Selected Characteristics of Stormflow and Base Flow Affected by Land Use and Cover in the Chickahominy River Basin, Virginia, 1989-91

By Michael J. Focazio and Robert E. Cooper

U.S. GEOLOGICAL SURVEY
Water-Resources Investigations Report 94–4225

Prepared in cooperation with the

DEPARTMENT OF PUBLIC UTILITIES,
CITY OF NEWPORT NEWS

Richmond, Virginia

1995

U.S. DEPARTMENT OF THE INTERIOR
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SELECTED CHARACTERISTICS OF STORMFLOW AND BASE FLOW AFFECTED BY LAND USE AND COVER IN THE CHICKAHOMINY RIVER BASIN, VIRGINIA, 1989-91

By Michael J. Focazio and Robert E. Cooper

Abstract

The Chickahominy River of Virginia is a principal source of raw-water supply managed by the Department of Public Utilities, City of Newport News. The water is used by more than 330,000 people and many industries on the York-James Peninsula in southeastern Virginia. The river, associated wetlands, and artificial reservoirs also are important wildlife habitat and recreational-use areas. Selected characteristics of stormflow and base flow, and major land use and cover factors affecting the quality of water and streamflow of the nontidal Chickahominy River from 1989 through 1991 are presented.

Five storms were sampled during the study at each of three continuous-record streamflow-gaging stations and at two partial-record streamflow-gaging stations on the main stem. Two of the continuous-record stations were located on the main stem of the Chickahominy River; one was located on a major tributary in an urban area. The characteristics of streamflow are primarily affected by basin size, shape, and geomorphology, but land use and cover also affect streamflow. Water flowing through the upstream station on the main stem of the Chickahominy River drains from residential land and produces hydrographs that have lower peaks, slower rises and falls during storms, and longer durations than hydrographs from the urban station. Hydrographs at the downstream rural station on the main stem of the Chickahominy River are dominated by base flow and rise and fall more gradually than hydrographs for the urban and residential stations.

The stormflow water-quality data indicate that mass loads per square mile of selected nutrients, selected trace metals, and suspended sediment generally are greater from the urban station than the residential and rural stations. Selected total recoverable metals and selected nutrients increase in concentration when suspended-sediment concentrations increase during storms at the urban station and, to a lesser extent, at the residential station. The greatest concentrations of suspended sediment and other constituents were consistently found before the peak of the hydrograph during storms at the urban and residential stations. This "first-flush effect" was not consistently observed at the rural station. Accordingly, input and transport of these constituents in the Chickahominy River Basin depends, to a major degree, on the suspended-sediment load in runoff from the urban and residential areas. Mass loads of suspended sediment, total recoverable zinc, and total recoverable manganese decreased downstream during storm 4, indicating that there was a sink for these constituents between the urban and rural areas during the storm. No sinks were found during storm 1; thus, peak flows of sufficient magnitude could be necessary to inundate the flood-plain wetlands with overbank flooding to result in sinks for suspended material.

Sedimentation rates are greatest in the flood-plain wetlands downstream from the urban areas. The extent to which the material deposited in these areas can be resuspended during runoff events is unknown, but visual observations indicate that resuspension occurs. Consequently, the differences in mass of suspended material upstream and downstream of the flood-plain wetlands depends on the characteristics of an individual runoff event.

Water-quality samples were collected three times during interstorm periods of base flow throughout the study period at the 5 stations where storm data were collected, and at least seven times preceding the study at 23 other stations in the basin. The greatest concentrations of many constituents analyzed at the 23 stations during base flow

were found at and near the urban station. The mean concentrations of 8 of 13 constituents were greater at the urban station than at the other four stations. Base-flow loads of total recoverable copper, nickel, zinc, and chromium increase with distance downstream through reaches with few or no known point discharges. Thus, ground water and (or) transport of constituents associated with sediment also can contribute constituents to the river during interstorm periods. Consequently, runoff is not the only important mechanism of constituent input to the stream channel.

The results of this study indicate that relations can be found among land use and cover, water quality, and streamflow. These relations are not well defined and require further study to assist management of the water resources, particularly as the urban and residential areas expand and affect the flood-plain wetlands.

INTRODUCTION

The Chickahominy River supplies raw water to more than 330,000 people and to many industries on the York-James Peninsula in southeastern Virginia (fig. 1). The first step to understand the factors that affect water quality of the river that supplies the reservoirs is to characterize the streamflow and quality of water in the basin that drains from different land covers. The information needed for this type of characterization includes analyses of water quality during intrastorm and interstorm periods for areas draining different land uses and for long periods of time. These water-quality and streamflow-characteristics data can be used to detect temporal and spatial patterns. These processes are important to understand, particularly as the Richmond metropolitan area, which includes the City of Richmond as well as Henrico and Hanover Counties, continues to increase in size; thus, increasing runoff and input of constituents to the river basin. Accordingly, the U.S. Geological Survey (USGS), in cooperation with the Department of Public Utilities, City of Newport News, Va., analyzed the streamflow, water quality, and processes affecting the quality of water and streamflow in the nontidal parts of the basin.

The field data for this study were collected from the fall of 1989 through the summer of 1991. The results of this study are part of a potential long-term monitoring program and represent a preliminary understanding of the water quality and streamflow characteristics.

Purpose and Scope

This report describes selected characteristics of stormflow and base flow and their possible relation to major land uses and covers in the Chickahominy River Basin from 1989 to 1991. The water-quality constituents that were analyzed include dissolved oxygen, nutrients, trace metals, and suspended sediment. Physical properties that were measured include pH, water temperature, and specific conductance.

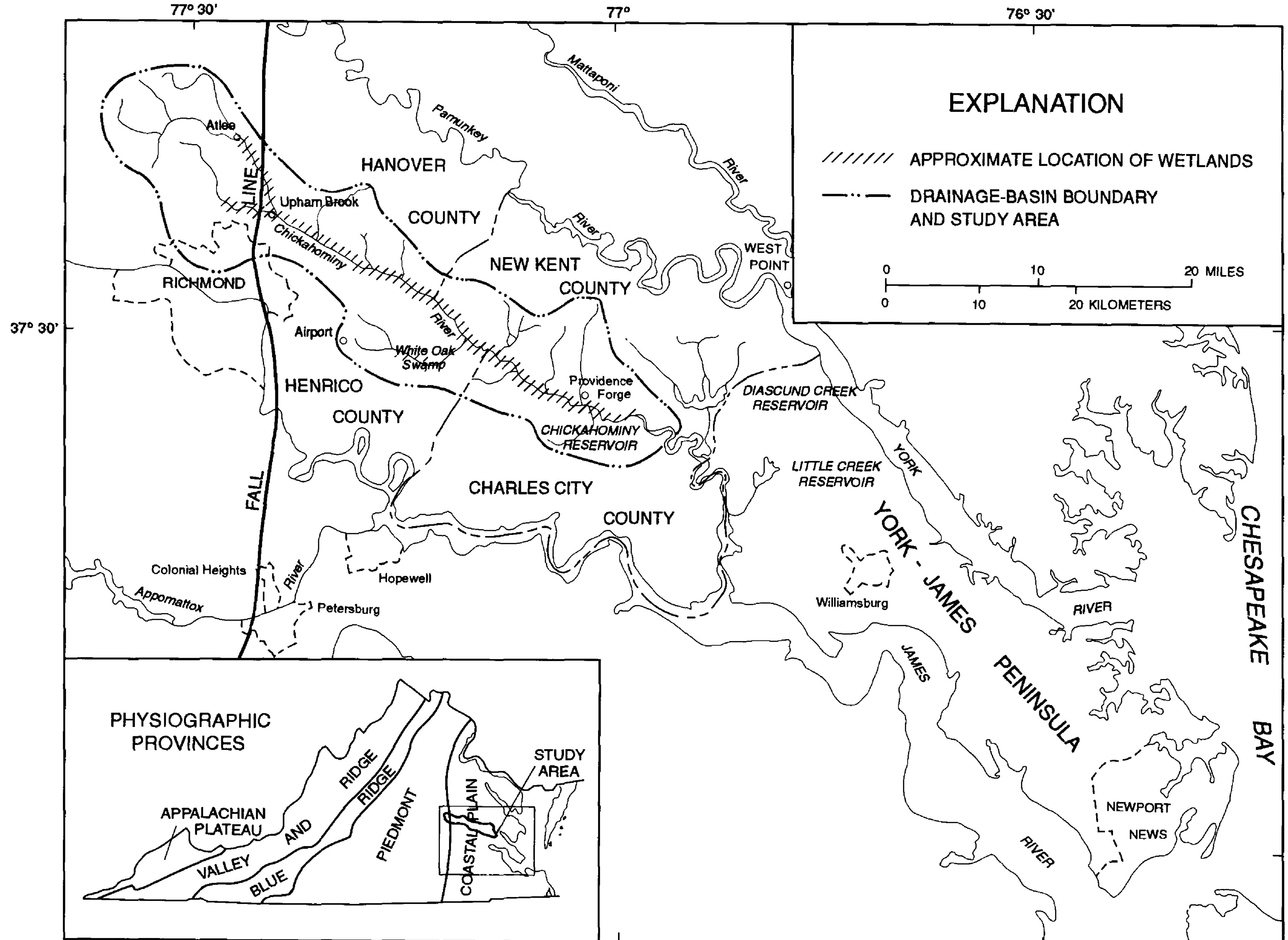
Five storms and three base flows were sampled for the 2-year period for each of three continuous-record streamflow-gaging stations and two partial-record streamflow-gaging stations. The stations selected are representative of different land use and covers in the Chickahominy River Basin. Data on base flow was supplemented by data from several other samples collected before this study (Prugh and others, 1990). Lynch (1993) described the limnology and water quality of the water-supply reservoirs for the City of Newport News.

Description of Study Area

The Chickahominy River Basin encompasses approximately 305 mi^2 in the York-James Peninsula of southeastern Virginia and includes parts of four counties and the northern part of the City of Richmond (fig. 1). The Chickahominy River is a major tributary of the James River, which discharges to the Chesapeake Bay. The study area starts at the headwaters of the Chickahominy River and extends to the free-flowing channel at Providence Forge, just upstream from Walkers Dam. The river is tidally influenced downstream from Walkers Dam.

The headwaters of the Chickahominy River are in the Piedmont Physiographic Province and are underlain by consolidated and fractured bedrock with an overburden of variable thickness (Daniels and Onuschak, 1974). The Piedmont is characterized by gently rolling hills with well defined stream channels. The primary use of the land has changed in the past 20 years from agriculture to residential and small-industry use.

Most of the river lies in the Coastal Plain Physiographic Province, which is underlain by unconsolidated, layered sedimentary deposits that lie on consolidated bedrock (Meng and Harsh, 1988). The Coastal Plain is characterized by low relief, poorly defined stream channels, broadly cut stream valleys, and flood plains dominated by palustrine, bottomland, and hardwood wetlands. The river basin gently slopes toward an estuarine environment.



Base from U.S. Geological Survey 1: 250,000

Figure 1. Location of study area. (Modified from Lynch, 1993, fig. 2.)

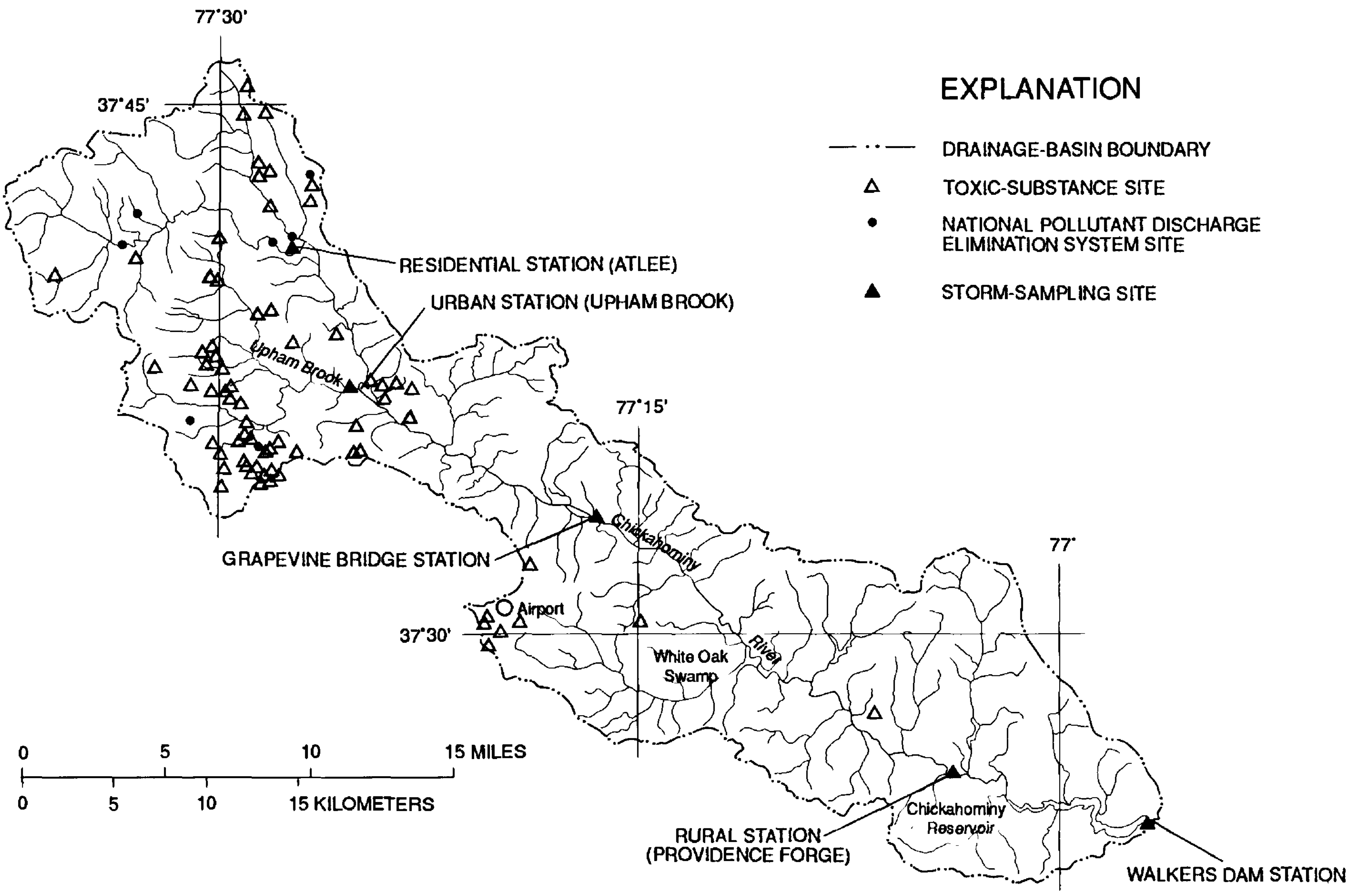


Figure 2. Location of Toxic Substance and National Pollutant Discharge Elimination System sites in the Chickahominy River Basin.

Urban development of the City of Richmond, and the surrounding counties of Hanover and Henrico, continues to expand within the Chickahominy River Basin. This urban land includes light and heavy industry, commercial, and residential land uses. East of Henrico County, land use has basically remained rural, with some residential areas.

The Virginia Toxic Substance Information Act required the Commonwealth of Virginia to compile a list of all constituents manufactured, used, and (or) stored by businesses in the State. Current land-use maps of the Chickahominy River Basin were unavailable for this study; however, locations of businesses on the Toxic Substance List are indicative of the land-use patterns in the area (fig. 2). Most of the businesses on the list are located in the Upham Brook Basin, in or near, the City of Richmond and surrounding urban areas. Sites permitted under the National Pollutant Discharge Elimination System (NPDES) as of 1988 also are shown in figure 2. The NPDES sites are all found in the urban areas of the basin. Other major land-use patterns were identified by visual observations in the field.

The precipitation patterns in the study area are typical of humid climates in the Mid-Atlantic area. Most storms are associated with large air masses in low-pressure systems that can last several days. These storms tend to produce spatially uniform precipitation patterns across the basin. In contrast, spatially non-uniform thermal-convection patterns are common in the summer months and produce storms that are more intense and short-lived.

Acknowledgments

The authors thank M. Eileen Rowan, now at the Virginia Department of Environmental Quality, for organizing and conducting the field work for this project. Thanks also are extended to Ronald Harris at the Newport News Water Works for reviewing the manuscript.

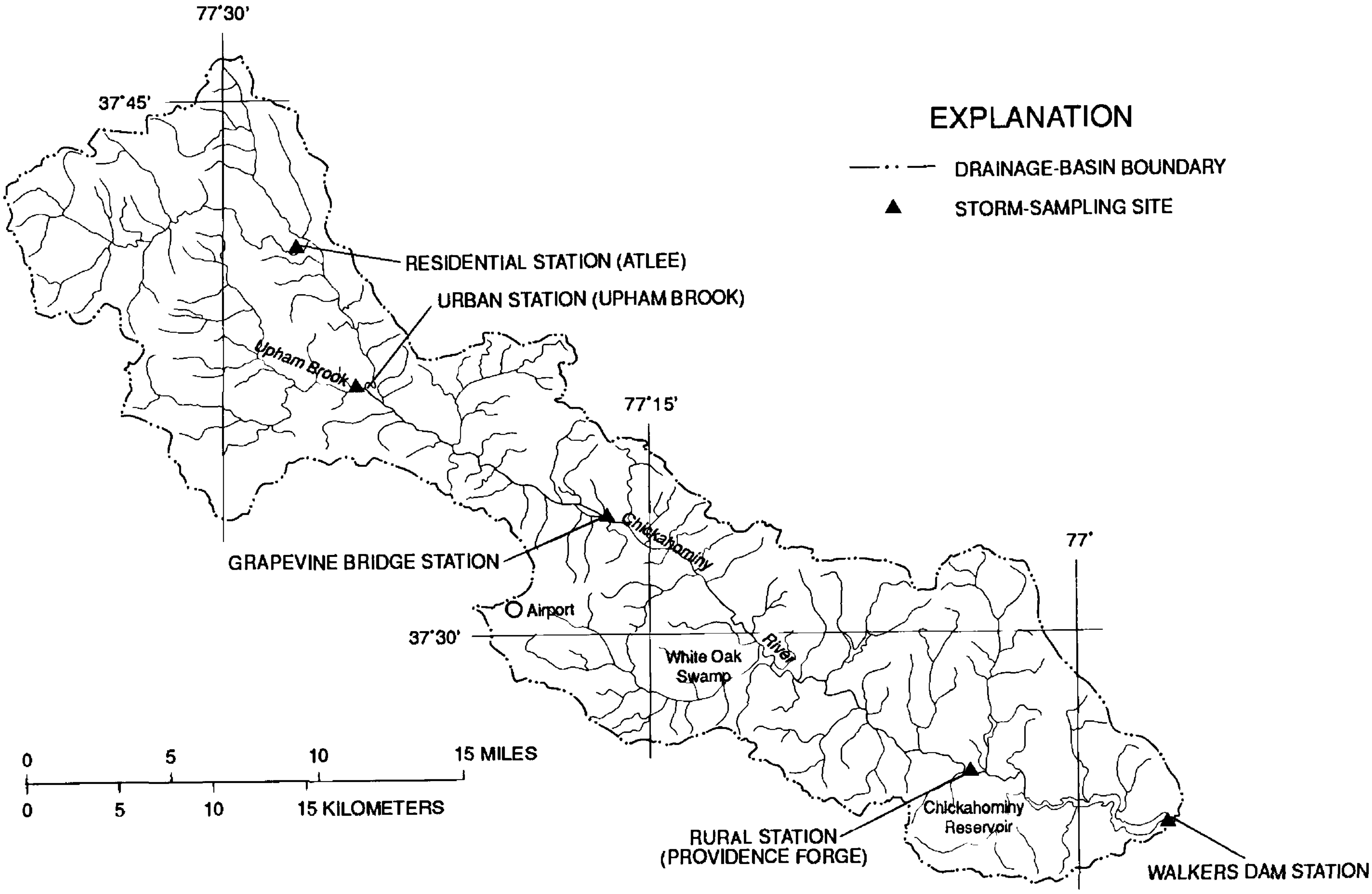


Figure 3. Location of storm-sampling sites in the Chickahominy River Basin.

METHODS OF INVESTIGATION

Standard USGS protocols (Ward and Harr, 1990; Edwards and Glysson, 1988; Guy, 1969) were used for all field and laboratory techniques and analyses. Methods that were unique to this study are described in this section, including location of sampling stations, constituents analyzed, hydrograph separations, and load calculations.

Five stations were established in the basin to collect hydrologic and water-quality data. Samples were collected during storms at three continuous-record gaging stations in the basin (fig. 3). For the purposes of this report, these three storm-sampling sites are referred to by general land-use setting. Land use was not based on any existing rigorous land-use classification. The farthest upstream station (hereafter called the residential station) is located at Atlee, Va., and was installed in 1989 for this study. Water from this station is representative of water draining from a residential basin. Upham Brook is a major tributary of the Chickahominy River and drains parts of the urban Richmond area and parts of Henrico County (fig. 1). A gage was installed on this tributary just upstream from its mouth (hereafter called the urban station). The flow through the urban station is representative of water from an urbanized basin. The site farthest downstream is on the main stem at Providence Forge, Va., above Walkers Dam (hereafter called the rural station) and has been in operation since 1943. This station is located in a rural area; however, water flowing to it drains from different upstream land uses and covers. Accordingly, water chemistry at the rural station is affected by a combination of urban, residential, and rural land uses and covers. This water is representative of the raw-water conditions upstream of the intake for the Chickahominy Reservoir (fig. 1); however, there are several miles of stream channel between Providence Forge and the water intake. Periodic samples of stormflow were collected from a fourth site on the main stem at Grapevine Bridge (fig. 3).

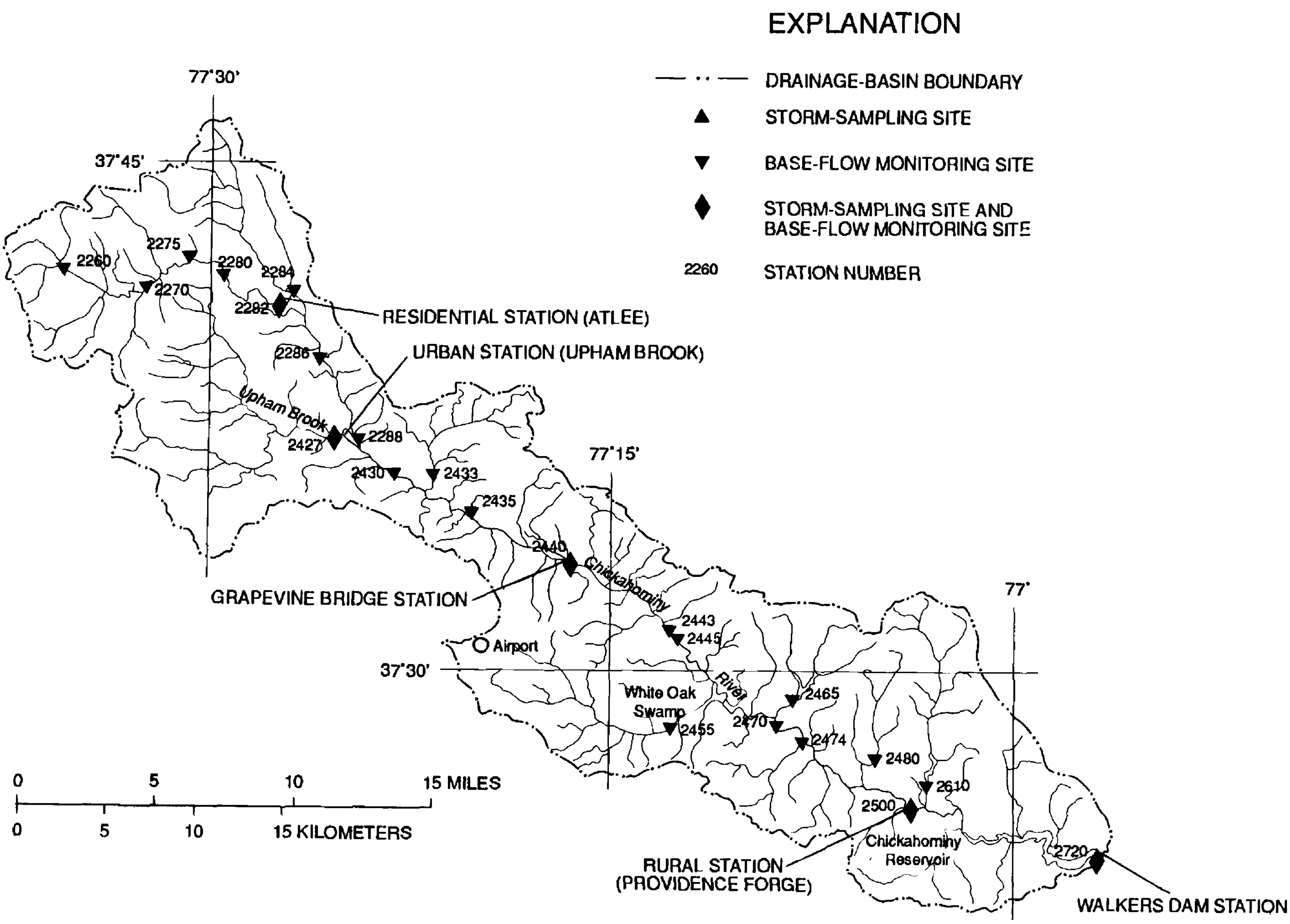


Figure 4. Location of base-flow monitoring sites in the Chickahominy River Basin.

This site was chosen because it is midway through a large wetland area, the upper part of which receives urban runoff from Richmond. The site is upstream from where the water travels through the remaining wetlands in the study area. The fifth site was located at Walkers Dam (fig. 3) near the raw-water intake, where periodic sampling also was conducted.

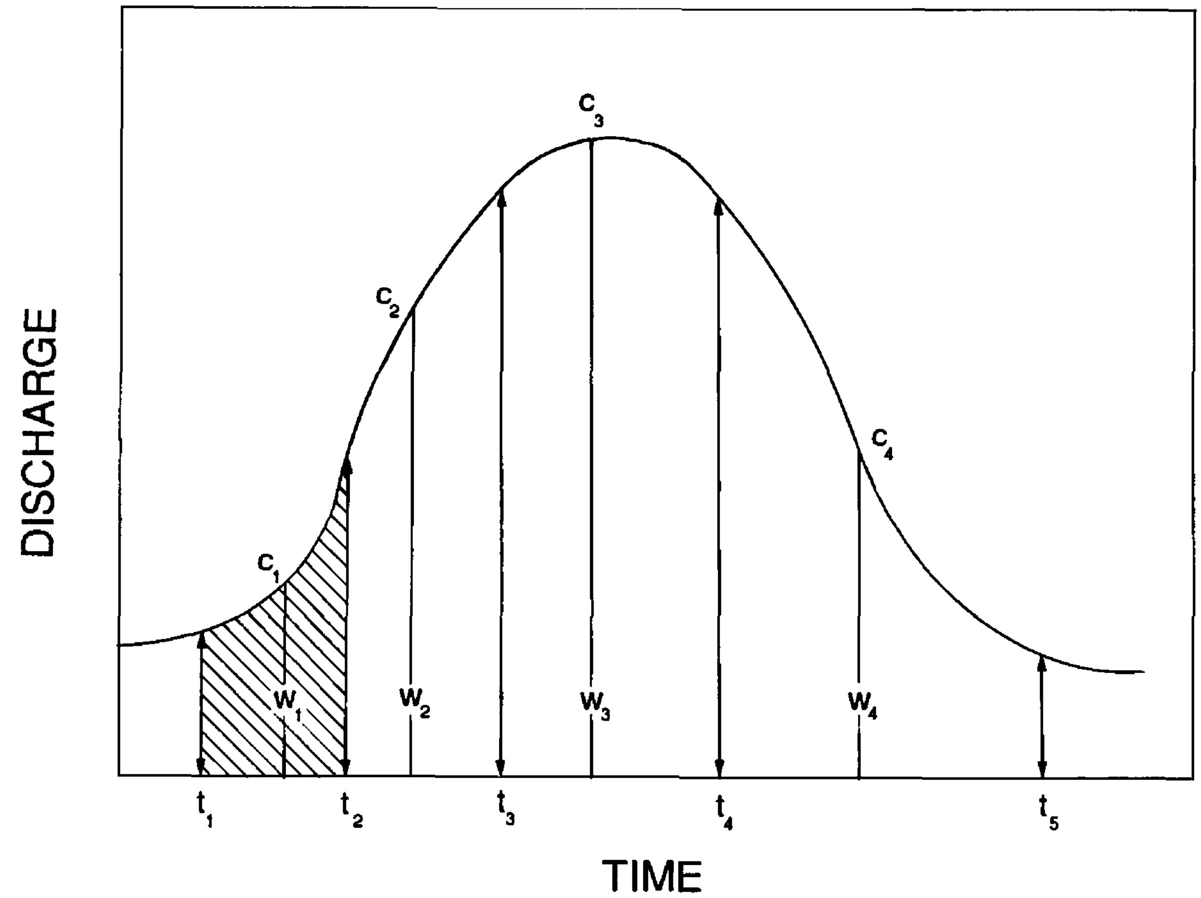
During interstorm periods, base-flow samples were collected three times at the five stations. Additional base-flow data collected at other sites before this study began were obtained from historical data. The historical data were collected at 23 bridge crossings where streamflow was measured (fig. 4).

Hydrograph Separation

Streamflow hydrographs (hereafter called hydrographs) are graphical representations of stream-discharge related to time at a gaging station. The total streamflow represents contributions to flow from precipitation and base flow (ground water). The part of the hydrograph that represents the contribution of ground water is separated from the part that represents the contribution of stormwater by a hydrograph-separation technique described by Rutledge (1993). The method estimates daily ground-water discharge, based on records of daily streamflow. This method provides an estimate of the total volume of flow at a gaging station that is due to ground water and that is due to surface runoff.

Constituents Analyzed

Water samples were analyzed at the USGS National Water Quality Laboratory in Denver, Colo., for determination of nutrient and trace-metal concentrations. Suspended-sediment concentrations were analyzed at the USGS Sediment Laboratory in Harrisburg, Pa. Specific conductance, dissolved oxygen concentration, pH, and



EXPLANATION

(hatched)	AREA UNDER THE CURVE FOR TIME PERIOD 1 BETWEEN t_1 AND t_2
C	CONCENTRATION OF THE SAMPLE FOR CORRESPONDING TIME PERIOD
W	LOAD FROM TIME PERIOD--Found by multiplying area of time period by C

Figure 5. Hypothetical hydrograph showing method used to calculate storm loads.

water temperature were measured in the field. The chemical constituents and physical properties that were analyzed in the laboratory included suspended sediment; color; alkalinity; total hardness; dissolved constituents (including chloride, sulfate, fluoride, iron, and manganese); total recoverable metals (including chromium, copper, lead, zinc, nickel, cadmium, iron, manganese, mercury, and arsenic); nutrients (including total nitrogen (ammonia + organic), dissolved nitrogen (ammonia), dissolved nitrogen (NO_2^- + NO_3^-), total orthophosphorus, total phosphate, total phosphorus, and total organic carbon); and organic compounds (including total cyanide, total phenols, and oil and grease).

Load Calculations

Chemical-constituent loads were estimated by dividing the storm hydrograph into time periods that represented the volume of flow associated with each water-quality sample (fig. 5). The periods were defined by first locating the time of the beginning of the rise in the hydrograph (t_1) and the time midway between the first sample (C_1) and the second sample (C_2), which is labeled by t_2. In this way, the first period is defined by the endpoints t_1 and t_2 and the corresponding concentration C_1. Accordingly, the representative volume for C_1 is the shaded area in figure 5. The individual periods thus represent the volume of the storm hydrograph characterized by the representative sample concentration. The hydrograph was integrated between the endpoints of each period to calculate the volume of flow for each period. These volumes were then multiplied by the representative sample concentration (which was assumed to remain constant within its period) to calculate the load (W_1 for sample C_1) for each individual period. The last period ends at the time where the hydrograph returns to prestorm discharge levels, which is determined on the basis of characteristics of the individual hydrograph. Finally, all the individual periods were summed to estimate the total load for the storm.

Annual loads of selected constituents during base flow were estimated from the mean concentration sampled during base flow and from the total volume of base flow for the year at a particular station, assuming that concentrations do not change much during the year. The hydrograph separations were used to calculate the total volume of base flow for the study period.

SELECTED CHARACTERISTICS OF STORMFLOW

Five storms were sampled during the study period at the three continuous-record streamflow gaging stations and at Grapevine Bridge, where periodic discharge was measured. Hydrographs of the five storms are shown in figure 6 and indicate the times that water-quality samples were collected at each station. Two of the five storms were selected for analysis of individual storm loads. Storm 1 (May 1990) and storm 4 (March-April 1991) were selected because they are representative of storms of different magnitudes and the sample times were adequate for load computations.

Hydrologic Characteristics

There are no known human-related controls or transfers of water in or out of the Chickahominy River Basin upstream from Providence Forge, and there are no known transfers within the basin that cross subbasin boundaries. Accordingly, water flow and chemistry at the gaging stations are representative of the water that drains from the basin to those points.

The hydrographs of discharge for the three continuous-record streamflow-gaging stations for the study period are shown in figure 7. Hydrographs show the relation of discharge (or streamflow) to time at a specific gaging station and are affected by precipitation and physiographic characteristics, such as basin size and shape, land use and cover, and geology and soils. During interstorm periods, the hydrograph represents base flow. Base flow is defined as the sustained input of water to the river channel from the ground-water system. During storms, and for a short time afterwards, the hydrograph represents base flow plus stormflow components. The stormflow component consists of a peak and rising and falling limbs. The peak of a hydrograph is the highest streamflow that was recorded during a storm. Rising and falling limbs of a hydrograph represent the increase in streamflow with time before the peak and the decrease in streamflow with time after the peak, respectively. These hydrographs and the individual storm hydrographs show that each basin responds differently.

The residential station at Atlee, Va., drains approximately 62 mi^2 and is representative of a basin larger than the urban station that drains Upham Brook Basin (38 mi^2) and smaller than the downstream rural station at Providence Forge (252 mi^2). Total annual volumes of water flowing past the urban station are less than the residential station. The largest total annual volumes are at the rural station. This pattern is not consistent, however, when the annual runoff per unit area from the basins or individual storms is compared to the effects of land use, land cover, or precipitation patterns.

Comparison of Hydrographs for Urban, Residential, and Rural Basins

The large amount of impervious material, storm-drainage structures, and channels associated with urban areas can produce larger volumes of rapid surface runoff, less infiltration to the subsurface, and less evapotranspiration, compared to undisturbed drainage basins of similar size and with similar characteristics. The volume of water that reaches a stream channel at any given time is the result of a complex interaction between the surface and subsurface water. Urban development has been shown to increase runoff, reduce base flow, decrease runoff times, and increase velocities (Walesh, 1989) compared to basins without urban development. Thus, hydrographs for urban basins generally exhibit lower base flows, higher peaks, and more rapid rising and falling limbs than do hydrographs from comparable natural basins.

The characteristics of runoff from the hydrograph from the urban station can be compared with hydrographs from the residential and rural stations (fig. 7). Total volume of stormwater drained from the urban basin could be greater during specific storms than the total volume of water drained from the residential basin, even though the drainage area of the urban basin is smaller. The hydrograph at the rural station exhibits a large base-flow component with a subdued storm peak that lasts longer than storm peaks at the urban and residential stations. Hydrographs from the residential station show the combined effects of urban and rural areas on runoff and, therefore, exhibit responses that are between the two.

Part of the differences in the hydrographs is caused by the differences in drainage-basin size, shape, and geomorphology. It is beyond the scope of this project to analyze

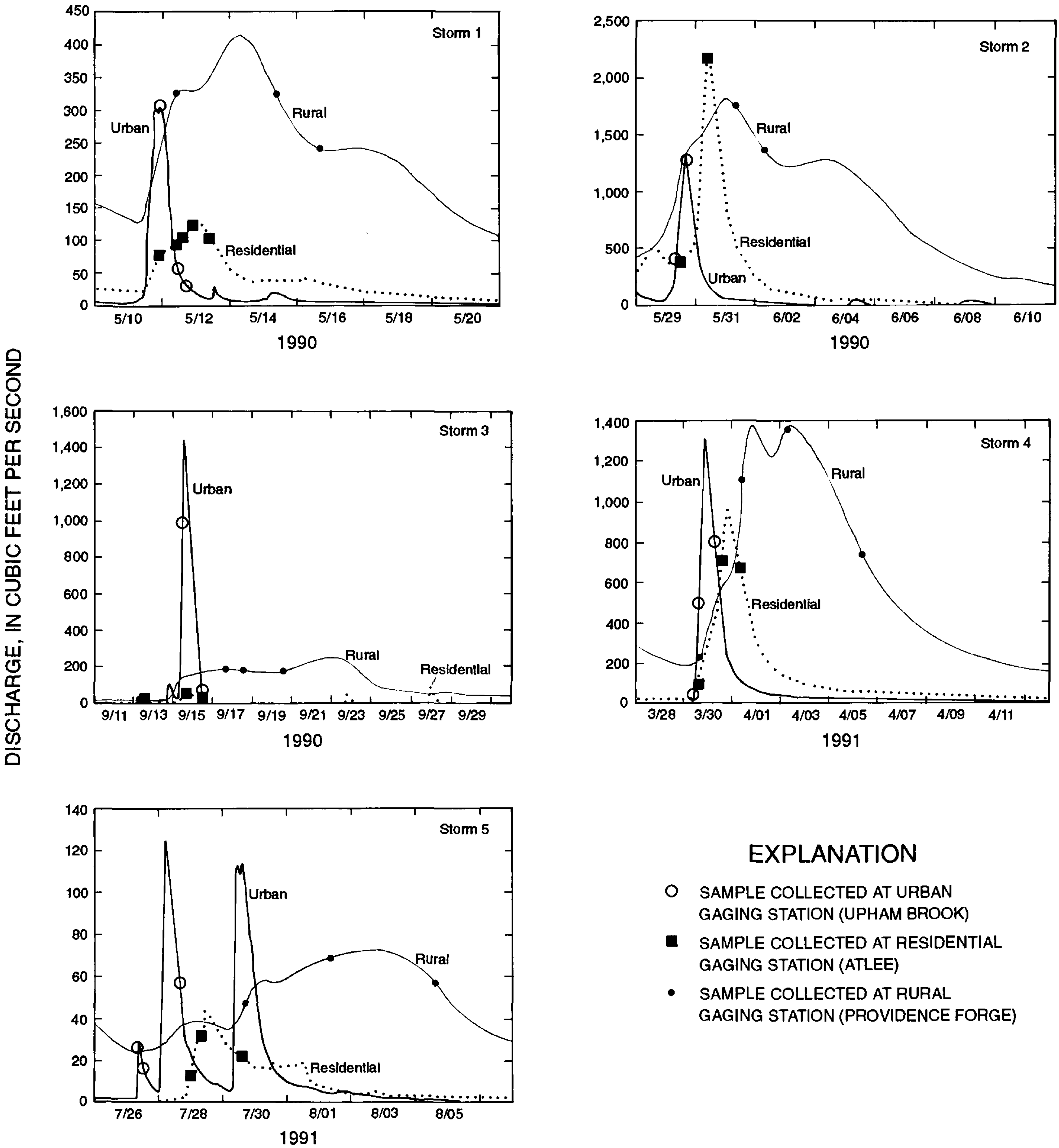


Figure 6. Stream discharge and times of sampling at three continuous-record gaging stations for storms 1 through 5 in the Chickahominy River Basin.

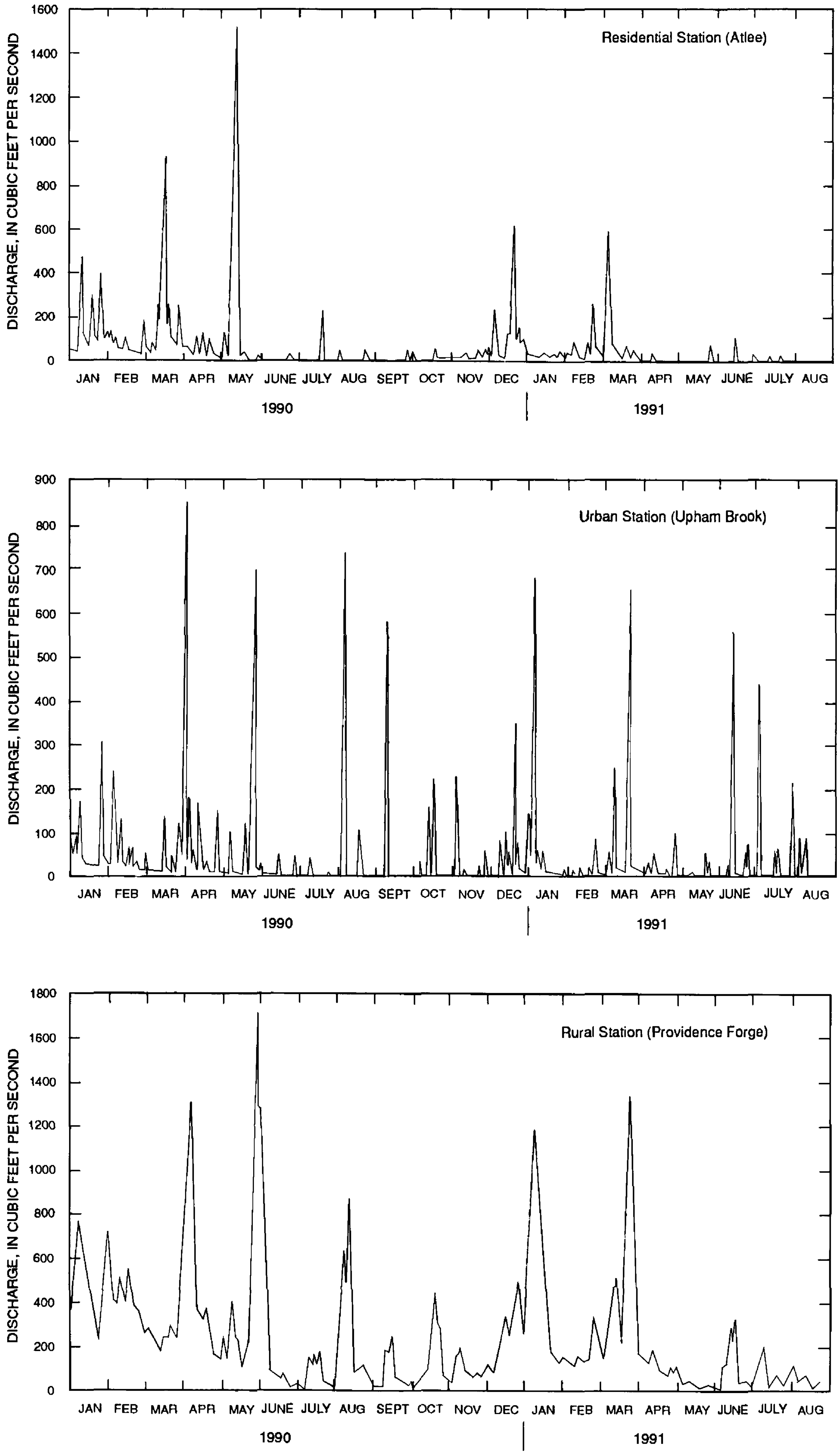

Residential Station (Atlee)
DISCHARGE, IN CUBIC FEET PER SECOND
0
200
400
600
800
1000
1200
1400
1600
JAN FEB MAR APR MAY JUNE JULY AUG SEPT OCT NOV DEC JAN FEB MAR APR MAY JUNE JULY AUG
1990
1991
Urban Station (Upham Brook)
DISCHARGE, IN CUBIC FEET PER SECOND
0
100
200
300
400
500
600
700
800
900
JAN FEB MAR APR MAY JUNE JULY AUG SEPT OCT NOV DEC JAN FEB MAR APR MAY JUNE JULY AUG
1990
1991
Rural Station (Providence Forge)
DISCHARGE, IN CUBIC FEET PER SECOND
0
200
400
600
800
1000
1200
1400
1600
1800
JAN FEB MAR APR MAY JUNE JULY AUG SEPT OCT NOV DEC JAN FEB MAR APR MAY JUNE JULY AUG
1990
1991

Table 1. Drainage areas and total flow volumes at three continuous-record gaging stations in the Chickahominy River Basin
[mi^2, square mile; ft^3, cubic foot; in., inch]

Station	Drainage area (mi^2)	Flow volume (ft^3)		Flow volume per unit area (in.)	
		Storm 1	Storm 4	Storm 1	Storm 4
Urban (Upham Brook)	38	19,400,000	108,000,000	0.22	1.22
Residential (Atlee)	62	16,700,000	156,000,000	.12	1.08
Rural (Providence Forge)	252	148,000,000	570,000,000	.26	.99

these differences in detail, but it is unlikely that the observed differences are entirely natural. For example, the residential drainage basin is about twice as large as the urban basin and they both drain land predominantly in the Piedmont Province, which is characterized by unconsolidated surficial deposits that overlie crystalline bedrock. The streamflow per unit area of drainage basin averaged 0.74 $(ft^3/s)/mi^2$ at the urban station and only 0.51 $(ft^3/s)/mi^2$ at the residential station in 1991. Therefore, on average, there is more runoff per unit area of drainage basin from the urban area than there is from the residential area, despite similar geologic and geomorphologic conditions and differences in drainage areas. This implies that land use can affect streamflow characteristics of the basins.

The area that drains to the rural station is the largest area (of the three basins being compared) and is underlain predominately by Coastal Plain deposits. The streamflow per unit area of drainage basin averaged 0.68 $(ft^3/s)/mi^2$ at the rural station in 1991, which is less than the streamflow from the urban basin. Despite the larger area drained at the rural station, the urban basin produces more streamflow per unit area. Distinguishing between the effect of the type of land use and natural processes is more difficult to ascertain at the rural station than it is for the urban and residential stations.

◀ **Figure 7.** Stream discharge at three continuous-record gaging stations from January 1990 through August 1991 in the Chickahominy River Basin.

Comparison of Hydrographs of Storms 1 and 4

The hydrographs of storms 1 and 4 were compared. The total volume of stormflow caused by each storm at each station is listed in table 1. Simple mass-balance analyses are limited because of the short durations of individual storms; however, some basic insights can be obtained on the general hydrologic response of the different basins to the two storms.

The combined storm volume for the urban and residential stations equals (approximately) 24 percent of the total storm volume at the rural station for storm 1. This percentage is low because the combined drainage area of the urban and residential basins is about 40 percent of the total drainage area draining to the rural station. This discrepancy is partly caused by the uneven rainfall distribution of this storm. Total precipitation at Richmond Airport was 1.35 in., whereas total precipitation for the same storm was 1.65 in., at West Point, Va. (fig. 1). Therefore, the amount of precipitation could have been greater at downstream locations than at upstream locations during this storm, which can partly explain the observed discrepancy in streamflow volumes. Another important factor that can affect streamflow is antecedent moisture conditions. For example, streamflows would be expected to be higher from a basin that has saturated soil prior to a storm than from a basin that has unsaturated soil.

Forty-six percent of the total storm volume of storm 4 can be attributed to the residential and urban drainage basins. This percentage corresponds more closely to the combined drainage area of 40 percent. However, the precipitation at the upstream precipitation gage was 2.82 in., for this storm, whereas the precipitation at the downstream gage was 1.92 in. Accordingly, the higher percentage of total flow from the upstream gages during storm 4 as compared with storm 1 can be explained partly by the rainfall distribution.

The total inches of runoff from a basin are calculated by dividing the volume of flow drained from the basin (in^3) by the area of drainage (in^2). Thus, two basins can differ in total volumes of runoff from a storm because of a difference in drainage area, but can produce the same amount of inches per unit drainage area of runoff. The urban basin produced more inches of runoff per unit drainage area than the residential station produced for storms 1 and 4 (table 1).

The storm hydrographs from the urban station are much steeper and last for a shorter duration than the residential and rural-station hydrographs. The peak of the storm hydrograph at the urban station occurs sooner than at the other stations. For storm 1, the peak at the urban station is approximately 1 day earlier than the peak at the residential station, and approximately 2 1/2 days earlier than the peak at the downstream rural station. For storm 4, the peak at the urban station is approximately 1 day earlier than the peak at the residential station, and more than 3 days earlier than the peak at the rural station. The storm hydrographs at the residential station are steeper and do not last as long as the storm hydrographs at the rural station, but have a smaller peak and longer duration than hydrographs at the urban station. Again, some of these differences are caused by basin size and shape and other natural characteristics of the basins, but the effects of urbanization likely contribute to the overall differences.

Wetlands also can affect storm hydrographs (Mitsch and Gosselink, 1986). In general, bottomland hardwood wetlands are associated with streams that maintain higher base flows (relative to storm-hydrograph peaks), longer duration storm hydrographs, and lower storm-hydrograph peaks than hydrographs from streams in upland areas that do not have wetlands. Thus, wetland areas attenuate the release of storm water. The wetland areas between the upstream gages and the downstream gage affect the hydrograph at the downstream gage. The peaks of the storm hydrographs at the downstream gage are more subdued and last longer than the hydrographs at the upstream gages. The total duration of the storm hydrographs at the rural station lasted for more than 10 days, but only 1 or 2 days at the upstream gages. Obviously, these differences also are due to the larger drainage area and other geologic and physiographic characteristics associated with the intervening wetlands.

Water Quality

The constituents analyzed from storm samples are listed in the "Methods" section. The constituent data collected during these storms are reported by Prugh and others (1990; 1991a,b; 1992a,b) and summarized in table 2. The chemical constituents that were consistently detected at concentrations slightly above laboratory detection limits and (or) not detected at all were not investigated further in this study. Of these constituents, total recoverable mercury, arsenic, and total phenol levels were found to be slightly above the detection limits at all four stations at various times throughout the study. The detection of these constituents is important from a management perspective because of the known and assumed adverse effects on human health and ecological processes and the potential for future increases in concentration. Total cyanide was the only constituent not found above detection limits (0.010 mg/L).

Concentrations of Selected Constituents

Many factors can affect the water quality of a river during a storm, including both natural and anthropogenic factors. Natural factors that affect the water quality of a river include weathering of minerals and subsequent geochemical processes that provide the source of a given constituent in river water. A major anthropogenic factor is the type of land use in the basin. Fertilizers applied to agricultural and residential areas are often classified as nonpoint sources of contamination. Other anthropogenic sources of contaminants, where constituents are directly discharged into the river system through pipes and other conveyance systems, are called point sources. Water from nonpoint sources is delivered to a river system by groundwater discharge and storm runoff; thus, nonpoint-source water typically takes longer to reach a river channel than does water from point sources. Nonpoint-source water can come in contact with soils and vegetation in the basin before reaching the stream channel.

During storms, chemical constituents can be transported in the waters in the dissolved phase and (or) adsorbed by the suspended sediment. The erosive force of the water from falling rain, runoff, and other forms of flowing water dislodges soil particles in the basin as the water moves toward streams. These particles include inorganic material, such as sand and silt, and various forms of organic matter, such as leaf litter. The particles originate in stream banks and bottoms or elsewhere in the basin, wherever the erosive forces are great enough for

Table 2. Summary of stormflow water-quality data

[Concentrations are given in milligrams per liter, except for specific conductance, which is given in microsiemens per centimeter at 25 degrees Celsius; count is number of samples above detection limits; -- indicates analysis is not available]

Statistic	Suspended Sediment	Specific conductance	Dissolved oxygen	pH	Alkalinity, as $CaCO_3$	Chloride	Sulfate, as SO_4	Organic carbon, as C	Ammonia plus, organic, total, as N	Ammonia, dissolved, as N	Nitrite + nitrats, dissolved, as N	Phosphorus, total, as P	Phosphats, total, as PO_4	Phosphorus, ortho total, as P
Residential Station (Atlee)														
Count	16	16	10	15	16	16	15	16	16	16	16	16	16	16
Minimum	7	41	3.4	5.7	8.0	.9	6.6	8.7	.5	.008	.079	.049	.077	.025
Maximum	94	370	8.7	8.3	50	18	32	15	1.6	.229	.826	.135	.267	.087
Median	21	124	6.1	6.6	20	15	9.4	13	.8	.062	.184	.099	.150	.049
Urban Station (Upham Brook)														
Count	14	14	6	12	12	12	12	12	13	12	13	13	14	14
Minimum	7	55	6.6	6.2	8.2	6.6	6.3	6.1	.7	.007	.278	.064	.101	.033
Maximum	208	223	9.6	8.7	34	35	15	19	1.4	.605	2.40	.169	.377	.123
Median	45	104	7.0	6.8	18	14	9.3	10	.9	.123	.410	.110	.204	.067
Grapevine Bridge Station														
Count	13	15	15	15	13	14	14	14	14	14	14	14	14	14
Minimum	5	48	4.4	5.5	5.0	6.8	1.8	8.1	.5	.025	.018	.062	.147	.048
Maximum	91	145	8.7	7.8	32	15	27	12	1.1	.115	5.30	.172	.224	.073
Median	16	101	5.8	6.6	12	12	6.8	11	.8	.043	.077	.087	.181	.059
Rural Station (Providence Forge)														
Count	13	14	14	14	13	13	13	13	14	14	14	14	14	14
Minimum	4	68	5.3	5.5	8.6	7.9	3.4	7.0	.5	.014	.015	.036	.071	.023
Maximum	19	122	9.2	7.1	33	13	25	12	0.8	.070	5.60	.110	.224	.073
Median	6	90	6.8	6.7	18	10	5.5	10	.6	.028	.120	.072	.158	.052
Walkers Dam														
Count	11	13	12	13	13	12	12	12	13	12	9	13	--	12
Minimum	4	40	3.7	5.4	11.0	6.9	3.1	9.1	.6	.010	.009	.021	--	.007
Maximum	12	100	9.8	7.0	123	13	14	12	1.1	.071	.227	.086	--	.044
Median	7	98	6.4	6.4	20	9	8.2	10	.6	.033	.032	.052	--	.016

Table 2. Summary of stormflow water-quality data—Continued

[Concentrations are given in micrograms per liter; count is number of samples above detection limits]

Statistic	Arsenic, total	Cadmium, total	Chromium, total	Copper, total	Lead, total	Iron, total	Iron, dissolved	Manganese, total	Manganese, dissolved	Mercury, total	Nickel, total	Phenols, total	Zinc, total
Residential Station (Atlee)													
Count	1	3	10	16	16	16	16	16	16	3	13	5	16
Minimum	45	1	1	2	2	1,400	300	50	50	1	1	1	20
Maximum	45	2	5	12	7	4,100	1,900	2,600	1,400	1	7	5	90
Median	45	2	3	3	3	2,950	765	295	205	1	2	2	30
Urban Station (Upham Brook)													
Count	11	3	11	12	12	12	12	12	11	2	11	5	12
Minimum	2	1	1	5	6	750	120	50	40	.1	2	1	10
Maximum	5	2	19	12	27	8,500	8,300	640	450	.5	6	14	90
Median	2	2	4	7	13	2,450	485	80	50	.3	2	2	40
Grapevine Bridge Station													
Count	7	8	10	14	14	14	14	14	14	0	13	8	11
Minimum	1	1	2	2	1	1,500	280	60	40	0	1	1	10
Maximum	28	8	6	18	5	4,100	1,400	620	680	0	20	5	140
Median	1	2	2	4	3	2,100	615	185	145	0	3	2	40
Rural Station (Providence Forge)													
Count	2	5	6	12	12	13	13	13	13	3	11	6	7
Minimum	1	1	2	1	1	660	560	30	30	.1	1	1	10
Maximum	1	4	3	14	4	2,600	1,700	210	140	.2	5	3	20
Median	1	2	2	3	2	1,400	780	150	90	.2	2	2.5	20
Walkers Dam													
Count	2	2	6	12	11	12	12	12	12	1	9	7	4
Minimum	1	3	1	1	1	680	260	40	10	.1	1	1	10
Maximum	1	4	4	4	7	2,100	900	440	390	.1	6	2	20
Median	1	3.5	1.5	3	2	1,300	625	100	45	.1	2	2	10

displacement. Eventually, some of the particles are suspended in the water and are called suspended sediment. Many point and nonpoint-source constituents are sorbed to suspended-sediment particles; therefore, whole-water samples (unfiltered) were analyzed to determine the total-recoverable concentrations of these constituents. Total-recoverable concentrations include the dissolved fraction of the constituent, as well as the fraction sorbed to suspended-sediment particles.

Spatial patterns related to land use and cover

The median concentrations (or values) of 12 of 27 constituents and properties are greater at the urban station than at the other four stations. Among the exceptions, ph, dissolved oxygen, total recoverable manganese, zinc, and nickel do not show distinct spatial patterns. Natural differences, such as mineralogy and dilution can account for some of the observed differences in water quality; however, the strong spatial pattern found in the urbanized area indicates that land use is a major effect on the observed stormwater quality. The urban area, therefore, is the source of water with greatest concentrations of many constituents of all the Chickahominy River stations that were monitored for this study.

The concentrations of suspended sediment are consistently greater at the urban station than the other stations and drop significantly at Grapevine Bridge, the next downstream station. The downstream decrease in concentrations of suspended sediment is a necessary (though insufficient) observation to support the hypothesis that the intervening wetlands function as a "sink" for suspended sediment. An area that functions as a sink will remove material from the river system by storage and (or) uptake processes. Accordingly, the total mass of material in the stream channel downstream of a sink area is less than the mass upstream of the sink.

Stormflow velocities decrease downstream from the urban station because of the lower relief and the increase in surface roughness because of vegetation. Trace metals and other constituents that are adsorbed to suspended-sediment particles are transported by the same processes that transport suspended sediment in the river system (Chan and others, 1982). Consequently, if the wetlands are a sink for suspended sediment during a storm, they also are a sink for adsorbed constituents. The wetlands potentially acting as a sink for suspended sediment and associated chemical constituents is reflected in the substantial decrease in concentration of total recoverable lead between the urban station and the downstream Grapevine Bridge station, followed by a decrease at the downstream rural stations at Providence Forge and Walkers Dam.

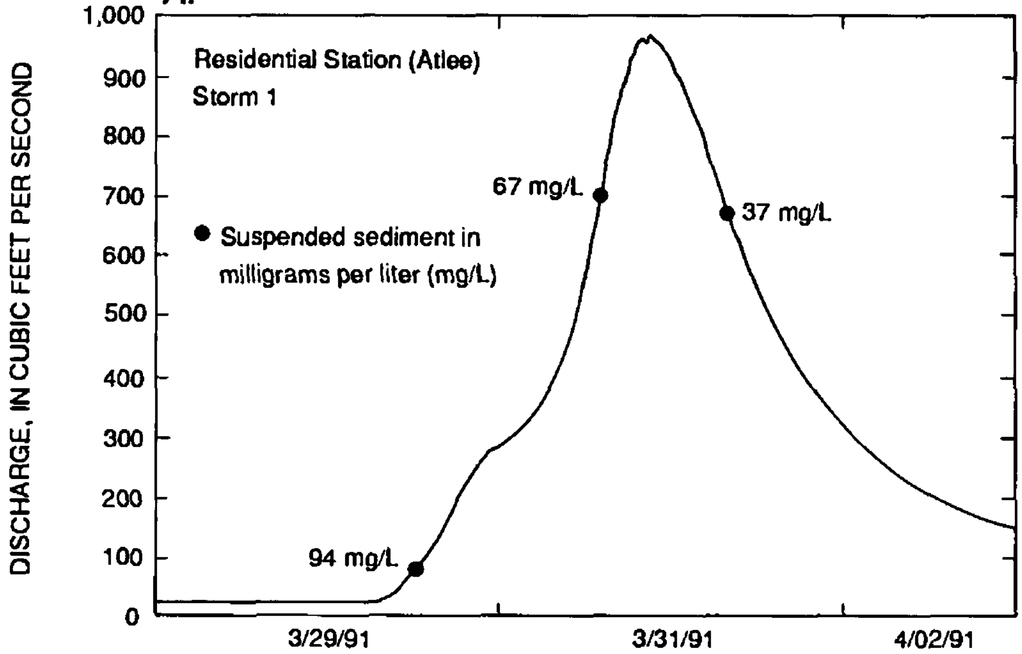
Temporal patterns related to land use and cover

Land use and cover can affect the timing of constituent delivery to a river system. Analysis of the water quality of a river often indicates a "first-flush effect" (Overton and Meadows, 1976), whereby the concentration of a constituent is highest before the stormflow peak and decreases thereafter. For example, the first flush of stormflow often has sufficient energy and volume to transport much of the loose soil in the basin's drainage area early in the storm; thereafter, the amount of erodible soil gradually decreases as the storm continues. Storm runoff from urban areas can reach the river channel quicker than storm runoff from rural areas because of the impervious surfaces and storm-water drainage systems and channels typical of urban areas. Accordingly, chemical constituents flushed from urban areas can reach a river earlier in a given storm than storms from non-urban areas, so that the first-flush effect can be most pronounced in urban areas. Accurate quantification of this effect is difficult without a continuous record of constituent concentrations throughout the storm. The effect can manifest itself, however, in recognizable patterns during a storm, even if the sampling frequency is low.

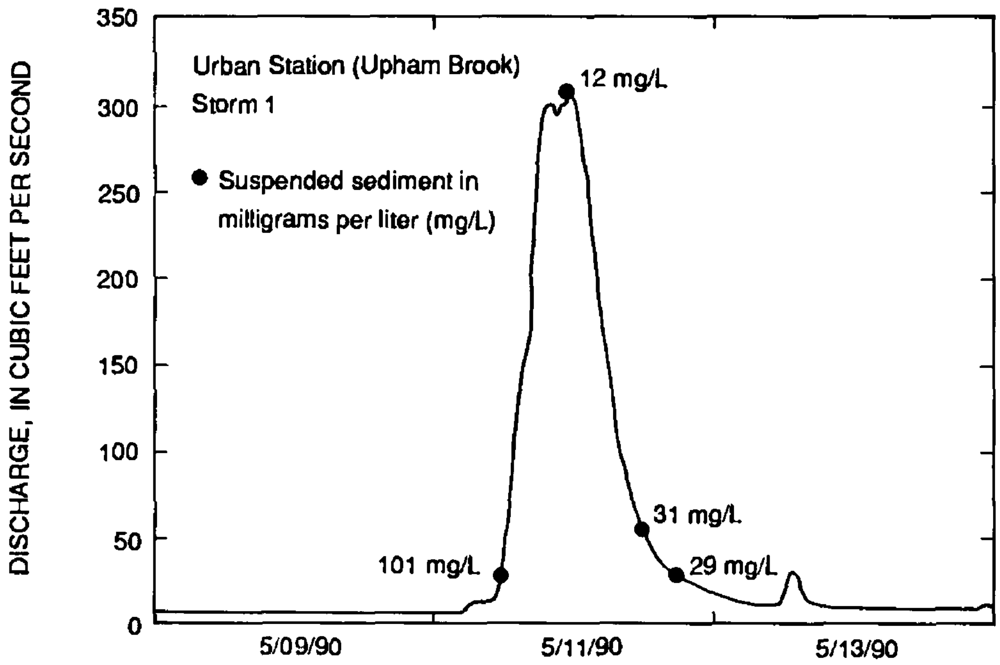
Evidence of the first-flush effect has been recorded at the urban and residential stations. The hydrograph for storm 1 at the urban station, with concentrations of suspended sediment at the times of sampling, is shown in figure 8B. The first water sample was collected early during the storm (before the peak of the hydrograph), when streamflow was about 25 ft^3/s. The sample contained 101 mg/L of suspended sediment. The second sample was collected at the peak of the hydrograph when streamflow was about 310 ft^3/s, the sample contained only 12 mg/L of suspended sediment. The fourth sample was collected near the end of the storm, when streamflow was about 25 ft^3/s but the water contained only 29 mg/L of suspended sediment.

The effects of dilution can be investigated by comparing the first suspended-sediment concentrations in samples collected at the hydrograph peak with the last concentration shown on the hydrograph (fig. 8B). The first sample was collected at the same flow rate as the fourth sample, but the suspended-sediment concentration of the first sample is about 3.5 times greater. This clearly shows that the source of suspended sediment decreased between

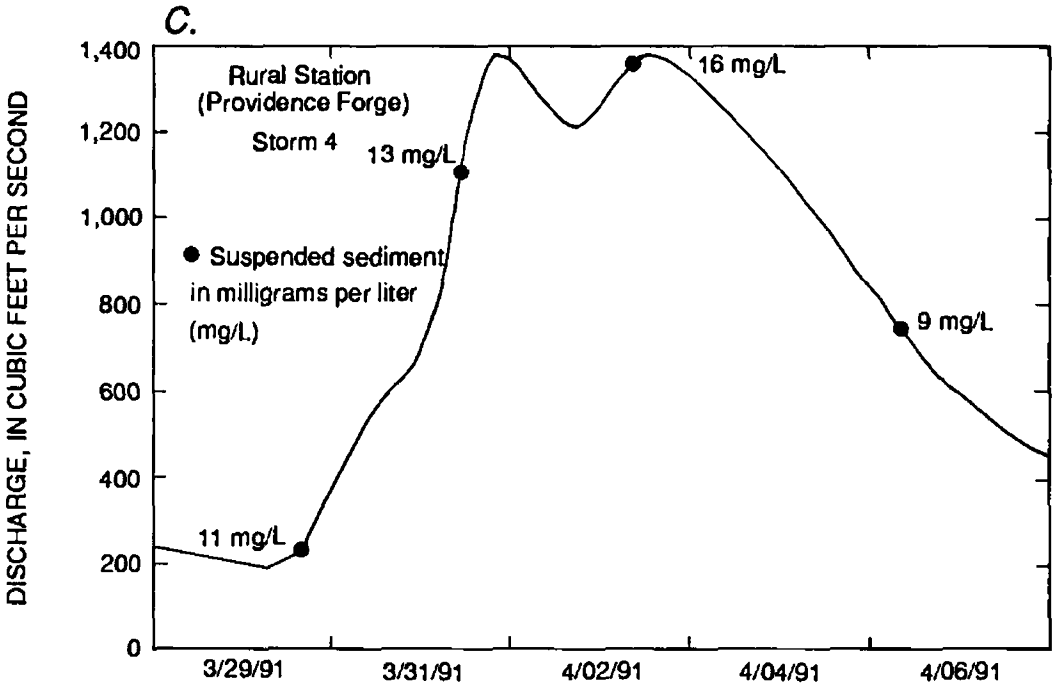
A.


1,000
900
800
700
600
500
400
300
200
100
0
DISCHARGE, IN CUBIC FEET PER SECOND
Residential Station (Atlee)
Storm 1
● Suspended sediment in
milligrams per liter (mg/L)
67 mg/L
37 mg/L
94 mg/L
3/29/91
3/31/91
4/02/91

B.


350
300
250
200
150
100
50
0
DISCHARGE, IN CUBIC FEET PER SECOND
Urban Station (Upham Brook)
Storm 1
● Suspended sediment in
milligrams per liter (mg/L)
12 mg/L
31 mg/L
29 mg/L
101 mg/L
5/09/90
5/11/90
5/13/90

C.


1,400
1,200
1,000
800
600
400
200
0
DISCHARGE, IN CUBIC FEET PER SECOND
Rural Station
(Providence Forge)
Storm 4
13 mg/L
16 mg/L
● Suspended sediment
in milligrams per liter
(mg/L)
9 mg/L
11 mg/L
3/29/91
3/31/91
4/02/91
4/04/91
4/06/91

the first and fourth samples, and that dilution did not take place. On the other hand, the suspended-sediment concentration in the first sample is more than 8 times greater than the suspended-sediment concentration in the sample collected at peak discharge, although the discharge at the first sample collection is only 8 percent that of the peak discharge. Dilution of 101 mg/L at 25 ft^3/s by an extra 285 ft^3/s (to equal 310 ft^3/s at the peak of the hydrograph) would result in about 8 mg/L at the peak of the hydrograph. The observed concentration at the peak of the hydrograph is 12 mg/L, indicating that dilution does not entirely control the change in concentration between the first sample and the peak, though it is likely the dominant process.

The effect of a storm's first flush is also shown for storm 4 at the residential station at Atlee by the concentrations of suspended sediment at the times of sample (fig. 8A). Suspended-sediment concentrations drop from 94 to 67 to 37 mg/L from the beginning of the storm hydrograph to its end. The second sample (67 mg/L) was collected before the peak of the hydrograph (at about 700 ft^3/s) and the third sample (37 mg/L) was collected after the peak of the hydrograph at a similar flow rate. The decrease in concentration after the peak of the hydrograph is further evidence of the first-flush effect. Suspended-sediment concentrations from storm 1 (not shown) at the residential station changed from 20 to 17 to 11 to 18 and finally to 7 mg/L. The peak of the hydrograph corresponds to the 18 mg/L concentration and the after-peak value was 7 mg/L. These results show that concentrations are slightly greater before and during the peak of the hydrograph than after the peak, but do not indicate a strong first-flush effect. The analysis of the data at the urban station indicates a more pronounced first flush than the residential-station analysis for both storms; which could be due, in part, to the timing of sample collection.

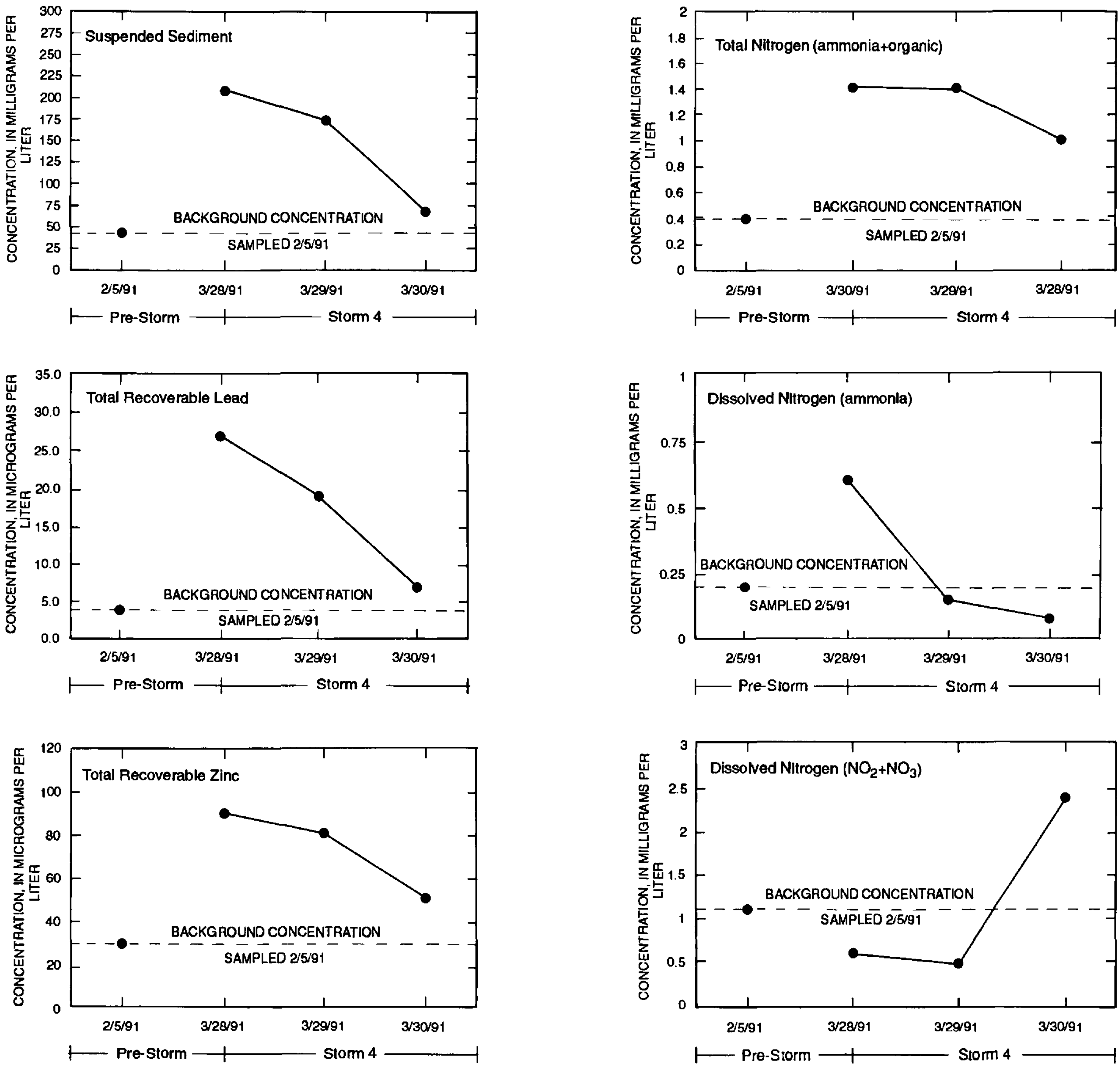
The results of suspended-sediment sampling at the rural station at Providence Forge emphasize the difference between the three gaged basins when compared with the other stations. The suspended-sediment concentrations during storms 1 (not shown) and 4 (fig. 8C) at this station only changed a small amount during the storm, compared with the other two stations. The concentrations of suspended sediment changed from 11 to 13 to 16 and to 9 mg/L during storm 4, with the greatest concentration sampled during the peak of the hydrograph. No discernible pattern could be related to first-flush effects. Analysis of other storms also supports the conclusion that the first-flush effect is most pronounced in the urban basin.

◀ **Figure 8.** Stream discharge and concentration of suspended sediment for storms 1 and 4 at the residential, urban, and rural stations in the Chickahominy River Basin.

Constituents that are typically associated with suspended sediment include certain metals and some nutrients. Plots of selected constituent concentrations show the relation to time during storm 4 at the urban station (fig. 9). The concentration of the base-flow sample collected before the storm also is shown in figure 9. This data point is shown to allow comparison of the prestorm concentration to the changes in concentration during the storm. A line is drawn connecting the data values to graphically emphasize the relative changes in concentrations before and during the storm. The suspended-sediment concentration was lower at base flow than at any time during the storm (fig. 9), though it returned toward prestorm levels after the hydrograph peaked. This pattern is similar to that of other constituents, including chromium (not shown), copper (not shown), lead, and zinc.

Concentrations of suspended sediment at the residential station (fig. 10), Grapevine Bridge (fig. 11), and the rural station (fig. 12), also exhibit an increase followed by a decrease toward prestorm levels. Concentrations of total recoverable zinc (fig. 10) and other metals (not shown) increased as concentrations of suspended sediment increased at the residential station and decreased toward prestorm levels; however, the patterns were not as closely related as were the patterns from the urban station. Concentrations of metals at the Grapevine Bridge station do not follow a pattern similar to suspended sediment. Concentrations of total recoverable lead (fig. 11) and other metals (not shown) fluctuate throughout the storm in patterns that are not consistent with patterns of suspended-sediment concentrations. No detectable relations were found for concentrations of metals and suspended sediment at the rural gage.

Nutrients that were analyzed included total phosphorus, total orthophosphorus, total phosphate, dissolved nitrogen ($NO_2^- + NO_3^-$), total nitrogen (ammonia + organic), dissolved nitrogen (ammonia), and total organic carbon. Total phosphorus and total orthophosphorus (not shown) concentrations are related to suspended sediment at the urban (fig. 9), residential (not shown), Grapevine Bridge (not shown), and rural (not shown) stations. Concentrations of total nitrogen (ammonia + organic) also are related to suspended sediment at the urban (fig. 9) and the residential (not shown) stations; however, no such relation to suspended sediment were found for dissolved nitrogen (ammonia) and dissolved nitrogen ($NO_2^- + NO_3^-$) at the



EXPLANATION

● MEASURED CONCENTRATION

— INTERPOLATED CONCENTRATION--for graphical purposes only

Figure 9. Concentration of selected constituents throughout storm 4 at the urban station (Upham Brook) in the Chickahominy River Basin.

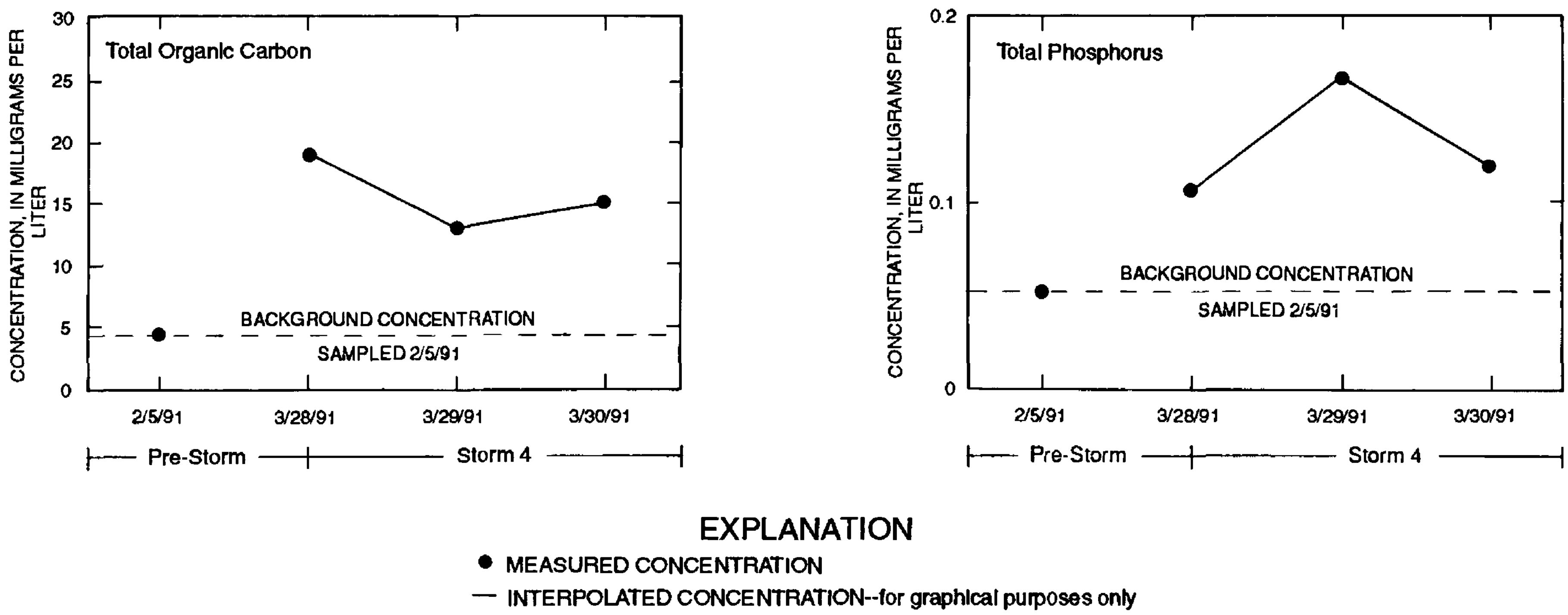


Figure 9. --Continued.

urban or residential stations. Total organic carbon includes suspended pieces of vegetation and other organic matter; therefore, it is related to suspended sediment. Concentrations of total organic carbon increase at all stations as concentrations of suspended sediment increase when the storm begins (figs. 9–12), but tend to remain at that level throughout the storm. The consistent high concentrations of total organic carbon throughout the storm could reflect high concentrations of dissolved organic carbon. Sampling procedures for suspended sediment, but not for total organic carbon, require a depth-integrated sample. Why concentrations of total organic carbon do not decrease toward prestorm levels as rapidly as concentrations of suspended sediment is unknown, but differences in sampling procedures could be involved.

Nutrient speciation and cycling information can yield important insights into the processes involved in the water quality of a river system. This study was not designed to assess nutrient cycling; however, concentrations of dissolved nitrogen (NO_2^- + NO_3^-) are consistently a higher percentage of the total nitrogen species at the urban station than at the other stations. The reason for this is unknown, but could result from a number of processes acting alone and (or) together, including: a more abundant source of NO_2^- and NO_3^- in the urban area than in other areas; more nitrification (the process by which ammonia is converted to NO_2^- and then to NO_3^-) in the urban area than in other areas; more uptake of NO_3^- by vegetation in other areas; or more denitrification (the process by which NO_3^- is converted to nitrogen gas) in the other areas.

Many of the same patterns were observed at all sites for storm 1, but were not as strong as for storm 4. Storm 1 was a less severe storm than storm 4, and the same erosive forces would not have been as strong as they were in storm 4. Thus, stormflow characteristics affect the timing and magnitudes of concentrations of constituents differently for different storms owing to suspended-sediment transport. These differences are amplified by effects of land use and cover.

Loads of Selected Constituents

Because of logistics and lack of available resources, the sampling frequency was minimal during storms. Also, the first-flush effect contributed the largest percentage of particular constituents to the stream channel before the peak of the hydrograph. These two facts make it impossible to quantify the margin of error for estimating loads from individual storms, but the estimated loads are expected to be fairly accurate in terms of relative values among the stations.

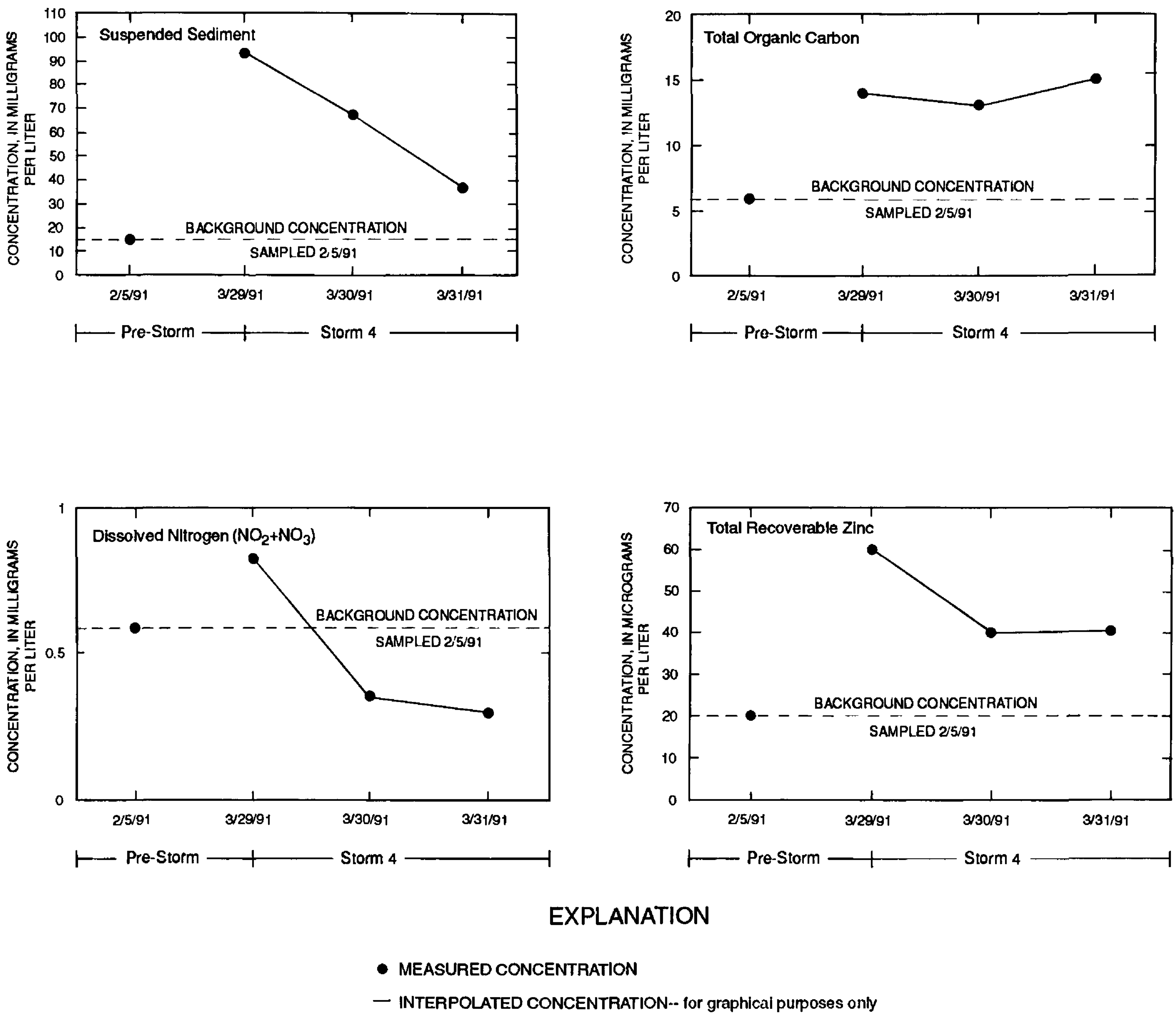


Figure 10. Concentration of selected constituents throughout storm 4 at the residential station (Atlee) in the Chickahominy River Basin.

Loads at the residential, urban, and rural stations for storms 1 and 4

The loads of selected constituents for storms 1 and 4 at the residential, urban, and rural stations are listed in tables 3, 4, and 5, respectively. Loads are presented in terms of total pounds of material for each storm and the pounds of material per square mile of drainage area for each station during each storm. As expected, the loads for storm 4 are greater for all constituents than for storm 1. For example, at the urban station, the total suspended-sediment load increased from 34,000 lb for storm 1 to 610,000 lb for storm 4; the total load of lead increased from 17 lb for storm 1 to 65 lb for storm 4. In comparison, the total load of lead at the rural station was 41 lb for storm 1 and 130 lb for storm 4.

Spatial patterns in loads related to land use and cover

The loads per unit drainage area indicate the effects of land use and cover (tables 3–5). The largest loads per square mile for suspended sediment, total recoverable

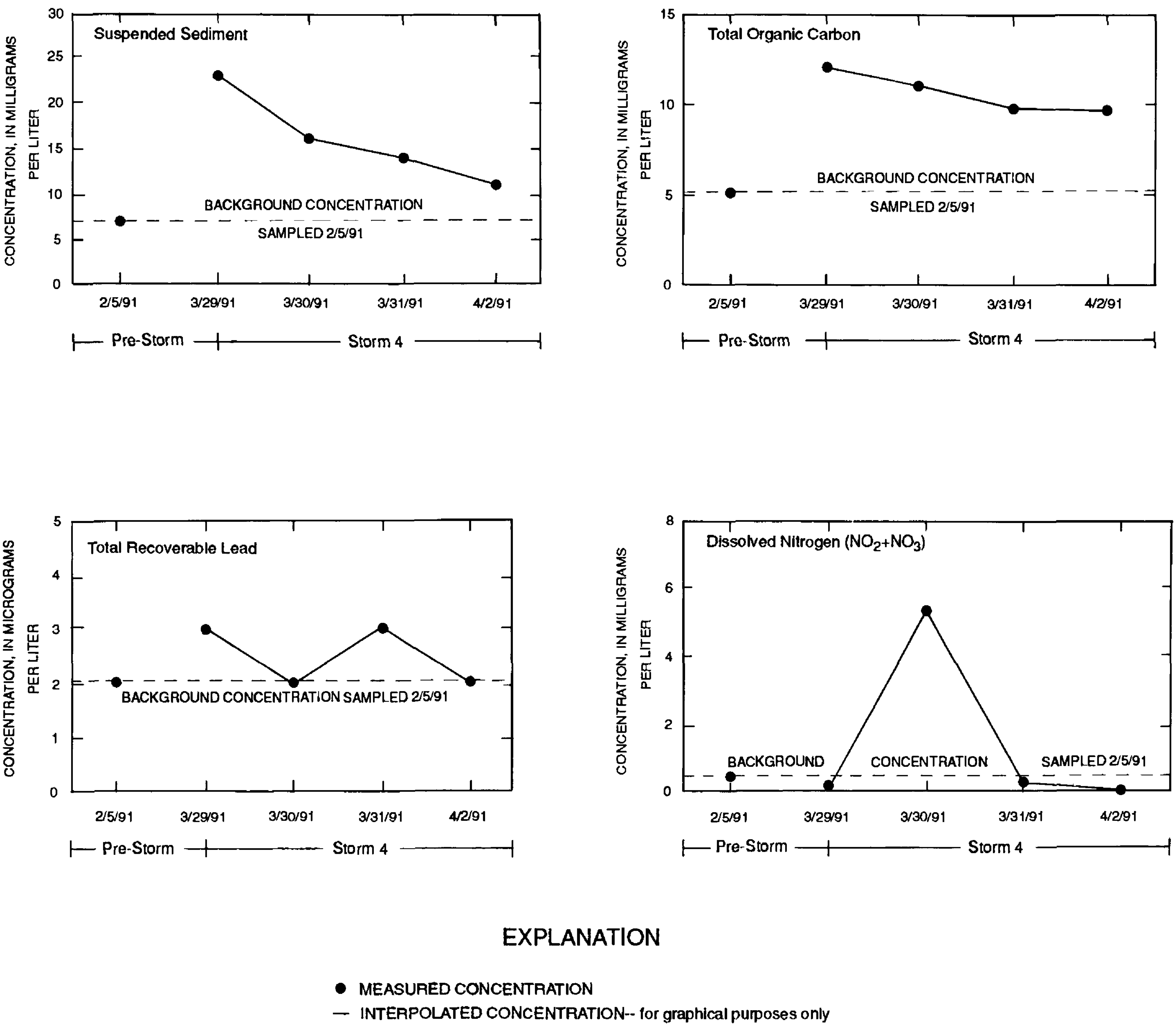


Figure 11. Concentration of selected constituents throughout storm 4 at the Grapevine Bridge station in the Chickahominy River Basin.

lead, total recoverable zinc, and total phosphate for storm 1 are at the urban station. The rural station had the largest loads per unit drainage area for both storms for dissolved chloride, dissolved iron (not shown), and total recoverable nickel. Total nitrogen (ammonia + organic), dissolved nitrogen ($NO_2^- + NO_3^-$), total orthophosphorus, total organic carbon, total phosphorus, and total recoverable copper loads per unit drainage area were highest for storm 1 at the rural station. The urban-station drainage basin is the major source per unit drainage area for many metals associated with suspended-sediment. The rural area, which integrates all drainage from upstream lands, is the major source for other constituents, including nutrients.

The loads per square mile for storm 4 were compared with the loads per square mile for storm 1. They were greater for more constituents at the urban station than at the other stations. The only constituents with lower loads per square mile at the urban station than at the rural station for storm 4 were dissolved chloride, dissolved sulfate, total recoverable nickel, and dissolved nitrogen

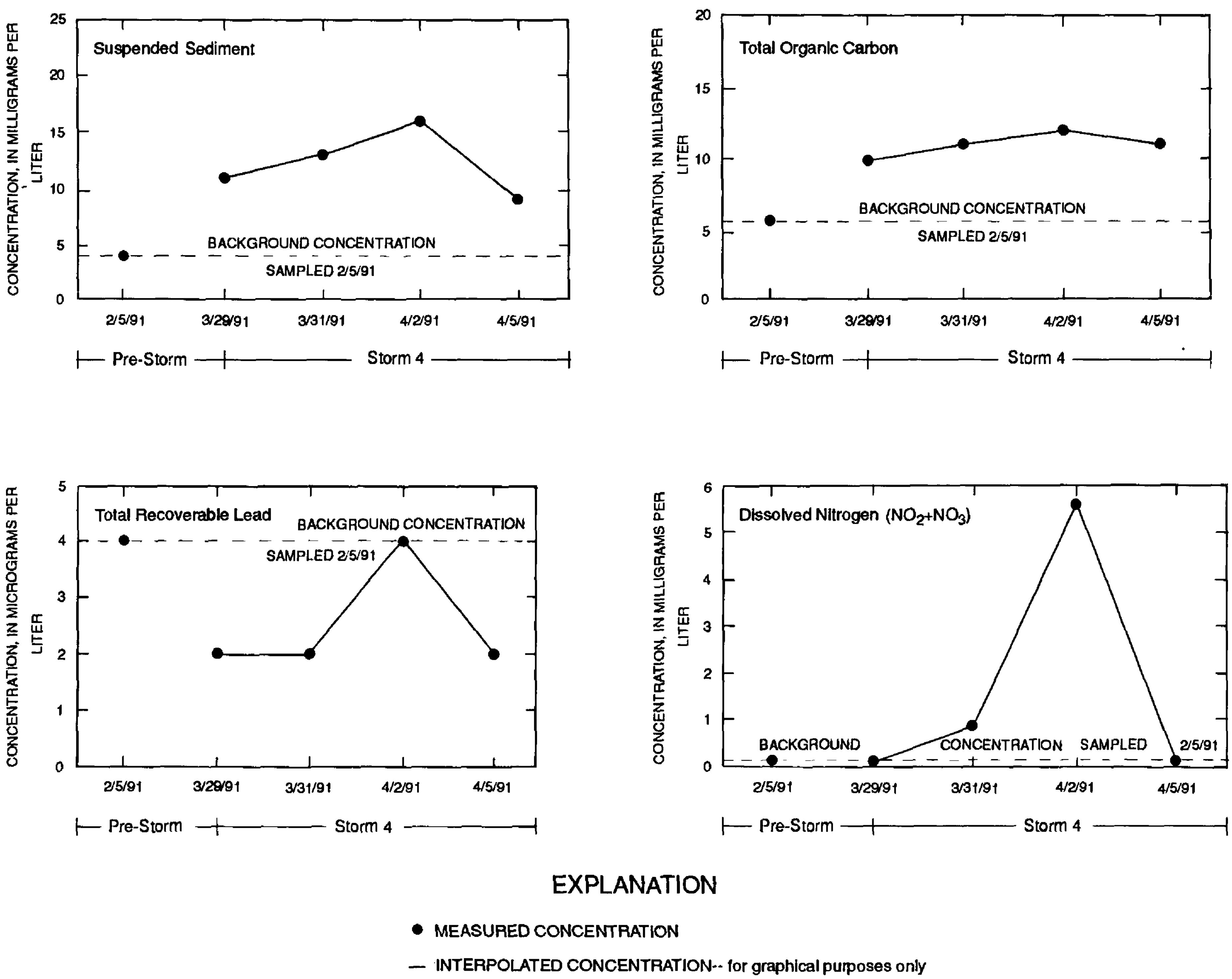


Figure 12. Concentration of selected constituents throughout storm 4 at the rural station (Providence Forge) in the Chickahominy River Basin.

(NO_2^- + NO_3^-). Again, this indicates the effects of different storms on the transport of constituents from areas of different land use in the Chickahominy River Basin.

The total load for suspended sediment at the urban station for storm 1 was less (34,000 lb) than at the rural station (180,000 lb), but for storm 4, was greater (610,000 lb) than at the rural station (590,000 lb). The total load of material at the rural station should equal or exceed the total load of material at the urban station, if there is no net loss of material between the urban and rural stations. The loads from storm 1 and 4 indicate a net loss or reduction of suspended sediment between the urban and rural stations. The flows characterized by storm 4 were sufficient to remove and transport more sediment per unit drainage area than those for storm 1 from the urban and rural basins. Additionally, the urban basin yielded higher total sediment loads per unit area than the rural basin during storm 4.

Table 6 lists the combined storm loads from the urban and residential stations as a percentage of the load at the rural station. Results of storm 1 indicate that the storm volume from the two combined basins contribute only

Table 3. Loads of selected constituents for storms 1 and 4 at the residential station (Atlee) in the Chickahominy River Basin

Conetituent	Load (pounds)		Load (pounds per square mile)	
	Storm 1	Storm 4	Storm 1	Storm 4
Suspended sediment	19,000	470,000	310	7,600
Dissolved chloride	19,000	89,000	310	1,400
Dissolved sulfate	12,000	97,000	190	1,600
Total organic carbon	19,000	130,000	310	2,100
Total recoverable lead	4	35	.1	.6
Total recoverable copper	8	27	.1	.4
Total recoverable zinc	30	400	.5	6
Total recoverable nickel	2	40	.03	.6
Total nitrogen (ammonia + organic)	1,000	10,000	16	160
Dissolved nitrogen (ammonia)	100	533	2	9
Dissolved nitrogen ($NO_2 + NO_3$)	280	3,310	5	53
Total phosphate (as PO_4)	234	1,140	4	18
Total orthophosphorus	76	371	1	6
Total phosphorus	136	658	2	11

Table 4. Loads of selected constituents for storms 1 and 4 at the urban station (Upham Brook) in the Chickahominy River Basin

Conetituent	Load (pounds)		Load (pounde per equare mile)	
	Storm 1	Storm 4	Storm 1	Storm 4
Suspended sediment	34,000	610,000	890	16,000
Dissolved chloride	20,000	58,000	530	1,500
Dissolved sulfate	9,900	53,000	260	1,400
Total organic carbon	10,000	85,000	260	2,200
Total recoverable lead	17	65	.4	2
Total recoverable copper	9	32	.2	.8
Total recoverable zinc	40	300	1	8
Total recoverable nickel	2	20	.05	.5
Total nitrogen (ammonia + organic)	1,010	6,680	27	176
Dissolved nitrogen (ammonia)	163	653	4	17
Dissolved nitrogen ($NO_2 + NO_3$)	163	10,500	4	276
Total phosphate (as PO_4)	439	1,590	12	42
Total orthophosphorus	55	518	1	14
Total phosphorus	177	803	5	21

Table 5. Loads of selected constituents for storms 1 and 4 at the rural station (Providence Forge) in the Chickahominy River Basin

Constituent	Load (pounds)		Load (pounds per square mile)	
	Storm 1	Storm 4	Storm 1	Storm 4
Suspended sediment	180,000	590,000	710	2,340
Dissolved chloride	160,000	430,000	630	1,710
Dissolved sulfate	53,000	390,000	210	1,550
Total organic carbon	160,000	540,000	630	2,140
Total recoverable lead	41	130	.2	.5
Total recoverable copper	100	210	.4	.8
Total recoverable zinc	100	700	.4	3
Total recoverable nickel	30	200	.1	.8
Total nitrogen (ammonia + organic)	9,070	33,200	36	132
Dissolved nitrogen (ammonia)	1,000	2,010	4	8
Dissolved nitrogen (NO_2 + NO_3)	2,900	106,000	12	421
Total phosphate (as PO_4)	2,860	5,500	11	22
Total orthophosphorus	933	2,130	4	8
Total phosphorus	1,500	3,250	6	13

24 percent of the total volume at the rural station. The percentages of loads from the two combined stations range from 13 percent (total recoverable nickel) to 70 percent (total recoverable zinc). However, the combined stations contribute 46 percent of the volume of storm 4, and loads range from 13 percent (dissolved nitrogen, as NO_2^- + NO_3^-) to 111 percent (suspended sediment) compared with the load at the rural station. The large percentage of volume from storm 4 shows the effects of storm size on stormflow volumes. The larger percentage of storm loads from storm 4 compared with loads from storm 1, indicate the combined effects of urbanization, storm characteristics, and flood-plain properties. Large storms can potentially move larger percentages of material off the urban areas, where the greatest source of sediment per unit area is found.

These results also are indicative of effects of sinks in the system. When the combined loads of the two upstream stations exceed 100 percent of the downstream rural station, there must be a loss of material from the river system between the upstream gages and the downstream gage. This loss of material is found in areas referred to as sinks. It is possible that storm 4 was of sufficient magnitude to cause overbank floods in parts of the river system that inundated the flood-plain wetlands with sediment-laden stormwater. In contrast, storm 1 might not have caused overbank flooding in the wetlands; therefore, the stormwater could have been contained in the major channels of the river system and conveyed downstream more efficiently and completely than it was during storm 4.

Table 6. Combined storm loads of selected constituents from the urban (Upham Brook) and residential stations (Atlee), as a percentage of storm load at the rural station (Providence Forge) for storms 1 and 4 for the Chickahominy River Basin

Constituent	Storm 1 (percent)	Storm 4 (percent)
Suspended sediment	29	111
Dissolved chloride	24	34
Dissolved sulfate	41	38
Total organic carbon	18	40
Total recoverable lead	51	77
Total recoverable copper	17	28
Total recoverable zinc	70	100
Total recoverable nickel	13	30
Total nitrogen (ammonia + organic)	22	50
Dissolved nitrogen (ammonia)	26	59
Dissolved nitrogen (NO_2 + NO_3)	15	13
Total phosphate (as PO_4)	24	50
Total orthophosphorus	14	42
Total phosphorus	21	45

This difference in storm magnitude could be the reason for the sinks that were observed during storm 4, while no sinks were observed during storm 1. Consequently, storms of sufficient magnitude could be necessary for the wetlands to be an effective sink for suspended material; however, this could affect the ecology of the wetlands, particularly if the sediment that is deposited has been contaminated by urban sources.

SELECTED CHARACTERISTICS OF BASE FLOW

Base flow is defined as the sustained discharge of water to the river channel from the ground-water system before, during, and after storms. Streams continue to flow between storms because of base flow. Samples were collected during interstorm periods of base flow on several separate occasions before and during the study period. Data before 1989 were collected at various times before the study from 23 stations (fig. 4). During the present study, base flow was monitored and sampled three times at each of the five stations.

Hydrologic Characteristics

Rivers interact with ground water in two ways. Reaches of rivers in which flow is sustained by ground water between storms are called gaining reaches, whereas reaches in which water in the river enters the ground-water system are called losing reaches. The hydraulic head differences between the stream and the ground water and the hydraulic conductivity of the intervening sediments control whether a stream is losing or gaining.

Gain/Loss Surveys

Gaining and losing reaches of streams can be determined by conducting gain/loss surveys when runoff of rain or snowmelt no longer contributes to streamflow. This type of survey must be completed within a short period to avoid the effects of changes in streamflow due to climatic change. The measurements indicate where downstream streamflow is different from upstream streamflow, indicating that the river either loses or gains water to or from the ground-water system. The interactions between a stream and the ground water are affected by evapotranspiration rates, geohydrology, and many other factors; it is beyond the scope of this study to determine the causes responsible for the gain/loss observations.

Ten surveys were completed from September 1984 through August 1989 during various seasons. The drainage areas associated with the individual measurement points and the percentage of times the various reaches lost water are shown in figure 13. The low relief and broad flood plains typical in the Chickahominy River Basin produce slow moving or stagnant water in the main channel during base-flow periods. This tends to make measurements of discharge difficult because velocities are below the rated range of the streamflow current meter at certain locations. Therefore, measurement errors can be introduced to the analysis during extreme low flows. Most of the surveys indicated that the Chickahominy is a gaining river, except for one area, which was a losing stretch 7 of the 10 times that it was surveyed (fig. 13). Rivers typically gain in humid climates.

Comparison of Hydrographs for Urban, Residential, and Rural Basins

Hydrographs can be separated into components of base flow and stormflow. The hydrographs for the three continuous-record stations were separated by the method described by Rutledge (1993) and are shown in figure 14. The contribution of base flow to the overall hydrograph is variable among the three stations. Base flow in the urban station at Upham Brook is consistently a small percentage of total flow. Base flow at the rural station at Providence Forge is a much larger percentage of the total flow, and base-flow percentages at the residential station at Atlee are between the other two stations.

The high base flows that are sustained at the rural station are, by definition, indicative of large ground-water inputs. This is a result of the land cover, geohydrology, and size of the drainage basin. The large expanse of wetlands and springs that are found in, and near, the flood plains and valley walls are predominantly ground-water discharge areas. The area associated with local ground-water inputs to the Chickahominy River is not limited to the streambed, but extends to the flood plain. The regional underlying confined-aquifer system could also discharge water to the river.

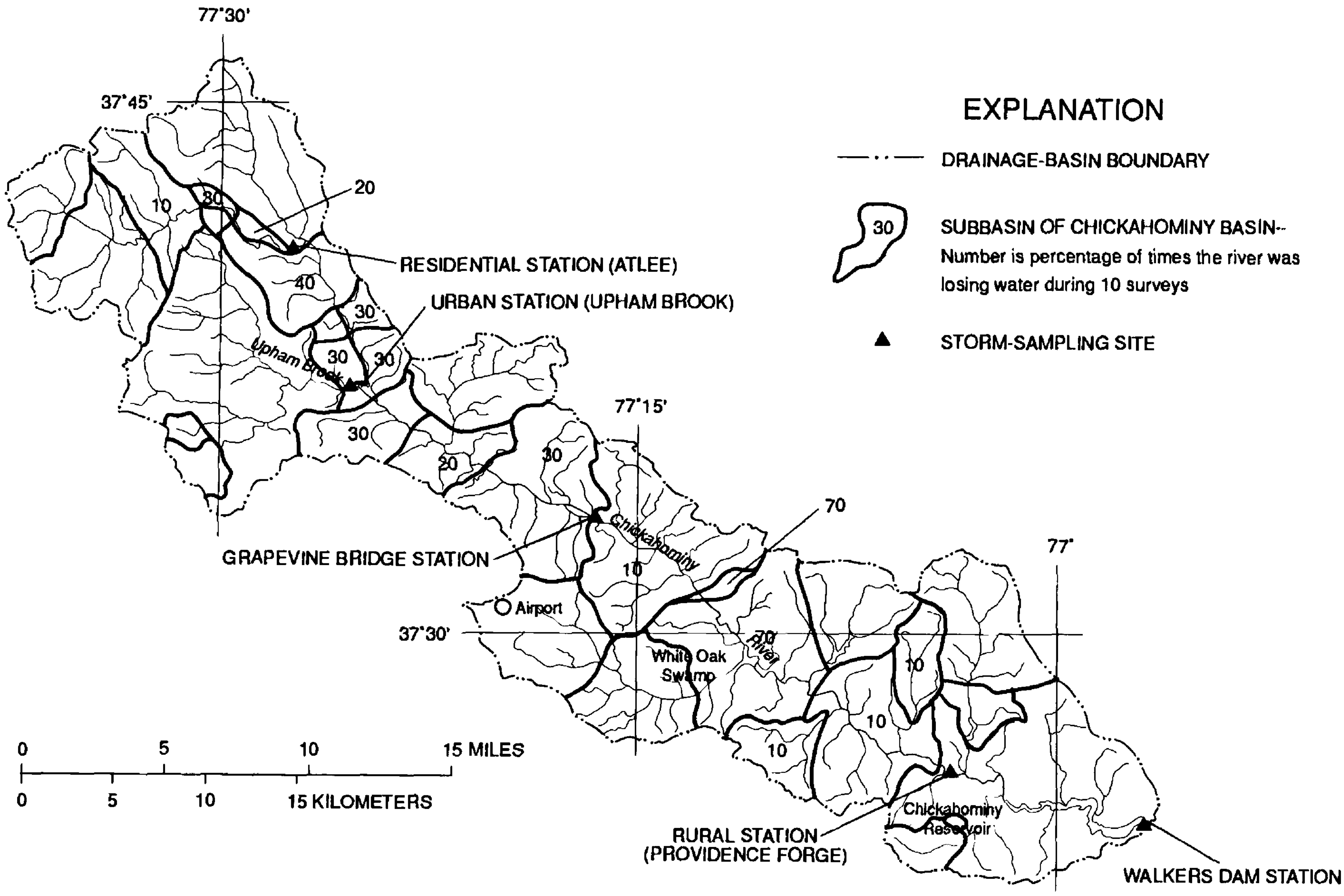


Figure 13. Summary of gain/loss surveys in the Chickahominy River Basin.

Water Quality

Water was analyzed for selected constituents and properties during base flow at the five stations and several times before the study at the gain/loss sites. Loads of selected constituents and properties were estimated from these samples.

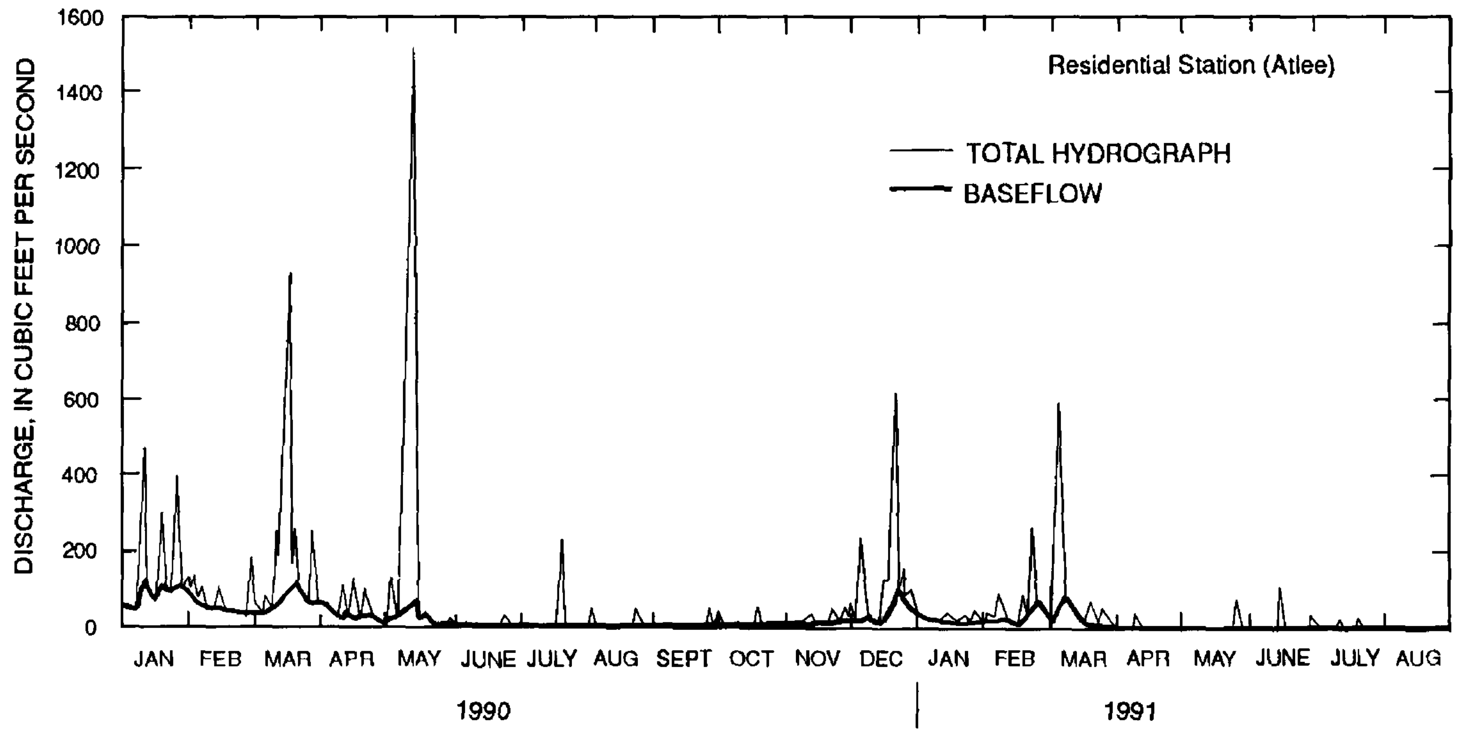
Concentrations of Selected Constituents

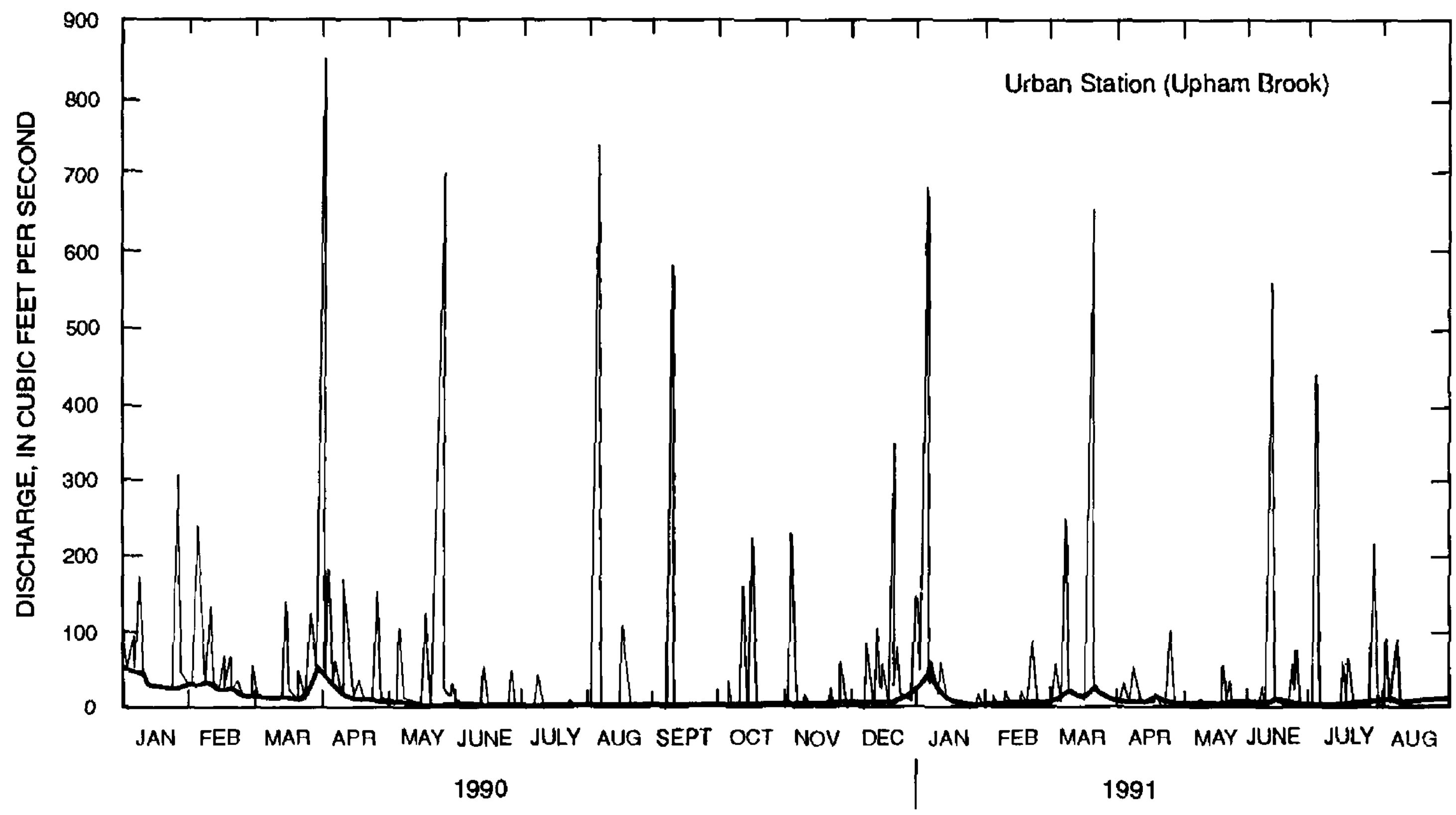
The greatest concentrations of many constituents are generally found at and near the urban station. The mean concentrations of 8 of 13 constituents are greater at the urban station than the other four stations. This indicates that the urban area is a major source of these constituents during base flow. The urban drainage basin contains point discharges that could be the source of the elevated concentrations of these constituents in base flow. Nonpoint sources also could be important contributors of constituents, but individual contributions of point and nonpoint sources of contamination in base flow were not ascertained in this study.

Loads of Selected Constituents

Tables 7, 8, and 9 list the total volume of base flow for selected time periods and the annual base-flow loads of selected constituents at the residential, urban, and rural stations, respectively. A full year of data was not possible for all constituents at all stations; however, a substantial part of 1990 and 1991 was monitored. As expected from the hydrologic data, the total annual base-flow volume is greatest at the rural station and smallest at the urban station. The loads of suspended sediment, total recoverable

Figure 14. Hydrographs showing base-flow separations at the residential, urban, and rural stations, Chickahominy River Basin. ▶


Residential Station (Atlee)
TOTAL HYDROGRAPH
BASEFLOW
DISCHARGE, IN CUBIC FEET PER SECOND
0
200
400
600
800
1000
1200
1400
1600
JAN FEB MAR APR MAY JUNE JULY AUG SEPT OCT NOV DEC JAN FEB MAR APR MAY JUNE JULY AUG
1990
1991


Urban Station (Upham Brook)
DISCHARGE, IN CUBIC FEET PER SECOND
0
100
200
300
400
500
600
700
800
900
JAN FEB MAR APR MAY JUNE JULY AUG SEPT OCT NOV DEC JAN FEB MAR APR MAY JUNE JULY AUG
1990
1991

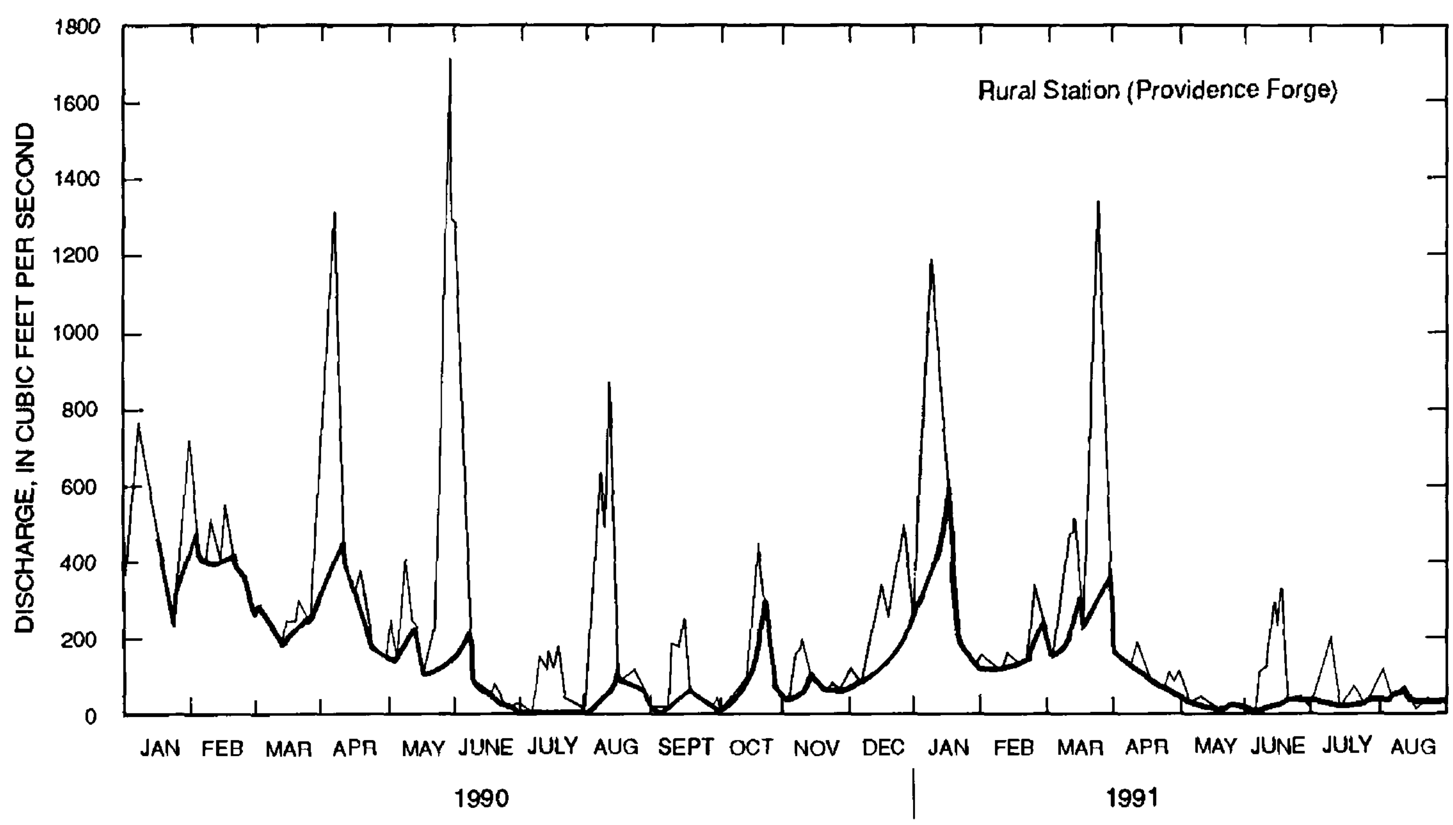

Rural Station (Providence Forge)
DISCHARGE, IN CUBIC FEET PER SECOND
0
200
400
600
800
1000
1200
1400
1600
1800
JAN FEB MAR APR MAY JUNE JULY AUG SEPT OCT NOV DEC JAN FEB MAR APR MAY JUNE JULY AUG
1990
1991

Table 7. Annual base-flow loads of selected constituents at the residential station (Atlee) [1] in the Chickahominy River Basin
[loads are in pounds]

Constituent	1990	1991
Suspended sediment	670,000	360,000
Dissolved chloride	1,007,995	550,000
Dissolved sulfate	930,000	510,000
Total organic carbon	430,000	230,000
Total recoverable lead	130	73
Total recoverable copper	140	78
Total recoverable zinc	800	400
Total nitrogen (ammonia + organic)	30,400	16,700
Dissolved nitrogen (ammonia)	3,380	1,850
Dissolved nitrogen ($NO_2 + NO_3$)	10,700	5,870
Total phosphate (as PO_4)	41,100	22,500
Total orthophosphorus	1,340	735
Total phosphorus	2,940	1,610

[1] Total base-flow volume in 1990 was 763,000,000 cubic feet. Total base-flow volume in 1991 was 418,000,000 cubic feet.

Table 8. Annual base-flow loads of selected constituents at the urban station (Upham Brook) [1] in the Chickahominy River Basin
[loads are in pounds]

Constituent	1990	1991
Suspended sediment	860,000	420,000
Dissolved chloride	560,000	280,000
Dissolved sulfate	250,000	120,000
Total organic carbon	130,000	65,000
Total recoverable lead	130	66
Total recoverable copper	79	40
Total recoverable zinc	300	200
Total nitrogen (ammonia + organic)	10,600	5,250
Dissolved nitrogen (ammonia)	2,620	1,300
Dissolved nitrogen ($NO_2 + NO_3$)	11,200	5,540
Total phosphate (as PO_4)	4,000	1,980
Total orthophosphorus	1,300	647
Total phosphorus	1,830	910

[1]Total base-flow volume in 1990 was 303,000,000 cubic feet. Total base-flow volume in 1991 was 151,000,000 cubic feet.

Table 9. Annual base-flow loads of selected constituents at the rural station (Providence Forge) [1] in the Chickahominy River Basin
[loads are in pounds; NA, not available]

Constituent	1990	1991
Suspended sediment	1,200,000	760,000
Dissolved chloride	5,700,000	3,500,000
Dissolved sulfate	2,000,000	1,200,000
Total organic carbon	2,300,000	1,400,000
Total recoverable lead	710	440
Total recoverable copper	710	440
Total recoverable zinc	NA	NA
Total nitrogen (ammonia + organic)	174,000	107,000
Dissolved nitrogen (ammonia)	11,300	6,990
Dissolved nitrogen ($NO_2 + NO_3$)	37,100	22,900
Total phosphate (as PO_4)	37,600	23,200
Total orthophosphorus	12,300	7,560
Total phosphorus	17,600	10,800

[1]Total base-flow volume for 1990 was 4,920,000,000 cubic feet. Total base-flow volume in 1991 was 3,030,000,000 cubic feet.

lead, total organic carbon, and some nutrients (such as total orthophosphorus) were greater at the rural station than the other stations. Total phosphate, however is greater at the residential station than at the other stations (for 1990). The reason for this is unknown, but could be from small industries located within the residential basin. The annual loads per unit drainage basin area (not shown) were greatest at the urban station for suspended sediment and for total recoverable lead and zinc.

Visual observations of the river during base flow indicated that the stream channel is poorly defined in the flood-plain wetlands. Water in these areas moves slowly and is sometimes stagnant, because of the low stream gradients and flow that commonly rises over the banks of many small channels, where the flow is dispersed throughout the wetlands. These areas of low streamflow velocities and overbank flow can become sinks for suspended material during base flow. For example, the combined annual base-flow load of suspended sediment for the urban and residential stations was 128 percent of the annual load at the rural station in 1990 and 103 percent in 1991. Total phosphate was the only other constituent to exhibit these high percentages; 120 percent in 1990 and 106 percent in 1991. These numbers indicate a net loss of

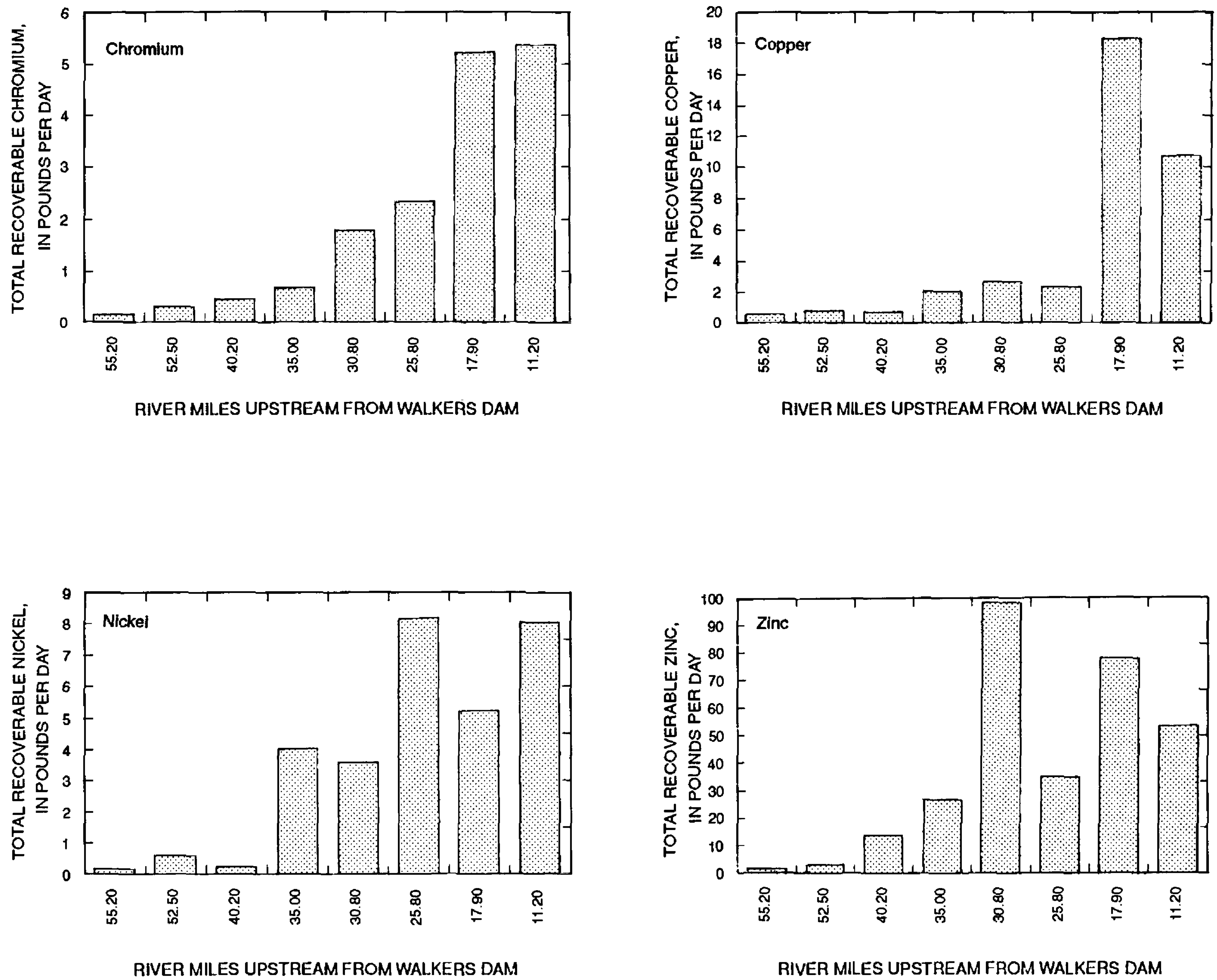


Figure 15. Loads of selected constituents in base flow at eight stations in the Chickahominy River Basin, April 5, 1989.

suspended sediment in the wetlands and can be the result of retention and storage between the upstream stations and the rural station during those time periods.

The spatial distribution of loads during base flow indicate no consistent patterns for many constituents and properties on any of the dates that were sampled. However, others consistently show distinct spatial patterns. For example, figure 15 shows plots of base-flow loads of chromium, copper, zinc, and nickel at eight stations on April 5, 1989 (one of four times that water was sampled for metals). The stations are ordered from upstream to downstream to emphasize the spatial patterns. When a source of material is constant from a particular basin (a reasonable assumption for non-point sources in base flow during a day), an increase in load from that basin to a downstream station indicates that a source of the constituent exists in the intervening reach. The loads increase downstream for many metals and suspended sediment (not shown) on April 5, 1989, and on the other three dates. If point sources caused this result, they would have to exist within almost every reach monitored for the gain/loss sampling run on April 5, 1989. However, most of the known point sources are concentrated in the upstream urban basins. Thus, it is more likely that ground water is a source for these constituents during base flow. The large change in mass of chromium, copper, and zinc between river mile 25.80 and 17.90 is probably related to inputs from White Oak Swamp Basin.

SELECTED CHARACTERISTICS OF COMBINED STORMFLOW AND BASE-FLOW WATER QUALITY

All historical water-quality data were combined with data collected for this study at each of the five stations. Medians and ranges of concentrations of many constituents were greater at the urban station than at the other four stations, with minor exceptions. For example, median concentrations of total recoverable lead, zinc, and copper, and suspended sediment are greater at the urban station (fig. 16); however, the range of concentrations of total recoverable zinc is greatest at the Grapevine Bridge station. Median nutrient concentrations also are generally highest at the urban station (figs. 17 and 18). Concentrations of dissolved ammonia nitrogen have the highest median value and the widest range at the urban station; however, concentrations of total nitrogen (ammonia + organic) have a wider range at Walkers Dam. The number of samples of total nitrogen (ammonia + organic) collected at the rural and Walkers Dam stations is much greater than at the other stations; consequently, a comparison of the range and median values of concentrations is not statistically sound and is only presented for a general indication of the data. Similar discrepancies in the number of samples can be found in total phosphorus, total phosphate, and total orthophosphate samples (fig. 18). Concentrations of dissolved oxygen (not shown) did not exhibit any spatial pattern.

COMPARISON OF STORMFLOW AND BASE-FLOW WATER QUALITY

The water quality of the Chickahominy River during base flow is an indication of ground-water contributions, point-source discharges to the river, intrastream biogeochemical processes, and interactions with the atmosphere. Mechanisms that affect ground-water quality differ from those that affect stormwater quality, in ways that include the effects of longer contact time with soil, streambed sediment, and vegetation. Concentrations of dissolved material generally increase as contact time increases with the source material. A common characteristic difference of natural ground-water and stormwater quality is that the ground water is more mineralized than the stormwater and, therefore, has a high dissolved-solids concentration (Hem, 1989). The solute concentration of river water in undisturbed basins thus tends to be inversely related to flow rate because the stormwater has limited contact time with minerals and tends to dilute constituents in the river. At high flow rates, the water can be nearly as dilute as rainwater in natural systems. Certain properties of water, such as specific conductance and hardness are indicators of the amount of dissolved solids in the water; high values indicate high concentrations of dissolved solids.

Concentrations and Loads of Selected Constituents

The difference in relations of flow rate to constituent concentrations between the urban and rural stations can be illustrated graphically. Hardness concentrations at the rural station tend to decrease with increases in flow rate (fig. 19). Other dissolved constituents exhibit similar patterns (not shown). This can be attributed to the diluting effects of stormwater and is expected in undisturbed basins. However, total recoverable concentrations of lead tend to increase when flow rate increases at the urban station (fig. 20). This effect indicates the possible resuspension of sediment-associated lead during storms in urban areas where water velocities are high and sources of lead are present. Consequently, the net effect of stormwater might raise concentrations above the base-flow value. The water-quality data are not sufficient to depict these relations accurately for all constituents at all stations, but the implication that concentrations of certain constituents can be directly related to streamflow magnitude (including stormflow and base flow) can affect management and planning perspective.

The total annual load of a given constituent consists of daily base-flows loads and loads for episodic storms during the entire year. However, the total annual load of a constituent is often dominated by loads from storms. Sometimes a few storms can account for most of the annual load. Though total annual loads were not assessed, the relative contributions of storms 1 and 4 to the total annual load can be illustrated by the percentage of the individual storm loads to the annual base-flow load (table 10). For example, the load from storm 4 is a much larger percentage of total base-flow loads for 1991 than the load from storm 1 is for 1990, for all constituents. The percentage of annual base-flow volume to total annual stormflow volume is nearly constant for the 2 years at all stations (table 11). Also, storm-load percentages of annual base-flow loads are characteristically higher at the urban station than at the other two stations.

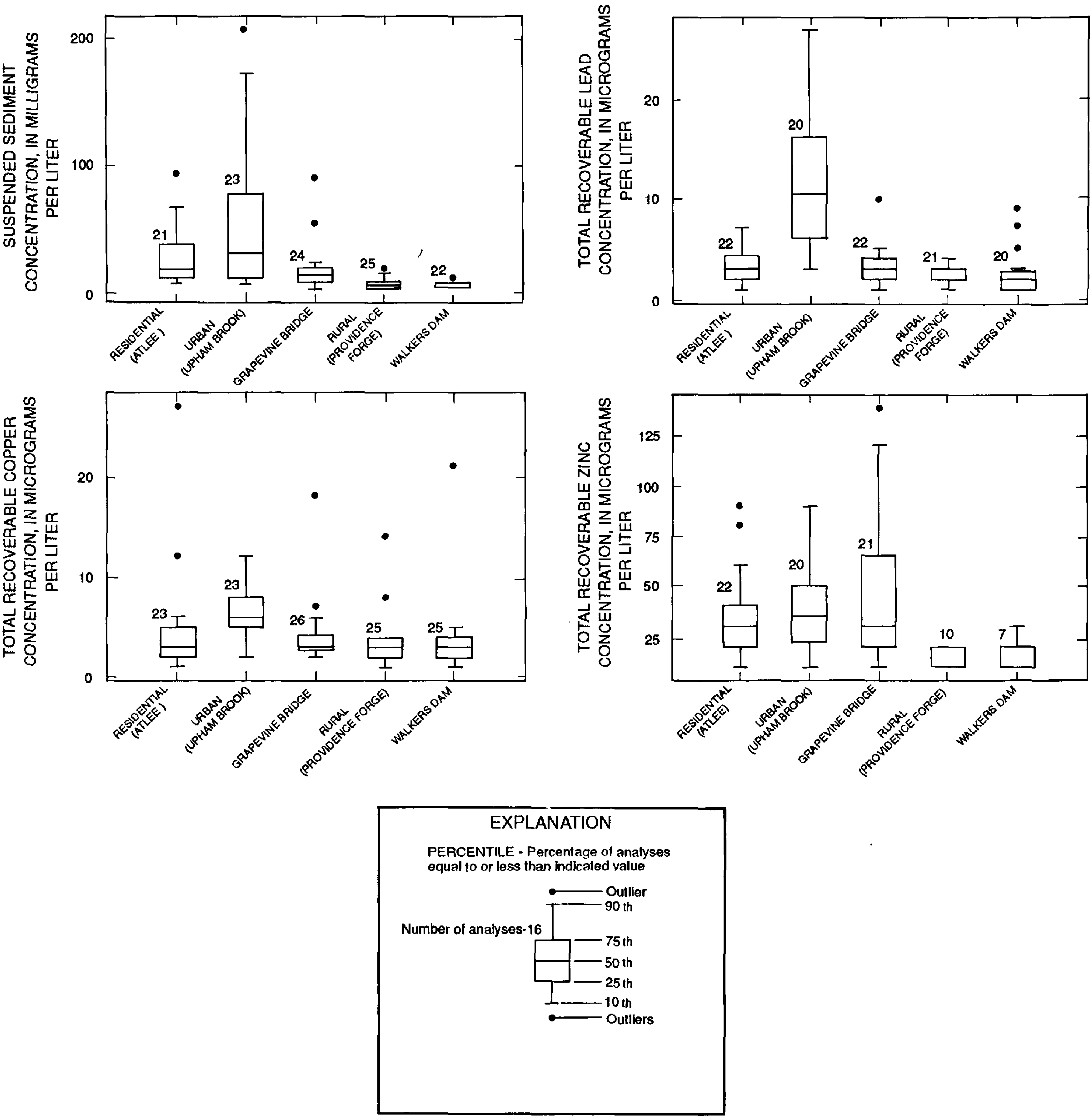


Figure 16. Water-quality summary of suspended sediment and selected metals at all sampling stations in the Chickahominy River Basin.

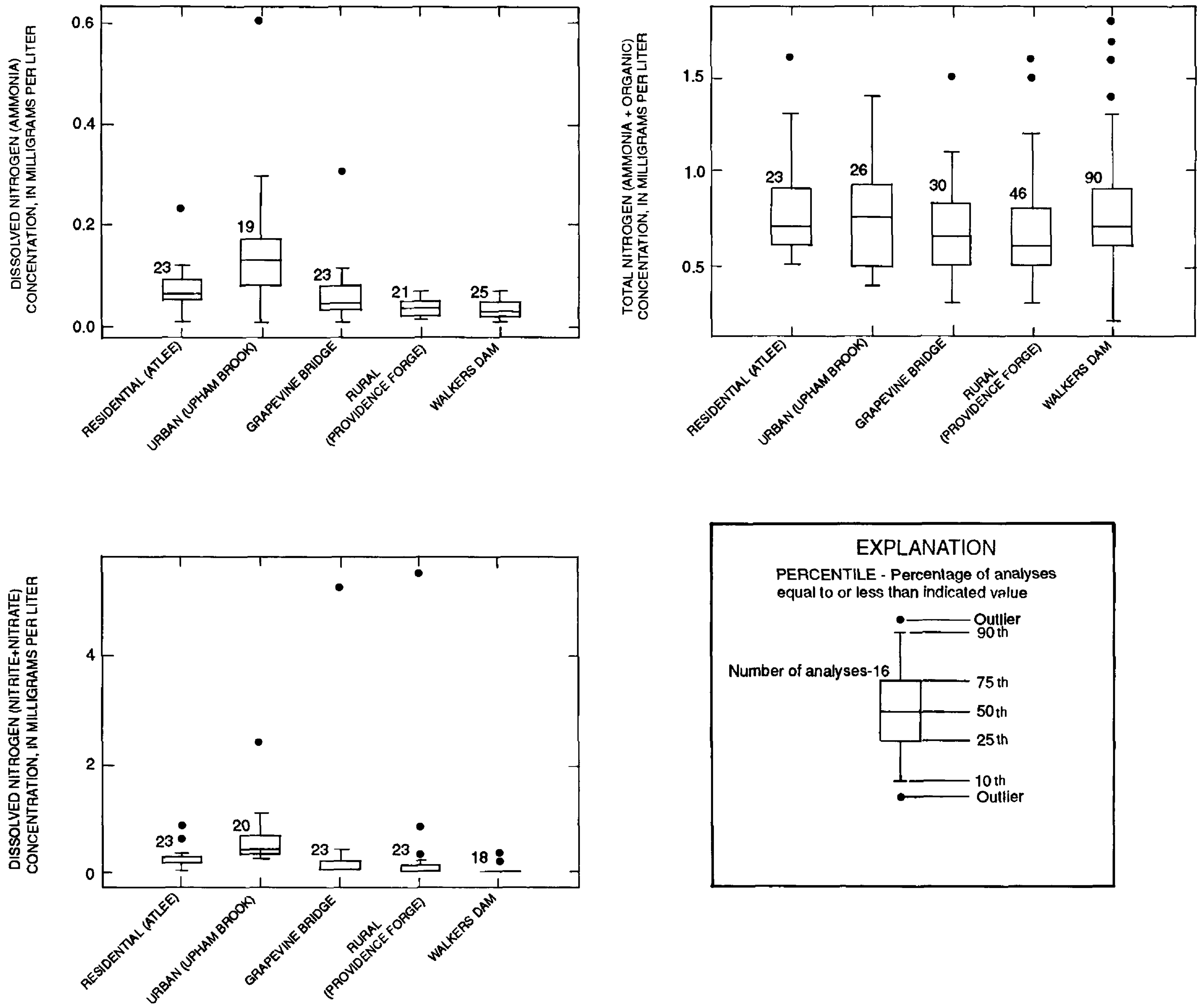


Figure 17. Water-quality summary of nitrogen at all sampling stations in the Chickahominy River Basin.

Hydrologic Controls on Selected Constituents

Dissolved constituents in the surface water of the river channel are typically stored in the water column for shorter periods of time than sediment-adsorbed constituents, because dissolved material is consistently transported downstream by a flowing river. Constituents that are adsorbed by sediment can be stored in areas where sediment accumulates in sinks, such as the streambed and the nearby flood plain. The constituents remain in storage with sediment until they are (1) chemically transformed, (2) removed from their adsorption sites and transported away as dissolved constituents, (3) resuspended with the sediment and eroded away by a storm of sufficient magnitude, or (4) leached from the sediments to the underlying ground water as dissolved material. Once in the ground water, a constituent is stored for longer periods of time than if it is in surface water. Constituents also can accumulate in the vegetative biomass of a basin through the uptake of water by plants. Thus, storage of a constituent depends on whether it is adsorbed by sediments or dissolved in the ground water or the surface water. Constitu-

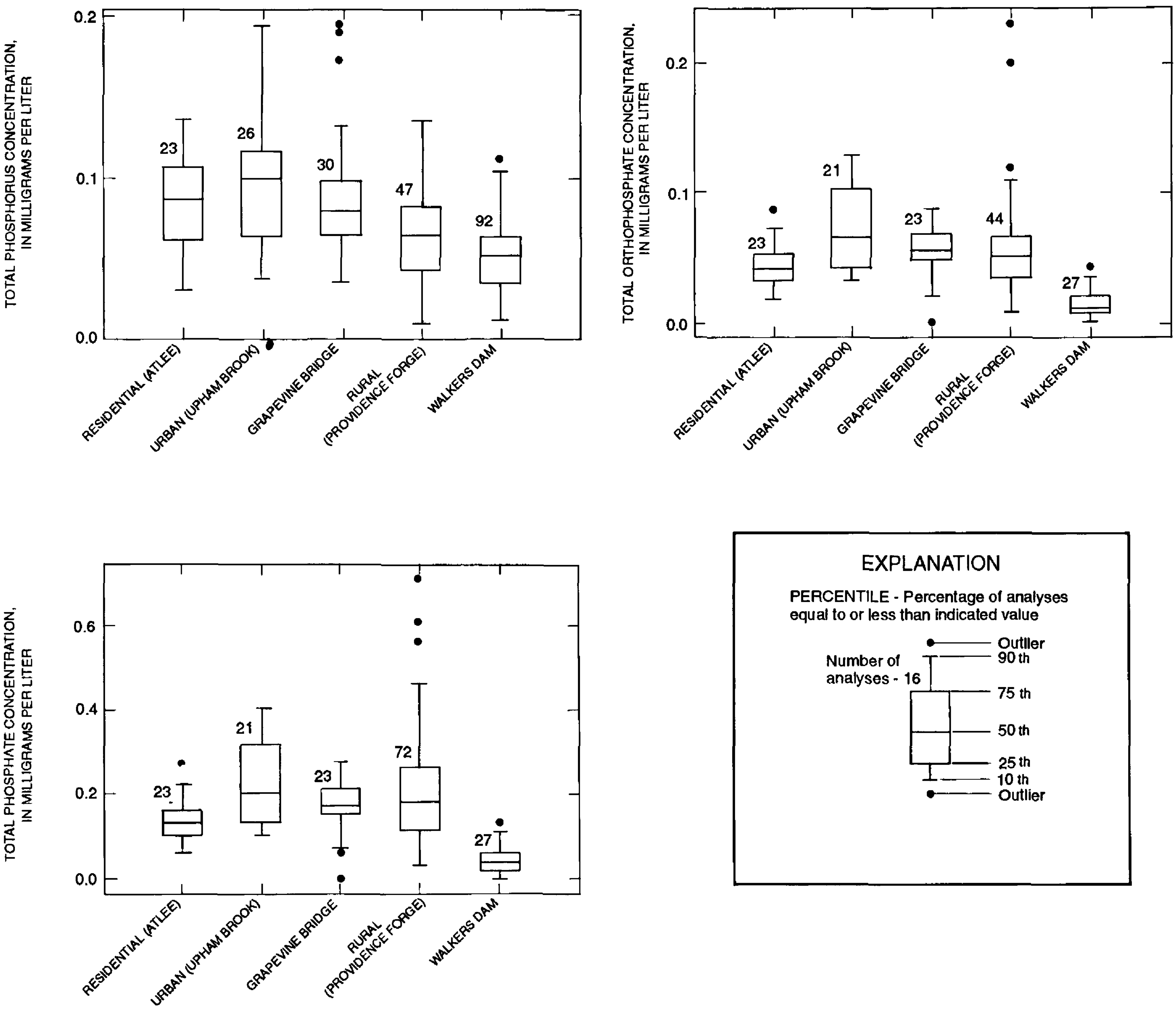


Figure 18. Water-quality summary of phosphorus at all sampling stations in the Chickahominy River Basin.

ent storage also can be affected by land use and by stormwater management practices. The length of time that individual constituents are stored within the basin depends on the constituent and the hydrologic and anthropogenic controls.

The distribution and movement of water plays a major role in the water quality of base flow and stormflow in the wetlands in the Chickahominy River Basin. For example, the potential for storage of sediment-associated constituents is great in the flood-plain wetlands, because these areas are characterized by low gradients and thick vegetation. Therefore, stormwater that travels through the flood-plain wetlands has a relatively slow velocity. Hupp and others (1992) showed that sedimentation rates are greatest in the wetland areas and have increased in the past 50 years as urbanization increased. Current (1993) rates of deposition range from 0.5 to 6.5 millimeters per year in different parts of the Chickahominy River Basin and vary depending on vegetation type and microtopography. Deposition rates are highest just downstream of the urban areas in wetlands. The upstream urban areas are the

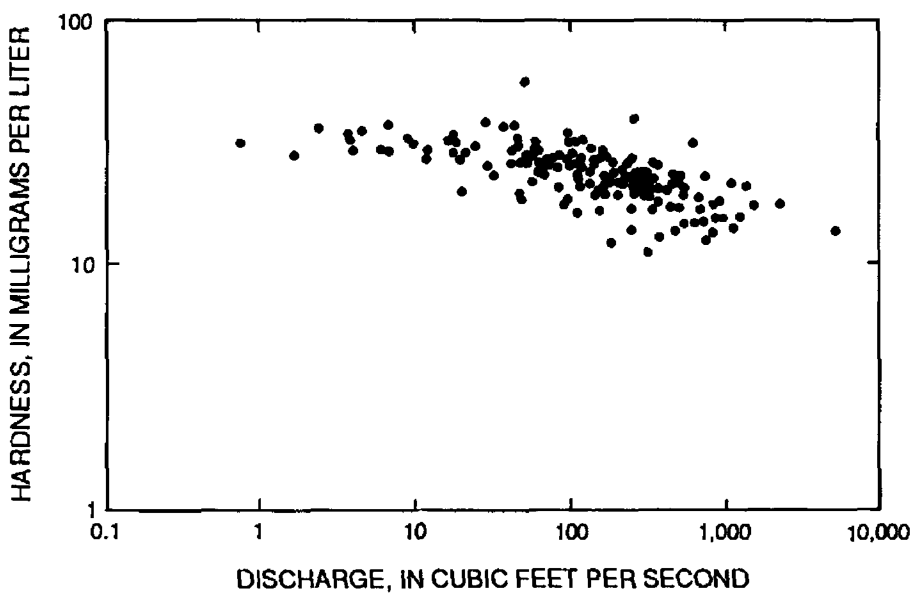


Figure 19. Hardness as a function of discharge for the period of record at the rural station (Providence Forge) in the Chickahominy River Basin, 1945-91.

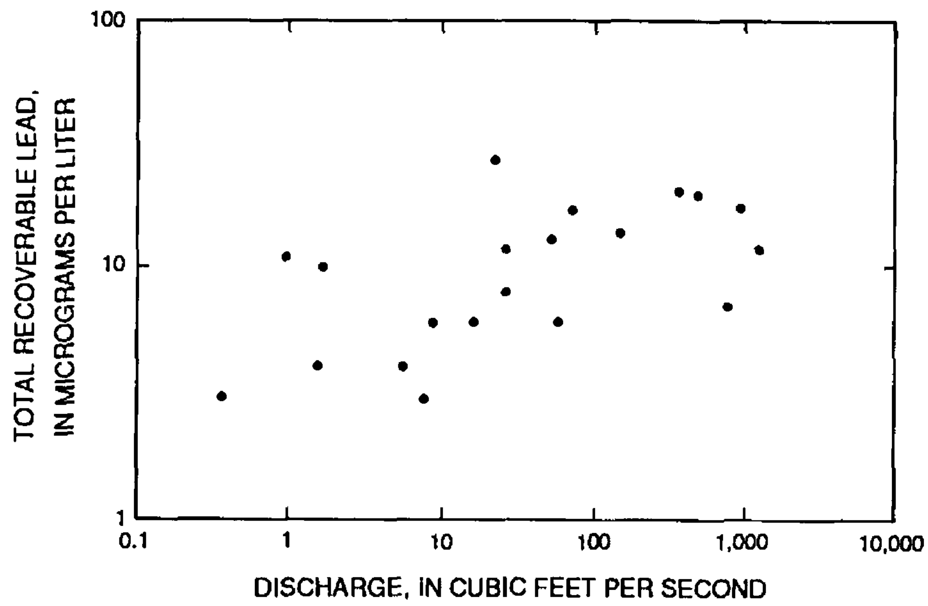


Figure 20. Total recoverable lead as a function of discharge at the urban station (Upham Brook) in the Chickahominy River Basin, 1989-91.

Table 10. Total storm loads (storms 1 and 4) of selected constituents as a percentage of annual base-flow loads at the residential (Atlee), urban (Upham Brook), and rural (Providence Forge) stations in the Chickahominy River Basin
[NA, not available]

Constituent	Residential station (percent)	Urban station (percent)	Rural station (percent)
	Storm 1		
Suspended sediment	3	4	15
Total recoverable lead	3	13	6
Total recoverable zinc	4	13	NA
Dissolved nitrogen ($NO_2 + NO_3$)	3	1	8
Total phosphorus	5	10	9
Total organic carbon	4	8	7
	Storm 4		
Suspended sediment	13	145	78
Total recoverable lead	48	98	30
Total recoverable zinc	100	150	NA
Dissolved Nitrogen ($NO_2 + NO_3$)	56	190	NA
Total phosphorus	29	89	30
Total organic carbon	57	131	39

Table 11. Annual base-flow volumes as a percentage of total stormflow volumes at the urban (Upham Brook), residential (Atlee), and rural (Providence Forge) stations in the Chickahominy River Basin

Station	1990 (percent)	1990 (percent)
Urban	20.3	17.4
Residential	30.0	29.5
Rural	38.0	37.7

greatest source of suspended sediment per unit area; thus, the material is supplied to the stream channel in greater abundance than elsewhere in the basin.

Trace metals and nutrients were found in the wetland sediments and streambed sediments of the Chickahominy River Basin by Puckett and Woodside (1992). The ecology of these wetland areas could be affected by the trace metals and nutrients, particularly if the sediments have been adsorbed by constituents that can be released and made available to plant and animal life. Sediment particles in the study area that were smaller than 63 micrometers in diameter, including the fine particles of clay and silt, were found to contain up to 62 ppm (parts per million) copper, 21 ppm nickel, 147 ppm lead, and 305 ppm zinc. Most contaminated sediment was found in the areas of greatest deposition slightly downstream of the urban basins. Therefore, the high deposition rates found by Hupp and others (1992), the contaminated sediments found by Puckett and Woodside (1992), and the spatial distribution of loads of suspended sediment and constituents adsorbed by sediment during stormflows and base flows shown in this study indicate that the intervening wetlands between the urban and rural stations are sinks for suspended sediment and associated constituent loads during some storms.

Quantitative analyses of the variability in the transport, storage, and subsequent release of constituents adsorbed by sediment in the wetland areas are not possible at this time; however, data indicate that the storage of these constituents in wetland sink areas could be temporary. Thus, areas that were sinks during some storms could become source areas for some constituents under certain hydrologic conditions. Some constituents are tightly adsorbed by sediments (Alloway, 1990) and are effectively stored in the wetlands until the chemical and hydrologic conditions change drastically; others are released more readily under certain conditions, such as when pH changes slightly (Alloway, 1990). Puckett and Woodside (1992) demonstrated a pattern of downstream attenuation in the lead and copper concentrations in the wetland sediments. The concentrations were highest in the upstream urban areas and decreased downstream, except for zinc concentrations which did not follow this pattern and were highest downstream from the urban area. This pattern was also indicated by the water-quality data (figs. 16–18). These concentrations could be caused by an unknown source of zinc in this area, but it could also indicate a resuspension and subsequent movement of the zinc adsorbed by sediment during storms (Puckett and Woodside, 1992). The weak relation of total recoverable lead concentration to discharge at the urban station also indicates the possible effects of sediment resuspension from these areas, because higher discharges are associated with more erosive potential. Visual observation also indicates that sediment is resuspended during storms. It also is possible that constituents adsorbed by sediment transported into an area during storms are subsequently leached into the ground water and transported to the stream in base flow. The flood-plain wetlands are occasionally inundated with sediment-laden water as the river overflows the natural levees along its banks. This inundation has been observed during interstorm periods of base flow in some of the wetlands in, and near, areas where the stream channel is poorly defined and could lead to the increase in loads found during interstorm base flow downstream (fig. 15).

The first-flush effect can also strongly affect the concentration of some constituents in the Chickahominy River (figs. 9–12). Most of the sediment is transported by the flush from the urban areas during storms. Therefore, constituents adsorbed by sediment are removed from these basins early during a storm.

SUMMARY AND CONCLUSIONS

The Chickahominy River of Virginia is a principal source of raw-water supply managed by the Department of Public Utilities, City of Newport News. The water is used by more than 330,000 people and many industries on the York-James Peninsula in southeastern Virginia. The river, associated wetlands, and artificial reservoirs also are important wildlife habitat and recreational-use areas. Selected characteristics of stormflow and base flow, and major land use and cover factors that affect the occurrence, distribution and movement of water in the nontidal Chickahominy River from 1989 through 1991 are presented. The Chickahominy River at Atlee, Va., represented a residential area, the Upham Brook tributary represented an urban area, and the Chickahominy River at Providence Forge, Va., represented a rural area for this study.

The hydrologic responses of the three drainage basins gaged for this study demonstrate the effects of drainage-basin size, shape, geomorphology, and land use and cover. Hydrographs from the urban station have relatively higher short-term peaks and lower base flow than the rural and residential stations, and indicate the possible effects of urbanization. Volumes of flow at the urban station can be greater than at the other two stations at a given time during certain storms, but the effects of a storm are short-lived. The total volume of runoff can be greater during some storms from the urban basin than from the residential basin, even though the drainage area is much smaller. Total runoff per unit area of drainage basin for storms 1 and 4 is greater for the urban basin than the residential basin. Storm hydrograph patterns are different for storms 1 and 4. The rural station has a larger base-flow component, with relatively lower hydrograph peaks that last longer than the other two stations. The base flow at the urban station is a lower percentage of total flow than at the other two stations and base flow at the rural station is a higher percentage of total flow than at the urban and residential stations. Hydrographs at the residential station show combined characteristics of the urban and rural land uses and covers.

The water quality differences in stormwater and base flow among the five stations used in this study show the effects of land use and cover and the combined effects of hydrologic controls. The medians and ranges of concentrations of many constituents are greater at the urban station than at the other four stations. Evidence of a "first flush" of suspended sediment and constituents adsorbed by sediment was found at the urban and residential gage. Concentrations of total recoverable chromium, copper, lead, and zinc follow temporal patterns that are similar to suspended sediment during storms at the urban and, to a lesser degree, at the residential station. Nutrient concentrations, including total phosphorus and total nitrogen also relate to suspended sediment concentrations during storms. In general, patterns of metal concentrations were unlike patterns of suspended-sediment concentrations at the rural station. A decrease in the source and (or) increase in the sink of total recoverable metals in the intervening wetlands between the upstream urban and downstream rural stations during storms was indicated.

The urban basin produced the largest storm loads per square mile for many constituents analyzed, including suspended sediment, total recoverable lead and zinc, and total phosphate. The combined load of suspended sediment from the urban and residential stations was 111 percent of the load at the downstream rural station for storm 4, which indicated that a sink exists for suspended sediment in the wetlands. A large percentage of the nutrient loads that were measured at the rural station originated downstream of the urban and residential basins.

Individual storm characteristics also affect the timing and magnitudes of concentrations and loads of constituents differently. These differences, magnified by the effects of land use and cover, could affect the ecology of the wetlands, particularly if the sediments are contaminated. Visual observation indicates that wetland areas could be sources of contamination during some storms, as sediment is resuspended and transported out of the wetlands in the stormflow.

The total volume of base flow per unit drainage area for 1990 is smallest at the urban and largest at the rural station. For 1990, annual base-flow loads of total phosphate are much higher at the residential station than at the other two stations. Annual base-flow loads per unit drainage area for several constituents, including suspended sediment and total recoverable lead, are generally greatest at the urban station. The urban basin is also a major source of many constituents during base flow. The combined suspended-sediment load for the urban and residential stations in base flow for 1990 was 128 percent of the load at the downstream rural station; thus, the intervening wetlands appear to annually function as a net sink for suspended sediment during base-flow periods. The spatial distribution of loads, plotted by river mile, indicate anomalies where point sources of contamination are not expected during base flow, especially in the wetlands. This anomaly indicates that nonpoint-source contamination of ground water or resuspension and transport of contaminated sediment could be contributing to base-flow loads in these wetlands.

The spatial and temporal information on stormflow and base-flow quality and discharges, constituents, and known land use and cover distributions indicate that urban areas are the dominant source of nutrients and metals for the Chickahominy River during storms. The areas of greatest sediment deposition are located in the wetlands just downstream of the urban areas. These areas correspond to areas where the highest concentrations of constituents are found in the sediments. Thus, constituents from the urban areas are stored, at least temporarily, in wetland sediments.

The results of this study indicate that relations can be found among land use and land cover, water quality, and the distribution and movement of water. These relations are not well defined and require further study to manage the water resources, particularly as the urban and residential areas expand and affect the flood-plain wetlands.

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