Rec'd
12/20/00

U.S. Department of the Interior
U.S. Geological Survey

Prepared in cooperation with the
City of Newport News

Dissolved Organic Carbon and Disinfection By-Product Precursors in Waters of the Chickahominy River Basin, Virginia, and Implications for Public Supply

Water-Resources Investigations Report 00-4175

USGS
science for a changing world

U.S. Department of the Interior
U.S. Geological Survey

Dissolved Organic Carbon and Disinfection By-Product Precursors in Waters of the Chickahominy River Basin, Virginia, and Implications for Public Supply

By Gary K. Speiran

Water-Resources Investigations Report 00-4175

Prepared in cooperation with the
City of Newport News

Richmond, Virginia
2000

U.S. DEPARTMENT OF THE INTERIOR
BRUCE BABBITT, *Secretary*

U.S. GEOLOGICAL SURVEY
Charles G. Groat, *Director*

For additional information write to:

District Chief
U.S. Geological Survey
1730 East Parham Road
Richmond, VA 23228-2202

Copies of this report can be purchased from:

U.S. Geological Survey
Branch of Information Services
Box 25286, Federal Center
Denver, CO 80225-0286

CONTENTS

FIGURES

TABLES

CONVERSION FACTORS, VERTICAL DATUM, AND ABBREVIATED WATER-QUALITY UNITS

Multiply	By	To obtain
Measurements Reported in Inch-Pound Units		
	Length	
inch (in.)	2.54	centimeter
foot (ft)	0.3048	meter
mile (mi)	1.609	kilometer
	Area	
square mile (mi^2)	2.590	square kilometer
	Flow	
inch per year (in/yr)	25.40	millimeter per day
million gallons per day (Mgal/d)	3,785	cubic meter per day
cubic foot per second ($ft^3/^s$)	0.028317	cubic meter per second
	Velocity (Speed)	
foot per second (ft/s)	0.3048	meter per second
Measurements Reported in International System Units		
	Length	
nanometers (nm)	0.000000003937	inch
micrometer (µm)	0.00003937	inch
centimeter (cm)	0.3937	inch
	Volume	
milliliter (mL)	0.0002642	gallon
liter (L)	0.2642	gallon

Water temperature is reported in degrees Celsius (C), which can be converted to degrees Fahrenheit (F) as follows: °F = (1.8 × °C) + 32

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

Abbreviated water-quality units: Chemical concentration is reported in milligrams per liter (mg/L) or micrograms per liter (µg/L). Milligrams per liter is a unit expressing the concentration of chemical constituents in solution as mass (milligrams) of solute per unit volume (liter) of water. One thousand micrograms per liter is equivalent to one milligram per liter. For concentrations less than 7,000 mg/L, the numerical value is the same as for concentrations in parts per million. Specific electrical conductance of water is reported in microsiemens per centimeter at 25 degrees Celsius (µS/cm). Stable-isotope concentration is reported in per mil, which is equivalent to parts per thousand.

Dissolved Organic Carbon and Disinfection By-Product Precursors in Waters of the Chickahominy River Basin, Virginia, and Implications for Public Supply

By Gary K. Speiran

ABSTRACT

Surface water that is treated for use in public supplies typically is disinfected with chlorine to help ensure potability. When water containing dissolved organic carbon (DOC) is chlorinated, chlorinated disinfection by-products (DBPs), such as trihalomethanes, are formed. Many of these DBPs are carcinogenic. Only certain types of dissolved organic compounds, however, produce DBPs; these compounds are commonly called DBP precursors. Water treatment removes a large part of the DOC from the water but cannot selectively remove DBP precursors. Although treating water before chlorination reduces concentrations of DBPs in finished water, concentrations can still exceed drinking-water standards. Knowledge of factors affecting the spatial and temporal variability in concentrations of DBP precursors in source waters will allow utilities to withdraw water when concentrations are low. This strategy will facilitate water treatment, reduce water-treatment costs, and provide finished water having lower concentrations of DBPs.

Results of field and laboratory studies conducted from April 1995 through September 1998 were used to evaluate spatial and temporal variability in concentrations of DOC and DBP precursors in the Chickahominy River Basin, a raw-water source for the City of Newport News, Va. During base-flow periods, concentrations of DOC and DBP precursors decreased as much as 50 percent where the river flowed through extensive wetlands. During stormflow periods, concentrations of DOC and DBP precursors increased to peak values at, or following, peak streamflow.

Variability in concentrations of DOC and DBP precursors in stream water depended on hydrologic conditions. During base-flow periods, ground-water discharge and stream-bed detritus were the principal sources of DOC and DBP precursors to the streams, while organic litter distributed across the wetlands was only an indirect source because it had little contact with stream water. Concentrations of DOC and DBP precursors decreased downstream because of dilution from tributary inflow having a low organic content and because of decomposition of DOC as water flowed through the broad and shallow channels of the Coastal Plain reaches of the Chickahominy River.

During stormflow periods, infiltrating precipitation leached DOC and DBP precursors from the organic litter into the soil and shallow ground water. Discharge of DOC and DBP precursors with interflow and shallow ground water likely accounts for the peak in concentrations of DOC and DBP precursor at, or following, the peak in streamflow.

Study results have important implications for the use of water for public supply. Water treatment costs would be reduced and concentrations of DOC and DBPs in finished water would be lower if (1) withdrawal points are placed as far downstream as possible and (2) water is withdrawn and stored during the early parts of stormflow periods and withdrawal is discontinued when concentrations of DOC and DBP precursors increase.

INTRODUCTION

Surface waters used for public supplies are commonly disinfected with chlorine to help ensure potability. When the water contains dissolved organic carbon (DOC), however, the chlorine and other halogens (primarily bromine) introduced by the disinfection process react with the organic carbon to produce a variety of halogenated organic compounds, commonly referred to as disinfection by-products (DBPs). Many of these DBPs are known, or suspected, carcinogens (U.S. Environmental Protection Agency, 1998).

The presence of DOC in raw water supplies presents treatment problems even if disinfection methods are used that do not form DBPs. DOC reacts with metal coagulants and oxidants used in the production of potable water. Thus, higher DOC concentrations require more chemicals for treatment, thereby increasing water-treatment costs. DOC also can impart unpleasant color, taste, and odor to the water. Consequently, knowledge of the occurrence of DOC and the processes that affect the concentration of DOC in raw water is needed to facilitate water treatment and minimize water-treatment costs.

In 1998, the City of Newport News, Va., used about 52 Mgal/d of water; approximately 43 percent of the raw water was withdrawn from the Chickahominy River at Walkers Dam (fig. 1) (Ronald E. Harris, City of Newport News, Planning and Programs, oral commun., 1999). Withdrawal from the river is not allowed to reduce streamflow below 10 ft^3/s at the dam. The Chickahominy River flows through extensive wetlands (primarily bottomland hardwood wetlands) in central Virginia and has a dark brown, "tea" color, indicative of the presence of humic substances. Withdrawn water can be stored in a network of reservoirs having a hydraulic retention time of 100 days or more, or the water can be pumped directly to terminal reservoirs that have hydraulic retention times of approximately 30 days prior to treatment. Consequently, the city has the following options: (1) pump water containing low concentrations of DOC into the main reservoirs for later use; (2) pump water containing high concentrations of DOC into the main reservoirs for later use, thereby allowing natural processes within the reservoirs to reduce concentrations of DOC; or (3) pump water containing low or high concentrations of DOC into terminal reservoirs for more immediate use. Stored water can be used during times when water in the Chickahominy River has high, or difficult to remove, concentrations of DOC or when streamflow in the river is low.

The U.S. Geological Survey (USGS), in cooperation with the City of Newport News, Va., conducted a study from April 1995 through September 1998 to evaluate spatial and temporal variations in the DOC content of waters of the Chickahominy River Basin. This study focused on the effects of different hydrologic conditions on the potential formation of DBPs.

PURPOSE AND SCOPE

The purpose of this report is to describe spatial and temporal variability in concentrations of DOC and DBP precursors in the Chickahominy River Basin during base-flow and stormflow periods and to identify the processes that likely affect the variability. Characteristics of DOC are presented that serve as indicators of the amount of DBPs likely to form when the water is chlorinated. Strategies to reduce water-treatment costs by adjusting operations to account for variability in the DOC content of the raw water also are discussed.

Descriptions are based on results of field and laboratory studies conducted from April 1995 through September 1998. Surface-water sampling was conducted to evaluate spatial and temporal variability in DOC and DBP precursors in stream water from the Chickahominy River Basin during base-flow and stormflow periods. Data were collected at main-stem and tributary stations throughout the basin upstream of Walkers Dam. Samples were collected quarterly during base-flow and during selected stormflow periods. Samples of ground water were collected from wells and seeps in a sub-basin near the middle of the Chickahominy River Basin to investigate ground water as a transport pathway for DOC to streams. Laboratory studies also were conducted to evaluate (1) the contribution of stream-bed detritus to the DOC content of stream water and (2) the degradation of DOC in stream water.

Background

Rook (1974) determined that the chlorination of water containing DOC produces several halogenated organic compounds that are volatile and have a low

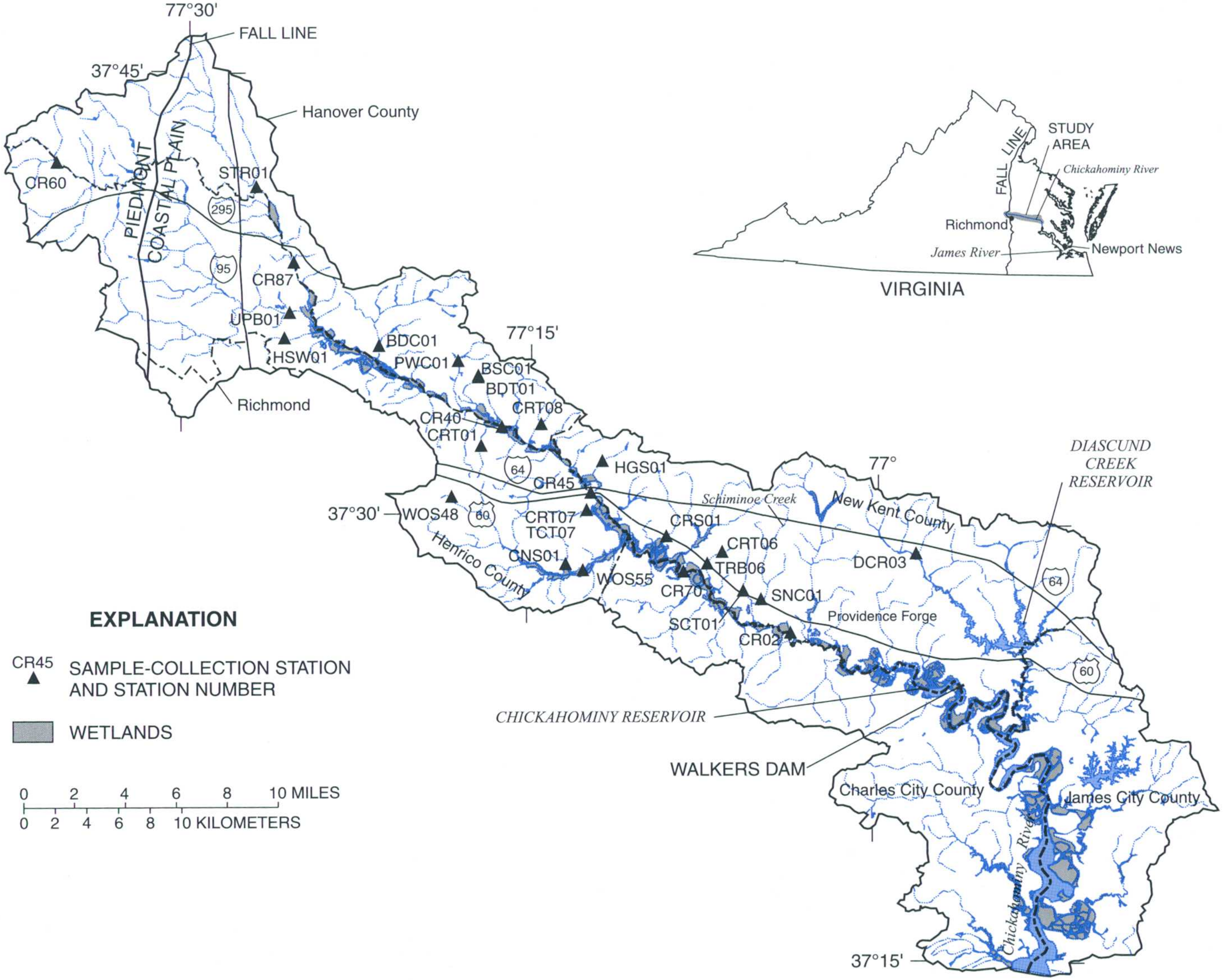

Figure 1. Location and features of study area and location of surface-water sample collection stations, Chickahominy River Basin, Virginia.

molecular weight. These compounds include carbon tetrachloride (CCl_4) and the trihalomethanes (THMs) chloroform ($CHCl_3$) (the primary product), dichlorobromomethane ($CHCl_2Br$), chlorodibromomethane ($CHClBr_2$), and bromoform ($CHBr_3$). Chlorination also produces a mixture of nonvolatile, high molecular weight, halogenated organic compounds (Johnson and Jensen, 1995).

Environmental regulations, however, have targeted THMs. A drinking-water standard, also known as a maximum contaminant level (MCL), of 100 µg/L was first established for THMs and has been lowered to 80 µg/L (U.S. Environmental Protection Agency, 1998). An MCL of 60 µg/L also has been established for the sum of the concentrations of five haloacetic acids (HAA5): monochloroacetic acid, dichloroacetic acid, trichloroacetic acid, monobromoacetic acid, and dibromoacetic acid. These also are low molecular weight compounds. Although an MCL has not been established, the combination of all halogenated organic compounds is commonly referred to as total organic halides (TOXs).

Researchers have attempted to identify those types of dissolved organic compounds that are precursors to the formation of THMs and other DBPs. Although tannic acid (Youseffi and others, 1978) and nitrogen-containing organic compounds (Morris and Baum, 1978) have been shown to contribute to the formation of DBPs, much of the research has focused on the role of humic substances in producing DBPs (Rook, 1974; Oliver and Visser, 1980; Oliver and Thurman, 1981; Saito and others, 1989). Humic substances are naturally occurring, high molecular-weight, organic substances that consist of humic acids (humic substances insoluble below pH 2) and fulvic acids (humic substances soluble throughout the pH range) (Aiken and others, 1985). Humic substances generally contribute from 40 to 60 percent of the DOC in natural waters (Thurman, 1985). Oliver and Visser (1980) determined that humic and fulvic acids in stream and lake water produce chloroform at similar rates per mass of the acid. Fulvic acids, however, produced much more chloroform than humic acids because fulvic acids dominate the composition of humic substances in water. The relations of chloroform production by humic and fulvic acids are consistent through the full range of molecular weights of the acids. The production of chloroform, however, was greatest for those humic substances having a molecular weight of 1,000 to 10,000 units and decreased rapidly as the molecular weight increased to 30,000 units.

Because of the variety of organic substances that are precursors to the formation of THMs and other DBPs, the use of surrogate analyses has been studied as a way to evaluate the likelihood of the formation of large concentrations of DBPs. For example, the absorbance of light at 253.7 nanometers (referred to as UV254) by water commonly correlates with the presence of precursors to the formation of THMs and other organic halides (Singer and others, 1981; Edzwald and others, 1985); this determination, therefore, is frequently used as such a surrogate for the precursors. Although strong correlations may exist between UV254 and DBP formation potential, UV254 is a measure of only one characteristic of the DOC; this characteristic does not necessarily contribute to the formation of DBPs. Thus, changes in the reactivity of the DOC with chlorine can differ from changes in UV254, thereby limiting the use of UV254 as a surrogate. The effectiveness of UV254 as a surrogate, therefore, likely depends on the system and the hydrologic conditions being studied.

Because commonly used treatment processes cannot selectively remove DBP precursors, all of the DOC must be treated to produce the lowest possible concentrations of DBPs in finished water supplies. Thus, the cost of removal of DBP precursors is heavily influenced by the total amount of DOC in the raw water. In general, high molecular-weight organic compounds are less soluble and more easily removed from water by conventional water-treatment processes than low molecular-weight organic compounds. Because the low molecular-weight compounds tend to form more DBPs (Oliver and Visser, 1980), as well as being more difficult to remove, reducing the concentration of DBPs in treated water supplies can be difficult and costly.

Description of Study Area

More than 80 percent of the Chickahominy River Basin lies within the Coastal Plain Physiographic Province in eastern Virginia (fig. 1). The headwaters of the river are in the Piedmont Physiographic Province, where consolidated bedrock is overlain by weathered rock (saprolite). Saprolite largely consists of silt and clay that contain variable amounts of sand. The thickness of the saprolite ranges from less than 1 ft to several tens of feet. The Coastal Plain is underlain by a wedge of interlayered gravel, sand, silt, and clay deposited on a base of consolidated bedrock.

The Chickahominy River flows in a general southeasterly direction and discharges into the tidal James River. Chickahominy Reservoir is formed on the Chickahominy River by Walkers Dam (fig. 1). The river is tidal below the dam and generally nontidal above the dam. One of the purposes of the dam is to minimize the upstream flow of salty water. During spring tides (periods of extremely low and high tides caused by the alignment of the sun and the moon), however, salty water can flow upstream over the dam if streamflow is low.

The City of Newport News withdraws water from the reservoir just upstream from the dam. The drainage area above the dam is 301 mi^2. The characteristics of the stream channel and adjacent flood plain vary, depending on the hydrogeology of the physiographic province. In the Piedmont, the river generally has a single channel that is deeply incised into a narrow flood plain that limits the extent of adjoining wetlands. The average gradient in the stream channel decreases from about 0.01 in the extreme headwaters to 0.005 at the uppermost water-quality sample-collection station (CR60, fig. 1), to 0.002 where the river enters the Coastal Plain. In the Coastal Plain, the flood plain widens to 1 to 2 mi and the width and depth of incision of the stream channel are highly variable. Although a deeply incised single channel is present along some reaches of the river, multiple shallow and wide channels spread across the broad flood plain along other reaches. The broad flood plain contributes to the presence of lowland wetlands. The channel slope generally is less than 0.001 along most stream reaches in the Coastal Plain.

Land use and cover in the uplands differ between the upper and lower parts of the basin. Most of the upper half of the basin (except for the extreme upper part) is primarily urbanized and consists of parts of the City of Richmond and the developed parts of Henrico and Hanover Counties. The lower half of the basin is primarily forested and contains some agriculture. For the entire basin in 1994, approximately 54 percent was forested (excluding forested wetlands), 16 percent was wetlands, 10 percent was residential, 7 percent was urban/developed, 9 percent was agriculture, 3 percent was grasslands, and 1 percent was old fields (Diane Eckles, U.S. Department of Agriculture, Natural Resources and Conservation Service, written commun., 1997).

The climate of the basin is characteristic of the humid Middle Atlantic states. Precipitation is plentiful (about 44 in/yr) and is fairly evenly distributed throughout the year (National Oceanic and Atmospheric Administration, 1996). The high summer and low winter air temperatures create seasonal changes in rates of evaporation and plant uptake of water (evapotranspiration); rates are highest in the summer and lowest in the winter. High rates of evapotranspiration in the summer remove large quantities of water from the soil and subsurface water, causing ground-water levels to decline and streamflow to decrease.

Acknowledgments

The author wishes to thank various individuals for involvement that was critical to the success of this study and completion of this report. Richard Mountcastle and Peter Daniel provided access to their property for local study components. Cody W. Reinitz, Karen J. Gregg, and Robert W. Jacobsen, who were employed by the USGS as a part of the cooperative program for students from Virginia Polytechnic and State University, assisted with data collection, data processing, and data presentation. Richard J. Ahlin, William V. Daniels, Jr., Karl M. Dydak, and Joel R. Guyer of the USGS Virginia District also collected data. Sherry Williams, Water Quality Manager for the City of Newport News Waterworks, and the rest of the laboratory staff analyzed samples for a variety of organic constituents. Robert B. Banks and Theodore B. Samsel III of the USGS Virginia District assisted in the preparation of illustrations. Technical content of this report was improved by reviews provided by Marcus C. Waldron (USGS, Northborough, Mass.) and William R. Green (USGS, Little Rock, Ark.). The readability of this report was significantly improved by the editing provided by Martha L. Erwin.

STUDY METHODS

The study consisted of field and laboratory studies. Field studies were designed to evaluate spatial and temporal variability in concentrations of DOC and DBP precursors in stream water and the contribution of ground water to the organic content of stream water. Laboratory studies were conducted to evaluate (1) the contribution of stream-bed detritus to the DOC content of stream water and (2) the degradation of DOC in stream water.

Samples were analyzed for numerous analytes depending on the purpose of the sample. Analyses included the absorbance of light at 253.7 nm (UV254) and concentrations of major ions, stable isotopes (oxygen-18/oxygen-16 ratios (^{18}O) and deuterium/hydrogen ratios (D)), DOC, and total organic carbon (TOC). Samples also were analyzed for THM formation potential (THMFP), TOX formation potential (TOXFP), and haloacetic acid formation potential (HAAFP).

UV254 of samples was analyzed by the USGS laboratory in Richmond, Va., using a method described by the U.S. Environmental Protection Agency (1994). Absorbance is defined by the following equation:

$$A = log\ P_o / P$$

where A is the absorbance, P_o is the power of the light beam after passing through de-ionized water, and P is the power of the light beam after passing through sample water (Skoog and West, 1963). Because cuvettes of different widths can be used, units of absorbance are reported as "per the width of sample cuvette through which the light beam passes." Units for absorbance in this report are "per centimeter" (cm^{1}).

Concentrations of stable isotopes were analyzed by the USGS laboratory in Reston, Va., using a method described by Coplen and others (1991). Concentrations of major ions were analyzed by the USGS National Water Quality Laboratory in Arvada, Colo., using methods described in Fishman and Friedman (1989) and Fishman (1993). Concentrations of DOC, TOC, THMFP, TOXFP, and HAAFP were analyzed by the Waterworks Laboratory of the City of Newport News using methods described by the American Public Health Association (1995) and the U.S. Environmental Protection Agency (1992; 1994). THMFP is expressed as the sum of the concentrations of the trihalomethanes that are formed, in micrograms per liter. TOXFP is expressed as the concentration of chlorine that reacts with the DOC, in micrograms per liter of chloride (Cl). HAAFP is expressed as the concentration of the sum of the haloacetic acids that are formed, in micrograms per liter. The complexity and cost of many of the analyses limited the number of samples that could be analyzed. Consequently, UV254 was used as a surrogate for the other organic analyses for many samples to provide a more comprehensive representation of the natural system than could otherwise be obtained. Only field parameters and UV254, therefore, were analyzed for many of the samples.

Results of analyses of stable isotopes, majors ions, and UV254 performed by USGS laboratories are published in White and others (1996; 1997; 1998; 1999). UV254 and results of analyses of DOC, TOC, THMFP, TOXFP, and HAAFP performed by the Waterworks Laboratory of the City of Newport News are included in the appendix of this report.

Field Studies

Field studies consisted of stream-water and ground-water sampling. Stream-water samples were collected at a network of stations located throughout the basin. Ground-water samples were collected at wells and seeps in a sub-basin of the Chickahominy River.

Stream-Water Sampling

Stream-water samples were collected from a network of 27 stations located throughout the basin upstream from Walkers Dam (table 1, fig. 1). The network consisted of 6 main-stem Chickahominy River stations and 21 tributary stations. The main-stem stations are identified by "CR" followed by a number (CR60, for example). Main-stem stations were distributed from station CR60 in the headwaters to station CR02 about 6.5 mi upstream from Walkers Dam. No stations were located farther downstream than station CR02 because of backwater effects of Chickahominy Reservoir and tidal flow downstream of the dam. Station CR02 is a focus of this report because it is the main-stem station closest to the water-supply withdrawal point for the City of Newport News. Tributary stations were selected to represent the range of tributary characteristics that include drainage area, characteristics of valley incisement into the uplands (narrow, steeply sloped valleys or broad valley), land use, location of the sub-basin in the main basin, and the amount of wetlands. The stream length bordered by

Table 1. Characteristics of water-sample collection stations, Chickahominy River Basin, Virginia

[B, base-flow synoptic sample collection; Q, quarterly sample collection; S, stormflow sample collection; –, not available

Down-stream sequence number	Station number	USGS station identification number	Station name	Stream length bordered by wetland (percent)	Drainage area (square miles)	Sampling regime
1	CR60	02042260	Chickahominy River at Rt. 624 nr. Farrington, Va.	48	6.8	B
2	STR01	02042284	Stony Run at Rt. 656 nr. Greenwood, Va.	54	18.1	B
3	CR87	02042287	Chickahominy River at US 301 nr. Atlee, Va.	45	62.2	B, Q, S
4	UPB01	02042426	Upham Brook at Wilkinson Road nr. Richmond, Va.	31	37.6	B
5	HSW01	02042429	Horse Swamp at Richmond/Henrico Turnpike at Richmond, Va.	0	1.9	B
6	BDT01	02042432	Beaverdam Creek Tributary nr. Mechanicsville, Va.	0	.1	B
7	BDC01	02042433	Beaverdam Creek at Rt. 156 nr. Mechanicsville, Va.	39	11.3	B
8	PWC01	02042437	Powhite Creek at Rt. 156 at Cold Harbor nr. Meadows, Va.	–	2.9	B
9	BSC01	02042438	Boatswain Creek nr. Highland Springs, Va.	53	0.9	B
10	CRT01	02042439	Chickahominy River Tributary No. 1 at Rt. 613 nr. Richmond, Va.	71	2.1	B
11	CR40	02042440	Chickahominy River at Rt. 156 nr. Seven Pines, Va.	45	149.3	B, Q
12	CRT08	020424410	Chickahominy River Tributary No. 8 at Rt. 613 nr. Seven Pines, Va.	82	1.0	B
13	HGS01	02042442	Higgins Swamp at Rt. 613 nr. White Oak Swamp, Va.	74	2.1	B
14	CR45	02042445	Chickahominy River at US 60 nr. White Oak Swamp, Va.	49	171.3	B
15	TCT07	02042446	Chickahominy River Tributary to Tributary 7 at White Oak Rd. nr. White Oak Swamp, Va.	0	.1	B
16	CRT07	02042447	Chickahominy River Tributary 7 at White Oak Rd. nr. White Oak Swamp, Va.	5	1.6	B, Q
17	WOS48	02042448	White Oak Swamp at Beulah Road at Seven Pines, Va.	0	1.0	B
18	CNS01	02042454	Canal Swamp at Portugee Rd. at Elko, Va.	82	2.3	B,Q
19	WOS55	02042455	White Oak Swamp at Rt. 156 at Elko, Va.	74	23.6	B, Q, S
20	CRS01	02042460	Crumps Swamp at US 60 nr. Roxbury, Va.	83	3.1	B
21	CR70	02042470	Chickahominy River at Rt 609 nr. Roxbury, Va.	55	225.6	B, Q
22	CRT06	02042475	Chickahominy River Tributary 6 at Rt 615 nr. Roxbury, Va.	0	.4	B
23	TRB06	02042476	Chickahominy River Tributary 6 at US 60 nr. Roxbury, Va.	0	.8	B
24	SCT01	02042478	Tributary to Schiminoe Creek at US 60 nr. Providence Forge, Va.	51	1.6	B, Q, S
25	SNC01	02042480	Schiminoe Creek at US 60 nr. Providence Forge, Va.	87	5.2	B
26	CR02	02042500	Chickahominy River at Rt. 618 nr. Providence Forge, Va.	56	252	B, Q, S
27	DCR03	02042726	Diascund Creek at Rt. 628 nr. New Kent, Va.	55	9.3	B, Q, S

wetlands (fig. 1) was derived from the 1994 wetlands delineation by the U.S. Fish and Wildlife Service (Diane Eckles, written commun., 1997).

Samples were collected at different frequencies during both base-flow and stormflow periods at different stations depending on the objective of the sample collection. Samples were collected at all stations during several synoptic base-flow collection periods (stations identified by a "B" in table 1). Synoptic base-flow sample collection was intended to provide a detailed assessment of the spatial distribution of the organic content of stream water throughout the basin during base-flow periods. Samples also were collected at five stations during selected stormflow periods (stations identified by an "S" in table 1) to evaluate changes in the organic content of the stream water as a result of stormflow. Samples were not collected at all five stations during each stormflow sample-collection period. Samples also were collected approximately once a quarter at nine stations to evaluate temporal changes in the organic content of stream water (stations identified by a "Q" in table 1). These included four main-stem and five tributary stations. Although quarterly sampling was intended to occur during base-flow periods, some samples were collected toward the end of stormflow periods at main-stem stations. Samples collected during quarterly sampling generally were analyzed for a more comprehensive group of analytes than samples collected during the synoptic sample collection.

The five stations in the stormflow sample-collection network were equipped with continuous stage recorders to assist in distributing the collection of samples over the stormflow hydrograph. At stations not equipped with continuous stage recorders, a temporary reference point was established, and the depth to the water surface from this reference point was measured when samples were collected. This measurement was subtracted from an arbitrary datum of 100 ft, according to protocols of the Virginia District of the USGS for establishing temporary reference points.

Samples were collected with a weighted glass bottle by depth integration at the center of streamflow when possible. Where water was too shallow, sample bottles were dipped near the center of streamflow. Water at all sampling stations was analyzed for field-measured properties (water temperature, dissolved oxygen concentration, specific conductance, and pH). In the laboratory, all samples were analyzed for UV254, and selected samples were analyzed for concentrations of major ions (dissolved sodium, potassium, calcium, magnesium, chloride, fluoride, and sulfate), stable isotopes (^{18}O and D), DOC, TOC, THMFP, TOXFP, and HAAFP. The analyses performed on a given sample varied depending on the reason the sample was collected and the workload of the laboratory that performed each analysis.

Samples were processed and preserved differently in the field depending on the intended analysis. Analyses for stable isotopes and for THMFP, TOXFP, and HAAFP used whole water samples that required no processing other than being poured into the sample bottle. Samples for analyses of stable isotopes were stored in clear-glass polyseal bottles with no head space. Samples for analyses of THMFP, TOXFP, and HAAFP were stored in separate amber-glass bottles with no head space and were chilled on ice. TOC analyses used whole-water samples stored in amber-glass vials to which two drops of concentrated hydrochloric acid (HCl) were added; samples were stored on ice. Samples for analysis of DOC and UV254 were filtered in the field by use of a 0.45-µm pore size, silver filter in a stainless-steel filter support. Filtered samples were stored in 60-mL, amber-glass vials and chilled on ice. Two drops of concentrated HCl were added to each DOC sample; the UV254 samples received no additional treatment. Major ion samples were filtered in the field using a 0.45-µm pore size, membrane capsule filter. Anion samples received no additional treatment and were stored in plastic bottles. Cation samples were stored in acid-rinsed plastic bottles to which 1 mL of concentrated nitric acid was added.

Ground-Water Sampling

Ground water provides a large part of the streamflow in the Chickahominy River Basin and is also a potential source of organic carbon to stream water. Consequently, samples of ground water were collected from wells and seeps in the basin of an unnamed creek that is a tributary to Schiminoe Creek (near station SCT01, fig. 1), a tributary to the Chickahominy River. Wells were constructed in clusters at different locations to determine the organic content of ground water at different locations within the ground-water flow system. Wells in each cluster were screened at different depths to identify any vertical differences in the organic content of the ground water. Water was collected from seeps in the stream bank of the creek because the seeps are sources of ground-water discharge to the stream.

Station SCT01 is near the lower end of the basin in which ground-water samples were collected. This part of the basin was selected for ground-water sampling because it appeared to represent the two major types of water-table aquifers in the Coastal Plain part of the Chickahominy River Basin. An upland water-table aquifer borders the creek (typical of the stream incision in fig. 2A) downstream of a reach that is bordered by an alluvial water-table aquifer overlain by a several-hundred-foot-wide wetland flood plain (typical of the stream incision in fig. 2B). Although it is not typical to have an upland water-table aquifer adjacent to a stream downstream of an alluvial water-table aquifer, this system provided an opportunity to evaluate the difference in the organic content of the ground water derived from both types of water-table aquifers.

One cluster of wells (wells UN30A, UN30B, and UN30C) was installed in the water-table aquifer about 50 ft from the creek where it is bordered by the upland water-table aquifer (fig. 3). A transect of wells also was constructed from the edge of the wetland flood plain across the flood plain overlying the alluvial water-table aquifer. Two wells at the edge of the flood plain (wells ULS-1 and ULD-1) were open to the upland water-table aquifer. Two wells in the middle of the flood plain (wells FPS and FPD) and one at the edge of the creek (well FP05) were open to the alluvial water-table aquifer. Wells were constructed of 2-in-diameter polyvinylchloride well casings and 1-ft-long screens.

Ground-water samples were collected after pumping water from the wells until field-measured properties stabilized. Because of the high clay content of parts of the water-table aquifer, several wells yielded water very slowly and were pumped dry. In these situations, the wells were allowed to refill with water that was then pumped for samples. Water was collected from seeps in the stream bed (SP01, SP02, and SP03) by placing plastic food-storage bags under the seep until the bag filled with sufficient water for analysis. Mini-piezometers were driven into the stream bed and pumped to collect ground water immediately before it discharged to the stream. Sufficient water could not be pumped from the mini-piezometers for analysis, however, because the stream bed had a high clay content and low permeability. Consequently, only water from seeps and wells was analyzed for organic carbon content. Water from the wells and seeps was analyzed for field-measured properties (water temperature, specific conductance, and pH), UV254, and concentrations of major ions, stable isotopes, and DOC. Ground-water samples were processed in the same manner as the surface-water samples.

Isotope Analysis

The abundance of ^{18}O and D, the heavy, stable isotopes of oxygen and hydrogen, was analyzed in stream water and ground water to determine the seasonal effects of ground-water discharge and evaporation on streamflow of the Chickahominy River Basin. ^{18}O and D occur in the natural environment, including in the water molecule, wherever the more abundant lighter-weight isotopes (^{16}O and H, respectively) are present (Gat and Gonfiantini, 1981; Coplen, 1993). The abundance of ^{18}O and D in water varies on global and local scales; therefore, measurement of the abundance of ^{18}O and D in water can be an important tool in evaluating hydrologic processes and pathways. This variability occurs because the heavy isotopes react chemically and physically in a different manner than the lighter weight isotopes. This difference in reaction results in fractionation that depletes or enriches their abundance in the source water. Evaporation and condensation are among the processes that fractionate ^{18}O and D.

Because of the limited abundance of ^{18}O and D, the ratios of ^{18}O to ^{16}O ($^{18}O/^{16}O$) and D to H (D/H) can be measured to an order of magnitude greater accuracy than actual concentrations (Coplen, 1993). To provide a common reference, ratios of the isotopic composition of samples typically are compared to those of a standard. Comparisons are expressed as delta (δ) values in units of parts per thousand (per mil) as indicated by the following equation for ^{18}O:

$$\delta^{18}O = \left(\frac{(^{18}O/^{16}O)sample}{(^{18}O/^{16}O)standard} - 1 \right) \times 1,000.$$

Values from oxygen and hydrogen isotope samples are reported relative to the Vienna Standard Mean Ocean Water (VSMOW). A negative δ value indicates that the sample is isotopically depleted relative to the standard and is referred to as isotopically "light." This is typical of waters in the Chickahominy River Basin.

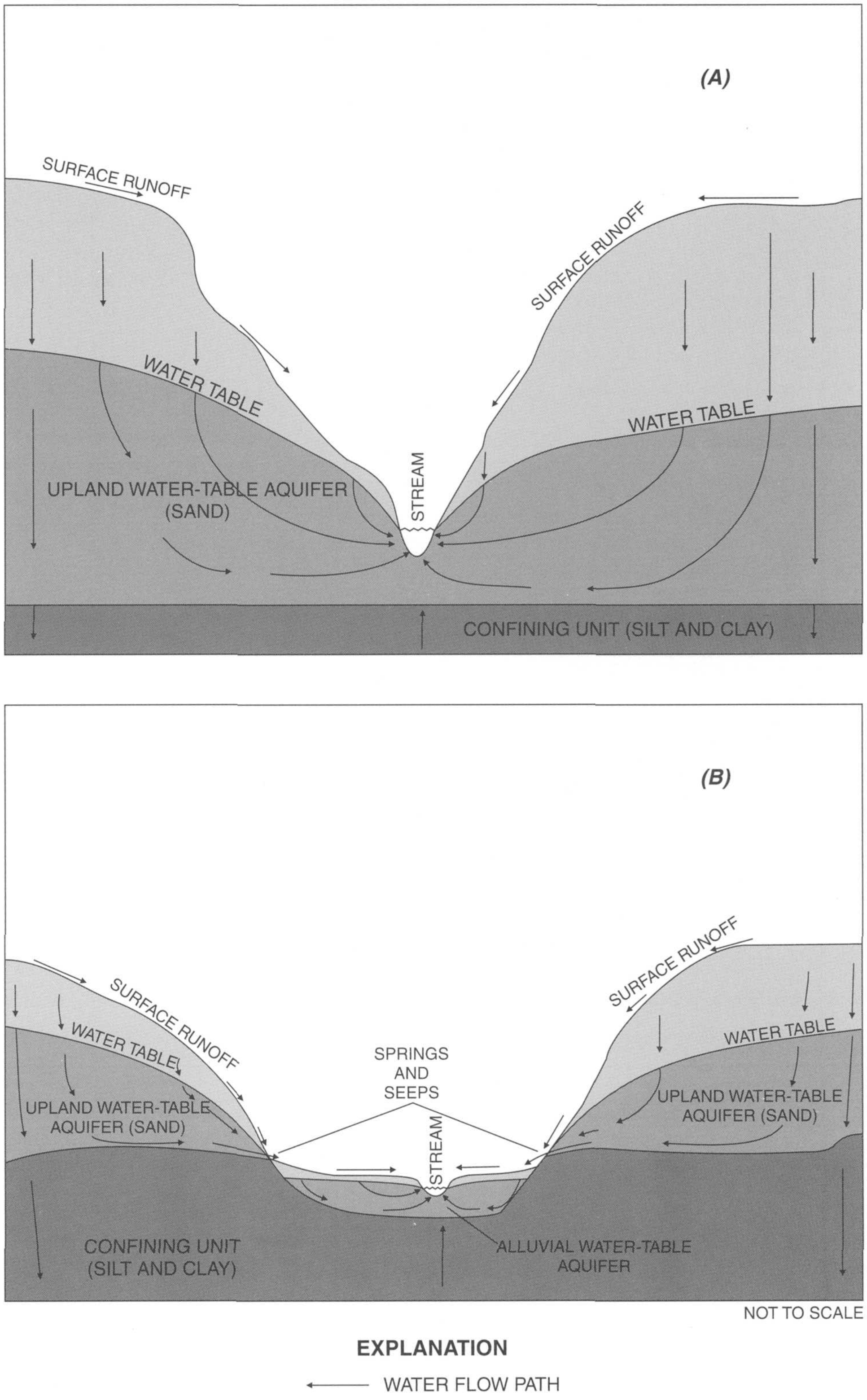

Figure 2. Conceptualized stream and ground-water interaction for a stream partly incised through the upland water-table aquifer *(A)*, and for a stream fully incised through the upland water-table aquifer and into the confining unit *(B)*.

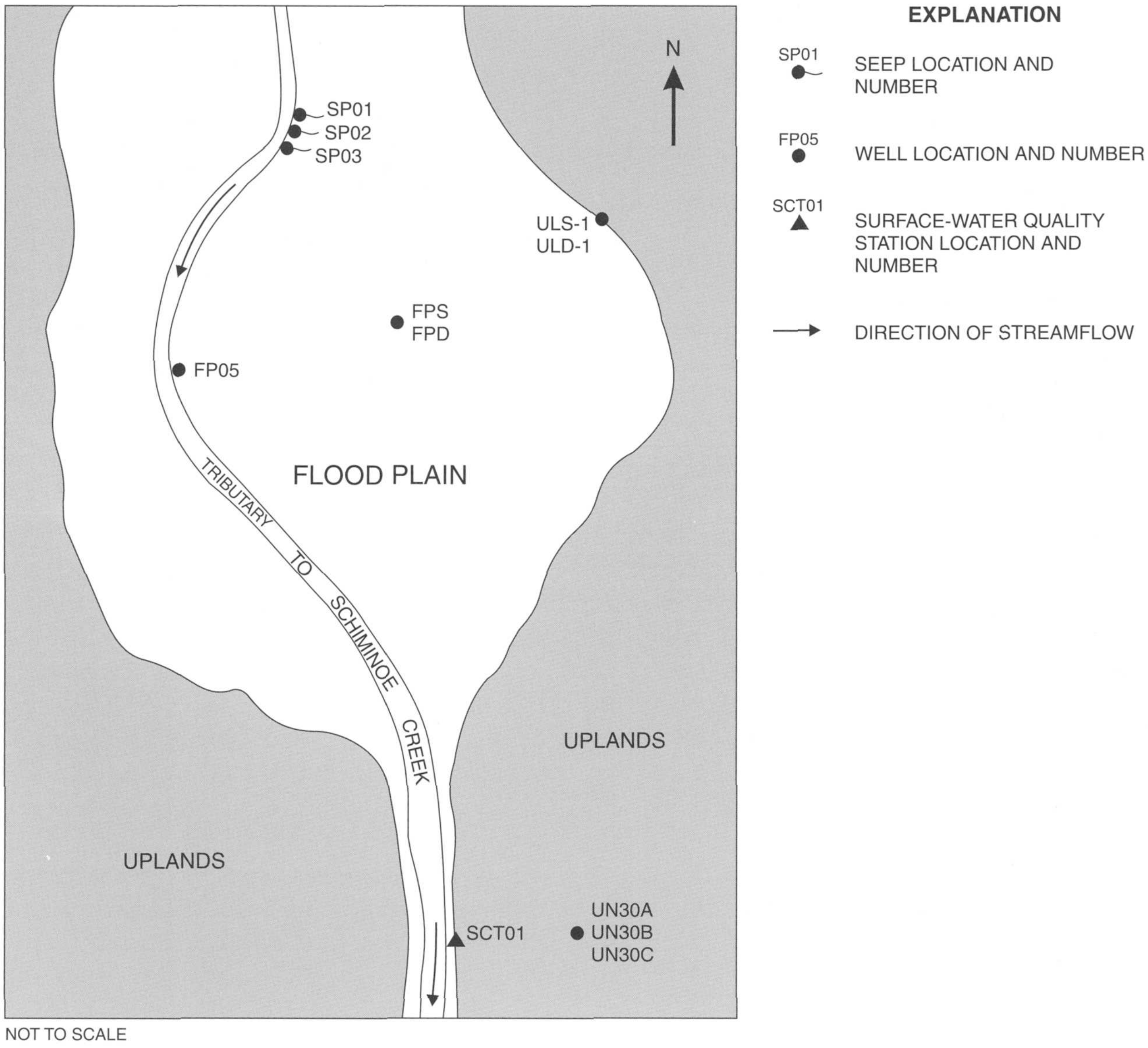

Figure 3. General locations of the flood plain, uplands, seeps, wells, and the surface-water quality station in part of the watershed of the tributary to Schiminoe Creek, Chickahominy River Basin, Virginia.

The relation of $\delta^{18}O$ and δD in precipitation is defined by the equation

$$\delta D = m\delta^{18}O - d,$$

where *m* is the slope of the relation and *d* is the deuterium excess. Globally, the mean deuterium excess is +10 per mil (Craig, 1961). The line formed by this relation applied globally is called the "global meteoric water line." Because the deuterium excess differs by location, a different equation can be derived for local precipitation. If isotopes in precipitation that contributes to streamflow are not fractionated, the isotopic composition of stream water will coincide with that of the local meteoric water line. If a substantial part of the stream water evaporates, the fractionated isotopes will result in a relation having a slope less than 8, and typically ranging from 3 to 6 (Coplen, 1993). In moderate climates such as that in the Chickahominy River Basin, evaporation typically is not a factor in the fractionation of isotopes in water except where large lakes or reservoirs provide a large surface area for evaporation (Gat and Gonfiantini, 1981).

Laboratory Studies

Laboratory studies were conducted to evaluate (1) the potential contribution of stream-bed detritus to the DOC content of stream water and (2) the potential for degradation of DOC in stream water.

Stream-Bed Detritus

Stream-bed detritus consisting of leaves, small branches, and pieces of porous wood was collected from the tributary to Schiminoe Creek near station SCT01 (fig. 1). These materials were selected because they were the predominant detritus in the stream bed. The materials were washed with tap water followed by an organic-free, de-ionized water rinse to remove stream water containing DOC and to leach readily soluble organic carbon from the surface of the material. The samples were then air dried for weighing purposes. The branches and wood were broken into pieces that would fit into the clear-glass, 1-L bottles in which the samples were incubated. Material was not broken up further to minimize exposure of surfaces not previously exposed to water in the stream. Three samples of each type of material were weighed and placed in separate bottles. Similar sizes of branches and wood were placed in each bottle to reduce the differences in the amount of exposed surface area in replicate samples. The amount of surface area per unit mass of material, however, clearly differed among the different types of material and likely differed among samples of the same material type. Each bottle was filled with organic-free, de-ionized water. Bottles were capped and incubated for 11 days in the laboratory at room temperature. Bottles were shaken once or twice a day.

Each bottle was shaken and uncapped, and approximately 5 mL of water were extracted with a syringe. Water samples were filtered through 0.45-µm pore size, glass-fiber syringe filters and analyzed for UV254. Samples were first analyzed as soon as possible after all bottles were filled and capped; this analysis provided a baseline reference for subsequent analyses. Samples were also analyzed at 4 hours and at 1, 4, 8, and 11 days.

Degradation of Dissolved Organic Carbon

DOC degradation studies were designed to evaluate the potential for DOC degradation in stream water and to determine if photodegradation is a significant factor in this process. Water was collected at station CNS01 (fig. 1) on October 22, 1997, as a part of quarterly sample collection. This site was selected because it is on a tributary that was shown to have a high DOC content based on results of the field studies. To evaluate DOC degradation, water was treated and incubated in several ways (fig. 4). Part of the water was filtered and part remained unfiltered. Unfiltered water was used to represent stream water that, among other factors, contains particulate organic material and large populations of microbes that can decompose the organic material. Water was filtered to remove particulate organic material and a large part of the microbial population. Samples were filtered in the field, and both filtered and unfiltered samples were chilled to 4°C and stored until the start of the incubation period. A 0.45-µm pore size, membrane capsule filter was used rather than the 0.45-µm pore size silver filter because a large quantity of water was needed for these studies. Silver filters are easily plugged and could not pass the needed volume of stream water.

To minimize possible contamination of the sample by organic residue from the capsule filter, the filter was washed with approximately 4 L of organic-free water. Approximately 0.5 L of sample water was then passed through the filter. Six amber-glass, 1-L bottles and six clear-glass, 1-L bottles were then filled with filtered water. Amber-glass bottles were used to inhibit light penetration to sample water; clear-glass bottles were used to permit light penetration to sample water. Bottles were filled sequentially with water directly discharged from the filter. Similarly, six amber-glass, 1-L bottles and six clear-glass, 1-L bottles were filled with unfiltered water.

Of the six bottles of each glass type containing filtered or unfiltered sample water, half were incubated at room temperature on a south-facing window sill to promote biological degradation and photodegradation of the DOC. The other half of the sample bottles were incubated at 4°C in a refrigerator to minimize degradation. This regime provided triplicate samples of each combination of filtration, bottle type, and incubation method.

Periodically, 5 to 10 mL of sample was poured from each bottle into individual small beakers. Water from unfiltered samples was filtered through 0.45-µm pore size, glass-fiber syringe filters to remove particles that would increase absorbance readings. A portion of each sample was poured into a quartz cuvette and analyzed for UV254. A subsample from one of the three bottles of each of the treatments also was analyzed for concentrations of DOC and THMFP at the beginning and end of the study. The degradation studies were continued for 83 days from October 22, 1997, through January 13, 1998.

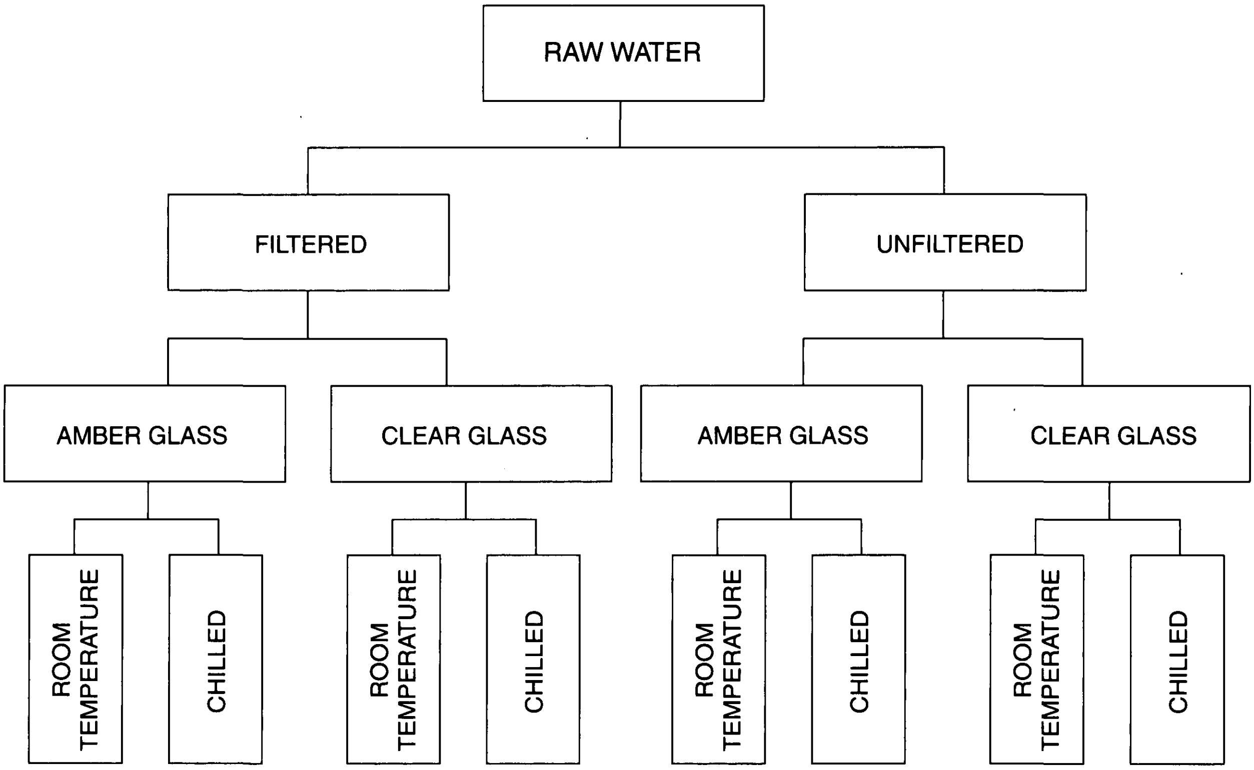

Figure 4. Treatment of water samples to evaluate degradation of dissolved organic carbon.

BASIN HYDROLOGY

The hydrology of the Chickahominy River Basin affects water quality within the basin, including the organic carbon content of streams. Ground and surface water are hydraulically interconnected, and both, therefore, can be important transport pathways for organic carbon.

Surface Water

Streamflow was variable during the study period (table 2). Mean annual flow at station CR02 in water year 1995 was about 57 percent of the mean annual flow for the period of record. A record low flow of 0.30 ft^3/s for station CR02 was recorded in September 1995. Mean annual flow in water year 1996 was near the long-term average. Mean annual flow in 1997 was about 16 percent greater than the long-term average. This, however, was a year of very contrasting flows. The monthly mean flow of 748 ft^3/s in December 1996 was about 2.6 times the monthly mean flow for the period of record for December. In contrast the mean monthly flow for September 1997 was 0.17 ft^3/s (less than 0.2 percent of the normal flow for the month). Another record low flow (0.06 ft^3/s) was recorded on several days in September 1997. Water year 1998 was the wettest year of the study; the mean annual flow of 380 ft^3/s was 144 percent of the mean annual flow for the period of record. This year, however, was another year of extremely contrasting flow. The low flow of record was nearly repeated in October 1997 before flows increased to a peak mean monthly flow of 1,198 ft^3/s in February 1998. This was 2.8 times the mean monthly flow for February for the period of record. Streamflow again decreased to approximately 15 percent or less of the mean monthly streamflow in August and September 1998.

Streamflow in the Chickahominy River Basin consists of either stormflow or base flow. Stormflow consists of ground-water discharge and surface runoff, but is largely surface runoff; base flow is entirely ground-water discharge. During stormflow periods, streamflow normally increases from base flow to a peak flow and then declines back to base flow. The

Table 2. Streamflow characteristics at station CR02 for the period of record and for each year of the study period, Chickahominy River Basin, Virginia (units are cubic feet per second) (White and others, 1996; 1997; 1998; 1999)

Month or flow category	Water year				
	1942-1998	1995	1996	1997	1998
October	144	84.7	113	508	24.9
November	209	237	209	373	287
December	287	144	154	748	150
January	380	300	524	329	643
February	430	195	534	447	1,198
March	481	334	297	490	1,055
April	384	102	377	266	561
May	240	254	155	260	350
June	165	71.6	97.2	111	169
July	146	44.4	181	97.0	157
August	161	5.53	156	20.6	15.2
September	107	13.8	459	.17	16.3
Mean annual flow	263	149	270	304	380
Instantaneous peak flow	7,710	1,040	2,230	1,450	2,880
Instantaneous low flow	.06	.30	7.7	.06	.07

response time to attain peak flow, the size of the peak, and the relative contribution of surface runoff and ground-water discharge to stormflow are influenced by land use and cover, soil composition, and basin size, shape, and geomorphology (Focazio and Cooper, 1995). Two of the most important aspects of land use and cover that affect stormflow characteristics are the amount of impervious area and the amount of wetland flood plains.

Typically, streamflow responds rapidly to precipitation in small basins and in basins that have large percentages of impervious area, high slopes, or only small areas of wetland flood plains. Response to precipitation is slower in large basins and in basins that have little impervious area, low slopes, or extensive wetland flood plains. Thus, streamflow responds more rapidly to precipitation in tributaries of the urbanized areas and headwaters than in downstream parts of the main stem of the Chickahominy River. In small tributaries, streamflow can attain peak flow within a few hours and return to base flow a few hours later. In contrast, streamflow typically requires 3 to 5 days after the precipitation to reach its peak at the farthest downstream main-stem station (CR02), and 10 to 14 days to return to base flow.

Although the total runoff from a given stormflow event generally increases downstream with increasing drainage area, the peak flow in the Chickahominy River for a given storm can be greater upstream because the peak is attenuated as the water flows downstream and spreads over the broad wetland flood plain. For example, the peak flow at stations CR87 and CR02 for water year 1996 (from October 1, 1995, through September 30, 1996) occurred during the same runoff event in January 1996. The peak flow at CR87 was 3,070 ft^3/s on January 20, but the peak flow downstream at CR02 on January 22 was only 2,230 ft^3/s (table 3).

During low, base-flow periods, the meandering nature of the Chickahominy River and the presence of multiple shallow stream channels results in sluggish flow and long traveltimes from the headwaters to the lower nontidal part of the basin. On the basis of average flow velocities measured throughout the basin during the August 1995 sample-collection period, the traveltime from the headwaters to station CR02 was estimated to be about 60 days. Because streamflow velocity was insufficient to measure with a current meter at many points in the streams, average measured velocities likely are greater than average actual

Table 3. Streamflow characteristics at stations CR87, UPB01, and CR02 (Prugh and others, 1995; White and others, 1997), Chickahominy River Basin, Virginia

[mi^2, square miles; ft^3/s, cubic feet per second; in/yr, inches per year; NR, no record]

Characteristic and units	CR87	UPB01	CR02
Drainage area (mi^2)	62.2	37.6	252
Period of record	Jan. 1990 to Oct. 1997	Dec. 1989 to Oct. 1994	Jan. 1942 to present
Mean annual flow for the period of record (ft^3/s)	56.4	39.4	260
Mean annual runoff for the period of record (in/yr)	12.32	13.88	14.04
Mean annual flow for water year 1996 (ft^3/s)	62.8	NR	270
Mean annual runoff for water year 1996 (in/yr)	13.74	NR	14.57
Instantaneous peak flow for the period of record (ft^3/s)	4,220	2,410	7,710
Date of instantaneous peak flow for the period of record	March 5, 1993	Nov. 28, 1993	Aug. 15, 1955
Instantaneous peak flow for water year 1996 (ft^3/s)	3,070	NR	2,230
Date of instantaneous peak flow for water year 1996	Jan. 20, 1996	NR	Jan. 22, 1996
Instantaneous low flow for the period of record (ft^3/s)	.00	.21	.06
Date of instantaneous low flow for the period of record	Aug. 1-6, 1993, and Aug. 29 to Sept. 1, 1995	June 25, 1993	Sept. 12,14-18, 1997

velocities for the stream reaches represented by a given measurement. Consequently, the actual traveltime probably was substantially longer than the estimated 60 days. The long traveltime and the shallow and meandering characteristics of much of the stream channel enhance the opportunity for degradation processes to decrease concentrations of DOC in the stream water.

The flow of water from a stream into adjacent alluvial sediments and back into the stream can significantly affect the chemistry of the stream water. The sediments through which infiltrating stream water flows are referred to as the hyporheic zone. Numerous studies have shown substantial effects of the exchange of water between the stream and the hyporheic zone on dissolved oxygen and DOC concentrations of stream water (Findlay, 1995). These studies generally have been conducted in mountain and headwater streams that flow through thick, permeable sand and gravel deposits (Bencala and others, 1984; Constanz, 1998; Harvey and Bencala, 1993). Harvey and Bencala (1993) indicate that pool and riffle sequences provide the head differences between the stream and the hyporheic zone that are needed for stream water to infiltrate into bed sediments and subsequently return to the stream. Because of the low gradient in the stream bed of the Chickahominy River, however, few pool and riffle sequences are present. Additionally, the alluvial bed sediments are composed of low permeability, fine-grained sand, silt, and clay. Thus, exchange of water between the Chickahominy River and the hyporheic zone is probably limited.

Evaporation

Evaporation from a stream surface can result in a a substantial loss of water from the stream, even in the humid and temperate climate of Virginia. The shallow, wide, and meandering stream channel of the Chickahominy River makes it prone to evaporation during warm summer months.

The abundance of ^{18}O and D in stream water of the Chickahominy River Basin, unlike that of most streams in moderate climates, indicates that evaporation of stream water is substantial in the basin (fig. 5A). A meteoric water line for the Chickahominy River Basin was developed from isotope data from stream samples collected during the cold-weather months (late November through April). This meteoric water line has a slope of 8 (making it parallel to the global meteoric water line) and a deuterium excess of 13.8 per mil VSMOW. During warm-weather months, the ^{18}O and D relation deviates from the meteoric water line, having a slope of 5.1, a deuterium excess of -4.0 per mil VSMOW, and an R^2 of 0.93 (fig. 5A). The slope of the warm-weather relation is consistent with the slope of relations that reflect isotopic enrichment from evaporation. Although Gat and Gonfiantini (1981) indicate that evaporation in moderate climates typically is not sufficient to fractionate isotopes, evaporation appears to be an important factor in the Chickahominy River Basin. The sluggish flow and shallow meandering channel that enhance evaporation would also enhance degradation of DOC by providing a large surface for exposure to sunlight and bacteria, as well as a long traveltime.

Ground Water

Ground-water discharge contributes a major part of the streamflow in the Chickahominy River Basin, and therefore, can substantially affect the quality of stream water. Ground-water discharge at station CR02 averaged 10.60 in/yr, or 70 percent of the mean annual flow from 1970 through 1990 (Richardson, 1994). Of the total ground water discharged to the river during that period, 6.36 in. discharged in the winter, 2.32 in. in the summer, and the remainder in the spring and fall. These seasonal differences result from the high rates of evapotranspiration in the summer that reduce the amount of ground water discharged to the streams.

Ground water flows through two major types of aquifer systems in the Chickahominy River Basin. In the Piedmont, water flows through fractures in the bedrock and pore spaces in the saprolite. In the Coastal Plain, water flows through pore spaces in the sand and gravel aquifers. In both the Piedmont and Coastal Plain systems, ground water is recharged by precipitation that infiltrates through the soils and percolates to the water table. Water flows vertically and laterally through the aquifers and confining units to areas of low elevation, where it discharges to streams, ditches, springs, seeps, and ponds. Ground water also discharges through evapotranspiration, particularly in wetlands. Ground-water discharge contributes part of the streamflow during stormflow periods and all of the natural streamflow during base-flow periods. Because most of the basin lies within the Coastal Plain, the remaining discussion focuses on the Coastal Plain aquifer system.

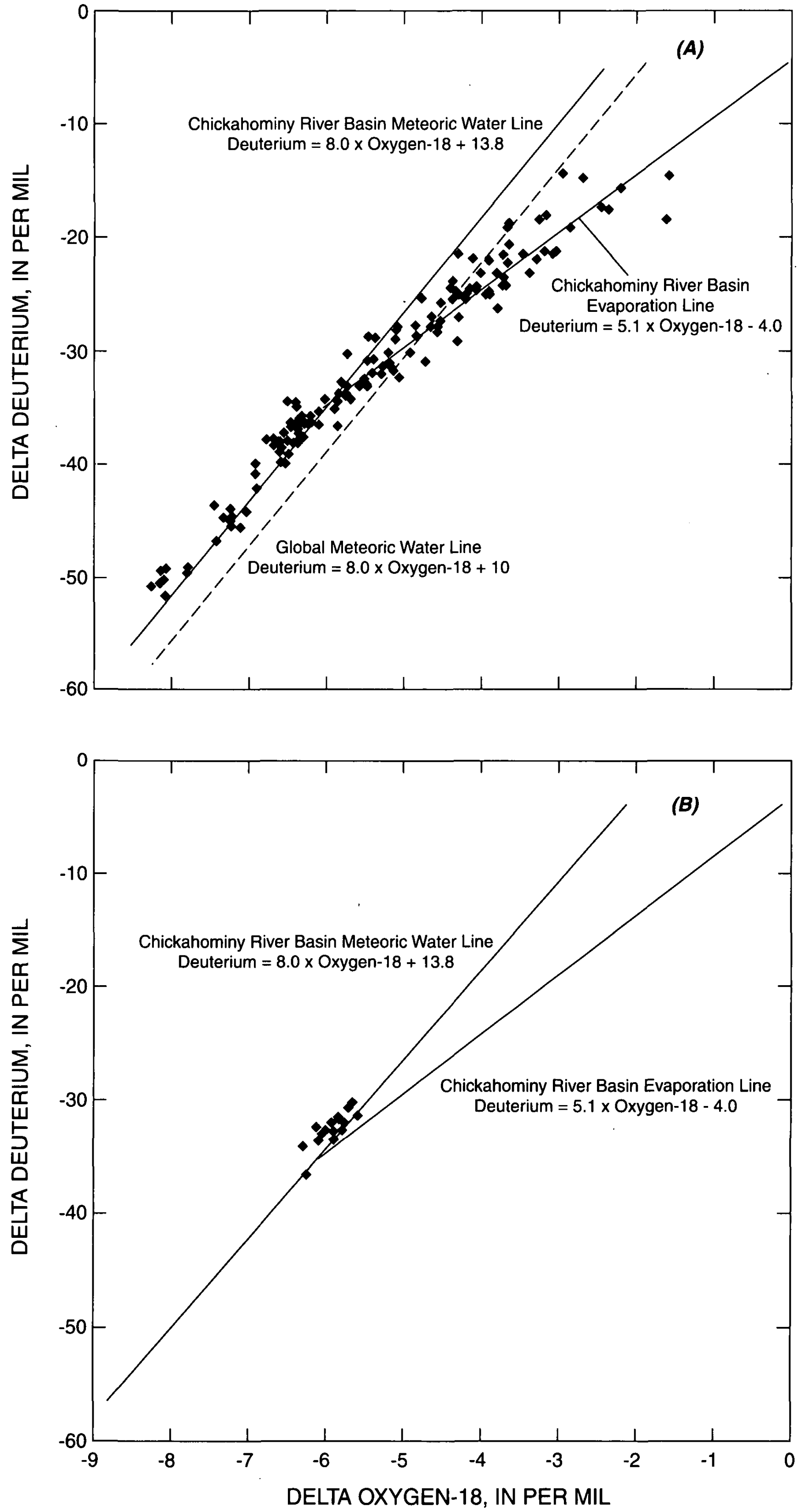

Figure 5. Relation of oxygen-18 and deuterium in streams showing the effects of evaporation *(A)* and in ground water *(B)*, Chickahominy River Basin, Virginia.

The Coastal Plain aquifer system consists of upper unconfined, or water-table, aquifers underlain by a confining unit and confined, or artesian, aquifers separated from one another by additional confining units (Meng and Harsh, 1988). Because surface waters are in better hydraulic connection with the water-table aquifers than with confined aquifers, the water-table aquifers have a more pronounced effect on streamflow and stream-water quality than the confined aquifers. Two types of water-table aquifers are present in the Chickahominy River Basin: (1) an upland aquifer and (2) alluvial aquifers. The organic content of the water discharged from each aquifer type differs because of differences in the characteristics of each type.

Upland sandy sediment (Daniels and Onuschak, 1974) forms the upland water-table aquifer. On the basis of the aquifer delineation of Meng and Harsh (1988), the upland water-table aquifer consists of unconfined parts of the Yorktown-Eastover aquifer. This aquifer is partly incised by the upstream parts of tributaries to the Chickahominy River, creating a good hydraulic connection between the aquifer and the tributaries (fig. 2A). The upstream parts of the tributaries generally form narrow, V-shaped valleys, providing limited wetlands and little available organic material.

Alluvial water-table aquifers are present where the Chickahominy River and downstream parts of the tributaries have eroded and fully incised through the sand of the upland water-table aquifer and into the underlying clayey confining unit. Because the clayey sediment erodes less readily than the upland sandy sediment, the Chickahominy River and lower parts of the tributaries meander and erode wider and flatter valleys than upstream parts of the tributaries, forming broad wetland flood plains (fig. 2B). This erosion creates wide “depositional basins” in the clayey sediment into which the eroded sediments have been redeposited. The redeposited sediments consist of organic and poorly sorted fluvial sediment ranging from clay to gravel in size. On the basis of information in Daniels and Onuschak (1974) and data from several holes that were augered in the flood plain, the thickness of the sediments that form the alluvial aquifers is less than 10 ft. In general, these aquifers tend to be of low permeability because of the high silt and clay content. The alluvial water-table aquifers appear to be discontinuous along some tributaries. The wetlands and high organic content of the aquifer sediment provide a large source of organic material for the ground water.

The contact between the upland water-table aquifer and the underlying confining unit is above the floor of the valleys in many areas. In such areas, the upland water-table aquifer is not in direct hydraulic contact with the alluvial water-table aquifers (fig. 2B). Consequently, seeps and springs commonly discharge from the upland water-table aquifer along valley walls at the basal contact between the aquifer and the confining unit. Because the tributaries intercept much of the discharge from the upland water-table aquifer, fewer seeps and springs discharge along the valley walls of the Chickahominy River than its tributaries. Water discharged from the upland water-table aquifer flows across the flood plains and is a locally important source of water for many of the wetland plants and animals. As the water flows across the flood plains, it dissolves soluble organic carbon in the flood plain and either recharges the alluvial aquifers or flows into the nearby streams. Water in the alluvial aquifers discharges as evapotranspiration or flows toward the streams where it discharges as seeps along the stream banks or directly through the stream beds to the streams. Seeps discharge through sediment of relatively high permeability in the stream banks that overlie sediment of relatively low permeability. These seeps typically occur in lines along the contact between the sediments. Water also discharges through macropores that vary in size and are as large as several inches in diameter. Discharge from the seeps and macropores appears to be derived from both interflow (lateral flow through soil above the water table) and ground water because some seeps and macropores only flowed for a short time after precipitation while others flowed during extended dry periods. Flow velocities from the macropores can be substantial; fans of sand were deposited in the stream bank at the mouth of many of the macropores. The channels of the tributaries are incised as much as 3 to 5 ft into the alluvial sediments.

Because the flood plain of the Chickahominy River is broad and fairly flat, gradients in the water table generally are small, which limits the amount of ground water discharged directly to the river. In areas where multiple channels are present, ground water has greater opportunity to discharge to surface waters. Because of the extensive vegetated wetland flood plain, evapotranspiration is a major discharge pathway for ground water, and because of the low permeability of much of the alluvial sediment, discharge to the river is commonly through seeps in the stream banks.

The isotopic composition of ground water and surface water in the Chickahominy River Basin indicates that ground water is the predominant source of stream water during base-flow periods. Water in both the alluvial and upland water-table aquifers has a consistent ^{18}O and D composition that plots on the meteoric water line at the point of intersection with the stream-water evaporation line for the Chickahominy River Basin (fig. 5B).

LIGHT ABSORBANCE AT 253.7 NANOMETERS (UV254) AS A SURROGATE ANALYTE

UV254 can be used as a surrogate for concentrations of DOC, THMFP, TOXFP, and HAAFP if sufficiently strong relations can be identified between the variables (Singer and others, 1981; Edzwald and others, 1985). Although specific UV254, or SUVA (UV254 divided by the concentration of DOC), commonly provides stronger relations than UV254 in many systems, SUVA was not strongly related to concentrations of the substances analyzed in the Chickahominy River Basin and is not used here.

Relations between UV254 and concentrations of DOC and THMFP generally were strong; relations between UV254 and TOXFP were not as strong (table 4). Relations varied depending on the sample-collection period. Relations between UV254 and HAAFP were weak and are not summarized in table 4 because HAAFP analyses were too few during most sample-collection periods to summarize. Relations between UV254 and concentrations of DOC, THMFP, and TOXFP are presented individually for each base-flow and stormflow collection period having sufficient

Table 4. Statistical relations between light absorbance at 253.7 nanometers and concentrations of dissolved organic carbon (DOC), trihalomethane formation potential (THMFP), and total organic halide formation potential (TOXFP) for surface-water samples, Chickahominy River Basin, Virginia

[R^2, coefficient of determination; N, sample size, values are for DOC, THMFP, and TOXFP; –, no value]

Sample-collection period	DOC		THMFP		TOXFP	
	R^2	p	R^2	p	R^2	p
All sample-collection periods						
All sample-collection periods (N=239, 214, 96)	0.67	0.0000	0.67	0.0000	0.70	0.0000
Base-flow periods						
All base-flow periods (N=156, 131, 52)	.71	.0000	.67	.0000	.54	.0000
August 1995 (N=23, 23, 0)	.79	.0000	.77	.0000	–	–
March 1996 (N=22, 22, 22)	.91	.0000	.94	.0000	.84	.0000
November 1996 (N=8, 9, 0)	.91	.0003	.95	.0000	–	–
December 1996 (N=25, 25, 0)	.94	.0000	.97	.0000	–	–
January 1997 (N=9, 7, 8)	.90	.0001	.91	.0008	.49	.0540
April 1997 (N=9, 7, 6)	.91	.0001	.88	.0018	.42	.1637
May 1997 (N=19,16, 0)	.95	.0000	.93	.0000	–	–
October 1997 (N=7, 5, 0)	.70	.0192	.62	.1139	–	–
January 1998 (N=18, 14, 18)	.68	.0000	.49	.0054	.57	.0003
Stormflow periods						
All stormflow periods (N=80, 80, 40)	.48	.0000	.60	.0000	.68	.0000
August 1996 (N=16, 16, 11)	.66	.0001	.12	.1906	.51	.0136
October 1996 (N=23, 22, 0)	.58	.0000	.50	.0002	–	–
November 1997 (N=22, 22, 13)	.58	.0000	.60	.0000	.08	.3568
February 1998 (N=19, 20, 16)	.91	.0000	.75	.0000	.74	.0000

data for analysis. Relations are also presented for all base-flow periods collectively, all stormflow periods collectively, and all sample-collection periods collectively.

UV254 appears to be an effective surrogate for DOC concentrations because relations between UV254 and DOC concentrations for individual sample-collection periods and for all data analyzed collectively generally were statistically significant ($p<0.05$) and strong (based on coefficient of determination (R^2) values) (table 4). The p values were 0.0192 or less for all sample-collection periods evaluated individually or collectively (table 4). The R^2 values for relations for individual sample-collection periods ranged from 0.58 ($p = 0.0000$) for the October 1996 and November 1997 stormflow periods (table 4; fig. 6A) to 0.95 ($p = 0.0000$) for the May 1997 base-flow period (table 4; fig. 6B). In general, UV254 and DOC concentrations were more closely related for individual sample-collection periods, particularly the base-flow periods, than for all sample-collection periods combined ($R^2 = 0.67$; $p = 0.0000$) (table 4; fig. 6C). The R^2 values for six of the nine base-flow periods were equal to, or greater than, 0.90. The R^2 values for the individual stormflow periods (0.58 to 0.91) generally were less than those of individual base-flow periods. The R^2 values for the individual sample-collection periods probably were higher than for the data evaluated collectively because the relation between UV254 and DOC concentrations likely changed seasonally and under different hydrologic conditions.

Similarly, UV254 appears to be an effective surrogate for THMFP concentrations because relations between UV254 and THMFP concentrations for individual sample-collection periods and for data evaluated collectively generally were strong and statistically significant (table 4). The p values for 11 of 13 sample-collection periods and for collectively analyzed data were less than 0.01. The p values were greater than 0.1 for the October 1997 base-flow period ($p = 0.1139$) and the August 1996 storm-flow period ($p = 0.1906$). The R^2 values for the relation between UV254 and THMFP concentrations ranged from 0.12 for the August 1996 stormflow sample-collection period (table 4; fig. 7A) to 0.97 for the December 1996 base-flow sample-collection period (table 4; fig. 7B). In general, UV254 and THMFP concentrations were more closely related for individual sample-collection periods, particularly the base-flow periods, than for all sample-collection periods combined ($R^2 = 0.67$; $p = 0.0000$) (table 4; fig. 7C). The R^2 values for five of the nine base-flow periods were greater than 0.90. The R^2 values for the individual stormflow periods (0.12 to 0.75) generally were less than those of individual base-flow periods. The low R^2 values and the high p value for the August 1996 storm-flow period indicate the lack of a significant relation at that time. As with DOC concentrations, the R^2 values for the individual sample-collection periods probably were higher than the R^2 values for the data evaluated collectively because the relation between UV254 and THMFP concentrations likely changed seasonally and under different hydrologic conditions.

Based on the statistical significance and the strength of fit of relations between UV254 and TOXFP concentrations, UV254 may not be an effective surrogate for TOXFP concentrations during certain sample-collection periods, but is an effective surrogate for all sample-collection periods combined. The p values of only three of seven periods were less than 0.01 and four were less than 0.05. The R^2 values of the relation between UV254 and concentrations of TOXFP ranged from 0.08 ($p = 0.3568$) (table 4; fig. 8A) for the November 1997 stormflow sample-collection period to 0.84 ($p = 0.0000$) for the March 1996 base-flow sample-collection period (table 4; fig. 8B). The R^2 value was 0.70 ($p = 0.0000$) for all sample-collection periods combined (table 4; fig. 8C). The R^2 values for all individual sample-collection periods except the March 1996 base-flow and the February 1998 stormflow period were less than the R^2 values for all sample-collection periods combined.

Based on the statistical significance and the strength of fit of relations between UV254 and HAAFP concentrations, UV254 was not an effective surrogate for HAAFP. The R^2 of the relation between UV254 and concentrations of HAAFP was only 0.16 for all data although the p value was 0.0000 (fig. 9).

Based on the statistical significance and strength of the relations between UV254 and concentrations of DOC, THMFP, and TOXFP, the use of UV254 generally is an effective surrogate for their concentrations. Because of the significance and strength of these relations, the following discussions focuses on UV254 results.

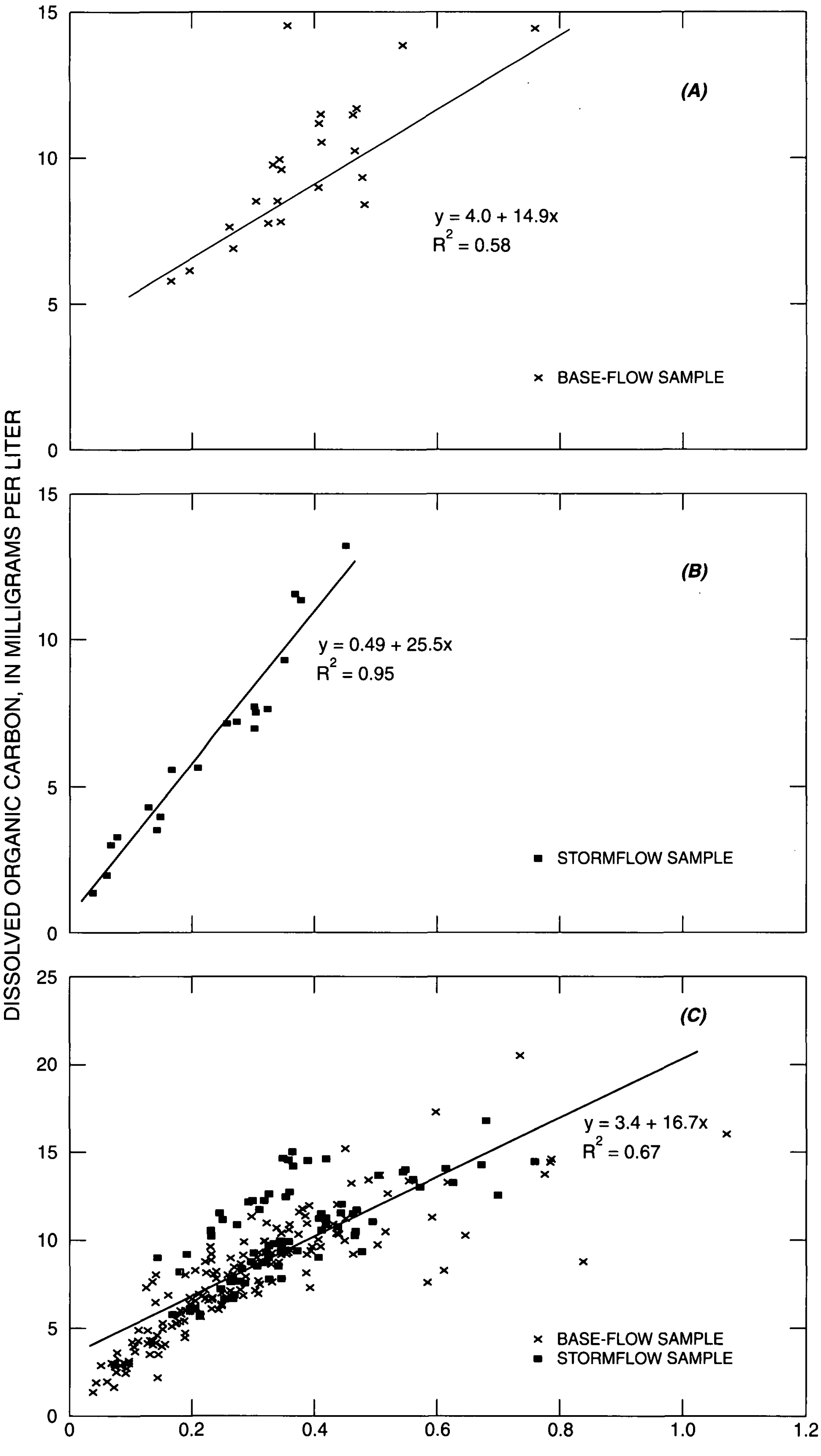

Figure 6. Relation of light absorbance at 253.7 nanometers and dissolved organic carbon concentrations for October 1996 *(A)*, May 1997 *(B)*, and all data *(C)*, Chickahominy River Basin, Virginia.

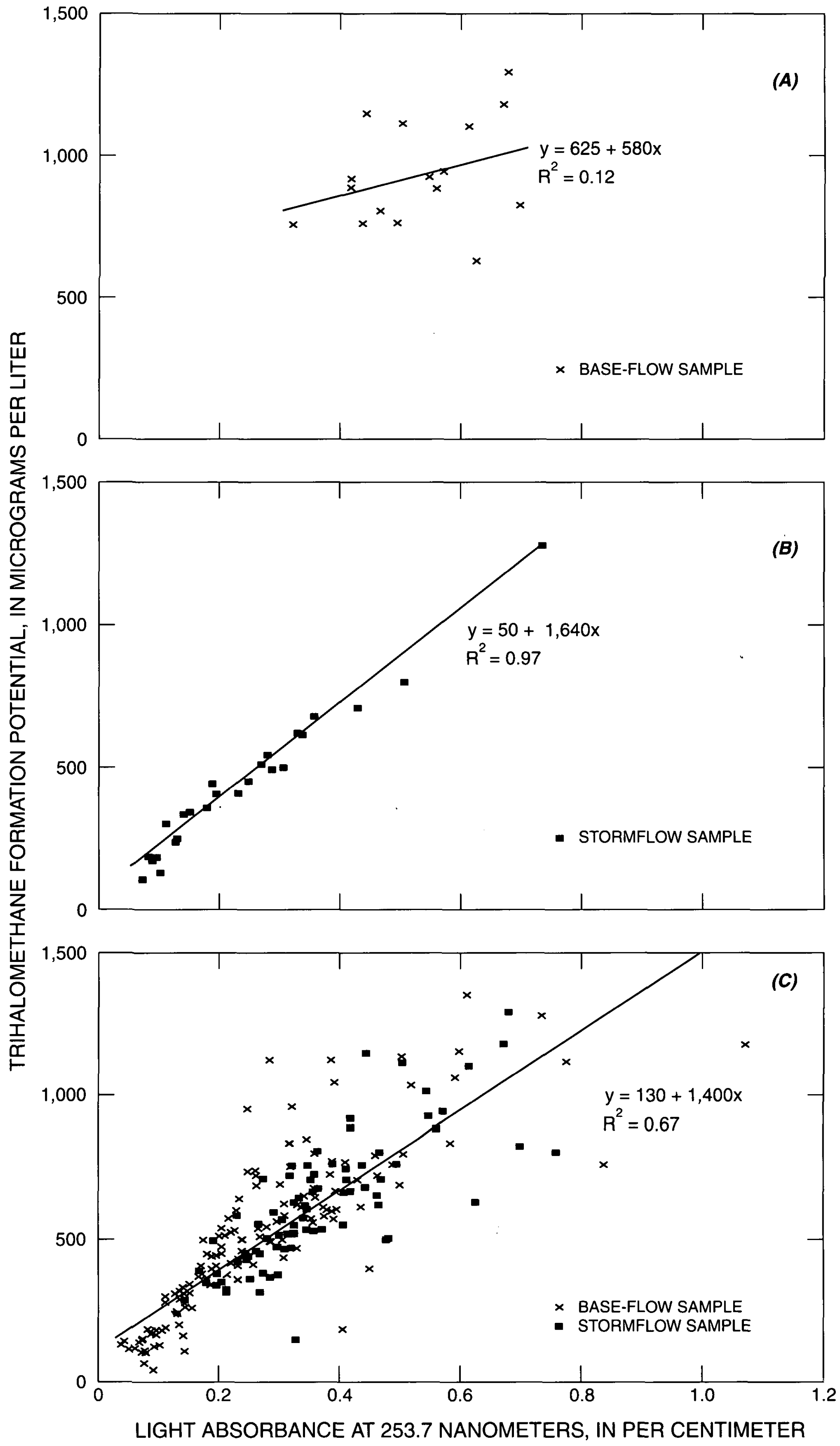

Figure 7. Relation of light absorbance at 253.7 nanometers and trihalomethane formation potential concentrations for August 1996 *(A)*, December 1996 *(B)*, and all data *(C)*, Chickahominy River Basin, Virginia.

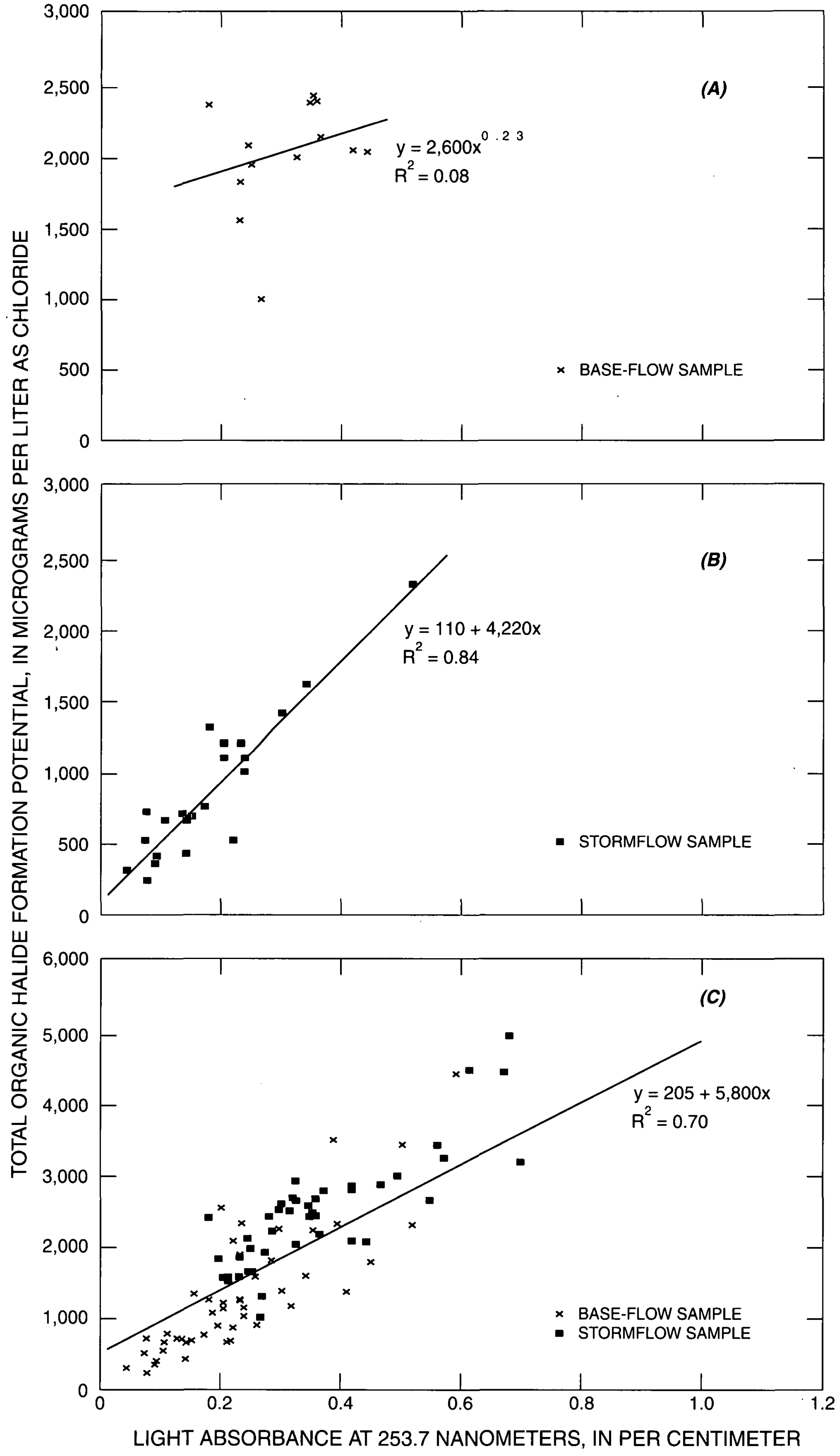

Figure 8. Relation of light absorbance at 253.7 nanometers and total organic halide formation potential concentrations for November 1997 *(A)*, March 1996 *(B)*, and all data *(C)*, Chickahominy River Basin, Virginia.

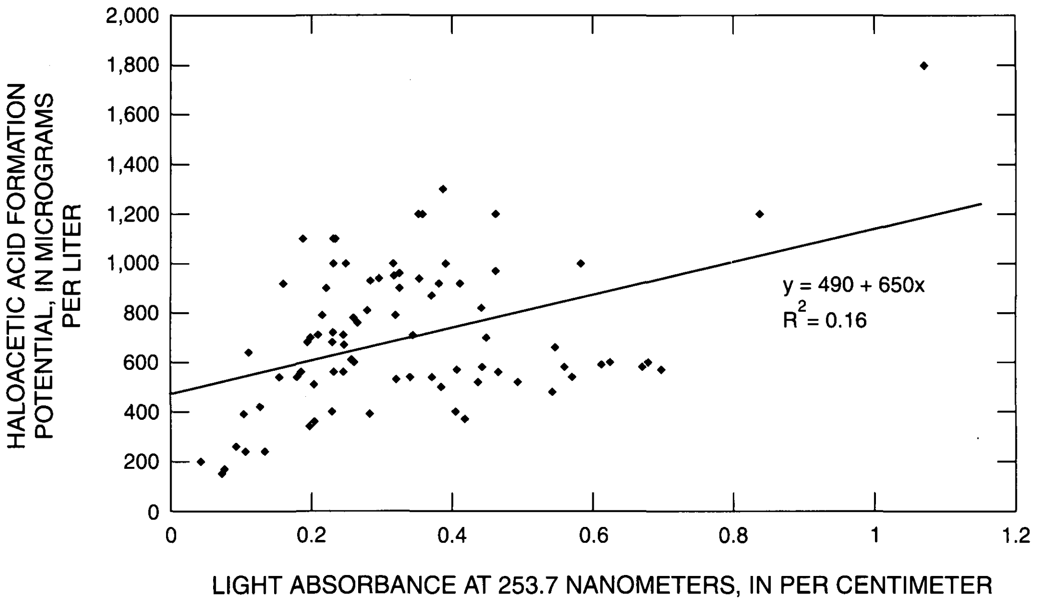

Figure 9. Relation of light absorbance at 253.7 nanometers and haloacetic acid formation potential concentrations for all data, Chickahominy River Basin, Virginia.

DISSOLVED ORGANIC CARBON (DOC) AND DISINFECTION BY-PRODUCT (DBP) PRECURSORS

The DOC content of streams of the Chickahominy River Basin varies spatially and temporally depending on the sources of organic carbon in the basin, transport pathways to the river, seasonal variability in climate and hydrologic conditions, and the hydrologic response to storm events. The DOC content of the streams also is influenced by instream processes such as the leaching of organic material from stream-bed detritus and biological and photodegradation of the DOC. Results of laboratory studies show the role of stream-bed detritus as a source of DOC in stream water and the role of degradation in reducing DOC concentrations in stream water. Results of analyses of surface-water samples from the Chickahominy River Basin show spatial and temporal variability in concentrations of DOC and DBP precursors in the river. Emphasis is placed on station CR02, the farthest downstream sampling point and the point nearest to the City of Newport News water intake. Results of analyses of samples from tributary streams and from ground-water sources show the importance of these water and DOC transport pathways.

Contributions of Stream-Bed Detritus to DOC in Stream Water

In the laboratory studies of stream-bed detritus, changes in UV254 varied considerably among replicate samples of each material type, as well as among material types (fig. 10). UV254 increased at the greatest rate in all samples in the first 4 hours (0.17 days) of incubation. A "tea color" common to waters having a high humic-substance content also developed within the first 4 hours of incubation. Although the intensity of the tea color and the UV254 generally increased with time, the rate of increase in UV254 generally decreased with time. The UV254 was 0.041 to 0.447 cm^{-1} after the first four hours (fig. 10), a range commonly observed in stream waters of the Chickahominy River Basin (fig 6C). At the end of the first day, the highest three UV254 values (0.773 to 0.991 cm^{-1}) were greater than those commonly observed in stream water of the basin. By the fourth day, UV254 ranged from 0.491 to 2.78 cm^{-1} in water from the samples incubated with branches, 1.53 to 2.3 cm^{-1} in water from the samples incubated with leaves, and 0.106 to 0.606 cm^{-1} in water from samples incubated with porous wood. Values for the leaf and small branch samples were greater than those commonly observed in stream water of the Chickahominy River Basin.

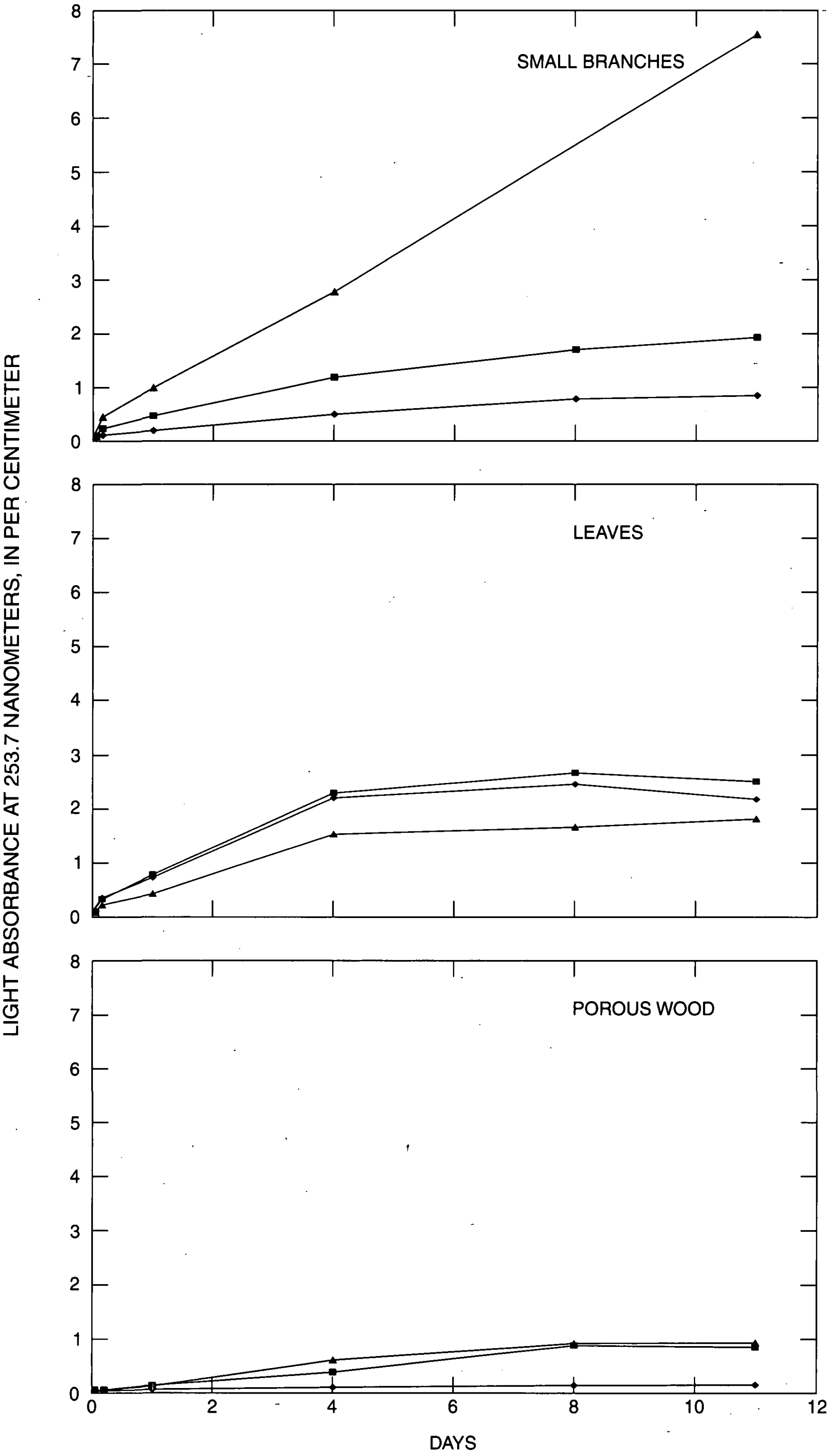

Figure 10. Change in light absorbance at 253.7 nanometers of organic-carbon-free water incubated with small branches, leaves, and porous wood.

The rapid development of the tea color and the rapid increase in UV254 in these laboratory studies indicate that leaves, small branches, and wood in stream beds likely are a substantial source of UV254, DOC, and THMFP in stream water. In order to equate values of UV254 and the contributions of stream-bed detritus to the organic content of the stream water, field studies must determine the amount of organic material in the stream bed and relate the amount of organic material to the amount of streamflow.

Degradation of DOC in Stream Water

Results of the degradation studies present UV254 as the decimal fraction of the original UV254 of sample in each bottle. Based on the UV254 of samples incubated at room temperature, degradation appears to reduce the DOC content of stream water (table 5; fig. 11). UV254 decreased 8 to 20 percent in both filtered and unfiltered samples incubated at room temperature in amber glass and 29 to 41 percent in filtered samples incubated at room temperature in clear glass. The greatest decrease in UV254 (45 to 58 percent) was in unfiltered samples incubated at room temperature in clear glass. Because UV254 decreased considerably more in samples in clear glass than in amber glass, a large part of the decrease in UV254 appears to result from photodegradation or photoenhancement of the degradation.

The role of biodegradation, however, is not clear. The decrease in UV254 in amber glass was similar in the filtered samples to that in the unfiltered samples. The decrease in UV254 in clear glass, however, was less in the filtered samples than in the unfiltered samples. These results indicate that biodegradation is likely an important process that may, in part, be mediated by sunlight.

In filtered samples incubated at room temperature, concentrations of DOC and THMFP decreased proportionally similar to UV254 (table 5). Thus, the decrease in UV254 of filtered samples during the study probably is representative of changes in concentrations of DOC and THMFP.

The UV254 of five of the six samples filtered in the field and chilled remained at least 99 percent of the original value over the 83 days of the study (table 5; fig. 11). UV254 of the sixth sample remained at least 99 percent of the original value to between 21 and 33 days of the study and remained at least 94 percent of the original value through the 57th day of the study. Similarly, the UV254 of the unfiltered and chilled samples remained 91 percent of the original value or

Table 5. Fraction of original light absorbance at 253.7 nanometers (UV254) and concentrations of organic carbon (dissolved for filtered samples and total for unfiltered samples) and trihalomethane formation potential (THMFP) remaining at the end of the laboratory study of the degradation of organic carbon in water collected October 1997 from station CNS01, Chickahominy River Basin, Virginia

[cm^{-1}, per centimeter; mg/L milligrams per liter; µg/l, micrograms per liter; –, no data]

Determination	Filtered samples						Unfiltered samples					
	Chilled			Room temperature			Chilled			Room temperature		
	1	2	3	1	2	3	1	2	3	1	2	3
							Amber glass					
UV254 (cm^{-1})	0.99	0.99	0.99	0.80	0.92	0.82	0.99	0.98	0.95	0.86	0.84	0.83
Organic carbon (mg/L)	.93	–	–	.78	–	–	.96	–	–	.95	–	–
THMFP (µg/L)	.80	–	–	.71	–	–	.90	–	–	.77	–	–
							Clear glass					
UV254 (cm^{-1})	.91	1.00	.99	.61	.59	.71	1.00	.91	.95	.55	.49	.42
Organic carbon	–	–	.89	–	–	.76	.86	–	–	.91	–	–
THMFP	–	–	.77	–	–	.75	.76	–	–	.66	–	–

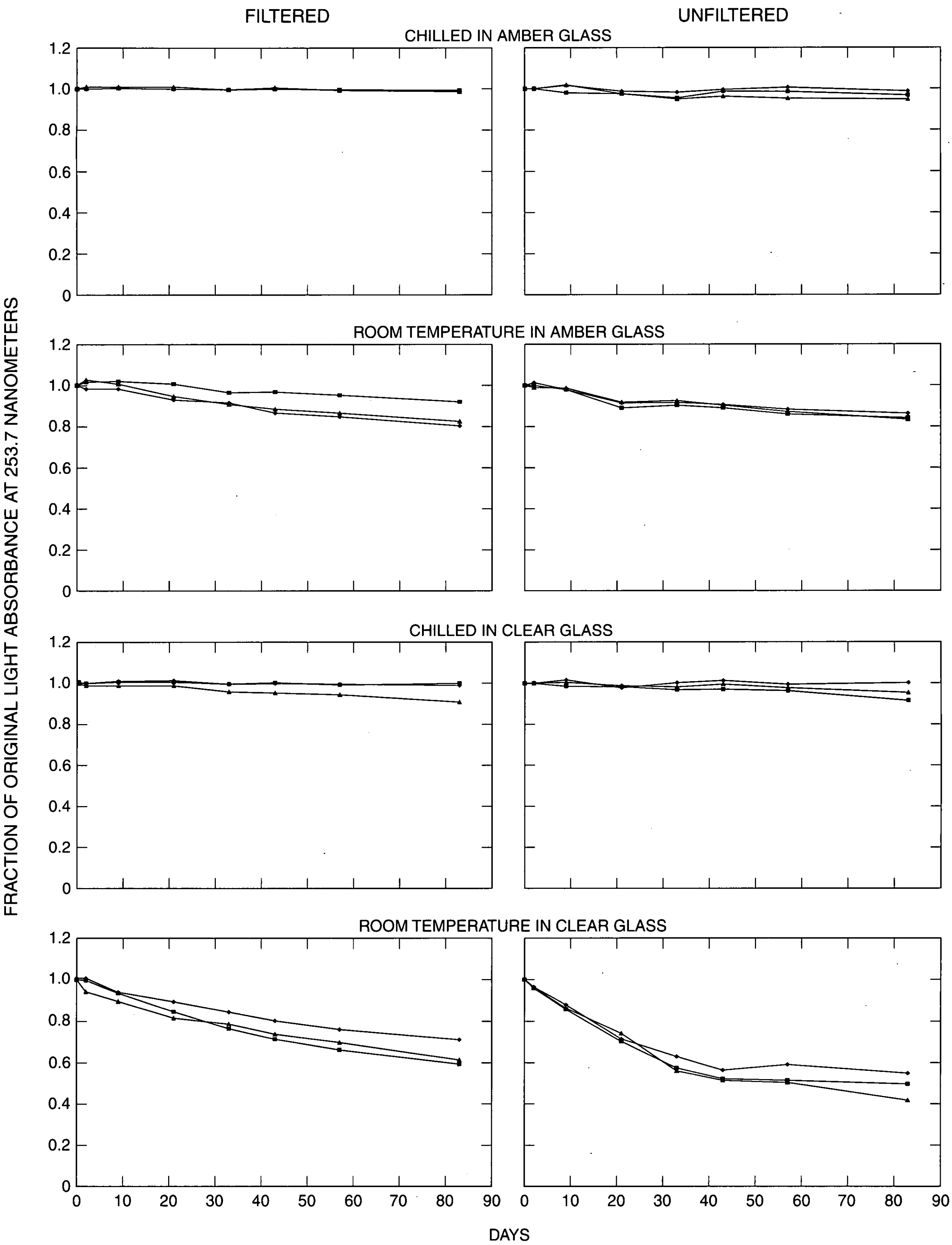

Figure 11. Changes in light absorbance at 253.7 nanometers of replicate samples.

greater through the 83rd day of the study; the UV254 of two of six samples remained at least 99 percent of the original value.

These results indicate that degradation of DOC and DBP precursors in stream water of the Chickahominy River Basin at least partly counterbalances input from sources such as stream-bed detritus. Instream degradation is likely to be greatest during summer base flows when stream-water temperatures are elevated, instream traveltime is high, and the duration and intensity of sunlight are greatest.

Temporal and Spatial Variability in Concentrations of DOC and DBP Precursors in Stream Water

The temporal and spatial variability in concentrations of DOC and DBP precursors varies depending on streamflow conditions. This variability results from changes in sources of organic carbon, in transport pathways, and in transformation processes that result from hydrologic changes.

Base-Flow Periods

During base-flow periods, UV254 and concentrations of DOC, THMFP, TOXFP, and HAAFP generally decreased along the main stem of the Chickahominy River from station CR60 to CR40 and stabilized between station CR40 and CR02 at the downstream end of the nontidal part of the river (fig. 12). This is somewhat surprising in that wetlands are more predominant in the middle and lower parts of the Chickahominy River Basin and were expected to be a substantial source of organic material. Thurman (1985) reports that rivers draining swamps and wetlands have the largest DOC concentrations. UV254 and the organic content of the river decreased downstream from the headwaters during both cold-weather months (November through March) and warm-weather months (April through October).

During each of these seasons, the organic content of the river increased slightly downstream from stations CR45 and CR70 to station CR02. This increase could have resulted in part from residual stormflow in the lower part of the basin. Because streamflow at station CR02 can take two weeks or more to return to base-flow conditions from a stormflow period, "base-flow" samples commonly reflect remnants of stormflow periods in the lower nontidal part of the basin. Although streamflow declines after peak flow in the lower nontidal part of the basin, the organic content of the water can be elevated as a result of the previous storm. Samples collected at station CR02, therefore, probably seldom reflect true base-flow conditions.

Synoptic sampling of tributary streams during base-flow conditions show that the downstream decline in the organic content of the Chickahominy River between sampling station CR60 and CR40 is in part due to dilution from the lower organic content of water discharged from the tributaries (fig. 13). The UV254 and concentrations of DOC of the tributaries were in all cases less than the concentrations of the main-stem Chickahominy River. Below station CR40, UV254 and DOC concentrations of the tributaries were also generally less than the main-stem Chickahominy River, yet concentrations at downstream sampling station CR45, CR70, and CR02 do not show similar declines. This indicates the presence of an additional source of organic carbon in or discharging to the lower Chickahominy River that counterbalances the effects of dilution from the lower tributaries. The most likely sources of DOC in the lower Chickahominy River during base-flow periods are ground-water discharge from the alluvial aquifer, leachate from stream-bed detritus, and residual effects from previous storms.

During base-flow periods, THMFP and TOXFP concentrations varied spatially in a manner similar to UV254 and DOC concentrations. THMFP concentrations exceeded the MCL for THMs in all samples collected during base-flow periods at station CR02 and at all other stations except for two samples collected at station CRT06. HAAFP concentrations exceed the MCL during base-flow periods for all samples.

Ground-Water Sources

Ground-water flow is an important transport pathway for organic carbon in the Chickahominy River Basin. Ground water discharge averaged 70 percent of the annual streamflow in the Chickahominy River from 1970 through 1990 (Richardson, 1994) and constitutes all of the base flow and part of the stormflow of the basin. The organic content of ground water in the Schiminoe Creek tributary was elevated, indicating that ground water can be a substantial source of DOC and DBP precursors.

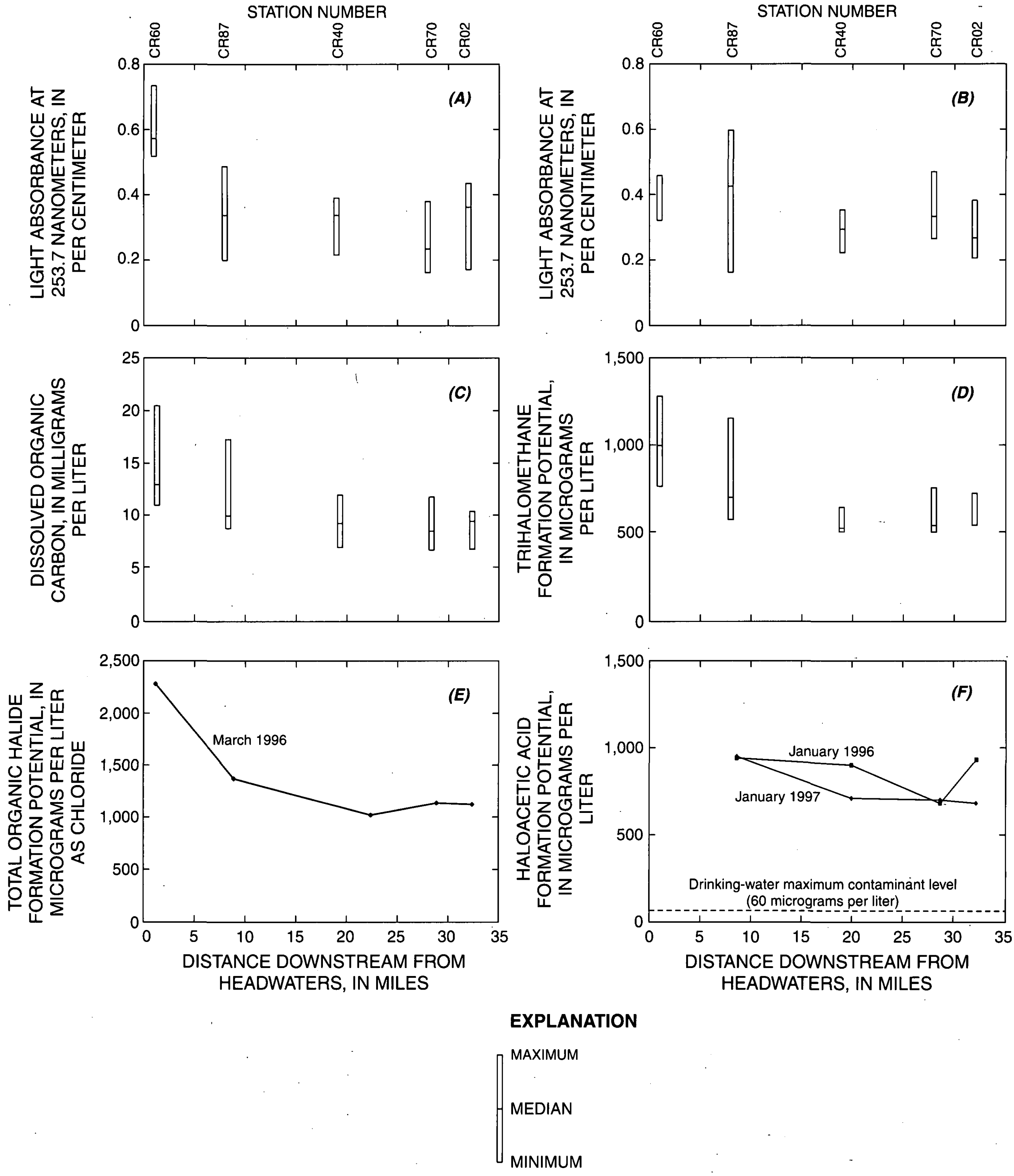

Figure 12. Downstream changes in light absorbance at 253.7 nanometers in cold-weather months (November through March) *(A)*, light absorbance at 253.7 nanometers in warm-weather months (April through October) *(B)*, concentrations of dissolved organic carbon *(C)*, concentrations of trihalomethane formation potential *(D)*, concentrations of total organic halide formation potential *(E)*, and concentrations of haloacetic acid formation potential *(F)* at base flow, Chickahominy River Basin, Virginia.

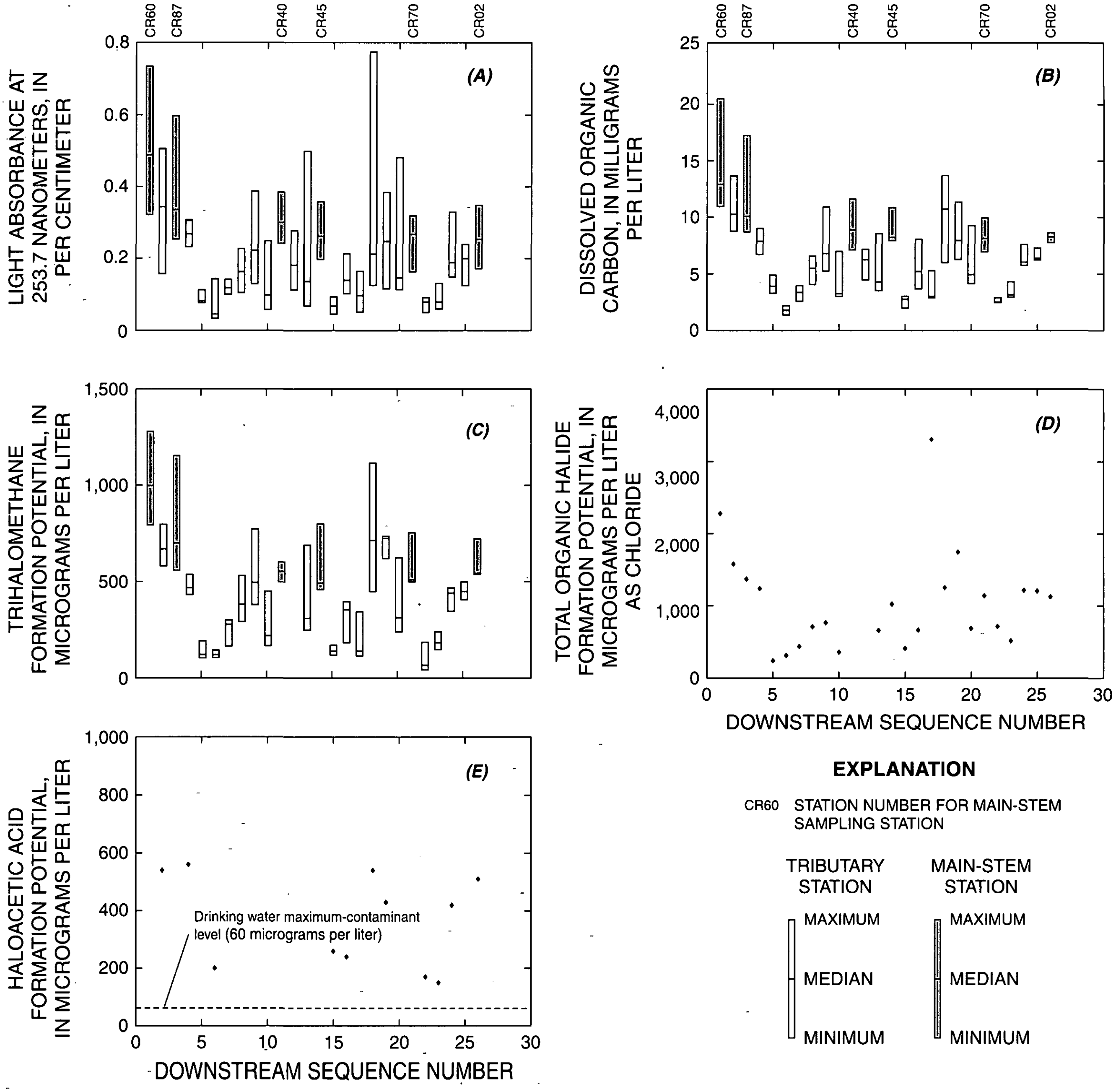

Figure 13. Light absorbance at 253.7 nanometers *(A)* and concentrations of dissolved organic carbon *(B)*, trihalomethane formation potential *(C)*, total organic halide formation potential *(D)*, and haloacetic acid formation potential *(E)* at the tributary (unidentified) and main-stem (identified by station number and shading) stations in downstream sequence number (Table 1) during synoptic sample-collection periods, Chickahominy River Basin, Virginia.

In the Schiminoe Creek Watershed, the organic content of the ground water from the upland water-table aquifer was less than that from the alluvial water-table aquifer. UV254 ranged from 0.017 to 0.209 cm^{-1} and DOC ranged from 0.60 to 1.4 mg/L in water from wells open to the upland water-table aquifer (table 6). UV254 ranged from 0.102 to 2.450 cm^{-1} and DOC ranged from 2.5 to 5.2 mg/L in water from wells open to the alluvial water-table aquifer. UV254 and DOC of water discharged from seeps ranged from 0.131 to 0.668 cm^{-1} and 4.1 to 9.5 mg/L, respectively.

The concentration of DOC of water discharging from the alluvial water-table aquifer through seeps in the stream bank was almost twice that of ground water from wells open to the same aquifer. The UV254 of water from the wells, however, was about twice that of water discharging through seeps. This difference in the characteristics of DOC of water discharging through seeps from that in ground water from the wells likely results from changes as the ground water flows through the aquifer to areas of discharge.

The organic content of the ground water only partly accounts for the organic content of stream water based on a comparison of the ground water from the alluvial aquifer and water in the tributary to Schiminoe Creek (station SCT01). Although the median and maximum UV254 values of water from the alluvial water-table aquifer are greater than median and maximum values from station SCT01, median and maximum values of the DOC of water from the alluvial water-table aquifer are less than equivalent values from station SCT01. This likely results from the different characteristics of the DOC of the ground water compared to that of the surface water: DOC derived from the ground water appears to have a greater UV254 for an equivalent DOC than that of the surface water. This difference may in part result from the contribution of DOC to stream water by stream-bed detritus.

Organic carbon in ground-water discharge from the alluvial aquifer is derived from two sources: (1) organic material in the aquifer sediment that was derived at the time the sediment was deposited, and

Table 6. Summary of light absorbance at 253.7 nanometers (UV254) and concentrations of dissolved organic carbon (DOC) of ground water from the upland water-table aquifer, ground water from wells and seeps in the alluvial water-table aquifer, and stream water during base-flow periods at stations SCT01 and CR02, Chickahominy River Basin, Virginia

Determination	Minimum	Maximum	Median	Number of samples
Upland Water-Table Aquifer				
UV254 (per centimeter)	0.017	0.209	0.040	7
DOC (milligrams per liter)	.60	1.4	1.3	5
Wells in the Alluvial Water-Table Aquifer				
UV254 (per centimeter)	.102	2.450	.600	10
DOC (milligrams per liter)	2.5	5.2	3.2	6
Seeps in the Alluvial Water-Table Aquifer				
UV254 (per centimeter)	.131	.668	.257	4
DOC (milligrams per liter)	4.1	9.5	5.6	4
Schiminoe Creek Tributary (SCT01)				
UV254 (per centimeter)	.148	.535	.270	15
DOC (milligrams per liter)	5.4	15	7.9	11
CR02				
UV254 (per centimeter)	.171	.616	.284	17
DOC (milligrams per liter)	6.7	13	9.1	12

(2) soluble organic carbon leached from the organic litter by infiltrating water. Because much of the alluvial aquifer consists of silt and clay deposited in low-energy environments of the flood plains where organic material had also accumulated, the sediment contains abundant organic carbon. As this organic carbon decomposes, the soluble organic carbon can leach into the ground water and be transported to streams. Although sorption of DOC to clay typically decreases the DOC of infiltrating water (Thurman, 1985), the natural abundance of organic material in alluvial sediment can limit the sorption of DOC in infiltrating water.

Precipitation and decomposition of the organic litter contribute DOC to ground water. The flood-plain wetlands are seasonally inundated and saturated; consequently, several months can pass without inundation of these wetlands. These periods typically occur during warm-weather months when rates of decomposition of the organic litter and evapotranspiration are high. Therefore, large amounts of soluble organic carbon can form and remain in the organic litter as the litter decomposes. Because the initial precipitation infiltrates through the organic litter and into the unsaturated soil rather than running off, the first transport pathway for soluble organic carbon is from the organic litter to the water table. Precipitation often is not sufficient to produce substantial runoff or to cause infiltrating water to reach the water table; therefore, a reservoir of soluble organic carbon can be created in the unsaturated soil. Even when precipitation is sufficient to produce surface runoff, the initial part of that precipitation will also infiltrate through the organic litter and into the unsaturated soil, adding to the reservoir of soluble organic carbon. This reservoir of soluble organic carbon will not be available for transport across the flood plain in surface runoff. When sufficient water infiltrates to recharge the ground water, DOC in the unsaturated zone will be transported to the ground water and can then be transported to the streams. Because streamflow during base-flow conditions is entirely ground-water discharge, ground water can, therefore, be a substantial source of DOC to the streams.

DOC also can be transported with water that flows above the water table through macropores and through relatively high permeability soils that overlie relatively low permeability soils. This flow, commonly referred to as interflow, occurs mostly during and immediately after significant storms and can affect the timing and the amount of DOC transported to streams.

Stormflow Periods

Stormflow response was similar seasonally and among sites in that the peak in the organic content of stream water generally occurred at, or after, peak streamflow (table 7, appendix 1). UV254 increased by 16 to almost 100 percent from base flow to after peak flow at station CR02; the greatest increase was by more than 200 percent at station CR87 in November 1997 (appendix). Increases in concentrations of DOC, THMFP, and TOXFP varied among stormflow periods and stations but generally ranged from 25 to 75 percent.

Two stormflow sample-collection periods (July 16–September 17, 1997, and February 16–March 13, 1998) for station CR02 exemplify the stormflow response. These two collection periods were selected because (1) one was in the middle of a summer base-flow period, (2) one was in the middle of a winter high-flow period, and (3) both are represented by samples collected before, during, and after the stormflow periods. These two stormflow collection periods occurred in the middle of the most extreme hydrologic conditions of the study.

Initially, stormflow sample collection was designed to represent stormflow from single, discrete storms at station CR02. Because 3 to 5 days typically pass between the time of precipitation and peak streamflow, and 10 to 14 days typically pass before streamflow returns to near base-flow conditions at station CR02, it was difficult to collect samples through a full stormflow period before another stormflow period began. Consequently, sample collection at station CR02 generally was not able to fully characterize the organic content of the stream water throughout a discrete stormflow period. During an extended dry period, however, the time before, during, and after a complete stormflow period was sampled from July 16–September 17, 1997 (hereafter referred to as the 1997 summer storm). The 1997 summer storm resulted primarily from a single precipitation period on July 21, 1997.

Daily streamflow averaged from 7.4 to 10 ft^3/s before the stormflow period and increased to a peak daily flow of 338 ft^3/s on July 26, 1997 (White and others, 1998) (fig. 14). Streamflow returned to near

Table 7. Timing of peak in light absorbance at 253.7 nanometers (UV254) and concentrations of dissolved organic carbon (DOC), trihalomethane formation potential (THMFP), total organic halide formation potential (TOXFP), and haloacetic acid formation potential (HAAFP) in relation to peak streamflow at selected stations during selected stormflow periods, Chickahominy River Basin, Virginia

[cm^{-1}, per centimeter; mg/L, milligrams per liter; µg/l, micrograms per liter; µg/l as Cl, micrograms per liter as chloride; IS, insufficient sample distribution to determine; =, at the time of peak flow; +, after peak streamflow; –, before peak streamflow]

Determination	Station number				
	CR87	WOS55	SCT01	CR02	DCR03
August 1-6, 1996					
UV254 (cm^{-1})	IS	+	+	=	+
DOC (mg/L)	IS	+	=	+	IS
THMFP (µg/L)	IS	+	=	=	IS
TOXFP (µg/L as Cl)	IS	+	+	=	IS
HAAFP (µg/L)	IS	IS	IS	+	IS
September 6-16, 1996					
UV254 (cm^{-1})	IS	+	–	+	IS
October 8-17, 1996					
UV254 (cm^{-1})	=	=	+	=	+
DOC (mg/L)	IS	=	=	=	+
THMFP (µg/L)	IS	+	=	=	+
March 13-16, 1997					
UV254 (cm^{-1})	–	–	–	=	IS
July 17 through September 17, 1997					
UV254 (cm^{-1})	+	=	IS	+	IS
November 7-20, 1997					
UV254 (cm^{-1})	+	+	–	–	IS
DOC (mg/L)	=	IS	IS	IS	IS
THMFP (µg/L)	=	IS	IS	IS	IS
February 16 through March 13, 1998					
UV254 (cm^{-1})	IS	IS	IS	+	+
DOC (mg/L)	IS	IS	IS	+	IS
THMFP (µg/L)	IS	IS	IS	+	IS
TOXFP (µg/L as Cl)	IS	IS	IS	+	IS

base-flow conditions about August 4, 1997, and decreased to record low flows (0.06 ft^3/s) by September 4, 1997 (White and others, 1998).

UV254 responded to changing streamflow at station CR02 (fig. 14). In three samples collected before the stormflow period and in the first sample collected during the stormflow period, UV254 ranged from 0.311 to 0.316 cm^{-1}. As streamflow initially increased, UV254 decreased to 0.201 cm^{-1} on July 23, 1997, and returned to near pre-storm values at about the time of peak flow. UV254 peaked at 0.551 cm^{-1} on August 4, 1997, 14 days after precipitation and 9 days after peak flow. The increase in UV254 was about 75 percent above pre-storm levels and 175 percent above the low value early in the stormflow period. UV254 then gradually declined through September 17, 1997, to a low of 0.245 cm^{-1}.

Changes in ^{18}O and D reflected the hydrologic response of the system during this stormflow period (fig. 15A). The composition of ^{18}O and D before and during the early part of the stormflow period indicates that stream water was affected by evaporation as streamflow increased from 7.7 to 55 ft^3/s. The isotopic composition then shifted to approximately that of global meteoric water as streamflow increased to a peak of 314 ft^3/s, and then slowly decreased to 25.2 ft^3/s. This shift reflected the presence of water that likely originated from recent precipitation and was transported through either surface runoff, interflow, or shallow ground-water flow. At the end of the sample-collection period (September 17), the isotopic composition of the stream water again reflected the effects of evaporation.

Changes in UV254 during this stormflow period can be explained by the hydrologic response inferred from the isotopic composition of the stream water. UV254 was stable early in the stormflow period when the stable isotopes were of uniform composition and reflected evaporation. The increased streamflow during this period probably reflects the flushing of water that had been in the basin prior to the storm. The decreases in UV254 occurred coincident with the isotopic shift toward that of meteoric water and probably resulted from dilution of the stream water by direct precipitation on the stream and by surface runoff from the watershed. The isotopic composition of the stream water (sample 4) at the time of the lowest UV254 (July 23) was that of meteoric water. As UV254 increased

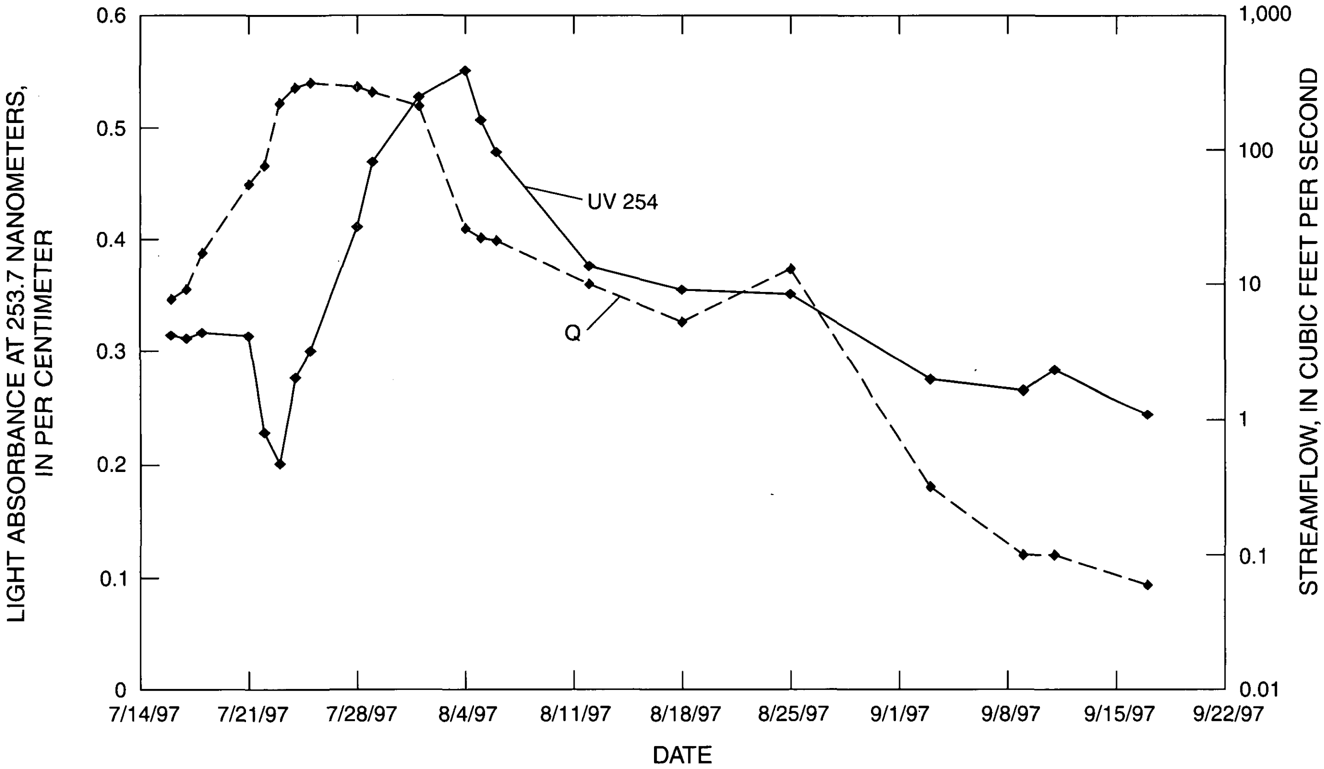

Figure 14. Changes in streamflow (Q) and light absorbance at 253.7 nanometers (UV254) during the 1997 summer storm at station CR02, Chickahominy River Basin, Virginia.

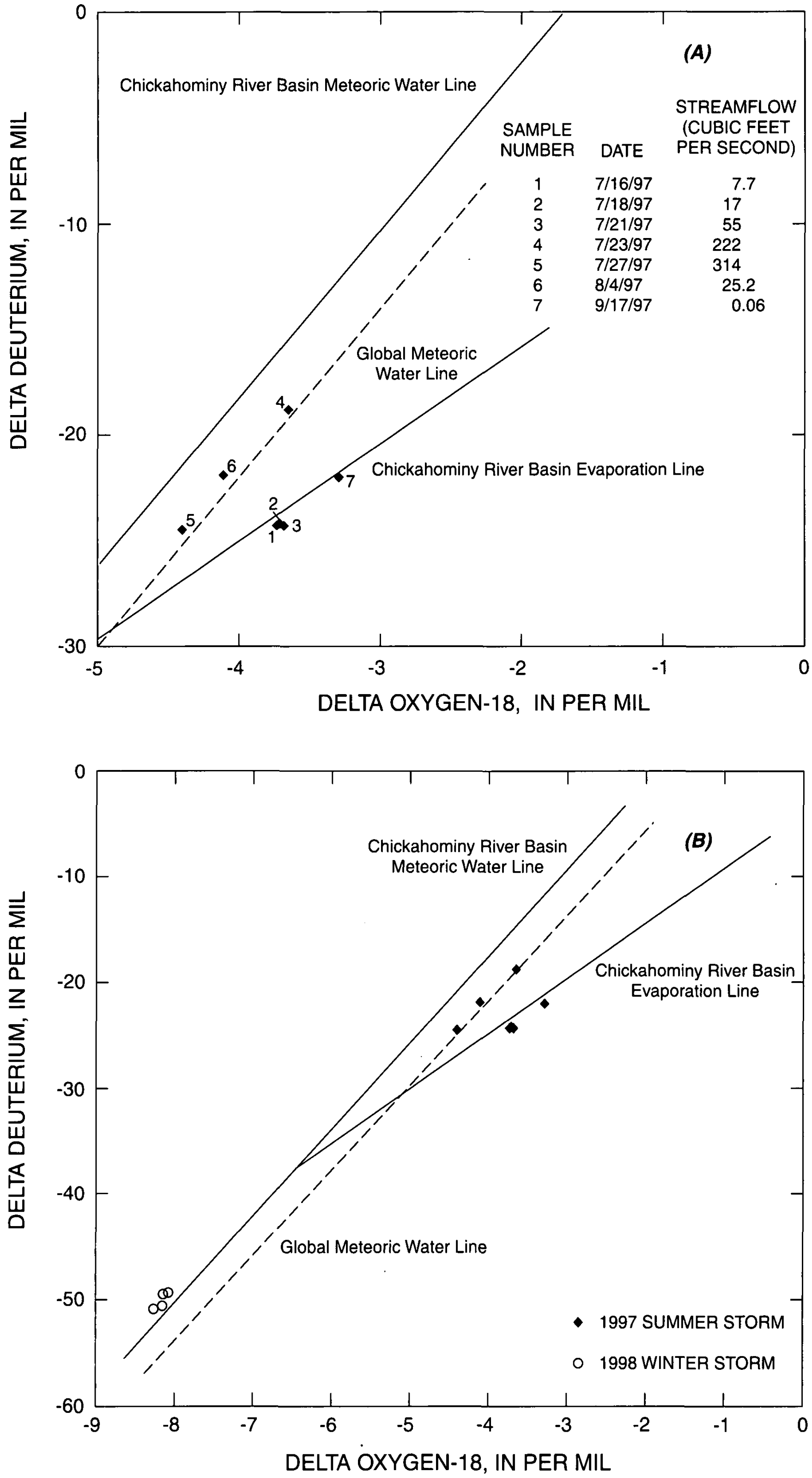

Figure 15. Relation of oxygen-18 and deuterium for the 1997 summer storm *(A)* and relation of oxygen-18 and deuterium for the 1997 summer and 1998 winter storms *(B)* at station CR02, Chickahominy River Basin, Virginia.

toward the end of the stormflow period, the isotopic composition of the stream water remained that of meteoric water, indicating the continued effects of recent precipitation. After the stormflow period ended, the isotopic composition of the stream water again reflected evaporation at the end of the sample-collection period.

The peak in UV254 after the peak in streamflow, as the stream began to return to base-flow conditions, likely resulted from the discharge of DOC transported through interflow and shallow ground water. Water flowing along these transport pathways has a longer traveltime than surface runoff and comprises a larger part of the streamflow as stormflows decrease. These transport pathways also have a greater likelihood of encountering soluble organic material as the water infiltrates through surface leaf litter and the shallow soil zone.

The February 16–March 13, 1998 sample-collection period (hereafter referred to as the 1998 winter storm) was a time of periodic precipitation and storm-water runoff. As such, samples collected in this period show the effects of one precipitation period superimposed on the effects of antecedent precipitation periods.

Streamflow at station CR02 in February 1998 averaged 1,198 ft^3/s, 2.8 times the long-term monthly average of 430 ft^3/s, and in March 1998 averaged 1,055 ft^3/s, about 2.2 times the long-term monthly average of 481 ft^3/s (table 3). Streamflow increased from 429 ft^3/s when the first sample was collected to a first peak of 1,330 ft^3/s on February 21, 1998, following precipitation on February 16-17; streamflow declined to 878 ft^3/s on February 26, then increased to 950 ft^3/s on February 27, 1998 (fig. 16A) following additional precipitation on February 22. Streamflow then declined to a low of 353 ft^3/s on March 6 before increasing to 1,590 ft^3/s on March 13, 1998, after precipitation on March 6. Sample collection ended March 13.

UV254 generally responded in a manner similar to its response in other storms, increasing from 0.242 cm^{-1} on February 16 to 0.371 cm^{-1} on February 23 (an increase of approximately 53 percent), two days after the first peak in streamflow (table 8; fig. 16A). UV254 declined to 0.280 cm^{-1} on February 27, the day before the small second peak in flow and again peaked at 0.345 cm^{-1} on March 4, four days after the second peak in streamflow. Concentrations of DOC, THMFP, and TOXFP responded similarly to UV254: the concentration of DOC peaked three days after the first peak in streamflow (fig. 16B), THMFP concentrations peaked two to three days after the first peak in streamflow (fig. 16C), and TOXFP concentrations peaked the day after the first peak in streamflow (fig. 16D). DOC and THMFP concentrations increased about 50 percent, TOXFP concentrations increased by more than 75 percent, and HAAFP concentrations increased less than 25 percent from antecedent to peak conditions. The isotopic composition of the stream water changed little during the 1998 winter storm as evaporation rates are low this time of year and the isotopic composition of stream water was similar to that of meteoric water for the Chickahominy River Basin (fig. 15B).

Although the antecedent hydrologic conditions were very different between the summer and winter storms, the responses of UV254 to increasing streamflow were similar. Of the seven storm periods sampled at station CR02 during the course of the study, the peak in UV254 lagged the peak in streamflow three times, occurred approximately at the peak in streamflow three times, and preceded the peak in flow once. In all cases, increasing streamflow resulted in increased concentrations of DOC, THMFP, TOXFP, and HAAFP compared to antecedent conditions.

IMPLICATIONS FOR PUBLIC SUPPLY

Results of this study have implications for the timing of withdrawal of water for public supply at Walkers Dam and for water treatment, as well as for the use of other rivers for public water supply. The City of Newport News withdraws water from the Chickahominy River at Walkers Dam because it is the closest point on the river to the water treatment plant that is not substantially affected by saltwater. This location is fortuitous because of the downstream decrease in concentrations of DOC and DBP precursors. Concentrations of DOC and DBP precursors at CR02, the closest sampling point to Walkers Dam, were among the lowest measured in the nontidal part of the Chickahominy River. The downstream decrease in the organic content of stream water observed in the Chickahominy River likely will be observed in other streams that have similar channel and flow characteristics. Therefore, locating withdrawal points in the lower part of basins, so long as other problems such as saltwater intrusion are not

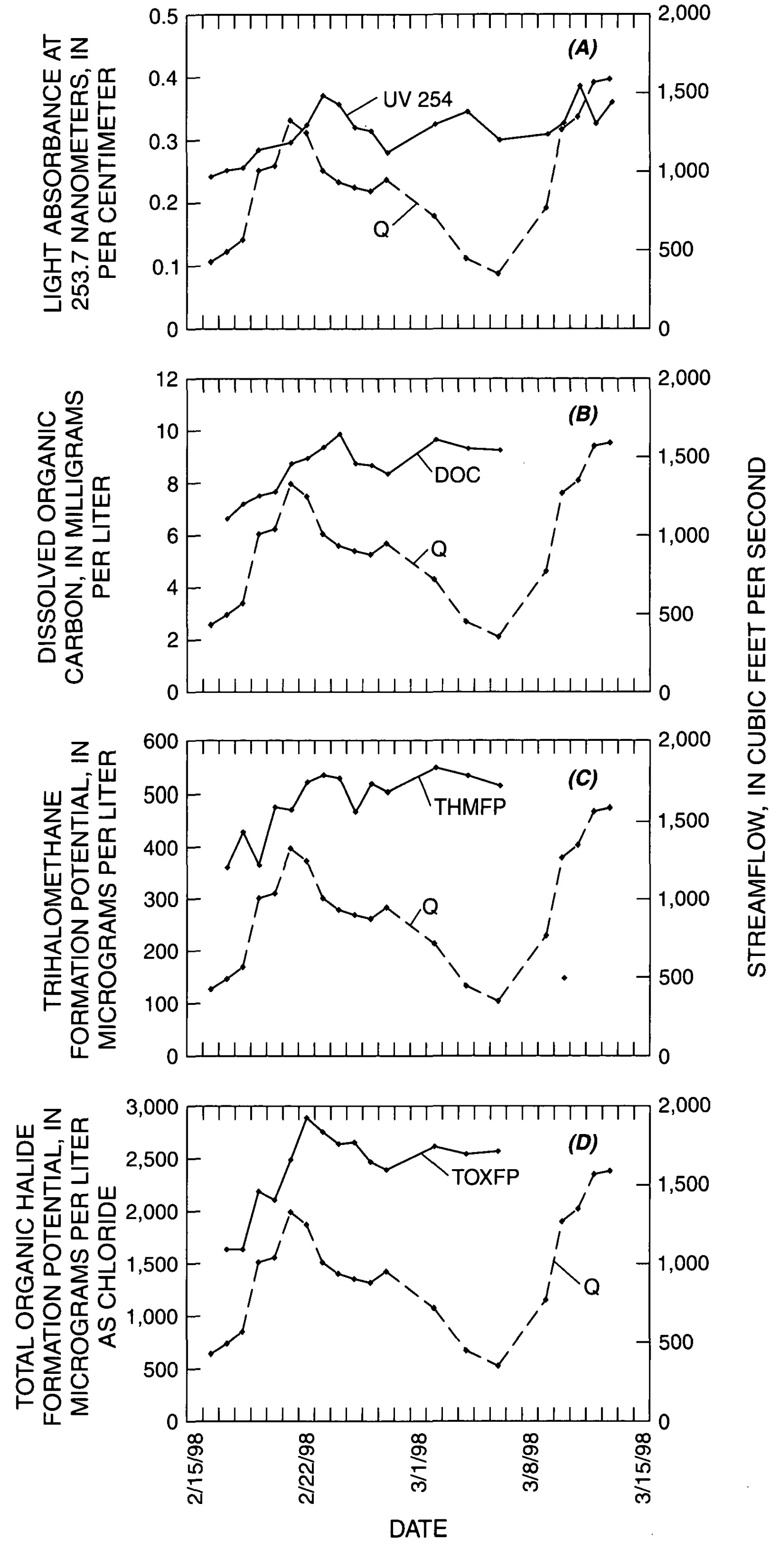

Figure 16. Relation of streamflow (Q) and light absorbance at 253.7 nanometers (UV254) (A) and concentrations of dissolved organic carbon (DOC) (B), trihalomethane formation potential (THMFP) (C), and total organic halide formation potential (TOXFP) (D) during the 1998 winter stormflow sample-collection period at station CR02, Chickahominy River Basin, Virginia.

Table 8. Stage, light absorbance at 253.7 nanometers (UV254), and concentrations of dissolved organic carbon (DOC), trihalomethane formation potential (THMFP), total organic halide formation potential (TOXFP), and haloacetic acid formation potential (HAAFP) at initial, peak, and after peak ("After") flow of selected stormflow periods at stations CR87, WOS55, and CR02, Chickahominy River Basin, Virginia

[cm, centimeter; –, no data; mg/L, milligrams per liter; µg/L, micrograms per liter; Cl, chloride]

Determination	Station number								
	CR87			WOS55			CR02		
	Initial	Peak	After	Initial	Peak	After	Initial	Peak	After
August 1-6, 1996									
Stage (feet)	–	–	–	2.41	3.24	2.78	4.15	5.75	5.25
UV254 (per cm)	–	–	–	0.625	0.679	0.679	0.437	0.571	0.547
DOC (mg/L)	–	–	–	13	17	17	11	14	14
THMFP (µg/L)	–	–	–	630	1,300	1,300	760	940	930
TOXFP (µg/L as Cl)	–	–	–	4,400	4,900	4,900	2,800	3,200	2,600
HAAFP (µg/L)	–	–	–	600	600	600	520	640	640
September 6-16, 1996									
Stage (feet)	–	–	–	2.12	3.25	2.59	2.99	8.81	7.45
UV254 (per cm)	–	–	–	.394	.615	.615	.376	.734	.734
October 8-17, 1996									
Stage (feet)	3.47	6.12	2.03	2.86	4.29	2.01	5.55	8.77	6.65
UV254 (per cm)	.197	.415	.335	.333	.758	.541	.325	.411	.340
DOC (mg/L)	6.1	9.9	9.6	9.8	14	14	7.8	11	8.5
THMFP (µg/L)	380	620	610	640	1,000	1,000	520	710	570
March 13-16, 1997									
Stage (feet)	2.72	4.04	2.87	2.15	2.65	2.16	5.96	6.01	5.70
UV254 (per cm)	.305	.408	.310	.304	.487	.288	.280	.353	.291
July 17 through September 17, 1997									
Stage (feet)	1.60	3.05	1.50	1.91	1.91	1.15	1.93	5.66	1.75
UV254 (per cm)	.224	.353	.162	.298	.432	.115	.311	.551	.245
November 7-20, 1997									
Stage (feet)	2.35	5.39	2.50	2.55	3.41	2.09	3.58	6.83	5.26
UV254 (per cm)	.143	.442	.266	.325	.478	.273	.179	.309	.197
DOC (mg/L)	7.6	12	6.7	13	15	11	8.2	12	10
THMFP (µg/L)	290	710	550	630	810	670	350	470	420
February 16 through March 13, 1998									
Stage (feet)	–	–	–	–	–	–	6.45	8.69	6.03
UV254 (per cm)	–	–	–	–	–	–	.242	.371	.280
DOC (mg/L)	–	–	–	–	–	–	6.6	9.9	8.4
THMFP (µg/L)	–	–	–	–	–	–	360	530	470
TOXFP (µg/L as Cl)	–	–	–	–	–	–	1,600	2,900	2,400
HAAFP (µg/L)	–	–	–	–	–	–	710	870	800

created, should reduce the cost of removing DOC and reduce the formation of DBPs as water is treated for public supply.

The observed change in the organic content of stream water resulting from stormflow is a consideration in timing the withdrawal of raw water. During stormflow periods, the organic content of stream water was typically lowest in the early part of stormflow periods and increased to higher levels at, or following, the peak in streamflow. Water having relatively low organic content could be withdrawn early in stormflow periods, and withdrawal could be stopped in the middle to later part of the stormflow period to minimize the cost of removing DOC and DBP precursors. This strategy would be particularly useful when storage in reservoirs is depleted. During extremely low base-flow periods, such as that in the summer of 1997, the City of Newport News Waterworks is not permitted to withdraw water from the Chickahominy River because flow cannot be reduced to less than 10 ft^3/s by withdrawals. When streamflow increases because of storm-water runoff, the delay in the increase in the organic content of stream water would provide an opportunity to withdraw water and store it in the large reservoirs for later use and (or) to pump it to the terminal reservoirs for more immediate use. Withdrawal of water could resume later in the stormflow period after the organic content of the stream water declines to acceptable levels.

Concentrations of THMFP and HAAFP exceeded the MCLs of 80 and 60 µg/L for THMs and HAAs, respectively, in all samples collected at station CR02 and in almost all samples collected at all other stations throughout the basin. Because treatment of the raw water with alum before chlorination removes 50 to 75 percent of the THMFP and HAAFP, concentrations of THMs and HAAs in treated water average 50 µg/L annually (Michael Hotaling, Newport News Waterworks, written commun., 1999). Thus, removal of DOC before chlorination of the raw water is essential in providing water having concentrations of THMs and HAAs less than the MCLs.

The fact that a large part of the TOXFP consists of organic halides other than THMs has important implications if MCLs for additional organic halides are developed. The percentage of THMFP concentrations composing TOXFP concentrations varied depending on

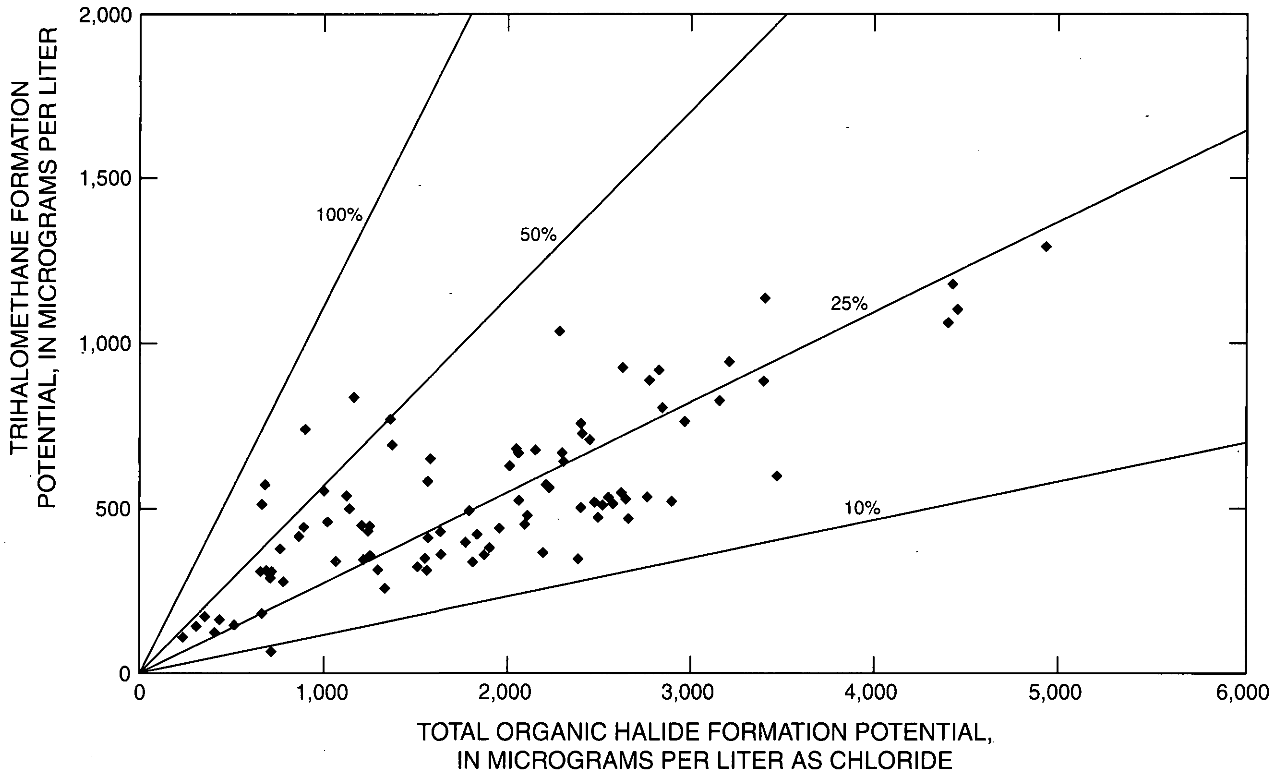

Figure 17. Percentage of total organic halide formation potential consisting of trihalomethane formation potential in samples, Chickahominy River Basin, Virginia.

TOXFP concentrations (fig. 17). Percentages are calculated by assuming that the THMs consist entirely of chloroform (THMs are largely chloroform) to determine how much of the THM concentration is chloride. This is necessary because the TOXFP concentration is expressed as chloride. At TOXFP concentrations less than 1,000 µg/L, THMFP concentrations composed from 10 to almost 100 percent of the TOXFP. The maximum THMFP concentrations increased proportionally less than the TOXFP concentrations as TOXFP concentrations increased from 1,000 to 5,000 µg/L, and the maximum percentage of the THMFP composing the TOXFP concentrations greater than 1,000 µg/L approached 25 percent.

Water suppliers can take advantage of natural spatial and temporal variability in the organic content of stream water in locating withdrawal points and in deciding when to make withdrawals. Raw-water withdrawal points can be located along a stream where the organic content of the stream water is lowest. By using reservoirs to store water temporarily, the water supplier can withdraw water when the organic content of the water is low. Reservoirs also allow time for degradation of the DOC to occur by natural processes.

The specific nature of changes in the organic content of water withdrawn from the Chickahominy River and stored in the reservoirs is not known. An evaluation of these changes using existing and possibly newly collected data would be useful in determining how to use the reservoirs to reduce the organic content of the raw water and, consequently, the cost of treating the water. Moreover, storing water in reservoirs has potential implications for the effects of the organic content on taste and odor, in addition to its effects on DBPs.

SUMMARY AND CONCLUSIONS

Surface waters used for public supply are commonly disinfected with chlorine to help assure potability. When chlorinated water contains dissolved organic carbon (DOC), however, the chlorine and other halogens react with the organic carbon to produce a variety of halogenated disinfection by-products (DBPs). Many of these DBPs are known, or suspected, carcinogens that include trihalomethanes (THMs) and haloacetic acids (HAAs). Knowledge of how concentrations of the precursors and DOC change spatially and temporally can be used to minimize water treatment and pumping costs and to allow for effective treatment of the raw water.

The Chickahominy River is used by the City of Newport News, Va., as a part of its raw-water supply. Because the DOC concentration in the river commonly ranges from 6 to 12 mg/L, formation of DBPs is of concern.

This report describes results of a study conducted by the U.S. Geological Survey, in cooperation with the City of Newport News, to evaluate spatial and temporal variations in the organic content of the Chickahominy River. Field studies evaluated variations in the organic content of stream water under a range of hydrologic conditions to determine possible effects on use of the water for public supply. Laboratory studies evaluated (1) the role of stream-bed detritus as a source of DOC to stream water and (2) degradation processes as a cause of decreasing DOC in stream water. The role of ground-water discharge as a source of organic carbon was evaluated by analyzing the organic content of water from wells and stream-bed seeps.

Selected samples were analyzed for concentrations of DOC, THM formation potential (THMFP), total organic halide formation potential (TOXFP), and HAA formation potential (HAAFP). Light absorbance at 253.7 nm (UV254) was used as a surrogate for these analyses in additional samples to provide a more comprehensive representation of the natural system than could otherwise be obtained. The stable isotopes oxygen-18 and deuterium were analyzed in selected samples to help evaluate the effects of hydrologic processes on the organic content of stream water.

Results indicate that stream-bed detritus can be a substantial source of DOC to stream water; UV254 of de-ionized water increased from 0.041 to 0.447 cm^{-1} after the first 4 hours of incubation. These values were similar to those commonly measured in stream water. Results also indicate that degradation of the DOC in stream water through photodegradation is an important process; the UV254 of samples exposed to sunlight at room temperature decreased by as much as 50 percent in 83 days.

Ground water can be a substantial source of organic carbon to stream water. UV254 of water from wells and seeps in alluvial sediments was equal to, or greater than, that of streams, ranging from 0.102 to 2.45 cm^{-1}. The DOC content of the seeps and ground water ranged from 2.5 to 9.5 mg/L.

During base-flow periods, UV254 and concentrations of DOC, THMFP, TOXFP, and HAAFP generally decreased downstream along the main stem of the Chickahominy River. Decreases of 50 percent or more were common. These analytes decreased because the input of organic carbon to the stream water was exceeded by decreases in the organic carbon. This probably occurred because (1) the organic content of water in the tributaries in the upper part of the basin was lower than, and diluted, the higher organic content of water in the main stem of the Chickahominy River; (2) during base-flow periods the direct contribution to the organic content of the stream water by the organic litter in the wetland flood plain was limited; (3) traveltimes were long between the headwaters and the lower nontidal part of the basin, thus allowing substantial time for DOC degradation; and (4) the meandering, broad channels and the presence of multiple shallow channels in the Coastal Plain part of the Chickahominy River enhanced the opportunity for degradation.

During stormflow periods, the time of peak organic content of stream water was generally at, or after, the time of peak streamflow. UV254 and concentrations of DOC, THMFP, and TOXFP generally increased from 16 to almost 100 percent above pre-storm levels during stormflow periods. During a stormflow period in the summer of 1997, for example, UV254 at the downstream station (CR02) first decreased from 0.311 cm^{-1} before the storm to 0.201 cm^{-1} early in the storm, then peaked at 0.551 cm^{-1} 10 days after the peak in streamflow. UV254 gradually declined to a low of 0.245 cm^{-1} 53 days after the peak in streamflow.

Several processes appear to control the organic content of stream water during stormflow periods. Decreases in UV254 such as those identified early in the 1997 summer storm are likely not a common occurrence but probably result from dilution by the high intensity and short duration of the precipitation that produces the stormflows during extremely dry periods. UV254 probably peaked after the peak in streamflow because organic carbon leached from the organic litter through the soil and discharged to the streams with interflow and shallow ground water late in the stormflow period. Because soluble organic carbon was leached from the organic litter layer by infiltrating precipitation, the amount of soluble organic carbon available to surface runoff was limited. The decrease in UV254 during and after return to base-flow conditions probably resulted from the decrease in the interflow and shallow ground-water contribution to streamflow and the degradation of organic carbon.

Study results have implications for use of the Chickahominy River and similar rivers for public supply. The downstream decrease in the organic content of stream water observed in the Chickahominy River likely will be observed in other streams that have broad, meandering channels and sluggish flow characteristics. Thus, locating withdrawal points as far downstream as possible likely would minimize the formation of DBPs. Such decreases probably would not occur in rivers that have deep channels and moderately flowing water.

Concentrations of THMFP and HAAFP exceeded the recently established maximum contaminant levels (MCLs) of 80 and 60 µg/L for THMs and HAAs, respectively, in all samples collected at the farthest downstream station on the Chickahominy River. Because treatment of the raw water with alum before chlorination removes 50 to 75 percent of the THMFP and HAAFP, concentrations of THMs and HAAs in treated water average 50 µg/L annually. Consequently, treatment of the raw water prior to chlorination helps to reduce the THM and HAA concentrations below the MCLs.

The organic content of stream water changes during stormflows; while streamflow increases and the organic content of the water remains low, water can be withdrawn and stored for a variable amount of time in the reservoirs. Withdrawal can be discontinued when the organic content of the river water exceeds a selected level, then resumed after the organic content drops below that level. The organic content of water can change when the water is stored in reservoirs, and an evaluation of these changes would be useful in determining how the reservoirs can be used to reduce the organic content of the raw water and, consequently, the cost of treating the water.

REFERENCES CITED

Aiken, G.R., McKnight, D.M., Wershaw. R.L., and MacCarthy, Patrick, 1985, Humic substances in soil, sediment, and water—Geochemistry, isolation, and characterization: New York, Wiley, 692 p.

American Public Health Association, 1995, Standard methods for the evaluation of water and wastewater (19th ed.): Washington, D.C., American Public Health Association, variously paged.

Bencala, K.E., Kennedy, V.C., Zellweger, G.W., Jackman, A.P., and Avanzino, R.J., 1984, Interactions of solutes and streambed sediment—1. An experimental analysis of cation and anion transport in a mountain stream: Water Resources Research, v. 20, no. 12, p. 1797-1803.

Constantz, Jim, 1998, Interaction between stream temperature, streamflow, and groundwater exchanges in alpine streams: Water Resources Research, v. 34, no. 7, p. 1609-1615.

Coplen, T.B., Wildman, J.D., and Chen, J., 1991, Improvements in the gaseous hydrogen-water equilibration technique for hydrogen isotope ratio analysis: Analytical Chemistry, v. 63, p. 910-912.

Coplen, T.B., 1993, Uses of environmental isotopes, *in* Alley, W.M., ed., Regional ground-water quality: New York, Van Nostrand Reinhold, p. 227-253.

Craig, H. 1961, Isotopic variations in meteoric waters: Science, v. 133, p. 1702-1703.

Daniels, P.A., Jr., and Onuschak, Emil, 1974, Geology of the Studley, Yellow Tavern, Richmond, and Seven Pines quadrangles, Virginia: Virginia Department of Conservation and Economic Development, Division of Mineral Resources, Report of Investigations 38, 75 p., 13 plates.

Edzwald, J.K., Becker, W.C., and Wattier, K.L., 1985, Surrogate parameters for monitoring organic matter and THM precursors: Journal of the American Water Works Association, v. 77, no. 5 p. 122-132.

Findlay, Stuart, 1995, Importance of surface-subsurface exchange in stream ecosystems—the hyporheic zones: Limnology and Oceanography, v. 40, no. 1, p. 159-164.

Fishman, M.J., ed., 1993, Methods of analysis by the U.S. Geological Survey National Water Quality Laboratory—determinations of inorganic and organic constituents in water and fluvial sediment: U.S. Geological Survey Open-File Report 93-125, 217 p.

Fishman, M.J., and Friedman, L.C., eds., 1989, Methods for determination of inorganic substances in water and fluvial sediment: U.S. Geological Survey Techniques of Water-Resources Investigations, book 5, chap. A1, 545 p.

Focazio, M.J., and Cooper, R.E., 1995, Selected characteristics of stormflow and base flow affected by land use and cover in the Chickahominy River Basin, Virginia, 1989-91: U.S. Geological Survey Water-Resources Investigations Report 94-4225, 37 p.

Gat, J.R., and Gonfiantini, R., eds., 1981, Stable isotope hydrology—deuterium and oxygen-18 in the water cycle: Vienna, Austria, International Atomic Energy Commission, Technical Report Series No. 210, 399 p.

Harvey, J.W., and Bencala, K.E., 1993, The effects of streambed topography on surface-subsurface water exchange in mountain catchments: Water Resources Research, v. 29, no. 1, p. 89-98.

Johnson, J.D., and Jensen, J.N., 1995, THM and TOX formation—routes, rates, and precursors: Journal of the American Water Works Association, v. 78, no. 4, p. 156-162.

Meng, A.A., and Harsh, J.F., 1988, Hydrogeologic framework of the Virginia Coastal Plain: U.S. Geological Survey Professional Paper 1404-C, 82 p., 4 plates.

Morris, J.C., and Baum, B., 1978, Precursors and mechanisms of haloform formation in chlorination of water supplies, *in* Jolley, R.L., Gorchev, H., and Hamilton, D.H., eds., Water chlorination—environmental impact and health effects, v. 2: Ann Arbor Mich., Ann Arbor Science, p. 29-48.

National Oceanic and Atmospheric Administration, 1996, Climatological data annual summary, Virginia: Asheville, N.C., National Climatic Data Center, v. 106, no. 13, 28 p.

Oliver, B.G., and Thurman, E.M., 1981, Influence of aquatic humic substance properties on trihalomethane potential *in* Jolley, R.L., Brungs, W.A., Cotruvo, J.A., Cumming, R.B., Mattice, J.S., and Jacobs, V.A., eds., v. 4, book 1, Chemistry and water treatment—Proceedings of the Fourth Conference on Water Chlorination, Environmental Impact and Health Effects, Pacific Grove, California, October 18-23, 1981: Ann Arbor Mich., Ann Arbor Science, p. 231-241.

Oliver, B.G., and Visser, S.A., 1980, Chloroform production from the chlorination of aquatic humic material—the effect of molecular weight, environment, and season: Water Research, v. 14, no. 8, p. 1137-1141.

Prugh, B.J., Herman, P.E., and Belval, D.L., 1995, Water resources data, Virginia, water year 1994, volume 1—surface-water-discharge and surface-water-quality records: U.S. Geological Survey Water-Data Report VA-94-1, 615 p.

Richardson, D.L., 1994, Ground-water discharge from the Coastal Plain of Virginia: U.S. Geological Survey Water-Resources Investigations Report 93-4191, 15 p.

Rook, J.L., 1974, Formation of haloforms during chlorination of natural waters: Water Treatment and Examination, v. 23 no. 2, p. 234-243.

Saito, S., Hattori, K., and Okumura, T., 1989, Outflows of organic halide precursors from forest regions: Water Science Technology, v. 21, p. 1877-1880.

Singer, P.C., Barry, J.J., III, Palen, G.M., and Scrivner, A.E., 1981, Trihalomethane formation in North Carolina drinking water: Journal of the American Water Works Association, v. 73, no. 8, p. 392-401.

Skoog, D.A., and West, D.M., 1963, Fundamentals of analytical chemistry: New York, Holt, Reinhart, and Winston, Inc., 786 p.

Thurman, E.M., 1985, Organic geochemistry of natural waters: Dordrecht, the Netherlands, Martinus Nijhoff,/ Dr. W. Junk Publishers, 497 p.

U.S. Environmental Protection Agency, 1992, Methods for the determination of organic compounds in drinking water, supplement 2: U.S. Environmental Protection Agency Report 600/92/129, 270 p.

U.S. Environmental Protection Agency, 1994, DBP/ICR Analytical methods guidance manual: U.S. Environmental Protection Agency Report 814/P94/001, p. 5910-1 to 5910-10.

U.S. Environmental Protection Agency, 1998, National primary drinking water regulations—Disinfectants and disinfection by-products, final rule: Code of Federal Regulations, Title 40, Part 9, 141, and 142, p. 69,3890-69,476.

White, R.K., Hayes, D.C., Eckenweiler, M.R., Belval, D.L., and Herman, P.E., 1996-99, Water resources data for Virginia, water years 1995-1998— v. 1, Surface-water-discharge and surface-water-quality records: U.S. Geological Survey Water-Data Reports VA-95-1 to VA-98-1 (published annually).

White, R.K., and Powell, E.D., 1997, Water resources data, Virginia, water year 1997, volume 2 — ground-water-levels and ground-water-quality records: U.S. Geological Survey Water-Data Report VA-97-2, 387 p.

Youseffi, M., Zenchelsky, S.T., and Faust, S.D., 1978, Chlorination of naturally-occurring organic compounds in water: Journal of Environmental Science and Health, v. 13, p. 629-637.

APPENDIX

Appendix 1. Streamflow and stage and selected organic analyses of stream-water samples, Chickahominy River Basin, Virginia

[–, no data; mg/L, milligrams per liter; µg/L, micrograms per liter; Cl, chloride]

Station number	USGS identification number	Date	Time	Streamflow (cubic feet per second)	Stage (feet)	Light absorbance at 253.7 nanometers (per centimeter)	Dissolved organic carbon (mg/L)	Total organic carbon (mg/L)	Trihalomethane formation potential (µg/L)	Total organic halide formation potential (µg/L as Cl)	Haloacetic acid formation potential (µg/L)
CR60	2042260	8/21/95	900	0.000	–	0.321	11	–	960	–	–
CR60	2042260	3/14/96	930	–	–	.518	13	–	1,000	2,300	–
CR60	2042260	12/9/96	1330	–	94.00	.734	20	20	1,300	–	–
CR60	2042260	2/11/97	1050	–	94.07	.572	–	–	–	–	–
CR60	2042260	5/29/97	830	–	93.09	.459	13	13	790	–	–
CR60	2042260	9/16/97	810	–	92.92	.321	–	–	–	–	–
STR01	2042284	8/21/95	1015	.103	–	.262	9.0	–	690	–	–
STR01	2042284	3/11/96	1050	–	–	.341	8.7	–	650	1,600	540
STR01	2042284	12/9/96	1445	–	95.55	.505	14	14	800	–	–
STR01	2042284	2/11/97	1135	–	93.68	.346	–	–	–	–	–
STR01	2042284	5/29/97	915	–	–	.374	12	12	580	–	–
STR01	2042284	9/16/97	910	–	91.65	.156	–	–	–	–	–
CR87	2042287	8/23/95	1815	–	1.43	.597	17	–	1,200	–	–
CR87	2042287	3/11/96	1220	–	2.77	.301	8.7	–	690	1,400	–
CR87	2042287	10/8/96	1500	–	3.47	.197	6.1	7.2	380	–	340
CR87	2042287	10/9/96	930	–	5.69	.262	7.6	7.7	460	–	–
CR87	2042287	10/9/96	1800	–	6.12	.415	–	–	–	–	–
CR87	2042287	10/10/96	1400	–	5.53	.343	9.9	10	620	–	–
CR87	2042287	10/12/96	1520	–	2.97	.346	9.6	10	610	–	–
CR87	2042287	10/14/96	1015	–	2.28	.335	–	–	–	–	–
CR87	2042287	10/17/96	1100	–	2.03	.345	–	–	–	–	–
CR87	2042287	11/13/96	945	–	2.91	.487	13	13	760	–	–
CR87	2042287	12/11/96	750	–	4.25	.429	11	11	710	–	–
CR87	2042287	1/14/97	1030	–	3.19	.317	9.9	10	840	1,200	950
CR87	2042287	2/11/97	1200	–	3.92	.315	–	–	–	–	–
CR87	2042287	3/13/97	1510	–	2.72	.305	–	–	–	–	–
CR87	2042287	3/14/97	1515	–	2.93	.408	–	–	–	–	–
CR87	2042287	3/14/97	1850	–	3.10	.331	–	–	–	–	–
CR87	2042287	3/15/97	935	–	3.79	.370	–	–	–	–	–
CR87	2042287	3/15/97	1525	–	4.04	.385	–	–	–	–	–
CR87	2042287	3/16/97	1315	–	3.58	.312	–	–	–	–	–
CR87	2042287	3/17/97	1045	–	3.10	.310	–	–	–	–	–
CR87	2042287	3/18/97	940	–	2.87	.313	–	–	–	–	–

Appendix 1. Streamflow and stage and selected organic analyses of stream-water samples, Chickahominy River Basin, Virginia—Continued

[–, no data; mg/L, milligrams per liter; µg/L, micrograms per liter; Cl, chloride]

Station number	USGS identification number	Date	Time	Streamflow (cubic feet per second)	Stage (feet)	Light absorbance at 253.7 nanometers (per centimeter)	Dissolved organic carbon (mg/L)	Total organic carbon (mg/L)	Trihalomethane formation potential (µg/L)	Total organic halide formation potential (µg/L as Cl)	Haloacetic acid formation potential (µg/L)
CR87	2042287	4/14/97	1500	–	2.91	.409	9.6	9.6	770	1,400	–
CR87	2042287	5/29/97	945	–	2.00	.356	9.3	9.3	560	–	–
CR87	2042287	7/16/97	1010	–	1.60	.315	–	–	–	–	–
CR87	2042287	7/16/97	1700	–	1.66	.317	–	–	–	–	–
CR87	2042287	7/16/97	1950	–	1.80	.340	–	–	–	–	–
CR87	2042287	7/17/97	915	–	3.05	.224	–	–	–	–	–
CR87	2042287	7/17/97	1400	–	3.04	.226	–	–	–	–	–
CR87	2042287	7/18/97	830	–	2.73	.225	–	–	–	–	–
CR87	2042287	7/21/97	1020	–	1.85	.350	–	–	–	–	–
CR87	2042287	7/22/97	830	–	1.79	.353	–	–	–	–	–
CR87	2042287	9/10/97	840	–	1.50	.224	–	–	–	–	–
CR87	2042287	9/11/97	905	–	1.53	.162	–	–	–	–	–
CR87	2042287	9/16/97	945	–	1.62	.253	–	–	–	–	–
CR87	2042287	10/22/97	900	–	1.87	.134	7.6	6.8	200	–	240
CR87	2042287	11/7/97	900	–	2.35	.143	9.0	7.8	290	–	–
CR87	2042287	11/7/97	1700	–	3.82	.191	9.2	8.9	500	–	–
CR87	2042287	11/8/97	915	–	4.59	.230	11	10	580	1,600	–
CR87	2042287	11/8/97	1415	–	4.88	.258	–	–	–	–	–
CR87	2042287	11/9/97	930	–	5.39	.352	12	13	710	2,400	1,200
CR87	2042287	11/9/97	1630	–	5.14	.420	–	–	–	–	–
CR87	2042287	11/10/97	1330	–	4.51	.442	12	11	680	2,000	820
CR87	2042287	11/12/97	1330	–	2.50	.266	6.7	10	550	1,000	760
CR87	2042287	11/13/97	1430	–	–	.309	–	–	–	–	–
CR87	2042287	1/14/98	930	–	2.48	.296	11	10	560	2,200	940
CR87	2042287	4/16/98	700	–	2.85	.350	–	9.3	–	–	–
CR87	2042287	7/8/98	845	–	1.70	.468	–	–	–	–	–
UPB01	2042426	8/23/95	1730	–	–	.265	8.0	–	540	–	–
UPB01	2042426	3/11/96	1305	–	–	.232	6.7	–	430	1,200	560
UPB01	2042426	12/11/96	840	–	–	.305	9.0	8.7	500	–	–
UPB01	2042426	2/11/97	1250	–	–	.270	–	–	–	–	–
UPB01	2042426	5/29/97	1010	–	–	.307	7.7	7.8	440	–	–
UPB01	2042426	9/16/97	1010	–	–	.250	–	–	–	–	–
HSW01	2042429	8/21/95	1245	.067	–	.112	4.9	–	190	–	–

Appendix 1. Streamflow and stage and selected organic analyses of stream-water samples, Chickahominy River Basin, Virginia—Continued

[–, no data; mg/L, milligrams per liter; µg/L, micrograms per liter; Cl, chloride]

Station number	USGS identification number	Date	Time	Streamflow (cubic feet per second)	Stage (feet)	Light absorbance at 253.7 nanometers (per centimeter)	Dissolved organic carbon (mg/L)	Total organic carbon (mg/L)	Trihalomethane formation potential (µg/L)	Total organic halide formation potential (µg/L as Cl)	Haloacetic acid formation potential (µg/L)
HSW01	2042429	3/11/96	1430	–	–	.077	3.6	–	110	240	–
HSW01	2042429	12/11/96	915	–	–	.102	4.2	4.6	130	–	–
HSW01	2042429	2/11/97	1325	–	–	.078	–	–	–	–	–
HSW01	2042429	5/29/97	1030	–	–	.079	3.3	3.4	100	–	–
HSW01	2042429	9/16/97	1035	–	–	.084	–	–	–	–	–
BDT01	2042432	8/21/95	1515	.023	–	.143	2.2	–	110	–	–
BDT01	2042432	3/12/96	845	–	–	.043	1.9	–	140	310	200
BDT01	2042432	12/9/96	1600	–	–	.072	1.6	1.9	100	–	–
BDT01	2042432	2/11/97	1420	–	–	.047	–	–	–	–	–
BDT01	2042432	5/29/97	1050	–	–	.038	1.4	1.3	130	–	–
BDT01	2042432	9/19/97	1130	–	–	.033	–	–	–	–	–
BDC01	2042433	8/21/95	1415	2.36	–	.142	4.2	–	280	–	–
BDC01	2042433	3/11/96	1545	–	–	.141	3.2	–	160	430	–
BDC01	2042433	12/9/96	1535	–	–	.111	5.8	4.1	300	–	–
BDC01	2042433	2/11/97	1405	–	–	.105	–	–	–	–	–
BDC01	2042433	5/29/97	1100	–	–	.100	–	–	–	–	–
BDC01	2042433	9/16/97	1150	–	–	.125	–	–	–	–	–
PWC01	2042437	8/22/95	830	.798	–	.226	6.6	–	530	–	–
PWC01	2042437	3/12/96	1015	–	–	.135	4.0	–	290	710	–
PWC01	2042437	12/9/96	1630	–	–	.179	5.4	5.3	360	–	–
PWC01	2042437	2/12/97	845	–	–	.104	–	–	–	–	–
PWC01	2042437	5/29/97	1530	–	–	.170	5.6	5.8	410	–	–
PWC01	2042437	9/16/97	1230	–	–	.154	–	–	–	–	–
BSC01	2042438	8/22/95	915	.011	–	.387	11	–	770	–	–
BSC01	2042438	3/12/96	1100	–	–	.172	5.2	–	380	760	–
BSC01	2042438	12/9/96	1705	–	–	.231	6.1	6.0	410	–	–
BSC01	2042438	2/12/97	915	–	–	.129	–	–	–	–	–
BSC01	2042438	5/29/97	1510	–	–	.309	7.5	7.9	580	–	–
BSC01	2042438	9/16/97	1250	–	–	.213	–	–	–	–	–
CRT01	2042439	8/21/95	1645	.552	–	.096	3	–	170	–	–
CRT01	2042439	3/12/96	1415	–	–	.090	3	–	170	360	–
CRT01	2042439	12/10/96	945	–	–	.247	7.0	6.7	450	–	–
CRT01	2042439	2/12/97	1040	–	–	.100	–	–	–	–	–

Appendix 1. Streamflow and stage and selected organic analyses of stream-water samples, Chickahominy River Basin, Virginia—Continued

[–, no data; mg/L, milligrams per liter; µg/L, micrograms per liter; Cl, chloride]

Station number	USGS identification number	Date	Time	Streamflow (cubic feet per second)	Stage (feet)	Light absorbance at 253.7 nanometers (per centimeter)	Dissolved organic carbon (mg/L)	Total organic carbon (mg/L)	Trihalomethane formation potential (µg/L)	Total organic halide formation potential (µg/L as Cl)	Haloacetic acid formation potential (µg/L)
CRT01	2042439	5/29/97	1410	–	–	.144	3.5	3.7	260	–	–
CRT01	2042439	9/16/97	1420	–	–	.058	–	–	–	–	–
CR40	2042440	11/13/96	1100	–	86.04	.390	12	12	570	–	–
CR40	2042440	12/11/96	1015	–	86.53	.337	11	9.8	610	–	–
CR40	2042440	1/14/97	1200	–	85.61	.210	6.9	7.0	510	670	710
CR40	2042440	2/12/97	940	–	85.81	.226	–	–	–	–	–
CR40	2042440	4/14/97	1330	–	–	.353	9.2	9.0	–	–	–
CR40	2042440	5/29/97	1440	–	82.50	.261	7.1	7.1	–	–	–
CR40	2042440	7/16/97	1120	–	83.82	.308	–	–	–	–	–
CR40	2042440	9/16/97	1325	–	84.51	.223	–	–	–	–	–
CR40	2042440	10/22/97	1015	–	84.88	.160	6.9	7.2	–	1,600	920
CR40	2042440	1/14/98	1100	–	85.71	.221	8.8	8.5	–	1,800	900
CR40	2042440	4/16/98	845	–	85.41	.335	–	–	–	–	–
CR40	2042440	7/8/98	920	–	85.35	.397	–	–	–	–	–
CRT08	2042441	8/23/95	845	.136	–	.242	6.0	–	–	–	–
CRT08	2042441	3/12/96	1515	–	–	.139	6.5	–	–	660	–
CRT08	2042441	12/10/96	1030	–	–	.187	4.5	4.9	–	–	–
CRT08	2042441	2/12/97	1000	–	–	.112	–	–	–	–	–
CRT08	2042441	5/29/97	1600	–	–	.277	7.2	7.3	–	–	–
CRT08	2042441	9/16/97	1550	–	–	.174	–	–	–	–	–
HGS01	2042442	8/23/95	1015	.224	–	.499	8.5	–	690	–	–
HGS01	2042442	3/12/96	1615	–	–	.142	4.6	–	310	660	–
HGS01	2042442	12/10/96	1110	–	–	.130	3.5	–	250	–	–
HGS01	2042442	2/12/97	1405	–	–	.068	–	–	–	–	–
HGS01	2042442	5/29/97	1620	–	–	.150	4.0	3.1	–	–	–
HGS01	2042442	9/16/97	1635	–	–	.109	–	–	–	–	–
CR45	2042445	8/22/95	1300	.213	–	.358	11	–	800	–	–
CR45	2042445	3/14/96	945	–	–	.238	8.2	–	460	1,000	–
CR45	2042445	12/10/96	1720	–	–	.286	7.9	7.7	490	–	–
CR45	2042445	2/12/97	1340	–	–	.197	–	–	–	–	–
CR45	2042445	5/30/97	930	–	–	.256	–	–	–	–	–
CR45	2042445	9/16/97	1705	–	–	.267	–	–	–	–	–
TCT07	2042446	8/22/95	1410	.014	–	.074	2.8	–	150	–	–

Appendix 1. Streamflow and stage and selected organic analyses of stream-water samples, Chickahominy River Basin, Virginia—Continued

[–, no data; mg/L, milligrams per liter; µg/L, micrograms per liter; Cl, chloride]

Station number	USGS identification number	Date	Time	Streamflow (cubic feet per second)	Stage (feet)	Light absorbance at 253.7 nanometers (per centimeter)	Dissolved organic carbon (mg/L)	Total organic carbon (mg/L)	Trihalomethane formation potential (µg/L)	Total organic halide formation potential (µg/L as Cl)	Haloacetic acid formation potential (µg/L)
TCT07	2042446	3/13/96	1415	–	–	.093	2.7	–	120	410	260
TCT07	2042446	12/10/96	1345	–	–	.088	3.0	3.0	170	–	–
TCT07	2042446	2/12/97	1255	–	–	.057	–	–	–	–	–
TCT07	2042446	5/30/97	845	–	–	.061	2.0	2.3	120	–	–
TCT07	2042446	9/17/97	855	–	–	.045	–	–	–	–	–
CRT07	2042447	8/22/95	1500	.137	–	.188	4.7	–	400	–	240
CRT07	2042447	3/13/96	1500	–	–	.106	3.7	–	180	660	230
CRT07	2042447	11/13/96	1315	–	–	.135	4.3	5.0	320	–	–
CRT07	2042447	12/10/96	1410	–	–	.140	8.0	8.2	330	–	–
CRT07	2042447	1/14/97	1515	–	–	.104	4.0	3.1	–	550	390
CRT07	2042447	2/12/97	1315	–	–	.102	–	–	–	–	–
CRT07	2042447	4/14/97	1100	–	–	.174	5.3	5.5	500	–	–
CRT07	2042447	5/30/97	915	–	–	.213	5.6	5.7	380	–	–
CRT07	2042447	7/16/97	1340	–	–	.249	–	–	–	–	–
CRT07	2042447	9/17/97	920	–	–	.138	–	–	–	–	–
CRT07	2042447	10/22/97	1400	–	–	.155	4.1	4.4	260	1,300	440
CRT07	2042447	1/14/98	1415	–	–	.111	4.3	3.8	280	780	640
CRT07	2042447	4/16/98	1230	–	–	.140	4.2	4.5	–	–	–
CRT07	2042447	7/6/98	1345	–	–	.280	–	–	–	–	–
WOS48	2042448	8/22/95	1100	.147	–	.051	2.9	–	110	–	–
WOS48	2042448	3/12/96	1300	–	–	.164	–	–	–	3,300	–
WOS48	2042448	12/10/96	1150	–	–	.151	5.3	5.5	343	–	–
WOS48	2042448	2/12/97	1105	–	–	.099	–	–	–	–	–
WOS48	2042448	5/29/97	1655	–	–	.068	3.0	3.1	140	–	–
WOS48	2042448	9/16/97	1450	–	–	.095	–	–	–	–	–
CNS01	2042454	8/22/95	1600	.132	–	.774	14	–	1,100	–	–
CNS01	2042454	3/14/96	830	–	–	.180	6.0	–	450	1,300	540
CNS01	2042454	11/14/96	1215	–	–	.373	10	11	610	–	–
CNS01	2042454	12/10/96	1225	–	–	.357	11	9.3	680	–	–
CNS01	2042454	1/13/97	1315	–	–	.260	6.9	7.8	740	900	780
CNS01	2042454	2/12/97	1135	–	–	.212	–	–	–	–	–
CNS01	2042454	4/14/97	945	–	–	.502	9.7	11	1,100	3,400	–
CNS01	2042454	5/30/97	815	–	–	–	11	12	750	–	–

Appendix 1. Streamflow and stage and selected organic analyses of stream-water samples, Chickahominy River Basin, Virginia—Continued

[–, no data; mg/L, milligrams per liter; µg/L, micrograms per liter; Cl, chloride]

Station number	USGS identification number	Date	Time	Streamflow (cubic feet per second)	Stage (feet)	Light absorbance at 253.7 nanometers (per centimeter)	Dissolved organic carbon (mg/L)	Total organic carbon (mg/L)	Trihalomethane formation potential (µg/L)	Total organic halide formation potential (µg/L as Cl)	Haloacetic acid formation potential (µg/L)
CNS01	2042454	7/16/97	1300	–	–	.339	–	–	–	–	–
CNS01	2042454	9/16/97	1745	–	–	.125	–	–	–	–	–
CNS01	2042454	10/22/97	1500	–	–	.387	9.2	9.4	600	3,500	–
CNS01	2042454	1/14/98	1240	–	–	.234	8.0	9.1	600	2,300	1,300
CNS01	2042454	4/16/98	1045	–	–	.282	6.8	8.1	–	–	–
CNS01	2042454	7/16/98	1015	–	–	.334	–	–	–	–	–
WOS55	2042455	4/20/95	830	–	–	.610	8.3	7.8	1,400	–	820
WOS55	2042455	6/13/95	830	–	–	.583	7.6	7.8	840	–	970
WOS55	2042455	8/22/95	900	–	1.05	.247	6.3	6.8	740	–	670
WOS55	2042455	11/30/95	815	–	2.02	.406	10	11	190	–	410
WOS55	2042455	1/26/96	900	–	2.50	.316	–	8.0	840	–	970
WOS55	2042455	3/14/96	830	–	2.02	–	6.6	–	–	1,700	430
WOS55	2042455	5/21/96	730	–	1.82	.783	14	17	–	–	–
WOS55	2042455	7/17/96	800	–	2.91	.785	15	17	–	–	–
WOS55	2042455	8/1/96	1515	–	2.41	.625	13	13	630	–	600
WOS55	2042455	8/2/96	930	–	3.10	.612	14	–	1,100	4,400	590
WOS55	2042455	8/2/96	1625	–	3.24	.671	14	–	1,200	4,400	580
WOS55	2042455	8/3/96	845	–	2.78	.679	17	–	1,300	4,900	600
WOS55	2042455	9/6/96	615	–	2.12	.394	–	–	–	–	–
WOS55	2042455	9/6/96	1520	–	2.48	.424	–	–	–	–	–
WOS55	2042455	9/7/96	1355	–	3.25	.543	–	–	–	–	–
WOS55	2042455	9/8/96	1255	–	2.59	.615	–	–	–	–	–
WOS55	2042455	10/8/96	1345	–	2.86	.333	9.8	11	640	–	–
WOS55	2042455	10/8/96	1920	–	3.40	.477	9.3	11	500	–	–
WOS55	2042455	10/9/96	1030	–	4.01	.468	12	12	710	–	–
WOS55	2042455	10/9/96	1700	–	3.73	.581	–	–	–	–	–
WOS55	2042455	10/10/96	1200	–	4.29	.758	14	14	800	–	–
WOS55	2042455	10/12/96	1330	–	2.89	.543	14	14	1,000	–	–
WOS55	2042455	10/17/96	1020	–	2.01	.541	–	–	–	–	–
WOS55	2042455	11/14/96	815	–	2.09	.395	9.6	11	610	–	–
WOS55	2042455	12/10/96	1255	–	2.96	.330	9.3	9.1	620	–	–
WOS55	2042455	1/14/97	1415	–	2.17	.216	6.8	7.2	570	680	790
WOS55	2042455	2/12/97	1205	–	2.33	.191	–	–	–	–	–

Appendix 1. Streamflow and stage and selected organic analyses of stream-water samples, Chickahominy River Basin, Virginia—Continued

[–, no data; mg/L, milligrams per liter; µg/L, micrograms per liter; Cl, chloride]

Station number	USGS identification number	Date	Time	Streamflow (cubic feet per second)	Stage (feet)	Light absorbance at 253.7 nanometers (per centimeter)	Dissolved organic carbon (mg/L)	Total organic carbon (mg/L)	Trihalomethane formation potential (µg/L)	Total organic halide formation potential (µg/L as Cl)	Haloacetic acid formation potential (µg/L)
WOS55	2042455	3/13/97	1600	–	2.15	.304	–	–	–	–	–
WOS55	2042455	3/14/97	1340	–	2.27	.478	–	–	–	–	–
WOS55	2042455	3/14/97	1800	–	2.37	.487	–	–	–	–	–
WOS55	2042455	3/15/97	1030	–	2.65	.327	–	–	–	–	–
WOS55	2042455	3/15/97	1415	–	2.65	.436	–	–	–	–	–
WOS55	2042455	3/16/97	1425	–	2.34	.309	–	–	–	–	–
WOS55	2042455	3/17/97	1200	–	2.21	.288	–	–	–	–	–
WOS55	2042455	3/18/97	1030	–	2.16	.343	–	–	–	–	–
WOS55	2042455	4/16/97	730	–	1.94	.591	11	11	1,100	4,400	–
WOS55	2042455	5/29/97	1720	–	1.69	.384	11	12	730	–	–
WOS55	2042455	7/16/97	1750	–	1.91	.298	–	–	–	–	–
WOS55	2042455	7/17/97	715	–	1.91	.432	–	–	–	–	–
WOS55	2042455	7/17/97	1015	–	1.83	.317	–	–	–	–	–
WOS55	2042455	9/9/97	745	–	1.18	.124	–	–	–	–	–
WOS55	2042455	9/10/97	1000	–	1.15	.122	–	–	–	–	–
WOS55	2042455	9/11/97	1000	–	1.21	.165	–	–	–	–	–
WOS55	2042455	9/16/97	1815	–	1.15	.115	–	–	–	–	–
WOS55	2042455	10/22/97	745	–	1.85	.231	9.2	9.4	360	1,900	1,100
WOS55	2042455	11/7/97	1015	–	2.55	.325	13	13	630	2,000	–
WOS55	2042455	11/7/97	1550	–	3.10	.363	15	15	810	–	–
WOS55	2042455	11/8/97	1030	–	3.41	.418	15	16	670	2,100	–
WOS55	2042455	11/8/97	1510	–	3.21	.478	–	–	–	–	–
WOS55	2042455	11/9/97	1100	–	2.88	.358	13	13	730	2,400	1,200
WOS55	2042455	11/10/97	1445	–	2.76	.317	12	12	720	–	–
WOS55	2042455	11/12/97	1500	–	2.09	.273	11	11	710	–	–
WOS55	2042455	1/15/98	830	–	1.14	.257	8.0	8.7	410	1,600	610
WOS55	2042455	4/16/98	745	–	2.08	.439	10	9.8	–	–	–
WOS55	2042455	7/16/98	745	–	1.44	.330	–	–	–	–	–
CRS01	2042460	8/22/95	1730	.016	–	.308	9.3	–	620	–	–
CRS01	2042460	3/13/96	1315	–	–	.151	4.9	–	310	690	–
CRS01	2042460	12/10/96	1650	–	–	.127	4.1	4.1	240	–	–
CRS01	2042460	2/12/97	1445	–	–	.113	–	–	–	–	–
CRS01	2042460	5/30/97	815	–	–	.481	–	–	–	–	–

Appendix 1. Streamflow and stage and selected organic analyses of stream-water samples, Chickahominy River Basin, Virginia—Continued

[–, no data; mg/L, milligrams per liter; µg/L, micrograms per liter; Cl, chloride]

Station number	USGS identification number	Date	Time	Streamflow (cubic feet per second)	Stage (feet)	Light absorbance at 253.7 nanometers (per centimeter)	Dissolved organic carbon (mg/L)	Total organic carbon (mg/L)	Trihalomethane formation potential (µg/L)	Total organic halide formation potential (µg/L as Cl)	Haloacetic acid formation potential (µg/L)
CRS01	2042460	9/17/97	1010	–	–	.140	–	–	–	–	–
CR70	2042470	8/23/95	1430	–	–	.318	9.9	–	750	–	–
CR70	2042470	3/14/96	1215	–	–	.238	7.9	–	500	1,100	–
CR70	2042470	11/13/96	1400	–	–	.379	12	11	600	–	–
CR70	2042470	12/11/96	1115	–	–	.268	8.4	7.6	510	–	–
CR70	2042470	1/14/97	1645	–	–	.199	6.6	6.6	–	750	700
CR70	2042470	2/12/97	1515	–	–	.162	–	–	–	–	–
CR70	2042470	4/14/97	1200	–	–	.328	8.6	8.6	–	–	–
CR70	2042470	5/30/97	1020	–	–	.307	6.9	7.0	–	–	–
CR70	2042470	7/16/97	1500	–	–	.310	–	–	–	–	–
CR70	2042470	9/17/97	1100	–	–	.265	–	–	–	–	–
CR70	2042470	10/22/97	1130	–	–	.188	8.0	8.3	–	1,800	1,100
CR70	2042470	1/14/98	1530	–	–	.230	8.8	8.7	–	2,000	700
CR70	2042470	4/16/98	1330	–	–	.345	9.2	9.3	–	–	–
CR70	2042470	7/6/98	1500	–	–	.480	–	–	–	–	–
CRT06	2042475	8/23/95	1400	.023	–	.091	2.5	–	42	–	–
CRT06	2042475	3/13/96	1100	–	–	.076	2.5	–	65	720	170
CRT06	2042475	12/10/96	1625	–	–	.082	2.9	2.8	185	–	–
CRT06	2042475	2/12/97	1600	–	–	.070	–	–	–	–	–
CRT06	2042475	5/30/97	1100	–	–	.090	–	–	–	–	–
CRT06	2042475	9/17/97	1210	–	–	.050	–	–	–	–	–
TRT06	2042476	3/13/96	1215	–	–	.073	3.0	–	150	520	150
TRT06	2042476	12/10/96	1600	–	–	.096	3.1	2.9	180	–	–
TRT06	2042476	2/12/97	1540	–	–	.059	–	–	–	–	–
TRT06	2042476	5/30/97	11210	–	–	.131	4.3	4.5	240	–	–
TRT06	2042476	9/17/97	1140	–	–	.079	–	–	–	–	–
SCT01	2042478	4/20/95	1130	–	–	.391	7.3	7.9	1,000	–	1,000
SCT01	2042478	6/13/95	1000	–	–	1.070	16	21	1,200	–	1,800
SCT01	2042478	11/30/95	1000	–	1.22	.229	9.6	10	600	–	400
SCT01	2042478	1/25/96	1215	–	1.28	.243	–	8.0	–	–	–
SCT01	2042478	3/14/96	1015	–	1.14	–	5.7	–	350	1,200	420
SCT01	2042478	5/21/96	930	–	0.98	.436	12	12	–	–	–
SCT01	2042478	7/17/96	930	–	1.02	.515	10	–	–	–	–

Appendix 1. Streamflow and stage and selected organic analyses of stream-water samples, Chickahominy River Basin, Virginia—Continued

[–, no data; mg/L, milligrams per liter; µg/L, micrograms per liter; Cl, chloride]

Station number	USGS identification number	Date	Time	Streamflow (cubic feet per second)	Stage (feet)	Light absorbance at 253.7 nanometers (per centimeter)	Dissolved organic carbon (mg/L)	Total organic carbon (mg/L)	Trihalomethane formation potential (µg/L)	Total organic halide formation potential (µg/L as Cl)	Haloacetic acid formation potential (µg/L)
SCT01	2042478	8/1/96	1030	–	1.12	.443	12	13	1,100	–	580
SCT01	2042478	8/1/96	1415	–	1.16	.521	–	–	–	–	–
SCT01	2042478	8/1/96	1612	–	1.36	.418	11	–	920	2,800	–
SCT01	2042478	8/1/96	1700	–	1.36	.503	14	–	1,100	–	–
SCT01	2042478	8/2/96	1040	–	1.05	.698	13	–	830	3,100	570
SCT01	2042478	8/3/96	945	–	0.98	.560	13	–	880	3,400	580
SCT01	2042478	9/5/96	1500	–	0.84	.401	–	–	–	–	–
SCT01	2042478	9/6/96	710	–	1.68	.430	–	–	–	–	–
SCT01	2042478	9/6/96	1015	–	1.73	.415	–	–	–	–	–
SCT01	2042478	9/6/96	1620	–	1.27	.402	–	–	–	–	–
SCT01	2042478	9/8/96	1140	–	0.90	.355	–	–	–	–	–
SCT01	2042478	10/8/96	1000	–	2.58	.407	11	12	660	–	570
SCT01	2042478	10/8/96	1230	–	3.54	.410	11	12	750	–	–
SCT01	2042478	10/8/96	1610	–	3.58	.462	11	12	650	–	1,200
SCT01	2042478	10/9/96	1145	–	1.32	.465	10	11	620	–	–
SCT01	2042478	10/9/96	1630	–	1.25	.483	–	–	–	–	–
SCT01	2042478	10/10/96	1120	–	1.42	.453	–	–	–	–	–
SCT01	2042478	10/12/96	1215	–	0.98	.356	15	9.8	660	–	–
SCT01	2042478	10/14/96	915	–	0.90	.345	7.8	–	–	–	–
SCT01	2042478	10/17/96	950	–	0.83	.455	–	–	–	–	–
SCT01	2042478	11/14/96	945	–	0.87	.297	7.8	8.1	470	–	–
SCT01	2042478	12/10/96	1530	–	1.22	.188	6.0	6.2	440	–	–
SCT01	2042478	1/15/97	1145	–	1.04	.186	5.4	5.6	340	1,100	560
SCT01	2042478	2/12/97	1635	–	1.03	.148	–	–	–	–	–
SCT01	2042478	3/13/97	1705	–	1.05	.174	–	–	–	–	–
SCT01	2042478	3/14/97	1100	–	1.23	–	–	–	–	–	–
SCT01	2042478	3/14/97	1225	–	1.29	.277	–	–	–	–	–
SCT01	2042478	3/14/97	1235	–	1.29	.241	–	–	–	–	–
SCT01	2042478	3/14/97	1255	–	1.30	.292	–	–	–	–	–
SCT01	2042478	3/14/97	1455	–	1.31	.316	–	–	–	–	–
SCT01	2042478	3/14/97	1655	–	–	.306	–	–	–	–	–
SCT01	2042478	3/14/97	1855	–	1.35	.305	–	–	–	–	–
SCT01	2042478	3/14/97	2055	–	1.33	.288	–	–	–	–	–

Appendix 1. Streamflow and stage and selected organic analyses of stream-water samples, Chickahominy River Basin, Virginia—Continued

—, no data; mg/L, milligrams per liter; µg/L, micrograms per liter; Cl, chloride]

Station number	USGS identification number	Date	Time	Streamflow (cubic feet per second)	Stage (feet)	Light absorbance at 253.7 nanometers (per centimeter)	Dissolved organic carbon (mg/L)	Total organic carbon (mg/L)	Trihalomethane formation potential (µg/L)	Total organic halide formation potential (µg/L as Cl)	Haloacetic acid formation potential (µg/L)
SCT01	2042478	3/14/97	2255	–	1.29	.283	–	–	–	–	–
SCT01	2042478	3/15/97	55	–	1.27	.248	–	–	–	–	–
SCT01	2042478	3/15/97	255	–	1.25	.285	–	–	–	–	–
SCT01	2042478	3/15/97	1140	–	1.17	.232	–	–	–	–	–
SCT01	2042478	3/16/97	1610	–	–	.210	–	–	–	–	–
SCT01	2042478	4/16/97	900	–	0.93	.220	7.1	8.9	520	2,100	–
SCT01	2042478	5/30/97	1145	–	0.85	.329	7.6	8.1	470	–	–
SCT01	2042478	6/18/97	1300	–	–	.535	–	–	–	–	–
SCT01	2042478	7/16/97	1845	–	0.68	.357	–	–	–	–	–
SCT01	2042478	7/17/97	830	–	0.66	.523	–	–	–	–	–
SCT01	2042478	7/17/97	1100	–	0.64	.500	–	–	–	–	–
SCT01	2042478	7/18/97	950	–	0.65	.455	–	–	–	–	–
SCT01	2042478	7/22/97	1524	–	–	.317	–	–	–	–	–
SCT01	2042478	7/22/97	1554	–	–	.320	–	–	–	–	–
SCT01	2042478	7/22/97	1754	–	–	.400	–	–	–	–	–
SCT01	2042478	7/22/97	1814	–	–	.402	–	–	–	–	–
SCT01	2042478	7/22/97	1909	–	–	.307	–	–	–	–	–
SCT01	2042478	7/22/97	2109	–	–	.450	–	–	–	–	–
SCT01	2042478	7/22/97	2309	–	–	.365	–	–	–	–	–
SCT01	2042478	7/23/97	1500	–	0.90	.511	–	–	–	–	–
SCT01	2042478	7/24/97	903	–	–	.439	–	–	–	–	–
SCT01	2042478	7/24/97	1103	–	–	.474	–	–	–	–	–
SCT01	2042478	7/24/97	1303	–	–	.503	–	–	–	–	–
SCT01	2042478	7/24/97	1503	–	–	.486	–	–	–	–	–
SCT01	2042478	7/24/97	1703	–	–	.512	–	–	–	–	–
SCT01	2042478	7/24/97	1903	–	–	.492	–	–	–	–	–
SCT01	2042478	7/25/97	1515	–	0.91	.438	–	–	–	–	–
SCT01	2042478	8/6/97	1830	–	–	.452	–	–	–	–	–
SCT01	2042478	10/22/97	930	–	0.74	.449	15	15	400	1,800	700
SCT01	2042478	11/7/97	800	–	0.99	.364	14	14	680	2,200	–
SCT01	2042478	11/7/97	825	–	1.20	.373	–	–	–	–	–
SCT01	2042478	11/7/97	955	–	1.35	.449	–	–	–	–	–
SCT01	2042478	11/7/97	1055	–	1.49	.388	14	15	760	–	–

Appendix 1. Streamflow and stage and selected organic analyses of stream-water samples, Chickahominy River Basin, Virginia—Continued

[–, no data; mg/L, milligrams per liter; µg/L, micrograms per liter; Cl, chloride]

Station number	USGS identification number	Date	Time	Streamflow (cubic feet per second)	Stage (feet)	Light absorbance at 253.7 nanometers (per centimeter)	Dissolved organic carbon (mg/L)	Total organic carbon (mg/L)	Trihalomethane formation potential (µg/L)	Total organic halide formation potential (µg/L as Cl)	Haloacetic acid formation potential (µg/L)
SCT01	2042478	11/7/97	1155	–	1.70	.387	–	–	–	–	–
SCT01	2042478	11/7/97	1230	–	1.91	.385	–	–	–	–	–
SCT01	2042478	11/7/97	1425	–	1.89	.347	15	14	760	2,400	–
SCT01	2042478	11/7/97	1612	–	–	.370	–	–	–	–	–
SCT01	2042478	11/7/97	1812	–	–	.359	–	–	–	–	–
SCT01	2042478	11/7/97	2012	–	–	.357	–	–	–	–	–
SCT01	2042478	11/7/97	2212	–	–	.346	–	–	–	–	–
SCT01	2042478	11/8/97	12	–	–	.347	–	–	–	–	–
SCT01	2042478	11/8/97	212	–	–	.338	–	–	–	–	–
SCT01	2042478	11/8/97	1645	–	0.99	.346	–	–	–	–	–
SCT01	2042478	11/9/97	1315	–	1.13	.331	–	–	–	–	–
SCT01	2042478	11/10/97	1630	–	0.91	.291	12.	12	590	–	–
SCT01	2042478	1/15/98	950	–	1.01	.353	9.4	9.7	570	2,200	940
SCT01	2042478	4/16/98	930	–	.85	.222	8.1	7.6	–	–	–
SCT01	2042478	7/16/98	900	–	0.62	.410	–	–	–	–	–
SNC01	2042480	3/13/96	845	–	–	.204	6.2	–	450	1,200	–
SNC01	2042480	12/10/96	1510	–	–	.195	6.4	6.2	410	–	–
SNC01	2042480	2/12/97	1620	–	–	.124	–	–	–	–	–
SNC01	2042480	5/30/97	1230	–	–	.239	7.3	7.5	500	–	–
CR02	2042500	4/19/95	1330	133	3.99	.385	8.1	8.3	1,100	–	500
CR02	2042500	6/12/95	1245	72	3.10	.462	9.2	9.3	720	–	970
CR02	2042500	8/21/95	1230	2.1	1.80	.261	7.8	–	720	–	600
CR02	2042500	11/29/95	1245	87	3.32	.283	9.1	9.3	1,100	–	390
CR02	2042500	12/11/95	905	130	3.95	–	–	9.2	660	–	–
CR02	2042500	1/24/96	1200	1,420	8.78	.352	–	8.7	–	–	–
CR02	2042500	2/13/96	850	935	8.05	–	–	6.6	430	–	–
CR02	2042500	3/13/96	1300	256	5.00	.204	8.3	–	540	1,100	510
CR02	2042500	5/22/96	1200	195	4.74	.616	13	13	–	–	–
CR02	2042500	6/24/96	905	26	2.28	–	–	12	770	–	–
CR02	2042500	7/17/96	1245	321	5.72	.448	10	10	–	–	–
CR02	2042500	8/1/96	1335	161	4.15	.473	11	10	760	–	520
CR02	2042500	8/2/96	1125	242	5.02	.466	10	–	800	2,800	560
CR02	2042500	8/3/96	1005	272	5.32	.494	11	–	760	3,000	520

Appendix 1. Streamflow and stage and selected organic analyses of stream-water samples, Chickahominy River Basin, Virginia—Continued

—, no data; mg/L, milligrams per liter; µg/L, micrograms per liter; Cl, chloride]

Station number	USGS identification number	Date	Time	Streamflow (cubic feet per second)	Stage (feet)	Light absorbance at 253.7 nanometers (per centimeter)	Dissolved organic carbon (mg/L)	Total organic carbon (mg/L)	Trihalomethane formation potential (µg/L)	Total organic halide formation potential (µg/L as Cl)	Haloacetic acid formation potential (µg/L)
CR02	2042500	8/5/96	1200	326	5.75	.571	13	–	940	3,200	540
CR02	2042500	8/6/96	1025	265	5.25	.547	13	–	930	2,600	660
CR02	2042500	9/6/96	1700	78	2.99	.376	–	–	–	–	–
CR02	2042500	9/8/96	1045	147	3.98	.374	–	–	–	–	–
CR02	2042500	9/9/96	945	1,450	8.81	.361	–	–	–	–	–
CR02	2042500	9/10/96	1130	1,330	8.70	.418	–	–	–	–	–
CR02	2042500	9/12/96	1005	1,620	8.99	.512	–	–	–	–	–
CR02	2042500	9/16/96	910	711	7.47	v	–	15	1,100	–	–
CR02	2042500	9/16/96	1030	704	7.45	.734	–	–	–	–	–
CR02	2042500	10/8/96	1700	277	5.55	.325	7.8	9.2	520	–	900
CR02	2042500	10/9/96	825	545	6.94	–	–	11	690	–	–
CR02	2042500	10/10/96	1040	874	8.05	–	9.3	9.5	530	–	–
CR02	2042500	10/12/96	1125	1,380	8.77	.411	11	10	710	–	920
CR02	2042500	10/14/96	835	902	8.14	.340	8.5	8.8	570	–	–
CR02	2042500	10/17/96	850	449	6.65	.335	–	–	–	–	–
CR02	2042500	11/14/96	1045	426	6.43	.435	10	11	610	–	–
CR02	2042500	12/11/96	1215	1,290	8.69	.279	8.6	8.7	540	–	–
CR02	2042500	1/15/97	1255	346	6.03	.195	6.7	6.5	440	890	680
CR02	2042500	2/13/97	905	428	6.52	.171	–	–	–	–	–
CR02	2042500	3/13/97	1755	362	6.12	.280	–	–	–	–	–
CR02	2042500	3/14/97	1635	339	5.96	.344	–	–	–	–	–
CR02	2042500	3/15/97	1345	345	6.01	.353	–	–	–	–	–
CR02	2042500	3/16/97	1520	330	5.89	.278	–	–	–	–	–
CR02	2042500	3/17/97	912	332	5.90	–	–	7.5	530	–	–
CR02	2042500	3/18/97	1210	315	5.7	.291	–	–	–	–	–
CR02	2042500	4/16/97	1015	212	4.93	.393	9.4	9.6	670	2,300	–
CR02	2042500	5/30/97	1245	105	3.62	.348	–	–	–	–	–
CR02	2042500	7/16/97	1130	7.7	1.90	.314	–	–	–	–	–
CR02	2042500	7/17/97	1150	9.1	1.93	.311	–	–	–	–	–
CR02	2042500	7/18/97	1030	17	2.12	.316	–	–	–	–	–
CR02	2042500	7/21/97	1130	55	2.83	.313	–	–	–	–	–
CR02	2042500	7/22/97	1100	74	3.16	.229	–	–	–	–	–
CR02	2042500	7/23/97	1215	222	4.96	.201	–	–	–	–	–

Appendix 1. Streamflow and stage and selected organic analyses of stream-water samples, Chickahominy River Basin, Virginia—Continued

[–, no data; mg/L, milligrams per liter; µg/L, micrograms per liter; Cl, chloride]

Station number	USGS identification number	Date	Time	Streamflow (cubic feet per second)	Stage (feet)	Light absorbance at 253.7 nanometers (per centimeter)	Dissolved organic carbon (mg/L)	Total organic carbon (mg/L)	Trihalomethane formation potential (µg/L)	Total organic halide formation potential (µg/L as Cl)	Haloacetic acid formation potential (µg/L)
CR02	2042500	7/24/97	900	189	4.65	.276	–	–	–	–	–
CR02	2042500	7/25/97	1330	314	5.66	.300	–	–	–	–	–
CR02	2042500	7/28/97	1115	293	5.48	.411	–	–	–	–	–
CR02	2042500	7/29/97	845	268	5.31	.469	–	–	–	–	–
CR02	2042500	8/1/97	920	212	4.85	.527	–	–	–	–	–
CR02	2042500	8/4/97	1400	26	2.29	.551	–	–	–	–	–
CR02	2042500	8/5/97	1445	22	2.21	.507	–	–	–	–	–
CR02	2042500	8/6/97	1430	21	2.18	.478	–	–	–	–	660
CR02	2042500	8/12/97	945	10	1.96	.376	–	–	–	–	–
CR02	2042500	8/18/97	1055	5.2	1.89	.355	–	9.3	–	–	–
CR02	2042500	8/25/97	1330	13	2.02	.351	–	–	–	–	–
CR02	2042500	9/3/97	1130	.32	1.81	.275	–	–	–	–	–
CR02	2042500	9/9/97	840	.10	1.77	.266	–	–	–	–	–
CR02	2042500	9/11/97	1050	.10	1.77	.283	–	–	–	–	–
CR02	2042500	9/17/97	1305	.06	1.75	.245	–	–	–	–	–
CR02	2042500	10/21/97	1200	50	2.74	.210	–	–	–	–	–
CR02	2042500	11/7/97	1130	105	3.58	.179	8.2	7.6	350	2,400	–
CR02	2042500	11/8/97	1140	253	5.20	.244	11	11	450	2,100	–
CR02	2042500	11/8/97	1610	–	5.33	.293	–	–	–	–	–
CR02	2042500	11/9/97	1415	413	6.32	.309	12	13	470	–	–
CR02	2042500	11/10/97	1545	–	6.80	.298	12	13	380	–	–
CR02	2042500	11/12/97	1550	520	6.83	.249	11	11	440	2,000	1,000
CR02	2042500	11/13/97	1315	–	–	.259	–	–	–	–	–
CR02	2042500	11/18/97	1330	262	5.26	.231	10	9.9	420	1,800	1,000
CR02	2042500	11/20/97	1345	–	–	.197	–	–	–	–	–
CR02	2042500	1/16/98	1115	340	6.36	.284	9.9	9.7	490	1,800	930
CR02	2042500	2/16/98	1520	429	6.45	.242	–	–	–	–	–
CR02	2042500	2/17/98	1140	493	6.73	.252	6.6	8.0	360	1,600	–
CR02	2042500	2/17/98	1715	–	7.03	.256	–	–	–	–	–
CR02	2042500	2/18/98	1115	569	7.03	.246	7.2	7.1	430	1,600	710
CR02	2042500	2/18/98	1515	812	7.75	.273	7.6	8.2	380	1,900	–
CR02	2042500	2/19/98	1515	1,010	8.18	.285	7.5	7.4	370	2,200	–
CR02	2042500	2/20/98	1100	1,040	8.25	–	7.7	7.7	480	2,100	800

Appendix 1. Streamflow and stage and selected organic analyses of stream-water samples, Chickahominy River Basin, Virginia—Continued

[–, no data; mg/L, milligrams per liter; µg/L, micrograms per liter; Cl, chloride]

Station number	USGS identification number	Date	Time	Streamflow (cubic feet per second)	Stage (feet)	Light absorbance at 253.7 nanometers (per centimeter)	Dissolved organic carbon (mg/L)	Total organic carbon (mg/L)	Trihalomethane formation potential (µg/L)	Total organic halide formation potential (µg/L as Cl)	Haloacetic acid formation potential (µg/L)
CR02	2042500	2/21/98	900	1,330	8.69	.296	8.8	9.0	470	2,500	840
CR02	2042500	2/22/98	910	1,250	8.59	.324	9.0	9.2	520	2,900	–
CR02	2042500	2/23/98	930	1,010	8.20	.371	9.4	9.5	530	2,800	870
CR02	2042500	2/24/98	915	935	8.06	.357	9.9	8.9	530	2,600	–
CR02	2042500	2/25/98	930	902	7.98	.320	8.8	8.8	470	2,700	790
CR02	2042500	2/26/98	945	878	7.91	.314	8.7	8.7	520	2,500	–
CR02	2042500	2/27/98	845	950	8.08	.280	8.4	8.2	500	2,400	810
CR02	2042500	3/2/98	1030	718	7.50	.325	9.7	9.2	550	2,600	960
CR02	2042500	3/4/98	1100	449	6.53	.345	9.3	9.4	530	2,500	–
CR02	2042500	3/6/98	930	353	6.03	.300	9.3	9.4	510	2,600	–
CR02	2042500	3/9/98	900	771	7.62	.309	–	–	–	–	–
CR02	2042500	3/10/98	915	1,270	8.61	.327	–	7.8	150	–	–
CR02	2042500	3/11/98	945	1,350	8.71	.386	–	–	–	–	–
CR02	2042500	3/12/98	850	1,570	8.93	.326	–	–	–	–	–
CR02	2042500	3/13/98	800	1,590	8.96	.360	–	–	–	–	–
CR02	2042500	4/16/98	1015	353	6.04	.450	11	11	–	–	–
CR02	2042500	7/16/98	1000	237	5.93	.388	–	–	–	–	–
DCR03	2042726	4/20/95	1330	1.9	–	.246	6.3	–	950	–	560
DCR03	2042726	6/13/95	1215	10	–	.837	8.8	8.9	760	–	1,200
DCR03	2042726	8/22/95	1100	2.7	–	.345	10	10	850	–	710
DCR03	2042726	11/30/95	1200	4.3	3.22	.204	6.5	6.7	470	–	360
DCR03	2042726	1/14/96	850	–	3.78	.305	–	–	–	–	–
DCR03	2042726	1/25/96	845	8.6	3.30	.189	–	6.2	–	–	–
DCR03	2042726	3/14/96	1145	4.9	3.04	–	–	–	–	790	–
DCR03	2042726	5/21/96	1100	4.2	3.06	.645	10	11	–	–	–
DCR03	2042726	7/17/96	1100	12	3.67	.553	13	14	–	–	–
DCR03	2042726	8/1/96	1200	–	3.48	.321	9.3	9.9	760	–	530
DCR03	2042726	8/2/96	1215	–	3.68	.372	–	–	–	–	–
DCR03	2042726	8/3/96	1105	–	3.44	.421	11	–	890	2,800	540
DCR03	2042726	9/6/96	835	–	3.84	–	–	–	–	–	–
DCR03	2042726	9/6/96	1230	–	3.95	.381	–	–	–	–	–
DCR03	2042726	9/7/96	1040	–	3.93	.355	–	–	–	–	–
DCR03	2042726	9/8/96	915	–	3.64	.371	–	–	–	–	–

Appendix 1. Streamflow and stage and selected organic analyses of stream-water samples, Chickahominy River Basin, Virginia—Continued

[–, no data; mg/L, milligrams per liter; µg/L, micrograms per liter; Cl, chloride]

Station number	USGS identification number	Date	Time	Streamflow (cubic feet per second)	Stage (feet)	Light absorbance at 253.7 nanometers (per centimeter)	Dissolved organic carbon (mg/L)	Total organic carbon (mg/L)	Trihalomethane formation potential (µg/L)	Total organic halide formation potential (µg/L as Cl)	Haloacetic acid formation potential (µg/L)
DCR03	2042726	10/8/96	1130	–	4.28	.167	5.8	5.8	390	–	374
DCR03	2042726	10/8/96	1805	–	6.04	.268	6.9	7.1	450	–	500
DCR03	2042726	10/9/96	930	–	4.24	.406	9.0	9.1	550	–	–
DCR03	2042726	10/9/96	1315	–	4.72	.481	8.4	9.3	500	–	920
DCR03	2042726	10/12/96	940	–	3.78	.305	8.5	8.9	570	–	–
DCR03	2042726	11/14/96	1215	–	3.82	.166	5.1	5.6	370	–	–
DCR03	2042726	1/15/97	1445	–	3.81	.127	4.9	4.4	310	720	420
DCR03	2042726	2/13/97	1015	–	3.74	.124	–	–	–	–	–
DCR03	2042726	4/16/97	1230	–	3.66	.200	6.1	7.0	510	2,500	–
DCR03	2042726	5/30/97	1345	–	3.43	.333	–	–	–	–	–
DCR03	2042726	7/17/97	1000	7.8	3.50	.394	–	–	–	–	–
DCR03	2042726	9/10/97	1130	–	3.63	.227	–	–	–	–	–
DCR03	2042726	9/10/97	1335	–	–	.170	–	–	–	–	–
DCR03	2042726	9/17/97	1635	–	3.66	.180	–	–	–	–	–
DCR03	2042726	10/22/97	1100	–	3.76	.261	–	–	–	–	–
DCR03	2042726	1/15/98	1120	–	3.67	.231	6.6	6.6	360	1,300	720
DCR03	2042726	2/16/98	1645	–	3.66	.154	–	–	–	–	–
DCR03	2042726	2/17/98	940	–	3.91	.145	–	–	–	–	–
DCR03	2042726	2/17/98	1430	–	4.16	.175	–	–	–	–	–
DCR03	2042726	2/17/98	1755	–	4.38	.196	5.9	5.5	340	1,800	–
DCR03	2042726	2/18/98	1000	–	4.10	.268	6.1	5.7	320	1,300	–
DCR03	2042726	2/18/98	1400	–	4.02	.212	5.8	5.8	320	1,500	–
DCR03	2042726	2/18/98	1405	–	4.02	.212	5.6	5.6	310	1,600	–
DCR03	2042726	2/19/98	1340	–	3.80	.204	5.8	6.7	350	1,600	–
DCR03	2042726	2/20/98	1300	–	3.72	.181	–	–	–	–	–
DCR03	2042726	4/16/98	1130	–	3.64	.302	7.1	6.8	–	–	–
DCR03	2042726	7/16/98	1745	–	3.39	.389	–	–	–	–	–

Speiran—Dissolved Organic Carbon and Disinfection By-Product Precursors in Waters of the Chickahominy River Basin, Virginia,
and Implications for Public Supply—WRIR 00-4175