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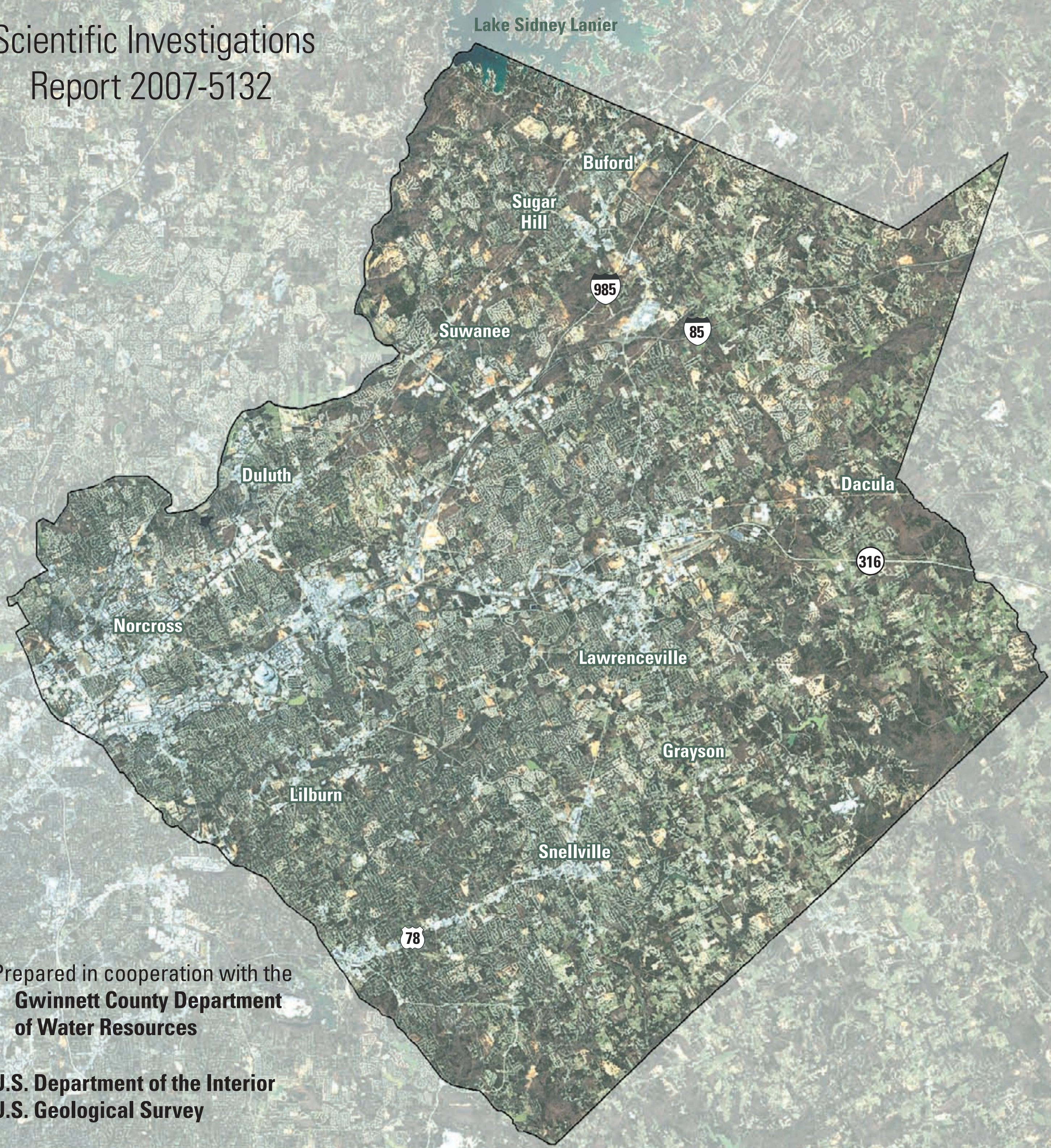
# Watershed Effects on Streamflow Quantity and Quality in Six Watersheds of Gwinnett County, Georgia

Scientific Investigations Report 2007-5132




Prepared in cooperation with the
**Gwinnett County Department of Water Resources**

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

*Cover image:* Landsat Thematic Mapper imagery taken March 3, 2001

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## Figures—continued

## Tables

# Conversion Factors and Datums

| Multiply | By | To obtain |
|---|---|---|
| | Length | |
| inch | 2.54 | centimeter (cm) |
| foot (ft) | 0.3048 | meter (m) |
| mile (mi) | 1.609 | kilometer (km) |
| | Area | |
| square mile ($mi^2$) | 2.590 | square kilometer ($km^2$) |
| acre | 4,047 | square meter |
| | Volume | |
| million gallons (Mgal) | 3,785 | cubic meter ($m^3$) |
| | Flow/Transport Rate | |
| cubic foot per second | 0.02832 | cubic meter per second |
| million gallons per day (Mgal/d) | 0.04381 | cubic meter per second ($m^3/s$) |
| pound per acre | 1.121 | kilogram per hectare |
| | Mass | |
| pound | 0.4536 | kilogram (kg) |

Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as follows:

$$°F = (1.8 \times °C) + 32$$

Temperature in degrees Fahrenheit (°F) may be converted to degrees Celsius (°C) as follows:

$$°C = (°F - 32) / 1.8$$

Vertical coordinate information is referenced to the North American Vertical Datum of 1988 (NAVD 88). Historical data collected and stored as National Geodetic Vertical Datum of 1929 have been converted to NAVD 88 for this publication.

Horizontal coordinate information is referenced to the North American Datum of 1983 (NAD 83). Historical data collected and stored as North American Datum 1927 have been converted to NAD 83 for this publication.

Altitude, as used in this report, refers to distance above the vertical datum.

# Watershed Effects on Streamflow Quantity and Quality in Six Watersheds of Gwinnett County, Georgia

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## Abstract

Watershed management is critical for the protection and enhancement of streams that provide multiple benefits for Gwinnett County, Georgia, and downstream communities. Successful watershed management requires an understanding of how stream quality is affected by watershed characteristics. The influence of watershed characteristics on stream quality is complex, particularly for the nonpoint sources of pollutants that affect urban watersheds.

The U.S. Geological Survey (USGS), in cooperation with Gwinnett County Department of Water Resources (formerly known as Public Utilities), established a water-quality monitoring program during late 1996 to collect comprehensive, consistent, high-quality data for use by watershed managers. Between 1996 and 2003, more than 10,000 analyses were made for more than 430 water-quality samples. Continuous-flow and water-quality data have been collected since 1998. Loads have been computed for selected constituents from 1998 to 2003.

Changing stream hydrology is a primary driver for many other water-quality and aquatic habitat effects. Primary factors affecting stream hydrology (after watershed size and climate) within Gwinnett County are watershed slope and land uses. For the six study watersheds in Gwinnett County, watershed-wide imperviousness up to 12 percent does not have a well-defined influence on stream hydrology, whereas two watersheds with 21- and 35-percent impervious area are clearly impacted. In the stream corridor, however, imperviousness from 1.6 to 4.4 percent appears to affect baseflow and stormflow for all six watersheds.

Relations of concentrations to discharge are used to develop regression models to compute constituent loads using the USGS LOAD ESTimator model. A unique method developed in this study is used to calibrate the model using separate baseflow and stormflow sample datasets. The method reduced model error and provided estimates of the load associated with the baseflow and stormflow parts of the hydrograph.

Annual load of total suspended sediment is a performance criterion in Gwinnett County's Watershed Protection Plan. Median concentrations of total suspended solids in stormflow range from 30 to 180 times greater than in baseflow. This increase in total suspended solids concentration with increasing discharge has a multiplied effect on total suspended solids load, 97 to 99 percent of which is transported during stormflow. Annual total suspended solids load is highly dependent on annual precipitation; between 1998 and 2003 load for the wettest year was up to 28 times greater than for the driest year. Average annual total suspended solids yield from 1998–2003 in the six watersheds increased with high-density and transportation/utility land uses, and generally decreased with low-density residential, estate/park, and undeveloped land uses.

Watershed characteristics also were related to annual loads of total phosphorus, dissolved phosphorus, total nitrogen, total dissolved solids, biochemical oxygen demand, and total zinc, as well as stream alkalinity.

Flow-adjusted total suspended solids, total phosphorus, and total zinc stormflow concentrations between 1996 and 2003 have a seasonal pattern in five of the six watersheds. Flow-adjusted concentrations typically peak during late summer, between July and August. The seasonal pattern is stronger for more developed watersheds and may be related to seasonal land-disturbance activities and/or to seasonal rainfall intensity, both of which increase in summer. Adjusting for seasonality in the computation of constituent load caused the standard error of annual total suspended solids load to improve by an average of 11 percent, and increased computed summer total suspended solids loads by an average of 45 percent and decreased winter total suspended solids loads by an average of 40 percent. Total annual loads changed by less than 5 percent on the average.

Graphical and statistical analyses do not indicate a time trend from 1996 to 2003 in flow- and seasonally adjusted stormflow concentrations of total suspended solids, total phosphorus, total zinc, or total dissolved solids for the sampled streams in the six watersheds studied. The absence of a trend, when land use was changing rapidly, may reflect the time lag of impacts, natural variability, and/or watershed management practices.

# Introduction

The streams of Gwinnett County, Georgia, provide multiple benefits—including water supply for use in homes, businesses, and industries; habitat for aquatic and riparian species; recreation; floodwater drainage and associated public safety; wastewater dilution and conveyance; and riparian property values. Watershed management is critical to protect and enhance these benefits for Gwinnett County and downstream communities. Successful watershed management requires an understanding of how stream quality is affected by watershed characteristics. Stream health, however—like that of an organism—is very complex. Stream quality is affected by both natural and human-influenced (cultural) factors that interact and operate at different time scales. This complexity is high for the diffuse, nonpoint sources of pollutants that affect urban watersheds, making informed watershed management decisions difficult. Consistent, long-term, accurate monitoring data can be used to describe the status and trends in stream quality. Interpretation of these data describe how stream quality is affected by natural factors (such as precipitation) and cultural factors (such as impervious area), and provide information that is essential for successful watershed management.

In recent years, watershed management has become more coordinated in Gwinnett County and in the greater Metropolitan Atlanta area, as summarized in the Gwinnett County Watershed Protection Plan (Gwinnett County Department of Public Utilities, 2000), and in the Metropolitan North Georgia Water Planning District, Watershed Management Plan (MNGWPD WMP) (2003). More complete and long-term data, as collected in this study, are needed to evaluate the effectiveness of watershed protection plans and to calibrate and verify the processes and models that plans such as these rely on. Successful watershed management is designed to adapt as additional information is collected. As stated in the MNGWPD WMP (2003):

> "The model allows updates for land cover, water quality, and best management practice (BMP) efficiency data to refine watershed management strategies as more data become available. This approach is consistent with the adaptive management concept promoted by the EPA and the National Academy of Sciences, whereby the management approach is modified as more data become available."

The U.S. Geological Survey (USGS), in cooperation with Gwinnett County Department of Water Resources (formerly known as Public Utilities), established a water-quality monitoring program during late 1996 to collect comprehensive, consistent, high-quality data. Water-quality sample collection began during 1996, and by 1998, six watersheds were being monitored continuously for streamflow, precipitation, temperature, specific conductance, and turbidity, with hydrograph-based sampling of three storm events and three baseflow periods every 6 months (fig. 1, table 1). Monitoring of six additional watersheds began during 2002. This report describes data collected from the first six watersheds, including water-quality sample data from 1996 to 2003 and loads computed for the 6-year period from 1998 to 2003. The hydrologic and water-quality data are supplemented by detailed watershed characteristic data that allow more detailed evaluation of nonpoint-source effects on water quality. The information provided herein is strategic to meet the needs of watershed managers as watershed protection plans are implemented and as the Metropolitan Atlanta area continues to grow.

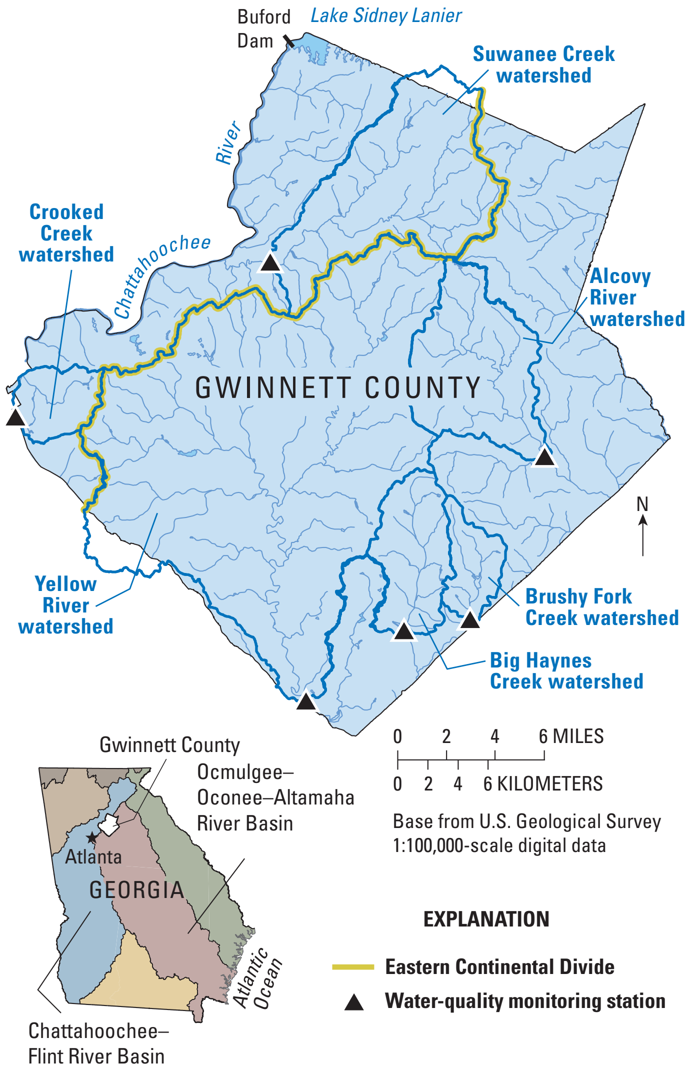



**Figure 1.** Location of study area, watershed boundaries, and monitoring stations in Gwinnett County, Georgia.

The overall purpose of USGS water-quality monitoring in Gwinnett County is to provide a long-term record of comprehensive and consistent hydrologic and water-quality data that can be used by county and State watershed managers and engineers to protect and enhance the streams in the county. This water-quality monitoring program provides comprehensive measurements of stream hydrology and constituent concentrations and loads. The methods used follow USGS protocols and quality-assurance procedures and are consistent between watersheds and over time.

**Table 1.** Water-quality monitoring stations, Gwinnett County, Georgia.

[USGS, U.S. Geological Survey; $mi^2$, square mile; Ga., Georgia]

| USGS station number | Station name | Data established | Drainange area ($mi^2$) |
|---|---|---|---|
| 02207400 | Brushy Fork Creek at Beaver Road near Loganville, Ga. | June 1996 | 8.15 |
| 02208150 | Alcovy River at New Hope Road near Grayson, Ga. | June 1997 | 30.8 |
| 02207385 | Big Haynes Creek at Lenora Road near Snellville, Ga. | June 1996 | 17.3 |
| 02334885 | Suwanee Creek at Buford Highway near Suwanee, Ga. | September 1996 | 47 |
| 02207120 | Yellow River at State Route 124 near Lithonia, Ga. | April 1996 | 162 |
| 02335350 | Crooked Creek at Spalding Drive near Norcross, Ga. | March 1996 | 8.89 |

Specific goals of the long-term monitoring program include:

- Monitoring water-quantity and water-quality status,
- Monitoring long-term and seasonal water-quantity and water-quality trends,
- Providing flood warning data for emergency managers,
- Providing data to water managers to evaluate and meet regulatory monitoring requirements of permits for water-supply withdrawals, wastewater discharges, stormwater, source-water watersheds, and total maximum daily load studies, and
- Providing data for computation of constituent loads.
- Providing constituent loads for calibration and verification of models used in watershed management,
- Educating the public about watersheds and water quality, and
- Providing data that support studies of stream habitat, biology, and geomorphology.

Results of this study are of particular interest to the USGS as they apply to flood warning, streamflow during droughts, and watershed effects on water quantity and water quality in urban watersheds throughout the United States.

## Purpose and Scope

This report describes and summarizes methods, data, and findings from the subject investigation. The major subjects within the scope of the report include monitoring methods, watershed characteristics, watershed effects on hydrology, water-quality concentrations and loads, trends in water quality, and watershed effects on water quality. The report describes methods and summarizes data within the sections for each major subject in an effort to improve coherence.

Specific goals of this report include:

- Reporting hydrologic, water-quality, and watershed data through 2003,
- Providing computed constituent loads through 2003,
- Describing how water quality is affected by natural (such as precipitation) and cultural (such as impervious surfaces) watershed characteristics,
- Describing long-term, overall effectiveness of watershed management practices on streamflow and water quality,

## Monitoring Plan and Methods

The watershed monitoring network described herein includes six watersheds in Gwinnett County (fig. 1 and table 1) selected on the basis of size, land use, parent basin, location within the county, stage-discharge controls, and suitability for instrumentation and measurement. Discrete water-quality sampling began at the six watersheds during 1996. Construction of stream monitoring stations and definition of stage-discharge relations were not completed until the beginning of the 1998 water year. (A water year is from October 1 to September 30 and is identified by the calendar year in which it ends.) Thus, summaries of water-quality sample data in this report are for the period from 1996 to 2003, whereas summaries of streamflow and constituents loads are for water years 1998–2003. A map description of the current monitoring network and links to real-time data and the database may be found at the project Web page: *ga2.er.usgs.gov/urban/gwinnett/*. The real-time data are valuable for flood-warning and emergency management, recreational use of the streams, identification of pollution issues as they occur, and water-quality sampling logistics.

## Continuous Monitoring of Streamflow and Water Quality

Stream monitoring stations, such as the one shown in figure 2, were constructed to monitor stream stage, streamflow, precipitation, water temperature, specific conductance, and turbidity continuously. Changes in these parameters are shown in figure 3 for a storm that occurred in the Yellow River watershed. Streamflow characteristics are a primary driver of nonpoint-source-associated water quality (Hirsch and others, 2006) and are the most important property affecting water quality in the streams of this study. Continuous streamflow data also are critical to compute constituent loads. Stream stage (or gage height) is measured to the nearest 0.01 foot every 15 minutes using an air bubbler system. Discharge measurements are routinely made to define and verify a stage to discharge relation at each site, so that stage and discharge are known continuously. The bubbler gage also is verified against an outside reference gage routinely (at least every 6 weeks), and levels are run periodically from established reference points to verify gage datums. Discharge for periods of missing or unreliable stage data were estimated using hydrographic comparisons with nearby basins having similar characteristics (Rantz, 1982b). Precipitation is measured using a calibrated tipping bucket rain gage that records every 15 minutes. Methods of monitoring precipitation and stream stage and of computing streamflow are further described in Rantz (1982a, b) and in the Surface-Water Quality-Assurance Plan of the USGS Georgia Water Science Center (Gotvald and Stamey, 2005).

**Figure 2.** Water-quality monitoring station at Crooked Creek at Spalding Drive near Norcross, Georgia. Photograph by Paul D. Ankcorn, U.S. Geological Survey.

Water-quality meters are deployed in the stream to measure water temperature, specific conductance, and turbidity continuously. Specific conductance is directly related to the total dissolved solids in water. Turbidity provides an indicator of the total suspended solids in water. Turbidity to suspended solids concentration relations, however, may be unreliable because turbidity readings vary with suspended solids size, gradation, and color, as well as concentration (Gray and Glysson, 2003). These water-quality properties are measured and recorded every 15 minutes. The water-quality meters are cleaned and calibrations checked at least every 4 weeks following the quality-assurance procedures described in Wagner and others (2000) and in the project quality-assurance plan (unpublished).

## Discrete Water-Quality Sampling

Assessment of nonpoint-source pollution requires water-quality sampling during rainfall runoff because the physical and chemical characteristics of water are different between baseflow and stormflow, as indicated in figures 3 and 4, and as discussed later in this report. The primary water-quality challenges for the study area are associated with nonpoint-source pollutants that enter the stream primarily during rainfall runoff; although baseflow also may be affected in the study area. It is essential to collect samples during storms to characterize nonpoint-source pollution in stormflow. Sampling of stormflow is logistically difficult, however, particularly for smaller watersheds with stormflow hydrographs from less than 1 to 24 hours. To improve the ability to collect discrete samples during rainfall runoff, pumping point samplers were installed at all monitoring stations for this study.

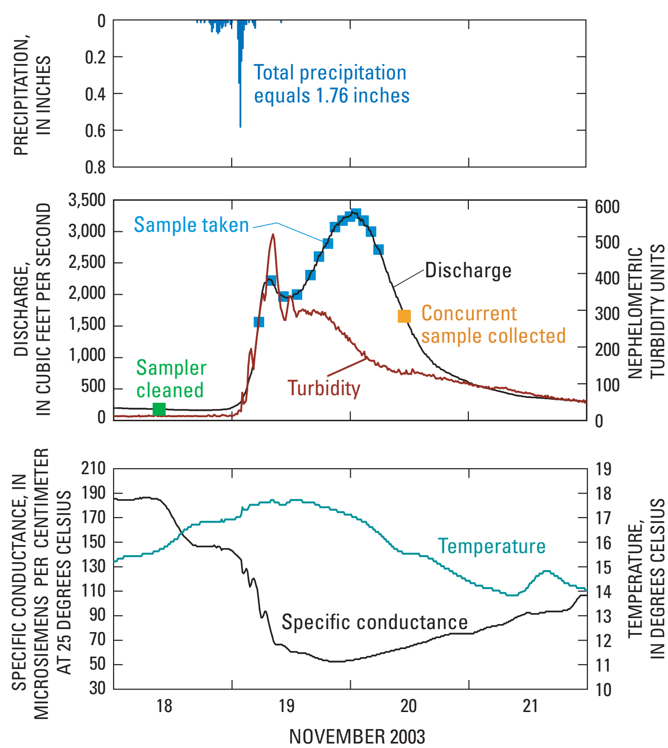



**Figure 3.** Precipitation, discharge, turbidity, sampler operation, specific conductance, and temperature in 15-minute intervals for storm of November 18–21, 2003, for Yellow River at Georgia State Highway 124 near Lithonia, Georgia.


**Figure 4.** Crooked Creek at Spalding Drive near Norcross, Georgia, during (*A*) baseflow and (*B*) stormflow conditions. Photographs by Paul D. Ankcorn, U.S. Geological Survey.

Storm composite water-quality samples were collected with in situ “automatic” point samplers, which are cleaned and prepared prior to each sampled storm. The sampler is programmed to begin sampling based on precipitation and/or stream stage thresholds and to collect subsamples each time a specified volume of water flows by the station at variable time intervals, as indicated in figure 3. The programmed volume at which subsamples are taken is set depending on the anticipated magnitude of the incoming storm. This method of sampling provides a composite sample of the storm that is discharge-weighted, and accounts for pollutant concentration differences throughout the storm hydrograph. All storm samples were collected in accordance with the applicable stormwater permit for Gwinnett County (Atlanta Regional Commission, 2000), which states that representative wet-weather events require a minimum precipitation of 0.3 inches. Additionally, a minimum time of 72 hours is required between each wet-weather event to ensure that the events are discrete and that the measured water-quality properties are associated with the sampled event. The samples are refrigerated at about 4 degrees Celsius until sample removal and processing. Sampler cleaning and maintenance procedures are followed as described in the project quality-assurance plan (unpublished).

Baseflow samples were collected with a USGS DH-81 manual sampler using depth and width integrating techniques (fig. 5) as outlined in the National Field Manual for the Collection of Water-Quality Data (Wilde and others, 1998). Baseflow samples were collected after no more than 0.1 inch of precipitation had fallen during the previous 72 hours. Baseflow and stormflow samples were processed and preserved following USGS field methods (Wilde and others, 1998), and analyzed in USGS laboratories in Lakewood, Colorado; Ocala, Florida; and Atlanta, Georgia.

**Figure 5.** Collecting a baseflow stream sample from Yellow River near Lithonia, Georgia. Photograph by Paul D. Ankcorn, U.S. Geological Survey.

## Properties Analyzed

During sample collection, standard field properties are measured including pH, turbidity, specific conductance, water temperature, and dissolved oxygen. At USGS laboratories, water samples are analyzed for the following properties: biological oxygen demand, chemical oxygen demand, total suspended solids, turbidity, total dissolved solids, total phosphorus, dissolved phosphorus, several nitrogen species, and hardness. Trace metals analyzed include cadmium, copper, lead, zinc, chromium, and magnesium. Trace metals were analyzed for unfiltered samples so that concentrations include the total recoverable amount including dissolved and particulate or sorbed fractions. Although filtered samples collected during 2001 and 2002 were analyzed for dissolved trace metals, those data are not included in this report. Samples collected from 1996 to 2000 were analyzed for fecal coliform, but these data also are not included in this report, except in the discussion of sediment as a water-quality indicator. Units of measurement, laboratory detection limits, and USGS parameter codes for constituents of interest are listed in table 2. Some properties have multiple detection limits because of changes in approved methods. Some samples from Big Haynes Creek and Brushy Fork Creek were analyzed for additional properties during part of the study to evaluate these source-water watersheds.

## Quality-Control Samples

The USGS develops quality-assurance and quality-control procedures to ensure that water-quality data meet standards and accurately represent stream conditions. These procedures cover all aspects of USGS work and are documented in published manuals, techniques, and quality-assurance plans (Rantz 1982a, b; Wagner and others, 2000; Wilde and others, 1998; Gotvald and Stamey, 2005). Although automatic point samplers are necessary to collect many storm samples, rigorous quality assurance is imperative to ensure collection of uncontaminated samples. Concurrent replicate and equipment-blank samples are primary quality-control measures for these samplers.

Because automatic point samplers collect samples from a single point in the stream cross section, concurrent replicate samples must be collected to ensure that the point sample is representative of the entire cross section. Concurrent samples are taken, one from the stream cross section using a USGS DH-81 sampler to collect depth integrated, equal-width-increment (EWI) samples as described in Wilde and others (1998); the second is from a point in the stream cross section using an automatic point sampler. Both sets of samples are independently processed and analyzed. Nineteen concurrent samples were evaluated for this report and results are shown in figure 6 and table 3. Not all samples were analyzed for all of the specified properties. An equal-value line is shown in figure 6 to show

**Table 2.** Water-quality constituents analyzed for samples from streams in Gwinnett County, Georgia.

[USGS, U.S. Geological Survey; $ft^3/s$, cubic feet per second; °C, degree Celsius, µS/cm, microsiemens per centimeter at 25°C; NTU, nephelometric turbidity units; mg/L, milligram per liter; <, less than; +, plus; $NO_2 + NO_3$, nitrite plus nitrate; µg/L, microgram per liter]

| Constituent group | USGS parameter code | Constituent | Measurement | Detection limit(s) |
|---|---|---|---|---|
| Physical parameters | 00065 | Gage height | Feet | |
| | 00061 | Discharge | $ft^3/s$ | |
| | 00010 | Water temperature | °C | |
| | 00095 | Specific conductance | µS/cm at 25°C | |
| | 00400 | Field pH | Standard pH units | |
| | 00076 | Turbidity | NTU | 0.05 |
| | 00530 | Suspended solids, total | mg/L | 1.0 |
| | 70300 | Dissolved solids, total | mg/L | 1.0 |
| Oxygen | 00300 | Dissolved oxygen | mg/L | 0.5 |
| | 00310 | Biochemical oxygen demand (BOD) 5-day at 20°C | mg/L | 0.1 |
| | 00340 | Chemical oxygen demand (COD) | mg/L | 5 |
| Biological | 31625 | Fecal coliform | Colonies per 100 milliliters | <1 |
| Nutrients | 00600 | Nitrogen, total | mg/L as N | Calculated |
| | 00625 | Nitrogen ammonia + organic | mg/L as N | 0.2 |
| | 00630 | $NO_2 + NO_3$, total | mg/L as N | 0.02 |
| | 00665 | Phosphorus, total | mg/L as P | 0.02 |
| | 00666 | Phosphorus, dissolved | mg/L as P | 0.02 |
| Trace metals | 01027 | Cadmium, total | µg/L as Cd | 0.5 |
| | 01034 | Chromium, total | µg/L as Cr | 1.0 |
| | 01042 | Copper. total | µg/L as Cu | 1, 2 |
| | 01045 | Iron, total | µg/L as Fe | 2 |
| | 01051 | Lead, total | µg/L as Pb | 1, 2 |
| | 01055 | Manganese, total | µg/L as Mn | 1 |
| | 01092 | Zinc, total | µg/L as Zn | 2 |
| Hardness parameters | 00916 | Calcium, total | mg/L as Ca | 0.02 |
| | 00927 | Magnesium, total | mg/L as Mg | 0.02 |

where concentrations from the concurrent samples would be equal. Of the analyses made, 79 percent of concentrations fell within 10 percent of the concurrent EWI concentrations, 97 percent were within the 25 percent band, and 3 percent exceeded 25 percent of the concurrent EWI concentrations. The number of concurrent samples that fall within the stated percentage of the equal value line are shown table 3. The three samples with differences greater than 25 percent ranged from 32 to 34 percent of the equal value line. The discrepancies generally are greater for total dissolved solids than for total suspended solids. This is unexpected because dissolved constituents generally are more well mixed in a stream than solid phase constituents; however, the cause of this result is not known. Discrepancies between concurrent samples do not have an evident trend with total suspended solids concentration or other factors.

Equipment-blank quality-control samples check for the presence of constituents arising from sampling equipment that could contaminate an environmental sample. Equipment contamination may occur due to inefficient cleaning of manual DH-81 or automatic point samplers. The results are evaluated in terms of the number and percentage of detections, the detected contamination concentration in comparison to concentration of the environmental samples (storm samples for the automatic sampler and baseflow samples for the DH-81), and whether the detections are increasing or decreasing over time.

Blank sample results (table 4) for the automatic point samplers indicate that more than 10 percent of the samples had detections for total dissolved solids and total unfiltered zinc; but the average contaminant concentration is less than 11 percent of the average storm sample concentration for both constituents. Detections have been decreasing during the project duration. After September 1999, there have been no nutrient detections, two total dissolved solids detections, two total suspended solids detections, and 10 total zinc detections.

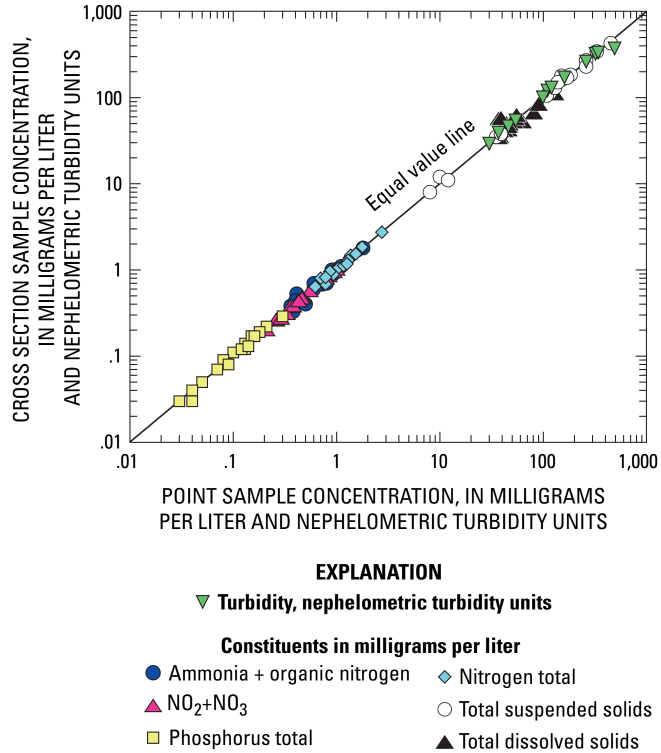



**Figure 6.** Concentrations of samples taken concurrently at point sample intake and across cross section at each of the six study watersheds in Gwinnett County, Georgia. [+, plus; $NO_2 + NO_3$ as N, nitrite plus nitrate as nitrogen]

**Table 3.** Quality-assurance sample results for concurrent point and cross-section samples for six watersheds in Gwinnett County, Georgia.

[<, less than; >, greater than; NTU, nephelometric turbidity units; +, plus; $NO_2 + NO_3$, nitrite plus nitrate]

| Parameter | Number of point samples having concentrations within stated percentage difference from the concurrent cross section sample concentration | | | Total number of samples |
|---|---|---|---|---|
| | < 10 percent | 10–25 percent | > 25 percent | |
| Total suspended solids | 15 | 3 | 0 | 18 |
| Total dissolved solids | 11 | 6 | 2 | 19 |
| Turbidity as NTU | 11 | 0 | 1 | 12 |
| Total ammonia + organic nitrogen | 13 | 5 | 0 | 18 |
| Total $NO_2+NO_3$ as nitrogen (N) | 18 | 0 | 0 | 18 |
| Total nitrogen as nitrogen (N) | 15 | 3 | 0 | 18 |
| Total phosphorus as phosphorus (P) | 12 | 4 | 1 | 17 |

Samples collected manually using the DH-81 have fewer potential sources of equipment contamination than samples collected using the automatic sampler with the pump tubing and discharge orifice. Blank sample results (table 5) for the DH-81 sampler indicate only one detection each of total suspended solids and total dissolved solids. These detections represent less than 10 percent of the blank quality-assurance samples and have concentrations at the laboratory detection limit. The contamination concentration is less than 13 and 2 percent of the average baseflow sample concentration for both total suspended solids and total dissolved solids, respectively.

## Acknowledgments

The authors wish to thank personnel of the Gwinnett County Department of Water Resources for their long-term commitment to improved data and understanding of water quality in their watersheds. This report is possible because of the field data collection efforts of the U.S. Geological Survey, Gwinnett Project personnel: Andrew Knaak, Karen Stull, Jolene Robichaux, and Don Dowling. Thanks also are extended to Bonnie J. Turcott and Caryl J. Wipperfurth of the U.S. Geological Survey for preparation of illustrations and Patricia L. Nobles of the U.S. Geological Survey for preparation of the manuscript.

**Table 4.** Quality-assurance equipment blank sample results for automatic point sampler for six watersheds in Gwinnett County, Georgia.

[mg/L, milligram per liter; <, less than; $NO_2 + NO_3$, nitrite plus nitrate; —, no data; µg/L, microgram per liter]

| Constituent | Number of blank samples | Number of detections | Range of detections | Average contamination concentration | Lab detection limits | Average of sampled storm concentrations |
|---|---|---|---|---|---|---|
| Total suspended solids | 38 | 3 | 1.0–2.0 mg/L | 1.3 mg/L | <1.0 mg/L | 370 mg/L |
| Total dissolved solids | 38 | 7 | 1.0–7.0 mg/L | 4.3 mg/L | <1.0 mg/L | 49.3 mg/L |
| Total ammonia plus organic nitrogen | 38 | 1 | 0.29 mg/L | 0.29 mg/L | <0.02 mg/L | 1.29 mg/L |
| Total $NO_2 + NO_3$ as nitrogen (N) | 37 | 0 | — | — | <0.02 mg/L | 0.63 mg/L |
| Total phosphorus as phosphorus (P) | 38 | 1 | 0.02 mg/L | 0.02 mg/L | <0.02 mg/L | 0.24 mg/L |
| Total unfiltered copper | 37 | 1 | 5.0 µg/L | 5.0 µg/L | [1]<2.0 µg/L | 7.66 µg/L |
| Total unfiltered lead | 38 | 0 | — | — | [2]<2.0 µg/L | 12.3 µg/L |
| Total unfiltered zinc | 37 | 17 | 3–17 µg/L | 5.6 µg/L | [3]<2.0 µg/L | 52.3 µg/L |

[1]Two samples had a detection limit of < 10.0 µg/L

[2]One sample had a detection limit of < 0.06, and two samples < 10.0 µg/L

[3]One sample had a detection limit of < 25 µg/L

**Table 5.** Quality-assurance equipment blank sample results for DH-81 manual sampler for six watersheds in Gwinnett County, Georgia.

[mg/L, milligram per liter; <, less than; $NO_2 + NO_3$, nitrite plus nitrate; —, no data; µg/L, microgram per liter]

| Constituent | Number of blank samples | Number of detections | Range of detections | Average contamination concentration | Lab detection limits | Average of sampled storm concentrations |
|---|---|---|---|---|---|---|
| Total suspended solids | 13 | 1 | 1.0 mg/L | 1.0 mg/L | <1.0 mg/L | 7.94 mg/L |
| Total dissolved solids | 14 | 1 | 1.0 mg/L | 1.0 mg/L | <1.0 mg/L | 63.2 mg/L |
| Total ammonia plus organic nitrogen | 14 | 0 | — | — | <0.02 mg/L | 0.31 mg/L |
| Total $NO_2 + NO_3$ as nitrogen (N) | 14 | 0 | — | — | <0.02 mg/L | 0.77 mg/L |
| Total phosphorus as phosphorus (P) | 14 | 0 | — | — | <0.02 mg/L | 0.04 mg/L |
| Total unfiltered copper | 14 | 0 | — | — | [1]<2.0 µg/L | 1.52 µg/L |
| Total unfiltered lead | 14 | 0 | — | — | [2]<2.0 µg/L | 1.51 µg/L |
| Total unfiltered zinc | 13 | 0 | — | — | [3]<2.0 µg/L | 8.33 µg/L |

[1]Two samples had a detection limit of < 10.0 µg/L

[2]One sample had a detection limit of < 0.06, and two samples < 10.0 µg/L

[3]One sample had a detection limit of < 25 µg/L

# Watershed Characteristics

Gwinnett County is in north-central Georgia in the greater Metropolitan Atlanta area (fig. 1). The county encompasses about 436 square miles in the Piedmont physiographic province.

## Location, Physiographic Setting, and Major Watersheds

The major hydrologic feature of Gwinnett County is the northeast- to southwest-trending Eastern Continental Divide (fig. 1). The divide separates the watersheds of the narrow Chattahoochee–Flint River drainage basin, which flows into the Gulf of Mexico, from headwater watersheds that flow into the Ocmulgee–Oconee–Altamaha drainage basin and into the Atlantic Ocean. The Chattahoochee River forms the northwestern boundary of the county for about 25 miles and drains about 26 percent of the county area. Buford Dam impounds Lake Sidney Lanier on the Chattahoochee River in the extreme northern corner of the county. Completed during 1957, the reservoir is the primary source of the county's water supply and a major recreation area. Suwanee Creek and Crooked Creek flow to the Chattahoochee River, whereas the Yellow River, Alcovy River, Big Haynes Creek, and Brushy Fork Creek lie within the Ocmulgee River watershed.

Altitudes range from about 720 to 1,290 feet above the North American Vertical Datum of 1988 (NAVD 88), as shown in figure 7, and are highest in the northern part of the county. Land-surface slope has an important effect on stream hydrology and water quality, as discussed later in this report. In Gwinnett County, land-surface slope ranges from zero to greater than 15 percent (fig. 8). The slope is generally higher in the northern part of the county and near large streams that have become incised in the landscape. Average watershed land-surface slope for the six monitored watersheds ranges from 5 to 11 percent; the average slope within a 100-foot buffer of the streams is steeper and ranges from 8 to 15 percent (table 1).

In Gwinnett County, stream-channel morphology has changed greatly since predevelopment times, as is characteristic of most Piedmont streams (Trimble, 1969). Poor land-use

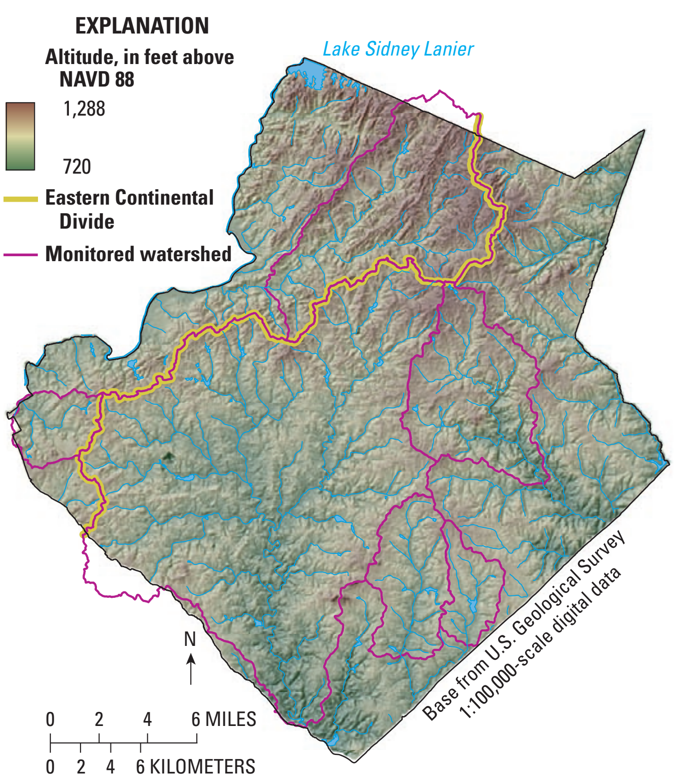



**Figure 7.** Altitude, relief, and monitored watershed boundaries for Gwinnett County, Georgia (altitude data from Gwinnett County Department of Public Utilities, 2001). See figure 1 for watershed name.

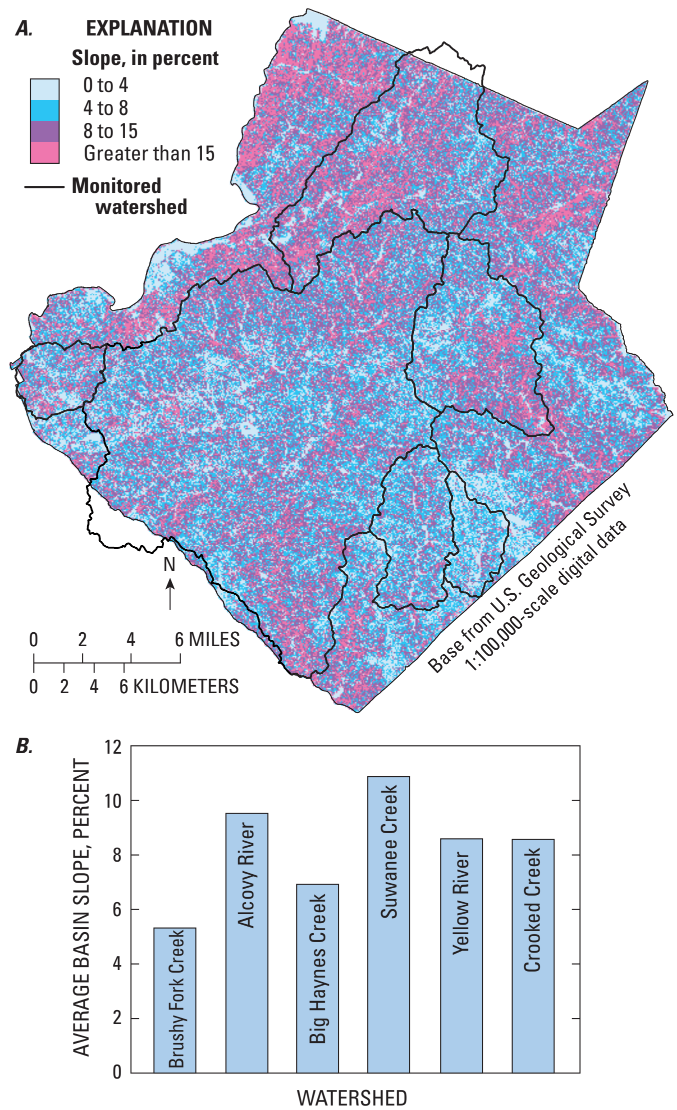



**Figure 8.** *(A)* Land surface slope and monitored watershed boundaries and *(B)* percent average basin slope for Gwinnett County, Georgia (altitude data from Gwinnett County Department of Public Utilities, 2001). See figure 1 for watershed name.

practices of clear-cut forestry followed by row-crop cultivation and then abandonment of farmland (due in part to loss of productivity), led to erosion of upland areas and sedimentation of headwater stream channels. This erosion of sediment from surrounding land areas, which typically peaked prior and up to the 1930s, led to the infilling and rise in stream channels (aggradation) and expansion of floodplains and wetland areas, rendering many bottomland areas unsuitable for agriculture (Ruhlman and Nutter, 1999; Trimble, 1969). The thickness of this deposition ranged upward to several feet in places (Trimble, 1969). Subsequent to the 1930s and largely through efforts of the Soil Conservation Service (now Natural Resources Conservation Service) to revegetate much of the Piedmont farmlands, aggradation was reduced substantially or ceased entirely in upper headwater stream reaches. This action allowed the sediment stored in these stream channels to begin to erode, causing degradation and stream entrenchment. The sediment was then redeposited farther downstream. This imbalance between sediment supply, channel capacity, and water discharge leads to channel instability that may last indefinitely (Julien, 1994; Sturm, 2001).

## Climate and Precipitation

The climate of Gwinnett County is categorized as humid subtropical, characterized by warm, humid summers and cool, wet winters. Average July high temperatures are about 88 degrees Fahrenheit (°F), and average January lows are about 32°F. Mean annual precipitation in Norcross, Georgia, is about 54 inches (fig. 9, 1949–2003, Southeast Regional Climatic Center [SERCC], accessed October 2004 at *www.ncdc.noaa.gov/oa/ncdc.html*) with most precipitation occurring December through April when mid-latitude cyclonic storms track from the north and west to bring warm, moist tropical air from the Gulf of Mexico. These storms tend to have a long duration, typically from 1 to 3 days, with an even distribution of precipitation. Consequently, the greatest ground-water recharge and subsequent contribution to streamflow occurs during the cooler months when rainfall is highest and evapotranspiration is lowest. Summer precipitation is usually from afternoon and evening thunderstorms of short duration with unevenly distributed rainfall. Although these summer storms may produce less cumulative rainfall, they may account for more erosion and wash off of constituents because of their greater intensity.

Mean annual precipitation for the period 1998–2003 is shown in figure 9*A*. This rainfall map was developed from rain gages operated by different agencies including the USGS, Gwinnett County, and the SERCC. Mean annual precipitation varies by more than 10 inches across the county for this period. Because water quality is strongly affected by hydrology, this variation is important when evaluating watershed water quality. Localized variation in annual rainfall contributes to the difficulty of regionalizing hydrologic properties and indicates the importance of monitoring. The mean annual precipitation for each watershed (taken from the map surface) is shown in figure 9*B*.

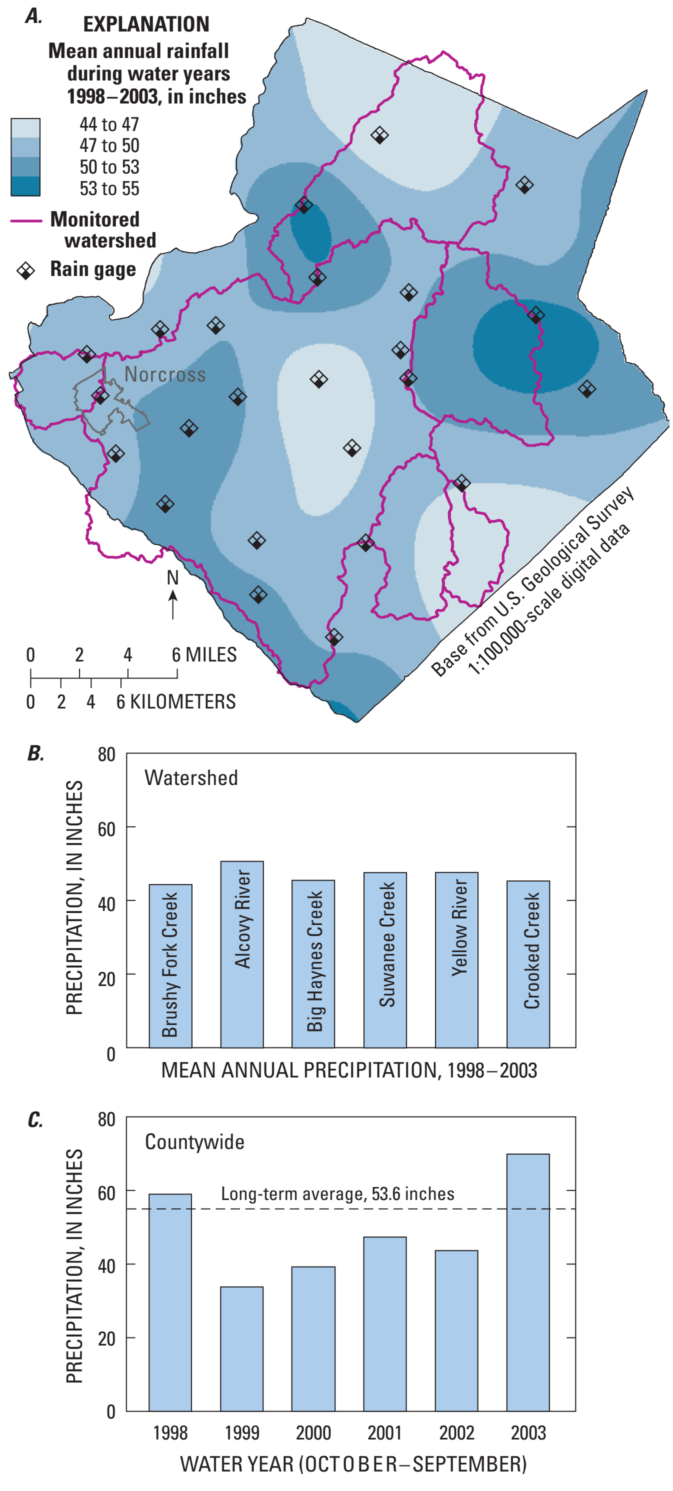



**Figure 9.** Precipitation for Gwinnett County, Georgia: *(A)* mean annual for water years 1998–2003, with precipitation gage locations and watershed boundaries, *(B)* mean annual for 1998–2003 over each watershed, and *(C)* annual mean by water year across the county and 55-year average (1949–2003) for Norcross, Georgia. See figure 1 for watershed name.

Although important, the regional variation in precipitation is much less than the year-to-year changes. Much of Georgia experienced an intense drought from late 1998 through the fall of 2002. As indicated in figure 9*C*, rainfall was well below normal throughout this period and was more than 10 inches below normal for the 1999 water year (October–September). The significant annual variation in water quality associated with annual precipitation is discussed later in this report.

## Population

Once primarily agricultural, Gwinnett County has had one of the fastest-growing populations in the United States during the last 25 years. The population of Gwinnett County grew by more than 250 percent from 1980 to 2000; the 2003 population was 673,300 (U.S. Census Bureau, accessed December 2004 at *www.census.gov*). From 1996 to 2003, the net population increase was 40 percent or 195,500 new residents (fig. 10*B*). As shown in figure 10*A*, the population density is greater in the southwestern part of the county, as well as along transportation corridors and near Lawrenceville, the county seat. Along with benefits, population growth brings challenges to increase and maintain supporting infrastructure including water supply and wastewater treatment. Watershed management becomes more challenging as land uses change from relatively undeveloped to developed uses that have a greater hydrologic and water-quality impact on streams.

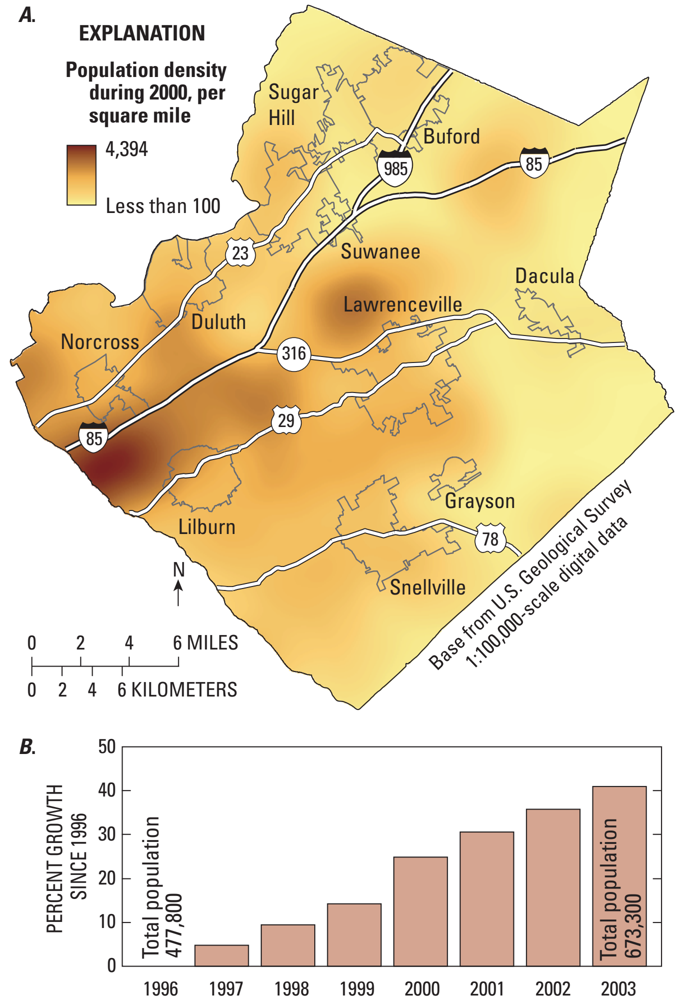



**Figure 10.** Population for Gwinnett County, Georgia, *(A)* density during 2000 and *(B)* trend from 1996 to 2003 (data accessed December 2004 at *www.census.gov*).

## Land Use and Impervious Area

Infrastructure and changes in land use to support the residents of Gwinnett County also have undergone rapid grown. Changing land use from an undeveloped to a developed condition has a large influence on hydrology and nonpoint-source pollution, which has a cascading effect on water quality. Clearing and grading land surfaces decreases rainfall transpiration, detention, and infiltration. Impervious surfaces that do not permit rainfall to soak into the soil cause large increases in rainfall runoff. These surfaces also efficiently collect nonpoint-source pollutants from automobiles, atmospheric deposition, and other sources (Novotny and Olem, 1994).

Land use during 2002 for the county and for the six study watersheds is shown in figure 11 and table 6 (Gwinnett County Department of Public Utilities, 2002). Land use in the county is broadly mixed, with residential being the largest component. Urban development is most dense in the southwestern part of the county and along major transportation corridors (fig. 11). Agricultural land use, which now accounts for only about 1 percent of the county area, peaked around 1920. Stream channels and floodplains, however, may still have large surpluses of sediment resulting from poor agricultural soil conservation practices of that period (Trimble, 1969). In developing the land use shown in figure 11 and table 6, land uses were grouped as follows. High-density land use includes commercial, industrial, construction, apartments, schools, religious, office parks, and residential with lots less than 1/3 acre. Low-density residential use includes residential lot sizes greater than or equal to 1/3 acre and less than 5 acres. Estate/park use includes residential lots greater than 5 acres, public and private parks, and agricultural land. Transportation/utilities land use includes pervious and impervious areas within the right-of-way for roads, railroads, communications, and utilities.

The distribution of land use varies widely among the six study watersheds, as shown in figure 11 and table 6 where the stations are listed in order of increasing development. For example, high-density land use makes up 8 percent of the relatively undeveloped Brushy Fork Creek watershed, whereas the highly developed Crooked Creek watershed has 53 percent high-density land use.

The land-use dataset (Gwinnett County Department of Public Utilities, 2002) provides actual measurements of transportation and building impervious area (table 6, fig. 12). Building impervious area includes rooftops and accounts for about one-third to one-fourth of the watershedwide impervious area for the six basins. Transportation impervious area includes

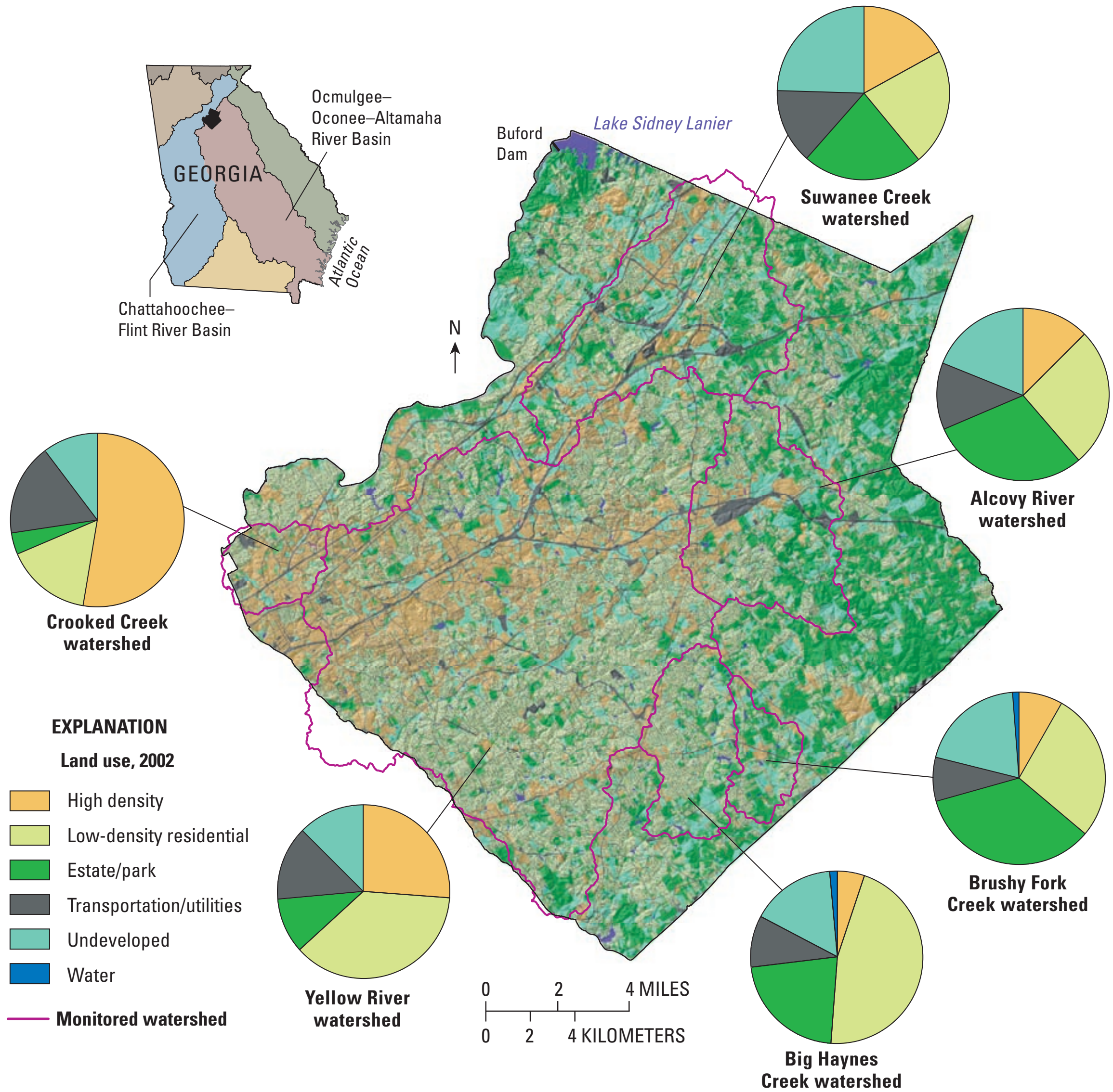



**Figure 11.** Land use for six monitored watersheds in Gwinnett County, Georgia (data from Gwinnett County Department of Public Utilities, 2002).

roadways, driveways, and sidewalks, from which drainage typically runs into constructed pathways that drain directly to streams. Transportation land use can be an important source of nonpoint-source pollution (Landers and others, 2002). In 2003, the county contained about 3,500 miles of roadway, an increase of about 550 miles since 1996 (Janet Vick, Gwinnett County Department of Water Resources, written commun., 2004).

Impervious area is a measure of nonpoint-source watershed effects that can be used across different land uses. Impervious area is a useful measure because different land uses tend to be highly correlated with each other, which complicates the evaluation of how individual land uses affect water quality. For example, total suspended solids load is positively correlated with high-density land use and with transportation-utilities land use. But the effect of either specific land use on total suspended solids is uncertain because of a potential surrogate effect from the intercorrelation of these land uses. Because of this correlation (positive and negative) between land uses, impervious area provides a valuable measure of all land-use effects.

Wastewater can be treated in public wastewater treatment facilities or using onsite septic tank treatment. Septic systems, however, are considered to return little to no water to streams, in contrast to public treatment systems. The county had about 128,200 customers on public sewer systems during 2004 and about 88,600 septic tank systems (Gwinnett County Department of Public Utilities, 2004; Metropolitan North Georgia Water Planning District, 2006). Figure 13 shows the density of septic tanks across the county and for each of the six study basins. The density of septic tanks is high where low-density residential land use is high, as can be seen by comparing figures 11 and 13. Yellow River and Big Haynes Creek have the highest septic tank density and percentage of low-residential land use, while Crooked Creek has the lowest septic tank density and the lowest low-density residential land use.

**Table 6.** Land use (2002) and watershed characteristics for six watersheds in Gwinnett County, Georgia.

(Data from Gwinnett County Department of Public Utilities, 2002)

| Station number | Watershed name | Land use, percent | | | | | | Watershed impervious area, percent | | | Stream buffer (25 foot) impervious area, percent | | | Slope, percent | | Mean precipitation, inches | Septic tank density |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | High density[1] | Low-density residential[2] | Estate/Park[3] | Transportation/utilities[4] | Undeveloped | Water | Transportation | Building | Total | Transportation | Building | Total | Average watershed | Average stream corridor | 1998–2003 | Septic tanks per square mile |
| 02207400 | Brushy Creek | 8 | 28 | 35 | 8 | 20 | 1 | 6 | 2 | 8 | 1.5 | 0.1 | 1.6 | 5 | 8 | 44.3 | 100 |
| 02208150 | Alcovy River | 12 | 26 | 29 | 13 | 19 | 1 | 8 | 3 | 11 | 2.3 | 0.5 | 2.8 | 10 | 15 | 50.6 | 79 |
| 02207385 | Big Haynes Creek | 5 | 46 | 22 | 10 | 16 | 1 | 8 | 4 | 12 | 2 | 0.2 | 2.2 | 7 | 10 | 45.4 | 224 |
| 02334885 | Suwanee Creek | 17 | 22 | 22 | 14 | 25 | 0 | 8 | 4 | 12 | 2.7 | 0.8 | 3.5 | 11 | 15 | 47.5 | 80 |
| 02207120 | Yellow River | 26 | 37 | 10 | 14 | 12 | 1 | 14 | 7 | 21 | 3.6 | 0.8 | 4.4 | 9 | 11 | 47.6 | 215 |
| 02335350 | Crooked Creek | 53 | 16 | 4 | 17 | 10 | 0 | 23 | 12 | 35 | 3.5 | 0.3 | 3.8 | 9 | 14 | 45.2 | 37 |

[1]High-density land use includes commercial, industrial, construction, apartments, schools, religious, office parks, and residential lots with less than 1/3 acre

[2]Low-density residential use includes residential lot sizes greater than or equal to 1/3 acre and less than 5 acres

[3]Estate/park use includes residential lots greater than 5 acres, public and private parks, and agricultural land

[4]Transportation/utilities land use includes pervious and impervious areas within the right-of-way for roads, railroads, commmunications, and utilities

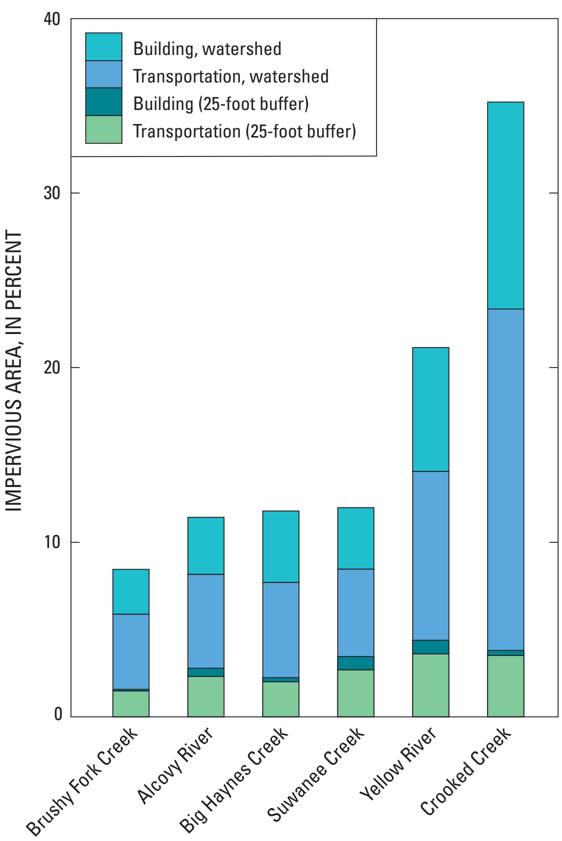
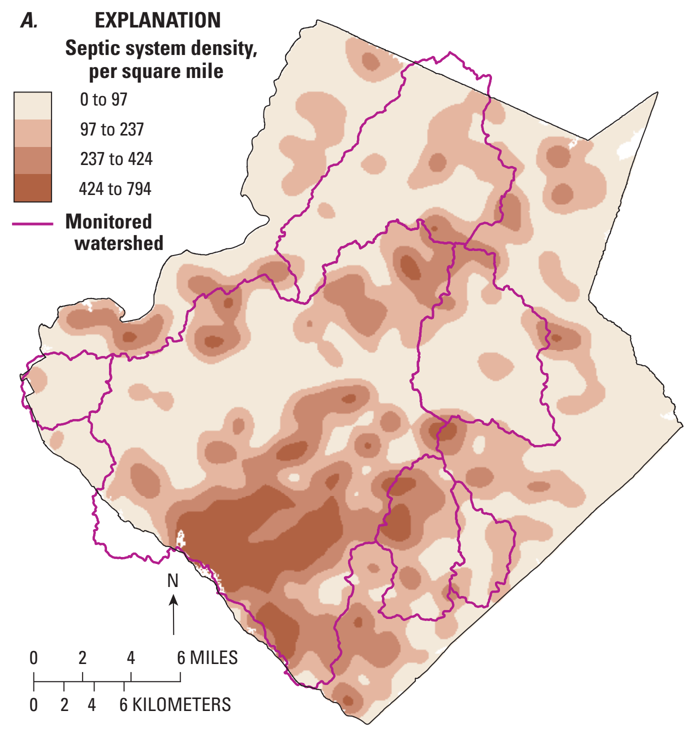



**Figure 12.** Impervious area in percent from transportation and building land cover in the stream corridor and watershedwide for six Gwinnett County, Georgia, watersheds (data from Gwinnett County Department of Public Utilities, 2001).



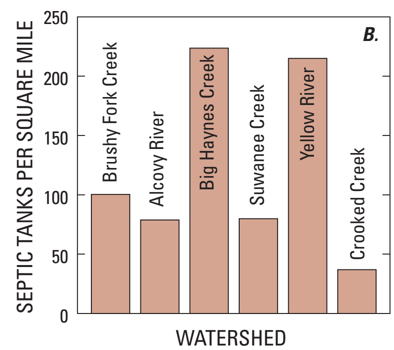




**Figure 13.** (*A*) Septic system density and monitored watershed boundaries and (*B*) septic tanks per square mile in Gwinnett County, Georgia (data from Gwinnett County Department of Public Utilities, 2003). See figure 11 for watershed name.

# Cumulative Watershed Effects on Streamflow

Changing stream hydrology is one of the earliest indicators of land-use effects in watersheds and is a driver for many other water-quality and aquatic habitat effects (Hirsch and others, 2006). Streamflow effects accumulate from several climatic and watershed characteristics including size, slope, geology, land cover, and land use. The cumulative effects of these characteristics on streamflow are interrelated and may be offsetting or synergistic.

## Effects of Altered Hydrology

Cumulative watershed effects are generated when two or more activities influence the same environmental property, transport process, or beneficial use. For the purposes of this report, a cumulative effect is any stream quality change that is influenced by a combination of land-use activities (Reid, 1993). Cumulative effects not only refer to the combined influence of multiple watershed characteristics, but also to the accumulating influence of these factors over time. For example, large streams in Gwinnett County (such as Yellow and Alcovy Rivers) may have an oversupply of sediment stored in the channel and floodplains from agricultural land uses during the early 20th century. Increased flow energy associated with urban development may erode and transport this sediment from a stream. The time scales for watersheds to obtain an equilibrium condition between sediment supply and sediment transport capacity, however, can be centuries (Knighton, 1984). Most water-quantity and nonpoint-source water-quality processes are the result of complex, interrelated, dynamic, and cumulative driving mechanisms (MacDonald, 2000).

Land-use changes in Gwinnett County during the last few decades have resulted in increased impervious surfaces and constructed drainage pathways. These changes cause rainfall to runoff faster, causing streamflow rises that are more frequent, of higher energy, and of shorter duration. The associated flood hazards are well known, and flood detention structures are standard practice in urban design. The effect of impervious area on baseflow is less documented and is due to reduced areas for infiltration and reduced time for infiltration as water is engineered to move off of upland watershed areas (Rose and Peters, 2001). For example, the baseflow component of total streamflow in Peachtree Creek in Atlanta, Georgia, has declined from about 50 to 30 percent from 1950 to 2001 (Calhoun and others, 2003).

*Effects of altered hydrology*

Decreased Baseflow

Reduced water supply in drought
Reduced habitat area
Increased sensitivity to temperature
Less available water for dilution
Reduced aquifer recharge

Increased Stormflow

Flood risk to human life
Property damage
Increased channel erosion
Habitat loss
Increased mobilization of pollutants
Large increase in constituent loads

## Methods of Hydrograph Separation

Daily streamflow hydrographs for 1998–2003 were separated into baseflow and stormflow components as shown in figure 14*A* for the 2003 water year for Suwanee Creek. Baseflow is that component of streamflow that is contributed from ground water and does not include rainfall runoff. Stormflow is predominately rainfall runoff, which mixes with baseflow. Hydrographs of daily streamflow for all six watersheds were separated using a graphical local minimum algorithm within the USGS HYSEP program (Sloto and Crouse, 1996). These daily value results also were used to classify daily flow conditions as primarily baseflow or stormflow driven in the loads analysis. Daily values were summed during each water year to determine annual baseflow and stormflow volumes.

Baseflow and stormflow volumes were converted to water yield, in inches per square inch, for comparison between watersheds and with precipitation. One inch of runoff is the volume of water required to cover the drainage area of a watershed 1 inch deep. Precipitation for each watershed was determined from a network of precipitation gages. Annual values of baseflow and stormflow yield and precipitation are shown for Suwanee Creek watershed in figure 14*B*. The drought that affected much of Georgia from late 1998 through 2002 is evident in the below-normal rainfall totals for those years in these Piedmont region streams (fig. 9). Annual baseflow contributes a higher percentage of the total annual flow during drought years such as 1999–2002 than during wet years such as 2003 (fig. 14*B*).

Average annual values of baseflow and stormflow yield and precipitation are shown for 1998–2003 for the six study watersheds in figure 14*C*. The watersheds are shown in order of increasing urbanization from left to right, with total impervious area varying from 8 to 35 percent. For the less urbanized watersheds, average baseflow yield is greater than stormflow yield, whereas for the two most urbanized watersheds, average stormflow yield exceeds baseflow yield.

The average annual baseflow and stormflow yields (1998–2003) were converted to percentage of average annual precipitation for the same period to normalize for the effects of annual and basin-to-basin precipitation differences. As noted above, climate has a dominant effect on the percentage of flow occurring as baseflow or stormflow. Normalizing for dominant hydrologic effects of watershed size (using units of yield) and precipitation differences (using percentage average annual precipitation) can reveal secondary effects from other watershed characteristics. The hydrologic differences between these six watersheds are quantified by considering anthropogenic (impervious area) and natural (watershed-slope) characteristics.

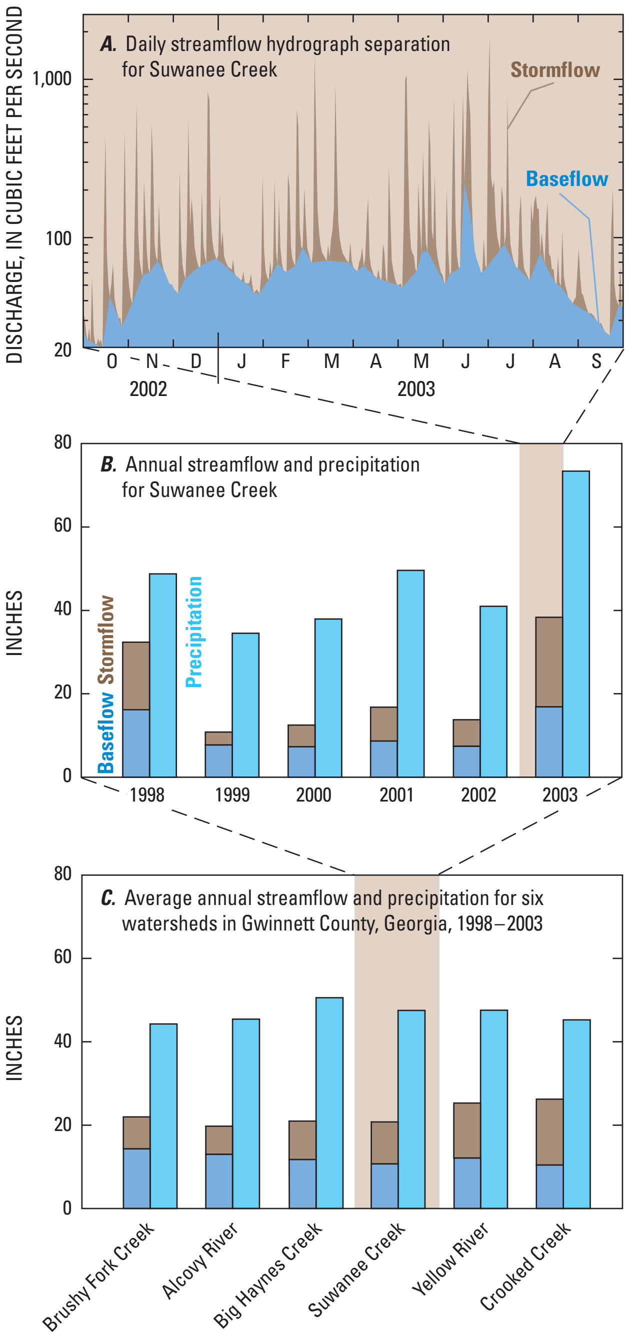



**Figure 14.** *(A)* Daily streamflow hydrograph separation for Suwanee Creek at Suwanee, Georgia, for water year 2003, *(B)* annual streamflow and precipitation for Suwanee Creek, and *(C)* average annual stormflow and precipitation for six watersheds in Gwinnett County, Georgia, 1998–2003.

## Effects of Watershed Slope and Imperviousness on Baseflow and Stormflow

Primary factors affecting hydrology (after watershed size and climate) within Gwinnett County are watershed slope and imperviousness. Baseflow yield as a percentage of precipitation is strongly influenced by the natural watershed characteristic of average slope (fig. 15); however, there is not a significant relation between stormflow yield and basin slope. Flat slopes provide opportunities for infiltration on the landscape and longer hydrograph shapes overall, resulting in increased baseflow. It is surprising that the relation, however, is this strong ($R^2=0.89$, $p<0.005$) in urban watersheds where the range of average slope is only from 5.3 to 10.9 percent. The slope in the stream corridor (buffer) may have even greater significance ($R^2=0.93$, $p<0.003$).

Stormflow yield as a percentage of precipitation increases with watershedwide imperviousness, as shown in figure 16*A*, where the relation has an $R^2$ of 0.91 and $p<0.004$; but the relation is influenced primarily by the group of four stations with

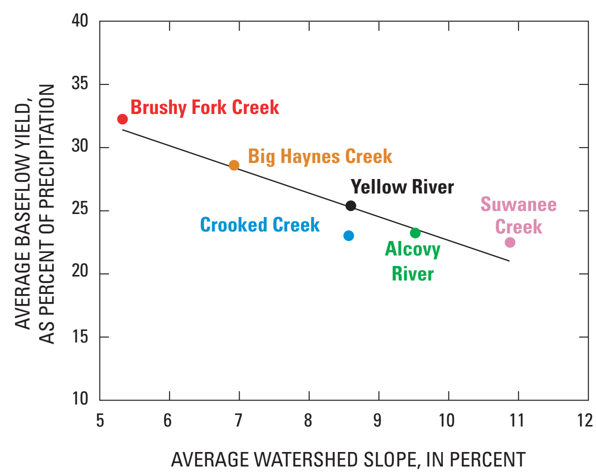



**Figure 15.** Relation between watershed slope and baseflow for six watersheds in Gwinnett County, Georgia, 1998–2003.

### *Correlation coefficients*

Correlation coefficients are a measure of the strength of association between two variables, and are meaningful when confirmed with graphical analysis. In this report, "$R$" refers to the Pearson correlation coefficient, which indicates linear correlation. "$R^2$" is the square of $R$ and also is known as the coefficient of determination. $R^2$ is used herein with least-squares regression to describe how much of the variance of the dependent variable is explained by the regression equation. Data in this study generally satisfy assumptions of normality, and thus parametric statistics are used to describe their relation.

impervious areas less than or equal to 12 percent and the two stations at 21 and 35 percent. Stormflow also increases with stream buffer imperviousness, although the linear relation is not as strong ($R^2=0.61$ and $p<0.07$) as for watershedwide imperviousness.

Baseflow yield as a percentage of precipitation is weakly defined with watershedwide imperviousness as indicated in figure 16*B*. Baseflow is influenced more strongly by imperviousness in the 25-foot stream buffer ($R^2=0.56$ and $p<0.09$). Although watershed imperviousness alone is not statistically significant in explaining baseflow, when combined with watershed slope, impervious area is statistically significant at a *p*-value of 0.005. A linear regression of baseflow as a percentage of precipitation on stream-buffer impervious area and stream-buffer slope has an $R^2$ of 0.99 and $p<0.001$.

## Thresholds of Influence of Impervious Area

The concept of a threshold of influence for impervious area can be a valuable watershed management tool. If the threshold of influence and the relative magnitude of impacts beyond the threshold are known, then watershed management may be focused accordingly. Klein (1979) reported that stream-quality impairment is first evidenced when watershed imperviousness reaches 12 percent, but does not become severe until imperviousness reaches 30 percent. Subsequent studies, however, have found lower thresholds of water-quality effects and ecological impairment. Phelps and Hoppe (2002) found 10-percent impervious area threshold for small watersheds in the highlands of New York and New Jersey. Booth and Jackson (1997) found that streams in western Washington have observable aquatic-system degradation at a "remarkably consistent" 10-percent impervious area threshold. Mallin and others (2000) found that for five estuarine watersheds of North Carolina, impairment of microbiological water quality occurs above 10-percent watershed impervious area, and highly degraded water occurs above 20-percent impervious area; while evidence of initial effects on microbiological water quality occurs in watersheds with 6.9- and 8.7-percent impervious area.

For the six study watersheds in Gwinnett County, watershedwide imperviousness up to 12 percent does not have a well-defined influence on streamflow, whereas the watersheds with 21 and 35 percent are clearly impacted (fig. 16*A*,*B*). These results agree with the general finding of the referenced previous studies regarding a threshold of influence from watershedwide impervious area of about 10 percent. In this study, however, stream corridor imperviousness from 1.6 to 4.4 percent appears to affect baseflow and stormflow for all six watersheds. The slope of the relation also is much steeper for the stream corridor than for the watershedwide imperviousness. This relation clearly implies that land uses in the stream corridor region have a greater hydrologic and, thus, water-quality influence than watershedwide land uses. As discussed previously, the apparent influence of impervious area probably is due to both its direct hydrologic effects and indirect factors of which impervious area is a surrogate.

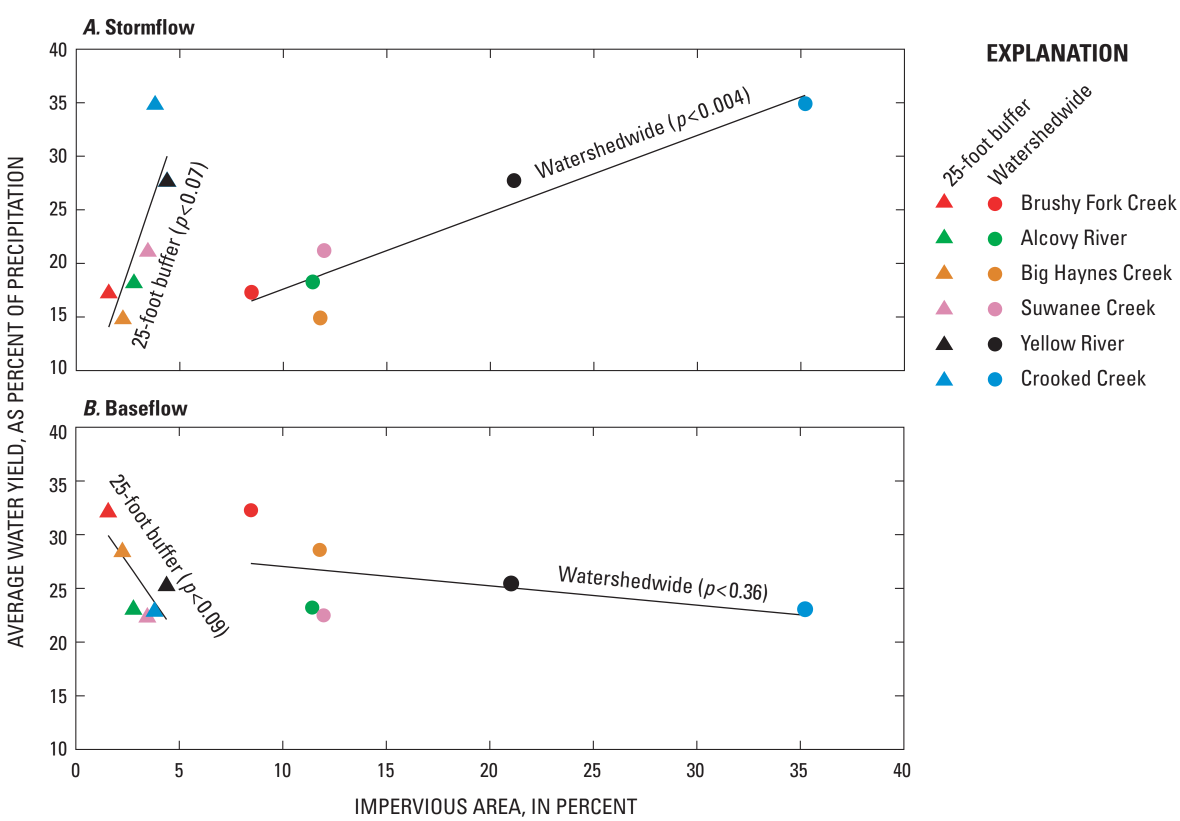



**Figure 16.** Water yield as a percent of precipitation versus impervious area watershedwide and in the 25-foot stream buffer for (*A*) stormflow and (*B*) baseflow conditions, 1998–2003. [<, less than]

# Water-Quality Concentrations and Loads

Water-quality samples were collected across a range of hydrologic conditions as described in the monitoring plan and methods section of this report. These concentration data were combined with streamflow data to compute loads for selected constituents.

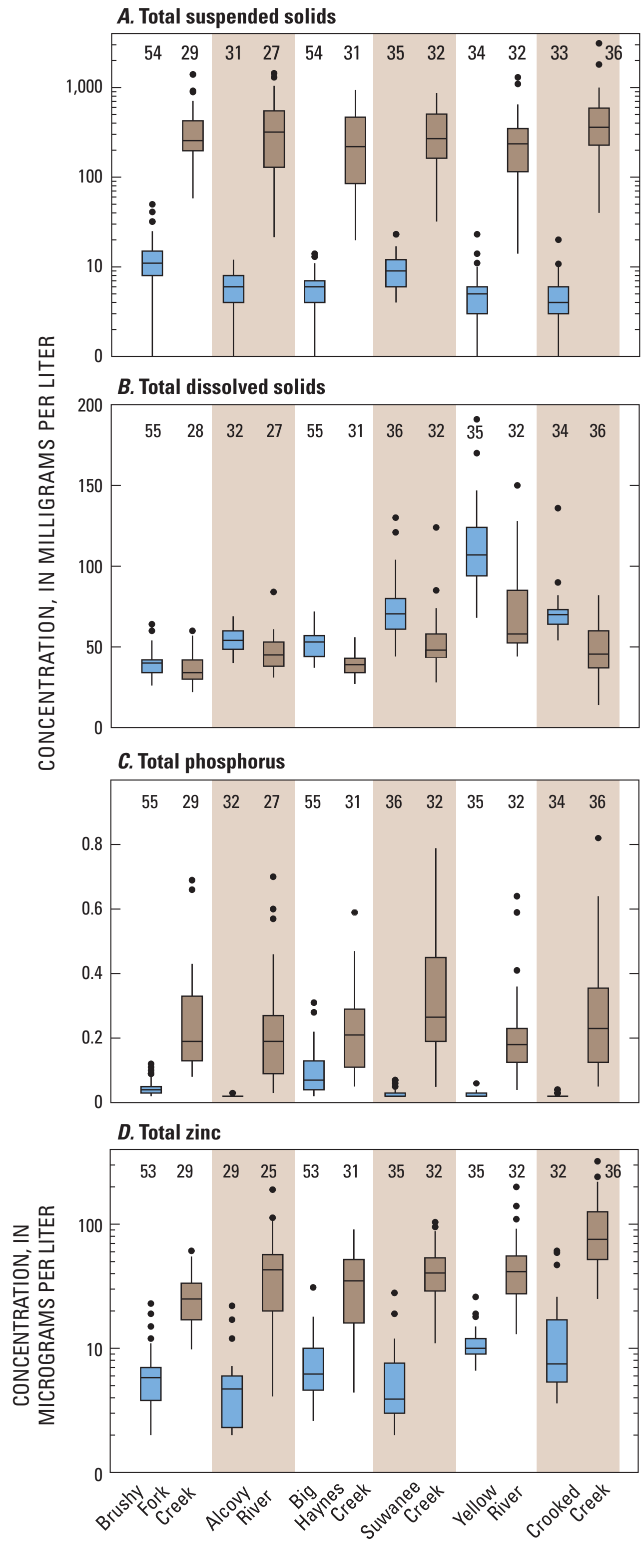
## Water-Quality Concentrations

Between 1996 and 2003, more than 10,000 analyses were conducted for more than 430 water-quality samples. Analytical results for individual samples have been provided to Gwinnett County and are available at *nwis.waterdata.usgs.gov/ga/nwis/qwdata*. Users also can access these data through the project Web site at *ga2.er.usgs.gov/urban/gwinnett,* which provides site summary pages and other supporting data. Statistical summaries of water-quality sample analytical results for each station are given in tables 7–12. These statistical summaries represent 25–36 stormflow samples and 29–55 baseflow samples collected at each site from 1996 to 2003. Quality-assurance samples are not included in these summaries.

The data distributions of baseflow and stormflow sample analyses for the six watersheds for four constituents—total suspended solids, total dissolved solids, total phosphorus, and total zinc—are illustrated in figure 17. The box plots of concentrations in figure 17 illustrate that total suspended solids, total phosphorus, and total zinc each have two unique statistical distributions with lower values for baseflow and higher values for stormflow. For example, median total suspended solids concentration of sampled storms is at least 30 times greater than for sampled baseflow conditions. Differences between sediment concentrations in baseflow and stormflow also are pictured in figure 18.

Constituent concentrations were less than laboratory reporting limits in many cases, particularly for samples collected at baseflow conditions. Mean values for sample datasets containing censored data (results below reporting limits) were computed using log-probability regression. Median values were determined using adjusted maximum likelihood estimation. These procedures are recommended and described in USGS Branch of Systems Analysis Technical Memorandum 90.1 (see also Cohn and others, 1992b; and Helsel and Hirsch, 1992). These methods are preferable to those that involve simple deletion or substitution of values (such as one-half the reporting limit), which can produce misleading results.

**Figure 18.** Sediment from stormflow into the Yellow River near Lithonia, Georgia. Photograph by Paul D. Ankcorn, U.S. Geological Survey.



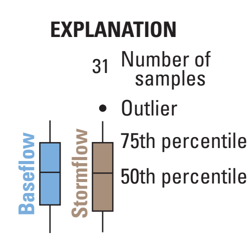




**Figure 17.** Concentration of *(A)* total suspended solids, *(B)* total dissolved solids, *(C)* total phosphorus, and *(D)* total zinc for six watersheds in Gwinnett County, Georgia, 1996–2003.

**Table 7.** Statistical summary for selected constituents, Brushy Fork Creek at Beaver Road near Loganville, Georgia, station 02207400, samples collected 1996–2003.

[%, percent of samples less than concentration; µS/cm, microsiemen per centimeter; —, no data; NTU, nephelometric turbidity unit; mg/L, milligram per liter; <, less than; +, plus; µg/L, microgram per liter]

| Constituent | Number of samples | | | Concentration[1] | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | Base-flow | Storm-flow | Below detection limit | Mean | Maximum | Minimum | 5% | 25% | 50% | 75% | 95% |
| Specific conductance (µS/cm) | 55 | 29 | — | 43 | 89 | 10 | 29 | 39 | 44 | 47 | 53 |
| pH | 54 | 28 | — | 6.4 | 8.2 | 5.4 | 5.6 | 6.1 | 6.5 | 6.7 | 7.1 |
| Turbidity (NTU) | 52 | 26 | 0 | 112 | 1,700 | 3.5 | 6.1 | 11 | 18 | 91 | 500 |
| Suspended solids, total (mg/L) | 54 | 29 | 1 | 152 | 1,400 | <1 | 4 | 10 | 15 | 230 | 860 |
| Dissolved solids, total (mg/L) | 55 | 28 | 0 | 38 | 64 | 22 | 28 | 32 | 38 | 42 | 54 |
| Biochemical oxygen demand (mg/L) | 51 | 25 | 1 | 2.1 | 7.4 | 0.1 | 0.6 | 1.0 | 1.4 | 2.9 | 5.7 |
| Chemical oxygen demand (mg/L) | 52 | 27 | 20 | 12 | 42 | 5 | 3 | 6 | 9 | 17 | 28 |
| Nitrogen, total (mg/L) | 55 | 28 | 0 | 1.04 | 3.50 | 0.26 | 0.46 | 0.60 | 0.72 | 1.30 | 3.01 |
| Ammonia + organic nitrogen as nitrogen (mg/L) | 55 | 29 | 3 | 0.73 | 2.9 | <0.2 | 0.20 | 0.30 | 0.40 | 0.98 | 2.55 |
| Nitrate + nitrite as nitrogen (mg/L) | 55 | 29 | 0 | 0.31 | 1.00 | 0.02 | 0.15 | 0.22 | 0.28 | 0.36 | 0.57 |
| Phosphorus, total (mg/L) | 55 | 29 | 6 | 0.11 | 0.69 | <0.02 | 0.01 | 0.03 | 0.05 | 0.14 | 0.39 |
| Phosphorus, dissolved (mg/L) | 55 | 29 | 60 | 0.02 | 0.13 | <0.02 | 0.00 | 0.01 | 0.01 | 0.02 | 0.05 |
| Cadmium, total (µg/L) | 55 | 29 | 83 | — | 0.8 | <0.5 | — | — | — | — | — |
| Chromium, total (µg/L) | 55 | 29 | 59 | 1.04 | 6 | <1 | 0.08 | 0.25 | 0.55 | 1.27 | 4.13 |
| Copper, total (µg/L) | 55 | 29 | 61 | 1.47 | 8 | <1 | 0.06 | 0.22 | 0.57 | 1.45 | 5.28 |
| Lead, total (µg/L) | 55 | 29 | 49 | 4.21 | 33 | <1 | 0.04 | 0.25 | 0.95 | 6.05 | 20.0 |
| Zinc, total (µg/L) | 53 | 29 | 0 | 13.9 | 61 | 2 | 2.91 | 5.13 | 7.15 | 18.8 | 44.9 |

[1]For constituents with values below detection limit, the mean is estimated from log-probability regression and percentiles are from adjusted maximum likelihood estimates.

**Table 8.** Statistical summary for selected constituents, Alcovy River at New Hope Road near Grayson, Georgia, station 02208150, samples collected 1996–2003.

[%, percent of samples less than concentration; µS/cm, microsiemen per centimeter; —, no data; NTU, nephelometric turbidity unit; mg/L, milligram per liter; <, less than; +, plus; µg/L, microgram per liter]

| Constituent | Number of samples | | | Concentration[1] | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | Base-flow | Storm-flow | Below detection limit | Mean | Maximum | Minimum | 5% | 25% | 50% | 75% | 95% |
| Specific conductance (µS/cm) | 32 | 26 | — | 71 | 101 | 42 | 51 | 61 | 72 | 79 | 86 |
| pH | 32 | 27 | — | 6.7 | 8.2 | 5.7 | 5.9 | 6.4 | 6.8 | 7.0 | 7.3 |
| Turbidity (NTU) | 30 | 27 | 0 | 180 | 2,600 | 2.8 | 4.2 | 8.9 | 23 | 230 | 650 |
| Suspended solids, total (mg/L) | 31 | 27 | 0 | 192 | 1,440 | <1 | 3 | 6 | 10 | 294 | 796 |
| Dissolved solids, total (mg/L) | 32 | 27 | 0 | 51 | 84 | 31 | 35 | 45 | 50 | 56 | 64 |
| Biochemical oxygen demand (mg/L) | 29 | 26 | 1 | 2.0 | 6.9 | <0.1 | 0.2 | 0.6 | 1.5 | 3.0 | 4.6 |
| Chemical oxygen demand (mg/L) | 32 | 26 | 21 | 10 | 52 | <5 | 2 | 4 | 7 | 12 | 28 |
| Nitrogen, total (mg/L) | 32 | 27 | 0 | 1.17 | 5.20 | 0.38 | 0.51 | 0.63 | 0.81 | 1.46 | 3.01 |
| Ammonia + organic nitrogen as nitrogen (mg/L) | 32 | 27 | 19 | 0.71 | 4.7 | 0.2 | 0.05 | 0.16 | 0.40 | 1.01 | 2.60 |
| Nitrate + nitrite as nitrogen (mg/L) | 32 | 27 | 0 | 0.43 | 0.76 | 0.18 | 0.27 | 0.35 | 0.41 | 0.49 | 0.62 |
| Phosphorus, total (mg/L) | 32 | 27 | 25 | 0.11 | 0.7 | <0.02 | 0.00 | 0.01 | 0.03 | 0.17 | 0.57 |
| Phosphorus, dissolved (mg/L) | 32 | 27 | 46 | 0.01 | 0.3 | <0.02 | 0.00 | 0.00 | 0.01 | 0.02 | 0.05 |
| Cadmium, total (µg/L) | 31 | 26 | 56 | — | 0.5 | <0.5 | — | — | — | — | — |
| Chromium, total (µg/L) | 31 | 25 | 33 | 3.72 | 23 | <1 | 0.02 | 0.18 | 0.73 | 4.67 | 19.5 |
| Copper, total (µg/L) | 31 | 25 | 32 | 3.83 | 23 | <1 | 0.08 | 0.39 | 1.20 | 6.25 | 15.0 |
| Lead, total (µg/L) | 31 | 25 | 30 | 8.34 | 68 | <1 | 0.04 | 0.32 | 1.45 | 12.8 | 42.6 |
| Zinc, total (µg/L) | 29 | 25 | 5 | 26.8 | 190 | 2 | 2.00 | 4.10 | 9.60 | 40.0 | 103 |

[1]For constituents with values below detection limit, the mean is estimated from log-probability regression and percentiles are from adjusted maximum likelihood estimates.

**Table 9.** Statistical summary for selected constituents, Big Haynes Creek at Lenora Road near Snellville, Georgia, station 02207385, samples collected 1996–2003.

[%, percent of samples less than concentration; µS/cm, microsiemen per centimeter; —, no data; NTU, nephelometric turbidity unit; mg/L, milligram per liter; <, less than; +, plus; µg/L, microgram per liter]

| Constituent | Number of samples | | | Concentration[1] | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | Base-flow | Storm-flow | Below detection limit | Mean | Maximum | Minimum | 5% | 25% | 50% | 75% | 95% |
| Specific conductance (µS/cm) | 55 | 30 | 0 | 64 | 110 | 20 | 42 | 55 | 62 | 72 | 90 |
| pH | 55 | 30 | 0 | 6.6 | 7.4 | 5.4 | 5.8 | 6.2 | 6.7 | 6.8 | 7.1 |
| Turbidity (NTU) | 52 | 30 | 0 | 88 | 910 | 1.7 | 3.2 | 4.8 | 7.8 | 61 | 490 |
| Suspended solids, total (mg/L) | 54 | 31 | 2 | 109 | 940 | <1 | 2 | 5 | 7 | 107 | 595 |
| Dissolved solids, total (mg/L) | 55 | 31 | 0 | 47 | 72 | 27 | 34 | 40 | 48 | 55 | 62 |
| Biochemical oxygen demand (mg/L) | 52 | 29 | 2 | 2.1 | 8.3 | <0.1 | 0.4 | 0.8 | 1.2 | 3.0 | 5.7 |
| Chemical oxygen demand (mg/L) | 52 | 30 | 25 | 11 | 43 | <5 | 2 | 5 | 8 | 14 | 30 |
| Nitrogen, total (mg/L) | 55 | 31 | 0 | 1.60 | 3.37 | 0.80 | 0.98 | 1.16 | 1.40 | 1.88 | 2.79 |
| Ammonia + organic nitrogen as nitrogen (mg/L) | 55 | 31 | 13 | 0.62 | 2.6 | <0.2 | 0.09 | 0.21 | 0.30 | 0.70 | 2.10 |
| Nitrate + nitrite as nitrogen (mg/L) | 55 | 31 | 0 | 0.96 | 2.20 | 0.42 | 0.52 | 0.76 | 0.92 | 1.10 | 1.60 |
| Phosphorus, total (mg/L) | 55 | 31 | 5 | 0.14 | 0.59 | <0.02 | 0.02 | 0.06 | 0.11 | 0.20 | 0.37 |
| Phosphorus, dissolved (mg/L) | 55 | 31 | 28 | 0.05 | 0.28 | <0.02 | 0.01 | 0.02 | 0.04 | 0.07 | 0.15 |
| Cadmium, total (µg/L) | 55 | 31 | 84 | — | 1.1 | <0.5 | — | — | — | — | — |
| Chromium, total (µg/L) | 55 | 31 | 63 | 1.18 | 12 | <1 | 0.03 | 0.15 | 0.40 | 1.10 | 5.12 |
| Copper, total (µg/L) | 55 | 31 | 63 | 1.60 | 10 | <1 | 0.05 | 0.21 | 0.56 | 1.49 | 4.85 |
| Lead, total (µg/L) | 55 | 31 | 57 | 4.22 | 33 | <1 | 0.01 | 0.11 | 0.55 | 4.08 | 20.6 |
| Zinc, total (µg/L) | 53 | 31 | 0 | 18.6 | 91 | 3 | 3.72 | 5.38 | 9.55 | 24.8 | 58.9 |

[1]For constituents with values below detection limit, the mean is estimated from log-probability regression and percentiles are from adjusted maximum likelihood estimates.

**Table 10.** Statistical summary for selected constituents, Suwanee Creek at Buford Highway near Suwanee, Georgia, station 02334885, samples collected 1996–2003.

[%, percent of samples less than concentration; µS/cm, microsiemen per centimeter; —, no data; NTU, nephelometric turbidity unit; mg/L, milligram per liter; <, less than; +, plus; µg/L, microgram per liter]

| Constituent | Number of samples | | | Concentration[1] | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | Base-flow | Storm-flow | Below detection limit | Mean | Maximum | Minimum | 5% | 25% | 50% | 75% | 95% |
| Specific conductance (µS/cm) | 35 | 31 | — | 96 | 223 | 39 | 50 | 71 | 94 | 108 | 171 |
| pH | 35 | 31 | — | 6.8 | 7.5 | 5.7 | 6.1 | 6.5 | 6.8 | 7.1 | 7.3 |
| Turbidity (NTU) | 32 | 31 | 0 | 170 | 1,000 | 2.9 | 4.5 | 12 | 19 | 306 | 570 |
| Suspended solids, total (mg/L) | 35 | 32 | 0 | 169 | 870 | 4 | 5 | 8 | 23 | 262 | 678 |
| Dissolved solids, total (mg/L) | 36 | 32 | 0 | 63 | 130 | 28 | 38 | 48 | 60 | 73 | 99 |
| Biochemical oxygen demand (mg/L) | 33 | 28 | 1 | 2.5 | 8.6 | <0.1 | 0.3 | 0.8 | 1.5 | 3.8 | 6.4 |
| Chemical oxygen demand (mg/L) | 34 | 31 | 26 | 10 | 32 | <5 | 2 | 4 | 7 | 14 | 27 |
| Nitrogen, total (mg/L) | 35 | 32 | 0 | 1.42 | 4.80 | 0.59 | 0.83 | 0.96 | 1.20 | 1.60 | 2.57 |
| Ammonia + organic nitrogen as nitrogen (mg/L) | 34 | 32 | 6 | 0.69 | 2.3 | <0.2 | 0.13 | 0.26 | 0.46 | 1.10 | 1.90 |
| Nitrate + nitrite as nitrogen (mg/L) | 35 | 32 | 0 | 0.73 | 4.20 | 0.32 | 0.37 | 0.49 | 0.64 | 0.79 | 1.10 |
| Phosphorus, total (mg/L) | 36 | 32 | 18 | 0.16 | 0.79 | <0.02 | 0.00 | 0.02 | 0.05 | 0.26 | 0.60 |
| Phosphorus, dissolved (mg/L) | 35 | 32 | 54 | 0.01 | 0.1 | <0.02 | 0.00 | 0.01 | 0.01 | 0.02 | 0.04 |
| Cadmium, total (µg/L) | 35 | 32 | 66 | — | 1.6 | <0.5 | — | — | — | — | — |
| Chromium, total (µg/L) | 35 | 32 | 33 | 6.36 | 42 | <1 | 0.04 | 0.32 | 1.50 | 8.70 | 23.4 |
| Copper, total (µg/L) | 35 | 32 | 32 | 5.28 | 29 | <1 | 0.12 | 0.58 | 1.79 | 9.00 | 18.8 |
| Lead, total (µg/L) | 35 | 32 | 31 | 6.15 | 28 | <1 | 0.11 | 0.60 | 1.96 | 9.50 | 21.8 |
| Zinc, total (µg/L) | 35 | 32 | 0 | 23.9 | 104 | 2 | 2.48 | 3.90 | 12.0 | 37.0 | 69.0 |

[1]For constituents with values below detection limit, the mean is estimated from log-probability regression and percentiles are from adjusted maximum likelihood estimates.

**Table 11.** Statistical summary for selected constituents, Yellow River at State Route 124 near Lithonia, Georgia, station 02207120, samples collected 1996–2003.

[%, percent of samples less than concentration; µS/cm, microsiemen per centimeter; —, no data; NTU, nephelometric turbidity unit; mg/L, milligram per liter; <, less than; +, plus; µg/L, microgram per liter]

| Constituent | Number of samples | | | Concentration[1] | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | Base-flow | Storm-flow | Below detection limit | Mean | Maximum | Minimum | 5% | 25% | 50% | 75% | 95% |
| Specific conductance (µS/cm) | 34 | 29 | 0 | 145 | 322 | 39 | 63 | 107 | 138 | 180 | 235 |
| pH | 34 | 29 | 0 | 7.0 | 8.0 | 5.5 | 6.2 | 6.6 | 7.0 | 7.4 | 7.6 |
| Turbidity (NTU) | 32 | 30 | 0 | 110 | 820 | 1.6 | 2.8 | 4.4 | 14 | 180 | 350 |
| Suspended solids, total (mg/L) | 34 | 32 | 2 | 145 | 1,300 | <1 | 2 | 5 | 14 | 233 | 604 |
| Dissolved solids, total (mg/L) | 35 | 32 | 0 | 91 | 191 | 44 | 48 | 60 | 89 | 112 | 145 |
| Biochemical oxygen demand (mg/L) | 33 | 29 | 0 | 2.1 | 7.4 | 0.1 | 0.3 | 0.7 | 1.2 | 3.2 | 5.2 |
| Chemical oxygen demand (mg/L) | 31 | 30 | 21 | 11.2 | 40 | 5 | 2 | 5 | 8 | 14 | 32 |
| Nitrogen, total (mg/L) | 34 | 32 | 0 | 2.30 | 4.20 | 1.30 | 1.50 | 1.80 | 2.10 | 2.60 | 3.65 |
| Ammonia + organic nitrogen as nitrogen (mg/L) | 34 | 32 | 3 | 0.78 | 3.6 | <0.2 | 0.14 | 0.28 | 0.40 | 1.23 | 2.06 |
| Nitrate + nitrite as nitrogen (mg/L) | 33 | 32 | 0 | 1.51 | 3.10 | 0.45 | 0.63 | 0.95 | 1.40 | 1.90 | 2.80 |
| Phosphorus, total (mg/L) | 35 | 32 | 19 | 0.11 | 0.64 | <0.02 | 0.00 | 0.02 | 0.04 | 0.17 | 0.39 |
| Phosphorus, dissolved (mg/L) | 34 | 32 | 48 | 0.02 | 0.05 | <0.02 | 0.01 | 0.01 | 0.01 | 0.02 | 0.04 |
| Cadmium, total (µg/L) | 34 | 32 | 63 | — | 1.2 | <0.5 | — | — | — | — | — |
| Chromium, total (µg/L) | 34 | 31 | 35 | 4.24 | 36 | <1 | 0.04 | 0.26 | 0.99 | 6.35 | 16.4 |
| Copper, total (µg/L) | 34 | 32 | 29 | 4.54 | 34 | <1 | 0.18 | 0.72 | 1.90 | 6.65 | 16.0 |
| Lead, total (µg/L) | 34 | 31 | 35 | 4.92 | 38 | <1 | 0.07 | 0.40 | 1.35 | 7.05 | 17.1 |
| Zinc, total (µg/L) | 35 | 32 | 0 | 30.3 | 200 | 6.6 | 7.40 | 10.0 | 15.0 | 40.5 | 88.4 |

[1]For constituents with values below detection limit, the mean is estimated from log-probability regression and percentiles are from adjusted maximum likelihood estimates.

**Table 12.** Statistical summary for selected constituents, Crooked Creek at Spalding Drive near Norcross, Georgia, station 02335350, samples collected for 1996–2003.

[%, percent of samples less than concentration; µS/cm, microsiemen per centimeter; —, no data; NTU, nephelometric turbidity unit; mg/L, milligram per liter; <, less than; +, plus; µg/L, microgram per liter]

| Constituent | Number of samples | | | Concentration[1] | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | Base-flow | Stormflow | Below detection limit | Mean | Maximum | Minimum | 5% | 25% | 50% | 75% | 95% |
| Specific conductance (µS/cm) | 32 | 34 | — | 90 | 238 | 32 | 43 | 79 | 93 | 104 | 108 |
| pH | 31 | 34 | — | 6.7 | 8.0 | 5.2 | 6.0 | 6.4 | 6.7 | 7.0 | 7.3 |
| Turbidity (NTU) | 30 | 34 | 0 | 150 | 2,100 | 2.5 | 3.4 | 6.8 | 24 | 210 | 520 |
| Suspended solids, total (mg/L) | 33 | 36 | 4 | 260 | 3,120 | <1 | 1 | 4 | 41 | 364 | 960 |
| Dissolved solids, total (mg/L) | 34 | 36 | 0 | 59 | 136 | 14 | 31 | 45 | 62 | 71 | 81 |
| Biochemical oxygen demand (mg/L) | 31 | 30 | 0 | 3.5 | 8.9 | 0.4 | 0.5 | 0.8 | 1.7 | 5.4 | 8.6 |
| Chemical oxygen demand (mg/L) | 33 | 36 | 24 | 15 | 60 | <5 | 2 | 4 | 10 | 20 | 44 |
| Nitrogen, total (mg/L) | 33 | 36 | 16 | 1.27 | 3.50 | 0.35 | 0.41 | 0.56 | 0.98 | 1.70 | 3.20 |
| Ammonia + organic nitrogen as nitrogen (mg/L) | 34 | 36 | 16 | 0.87 | 3.1 | <0.2 | 0.08 | 0.21 | 0.60 | 1.33 | 2.68 |
| Nitrate + nitrite as nitrogen (mg/L) | 33 | 36 | 0 | 0.37 | 1.10 | 0.10 | 0.16 | 0.28 | 0.36 | 0.44 | 0.62 |
| Phosphorus, total (mg/L) | 34 | 36 | 20 | 0.15 | 0.82 | <0.02 | 0.00 | 0.02 | 0.07 | 0.23 | 0.58 |
| Phosphorus, dissolved (mg/L) | 34 | 36 | 53 | 0.01 | 0.09 | <0.02 | 0.00 | 0.01 | 0.01 | 0.02 | 0.04 |
| Cadmium, total (µg/L) | 34 | 36 | 64 | — | 3.5 | <0.5 | — | — | — | — | — |
| Chromium, total (µg/L) | 34 | 35 | 33 | 5.23 | 37 | <1 | 0.06 | 0.38 | 1.60 | 6.90 | 22.0 |
| Copper, total (µg/L) | 34 | 36 | 31 | 7.25 | 56 | <1 | 0.12 | 0.68 | 2.55 | 10.28 | 25.2 |
| Lead, total (µg/L) | 33 | 36 | 34 | 8.56 | 76 | <1 | 0.06 | 0.47 | 1.90 | 12.00 | 35.0 |
| Zinc, total (µg/L) | 32 | 36 | 0 | 57.4 | 322 | 4 | 4.64 | 8.00 | 37.5 | 77.8 | 163 |

[1]For constituents with values below detection limit, the mean is estimated from log-probability regression and percentiles are from adjusted maximum likelihood estimates.

## Water-Quality Constituent Loads

The load of a constituent is the mass transport per unit time (for example, pounds per year). If the discharge and concentration were known for every instant, then the load for a time period simply would be computed as:

$$L_T = \int_0^T QCdt \qquad (1)$$

where

- $L_T$ is total load (mass) for a time period T,
- $C$ is concentration (mass per unit volume),
- $Q$ is streamflow (volume per unit time), and
- $t$ is unit time.

Although continuous discharge data are available for the gaged watersheds of this study, values of $C$ are available only for sampled times. The concentration, $C$, can be estimated for unsampled times using continuous discharge and concentration to discharge relations, as illustrated in figure 19 for four constituents in Crooked Creek. Concentration-discharge relations were used to develop regression models to compute constituent loads within the USGS LOADEST (Runkel and others, 2004) model. A unique method was developed in this study that allows separation of baseflow load and stormflow load for parameters having two unique statistical distributions. The importance of model time step also was explored. Annual yields are presented from 1998 to 2003 for selected constituents for each watershed in tables 13–18.

### *Loads and Yields*

The ***Load*** of a constituent is the quantity (pounds or tons) carried in a stream per unit time. The ***Yield*** is simply the load per unit area. Yield is obtained by dividing the load by the watershed area. Yields are loads, normalized for the watershed size. Thus, yields are used to compare loads between watersheds.

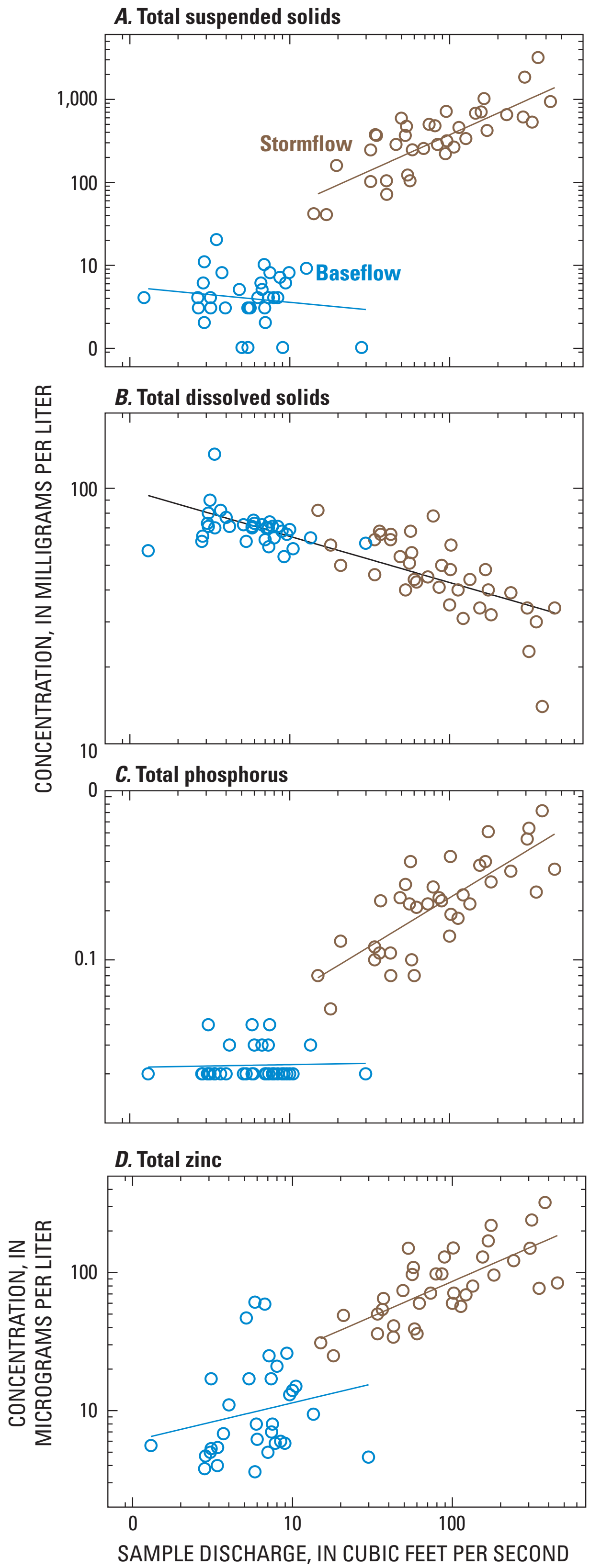



**Figure 19.** Concentration of *(A)* total suspended solids, *(B)* total dissolved solids, *(C)* total phosphorus, and *(D)* total zinc and discharge in the Crooked Creek watershed in Gwinnett County, Georgia, 1996–2003.

**Table 13.** Constituent annual yields, Brushy Fork Creek at Beaver Road near Loganville, Georgia, station 02207400, 1998–2003.

[+, plus; %, percent]

| Water year | Constituent yield in pounds per acre per year | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Suspended solids, total | Dissolved solids, total | Biochemical oxygen demand | Phosphorus, total | Phosphorus, dissolved | Nitrogen, total | Nitrate + nitrite as nitrogen | Zinc, total |
| 1998 | 2,980 | 294 | 21.4 | 1.52 | 0.30 | 11.9 | 3.0 | 0.19 |
| 1999 | 519 | 104 | 8.4 | .35 | .10 | 3.3 | 0.9 | .04 |
| 2000 | 402 | 82 | 6.4 | .28 | .08 | 2.5 | 0.7 | .03 |
| 2001 | 919 | 150 | 11.5 | .59 | .14 | 5.1 | 1.3 | .07 |
| 2002 | 544 | 107 | 8.5 | .37 | .10 | 3.4 | 0.9 | .04 |
| 2003 | 3,490 | 343 | 24.8 | 1.95 | .34 | 14.3 | 3.4 | .23 |
| 1998–2003 average | 1,480 | 180 | 13.5 | .84 | .18 | 6.8 | 1.7 | .10 |
| **Standard error** | **63%** | **4%** | **18%** | **31%** | **39%** | **17%** | **14%** | **22%** |
| **Average carried by stormwater runoff** | **97%** | **49%** | **74%** | **88%** | **51%** | **76%** | **55%** | **86%** |

**Table 14.** Constituent annual yields, Alcovy River at New Hope Road near Grayson, Georgia, station 02208150, 1998–2003.

[+, plus; %, percent]

| Water year | Constituent yield in pounds per acre per year | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Suspended solids, total | Dissolved solids, total | Biochemical oxygen demand | Phosphorus, total | Phosphorus, dissolved | Nitrogen, total | Nitrate + nitrite as nitrogen | Zinc, total |
| 1998 | 2,810 | 290 | 17.1 | 1.39 | 0.25 | 9.9 | 2.9 | 0.33 |
| 1999 | 330 | 137 | 5.2 | .21 | .10 | 2.7 | 1.1 | .05 |
| 2000 | 429 | 127 | 5.3 | .26 | .09 | 2.8 | 1.1 | .06 |
| 2001 | 1,070 | 180 | 9.4 | .56 | .14 | 5.0 | 1.6 | .13 |
| 2002 | 1,230 | 148 | 7.8 | .60 | .12 | 4.4 | 1.4 | .14 |
| 2003 | 9,080 | 368 | 24.7 | 3.52 | .35 | 17.7 | 3.9 | .81 |
| 1998–2003 average | 2,490 | 208 | 11.6 | 1.09 | .18 | 7.1 | 2.0 | .25 |
| **Standard error** | **45%** | **2%** | **17%** | **30%** | **66%** | **12%** | **6%** | **32%** |
| **Average carried by stormwater runoff** | **99%** | **40%** | **84%** | **96%** | **50%** | **76%** | **50%** | **95%** |

**Table 15.** Constituent annual yields, Big Haynes Creek at Lenora Road near Snellville, Georgia, station 02207385, 1998–2003.

[+, plus; %, percent]

| Water year | Constituent yield in pounds per acre per year | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Suspended solids, total | Dissolved solids, total | Biochemical oxygen demand | Phosphorus, total | Phosphorus, dissolved | Nitrogen, total | Nitrate + nitrite as nitrogen | Zinc, total |
| 1998 | 1,180 | 231 | 16.4 | 0.85 | 0.18 | 9.6 | 4.5 | 0.17 |
| 1999 | 297 | 139 | 7.0 | .37 | .16 | 4.6 | 2.8 | .06 |
| 2000 | 319 | 124 | 7.0 | .39 | .15 | 4.3 | 2.5 | .05 |
| 2001 | 729 | 156 | 10.3 | .56 | .16 | 6.1 | 3.1 | .10 |
| 2002 | 649 | 137 | 7.9 | .47 | .16 | 5.2 | 2.8 | .08 |
| 2003 | 6,050 | 339 | 29.9 | 2.22 | .20 | 19.4 | 6.4 | .48 |
| 1998–2003 average | 1,540 | 188 | 13.1 | .81 | .17 | 8.2 | 3.7 | .16 |
| **Standard error** | **82%** | **2%** | **38%** | **35%** | **31%** | **7%** | **7%** | **37%** |
| **Average carried by stormwater runoff** | **99%** | **27%** | **74%** | **78%** | **6%** | **54%** | **24%** | **84%** |

**Table 16.** Constituent annual yields, Suwanee Creek at Buford Highway near Suwanee, Georgia, station 02334885, 1998–2003.

[+, plus; %, percent]

| Water year | Constituent yield in pounds per acre per year | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Suspended solids, total | Dissolved solids, total | Biochemical oxygen demand | Phosphorus, total | Phosphorus, dissolved | Nitrogen, total | Nitrate + nitrite as nitrogen | Zinc, total |
| 1998 | 3,240 | 350 | 22.5 | 2.89 | 0.24 | 11.2 | 3.9 | 0.30 |
| 1999 | 281 | 160 | 6.9 | .31 | .08 | 3.3 | 1.8 | .05 |
| 2000 | 491 | 178 | 9.2 | .50 | .09 | 4.1 | 2.0 | .07 |
| 2001 | 1,150 | 217 | 12.8 | 1.04 | .12 | 5.8 | 2.4 | .13 |
| 2002 | 689 | 185 | 10.4 | .69 | .10 | 4.6 | 2.1 | .09 |
| 2003 | 4,600 | 404 | 27.2 | 3.78 | .28 | 14 | 4.5 | .41 |
| 1998–2003 average | 1,740 | 249 | 14.8 | 1.54 | .15 | 7.1 | 2.8 | .17 |
| **Standard error** | **44%** | **2%** | **14%** | **56%** | **36%** | **11%** | **10%** | **20%** |
| **Average carried by stormwater runoff** | **99%** | **41%** | **87%** | **97%** | **56%** | **68%** | **41%** | **93%** |

**Table 17.** Constituent annual yields, Yellow River at State Route 124 near Lithonia, Georgia, station 02207120, 1998–2003.

[+, plus; %, percent]

| Water year | Constituent yield in pounds per acre per year | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Suspended solids, total | Dissolved solids, total | Biochemical oxygen demand | Phosphorus, total | Phosphorus, dissolved | Nitrogen, total | Nitrate + nitrite as nitrogen | Zinc, total |
| 1998 | 4,040 | 604 | 30.8 | 2.27 | 0.27 | 19.7 | 9.5 | 0.50 |
| 1999 | 377 | 348 | 9.2 | .34 | .11 | 8.5 | 5.8 | .09 |
| 2000 | 825 | 360 | 11.9 | .59 | .12 | 9.8 | 6.0 | .15 |
| 2001 | 853 | 384 | 12.1 | .60 | .14 | 10.1 | 6.3 | .15 |
| 2002 | 825 | 338 | 10.6 | .55 | .11 | 8.9 | 5.6 | .14 |
| 2003 | 5,690 | 599 | 29.9 | 2.73 | .26 | 20.2 | 9.4 | .59 |
| 1998–2003 average | 2,100 | 439 | 17.4 | 1.18 | .17 | 12.9 | 7.1 | .27 |
| **Standard error** | **14%** | **3%** | **24%** | **12%** | **20%** | **6%** | **6%** | **10%** |
| **Average carried by stormwater runoff** | **99%** | **38%** | **88%** | **95%** | **56%** | **58%** | **34%** | **83%** |

**Table 18.** Constituent annual yields, Crooked Creek at Spalding Drive near Norcross, Georgia, station 02335350, 1998–2003.

[+, plus; %, percent]

| Water year | Constituent yield in pounds per acre per year | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Suspended solids, total | Dissolved solids, total | Biochemical oxygen demand | Phosphorus, total | Phosphorus, dissolved | Nitrogen, total | Nitrate + nitrite as nitrogen | Zinc, total |
| 1998 | 2,390 | 377 | 35.3 | 1.34 | 0.23 | 10.3 | 3.0 | 0.49 |
| 1999 | 919 | 275 | 19.9 | .58 | .15 | 5.6 | 1.7 | .23 |
| 2000 | 3,070 | 253 | 24.5 | 1.41 | .16 | 8.7 | 2.0 | .48 |
| 2001 | 1,860 | 269 | 25.1 | .99 | .16 | 7.6 | 2.0 | .35 |
| 2002 | 3,110 | 241 | 19.9 | 1.12 | .15 | 7.2 | 2.0 | .37 |
| 2003 | 9,120 | 375 | 40.1 | 3.27 | .26 | 17.5 | 3.6 | 1.05 |
| 1998–2003 average | 3,410 | 299 | 27.5 | 1.45 | .19 | 9.5 | 2.4 | .50 |
| **Standard error** | **18%** | **5%** | **16%** | **12%** | **30%** | **8%** | **14%** | **16%** |
| **Average carried by stormwater runoff** | **99%** | **47%** | **92%** | **97%** | **64%** | **86%** | **69%** | **94%** |

## Methods of Computation: USGS LOADEST Model

The LOADEST model can be used in developing a regression model for the estimation of constituent load and includes statistical algorithms to handle problems that arise when dealing with real-world data. LOADEST includes routines to address retransformation bias, data censoring, and nonparametric sample distributions. The regression model formulated in LOADEST is used to estimate mean loads and standard errors.

In regression analysis using streamflow data, it is common to transform explanatory and response variables in an effort to achieve linearity of the regression function, normality of residuals, and to reduce model standard error. A logarithmic transformation was used in this analysis. When the regression model results are retransformed from logarithmic space, a bias is introduced that may underestimate the true load by as much as 50 percent (Ferguson, 1986). LOADEST uses bias correction factors to handle this problem (Runkel and others, 2004).

Some samples contain constituent concentrations less than laboratory reporting limits resulting in “less than” or censored values, particularly for baseflow samples. LOADEST includes a rigorous statistical treatment of censored data, based on the distribution of data above detection limits (Runkel and others, 2004) using log-probability regression. LOADEST also includes methods for estimating model coefficients using adjusted maximum likelihood estimation when model residuals do not follow a normal distribution.

The primary load estimation method used within LOADEST is adjusted maximum likelihood estimation (Cohn and others, 1992b). This method has negligible bias when the calibration dataset is censored. For the case where the calibration dataset is uncensored, the adjusted maximum likelihood estimation method converges to maximum likelihood estimation (Cohn and others, 1992b), resulting in a minimum variance unbiased estimate of constituent loads.

### Methods of Separation of Baseflow and Stormflow Loads

LOADEST develops a linear-regression model from a calibration dataset of water-quality sample date, discharge, and concentration for a given site and constituent. Concentrations of some constituents in baseflow and stormflow, however, may form datasets with separate, noncontinuous statistical distributions, as illustrated in figures 17 and 19. These two-distribution parameters also have unique concentration to discharge relations for baseflow and stormflow. As shown in figure 19*A–D*—for total suspended solids, total phosphorus, and total zinc—the baseflow and stormflow samples cannot be fit by a single log-linear curve. A single nonlinear curve using polynomial discharge could be tried; however, there is a narrow range of streamflow that may occur either as high (winter) baseflow or as low stormflow. In this range, for two-distribution constituents, a single curve cannot represent the concentration-to-discharge relation. Also, stormflow concentrations are often affected by seasonal factors, which should be accounted for in the regression model, whereas baseflow concentration is not as seasonally affected. Thus, more accurate total load results may be obtained by fitting separate curves to the two-distribution constituents.

In this study, two-distribution constituents for which separate baseflow and stormflow sample calibration datasets were used include total suspended solids, biological oxygen demand, total phosphorus, total nitrogen, and total zinc. Combined stormflow and baseflow sample calibration datasets were used for total dissolved solids, dissolved phosphorus, and nitrate plus nitrite.

In addition to providing improved overall accuracy of total load estimates, separation of baseflow and stormflow load models can be used to determine the portion of total load associated with each flow component. The portion of total load carried in baseflow varies widely with constituent, watershed characteristics, and hydrology. This information is valuable to assess general watershed management approaches to mitigate excessive constituent loading.

A unique method was developed in this study to handle two-distribution sample datasets and to evaluate that portion of the load being transported in baseflow and in stormflow. Each water-quality sample of the dataset for each site is collected for a known baseflow or stormflow condition. The continuous discharge data also were evaluated to classify each time step as representing stormflow or baseflow conditions. Graphical hydrograph separation was performed on the continuous discharge time series using a graphical local minimum algorithm within a program (HYSEP) developed by the USGS (Sloto and Crouse, 1996). From this analysis, daily time series of baseflow discharge values and total discharge values were obtained. Each time step was assigned to stormflow if stormflow accounted for more than 15 percent of the total flow on the day of that time step, as illustrated in figure 20*B*. Alternate criterions of 10, 15, and 20 percent were evaluated based on analysis of flow-duration curves for each site, on the location along runoff-recession curves where flow classification would become baseflow, and on an evaluation of the relative concentration of constituents in stormflow and baseflow. The 15-percent criterion was the most representative for these watersheds.

For single-distribution constituents, such as total dissolved solids, LOADEST was calibrated with the combined stormflow and baseflow sample dataset and run first using the total flow discharge time series and then run a second time using the baseflow discharge time series for each site. For two-distribution constituents, such as total suspended solids, LOADEST was calibrated and run three times for each site and constituent. First, the model was calibrated with the stormflow sample dataset and run using the total flow discharge time series to generate the total load for each time step classified as stormflow. Second, the model was calibrated with the baseflow sample dataset and run using the total flow discharge time series to generate the total load for each time step classified as baseflow. Third, the model was calibrated with the baseflow sample dataset and run using the baseflow discharge time series. Stormflow includes both rainfall runoff *and* increased levels of baseflow; and samples of stormflow represent this combined flow. The third model run determines the baseflow portion of the total load for time steps classified as stormflow so that the stormflow and baseflow load components can be separated.

The results are illustrated in figure 20*C* for Suwanee Creek for total suspended solids during water year 2003. Suwanee Creek has a 24-hour time step. Days classified as stormflow have a stacked bar where the blue represents the portion of the load from baseflow and the brown represents the daily load from stormflow. Days classified as baseflow have only a baseflow component. Daily values of load are summed across the water year to obtain the annual load as shown in figure 20*D*. The annual yields transported in baseflow and stormflow are illustrated for each site for selected constituents shown in figures 21–26.

The load equations for each calibration take the following form, including some or all of the explanatory variables:

$$\log(L) = \beta_o + \beta_1 \log(Q) + \beta_2 \sin(2\pi t) + \beta_3 \cos(2\pi t)\ \beta_4(t), \quad (2)$$

where

- $L$ is the constituent load computed for the time step,
- $Q$ is the discharge for the time step,
- $t$ is decimal time minus the center of decimal time (described in Runkel and others, 2004),
- $\beta_o$ is the intercept, and
- $\beta_{1-4}$ are slope coefficients for the explanatory variables.

The third and fourth terms are included for parameters that vary seasonally (after flow adjustment), and the last term is included for parameters that have long-term trends (after flow adjustment).

Time-related explanatory variables were included or excluded based on the analysis of seasonality and trends, which are discussed in the next section of this report. Seasonality was significant and was accounted for in the stormflow model for the two-distribution constituents, with the exception of biological oxygen demand. Long-term trend was included as an explanatory variable only for the baseflow zinc model.

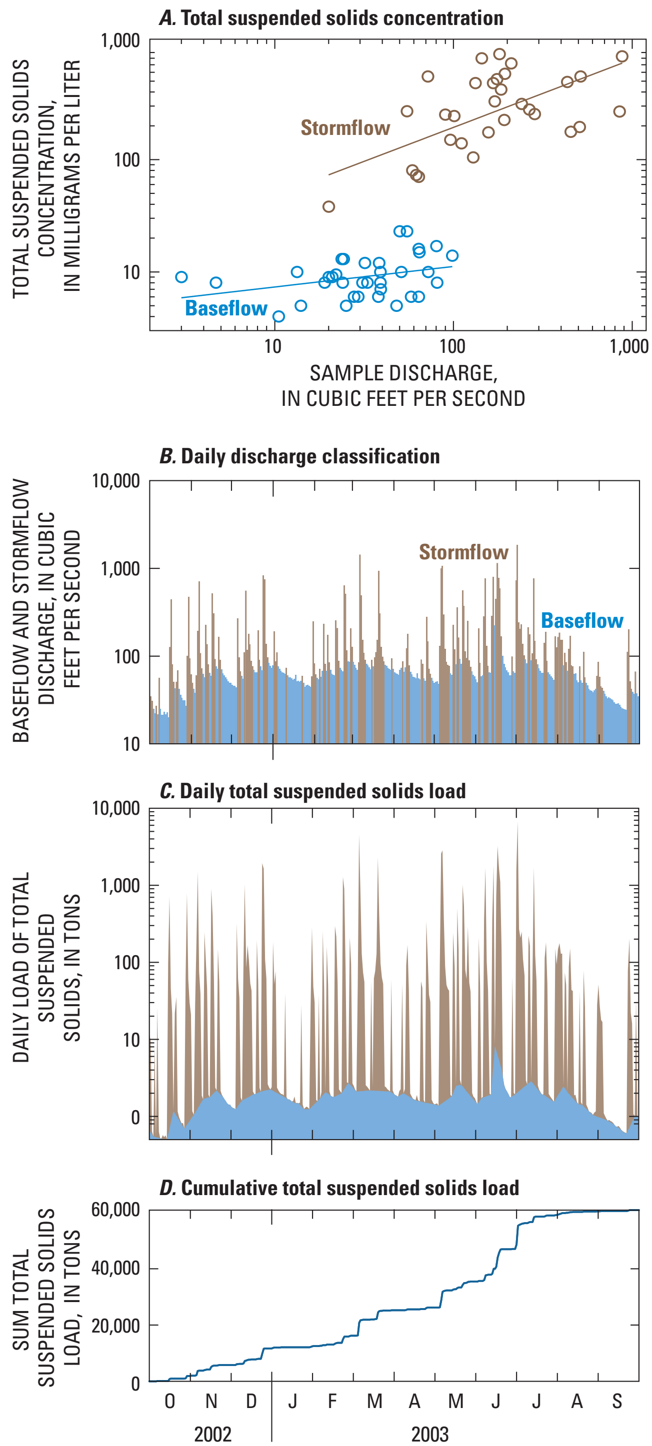



**Figure 20.** *(A)* Total suspended solids concentration, *(B)* daily discharge classification, *(C)* daily total suspended solids load, and *(D)* cumulative total suspended solids load in the Suwanee Creek watershed in Georgia for water year 2003.

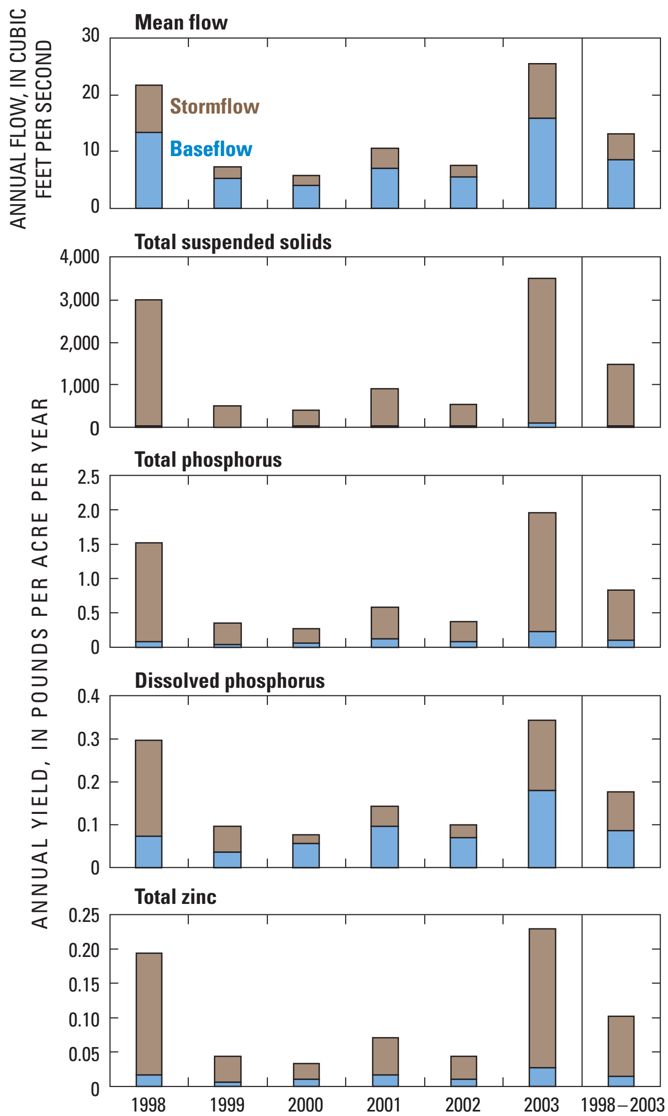



**Figure 21.** Annual flow and yields for the Brushy Fork Creek at Beaver Road near Loganville, Georgia, station 02207400, 1998–2003.

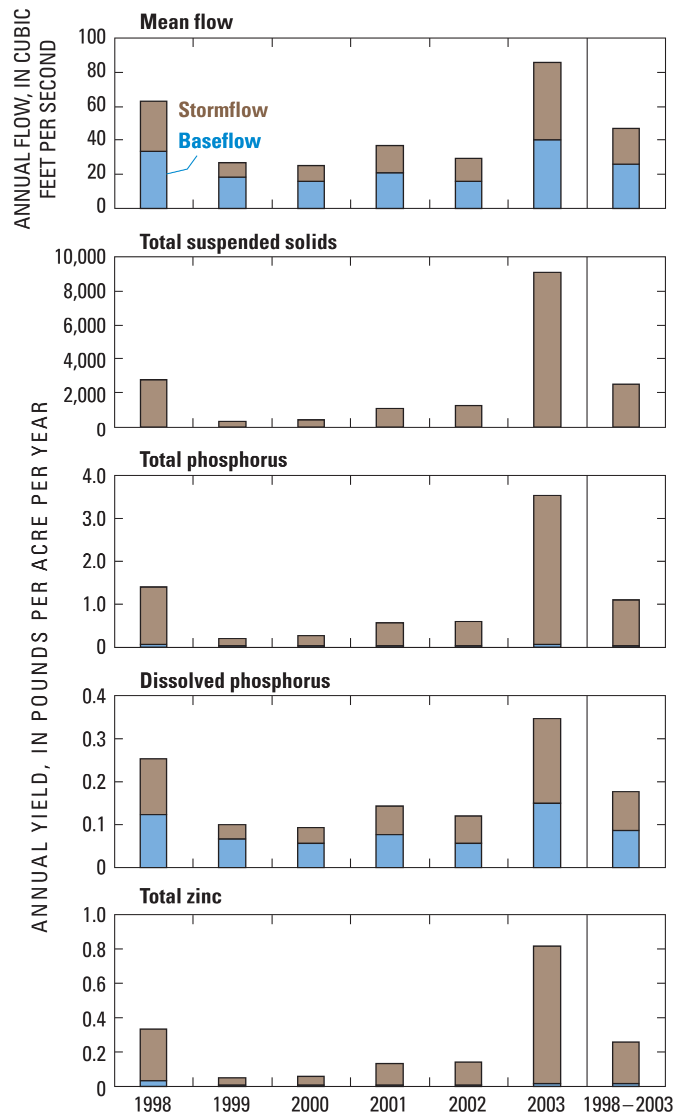



**Figure 22.** Annual flow and yields for the Alcovy River at New Hope Road near Grayson, Georgia, station 02208150, 1998–2003.

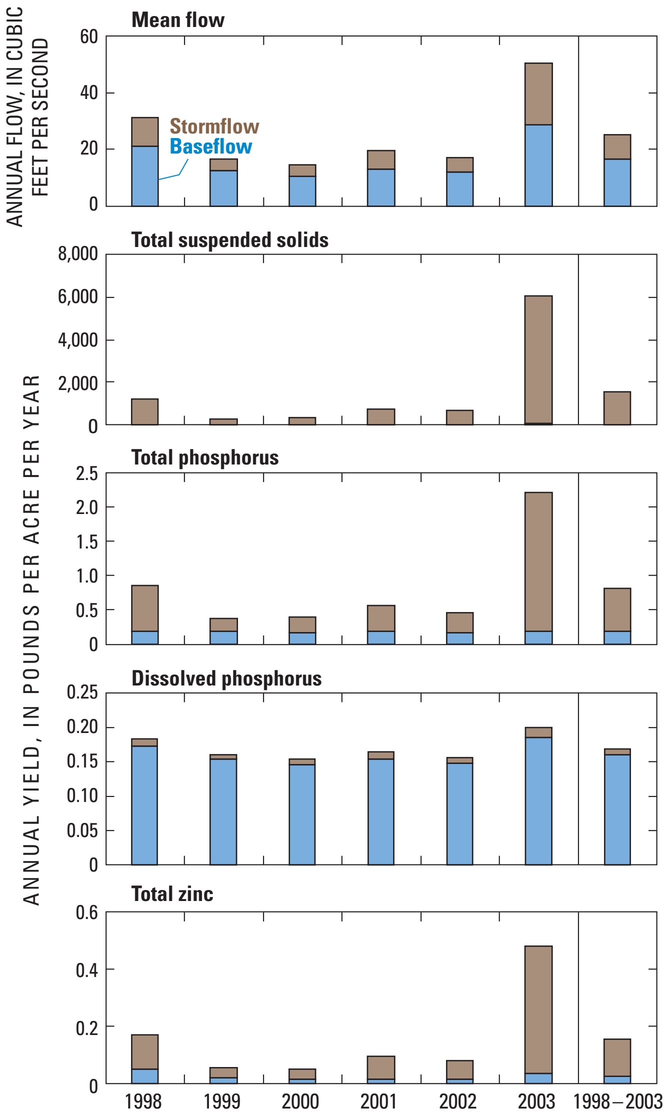



**Figure 23.** Annual flow and yields for the Big Haynes Creek at Lenora Road near Snellville, Georgia, station 02207385, 1998–2003.

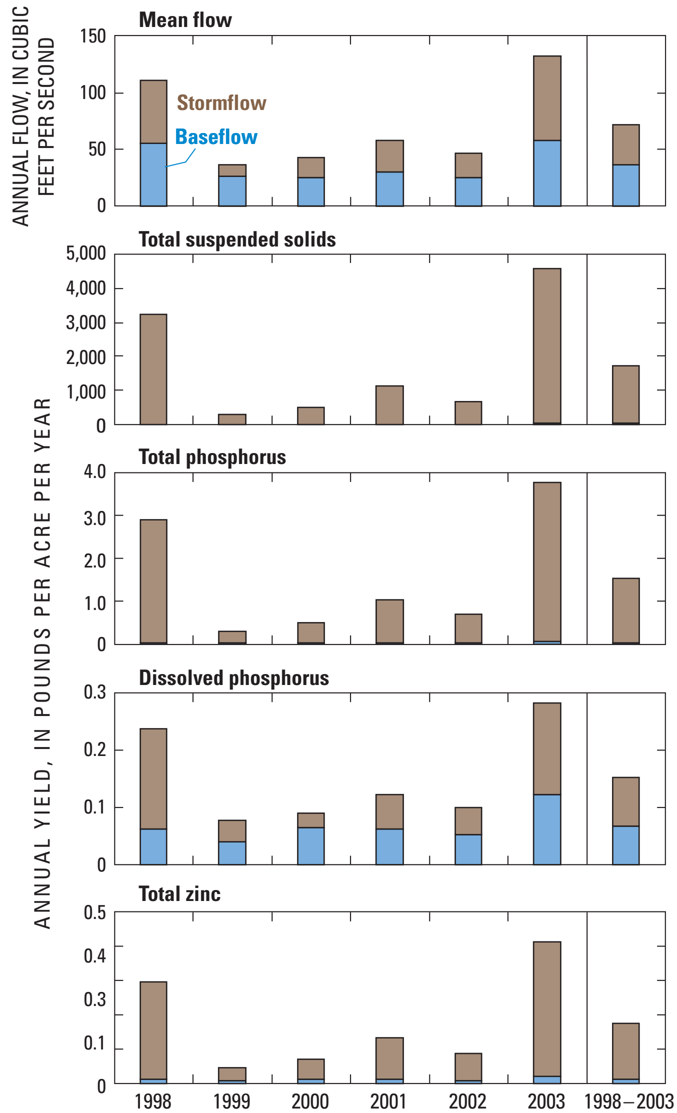



**Figure 24.** Annual flow and yields for the Suwanee Creek at Buford Highway near Suwanee, Georgia, station 02334885, 1998–2003.

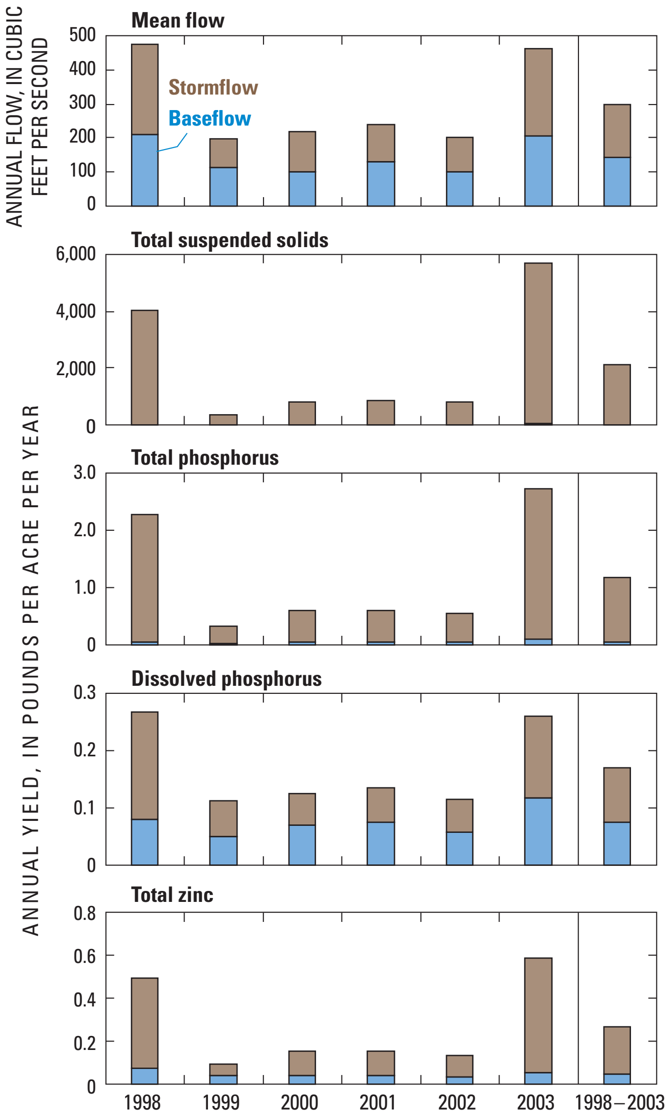



**Figure 25.** Annual flow and yields for the Yellow River at State Route 124 near Lithonia, Georgia, station 02207120, 1998–2003.

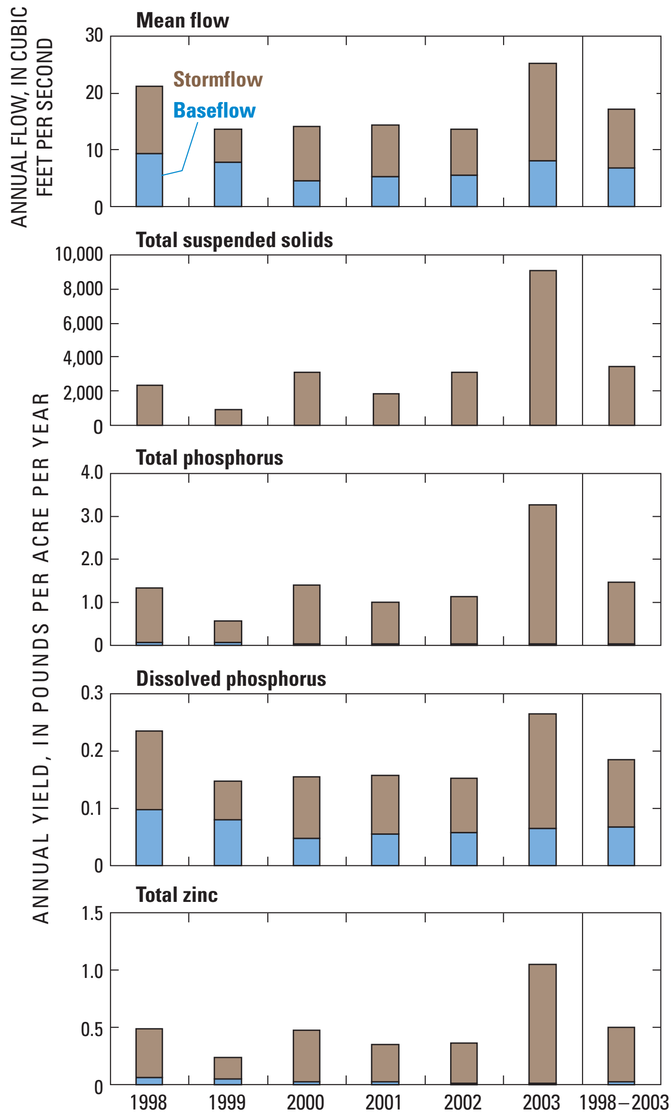



**Figure 26.** Annual flow and yields for the Crooked Creek at Spalding Drive near Norcross, Georgia, station 02335350, 1998–2003.

## Model Time-Step Analysis

A representative model time step is essential to load estimation. As time step increases for a discharge time series, averaging of values will reduce the peaks in the series and, to a lesser extent, increase instantaneous low flows in the time series. Inversely, a short time step will increase peak stormflow discharges in the time series. Load increases exponentially with discharge, so running a model with discharge time steps that are shorter or longer than the discharge duration represented by the samples used for model calibration will bias the load estimates higher or lower, respectively.

A representative model time step should reflect the typical duration represented by the samples in the calibration dataset. Because the stormflow sample concentrations in this study represent flow-weighted composites collected across storm hydrographs, the duration of the sampled flow is the storm duration and the discharge associated with these samples is taken as the average discharge across the storm event, from storm inception to the recession. Thus, the time interval of the stormflow calibration dataset is defined by the typical storm duration. For Suwanee Creek, the duration of 32 sampled storms ranged from 10 to 52 hours, and the median duration was 30 hours. A model time step of 24 hours was selected (fig. 27).

The effects of model time step on computed load were evaluated in a sensitivity analysis. The LOADEST model was run using four time steps of 1, 6, 12, and 24 hours to compute the load of total suspended solids and other constituents for Suwanee Creek. Loads were computed for 12- and 24-hour time steps for Alcovy River and Big Haynes Creek. The load and standard error for baseflow and stormflow were compared for each run. Load results were more sensitive to time step for wetter years and for parameters related more to stormflow. Running the model for Suwanee Creek using a 1-hour time step compared to a 24-hour time step produced a 62-percent increase (overestimate) in total suspended solids load for the period 1998–2001. A separate study of Metropolitan Atlanta streams found that models calibrated with instantaneous (rather than composite) storm samples significantly underestimate loads if daily time steps are used and that 1-hour or even 15-minute time steps may be appropriate (Arthur J. Horowitz, U.S. Geological Survey, written commun., 2006). Baseflow samples represent flow conditions that are steady with respect to time, so time step has little affect on model results for low-flow conditions.

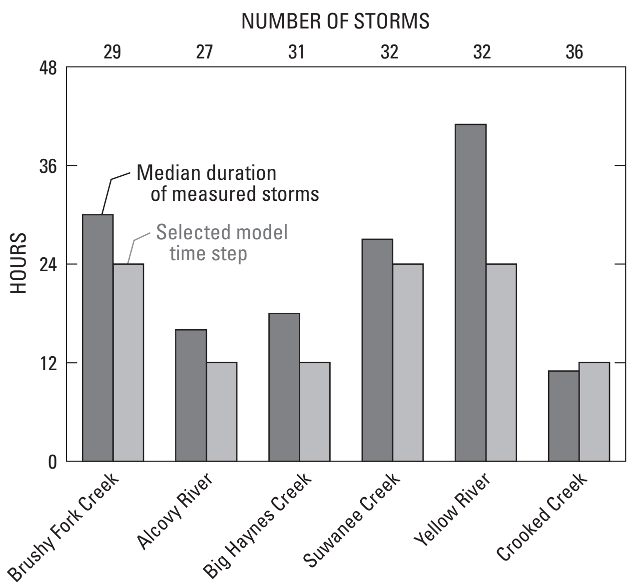



**Figure 27.** Median storm duration and model time step for six watersheds in Gwinnett County, Georgia, 1998–2003.

The number of sampled storms, median storm duration, and model time step for the six watersheds of this study are shown in figure 27. Daily time steps were used for Yellow River, Suwanee Creek, and Brushy Fork Creek. Twelve-hour time steps were used for Big Haynes Creek, Alcovy River, and Crooked Creek. For Yellow River, running the model at a 24- and a 48-hour time step did not significantly affect estimated loads.

## Accuracy of Estimated Loads

The load estimates in this study are based on fitting regression curves to an extensive dataset of concentration and discharge measured at each site following the study design methods and quality-assurance procedures described previously. Overall accuracy refers to the actual instream load compared to the computed load. The overall accuracies of the load estimates depend on errors associated with field sampling and processing, laboratory analysis, the number of samples in the calibration dataset, the range of measured and observed conditions, time duration of the estimate, and model uncertainty.

Sampling and analytical accuracy must be considered because loads estimated using any method would not have accuracy greater than that of the data used for the calibration. The data used to derive these load estimates are time (date), discharge, and concentration measurements. Streamflow discharge measurements have mean errors at the 95-percent confidence limit on the order from ± 5 to 8 percent (Kennedy, 1983; Sauer and Meyer, 1992). Water-quality concentration measurements have sampling errors and analytical errors. Analytical errors vary with concentration (typically greater accuracy for higher concentrations), analytical method, and other factors. Sampling errors tend to vary with how uniformly mixed the constituent is in the streamflow (more representative samples collected with better mixing), sample methods, concentration, and, for sediment-associated constituents, grain-size distribution (Edwards and Glysson, 1999; Hem, 1985). As noted by Horowitz (2003) for suspended sediment concentration, however, replicate sample differences can be on the order of ± 10 percent, at concentrations above 20 milligrams/liter (Edwards and Glysson, 1999; Horowitz, 2003). From these measurement errors, Horowitz (2003) concluded that differences between actual and concentration to discharge rating-curve-derived load estimates (prediction) on the order from ± 15 to 20 percent should be viewed as falling within the normal range of measurement/prediction error for suspended sediment concentration. This finding should be applicable for sediment-associated constituents.

Sampling and analytical accuracy for dissolved constituents may be more or less accurate than for sediment-associated constituents depending on factors already mentioned. Constituents are typically well mixed in the stream for the dissolved constituent loads computed herein (total dissolved solids, dissolved phosphorus, and nitrate-plus-nitrite). Concentrations are usually above detection limits, except for dissolved phosphorus where more than two-thirds of the results were below detection limits for all except Big Haynes Creek (tables 7–12). Thus, the overall accuracy of load estimates for total dissolved solids and nitrate plus nitrite is likely better than for the sediment-associated constituents, as is implied in the model standard errors for these constituents.

Sampled conditions cover a wide, but incomplete, range of the flows observed from 1998 to 2003. Baseflows generally were sampled near the observed minimum at all sites. For high flows, however, the maximum observed discharge (for the model time step) was from 1.9 to 2.6 times the maximum sampled discharge for five of the six sites, and was 8.2 times the maximum sampled discharge for one site (Alcovy River). Load estimates based on extrapolation of the rating curves into these unmeasured discharge ranges have greater uncertainty than estimates within the measured range of conditions. The unverified assumption in using these datasets is that the rating curves (linear in logarithmic space) have the same definition in the extrapolated range as in the measured range from which they are defined.

The model calibration datasets include from 25 to 36 stormflow samples and from 29 to 55 baseflow samples collected at each site from 1998 to 2003, in addition to quality-assurance samples. For single-distribution constituents (total dissolved solids, dissolved phosphorus, and nitrate plus nitrite), the datasets ranged from 59 to 86 samples for each site. These are large calibration datasets, compared to most urban water-quality datasets, and provide adequate basis for some evaluation of the data distribution.

The accuracy of load estimates from sediment rating curve methods will increase with the duration being estimated (Horowitz, 2003). That is, an annual estimate is more accurate than a seasonal estimate, which is more accurate than a monthly estimate. As noted in Horowitz (2003), this is largely because as the time period increases, the overpredictions and underpredictions tend to balance out. In this study, annual and average annual loads were evaluated. Trends were not found in flow-adjusted stormflow concentrations for 1998–2003, as discussed in the next section; so all measurements from this period were used to compute annual loads. Horowitz (2003), however, found significant year-to-year variability in concentration to discharge relations on larger rivers.

The standard error of estimate in percent for the regression models for each site and constituent is shown in tables 13–18 for the average annual load estimates for 1998–2003. The standard error for total suspended solids ranges from 14 percent for Yellow River to 82 percent for Big Haynes Creek. For two-distribution constituents, the baseflow rating curve and the stormflow rating curve typically have unique standard errors. Baseflow discharge is not significantly related to concentration for many constituents, as illustrated in figure 19; however, this does not create a large error because most of the transport occurs during the higher concentration and discharges of stormflow for these constituents. The standard error shown for the two-distribution constituents is the average of the rating curve errors, weighted by the average stormflow and baseflow load. A more sophisticated weighting method is not warranted because most of the load is carried in the stormflow for two-distribution constituents in this study.

Problems can arise in interpreting standard error in percent for these models because they were developed in logarithmic space. The error is not normally distributed around the regression estimate, but is asymmetrical and skewed to the positive side. While two-thirds of the estimated values lie within plus-or-minus one standard error, the error is greater on the positive side of the estimate. For example, for Suwanee Creek, the average annual total suspended solids yield for 1998–2003 is 1,740 pounds per acre per year and the average model standard error is 44 percent; but this is distributed asymmetrically, so that the error is not between ± 44 percent of 1,740. Instead, two-thirds of the error lies between +53 percent and –35 percent; that is, between 2,660 and 1,130 pounds per acre per year. When viewing standard errors from models transformed from logarithmic space, it is important to remember that the errors are skewed to the high side.

# Seasonal and Long-Term Trends in Water Quality

An important objective of the Gwinnett County monitoring program is to assess long-term trends in water quality that may relate to management and land-use practices. The evaluation of long-term trends requires the analysis of seasonal trends as well. Natural causes of seasonality and trends in water quality—for example, precipitation changes—must be accounted for in order to evaluate trends resulting from human influences.

## Seasonality

Many physical, chemical, and biological stream characteristics can show strong seasonal patterns (Helsel and Hirsch, 1992). Streamflow quantity varies directly with seasonal precipitation, temperature, and evapotranspiration. In response to seasonal streamflow patterns, concentration and mass transport of some constituents may follow seasonal patterns. Much of the seasonal variation in water quality may be explained by normalizing for changes in streamflow quantity; however, water quality may vary seasonally in response to seasonal patterns in rainfall intensity, biological activity, or land-use practices, such as construction and fertilizer application.

Trends in concentration were evaluated using more than 400 water-quality samples collected during baseflow and stormflow conditions in the six watersheds for 1996–2003. Stormflow and baseflow samples were evaluated separately because they represent unique populations for many constituents. The effect of variable streamflow will often mask the effect of less influential factors, such as seasonal or long-term trends. To normalize for streamflow effects, evaluation of seasonality and trends is performed on the residuals of a linear regression of concentration as a function of sample discharge (Hirsch and others, 1991). Residuals were obtained from linear-regression analyses of log-transformed streamflow and constituent concentration, for each site, for stormflow and baseflow. In the graphical analysis of seasonality shown in figure 28, residuals of a regression of concentration as a function of discharge (in logarithmic space) are plotted with the month of the sample. Seasonality is indicated by nonrandom seasonal variation of the residuals. A locally weighted scatterplot smooth (LOWESS) through the residuals helps identify the seasonal trend. In the graphical analysis, seasonality was evaluated statistically using a periodic function (sine and cosine) of time, and log discharge, as explanatory variables for log concentration in linear-regression models (Helsel and Hirsch, 1992). Seasonality was considered to be significant where the slope of the seasonal function in the linear regression was different from zero at a 0.1 level of significance (*p*-value) and where this conclusion was supported by the graphical analysis.

Stormflow water quality varies seasonally for total suspended solids, total zinc, and, to a lesser extent, total phosphorus for five of the six streams, after adjusting for the effects of streamflow, as shown in figure 28 for flow-adjusted residuals of logarithmic total suspended solids concentration for samples collected from 1996 to 2003. Seasonal patterns in flow-adjusted total phosphorus and total zinc concentrations are similar to those for total suspended solids. Seasonal effects on stormflow total suspended solids are stronger for more developed watersheds, as indicated in figure 28 (the six basins are in the order of increasing development from top to bottom). Seasonal effects are not significant in the Brushy Fork Creek watershed, possibly because of an upstream reservoir and a less developed watershed.

Seasonality in stormflow water quality results in concentrations that typically are lower during winter months and peak during late summer, between July and August (fig. 28). The seasonal pattern of total suspended solids, total phosphorus, and total zinc may be related to seasonal land-use patterns, including land-disturbance activities that generally increase during spring and summer, and to seasonal variations in rainfall intensity. More intense rainfall during spring and summer can cause greater erosion and wash load than more gradual winter rainfall patterns. Typical rainfall patterns in the Georgia Piedmont in late summer result in intense afternoon thunderstorms. The probability of intense 1-hour rainfall is highest during summer and peaks during the month of July for the Southeastern United States (Hershfield, 1961). Seasonal land-disturbance activities and rainfall intensity would have a more pronounced effect in more developed watersheds, as indicated by the results.

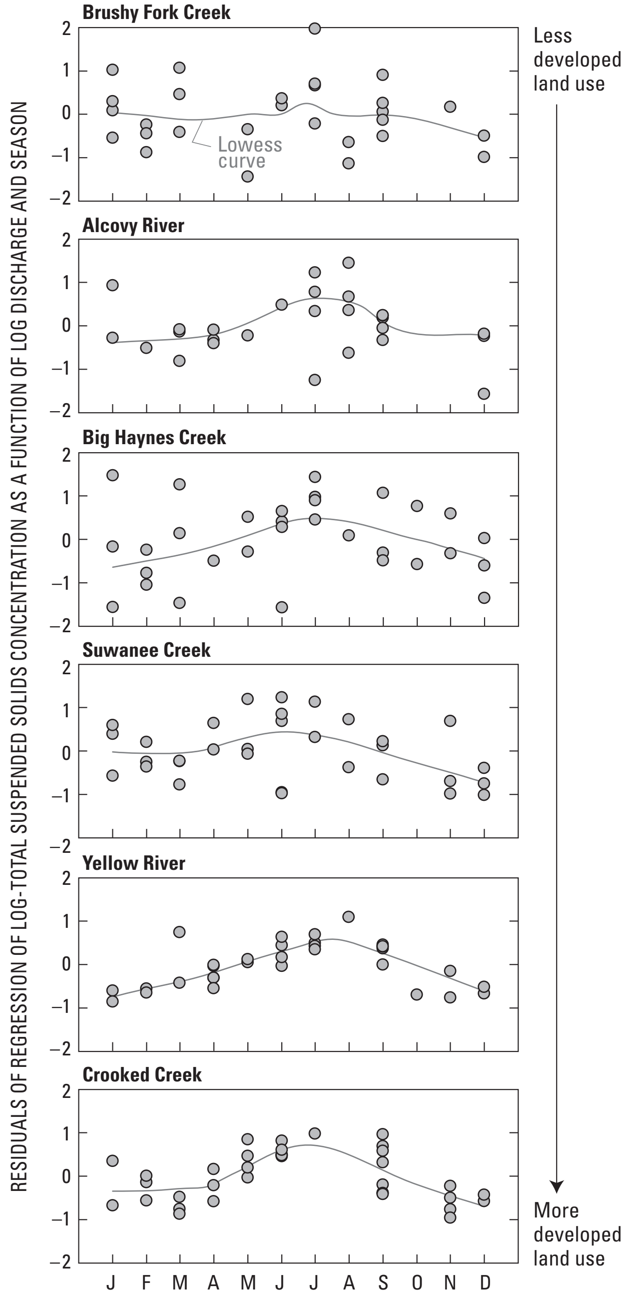



**Figure 28.** Stormflow seasonality in flow-adjusted residuals of logarithmic total suspended solids concentrations for samples collected from 1996 to 2003 in six watersheds in Gwinnett County, Georgia. The six basins are in the order of increasing development from top to bottom.

Baseflow water quality does not have a statistically significant seasonal variation, after adjusting for the effects of streamflow, for total suspended solids, total phosphorus, and total zinc. This result is expected in streams that are not strongly influenced by seasonally varying point-source pollution. This result also is reasonable because total suspended solids, total phosphorus, and total zinc are typically associated with suspended-phase pollutants in stormflow. Seasonality in total dissolved solids also was evaluated and found to be insignificant in baseflow and in stormflow samples.

Seasonality is important in the computation of constituent loads for watershed characterization. Seasonality was accounted for using a periodic function of time in the rating-curve models used to compute watershed load in each of the watersheds. After adjusting for seasonality, model results for summer total suspended solids loads increased by an average of 45 percent, and winter total suspended solids loads decreased by an average of 40 percent, whereas changes were negligible in the spring and fall load rates. Seasonal adjustment changed total annual loads by less than 5 percent on average, with some sites showing an increase and others a decrease in total load. Adjusting for seasonality in the load model caused the standard error of computed annual total suspended solids load to improve by an average of 11 percent in the five watersheds adjusted for seasonality.

## Long-Term Trends

Long-term trends are a critical indicator of the overall effectiveness of watershed management strategies and practices. Reliable, continuous water-quality data are essential to assess and improve watershed management efforts, which can represent a substantial investment for public and private entities. Evaluation of water-quality trends, however, often requires a decade or more of monitoring because of factors such as natural variability from year to year; lag time between watershed changes and water-quality effects; and cumulative, offsetting effects from multiple activities in the watershed. The lag time between watershed changes and water-quality effects may be shortened when watershed land use is changing rapidly, as has occurred in many areas of Gwinnett County. Land use has changed by varying extents in the study watersheds, with more than 10,000 acres changing from undeveloped to developed land-use classifications between about 1998 and 2002, as shown in figure 29 (Gwinnett County Department of Public Utilities, 1998 and 2002).

Methods to evaluate long-term water-quality trends in concentrations include analyzing baseflow and stormflow separately, transforming data to logarithmic space, and normalizing concentrations for flow and, for stormflow samples, seasonality. Long-term trends were considered to be significant where the slope of the time function in the linear regression was different from zero at a 0.1 level of significance (*p*-value) and where this conclusion was supported by the graphical analysis.

Seasonal- and flow-adjusted residuals of logarithmic total suspended solids stormflow concentrations for the six study watersheds from early 1996 to late 2003 are shown in figure 30. Graphical and statistical analyses, as shown for total suspended solids in figure 30, do not indicate a trend from 1996 to 2003 in adjusted stormflow concentrations of total suspended solids, total phosphorus, total zinc, or total

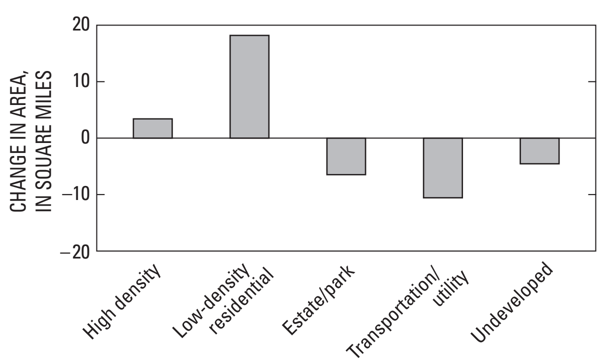



**Figure 29.** Change in land use in six watersheds in Gwinnett County, Georgia, from 1998 to 2002.

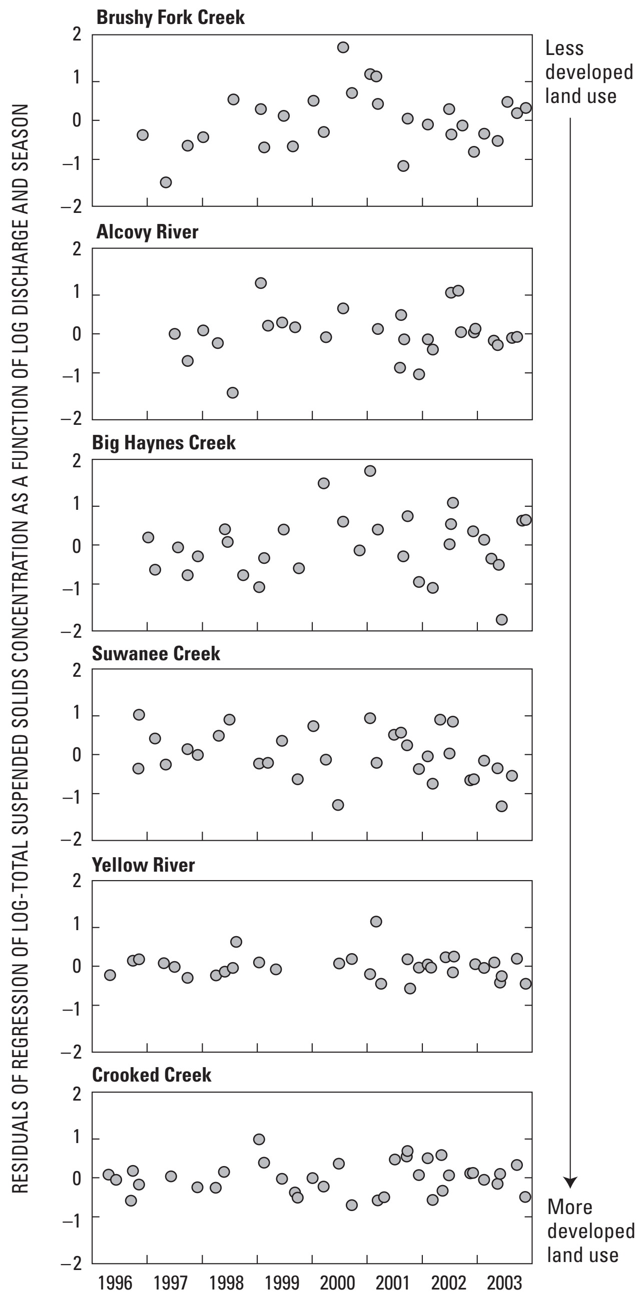



**Figure 30.** Absence of trends in stormflow total suspended solids concentrations adjusted for discharge and season in six watersheds in Gwinnett County, Georgia, 1996–2003.

dissolved solids for the sampled streams in the six watersheds studied. The absence of a trend in nonpoint-source-driven stormflow concentrations from 1996 to 2003, when land use was changing rapidly, may reflect ongoing implementation of watershed management practices, in addition to the effects of natural variability and the time lag between watershed changes and water-quality effects.

Baseflow water quality also did not show trends from 1996 to 2003 for total suspended solids, total phosphorus, and total dissolved solids, after adjusting for streamflow. Flow-adjusted total-zinc trace-metal concentrations during baseflow, however, have been decreasing since 1996, as shown in figure 31. Zinc concentrations in baseflow do not have a seasonal variation and are marginally related to sample discharge; thus, sample concentrations were flow adjusted. Flow-adjusted zinc concentrations have a strong significant time trend ($p$-value less than 0.01 for five sites, and less than 0.04 for all sites). Baseflow concentrations of trace metals other than zinc were almost always below analytical detection limits; therefore, evaluation of trends was not possible.

The cause of decreasing baseflow zinc concentrations may be changing alkalinity (pH), which is affected by impervious areas as discussed in the next section of this report. In five of the six sites, the pH has an increasing time trend ($p$-value less than 0.01). More alkaline (higher pH) water may mobilize less zinc from sediments.

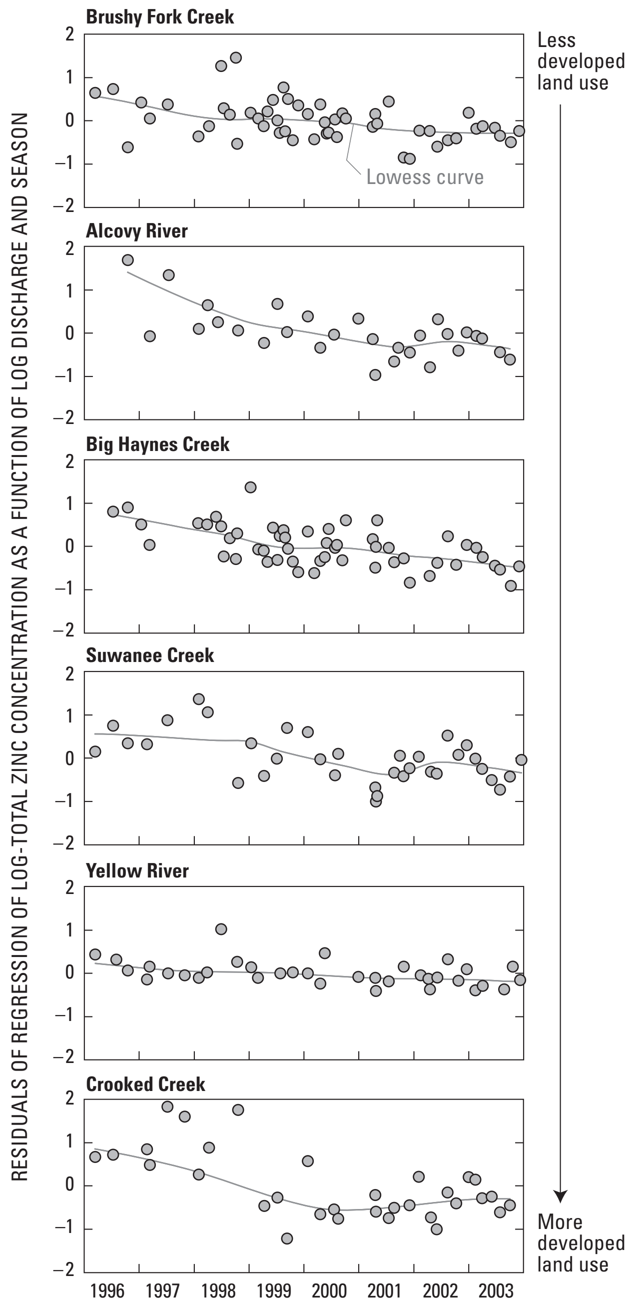



**Figure 31.** Trend in flow-adjusted residuals of logarithmic total zinc baseflow concentration in six watersheds in Gwinnett County, Georgia, 1996–2003.

# Cumulative Watershed Effects on Water Quality

A key objective of this study is to describe how natural and cultural watershed characteristics affect stream quality to inform watershed management efforts. Cumulative watershed effects on streamflow, which is a primary driver for water quality, were discussed previously. This section describes cumulative watershed effects on stream quality, including alkalinity, total suspended solids, nutrients, biological oxygen demand, and trace metals. This information may help resource managers focus watershed management approaches and may provide relations that are quantitatively adequate for predictive equations.

## Measures of Cumulative Watershed Effects

The quality of a stream or watershed may be assessed on the basis of several distinct, but functionally related, measures (metrics). Metrics of stream quality include hydrologic properties, temperature, alkalinity, constituent concentrations, constituent loads, biological indices, geomorphic indices, and land use. A metric may be measured in different ways or in different time scales that will determine how well the metric relates to some aspect of watershed quality. For example, annual loads are more effective than concentration in measuring cumulative watershed effects on constituents such as nutrients, sediment, and trace-metal pollutants because the total loading of these constituents is of concern, whereas daily or hourly maximum concentration is more effective for indicating acute effects from toxic pollutants (U.S. Environmental Protection Agency [USEPA], 1991). The "best" measure of stream quality will depend on the specific question or issue being addressed. It is useful, however, to have a primary measure that relates to a range of watershed values or beneficial uses. Loads generally represent the cumulative effect over time of many complex, interrelated watershed characteristics, constituent sources, chemical and transport processes, and other factors.

Watershed changes will work cumulatively to affect many processes in the watershed (Reid, 1993; MacDonald, 2000), as discussed previously in the section on hydrologic effects. Several watershed characteristics can be measured separately, such as slope and percent imperviousness; water-quality effects usually cannot be measured separately, only cumulatively. The load of a constituent, however, links several of these effects including hydrology, geomorphology, and geochemistry and includes effects from multiple sources occurring at a range of temporal and spatial scales (Slaymaker, 2003). One advantage of working with constituent load is that it accumulates hydrologic conditions and the range of concentration characteristics for the measurement period. For these reasons, load is often the preferred measure of cumulative watershed effects on water quality.

The annual load of total suspended sediment was selected to be the primary target or performance criterion in Gwinnett County's Watershed Protection Plan (Gwinnett County Department of Public Utilities, 2000). Also, Gwinnett County's Storm Water Design Manual for best-management practices uses total suspended solids as a performance criterion for new development to minimize impacts to the county's watersheds (Gwinnett County Department of Public Utilities, 1999). Constituent loads, computed from a watershed process model, also are used by the MNGWPD to evaluate the effectiveness of the WMP recommendations (Metropolitan North Georgia Water Planning District, 2003, sec. 3). As noted in the plan:

> "A water quality model was included in development of the District-wide WMP to help evaluate nonpoint-source and point source pollutant loadings under existing conditions and to evaluate various future management scenarios. Results of the water quality modeling were used to define watershed management programs to reduce nonpoint-source pollutant loadings in the District and to identify the most appropriate upgrades of existing infrastructure."

Loads also are being used in many total maximum daily load (TMDL) studies. Under section 303(d) of the Clean Water Act (40 CFR Part 130), the TMDL must be determined for streams that do not meet the water-quality standards set for their designated beneficial use. A TMDL is an estimate of the maximum amount of a pollutant that a water body can assimilate and still meet water-quality standards. A TMDL typically is determined from a model, and the result is allocated to the pollutant's sources for regulation and management. The quality of models used in watershed assessment and TMDL studies, and the inability to characterize the uncertainty of these models is a primary concern for practitioners (U.S. Environmental Protection Agency, 2002a).

Models used in watershed assessment studies often estimate load by simulating the hydrology and the point- and nonpoint-source yields in a watershed. In general, watershed assessment models are more accurate in simulating hydrology than streamflow water quality (Hummel and others, 2003). Also, sediment and sediment-associated constituents (such as nutrients, bacteria, and trace metals) are among the most difficult water-quality constituents to represent accurately in simulation models (Donigian and Love, 2003). An application of the results of this report and related studies is to provide observed data to improve watershed assessments. Before discussing cumulative effects on constituent loads, a simple and well-defined example of cumulative effects on stream alkalinity is presented in the following section.

## Alkalinity

The effect of natural and cultural watershed characteristics on stream chemistry is evident in the sample pH values for the six study watersheds. Examples of natural sources affecting pH include precipitation, which is slightly acidic and causes a short duration decrease (more acidic) in pH during rainfall runoff, weathering of carbonate rocks, which causes a higher (more alkaline) pH, production of organic acids in wetland areas, and diurnal changes caused by uptake of carbon dioxide (increasing pH) for photosynthesis. A human-made source of alkalinity is concrete impervious areas and drainage ways (Prestegaard, and others, 2005) such as concrete pipes, curbs, and lined channels. As shown in figure 32, there is a strong relation between impervious area in the 25-foot stream buffer, and the average sample pH for the six study watersheds ($R^2 = 0.90$). Because this relation is similar for baseflow and stormflow, the points shown in figure 32 are average pH values for all samples—stormflow and baseflow (from 59 to 85 samples per average).

Watershed characteristics close to the stream may have a greater effect on water quality than those farther from the stream, as was discussed previously for hydrologic effects. In relation to mean sample pH (combined stormflow and baseflow), the impervious area in the 25-foot stream buffer is statistically significant ($R^2 = 0.90$, $p$-value $= 0.004$), whereas watershedwide impervious area is not significant ($R^2 = 0.19$, $p$-value $= 0.40$). Runoff and infiltration from alkaline impervious areas close to streams have less time and space to be balanced by natural factors affecting pH, compared to areas more distant from streams.

The average pH for stormflow and baseflow samples from the six watersheds in this study ranges from 6.3 to 7.2, which is within minimum and maximum State criteria of 6.0 to 8.5 (Georgia Department of Natural Resources, 2004). Small changes in pH, however, can cause changes in mobilization of metals that are absorbed onto sediment particles (Drever, 1998). As discussed in the trends analysis section of this report, concentrations of total zinc during baseflow were found to be declining from 1996 to 2003. The cause for this decline may be attributed to a concurrent increasing trend in pH, which would decrease mobilization of zinc. While changes in stream pH provide an interesting and sensitive measure of watershed characteristics, loads generally are a more valuable metric of watershed effects.

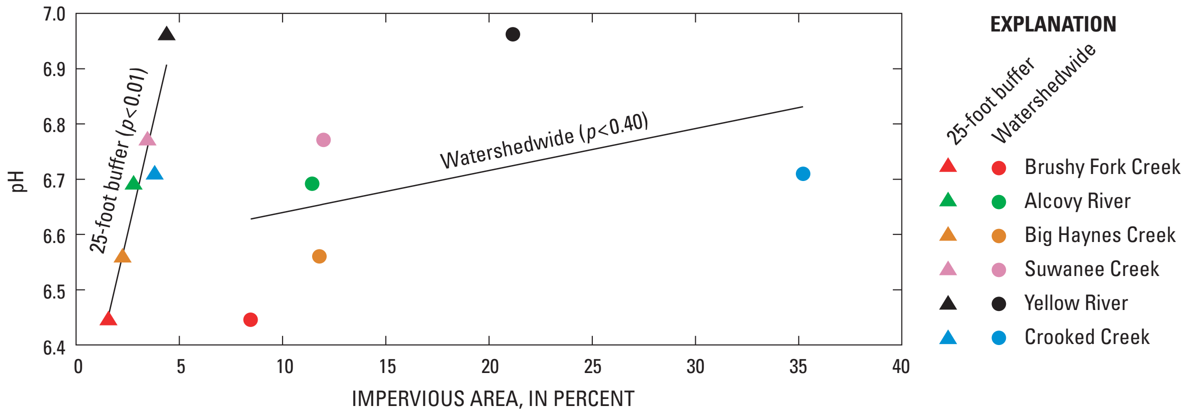



**Figure 32.** Stream pH and impervious-area watershedwide and in the 25-foot stream buffer for six watersheds in Gwinnett County, Georgia. [<, less than]

## Total Suspended Solids

Leading causes of stream impairment in the United States are sediment-associated constituents, including bacteria, excessive sediment, nutrients, and trace metals U.S. (Enivonmental Protection Agency, 2002b). Excessive sediment (siltation) can fill in channels and increase overbank flooding, fill in culverts and cause roadway overtopping, reduce aesthetic and recreational benefits, increase water-supply treatment costs, and decrease the value and usability of ponds and reservoirs. Excessive sediment also affects stream habitat, especially for organisms that live in or on the streambed at some time during their life cycle. Fine sediments and sands fill in around (embed) gravel and cobbles and eliminate vital habitat areas. Suspended sediment can directly affect aquatic fauna and reduces water clarity affecting photosynthesis (American Society of Civil Engineers, 2006; Novotny and Olem, 1994).

In addition to these direct effects on a stream, fine sediment in stormflow is closely correlated with and facilitates the transport of many other constituents, including nutrients, metals, and bacteria—as shown for stormflow samples in figure 33. Positively charged trace metal and phosphate ions tend to adsorb strongly onto negatively charged clay and fine-sediment particles (Horowitz, 1991; Hem, 1985). The correlation of total suspended solids with bacteria concentrations is likely because most bacteria are delivered to the stream during rainfall runoff (Christensen and others, 2000). The correlation of sediment with total phosphorus, total lead, and fecal coliform (fig. 33) can be due to adsorption and/or to the fact that sediment and these constituents are affected by similar sources and processes. The land uses and transport processes that increase sediment also increase many other nonpoint-source pollutants. Because these processes of pollutant wash off and transport occur primarily during stormflow, the correlations in figure 33 exist for stormflow, but not for baseflow conditions.

Erosion and sediment transport are the cumulative effect of many natural and cultural watershed factors. Natural watershed characteristics affecting instream sediment include climate, geology, soil erodibility, vegetation, area, and slope. Cultural watershed characteristics affecting instream sediment include land use and impervious surfaces, soil-disturbing activities, changes in vegetative cover, and management practices. Important watershed processes affecting instream sediment load include precipitation intensity and quantity, hydrograph characteristics, landscape erosion, delivery of eroded material from the landscape to the stream, and instream sediment scour, transport, deposition, and storage (Julien, 1994; American Society of Civil Engineers, 2006).

Because these processes operate primarily during precipitation and runoff, baseflow and stormflow total suspended solids sample results are distinct and have distinct relations with discharge (fig. 19). As indicated in figure 17, the median concentration of total suspended solids in stormflow is about 30 to 180 times greater than in baseflow. This increase in total suspended solids with increasing discharge has an exponential effect on total suspended solids load, with 97 to 99 percent transported during stormflow as shown in figures 21–26. Changes in precipitation and discharge can cause an exponential change in the sediment load; thus, hydrology often drives water-quality conditions.

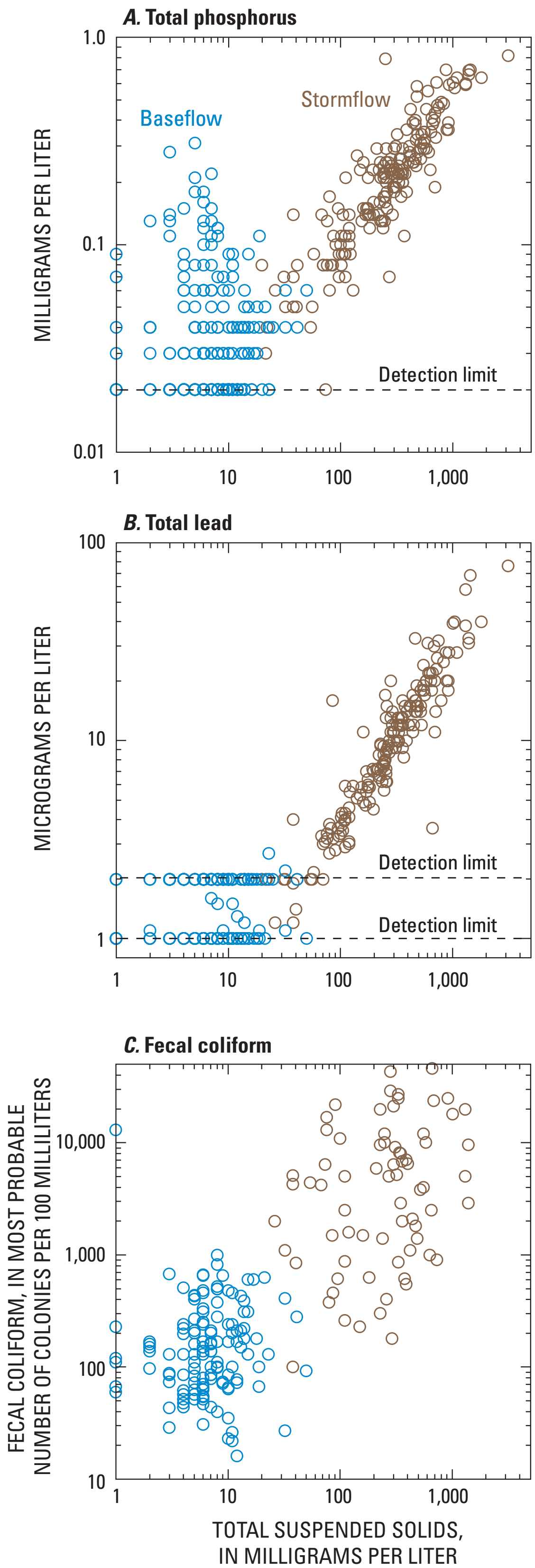



**Figure 33.** *(A)* Total phosphorus, *(B)* total lead, and *(C)* fecal coliform for six watersheds in Gwinnett County, Georgia, for water year 2003.

*Does sediment come from watershed erosion or stream channel erosion?*

Sources of sediment transported in a stream include the watershed landscape and stream channel. While instream sediment transport can be measured, the relative contributions from erosion of the landscape and stream channel are usually unknown. Many factors affect this relative contribution. The delivery of sediment eroded from the landscape to the stream decreases with increasing watershed size and increases with increasing watershed development (Novotny and Olem, 1994). Stream channel erosion is affected by the hydraulic capacity to erode and transport sediment relative to the supply of sediment stored along the channel and delivered from the landscape (Julien, 1994). Estimates of the relative contributions from the landscape and stream channel to sediment yield vary widely. In an arid, urbanizing watershed of southern California, Trimble (1997) compared measured channel erosion from more than 100 channel sections and total sediment transport from station data during a 10-year period and found that channel erosion accounted for about two-thirds of the measured sediment yield. The rate of channel erosion found by Trimble (1997) for an arid region is unlikely to be representative of Georgia's Piedmont physiographic province, with its typically more cohesive soils and more abundant streambank vegetation. In a study of the contribution of streambed and stream bank erosion to the sediment budget of Peachtree Creek in Atlanta, Georgia, from 1970 to 1990, Weber and others (2004) estimated channel erosion to be contributing about 50 percent of the total sediment discharge at the watershed outlet. They also found a trend of upstream channel degradation and downstream channel aggradation typical of eroding channels. The question of sediment source areas cannot be solved in this study; however, the relation between sediment yield and watershed characteristics can be described. The strong relations between watershed characteristics and instream sediment yield exist in part because similar factors affect landscape erosion and delivery of eroded material to the stream (sediment delivery ratio), and the erosion and resuspension of sediments in the streambed and stream banks. Management of these factors may help control erosion and transport from both landscape and stream-channel sources.

As shown in figures 34 and 35, average annual total suspended solids yield (1998–2003) increases with high-density and transportation/utility land uses; this average annual yield generally decreases with low-density residential, estate/park, and undeveloped land uses. Watershedwide impervious area provides a measure of watershed effects from multiple land uses that may increase sediment yield ($R = 0.86$). The correlation of average annual precipitation with average annual total suspended solids yield is positive, but weak because there is little variation between these neighboring watersheds and because of the outlier effect of Crooked Creek (highest yield point, fig. 34). Drainage area may have a weak correlation, but in the correct direction, with larger basins having smaller sediment yield (Julien, 1994).

The strength of the relations between average annual total suspended solids yield and watershed characteristics provides an opportunity to create a lumped parameter regression model. Watershed precipitation and area are statistically significant ($p < 0.05$ and $p < 0.07$, respectively) in relation to total suspended solids yield, when combined with watershedwide impervious area and when all parameters are log transformed. Although the dataset is limited to Gwinnett County, the regression model shown in figure 36 demonstrates how watershed characteristics can be used to estimate total suspended solids yield. The standard error of the curve is 8 percent.

Year-to-year differences in precipitation cause annual differences in sediment load that far exceed those caused by other changing watershed characteristics. For example, total suspended solids yield in these watersheds for 2003 (a wetter than average year) ranged from 7 to 28 times greater than that during 1999 (an extreme drought year). The average annual total suspended solids load for 1998–2003 is 3 to 8 times greater than the load for the 1999 drought year, but is only 35 percent to 42 percent of the load in the wet 2003 year for these six watersheds, as indicated in figures 21–26.

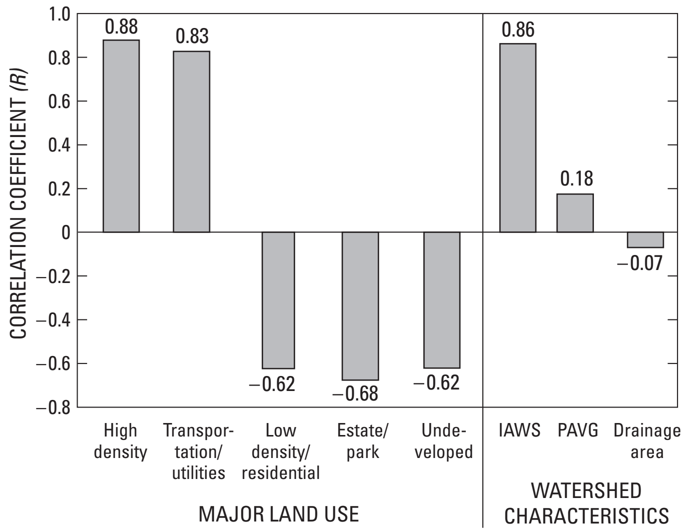



**Figure 35.** Correlation *(R)* of average annual (1998–2003) total suspended solids yield with major land uses and with watershed impervious area (IAWS), average annual precipitation (1998–2003, PAVG), and drainage area for six watersheds in Gwinnett County, Georgia.

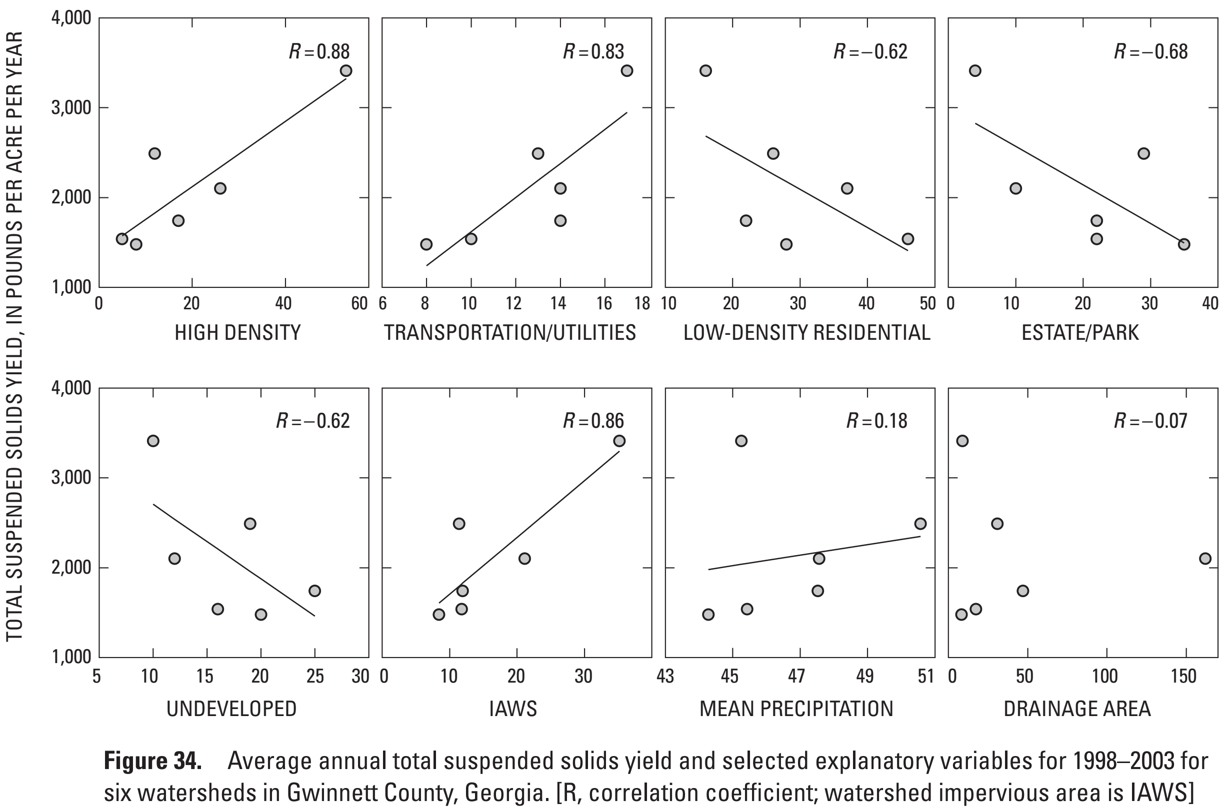



**Figure 34.** Average annual total suspended solids yield and selected explanatory variables for 1998–2003 for six watersheds in Gwinnett County, Georgia. [R, correlation coefficient; watershed impervious area is IAWS]

The countywide average precipitation for 1998–2003 is about 7 inches less than the long-term average of 53.6 inches for the rain gage at Norcross (SERCC, Norcross 4 N, 1949–2003). If the long-term average rainfall had occurred during 1998–2003, the result would have been higher yields. Total suspended solids yields computed with the regression shown in figure 36 using the long-term *average* 53.6-inch rainfall range from 3,060 to 7,310 pounds per acre per year [(lb/acre)/yr] for the six watersheds. These estimates are 90 percent greater, on average, than the observed total suspended solids yield from 1,480 to 3,410 (lb/acre)/yr for 1998–2003. This discrepancy, given 6 years of data collection to obtain an average value, highlights the potential problems of using an average-year target value for total suspended solids.

Figure 37 shows how a regression of log-transformed total suspended solids yield on log transformed *annual* precipitation (instead of average annual precipitation), watershed impervious area, and watershed size can account for about 80 percent of the observed variation. Only the precipitation values and loads change from year to year in this dataset. Total suspended solids yields computed with the regression shown in figure 37 for an *annual* 53.6-inch rainfall range from 1,880 to 5,490 (lb/acre)/yr for the six watersheds. These estimates are 23 percent greater, on average, than the observed total suspended solids yield for 1998–2003.

Comparison of the standard errors shown in figures 36 and 37—8 percent and 52 percent, respectively—illustrates how uncertainty decreases with time averaging; that is, a 6-year average can be estimated with more accuracy than an individual year. Because of the natural, exponential variation of load with precipitation, however, it is problematic to compare an average target yield to a monitored yield for a single year or from only a few years of data. Precipitation that differs from the long-term average may affect measured average yield much more than watershed management practices. Comparisons of equations to estimate annual and average annual total suspended solids yields indicate a sound basis for a more meaningful annual criterion that could be adjusted or normalized for annual precipitation.

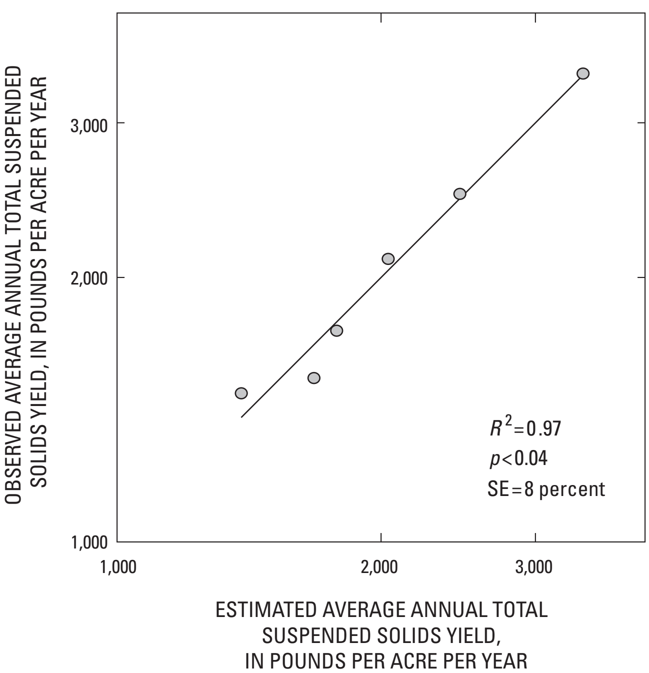



**Figure 36.** Observed and estimated average annual total suspended solids yield for 1998–2003 for six study watersheds in Gwinnett County, Georgia. Estimated yield is a function of watershed impervious area, average precipitation, and drainage area. [<, less than; SE, standard error]

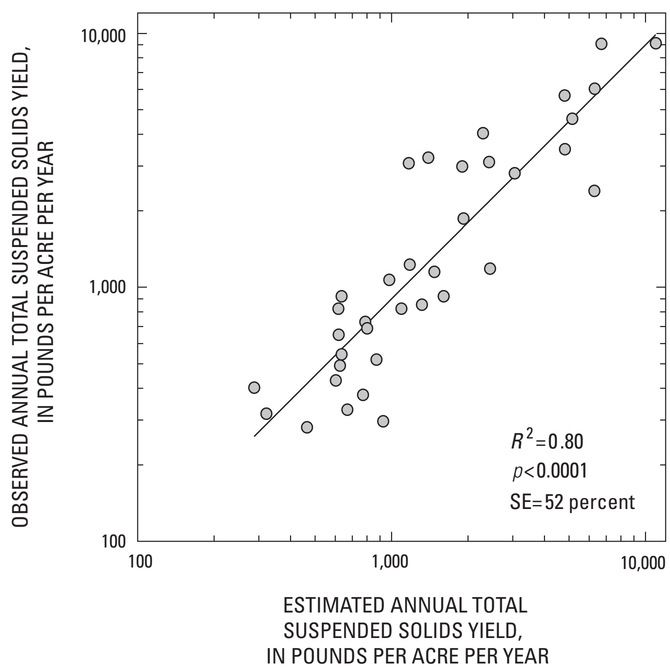



**Figure 37.** Observed and estimated annual total suspended solids yield for 1998–2003 for six watersheds in Gwinnett County, Georgia. Estimated yield is a function of watershed impervious area, annual precipitation, and drainage area. [<, less than; SE, standard error]

*Do total suspended solids measure how much sediment is in the streams?*

Analyses in this study and previous investigations show that the amount of suspended sediment in streams is greater than indicated by the total suspended solids (TSS) analysis. The amount of suspended material in water is usually determined using laboratory analytical methods for TSS and/or suspended sediment concentration (SSC). The TSS and SSC analytical methods are different and typically produce different results. The SSC analytical method measures the dry weight of the sediment in a sample of a known volume. The TSS analytical method was originally developed for use on wastewater samples, but has become a common measure of suspended material in streams because the method is used broadly as a regulatory parameter, and is an inexpensive laboratory analysis. Laboratory methods for TSS differ among laboratories, but usually involve measuring the dry weight of sediment in *a subsample* of the available sample volume, rather than in the entire sample. Gray and others (2000) evaluated 3,235 paired SSC and TSS sample analyses and found that this subsampling procedure can undermeasure the total sediment in a sample, particularly when the amount of sand (particles larger than 0.062 millimeter [mm] and less than 2 mm) in a sample exceeds about one quarter of the total sediment mass.

In this study, SSC analyses did not begin until 2001. Paired TSS and SSC data were evaluated from 160 samples collected between 2001 and 2004 at the six study watersheds. Sand sizes larger than 0.062 mm composed 37 percent of the sediment on average for 81 stormflow samples with size data. The concentration of TSS typically was less than SSC, in agreement with the findings of Gray and others (2000) as shown in figure 38, in which most of the data plot on the SSC side of the line of equal value. From a regression of these data, SSC is equal to about 1.6 times TSS with an $R^2$ of 0.96 and a *p*-value of zero. Thus, actual SSCs in these streams are about 60 percent more than that indicated by TSS.

The total sediment load in a stream is the sum of the suspended load and the bed load. Bed load is typically made up of sand and gravel particles that are not suspended by the flow but instead move by rolling or sliding along the channel bottom. Bed load is important to stream functions, but it is often not measured and is not included in these measurements. Total suspended plus bed load for these streams, however, is greater than the suspended sediment load alone, as reported herein. Although not a measure of total load, TSS is quantitatively related to SSC and bed load in these streams.

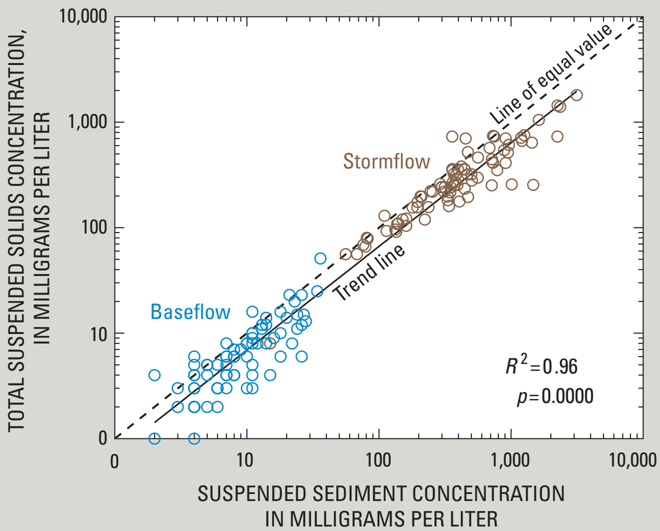



**Figure 38.** Total suspended solids and suspended sediment concentration for 160 samples from the six study watersheds in Gwinnett County, Georgia, 1996–2003.

## Total Phosphorus

Phosphorus and nitrogen are essential plant nutrients, which can cause excessive growth of undesirable plants and algae in water bodies, leading to reduced oxygen levels and eutrophication of ponds and lakes. Phosphorus is not very soluble and tends to remain attached to sediment particulates. Total phosphorus includes dissolved and sediment-associated fractions. Both phosphorus and nitrogen are affected by biological and chemical processes that can mobilize both nutrients to or from soil, water, the atmosphere, and organisms.

Under normal conditions algae and other aquatic plants will grow until limited by available phosphorus or nitrogen. Algal blooms can impair habitat, reduce recreational value, increase water-supply treatment costs, and (under some conditions) lead to increased trihalomethanes on disinfection with chlorine (Novotny and Olem, 1994). Excessive growth and decomposition of aquatic plants and algae cause reduced oxygen levels in water bodies. High phosphate loads typically cause eutrophication of freshwater lakes, whereas high nitrate loads typically cause eutrophication of coastal waters and estuaries (Mueller and Helsel, 1996; Drever, 1998).

Common nonpoint sources for phosphorus include weathering of natural rocks and soils and applied fertilizers. Common point sources are discharges of treated municipal wastewater, sewer overflows, and leaking septic tanks. Legislated restrictions on the use of phosphate detergents and improvements to wastewater treatment facilities during the late 1980s and early 1990s, resulted in substantial reductions of phosphorus concentrations in wastewater effluent and in rivers at many locations during the 1990s (Frick and others, 1996). Phosphorus concentrations, however, still increase substantially through urban areas along the Chattahoochee River from the combination of point and nonpoint sources.

Big Haynes Creek watershed had a small wastewater treatment plant until about 2004 that did not include advanced treatment and removal of phosphorus. The dilution of this point-source phosphorus with increasing baseflow is evident in figure 39, which illustrates the typical concentration to discharge relations for both point sources (decreasing concentration with increasing discharge in baseflow) and nonpoint sources (increasing concentration with increasing discharge in stormflow). Although this phosphorus point source contributed to higher concentrations and yields in baseflow, nonpoint sources still produced higher concentrations and account for 78 percent of the yield for Big Haynes Creek.

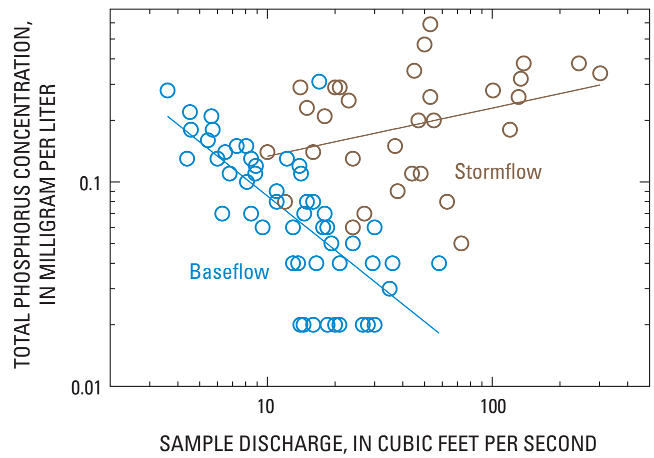



**Figure 39.** Total phosphorus concentration and discharge at Big Haynes Creek, Gwinnett County, Georgia, 1996–2003.

Water-quality criteria have not been established for nutrients in Gwinnett County, because nitrogen and phosphorus are not directly toxic except at very high concentrations. The USEPA, however, has developed recommended concentration criteria for phosphorus and nitrogen for lakes in the ecoregion including Gwinnett County (U.S. Environmental Protection Agency, 2000). Cumulative phosphorus load, rather than concentration, is the preferred metric for assessing impacts of nutrients on aquatic plant growth in a water body. GaEPD has not set phosphorus load limits for any of the watersheds within Gwinnett County. GaEPD, however, has set phosphorus load limits for Alcovy River and Yellow River upstream from their impoundment in Jackson Lake. The load limits for Alcovy River and Yellow River are 0.34 and 0.41(lb/acre)/yr, respectively (Georgia Department of Natural Resources, 2004).

Phosphorus concentrations typically are several hundred percent higher in stormwater than in baseflow for these six watersheds (fig. 17*C*). Phosphorus concentrations are closely related to total suspended solids, as discussed previously (fig. 33). Stormflow carries 92 percent of the total phosphorus load for the six watersheds, because of its increased concentration and discharge. This is an example of how constituent concentration and load are affected by an accumulation of drivers including varying sources, chemical interactions with other constituents, and transport processes.

Phosphorus loads have a fairly strong positive correlation with high-density and transportation/utility land uses and a fairly strong negative correlation with low-density residential and estate/park uses (fig. 40). There is no significant correlation with undeveloped land use. The negative correlation with low-density residential land use (from 1/3 to 5 acres, $R = -0.72$) is somewhat surprising, because urban residential fertilizer application has been considered as a phosphorus source in past studies (Mueller and Helsel, 1996). This negative correlation with residential land use is slightly stronger ($R = -0.81$) for large-lot (from 1 to 5 acres) residential land uses. This negative correlation may be partly due to the similar effect of large-lot residential land use on streamflow hydrology and on total suspended solids yield. Impervious area provides a measure of watershed effects that increase phosphorus yield from multiple land uses. Total phosphorus load has a positive correlation with watershedwide impervious area ($R = 0.56$) and a stronger correlation with impervious area in the 25-foot stream buffer ($R = 0.75$).

Septic tanks are a suspected source of nutrients in urban watersheds; however, there was no clear relation between watershedwide septic tank density and total phosphorus concentration or load for these watersheds. This lack of relation was true even when working with only the baseflow part of phosphorus load. Further study of the potential effects of septic tanks on water quality is needed.

Watershed characteristics can be used to estimate the average annual phosphorus load for these six watersheds. Figure 41 shows the observed and predicted *average annual* total phosphorus load (1998–2003), where the predicted values are based on average annual precipitation, slope, and the percentage of large-lot (from 1 to 5 acres) residential land use in each watershed. This relation is statistically significant and explains 90 percent of the variation in average annual phosphorus load ($R^2 = 0.90$, $p$-value $< 0.04$). A similar regression of *annual* values of total phosphorus for the period 1998–2003 from annual precipitation, watershed slope, and large-lot residential land use also is statistically significant ($R^2 = 0.76$, $p$-value $< 0.001$) and could be useful in evaluating phosphorus load for a single year.

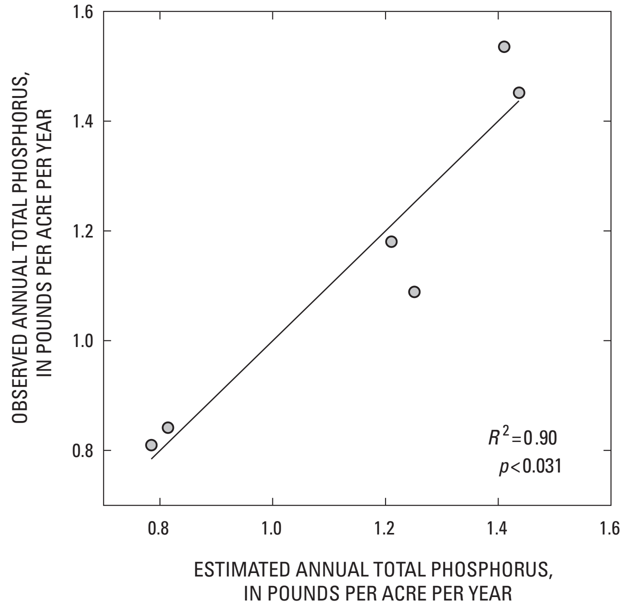



**Figure 41.** Observed and estimated average annual total phosphorus yield (1998–2003) for six watersheds in Gwinnett County, Georgia. Estimated values are a function of watershed slope and land use. [<, less than]

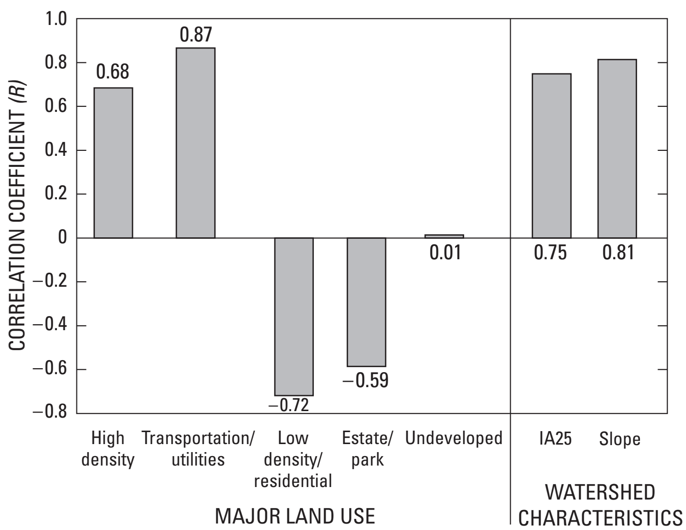



**Figure 40.** Correlation *(R)* of average annual (1998–2003) total phosphorus yield with major land uses and with impervious area in the 25-foot stream buffer (IA25), and average watershed slope for six watersheds in Gwinnett County, Georgia.

## Dissolved Phosphorus

The relation of dissolved constituents to watershed characteristics is particularly complex because of the different sources associated with baseflow and stormflow conditions. As shown in figure 42, most watershed characteristics have a positive relation to dissolved phosphorus for one flow regime, and an inverse relation for the other, which is due in part to how these land uses affect hydrology. Nonpoint-source dissolved phosphorus in baseflow comes from ground water (from natural and cultural sources) and, thus, has a relation to watershed characteristics similar to that found for baseflow itself. The relations of land use to dissolved phosphorus in stormflow (nonpoint sources) are similar to those described for total phosphorus. Although dissolved phosphorus appears to have different sources in baseflow and stormflow, the mean concentrations for baseflow and stormflow differ by less than

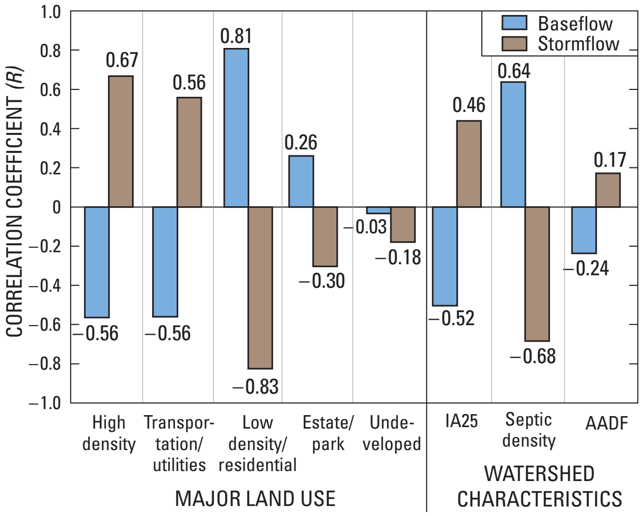



**Figure 42.** Correlation *(R)* of average annual (1998–2003) dissolved phosphorus yield with major land uses and with impervious area in the 25-foot stream buffer (IA25), septic tank density (per square mile), and average annual daily flow (AADF) of treated wastewater in million gallons for six watersheds in Gwinnett County, Georgia.

30 percent, except for Big Haynes Creek, where the difference is 70 percent. Also, there is not a statistically significant relation between dissolved phosphorus yield and the average annual daily flow of wastewater treatment plants for Yellow River, Suwanee Creek, and Big Haynes Creek.

Dissolved phosphorus makes up less than 15 percent of the total phosphorus load for these six watersheds for 1998–2003. For dissolved phosphorus load, an average of 45 percent is transported during baseflow for all of the watersheds except Big Haynes Creek, in which 94 percent is transported during baseflow because of the upstream wastewater point source.

Septic tank density and low-density residential land use are statistically significant ($p<0.001$) in relation to annual dissolved phosphorus yields in baseflow, but not stormflow, after adjusting for differences attributed to precipitation. Septic tank density and low-density residential land use, however, are highly correlated ($R=0.96$), so the specific influence of either characteristic on dissolved phosphorus is uncertain. It is reasonable to assume that dissolved phosphorus yield is related to septic tank density (at least in the stream buffer); but this result is not expected for low-density residential land use, which is inversely correlated to total phosphorus yield. Low-density residential land use may be operating as a surrogate for septic tank density in this case. If the statistical relation of septic tank density to baseflow dissolved phosphorus yield reflects a real process, then a portion of water treated in septic tanks is nonconsumptive and does return to streams through the ground as baseflow. Further research is needed to address whether septic tanks (particularly in the riparian zone) influence nutrient concentration and loads in these watersheds.

## Nitrogen

Nitrogen, like phosphorus, is an essential plant nutrient in natural waters. The major sources of nitrogen are point-source effluent from sewage treatment plants, rainfall, fertilizer application, and natural dissolution of minerals by surface and ground waters. Nitrogen occurs in several different forms in natural waters, including dissolved and particulate organic nitrogen and inorganic nitrogen (ammonium, nitrite, and nitrate). Nitrogen is readily converted from one form to another, and the relative amount in different forms is controlled by environmental conditions. Nitrate loads typically do not threaten water quality in freshwater bodies where the limiting nutrient for algal growth typically is phosphorus (Mueller and Helsel, 1996).

Stormflow carries 70 percent of average annual total nitrogen (1998–2003) for these six streams. Therefore, cumulative watershed effects on hydrology also affect total nitrogen load, as indicated in figure 43. Total nitrogen load is more highly correlated with impervious area in the 25-foot stream buffer ($R=0.76$) than with watershedwide impervious area ($R=0.58$). Treated wastewater contributes much of the nitrogen load associated with baseflow for Yellow River, Suwanee Creek, and Big Haynes Creek, as seen in the relation with average annual daily effluent flow (fig. 43, $R=0.89$).

Cumulative watershed effects on nitrate plus nitrite are similar to those for total nitrogen, except wastewater effluent is more significant. Wastewater treatment operations since the late 1970s convert nitrogen as ammonia to nitrogen as nitrate. Nitrate plus nitrite accounts for 46 percent of the total nitrogen load for the three watersheds with wastewater treatment facilities, whereas nitrate plus nitrite accounts for only 26 percent in the other three watersheds. The nitrate-plus-nitrite load for the three watersheds with wastewater treatment facilities is, on average, more than two times the load in the watersheds without treated wastewater.

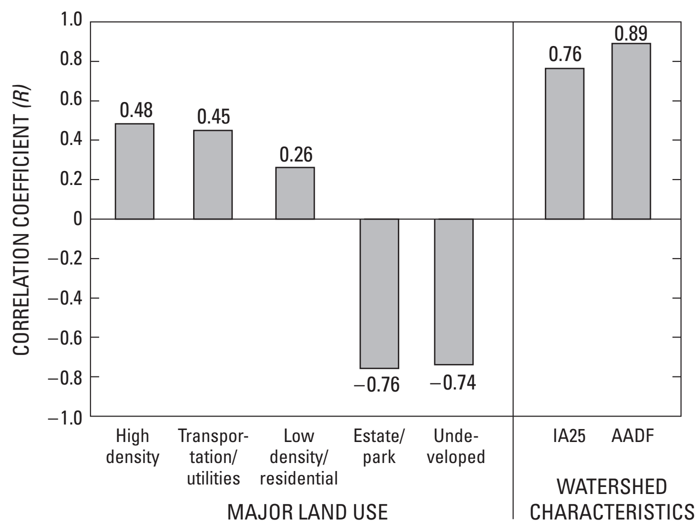



**Figure 43.** Correlation *(R)* of average annual (1998–2003) total nitrogen yield with major land uses and with impervious area in the 25-foot stream buffer (IA25) and with average annual daily flow (AADF) of treated wastewater in million gallons for six watersheds in Gwinnett County, Georgia.

## Total Dissolved Solids

Total dissolved solids represent constituents in the dissolved phase. As ground water travels through the subsurface, it dissolves soluble constituents and, thus, has relatively high total dissolved solids concentrations when entering the stream as baseflow; conversely stormflow is diluted by precipitation, which has extremely low total dissolved solids, as shown in figure 17*B*. This relation also is true for specific conductance (which serves as a surrogate of total dissolved solids) as indicated in figure 3.

Concentrations of total dissolved solids in baseflow and stormflow increase with increasing urbanization (from left to right on figure 17*B*). Total dissolved solids in baseflow also are impacted by point-source wastewater treatment outflows on Suwanee Creek and Yellow River (fig. 17*B*). Concentrations of total dissolved solids are diluted with increasing discharge in both baseflow and stormflow as shown in figure 19*B* for Crooked Creek. The concentration to discharge relation is continuous for baseflow and stormflow, and is linear in logarithmic space (fig. 19*B*). The portion of total dissolved solids transported in stormflow varies from 27 to 49 percent.

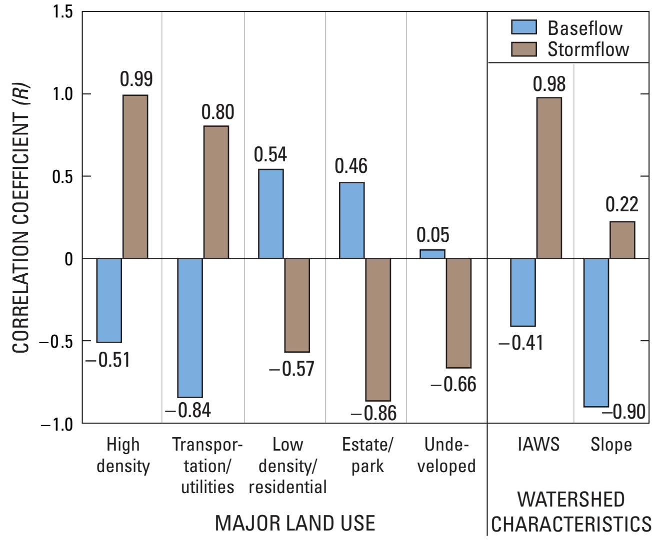



**Figure 44.** Correlation *(R)* of average annual (1998–2003) biochemical oxygen demand yield with major land use and with watershed impervious area (IAWS) and average watershed slope for six watersheds in Gwinnett County, Georgia.

## Biochemical Oxygen Demand

Dissolved-oxygen concentration is an important measure of the capacity of a water body to support oxygen-consuming (aerobic) aquatic life. Oxygen is supplied to surface water by direct assimilation from the atmosphere and by photosynthesis. Oxygen is used in biological processes of metabolism and decay acting on organic constituents. If the oxidizable load is excessive, dissolved oxygen concentrations can drop to levels that will not support fish and other aerobic organisms. Biochemical oxygen demand (biological oxygen demand) is a measure of the oxygen that is required by microbes to digest the load of organic constituents in the water. This process is measured in this study using the standard 5-day incubation and reaction period (biological oxygen demand-5; Hem, 1985). Chemical oxygen demand is a similar measure determined using chemicals to oxidize the organic material in a sample (Hem, 1985).

Prior to enactment of the Clean Water Act, and the extensive treatment of wastewater point sources, organic loading and oxygen depletion were primary water-quality issues and biological oxygen demand and chemical oxygen demand (COD) were closely monitored. With the control of point sources, however, biological oxygen demand is primarily a nonpoint-source pollutant, and watershedwide impervious area is an effective explanatory variable for biological oxygen demand load, as indicated in figures 44 and 45. Although figure 44 includes the correlation of biological oxygen demand with baseflow, it is stormflow that is the primary driver, because 83 percent of the load, on average, is carried by stormflow for these six watersheds.

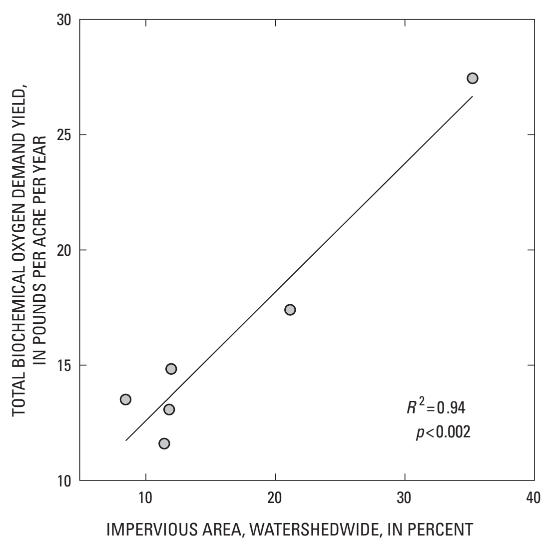



**Figure 45.** Observed average annual (1998–2003) biochemical oxygen demand yield and watershed impervious area for six watersheds in Gwinnett County, Georgia. [<, less than]

## Total Zinc

Zinc is a naturally-occurring constituent in the environment; however, cultural factors cause elevated zinc levels in the six study watersheds. Zinc oxide is used in the manufacture of a broad array of products such as rubber, plastic, paint, adhesives, batteries, fungicides, lubricants, cosmetics, and foods. The largest contributor to worldwide anthropogenic emissions of zinc is regarded to be fossil fuel combustion from coal-fired power plants and automobile emissions (Nriagu, 1980). In urban areas such as Metropolitan Atlanta, however, other transportation-related sources, particularly from tire wear, also may contribute substantially to zinc loads (Rose and others, 2001; Callender and Rice, 2000). Zinc oxide is added in the manufacturing of automobile tires to accelerate the cure time, improve the vulcanization process, and reinforce the rubber. Zinc oxide as a percentage of total tire mass in typical tire compositions was found in one study to be about 1.4 percent for automobile tires and 2.8 percent for truck tire retreads (California Integrated Waste Management Board, 1996).

Concentrations of total zinc (for total unfiltered water samples) are highly correlated with those of lead, copper, and chromium ($R$ values range from 0.79 to 0.91). Cadmium results had too few uncensored values for statistical evaluation. Thus, elevated zinc concentrations may be indicative of elevated concentrations of other trace metals. Zinc concentrations, however, range from 3 to 20 times greater than those of lead, copper, and chromium at the six study sites. Zinc concentrations were typically above detection limits, whereas for other metals, concentrations were below detection limits in more than half of the baseflow samples and in stormflow samples, as noted in tables 7–12.

Callender and Rice (2000) found that total zinc concentrations in stream and reservoir sediments of the Chattahoochee River Basin peaked in Metropolitan Atlanta and declined rapidly moving upstream and more gradually moving downstream from Atlanta. Their study found strong correlations between zinc concentrations and traffic density. In a study of dissolved zinc concentrations, Rose and others (2001) found dissolved concentrations to decrease by several factors between samples collected from urban street runoff, shopping center runoff, suburban street runoff, instream stormflow, and instream nonstormflow.

Van Metre and Mahler (2003) found that rooftop washoff contributed 55, 46, and 45 percent of the instream load of zinc, mercury, and lead, respectively, in a 12.93-square-mile watershed with 29-percent rooftop impervious area. Disintegration of asphalt and metal roofing materials contributed an estimated 20 and 18 percent of the instream load of zinc and lead, respectively. Atmospheric deposition of particles onto rooftops accounted for more of the zinc and lead in rooftop runoff than did roofing materials. These findings are for the sediment-bound trace elements, not the dissolved phase fraction. In the Gwinnett County study, the concentrations reported for total trace metals and total nutrients include the dissolved and sediment-bound fractions. Most of the trace metals, however, are bound to particulates at the pH levels found in natural streams.

Total zinc yield is strongly correlated with high-density urban land use and transportation/utility land use, and is inversely correlated with estate/park and undeveloped land use, as shown in figures 46 and 47. The strong correlation of total zinc load with transportation impervious area and with total watershed impervious area ($R=0.96$ and $R=0.95$, respectively) confirms the impacts of impervious surfaces both as source areas and as efficient transport pathways for trace metals. From 83 percent to 95 percent of the total zinc load is transported in stormflow.

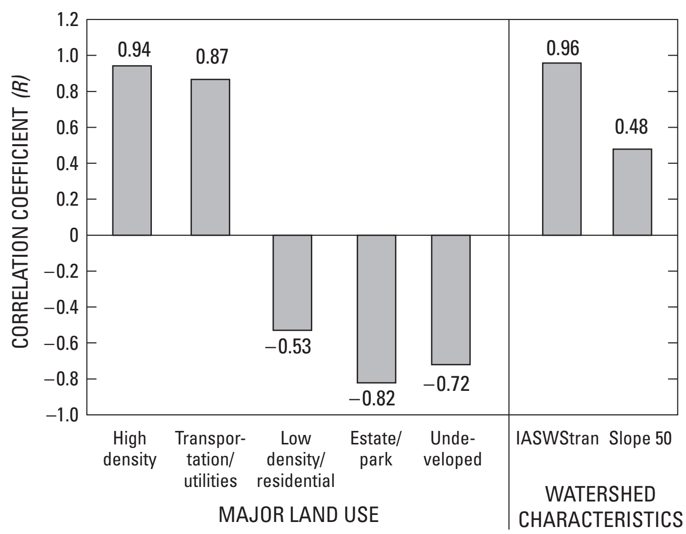



**Figure 46.** Correlation *(R)* of average annual (1998–2003) total zinc yield with major land uses and with watershed transportation impervious area (IAWStran) and slope in the 50-foot stream buffer (Slope 50) for six watersheds in Gwinnett County, Georgia.

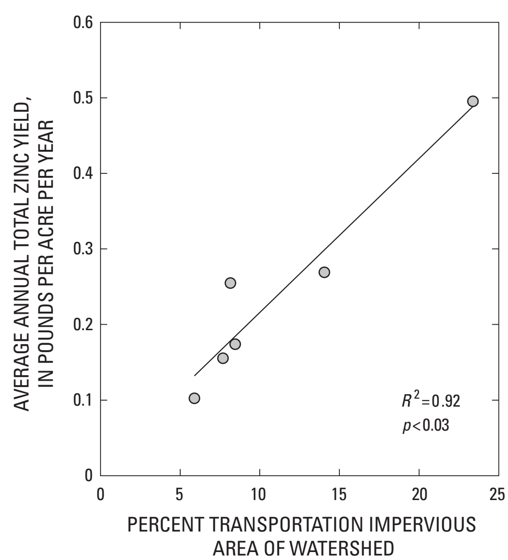



**Figure 47.** Average annual (1998–2003) total zinc yield and percent of watershed in transportation impervious area, for six watersheds of Gwinnett County, Georgia. [<, less than]

# Summary

The results of this investigation provide comprehensive, consistent, long-term, watershed-based information that resource managers can use in watershed management in Gwinnett County, Georgia. Findings are based on continuous flow and water-quality data and more than 10,000 analyses of more than 430 water-quality samples of monitored streams in six study watersheds. Sample concentrations and continuous discharge data were used to compute loads for selected constituents from 1998 to 2003. Analytical results for individual samples are available at *nwis.waterdata.usgs.gov/ga/nwis/qwdata,* and the project Web page may be viewed at *ga2.er.usgs.gov/urban/gwinnett*.

Changing stream hydrology has an important effect on water-quality and aquatic habitat. Primary factors affecting stream hydrology (after watershed size and climate) within Gwinnett County are watershed slope and land use. Baseflow yield as a percentage of precipitation is strongly influenced by watershed slope ($R^2 = 0.89$, $p<0.005$); however, there is not a significant relation between stormflow and slope. Watershed imperviousness is statistically significant in explaining baseflow, when combined with watershed slope at a *p*-value of 0.005. A linear regression of average baseflow yield (1998–2003) as a percentage of precipitation on stream buffer impervious area and stream buffer slope has an $R^2$ of 0.99 and $p<0.001$. Stormflow yield as a percentage of precipitation increases with watershedwide imperviousness ($R^2$ of 0.91, $p<0.01$), but the relation is primarily defined by the group of four watersheds with impervious areas less than or equal to 12 percent and the two watersheds with impervious areas of 21 and 35 percent.

For the six study watersheds in Gwinnett County, watershedwide imperviousness up to 12 percent does not have a well-defined influence on stream hydrology, whereas the watersheds with 21 and 35 percent imperviousness are clearly impacted. These results agree with previous studies that describe a threshold of influence from watershedwide impervious area of about 10 percent. In the stream corridor, however, imperviousness from 1.6 to 4.4 percent appears to affect baseflow and stormflow for all six watersheds. The slope of the relation also is much steeper for the stream corridor compared to the watershedwide imperviousness. This relation clearly implies that land uses in the stream corridor region have a greater hydrologic and, thus, water-quality influence than watershedwide land uses. Impervious area probably affects hydrology both directly and as an indicator of other factors, including high-intensity land uses and paved drainage networks.

Concentration to discharge relations were used to develop regression models to compute constituent loads using the USGS LOAD ESTimator program. A unique method was developed in this study for two-distribution sample data that have unique concentration to discharge relations for baseflow and stormflow. The method calibrates the model using separate baseflow and stormflow sample datasets and runs the model on hydrographs of the total flow as well as the baseflow. Without this method, a linear-regression model overestimated loads in attempting to fit a single curve to discharge concentrations of both baseflow and stormflow. The method reduces model error and provides estimates of the load associated with the baseflow and stormflow parts of the hydrograph. The portion of total load carried in baseflow varies widely with constituent, watershed characteristics, and hydrology. This information is valuable to assess general watershed-management approaches to mitigate excessive constituent loading.

An evaluation of the effects of model time step found that the model should be run at a time step similar to the time intervals represented by the water-quality samples used for model calibration. As the time step increases for a discharge time series, averaging will reduce the instantaneous peaks. Load increases exponentially with discharge, so running a model with discharge time steps that are shorter or longer than the discharge duration represented by the samples used for model calibration will bias the load estimates higher or lower, respectively.

The quality of a stream or watershed may be assessed using several different methods and time scales that will determine how well that metric describes some aspect of watershed quality. The “best” measure of stream quality will depend on the specific question or issue being addressed. Loads generally represent the cumulative effect over time of many complex, interrelated watershed characteristics, constituent sources, chemical and transport processes, and other factors.

Annual load of total suspended sediment is a target or performance criterion in Gwinnett County’s Watershed Protection Plan and its Storm Water Design Manual. Because erosion and sediment transport processes operate primarily during precipitation and runoff, baseflow and stormflow total suspended solids concentrations have distinct populations and distinct relations with discharge. The median concentration of total suspended solids in stormflow ranges from 30 to 180 times greater than in baseflow. This increase in total suspended solids concentration with increasing discharge has a multiplied affect on total suspended solids load, 97 to 99 percent of which is transported during stormflow. Average annual total suspended solids yield for 1998–2003 in the six watersheds increases with high-density and transportation/utility land uses, and generally decreases with low-density residential, estate/park, and undeveloped land uses. Watershedwide impervious area provides a measure of watershed effects that increase sediment yield ($R = 0.86$) from multiple land uses.

Annual loads are a good metric of watershed protection because they indicate the cumulative watershed effects relating to nonpoint-source pollution. Annual total suspended solids loads vary exponentially with changing annual precipitation and load for the wettest year was up to 28 times greater than for the driest year between 1998 and 2003. The *average* annual total suspended solids load for 1998–2003 is from 3 to 8 times greater than the load for the 1999 drought year, and only from 35 to 42 percent of the load in the wet 2003 year for these six watersheds. Thus, average annual metrics of watershed performance may have limited value because of these large annual variations. Comparisons of equations to estimate annual

(for a given year) and average annual total suspended solids yield indicate a sound basis for a more meaningful annual criterion that could be adjusted or normalized for annual precipitation.

Total phosphorus loads have a positive correlation with high-density and transportation/utility land uses and a negative correlation with estate/park and low-density residential land uses. Total phosphorus load has a positive correlation with watershedwide impervious area ($R=0.56$) and a stronger correlation with impervious area in the 25-foot stream buffer ($R=0.75$). A regression of average annual total phosphorus load (1998–2003) on average annual precipitation, slope, and large-lot (from 1 to 5 acres) residential land has an $R^2$ of 0.90 and a $p$-value less than 0.04. A similar regression of *annual* values of total phosphorus for the period 1998–2003 from annual precipitation, watershed slope, and large-lot residential land use has an $R^2$ of 0.76 and a $p$-value less than 0.001.

Dissolved phosphorus makes up less than 15 percent of the total phosphorus load for these six watersheds for 1998–2003. For dissolved phosphorus load, an average of 45 percent is transported during baseflow for all of the watersheds except Big Haynes Creek, in which 94 percent is transported during baseflow because of a wastewater point source. Dissolved phosphorous appears to have different sources in baseflow and stormflow; however, the mean concentrations for baseflow and stormflow differ by less than 30 percent, except for Big Haynes Creek, where the difference is 70 percent.

Stormflow carries 70 percent of average annual total nitrogen (1998–2003) for these six streams. Total nitrogen load is more highly correlated with impervious area in the 25-foot stream buffer ($R=0.76$) than with watershedwide impervious area ($R=0.58$). Treated wastewater contributes much of the nitrogen load associated with baseflow for Yellow River, Suwanee Creek, and Big Haynes Creek. Cumulative watershed effects on nitrate plus nitrite are similar to those for total nitrogen, except that wastewater effluent is more significant.

Concentrations and loads of total dissolved solids in baseflow and stormflow increase with increasing urbanization and with point-source wastewater. Concentrations of total dissolved solids are diluted with increasing discharge in both baseflow and stormflow. Biochemical oxygen demand load increases with watershedwide impervious area. Stormflow transports 83 percent of the biological oxygen demand load, on average, for these six watersheds.

Concentrations of total zinc (for total unfiltered water samples) are highly correlated with those of lead, copper, and chromium ($R$ values range from 0.79 to 0.91). Thus, elevated concentrations of zinc may be indicative of elevated concentrations of these trace metals. Total zinc yield is strongly correlated with high-density and transportation/utility land use, and is inversely correlated with estate/park and undeveloped land use. The strong correlation of total zinc load with transportation impervious area ($R=0.96$) confirms the impacts of impervious surfaces both as source areas and as efficient transport pathways for trace metals. From 83 percent to 95 percent of the total zinc load is transported in stormflow.

Mean alkalinity, measured as pH (combined stormflow and baseflow), is related to impervious area in the 25-foot stream buffer with an $R^2$ and $p$-value of 0.90 and 0.004, respectively, and to watershedwide impervious area with an $R^2$ and $p$-value of 0.19 and 0.40 (not statistically significant), respectively. Runoff and infiltration from alkaline impervious areas close to streams have less time and space to be balanced by natural factors affecting pH, compared to areas more distant from streams.

Flow-adjusted total suspended solids, total phosphorus, and total zinc stormflow concentrations have a seasonal pattern that peaks between July and August in five of the six watersheds. The seasonal pattern is stronger for more developed watersheds and may be related to seasonal land-disturbance activities and/or to seasonal rainfall intensity, both of which increase during summer. Adjusting for seasonality in the computation of constituent load decreased the standard error of annual total suspended solids load by an average of 11 percent, increased computed summer total suspended solids loads by an average of 45 percent, and decreased winter total suspended solids loads by an average of 40 percent. Total annual loads changed by less than 5 percent on the average.

Graphical and statistical analyses do not indicate a time trend from 1996 to 2003 in flow- and seasonally adjusted stormflow concentrations of total suspended solids, total phosphorus, total zinc, or total dissolved solids for the sampled streams in the six watersheds studied. The absence of a trend, when land use was changing rapidly, may reflect the time lag of impacts, natural variability, and/or watershed management practices. The only long-term trend detected was in declining baseflow concentrations of total zinc, which may be due to increasing stream alkalinity during this period. The findings of this report may provide watershed managers with information leading to improved stream quality.

Water-quality monitoring in Gwinnett County is providing a long-term record of comprehensive and consistent hydrologic and water-quality data for selected watersheds. These data indicate how natural and human-related watershed characteristics affect streamflow quantity and quality in Gwinnett County.

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