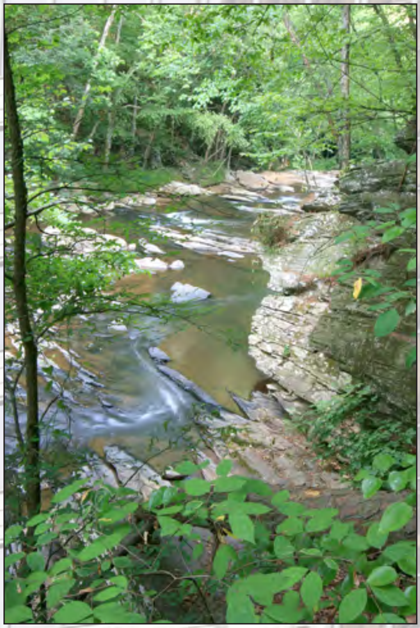
Physical, Chemical, and Biological Responses of Streams to Increasing Watershed Urbanization in the Piedmont Ecoregion of Georgia and Alabama, 2003



Scientific Investigation Report 2006-5101-B

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

Front cover: All photographs by Alan M. Cressler, USGS

Background image: The Promenade II building, Atlanta, Fulton County, Georgia, 2007

Photograph on left: Sope Creek at Marietta Paper Mill Ruins, Chattahoochee River National Recreation Area, Cobb County, Georgia, 2007

Photograph in middle: Flint River at Sprewell Bluff State Park, Upson County, Georgia, 2007

Photograph on right: Towaliga River above High Falls, High Falls State Park, Monroe County, Georgia, 2006

National Water-Quality Assessment Program

Physical, Chemical, and Biological Responses of Streams to Increasing Watershed Urbanization in the Piedmont Ecoregion of Georgia and Alabama, 2003

By M. Brian Gregory and Daniel L. Calhoun

Chapter B of
Effects of Urbanization on Stream Ecosystems in Six Metropolitan Areas of the United States

Scientific Investigations Report 2006–5101-B

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

U.S. Department of the Interior
DIRK KEMPTHORNE, Secretary

U.S. Geological Survey
Mark D. Myers, Director

U.S. Geological Survey, Reston, Virginia: 2007

For product and ordering information:
World Wide Web: *http://www.usgs.gov/pubprod*
Telephone: 1-888-ASK-USGS

For more information on the USGS--the Federal source for science about the Earth, its natural and living resources, natural hazards, and the environment:
World Wide Web: *http://www.usgs.gov/*
Telephone: 1-888-ASK-USGS

Suggested citation:
Gregory, M.B., and Calhoun, D.L., 2007, Physical, chemical, and biological responses of streams to increasing watershed urbanization in the Piedmont Ecoregion of Georgia and Alabama, Chapter B *of* Effects of urbanization on stream ecosystems in six metropolitan areas of the United States: U.S. Geological Survey Scientific Investigations Report 2006–5101-B, 104 p., available online only at *http://pubs.usgs.gov/sir/2006/5101B*

Foreword

The U.S. Geological Survey (USGS) is committed to providing the Nation with credible scientific information that helps to enhance and protect the overall quality of life and that facilitates effective management of water, biological, energy, and mineral resources (*http://www.usgs.gov/*). Information on the Nation's water resources is critical to ensuring long-term availability of water that is safe for drinking and recreation and is suitable for industry, irrigation, and fish and wildlife. Population growth and increasing demands for water make the availability of that water, now measured in terms of quantity and quality, even more essential to the long-term sustainability of communities and ecosystems.

The USGS implemented the National Water-Quality Assessment (NAWQA) Program in 1991 to support national, regional, State, and local information needs and decisions related to water-quality management and policy (*http://water.usgs.gov/nawqa*). The NAWQA Program is designed to answer: What is the condition of our Nation's streams and ground water? How are conditions changing over time? How do natural features and human activities affect the quality of streams and ground water, and where are those effects most pronounced? By combining information on water chemistry, physical characteristics, stream habitat, and aquatic life, the NAWQA Program aims to provide science-based insights for current and emerging water issues and priorities. During 1991–2001, the NAWQA Program completed interdisciplinary assessments and established a baseline understanding of water-quality conditions in 51 of the Nation's river basins and aquifers, referred to as Study Units (*http://water.usgs.gov/nawqa/studyu.html*).

In the second decade of the Program (2001–2012), a major focus is on regional assessments of water-quality conditions and trends. These regional assessments are based on major river basins and principal aquifers, which encompass larger regions of the country than the Study Units. Regional assessments extend the findings in the Study Units by filling critical gaps in characterizing the quality of surface water and ground water, and by determining status and trends at sites that have been consistently monitored for more than a decade. In addition, the regional assessments continue to build an understanding of how natural features and human activities affect water quality. Many of the regional assessments employ modeling and other scientific tools, developed on the basis of data collected at individual sites, to help extend knowledge of water quality to unmonitored, yet comparable areas within the regions. The models thereby enhance the value of our existing data and our understanding of the hydrologic system. In addition, the models are useful in evaluating various resource-management scenarios and in predicting how our actions, such as reducing or managing nonpoint and point sources of contamination, land conversion, and altering flow and (or) pumping regimes, are likely to affect water conditions within a region.

Other activities planned during the second decade include continuing national syntheses of information on pesticides, volatile organic compounds (VOCs), nutrients, selected trace elements, and aquatic ecology; and continuing national topical studies on the fate of agricultural chemicals, effects of urbanization on stream ecosystems, bioaccumulation of mercury in stream ecosystems, effects of nutrient enrichment on stream ecosystems, and transport of contaminants to public-supply wells.

The USGS aims to disseminate credible, timely, and relevant science information to address practical and effective water-resource management and strategies that protect and restore water quality. We hope this NAWQA publication will provide you with insights and information to meet your needs, and will foster increased citizen awareness and involvement in the protection and restoration of our Nation's waters.

The USGS recognizes that a national assessment by a single program cannot address all water-resource issues of interest. External coordination at all levels is critical for cost-effective management, regulation, and conservation of our Nation's water resources, The NAWQA Program, therefore, depends on advice and information from other agencies—Federal, State, regional, interstate, Tribal, and local—as well as nongovernmental organizations, industry, academia, and other stakeholder groups. Your assistance and suggestions are greatly appreciated.

Robert M. Hirsch
Associate Director for Water

Contents

Abstract 1
Introduction 2
    Purpose and Scope 3
    Study Area 3
        Land-Use History 3
    Acknowledgments 8
    Site Selection 8
    Network Design 8
    Data Collection and Processing 12
        Water Quality 12
        Hydrology 13
        Water Temperature 14
        Stream Habitat 14
        Algal Communities 14
        Invertebrate Communities 15
        Fish Communities 15
Statistical Analysis 16
    Correlation Analysis 16
    Multivariate Community Analysis 16
Physical, Chemical, and Biological Responses to Urbanization 19
    Water-Quality Response 20
    Hydrologic Response 24
    Temperature Response 24
    Algal Metric Responses 26
    Invertebrate Metric Responses 29
    Fish-Metric Responses 34
    Algal Community Responses 37
    Invertebrate Community Responses 40
    Fish Community Responses 42
Summary and Conclusions 44
References Cited 47
Appendix A. GIS Variable Names, Abbreviations, and Descriptions 51
Appendix B. Chemical Variable Names and Descriptions 59
Appendix C. Physical Variable Names and Descriptions 67
Appendix D. Biological Variable Names and Descriptions 73
Appendix E. Species Lists for Algal, Invertebrate, and Fish Communities 89

Figures

1–2. Maps showing—

1. Location of Metropolitan Atlanta study area and sampling sites in the Southern Inner and Outer Piedmont Ecoregions in Georgia and Alabama, 2003: *(A)* major river basins and urban-study watersheds and *(B)* population density 4
2. Percent change in population density in major river basins and urban study watersheds in the Metropolitan Atlanta study area in the Southern Inner and Outer Piedmont Ecoregions, Georgia and Alabama, 1990–2001 6

3. Diagram showing the evolution of channel geomorphology in many small streams of the Georgia Piedmont 7

4. Graph showing population growth in the 28-county Metropolitan Atlanta area, 1900–2000, and projected through 2025 7

5. Maps showing land-cover classes and urban growth patterns in four representative watersheds in the Piedmont Ecoregion of Georgia and Alabama, 2001: *(A)* Hillabahatchee Creek, least-developed and predominantly forested; *(B)* Beech Creek, rural with mixed forest and pasture; *(C)* Powder Springs Creek, suburban with mixed forest and pasture; and *(D)* Sope Creek, predominantly developed 10

6. Diagram showing analysis of site differences based on watershed characteristics used in the urban index. *(A)* Two-dimensional representation of nonmetric multidimensional scaling analysis. *(B)* Cluster delineation using 1.5 units as the threshold of inclusion within groups 17

7–8. Scatter plots for 30 stream sites in the Piedmont Ecoregion of Georgia and Alabama, 2003, showing—

7. Selected variables along a gradient of urban intensity: *(A)* specific conductance, *(B)* chloride, *(C)* sulfate, *(D)* total nitrogen, *(E)* ammonia plus organic nitrogen, and *(F)* total phosphorus 22
8. Selected pesticides and pesticide indices along a gradient of urban intensity: *(A)* atrazine, *(B)* simazine, *(C)* sum of insecticides, and *(D)* sum of herbicides 23

9–12. Graphs for 30 stream sites in the Piedmont Ecoregion of Georgia and Alabama, 2003, showing—

9. Selected semipermeable membrane device (SPMD) assay results and extracted chemical constituents along a gradient of urban intensity: *(A)* CYPIA1 induction in toxic equivalents and pyrene fluorescence, and *(B)* flouranthene and benzophenanthrene....24

10. Selected algal metrics along gradients of hydrology, chemistry, and land use: *(A)* percent highly sensitive taxa and stage increases, *(B)* percent abundance of taxa tolerant to low levels of oxygen saturation (less than 30 percent) and dissolved oxygen, *(C)* percent richness of mesosaprobic taxa and forested land, and *(D)* percent abundance of mesosaprobic taxa and specific conductance 27

11. Selected invertebrate metrics along gradients of hydrology, chemistry, and land use: *(A)* average EPA tolerance value for sample based on richness and developed land in buffer, *(B)* percent of total richness of mayflies, stoneflies, and caddisflies and urban intensity index, *(C)* richness of mayflies, stoneflies, and caddisflies and SPMD extract toxic equivalents, and *(D)* richness of mayflies, stoneflies, and caddisflies and specific conductance 30

12. Selected fish metrics along gradients of hydrology, chemistry, and land use: *(A)* percent pool dwellers and developed land, *(B)* percent cyprinids and roads, *C)* fish index of biotic integrity and events with rapid decline in stage, *(D)* percent cyprinids and total rise and fall of hydrograph, *(E)* percent simple nesters and woody debris, and *(F)* percent cyprinids and specific conductance....35

13. Two-dimensional representation of nonmetric multidimensional scaling analysis of algal community presence/absence in *(A)* depositional targeted habitat (DTH), ANOSIM (urban groups), $R = 0.22$, $p < 0.01$; and *(B)* richest targeted habitat (RTH) samples, ANOSIM (urban groups), $R = 0.19$, $p < 0.01$....38

14–15. Bar graphs showing—

14. Pair-wise comparisons of analysis of similarity (ANOSIM) R statistics between least developed sites and sites with increasing levels of urbanization. 39

15. Multivariate dispersion within site cluster groups for algal, invertebrate, and fish communities with increasing levels of urbanization 39

16–17. Two-dimensional representation of nonmetric multidimensional scaling analysis of—

16. Invertebrate community relative abundance in *(A)* richest targeted habitat (RTH), ANOSIM (urban groups), $R = 0.39$, $p < 0.001$; and *(B)* multi-habitat qualitative (QQ) samples, ANOSIM (urban groups), $R = 0.25$, $p < 0.001$....41

17. Fish community relative abundance....43

Tables

1. Watershed identification, station names and codes, drainage areas, land-use characteristics, and calculated urban intensity index of watersheds sampled in the Metropolitan Atlanta study area, 2002–2003 9
2. Reach lengths and selected geomorphic, hydrologic, and habitat characteristics of streams sampled in the Metropolitan Atlanta study area during, 2002–2003 11
3. Approximate dates of samples and data collection in the Metropolitan Atlanta study area, 2002–2003 12
4. Spearman rho (r_s) values for significant correlations ($p < 0.005$) between water–quality properties and the urban intensity index, components of the urban intensity index, and impervious surface estimates in the Metropolitan Atlanta study area, 2002–2003 21
5. Spearman rho (r_s) values for significant correlations ($p < 0.005$) between hydrologic variability metrics and the urban intensity index, components of the urban intensity index and impervious surface estimates in the Metropolitan Atlanta study area, 2002–2003 25
6. Spearman rho (r_s) values $\geq |0.60|$ for the highest, but nonsignificant ($p < 0.005$), correlations between algal metrics and the calculated urban intensity index, components of the urban intensity index and impervious surface estimates in the Metropolitan Atlanta study area, 2002–2003...26
7. Significant ($p < 0.005$) episammic diatom community metric responses to environmental variables in the Metropolitan Atlanta study area, 2002–2003...................28
8. Spearman rho (r_s) values for significant ($p < 0.005$) correlations between invertebrate metrics and calculated urban intensity index, components of the urban intensity index and impervious surface estimates in the Metropolitan Atlanta study area, 2002–2003 29
9. Significant ($p < 0.005$) invertebrate community metric responses to environmental variables in the Metropolitan Atlanta study area, 2002–2003...................32
10. Spearman rho (r_s) values for significant ($p < 0.005$) correlations between fish metrics and urban intensity index, components of the urban intensity index and impervious surface estimates in the Metropolitan Atlanta study area, 2002–2003 34
11. Spearman rho (r_s) values for significant ($p < 0.005$) correlations between fish metrics and environmental variables in the Metropolitan Atlanta study area, 2002–2003 36
12. Index of Multivariate Seriation (IMS) values, overall correlation coefficients (ρ) and significance levels between aquatic community sample types and explanatory variable data sets in the Metropolitan Atlanta study area, 2002–2003. 40

Appendix Tables

A1. Sources of Geographic Information System and digital information used to derive study variables....52
A2. Basin variable abbreviations and definitions....54
A3. FRAGSTATS variables and definitions....56
A4. Variables used to calculate Urban Intensity Index used for site selection. 57
B1. Measured water-chemistry constituents, abbreviations, parameter codes and chemical classification 60
B2. Semipermeable membrane device chemical extract abbreviations, descriptions, and measurement techniques....63
C1. Stream reach habitat variables and definitions 68
C2. Hydrologic metric abbreviations and definitions 71
D1. Algal metric names, abbreviations and definitions....74
D2. Invertebrate metrics names, abbreviations and definitions 84
D3. Fish metrics names, abbreviations and definitions....86
E1. Scientific names and number of occurrences of diatoms on snags (epidendric) and sand (episammic) habitat in 30 streams sampled in the Metropolitan Atlanta study area, 2003 90
E2. Scientific names, number of site occurrences of invertebrates in qualitative multihabitat and semiqualitative snag samples and mean and maximum densities of individuals on snags collected from 30 streams in the Metropolitan Atlanta study area, 2002–2003....96
E3. Scientific names, common names, basin distribution, numbers collected, and site occurrences of fishes collected from 30 streams in the Oconee–Ocmulgee and Chattahoochee–Flint River Basins in the Metropolitan Atlanta study area, 2002–2003....102

Conversion Factors and Datums

Multiply	By	To obtain
	Length	
centimeter (cm)	0.3937	inch
meter (m)	3.281	foot (ft)
meter (m)	1.094	yard (yd)
kilometer (km)	0.6214	mile (mi)
	Area	
square meter (m^2)	0.0002471	acre
hectare (ha)	2.471	acre
square kilometer (km^2)	247.1	acre
	Volume	
milliter (mL)	0.03382	ounce, fluid (fl. oz)
liter (L)	33.82	ounce, fluid (fl. oz)
	Mass	
gram (g)	0.03527	ounce, avoirdupois (oz)

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

$$°F = (1.8 \times °C) + 32$$

Vertical coordinate information is referenced to the insert North American Vertical Datum of 1988 (NAVD 88).

Horizontal coordinate information is referenced to the North American Datum of 1983 (NAD 83).

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

Specific conductance is given in microsiemens per centimeter at 25 degrees Celsius (µS/cm at 25°C).

Concentrations of chemical constituents in water are given either in milligrams per liter (mg/L) or micrograms per liter (µg/L).

Acronymns and Abbreviations

ADAPS	Automatic Data Processing System
AFDM	ash-free dry mass
AhR	aryl hydrocarbon receptor
ANOSIM	analysis of similarity (multivariate)
ANOVA	analysis of variance
CERC	Columbia Environmental Research Center
CYP1A1	cytochrome P450, family 1, subfamily a, polypeptide 1 gene
DTH	depositional targeted habitat
ECNI	electron-capture negative ionization
EI	electron ionization
EPT	Ephemeroptera, Plecoptera, and Tricoptera
EST	Environmental Sampling Technologies, Inc.
EUSE	Effects of Urbanization on Stream Ecosystems
EWI	equal-width increment
GC/MS	gas chromatography/mass spectrometry
GIS	geographic information system
IBI	index of biotic integrity
IDAS	Invertebrate Data Analysis System
IMD	Index of Multivariate Dispersion
IMS	Index of Multivariate Seriation
LDPE	low-density polyethylene
MDS	nonmetric multidimensional scaling
MSA	metropolitan statistical area
MVDISP	multivariate dispersion
NAWQA	National Water-Quality Assessment Program
NWQL	National Water Quality Laboratory
PAH	polycyclic aromatic hydrocarbons
PCA	Principal Component Analysis
PCB	polychlorinated biphenyls
POR	period of record
QQ	qualitative plus quantitative (synthetic multihabitat invertebrate sample)
R	ANOSIM test statistic
r_S	Spearman correlation coefficient
RTH	richest targeted habitat
SIMPER	similarity percentage (multivariate)
SPMD	semipermeable membrane device
TEQ	toxic equivalents
UII	urban intensity index
USEPA	U.S. Environmental Protection Agency
USGS	U.S. Geological Survey
UV	ultraviolet

Chapter B
Physical, Chemical, and Biological Responses of Streams to Increasing Watershed Urbanization in the Piedmont Ecoregion of Georgia and Alabama, 2003

By M. Brian Gregory and Daniel L. Calhoun

Abstract

As part of the U.S. Geological Survey National Water-Quality Assessment Program's effort to assess the physical, chemical, and biological responses of streams to urbanization, 30 wadable streams were sampled near Atlanta, Ga., during 2002–2003. Watersheds were selected to minimize natural factors such as geology, altitude, and climate while representing a range of urban development. A multimetric urban intensity index was calculated using watershed land use, land cover, infrastructure, and socioeconomic variables that are highly correlated with population density. The index was used to select sites along a gradient from low to high urban intensity. Response variables measured include stream hydrology and water temperature, instream habitat, field properties (pH, conductivity, dissolved oxygen, turbidity), nutrients, pesticides, suspended sediment, sulfate, chloride, *Escherichia coli (E. coli)* concentrations, and characterization of algal, invertebrate and fish communities. In addition, semipermeable membrane devices (SPMDs)—passive samplers that concentrate hydrophobic organic contaminants such as polycyclic aromatic hydrocarbons (PAHs)—were used to evaluate water-quality conditions during the 4 weeks prior to biological sampling. Changes in physical, chemical, and biological conditions were evaluated using both nonparametric correlation analysis and nonmetric multidimensional scaling (MDS) ordinations and associated comparisons of dataset similarity matrices.

Many of the commonly reported effects of watershed urbanization on streams were observed in this study, such as altered hydrology and increases in some chemical constituent levels. Analysis of water-chemistry data showed that specific conductance, chloride, sulfate, and pesticides increased as urbanization increased. Nutrient concentrations were not directly correlated to increases in development, but were inversely correlated to percent forest in the watershed. Analyses of SPMD-derived data showed that bioassays and certain chemical constituents such as pyrene and benzo-phenanthrene, both PAHs found in coal tar, were strongly correlated with measures of watershed urbanization. Hydrologic variability metrics indicated that as urban development increased, streams became flashier, with characteristic high flows having shorter duration. The hydrologic effects associated with urbanization were greatest during the fall and least apparent during the winter. No correlations were observed between increasing urbanization and stream temperature or changes in stream habitat.

Algal, invertebrate, and fish communities exhibited statistically significant changes as watersheds became increasingly urban, with the strongest responses observed in the invertebrate community followed by fishes, then algal diatom communities. Invertebrate communities were the most responsive to increasing urbanization with Ephemeroptera, Plecoptera, and Tricoptera taxa, especially Plecoptera (stoneflies) responding negatively and most strongly to increasing urbanization. Invertebrate communities were influenced more significantly by water quality, although significant responses to altered hydrology also were noted. In terms of the fish community, the percentage of cyprinids present in the stream was the only Index of Biotic Integrity metric that responded negatively to increases in watershed urbanization. Fish community response to urbanization was intermediate relative to algae and invertebrates with respect to significant metric responses as well as the overall community response to increasing urbanization. Measures of hydrologic variability were the most influential environmental variables affecting the algal community.

Although sites were originally chosen to represent a gradient of increasing urbanization, a cluster analysis performed on the component metrics of the urban index categorized sites into four distinct groups. Multivariate analysis based on non-metric MDS and related analyses of data matrices indicated varying degrees of significant separation of algal, invertebrate, and fish communities from corresponding groups of sites. Pair-wise analysis of similarity of communities among these groups indicated progressive separation (more differences based on species compositions) as sites transitioned from rural, to suburban, to highly developed. Invertebrates and fish communities showed a greater range in community separation

than did algal communities. Dispersion, a measure of community variability, decreased as sites became more urbanized, with the least developed group having higher dispersion indices (more different species) and the most developed sites having lower dispersion indices (fewer species) for algal, invertebrate, and fish assemblages. In general, algal, invertebrate, and fish communities in highly urbanized areas are more similar to each other than the communities are to each other in the least developed areas.

Introduction

The highest rates of population growth and land development in the United States are currently occurring at the edges of existing cities and metropolitan areas, where annual population growth increased from about 7 percent from 1982–87 to more than 10 percent from 1992–97 (Heimlich and Anderson, 2001). During this recent 6-year period, more land was developed—in excess of 6.4 million hectares—than during the previous 20 years (U.S. Environmental Protection Agency, 2004). Sprawling metropolitan development and urbanization of these previously nonurbanized areas have been linked to degradation of water quality, aquatic communities, and habitat conditions of streams and rivers. The U.S. Environmental Protection Agency (USEPA) has estimated that urban runoff accounted for 11 percent of impaired river kilometers nationally, in addition to 43 percent of impaired estuary hectares and 24 percent of impaired lake hectares (U.S. Environmental Protection Agency, 1994). More recent estimates implicate runoff from urban areas impairing as many as 56,119 stream kilometers or about 13 percent of assessed stream kilometers in the United States (U.S. Environmental Protection Agency, 2000).

Interest in the effects of urbanization on streams and stream ecosystems is reflected in the large number of recent studies relating watershed urbanization to the biological and physical conditions of streams and stream ecosystems. Studies have examined the many aspects of this relation including linkages between watershed urbanization and water quality (Coulter and others, 2004; Klein, 1979; Wilber and Hunter, 1977; Williams and others, 2005), biological communities including algae (Newall and Walsh, 2005; Taylor and others, 2004), invertebrates (Freeman and Schorr, 2004; Garie and McIntosh, 1986; Gray, 2004; Murphy and Davy-Bowker, 2005; Roy and others, 2003a; Roy and others, 2003b; Wang and Kanehl, 2003), fishes (Walters and others, 2003a; Walters and others, 2003b; Wang and others, 2001), physical conditions including hydrology (Booth and Hartely, 2002; Booth and Jackson, 1997; Rose and Peters, 2001; Simmons and Reynolds, 1982), geomorphology and habitat (Davis and others, 2003) and water temperature (LeBlanc and others, 1997; Paul and others, 2001). Paul and Meyer (2001) provided a thorough review of the literature and addressed the various hypothesized direct and indirect effects of watershed urbanization on stream ecosystems. Generally, with increased watershed urbanization, one may expect to observe a decline in water-quality and habitat conditions as well as a decrease in algal, invertebrate, and fish species diversity, although the magnitudes of these observed effects vary from study to study.

During the 1990s, the U.S. Geological Survey's (USGS) National Water-Quality Assessment (NAWQA) Program documented patterns in water quality in selected urban areas throughout the United States (U.S. Geological Survey, 1999) and found that:

- complex mixtures of pesticides commonly occur in urban streams,
- insecticides such as diazinon, carbaryl, chlorpyrifos, and malathion were commonly detected in urban streams at concentrations that exceeded guidelines for the protection of aquatic life,
- phosphorus concentrations generally were higher in urban streams than in nonurban streams, and
- hydrology and land use were major factors controlling nutrient and pesticide concentrations in major rivers.

Based on these national findings from studies conducted by the USGS, as well as the scientific and regulatory community's interest in the effects of urbanization on streams, the subject of urbanization was selected for a systematic national assessment in areas of the country where urbanization issues were deemed a priority concern. The USGS NAWQA Program funded and administered this study, Effects of Urbanization on Stream Ecosystems (EUSE). During 1999, this program began investigating the effects of urbanization on stream ecosystems through pilot studies conducted in metropolitan areas of Anchorage, Alaska; Birmingham, Ala.; Boston, Mass.; Chicago, Ill.; Cincinnati–Dayton, Ohio; Los Angeles, Calif.; Philadelphia, Pa.; Trenton, N.J.; and Salt Lake City, Utah. The successful implementation and findings from these pilot studies led to the implementation of a national study designed to increase understanding of linkages between watershed urbanization and biological responses in wadable streams nationwide.

During 2001, six study areas—Atlanta, Ga.; Raleigh, N.C.; Denver, Colo.; Portland, Oreg.; Dallas–Fort Worth, Tex.; and Milwaukee, Wis.—were selected and began planning intensive, nationally consistent, 1-year field studies designed to investigate the effects of urbanization on the aquatic ecosystems of small wadable streams. The overall objectives of this national study were to identify watershed features most highly correlated with urbanization or rapidly urbanizing areas (for example, landscape, census, and infrastructure variables), characterize to what extent urbanization influences the physical and chemical characteristics of streams (hydrology, temperature, physical habitat, and water chemistry) and investigate the linkages between watershed and land-use changes and alterations in stream communities (algae, invertebrates, and fish). Data were collected for these studies during 2003 and 2004; additional studies are planned as of 2007 in other areas of the United States where urbanization has been identified as a priority concern.

Purpose and Scope

This report describes the physical, chemical, and biological responses to increasing urbanization in streams in the southern Piedmont region of the southeastern United States, near Metropolitan Atlanta, Ga. Specifically, this study investigates changes in the biological communities using a multimetric and multivariate approach to describe major physical and chemical changes coincident with increasing urban land use, and relates these changes to patterns in stream algal, invertebrate, and fish communities. The metric approach is based on various species diversity, indicator groups, or natural distribution indices, and was used because metrics have a long history of use in Europe and North America. Algal, invertebrate, and fish metrics are used by watershed managers to detect changes in aquatic communities and can be used to communicate these changes to regulators as well as to the general public. Nonparametric correlation analyses are used to investigate the response of biological metrics within each group of taxa (algae, invertebrate, and fish) to increasing watershed urbanization. To characterize the influence of urbanization on species composition and community structure, nonmetric multidimensional scaling (MDS) based multivariate ordinations and multivariate comparisons are reported.

Study Area

The Metropolitan Atlanta area is located in the southern region of the Piedmont Physiographic Province and generally straddles the divide between the Level IV Southern Inner Piedmont and the Southern Outer Piedmont Ecoregions (Griffith and others, 2001; fig. 1). This area is characterized by gently rolling topography with about 60 meters of local relief and by dissected irregular plains. Streams are typified by low to moderate gradients, some bedrock outcroppings and cobble, gravel, and sandy substrates. Within the study area, the major physical differences between the Southern Inner and Southern Outer Piedmont Ecoregions are with respect to altitude and climate, with the Southern Inner region slightly higher in altitude (from 106 to 880 meters compared with 58 to 485 meters, NGVD 29), slightly wetter (from 132 to 152 centimeters compared with 116 to 142 centimeters of yearly rainfall), and slightly warmer during the winter months (Griffith and others, 2001). Streamflow conditions in Piedmont streams of this area generally are highest from January to May and lowest from June to December. About 10 percent of rainfall in undeveloped portions of this area is yielded as direct runoff to streams (Hewlett, 1967).

Natural vegetation in both ecoregions is oak-hickory-pine forest; however, current land use and land cover in the study area includes forested areas with pine plantations, pastures, hay fields, cattle, and poultry production with minimal row-crop agriculture (Griffith and others, 2001). Relatively recent changes in land use include an increase of urbanized and suburbanized areas, as well as population increases within an approximate radius of 95–130 kilometers from the downtown area of Atlanta. The greatest change in recent population has occurred in the northeastern and southern sections of the Metropolitan Atlanta area (fig. 2).

Land-Use History

Historic patterns of land use, particularly row-crop agriculture, have substantially influenced the landscape of the Southern Piedmont. This is relevant to understanding the current geomorphology, and potentially the ecology, of the region's streams. Prior to European settlement, land use in the Southern Piedmont was a mosaic of old-growth hardwoods interspersed with relatively few, small settlements of between 1,000 to 5,000 people. These agrarian settlements were located mainly along the floodplains of the region's large rivers that in some cases had expanded into upland areas (J.E. Worth, Assistant Director, Randal Research Center, Florida Museum of Natural History, written commun., 2005). After Native Americans ceded their lands to the State of Georgia during the 1700s and 1800s, European settlers began moving into northern Georgia and the Southern Piedmont. The invention of the cotton gin during 1793 made large-scale cotton farming highly profitable; land was cleared for fields, and an economy based on row-crop agricultural production was rapidly established. The availability of inexpensive land and the lack of modern farming practices along with easily erodable clay soils and high rates of rainfall set the stage for large-scale changes to the natural landscape and the physical conditions of streams of this region.

Trimble (1969) documented land-use change in the Southeast during this era and the impact that intensive row-crop agriculture had on regional stream morphology. By doing near-stream subsurface soil surveys, as well as examining land-survey records and bridge-and-dam construction records, Trimble documented massive loss of topsoil from the steeply sloped upland areas. These soils were transported to streams and floodplains, burying productive instream shoal and riffle habitats. Streambed aggradation further exacerbated flooding already worsened by the loss of upland vegetation. Many, if not the majority, of small streams in this region may have been transformed from hard-bottomed, clear-flowing streams described by the early land surveys into conduits of turbid water and sand. This pattern of land use and associated geomorphic response continued until about 1919 when about 40 percent of the Piedmont in Georgia was cropped in cotton and corn, both of which exacerbated soil erosion (Trimble, 1969).

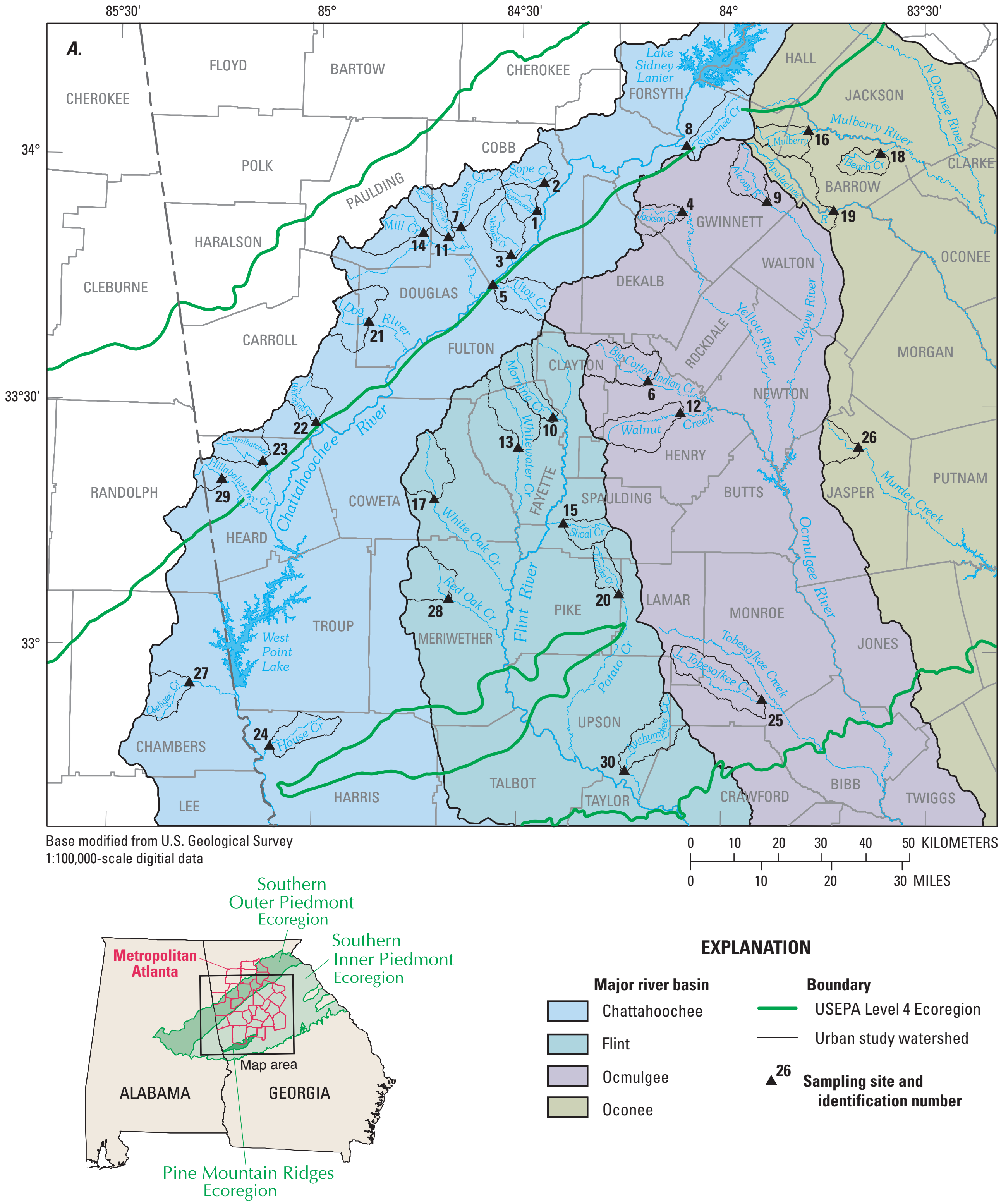


Figure 1. Location of Metropolitan Atlanta study area and sampling sites in the Southern Inner and Outer Piedmont Ecoregions in Georgia and Alabama, 2003: *(A)* major river basins and urban-study watersheds and *(B)* population density. (Sampling sites and identification numbers listed in table 1; ecoregions from digital files of U.S. Environmental Protection Agency [USEPA], 2005; population density derived from census block data, U.S. Census Bureau, 2000.)

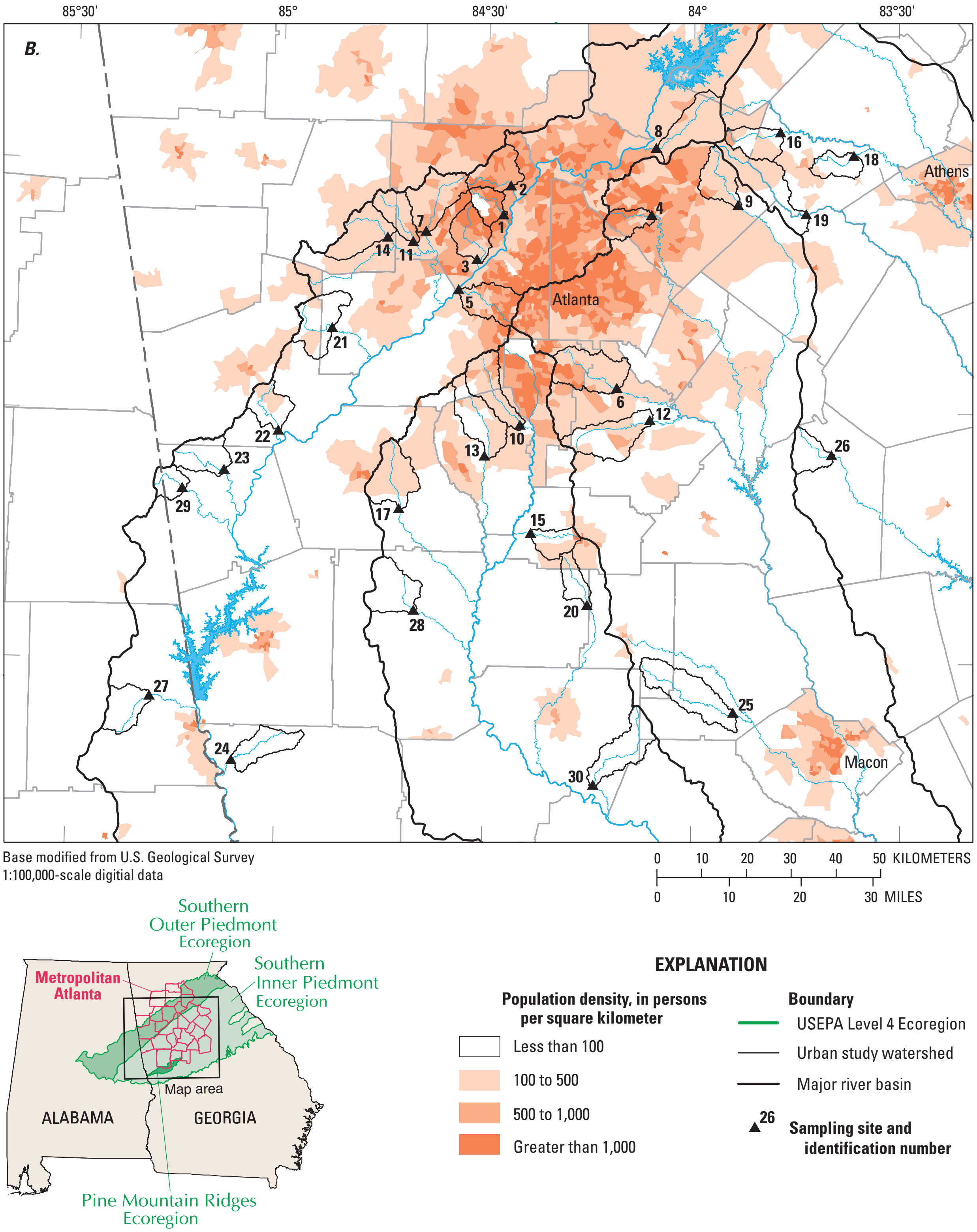


Figure 1. Location of Metropolitan Atlanta study area and sampling sites in the Southern Inner and Outer Piedmont Ecoregions in Georgia and Alabama, 2003: *(A)* major river basins and urban-study watersheds and *(B)* population density. (Sampling sites and identification numbers listed in table 1; ecoregions from digital files of U.S. Environmental Protection Agency [USEPA], 2005; population density derived from census block data, U.S. Census Bureau, 2000.)—Continued

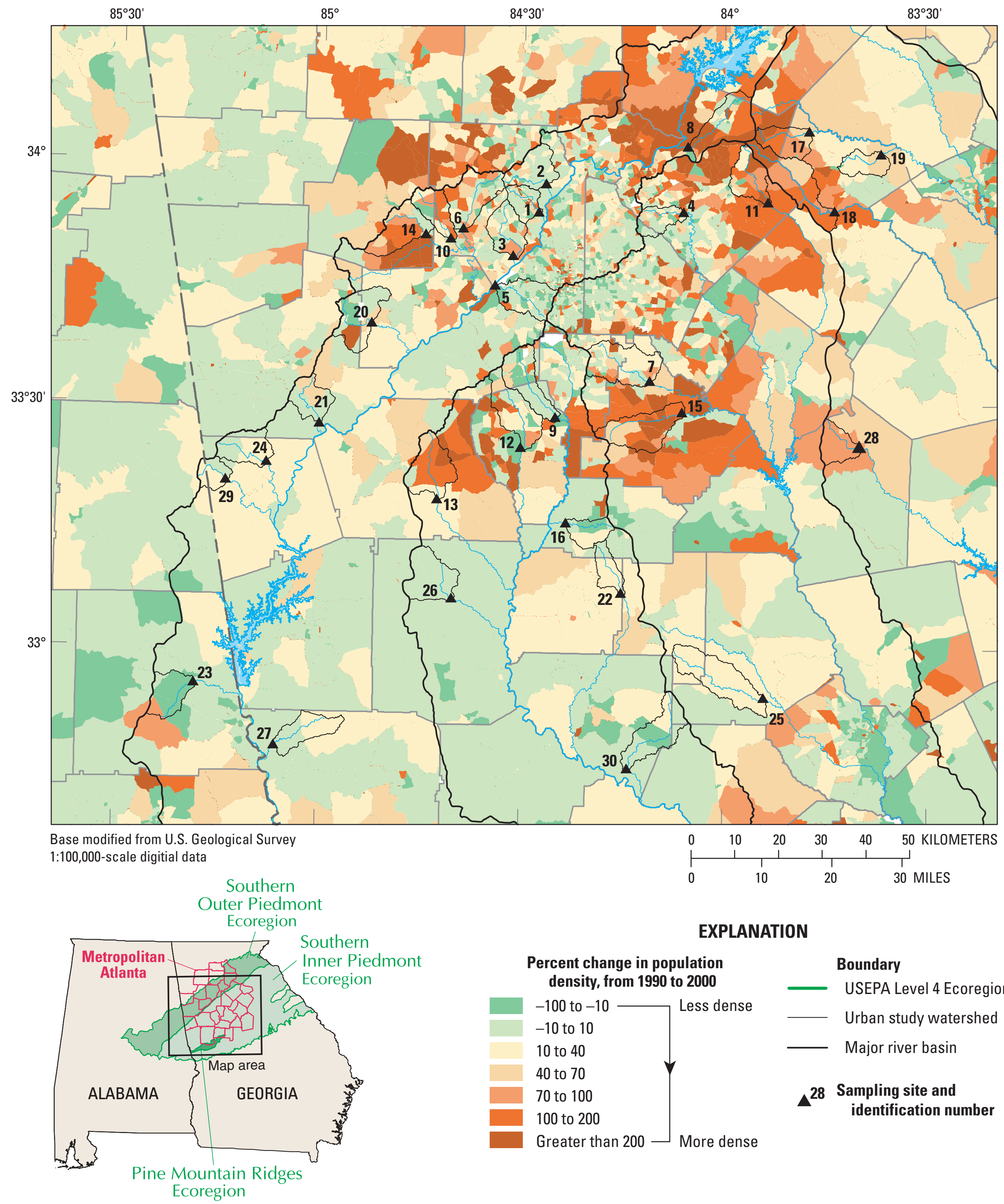


Figure 2. Percent change in population density in major river basins and urban study watersheds in the Metropolitan Atlanta study area in the Southern Inner and Outer Piedmont Ecoregions, Georgia and Alabama, 1990–2001. (Sampling sites and identification numbers listed in table 1; ecoregions from digital files of U.S. Environmental Protection Agency [USEPA], 2005; population density derived from census block data, U.S Census Bureau, 2000.)

After the boll weevil devastated the cotton market during the 1920s, large areas of cropland were abandoned. Between 1920 and 1940, some of the worst accounts of sedimentation and erosion were recorded in the Southern Piedmont; however, as row-crop agriculture became less dominant on the landscape and forest cover increased, sediment delivery to streams slowed. Streambeds began to degrade back to altitudes closer to early historic levels (Trimble, 1969). During the 1950s and 1960s, some of the historical milldams and bridge structures became visible again after having been buried in as much as 3 meters of sediment (fig. 3). Today, streambeds of many of the region's small streams have degraded back to historic or near historic levels. However, the geomorphic changes brought about by this period of accelerated erosion and sedimentation can be still observed—even in undeveloped watersheds that are often used to approximate reference conditions.

During the antebellum and post-Civil War period of agricultural dominance on the landscape, population densities in the Southern Piedmont remained relatively low; however, since World War II, the human population in this area has increased rapidly. This population growth has been driven primarily by growth near Atlanta and its sprawling suburbs, which are unimpeded by natural barriers such as an ocean or mountain range. Since 1900, the population of the Atlanta area has increased more than 690 percent with most of the growth occurring since 1970 (Atlanta Regional Commission, 2005; U.S. Geological Survey, unpub. data) (fig. 4). The Atlanta Metropolitan Statistical Area (MSA) was recently expanded to 28 counties (inset maps, figs. 1*A*, *B*). With a population of more than 4.5 million, it is now the 6th largest metropolitan area in the United States and encompasses an area of about 21,960 square kilometers (km^2). During the 1990s, the population of the Metropolitan Atlanta area grew by 48 percent—none of the 10 largest metropolitan areas in the United States grew faster (Hairston and Tamman, 2003). The new Atlanta MSA is larger in area than the States of Rhode Island, Delaware, and Connecticut and is about the size of the entire State of New Jersey. Its total population is greater than the individual populations of 29 U.S. States, and population in the Metropolitan Atlanta area continues to increase along with the infrastructure to support it. Recent studies have estimated that 502 people move to the 4-county core area of the MSA everyday (Hairston and Tamman, 2003), while a larger portion of the MSA (16 counties) looses about 54 acres of tree canopy and receives an additional 28 acres of asphalt, concrete, and rooftops each day (Kramer, 2006). It is estimated that the population in the Metropolitan Atlanta area will increase by more than 2.3 million people by 2030 (Atlanta Regional Commission, 2007), resulting in the need for more than 500,000 new housing units, which will require an estimated additional 300 million gallons of water per day.

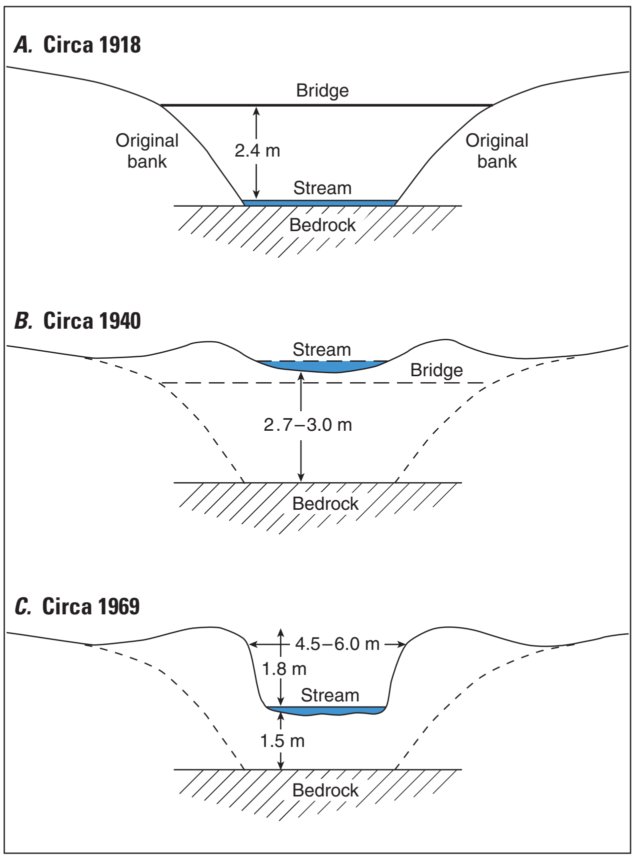


Figure 3. Diagram showing the evolution of channel geomorphology in many small streams of the Georgia Piedmont. *(A)* Prior to the erosion and sedimentation that accompanied row-crop agriculture of the late-19th century, many of these streams meandered in wide channels often with streambeds of bedrock or other hard substrates. *(B)* In areas where erosion and sedimentation were severe, as much as 3 meters (m) of soils was deposited in the channels, leaving the streams perched above the original streambed. *(C)* Presently, due to increased forest cover, lack of row-crop agriculture, and lower sediment loads these streams are cutting downward to the prefarming levels and in many cases are narrower and have much steeper banks (diagram modified from Trimble, 1969).

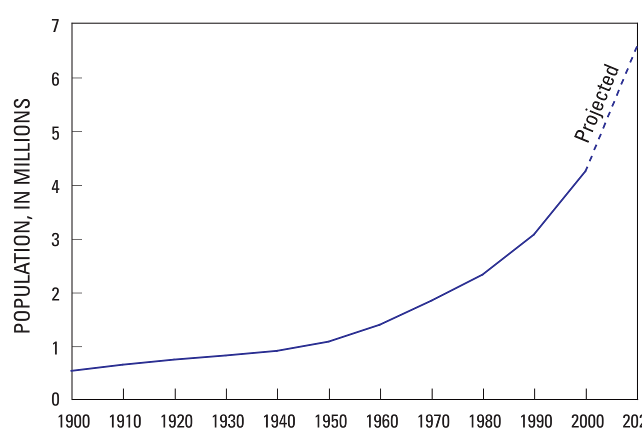


Figure 4. Population growth in the 28-county Metropolitan Atlanta area, 1900–2000, and projected through 2025 (data from U.S. Census Bureau, 2006; Atlanta Regional Commission, 2007).

Acknowledgments

Many individuals contributed significantly to the successful completion of this study. USGS personnel involved in the study design included Cathy Tate, Evelyn Hopkins (retired), Gary Buell, Brian Hughes, and Wade Bryant. USGS personnel involved in the extensive effort of data collection included: Deirdra Black, Alan Cressler, Dianna Crilley, Melinda Dalton, Andy Hickey, Sara Jones, James Kingsbury, Jessica Ogden, Jeff Powell, Rick Treece, and Chris Walls. The authors also would like to thank Robin Brightbill (USGS) for compiling and organizing temperature data into a usable format and Paula Marcineck (University of Georgia) for field assistance and fish taxonomic expertise.

Site Selection

Thirty stream monitoring sites were selected in the Chattahoochee, Flint, Ocmulgee, and Oconee River drainages within the Inner and Outer Piedmont Level IV Ecoregions of Georgia and Alabama (fig.1; table 1). Candidate watersheds were compiled using a Geographic Information System (GIS) to select watersheds ranging in size from 40 to 150 km^2 along a gradient of urbanization ranging from highly developed watersheds to watersheds with little development (fig. 5; table 1). An environmental framework—which considered natural factors such as soil texture and drainage characteristics, bedrock litho-chemical zones, as well as watershed altitudes and slopes—was developed using cluster analysis. As a result of this clustering, 217 candidate watersheds were assigned to relatively homogeneous groups based on these natural landscape features that could increase variability in water quality (Hopkins, 2003).

The urban character of these 217 candidate watersheds was estimated using a calculated "site selection" urban intensity index that quantifies multiple dimensions of human influence on the landscape. This index included factors such as land use, infrastructure, population, and socioeconomic characteristics and was developed using the methods of McMahon and Cuffney (2000). Datasets used included the 2000 census population density (Geolytics, 2000), 21 socioeconomic variables from the 1990 census (Geolytics, 2000), and several metrics that combined census variables (McMahon and Cuffney, 2000; Falcone and others, 2007). The Multi-Resolution Land Characteristics Consortium provided land cover/land use from Landsat Thematic Mapper satellite images collected from 1989 to 1993 (U.S. Geological Survey, 1992). In addition, infrastructure variables derived from roads data (TIGER Line Files, U.S. Census Bureau, 2000) and the U.S. Environmental Protection Agency's Toxic Release Inventory (U.S. Environmental Protection Agency, 2001) were examined. A complete list of GIS variable names, abbreviations, and data sources for variables used in site selection and further analyses can be found in Appendix A, Tables A1–A4. Eighteen of these variables were strongly related to population density and were chosen to be part of the multimetric site selection index (see Appendix A, table A4).

In brief, the calculation of the index consisted of (1) adjusting urban variables for basin size and measurement units; (2) standardizing the original variables so their values ranged from 0 to 100; (3) retaining variables correlated with population density (absolute value of Spearman rank correlation cooefficients, $|r_s|$, greater than or equal to 0.5) and uncorrelated with basin area ($|r_s|$ less than or equal to 0.5) and adjusting the variables so they all increased with increasing population density; (4) averaging retained variables across each site to obtain an urban intensity index (UII); and (5) standardizing the UII at each site so the values collectively ranged from 0 to 100 (McMahon and Cuffney, 2000; Falcone and others, 2007).

To further minimize natural variability in stream ecologic response, reconnaissance visits were conducted to select sites that were as similar as possible to each other in terms of instream habitat types and natural geomorphic controls. For example, during site visits potential sampling reaches were mapped; types of instream habitat and extent of riparian cover and flow conditions were assessed. Sites that were not compatible in terms of any of these characteristics were eliminated from further consideration. Selection of final sites was not random, but was conducted to ensure that final sites represented a gradient of increasing urban intensity across the study area. General habitat characteristics of streams sampled for this study are presented in table 2. The simultaneous use of the environmental framework and the calculated UII to select watersheds, as well as presampling reconnaissance visits, allowed for the selection of streams in which the influence of natural factors was minimized while the observable effects of urbanization on water quality and aquatic communities would be more apparent.

Network Design

The study design consists of a 10-site, bimonthly sampling network within a 30-site semiannual synoptic network (fig. 1*A*, table 1). Water chemistry at the 10-site intensive network was sampled at a fixed frequency and consisted of six samples collected at a variety of flow conditions throughout the year. Sampling frequency at the 30-site synoptic network consisted of two sampling events, one during early spring at elevated baseflow and one during mid to late summer at low baseflow (table 3). This network also included two sites—Sope Creek and Hillabahatchee Creek—that are part of the national USGS NAWQA status and trends monitoring network. These two sites have been sampled for similar sets of constituents on an approximately monthly basis since 1993—Sope Creek since 1993, Hillabahatchee Creek since 2001.

Table 1. Watershed identification, station names and codes, drainage areas, land-use characteristics, and calculated urban intensity index, of watersheds sampled in the Metropolitan Atlanta study area, 2002–2003.

[Watershed identifier (ID) used in table and figures 1*A*, *B*, and 2 represent rank ordering of sites along the urban gradient; urban group catagories represent groupings based on cluster analysis of urban intensity index constituents; bolded station names indicate bimonthly sampling sites; USGS, U.S. Geological Survey; km², square kilometer]

Watershed ID and urban rank	USGS station number	Station name	Station code	Urban group catagories	Drainage area (km²)	[1]Population density (persons/km²)	Percent impervious	Percent impervious (stream buffer)	[2]Housing density (units/km²)	[2]Road density (km road/km²)	[2]Percent developed	[2]Percent developed in stream buffer	[2]Percent forest	Urban intensity index
1	02335910	Rottenwood Creek near Smyrna, GA	Rot	Most developed	48.2	1197.7	38.2	29.7	502.4	6.4	85.4	65.0	11.3	100.0
2	**02335870**	**Sope Creek near Marietta, GA[3]**	**Sop**	Most developed	79.5	901.1	19.6	13.3	303.5	7.1	72.5	52.9	23.0	83.0
3	**02336635**	**Nickajack Creek near Mabelton, GA**	**Nic**	Most developed	80.8	899.7	18.1	11.3	310.7	6.6	66.2	42.3	27.3	75.0
4	02206314	Jackson Creek near Lilburn, GA	Jac	Most developed	55.4	1015.4	20.1	13.3	328.5	5.9	67.0	40.6	25.0	74.1
5	02336728	Utoy Creek near Atlanta, GA	Uto	Most developed	90.1	915.2	16.9	9.4	321.5	5.9	60.6	34.7	35.0	67.0
6	02204230	Big Cotton Indian Creek near Stockbridge, GA	BCI	Suburban	129.5	471.9	13.0	6.3	144.9	4.4	43.2	21.3	34.8	46.4
7	**02336968**	**Noses Creek at Powder Springs, GA**	**Nos**	Suburban	114.7	513.3	9.5	5.5	158.8	4.5	43.1	23.6	40.8	46.0
8	**02334885**	**Suwanee Creek at Suwanee, GA**	**Suw**	Suburban	121.9	267.6	13.5	9.9	89.2	3.4	42.6	25.3	38.0	41.0
9	02208150	Alcovy River near Grayson, GA	Alc	Suburban	79.5	277.8	14.6	10.4	78.3	3.1	39.7	27.2	36.2	40.2
10	02344340	Morning Creek near Fayetteville, GA	Mor	Suburban	101.5	352.4	12.0	6.8	115.8	3.5	38.3	20.3	39.7	39.3
11	02336876	Powder Springs Creek near Powder Springs, GA	Pow	Suburban	66.0	312.5	8.9	4.0	92.9	3.8	35.6	17.4	39.6	37.7
12	02204468	Walnut Creek near McDonough, GA	Wal	Rural	125.1	218.2	6.7	3.5	59.3	3.0	24.8	12.1	37.9	30.0
13	**02344737**	**Whitewater Creek near Fayetteville, GA**	**Whw**	Rural	110.5	186.7	6.3	3.5	58.4	3.0	25.1	13.4	45.6	27.6
14	02336822	Mill Creek near Hiram, GA	Mil	Rural	100.7	202.1	4.6	2.0	58.1	3.3	22.1	8.9	44.8	26.6
15	**02344480**	**Shoal Creek near Griffin, GA**	**Sho**	Rural	53.4	186.2	6.4	2.9	61.6	3.0	22.9	11.1	46.6	26.1
16	02217293	Little Mulberry River near Hoschton, GA	Lmul	Rural	73.5	192.8	5.8	3.5	50.4	2.7	20.4	10.8	41.2	26.1
17	**02344797**	**White Oak Creek near Raymond, GA**	**WhO**	Rural	112.6	153.4	6.8	4.1	51.8	2.6	25.7	15.2	48.6	25.9
18	02217471	Beech Creek near Statham, GA	Bch	Rural	52.6	123.2	5.0	2.4	28.3	2.6	16.4	7.5	38.3	23.7
19	02218700	Apalachee River near Bethlehem, GA	Apa	Rural	138.6	131.8	5.9	3.1	38.3	2.3	17.8	8.4	39.3	23.5
20	02346358	Turnpike Creek near Millner, GA	Tur	Rural	48.2	48.0	2.8	1.0	21.5	2.2	11.0	5.3	45.7	17.6
21	**02337395**	**Dog River near Winston, GA**	**Dog**	Rural	109.0	71.4	2.4	1.7	29.7	2.4	13.4	9.5	58.0	16.3
22	02338280	Whooping Creek, near Whitesburg, GA	Whp	Least developed	68.6	56.1	1.5	0.6	22.0	1.8	7.3	2.9	59.2	9.9
23	02338375	Centralhatchee Creek near Centralhatchee, GA	Cen	Least developed	82.6	16.7	0.8	0.4	6.0	1.5	4.8	1.8	55.3	8.6
24	02340282	House Creek near Whitesville, GA	Hou	Least developed	77.7	10.9	0.7	0.5	5.0	1.2	4.9	3.6	62.0	5.9
25	02213450	Little Tobesofkee near Bolingbroke, GA	LTob	Least developed	146.3	7.3	0.3	0.1	4.5	1.1	3.6	1.2	58.4	5.8
26	02221000	Murder Creek near Monticello, GA	Mur	Least developed	61.4	6.9	0.4	0.2	5.6	1.2	3.8	2.1	63.0	4.8
27	02339480	Oseligee Creek at County near Fredonia, AL	Ose	Least developed	77.2	21.7	1.0	0.5	5.1	1.3	5.9	3.2	68.1	4.4
28	02344887	Red Oak Creek near Greenville, GA	RdO	Least developed	109.0	24.3	0.8	0.2	6.7	1.3	4.5	1.6	66.9	4.0
29	**02338523**	**Hillabahatchee Creek near Franklin, GA[3]**	**Hil**	Least developed	43.3	7.8	0.4	0.2	4.0	0.9	2.8	1.2	70.4	0.9
30	**02347748**	**Auchumpkee Creek near Roberta, GA**	**Auc**	Least developed	111.8	5.1	0.3	0.1	2.2	0.8	2.3	0.6	70.6	0.0

[1]U.S. Census Bureau, 2000, redistricting data summary file: U.S. Census Bureau Technical Documentation Public Law 94-171, 223 p.

[2]Variable highly correlated with watershed population density (r>|95|) and used to calculate urban intensity index

[3]National Water-Quality Asssessment Program trend sampling sites

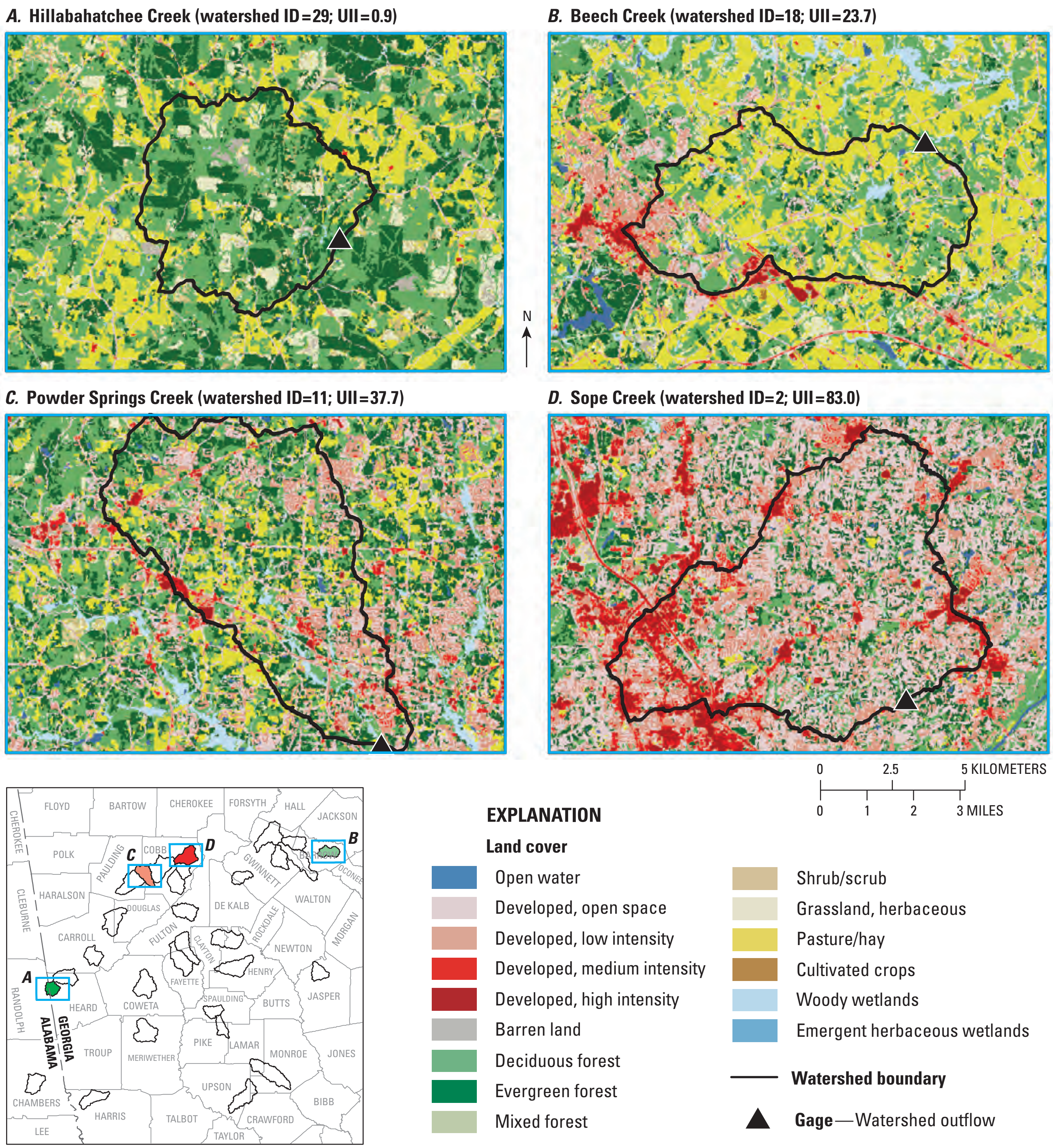


Figure 5. Land-cover classes and urban growth patterns in four representative watersheds in the Piedmont Ecoregion of Georgia and and Alabama, 2001: *(A)* Hillabahatchee Creek, least-developed and predominantly forested; *(B)* Beech Creek, rural with mixed forest and pasture; *(C)* Powder Springs Creek, suburban with mixed forest and pasture; and *(D)* Sope Creek, predominantly developed. (Colors in inset map correspond to symbol colors in following figures. Sampling sites numbers listed in table 1 and figures 1 and 2; urban intensity index (UII) calculated from five variables which were positively correlated with population density listed in table 1; land-cover data derived from National Land-Cover Dataset, 2001.)

Table 2. Reach lengths and selected geomorphic, hydrologic, and habitat characteristics of streams sampled in the Metropolitan Atlanta study area during, 2002–2003.

[ID, identifier; m, meter; m³/sec, cubic meter per second]

Watershed ID (figure 1*A* and 1*B*) and urban rank	Station code	Reach length (m)	Channel geomorphic units (percent)			Hydrologic charactersitics						Dominant substrate in transects (percent)			Habitat cover in transects (percent)			Riparian canopy	
			Pool	Riffle	Run	Mean wetted width (m)	Maximum depth (m)	Mean depth (m)	Stream discharge (m^3/sec)	Mean current velocity	Water-surface gradient	Large cobble	Sand	Mean riffle embeddedness	Boulders	Overhanging vegetation	Woody debris	Mean bank closure (percent)	Mean open angle (degrees)
1	Rot	300	2	55	42	12.1	0.6	0.3	0.94	0.40	0.005	73	15	50	85	97	0	97	17
2	Sop	180	0	13	87	13.2	1.8	0.5	0.85	0.21	0.002	13	69	81	42	58	0	76	32
3	Nic	232	3	12	85	12.3	0.9	0.4	1.05	0.37	0.001	0	67	98	0	58	3	83	33
4	Jac	160	0	0	100	8.4	0.6	0.4	0.84	0.39	0.001	0	91	NA	0	93	10	99	5
5	Uto	160	41	30	29	9.9	1.1	0.5	0.68	0.18	0.006	30	30	76	56	56	0	85	19
6	BCI	170	0	0	100	8.9	2.7	0.5	0.90	0.25	0.001	0	91	NA	0	100	6	94	0
7	Nos	260	0	0	100	11.8	2.6	0.7	3.06	0.42	0.001	0	97	NA	0	94	19	94	21
8	Suw	180	7	0	93	10.0	1.8	0.7	1.08	0.18	0.001	0	94	NA	0	58	39	95	28
9	Alc	180	0	0	100	10.1	1.0	0.5	1.19	0.42	0.002	0	88	NA	0	100	12	95	4
10	Mor	180	16	0	84	8.3	1.5	0.6	0.30	0.11	0.000	0	39	NA	7	25	36	84	24
11	Pow	160	8	0	93	10.2	0.8	0.4	0.60	0.25	0.001	0	94	NA	0	71	57	92	9
12	Wal	260	0	18	82	13.4	1.2	0.6	1.44	0.18	0.001	61	36	22	0	76	3	85	21
13	Whw	200	0	0	100	12.1	1.2	0.5	0.89	0.24	0.001	0	88	NA	0	44	19	91	19
14	Mil	230	0	0	100	10.5	1.1	0.6	0.60	0.23	0.003	0	85	NA	0	53	37	96	13
15	Sho	150	0	0	100	7.3	0.6	0.3	0.40	0.25	0.001	3	82	NA	3	76	0	84	23
16	Lmul	220	0	0	100	12.2	1.0	0.4	NA	0.33	0.001	0	94	NA	0	79	0	92	19
17	WhO	220	0	0	100	10.1	0.9	0.4	0.44	0.22	0.001	0	70	NA	0	91	6	97	14
18	Bch	214	0	0	100	11.5	1.0	0.3	NA	0.34	0.003	0	27	93	0	100	0	97	8
19	Apa	260	0	3	97	13.1	1.4	0.5	1.09	0.38	0.002	15	55	78	0	76	3	93	11
20	Tur	150	0	0	100	8.5	1.5	0.4	0.28	0.13	0.001	0	64	NA	0	64	3	83	24
21	Dog	300	0	23	77	16.0	1.1	0.5	1.85	0.26	0.002	18	70	67	9	67	6	95	21
22	Whp	260	0	60	40	16.9	0.6	0.4	0.75	0.31	0.003	52	3	31	0	52	0	94	30
23	Cen	300	12	51	37	15.4	1.0	0.4	1.12	0.28	0.003	70	15	64	27	64	0	96	33
24	Hou	170	0	0	100	9.1	0.9	0.4	0.80	0.40	0.004	0	100	NA	0	87	10	95	7
25	LTob	150	0	0	100	10.8	0.9	0.3	1.04	0.37	0.001	0	97	NA	0	91	21	93	7
26	Mur	150	25	36	39	9.1	2.1	0.4	NA	0.23	0.005	76	15	49	27	73	0	97	16
27	Ose	150	0	0	100	12.6	1.0	0.5	0.93	0.20	0.001	0	94	NA	0	58	12	88	22
28	RdO	180	0	0	100	9.9	1.2	0.6	0.77	0.28	0.002	0	100	NA	0	76	24	96	14
29	Hil	190	0	32	68	11.9	0.5	0.3	0.88	0.32	0.003	58	18	45	0	76	3	90	19
30	Auc	190	0	37	63	11.4	0.9	0.3	0.69	0.37	0.007	64	15	100	52	38	3	84	35

Data Collection and Processing

Data collection followed published USGS and NAWQA methods and protocols for water-quality (U.S. Geological Survey, 1997 to present) physical habitat (Fitzpatrick and others, 1998) and algal, invertebrate, and fish communities (Moulton and others, 2002). Nonstandard methods used to collect additional datasets—such as chemistry and toxicity from extracts of semipermeable membrane devices (SPMD), stream stage (cross-sectional area), and temperature data—employed previously unpublished protocols and are outlined below in more detail. Dates of collection for various datasets are presented in table 3.

Table 3. Approximate dates of samples and data collection in the Metropolitan Atlanta study area, 2002–2003.

Data type	Dates collected
Stage (cross-sectional area)	October 2002–September 2003
Reach habitat	May–August 2003
Synoptic water samples	High-baseflow (spring)—March 2003 Low-baseflow (summmer)—September 2003
Bimonthly water samples (also collected at synoptic sites)	November 2002 January 2003 May 2003 July 2003
Semipermeable membrane device exposure	March–April 2003
Algae	April–May 2003
Invertebrates	April–May 2003
Fishes	July–September 2003

Water Quality

Water samples were collected twice for nutrients, pesticides, chloride, sulfate, dissolved and particulate organic carbon, particulate nitrogen, suspended sediment, turbidity, and *Escherichia coli* (*E. coli*) at all 30 sites during synoptic surveys conducted during spring (high baseflow) and summer (low baseflow) and bimonthly at 10 of the 30 sites. Water samples were collected isokinetically at all sites using equal-width increment (EWI) methods unless conditions were too shallow or water velocity was insufficient, in which case samples were collected as multivertical grabs (U.S. Geological Survey, 1997 to present). Field properties were measured at each sampling event and include water temperature, dissolved oxygen, specific conductance, and pH using a multiparameter sonde, which was calibrated daily prior to use. Turbidity was analyzed using portable turbidity meters. Nutrients, pesticides, chloride, sulfate, dissolved and particulate organic carbon, and particulate nitrogen were analyzed at the USGS National Water Quality Laboratory (NWQL) in Denver, Colo., using methods described in Fishman (1993), Zaugg and others (1995), and Fishman and Friedman (1989). Suspended sediment concentration and particle size splits were determined at the USGS Georgia Water Science Center. Additionally, *E. coli* bacteria concentrations were determined using the membrane filtration method using modified mTEC media (U.S. Geological Survey, 1997 to present) at laboratories in the USGS Georgia Water Science Center or in mobile labs equipped with incubators. A complete list of sampled constituents and properties is listed in Appendix B, table B1. All standard water-quality data collected for this study have been published separately in the 2003 USGS Georgia Water Science Center Data Report (Hickey and others, 2004).

SPMDs are low-density polyethylene (LDPE) lay-flat tubing that contains a purified synthetic lipid (triolein), which passively accumulates hydrophobic contaminants from the environment. The devices are designed to mimic the bioaccumulation of organic contaminants in fatty tissues of aquatic organisms. One 15-centimeter SPMD housed in a protective aluminum container was installed in each stream for a 4-week period just prior to biological sampling (March–April 2003). SPMDs were positioned in areas of moderate flow either near midchannel, fastened to rebar stakes, or along the stream bank fastened to tree roots or immobile snags. After retrieval, the SPMDs were placed in an airtight can, refrigerated, and shipped to Environmental Sampling Technologies, Inc. (EST) laboratory in St. Joseph, Mo. for dialysis to remove the residues using methods described by Huckins and others (1990).

After dialysis, the dialysate was separated into four aliquots and submitted for various assays. The USGS Columbia Environmental Research Center (CERC) in Columbia, Mo., conducted two assays, which included an ultraviolet (UV) fluorescence scan and a Microtox® bioassay (Johnson, 1998). The UV fluorescence scan provided a semiquantitative screen for polyaromatic hydrocarbons (PAHs) using UV light and a standard curve developed by using various concentrations of pyrene under a specific wavelength of UV light. The results of this assay are reported as a pyrene index based in milligrams per SPMD extract. The Microtox® bioassay (Johnson, 1998) measured the decrease in light production of photo-luminescent bacteria when exposed to the SPMD residues. Bacteria mortality results in a reduction in photoluminescence that is proportional to the toxicity of the residue. Results from the Microtox® assay are reported as an EC_{50}—the concentration at which a 50-percent reduction in light output was observed.

The U.S. Army Corps of Engineers Environmental Laboratory in Vicksburg, Miss. (Murk, 1996) conducted a third assay, the P450RGS test. This assay provides a rapid screen for aryl hydrocarbon receptor (AhR) type compounds that include polychlorinated biphenyls (PCBs), PAHs, dioxins, and furans. All vertebrates produce a detoxifying enzyme when exposed to an AhR compound; the amount of enzyme produced is directly proportional to the concentration of the compounds. Quantifying one of these enzymes produced by the CYP1A1 (cytochrome P450, family 1, subfamily a, polypeptide 1) gene serves as a measure of dioxin activity. The concentration of AhR compounds in the SPMD extract that induces CYP1A1 production is expressed as the amount of dioxin, in toxic equivalents (TEQs), that would induce a similar response.

The NWQL was sent a fourth aliquot of the dialysate from SPMDs for identification and quantification of a set of target compounds using gas chromatography/mass spectrometry (GC/MS) analysis under two different ionization conditions (Tom Leiker, U.S. Geological Survey, written commun., 2005). Samples were concentrated to about 0.250 milliliter (mL) and transferred to 1.8-mL amber glass vials with 400-microliter (μL) inserts, and the volume adjusted to 400 μL and internal standards were added to the dialysates. First, electron-capture negative ionization (ECNI) was used to measure constituents such as pesticides, PCBs, and brominated diphenyl ethers in the SPMD extracts (Appendix B, table B2). Second, electron ionization (EI)—the conventional method for analyzing dialysates via mass spectrometry—was used to measure constituents such as alkyl phenols, polycyclic musks, and plant and fecal steroids. Mass spectra for individual target compounds and retention times from sample extracts were compared with authentic standards from the standard curve for identification. A six-point linear calibration curve was used for quantification of results.

Quality-control samples used to assess SPMD results included dialysis blanks, solvent blanks, trip blanks, and replicate samples. Dialysis and solvent blanks were used to assess potential contamination problems during laboratory processing. Trip blanks which were handled, processed, and analyzed exactly as the deployed SPMDs, and were used to access contamination during deployment. Values of field samples were considered nondetects if less than the maximum value reported for any trip blank. This conservative approach was used because each trip blank was exposed at 10 sites while the SPMD was being deployed. Due to isolated problems with contamination of trip blanks, unknown compounds detected at sites that also were detected in the trip blanks were censored to 10 times the highest level of contamination in the set of samples for which that trip blank was exposed. Compounds found in trip blanks whose values were greater than values measured from field samples were not included in subsequent analyses relating detections or concentrations to urban land use. Values of field samples greater than quality control samples were corrected by subtraction.

Since the SPMDs were not deployed the identical amount of time, all values for toxicity endpoints and chemical concentrations after corrections were normalized for time of exposure to allow comparison between sites. Chemical variable names, abbreviations, and definitions are presented in Appendix B, table B2.

Hydrology

Sampling sites were instrumented with unvented pressure transducers equipped with temperature probes for the collection of continuous stage and temperature and were programmed to record data at 15-minute intervals. Stevens Water Monitoring Systems Model PS310 pressure transducers, with an internal data logger and a range from 0 to 30 meters, were used to measure stream-stage fluctuation during the study (Greenspan Technology User Manual, 7th edition, available at *http://www.stevenswater.com/catalog/products/water_quality_sensors/manual/Smart2-manual.pdf,* accessed October 20, 2006). Stage data from the Model PS310 have a precision of ±0.036 meter, which does not meet USGS requirements for the precision of stage data used for streamgaging (±0.003 meter) (Sauer, 2002); these data, however, were considered adequate to characterize differences in hydrologic response among streams differing in land use and for the development of response variables to correlate with stream biological communities.

The use of unvented pressure transducers necessitated a correction for changes in barometric pressure, which was accomplished by using continuously recorded data from the nearest airport with obtainable data. Barometric data from airports were matched to the 15-minute time step of the transducer data by linearly interpolating the hourly data. Differences between barometric pressure at the airport locations and the stream monitoring sites due to differences in altitude were corrected using the following equation:

$$h = [T * 287 * \ln(P_0 / P_1)] / 9.8$$

where

h = differences in altitude between the airport and the study site (in meters)

T = average temperature of the layer of the atmosphere, assumed from the ambient airport temperature (in degrees Kelvin)

P_0 = station pressure of the airport or site, whichever is at the lower altitude (in millibars)

P_1 = station pressure of the airport or site, whichever is at the higher altitude (in millibars)

It was determined prior to data analysis that an insufficient number of stream discharge measurements over the range of flow conditions were available to convert stage data into a continuous discharge record for all 30 sites for the study period. To compensate for these limitations in the stage record, channel cross-section measurements were used to develop a stage/cross-sectional area rating curve using the AreaComp software (version 1; Rehmel, 2005). This rating curve was used within the USGS Automatic Data Processing System (ADAPS) to generate a continuous record of stream cross-sectional area from the stage records. Although data were originally collected in 15-minute increments, 1-hour time periods were used to generate a dataset comparable among all sites in the study area and, for consistency, among other USGS EUSE studies throughout the country. Although these stage data do not have the level of accuracy normally associated with USGS stage data, they were deemed acceptable for the purposes of this study.

Streamflow responses were characterized using rates of change in cross-sectional area as a surrogate for rates of change in stream discharge. The variability of the area-based record was analyzed both for the 2003 water year (October 1– September 31) and by season within that water year. Metrics were calculated that characterize the overall variability of flow defined by the duration of flows, the magnitude of change, rate of change (flashiness) and the frequency that streams were above or below certain magnitudes (McMahon and others, 2003).

Due to isolated and periodic problems with instrumentation, which resulted in loss of data during the study, the number of sites used in the water year and seasonal analyses varied from 26 to 29 and resulted in slight adjustments to minimum levels of significance for r_s values. A complete list of hydrologic variability metrics analyzed for this study is presented in Appendix C, table C2.

Water Temperature

Continuous water-temperature data were recorded using the Stevens Water Monitoring Systems Model PS310 pressure transducers and were standardized to an hourly time step. Temperature data were analyzed to investigate relations among maximum annual or seasonal temperatures, maximum annual or seasonal temperature ranges, and degree days (summed seasonally and by water year). Additional analysis of stream temperature records was conducted by manually inspecting summer and fall seasons records at highly urbanized sites with high levels of impervious surface in the basin and the riparian zone. This analysis was conducted to investigate the possibility that individual rain events occurring at critical times might cause brief but biologically important periods of elevated stream temperatures in the most-developed group of sites.

Stream Habitat

Habitat conditions at all stream reaches were measured during the summer using a protocol designed to balance qualitative and quantitative measures of habitat integrity (Fitzpatrick and others, 1998). Reach lengths were designated as 20 times mean wetted channel width, and marked with capped rebar stakes. Measures of instream habitat were made along 11 equally spaced transects perpendicular to the direction of streamflow. Along each transect, instream channel features—including geomorphic unit type (riffle, run, and pool), water velocity, depth, dominant substrate, substrate size, substrate embeddedness, and instream cover—were measured. Outside the channel, stream bank angles, bank heights, and estimates of bank stability were recorded. Estimates of canopy closure were made using a clinometer to measure the angle of the open canopy above each stream transect. Instantaneous discharge was either measured at the time of data collection or acquired from USGS streamflow gaging records for gaged locations. Channel gradients (percent slope) were determined using a laser level. Digital photographs were taken at each habitat transect to document habitat conditions during collection. All habitat data were recorded on standardized data sheets where habitat data for each site were summarized at the reach level. Habitat variable names, abbreviations and definitions are presented in Appendix C, table C1.

Algal Communities

Algal biomass, chlorophyll *a*, and algal community composition were assessed from two habitat types at each stream. Samples were collected from stable woody substrates to assess what is typically the richest habitat type (RTH, richest targeted habitat) in terms of species composition and from depositional areas (DTH, depositional targeted habitat) in shallow pools and along the stream margins using standardized protocols (Moulton and others, 2002) during spring 2003. Depositional areas were sampled by collecting episammic samples from shallow, slow-moving areas along the margins of streams within the reach using a 5-centimeter (cm) diameter petri dish cover to stabilize bottom material (coarse sands) while gently lifting the top 1–2 cm of substrate with a spatula and placing into a container. Five to 10 depositional algal samples were collected in this manner and composited into a single sample at each site. The composite sample was mixed thoroughly prior to removal of multiple 5–15 mL aliquots, which were filtered onto glass fiber filters and analyzed for chlorophyll *a* and ash-free dry mass (AFDM).

Hard substrates were sampled by gently scraping the algal film from 5 to 10 medium- to small-sized pieces of stable conditioned native wood with a soft brush and rinsing with bottled water. The material scraped from each of the pieces of wood was composited into a single sample and mixed thoroughly prior to the removal of multiple 5–15 mL aliquots. These were filtered onto glass fiber filters (47 mL) and analyzed for chlorophyll *a* and AFDM. Area estimates for biomass, chlorophyll *a*, and AFDM were made by using the surface area sampled in the depositional areas and the surface area estimates made from of the sampled pieces of woody debris using the formula for the surface area of a regular cylinder.

The remaining volumes of both the depositional sample and the hard substrate sample were preserved with full-strength buffered formaldehyde for taxonomic identifications, counts, and biovolume estimates, which the Philadelphia

Academy of Natural Science in Philadelphia, Pa., conducted by using protocols by Charles and others (2002).

Algal community data were processed using a version of the Invertebrate Data Analysis System (IDAS) modified to process algae data files (Tom F. Cuffney, U.S. Geological Survey, written commun., 2006). This program allows for the consistent and systematic handling of multiple levels of taxonomic resolution and ambiguous taxonomic data and calculates community and tolerance metrics using an attribute file of published values (Stephen D. Porter, U.S. Geological Survey, written commun., 2005). All algal taxa were included in the generation of metrics including soft algae and diatoms; this analysis, however, was limited to those taxa whose attributes were available and defined. Algal metrics names, abbreviations, and definitions are presented in Appendix D, table D1.

Due to issues regarding collection, processing, and/or identification of soft algae, only the diatom communities were used in the community analysis. Additional problems with DTH algal sample collection and processing resulted in data collected at sites 6, 7, 20, 24, 25, 27, and 28 (table 1) being removed from DTH analysis. Site 27 also was removed from the RTH analysis for similar reasons.

Invertebrate Communities

During spring 2003, invertebrates were sampled at each stream using both a semiquantitative and a qualitative method. D-frame nets and modified surber samplers with 500-micron mesh nets were employed (Moulton and others, 2002). Semiquantitative assessment involved collecting invertebrates from the dominant stable habitat found in all streams. Although riffle habitat is the generally preferred habitat to sample in medium to higher gradient streams, only 10 sites selected for this study contained riffle habitat. In order to make valid comparisons across the defined urban gradient at all 30 sites, pieces of stable woody debris were sampled at all sites. At the 10 sites where riffle habitat was common, a riffle sample also was collected using the modified surber sampler to determine if the choice of RTH for the full group of sites was able to properly characterize the invertebrate community. These data were analyzed and have been reported separately (Gregory, 2005). A qualitative invertebrate sample also was collected at each site from all available habitats in the reach using a timed sampling method.

The semiquantitative invertebrate samples collected from woody debris were collected by selecting about 10 pieces of small, medium, and large pieces of conditioned, native woody debris from a variety of current velocities within the reach. Small- and medium-sized pieces were either collected whole, or carefully cut with loppers or a small handsaw while an assistant positioned the modified D-frame net directly downstream from the piece of wood. Smaller pieces and the cut pieces of woody debris were brushed while in the bucket and washed with filtered native water to remove all epidendric material. Larger pieces of woody debris were sampled *in situ* by placing a slack sampler directly downstream from the piece of woody debris and vigorously brushing the epidendric material into the net with a large brush. Surface-area estimates made from the sampled pieces of woody debris were made using the formula for the surface area of a regular cylinder. All material collected in the net and from cleaning the pieces of wood was composited into a 5-gallon container.

The qualitative sample was collected by using a D-frame net to sample all available habitats within the stream reach. All material collected in this manner was composited in a separate 5-gallon container.

Composited material from all three sample types was elutriated to remove sediment and heavier material, then sieved through a 500-micron sieve where larger pieces of detritus were removed. Large or fragile individual invertebrates were removed and placed in a separate container to avoid damage to specimens. The remaining material on the sieve was placed into 1-liter bottles, preserved with 10-percent formalin, and shipped to the NWQL where the Biological Group, part of the USGS NWQL, conducted identifications and enumerations by using protocols developed by Moulton and others (2000).

Invertebrate data were processed using IDAS (Cuffney, 2003) to systematically and consistently adjust the entire dataset in terms of ambiguous taxa and to calculate data for synthetic samples, based on the presence or absence of taxa in both the snag and the multihabitat samples (QQ, qualitative plus quantitative). IDAS also was used to calculate a suite of 139 community metric—including those based on organism tolerance, functional feeding group, diversity indices, and similarity indices. Tolerance metrics calculated using IDAS used tolerance data published by Barbour and others (1999). Invertebrate metrics names, abbreviations, and definitions are presented in Appendix D, table D2.

Fish Communities

Fish communities were sampled during late summer and fall 2003 using a two-pass method of electrofishing. Reach lengths were designated as 20 times mean wetted channel width, and sampling was conducted by teams of between four and six persons depending on stream width and habitat complexity (Moulton and others, 2002). Collection involved the use of backpack electrofishers (Smith Root, Model 12-B) to stun fishes, which were captured using 6-millimeter mesh nets and seines. Captured fishes were held in aerated live wells until each pass was completed, after which the fishes were identified, weighed, measured, and released. Fishes captured and released after the first pass were released sufficiently far downstream from the study reach to ensure that they would not be recaptured during the second pass. Most captured fishes were released unharmed; however, specimens that expired due to handling stresses, as well as those kept as vouchers, were preserved in 10-percent formalin and are housed at the Georgia Museum of Natural History in Athens, Ga.

Fish community data from each site were used to calculate metrics based on percent relative abundance in samples using tolerance and trophic guild data (Barbour and others, 1999), physical and behavioral trait information assigned to individual fish species (Goldstein and Meador, 2004), and metrics designated by the Georgia Department of Natural Resources for use in a local fish Index of Biotic Integrity (IBI) for north Georgia Piedmont streams (Georgia Department of Natural Resources, 2005). Species with no tolerance or trophic information were analyzed as “unknowns.” Species with missing physical and behavioral trait information were assigned trait categories based on literature searches, consultation with local experts or the best professional judgment of the authors. Fish metric names, abbreviations, and definitions are presented in Appendix D, table D3.

Statistical Analysis

Although initial site selection was based on an index calculated from a suite of 19 variables that were rank correlated ($r_s \geq |0.50|$) with 1997 population density (see Appendix A, table A4), these variables were not used to correlate biological and environmental responses. Rather, a similar method was used to calculate UII using updated datasets and only a subset of variables that were highly correlated with 2000 population density ($r_s \geq |0.90|$). This more restrictive criterion for variable selection represented census based, infrastructure based, basin and riparian land cover based datasets—datasets that are commonly used by resource managers and urban planners. These variables included housing density ($r_s = 0.99$), watershed road density ($r_s = 0.98$), percentage of developed land in watershed ($r_s = 0.98$), percentage of developed land in the 90-meter stream buffer ($r_s = 0.96$), and percent forest in watershed ($r_s = -0.91$). Based on these five variables, a range standardized (0–100) UII was calculated using the same method as that used for site selection (McMahon and Cuffney, 2000; Falcone and others, 2007). This UII was assigned to each site along with the site's corresponding rank (1–30) in urban intensity (table 1). The percent imperviousness in each watershed and percent imperviousness in the 90-meter stream buffer also were correlated with biological responses; however, these two variables were not included in the calculated UII.

As an aid in graphical presentation of data and for use in multivariate and community comparisons, cluster analysis (Primer® version 6; Clarke and Gorley, 2006b) was used to aggregate sites into relatively homogeneous groups based on only the five variables used to calculate the explanatory UII (fig. 6). Group inclusion is denoted by a color change from dark green (least developed sites), to light green (rural sites), to orange (suburban sites), and to red (developed sites). Land cover in four watersheds, which are representative of sites in each of these four groups, are shown in figure 5*A*–*D*. Site numbers used throughout this report refer to the rank in urban intensity, 1 being most developed (highest urban intensity) and 30 being the least developed (lowest urban intensity).

Two general methods were used to analyze the data collected during this study. The first approach used nonparametric Spearman correlation analysis to examine relations between characteristics of urbanization and the chemical, hydrological, and biological metric datasets. The second approach used multivariate statistical analysis to link environmental data to the chemical, hydrological, and biological community datasets using nonmetric MDS and related comparative methods. For multivariate analyses, environmental datasets were initially reduced to remove highly intercorrelated variables through the use of Principal Component Analysis (PCA) and Spearman correlation analysis using Primer® software (Clarke and Gorley, 2006b). Variables were removed when the absolute value of intercorrelations exceeded 0.8 ($r_s > |0.8|$). Surrogate variables were retained that had the highest loadings (most explanatory power) on the primary PCA axis to represent the intercorrelated variables. Both the urban ranks from the range standardized UII and the urban groups defined by cluster analysis were used to analyze data.

Correlation Analysis

Metrics calculated from algal, invertebrate, and fish community data were used to assess possible impacts of urbanization. The global significance level for biological metric comparisons presented in this study were set at $\alpha = 0.005$; however, Bonferroni adjustments were made to the significance levels between paired datasets on an individual basis (that is, water quality and biological community metrics, hydrologic variability metrics and biological community metrics, and so forth) and multiple levels of significance are reported (Sankoh and others, 1997). Although there is some debate whether to use the number of comparisons within the entire study or the number of comparisons in the specific analysis in making this adjustment, the less-conservative approach was chosen and was an analysis-by-analysis adjustment (James and McCulloch, 1990; Perneger, 1998). Furthermore, some sites were not available for every comparison and some variables were not available for every site; thus, significance levels vary among comparisons and are reported separately for each analysis.

Multivariate Community Analysis

Multivariate data-analysis techniques were applied to the biological community data and included several ordination techniques available in the Primer® statistical software package (version 6; Clarke and Gorley, 2006b). These methods use resemblance matrices (Clarke and Warwick, 2001; Clarke and Gorley, 2006a), which are generally considered the most effective ordination methods for ecological community analysis. This assertion is based on multiple factors including (1) avoiding assumptions of linear relations among variables, (2) eliminating the problem of “zero truncated” data, and (3) allowing the use of multiple between-site distance measures including Bray-Curtis and Euclidian-based measures.

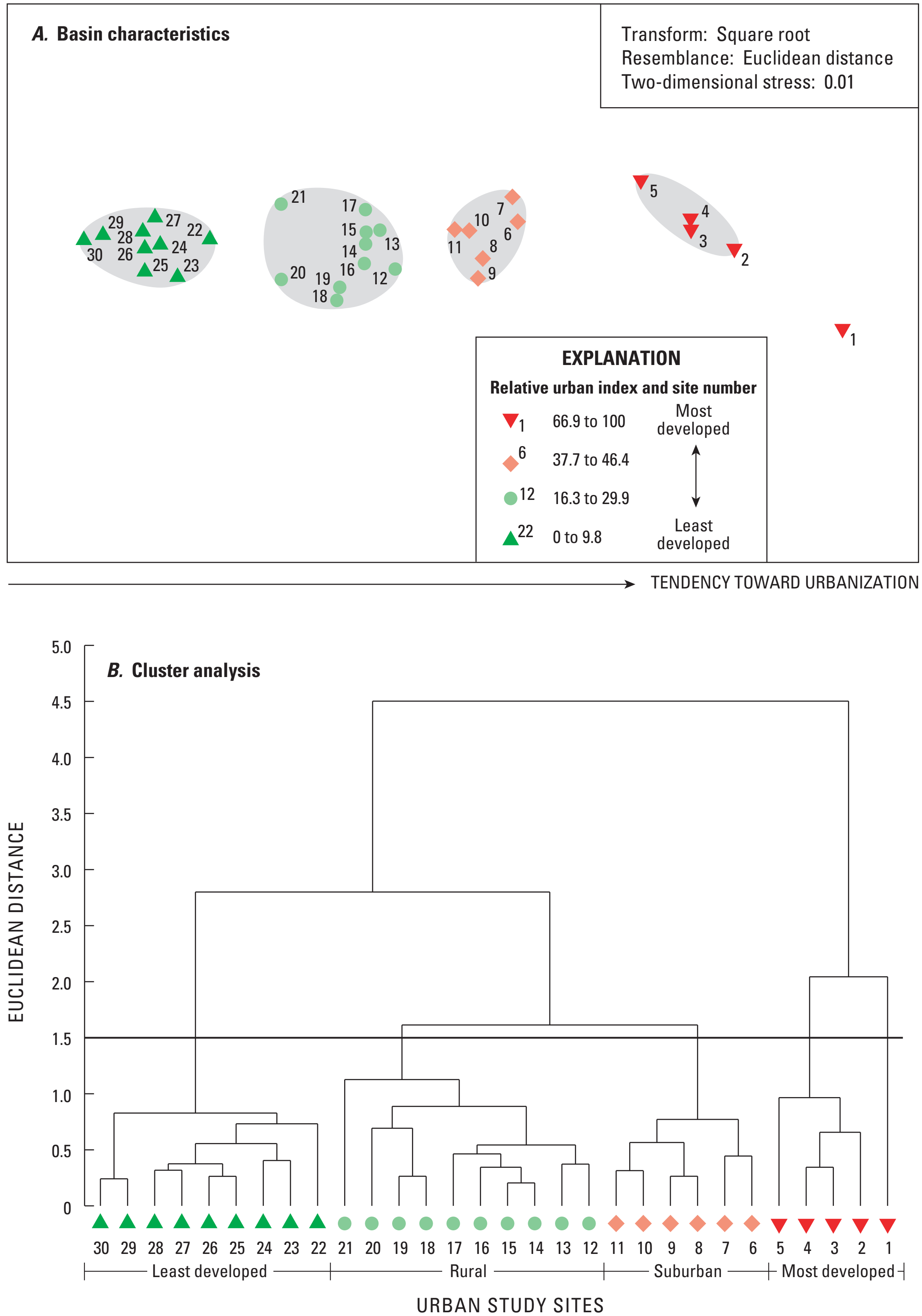


Figure 6. Analysis of site differences based on watershed characteristics used in the urban index. *(A)* Two-dimensional representation of nonmetric multidimensional scaling analysis. *(B)* Cluster delineation using 1.5 units as the threshold of inclusion within groups. Site numbers refer to the rank order along gradient of urbanization shown in table 1. Shaded areas in A indicate group clusters derived from Euclidean distance similarities illustrated in *B*. Symbol color corresponds to urban intensity level from inset map in figure 5.

These have the quality of maintaining the original distances among sites in terms of species composition or degrees of variability in environmental datasets (McCune and Grace, 2002). Initial views of the structure of biological community data and possible relations to the gradient of urbanization used MDS and were deemed appropriate for further analyses if MDS stress values for ordinations equaled about 0.2 or less.

Primer® software allowed for *post-hoc* hypothesis testing on datasets using environmental variables as factors to test for differences between groups of community samples defined by the cluster analysis on UII variables. These land-use groups were defined *a priori* using cluster analysis on selected components of the UII (table 1, fig. 6). Additional analysis of the structure of biological communities and their linkages to environmental variables also used functions available within the Primer® statistical package. The following briefly describes these procedures and the rational for their use.

The ANOSIM procedure is a multivariate analysis of similarity test (analogous to an ANOVA in parametric statistics) and was used to calculate a test statistic (R), which reflects the differences *between* defined groups of sites along the urban gradient in contrast to differences *within* each group. In essence, this test is a type of multivariate threshold analysis done to access the similarity of sites in terms of species composition in adjacent urban categories. Significant differences between adjacent groups are indicative of a multivariate threshold in terms of the biological community (K. Robert Clarke, Plymouth Marine Laboratory, written commun., 2005). To circumvent problems associated with using distances between sites in MDS space, R is calculated as a ratio of the differences between the average rank similarities among sites in a group and between groups to the total number of sites. The values of R will generally fall between 0 and 1 and will be 1 only if all sites within a group are more similar to each other than to any sites from another group (complete separation of the MDS ordination). R will be 0 (or less than 0) if similarities among sites within a group are the same, on average, as similarities between sites in different groups. A global test for the significance of the ANOSIM is done by comparing the value of R calculated for the original dataset to one calculated on the same dataset with labels permuted in all possible combinations. The significance level is proportional to the number of times the calculated R is exceeded by the simulated R values. If the global test indicated significant differences in the distribution of sites, pair-wise tests between all groups were conducted by performing the same procedure between individual pairs of groups and comparing both the R statistic as well as the resulting significance level.

The RELATE procedure was used to test for the relative strength of rank-based relations between specific environmental datasets and algal, invertebrate, and fish communities and for the presence of gradients in both species and environmental space. In essence, the RELATE procedure conducts a meta-scale multivariate regression on two independently collected datasets. It specifically tests the hypothesis that there is no relation between the resemblance matrix of the biological community and that of an environmental dataset by calculating the overall rank correlation coefficient, ρ, between the community and environmental matrices. Statistical significance is inferred by a permutation test that randomly recalculates ρ. Under the null hypothesis (no relation between environmental and biological datasets) ρ values will be near 0. If the datasets are highly related, ρ values based on a permutation will be near 1 and the null hypothesis is rejected.

A special case of the RELATE procedure compares biological community data to an ordered model matrix. This overall correlation coefficient between the two datasets is known as an Index of Multivariate Seriation (IMS). Seriation refers to change that is gradual and continuous (Clarke and Warwick, 2001, Clarke and others, 1993). In the present study, this model matrix consisted of a similarity matrix constructed from the ranks of the urban sites that were earlier defined by the explanatory (five variables) UII. The IMS specifically indicates how well the biological community matrix matches the ranked site model or, in this case, responded to the gradient of urbanization. Statistical significance for both ρ and the IMS test statistic is inferred by comparing simulated ρ and IMS values from randomly permuted samples within the same dataset. Significance is proportional to the number of times the actual IMS value is exceeded by the simulated IMS values. The number of iterations in these significance tests was set to 9,999 and reported significant at 0.05, 0.01, and 0.001 levels.

Another test that used the resemblance matrices was the test for multivariate dispersion (MVDISP). Dispersion values for groups of sites shows the internal separation of samples in species space or the variability in species composition and abundances. Increased variability in biological communities has been associated with environmental stressors (Clarke, 1993). This test assesses the overall level of variability and potentially the homogenization that occurs in streams as watersheds become more urban. The procedure determines the internal separation of samples in species space within a given group and allows for the semiquantitative assessment of change through comparison to the same separation within another group of sites. The test specifically contrasts the average rank similarities among groups of sites derived from the resemblance matrix underlying the original MDS. It calculates both the dispersion within a group and a test statistic that is calculated as an Index of Multivariate Dispersion (IMD), which is a dispersion factor proportional to the relative amount of variation in the group as compared to other groups in the analysis. Dispersion values increase proportionally but IMD values vary between a maximum of +1 (indicating that similarities among sites in groups with less urban development are lower than similarities among sites with more urban development) to –1 (indicating that similarities in the group of sites with more urban developed are lower than similarities in the sites with less urban development). Values near 0 imply no difference in variation between groups.

A final element in the community analysis describes the relative contribution that individual species made to overall differences in the algal, invertebrate, and fish communities. The SIMPER procedure contrasts with the previous methods described to report relations among sites (cluster analysis), groups of sites (ANOSIM, MVDISP), and species and environmental datasets (RELATE). Using the SIMPER (similarity percentage) routine, the contribution that each species makes to the average dissimilarity among the site groupings was examined. The SIMPER routine essentially disaggregates the information used to produce the MDS plots and uses the average Bray-Curtis dissimilarity between pairs of groups of samples as well as the contributions to the average similarity within a group to produce separate contributions from each species. The procedure reports average species abundance within the groups, average dissimilarity, percent contribution, and cumulative percent contribution. Average group abundance data was used to compile groups of taxa that were excluded from highly urban streams (developed group) and a list that only were found in streams with watersheds that were included in the least developed group of sites, which are considered to be sites that are near-reference in terms stream habitat conditions. No significance tests are appropriate for the results of this procedure.

Physical, Chemical, and Biological Responses to Urbanization

The most densely populated area of the Metropolitan Atlanta region is the central part of the city (fig. 2), but much of the population growth since 1990 has occurred in a ring-shaped area around this core area and the original suburbs. Growth rates in these areas have been especially high in areas to the north and south of Metropolitan Atlanta, although some areas near the center of the Metropolitan Atlanta area and in areas just beyond the ring-shaped area of high growth rates have grown little or in some cases have lost population since 1990, as indicated by the light and dark green areas outside the metropolitan area.

Land-use and infrastructure variables that are strongly correlated ($r_s > |0.90|$) to population density in the Metropolitan Atlanta area included housing density (range from 2.2 to 502 units per km^2, road density (range from 0.8 to 7.1 km of road per km^2), percent of developed land in the watershed (range from 2.3 to 85.4 percent), percent of developed land in the 90-meter stream buffer (range from 0.6 to 65.0 percent), percent impervious area in watershed (range from 0.3 to 38.2 percent), and percent impervious in the stream buffer (range from 0.1 to 29.7 percent). Percent forest in the basin (range from 11.3 to 70.6 percent) is inversely correlated with population density (table 1).

Figure 5 shows examples of the types of urban growth patterns occurring in the Metropolitan Atlanta area in representative watersheds from the four groups of sites delineated using cluster analysis (fig. 6*B*). The two-dimensional MDS graph (fig. 6*A*) shows the relative similarity between the sites based on the differences in the five variables used to calculate the UII and the implicit groupings along a gradient of increasing development and urbanization. Sites plotted on the far left are the least developed sites in the study area, and several of these are used as regional reference streams that represent least disturbed conditions. Sites plotting to the right are progressively more developed. Similar patterns of site groupings were observed when this procedure was applied to the original 217 candidate watersheds.

Cluster analysis is a complementary way to show the relation among sites based on the five variables used to calculate the UII. Figure 6*B* illustrates the relations among the sites based on the five variables used to calculate the UII. Using 1.5 units (from the original root transformed percentages) as the threshold of group inclusion, five groups were defined. For the purpose of group-based data analysis and presentation, Site 1 was included with the four other sites in the developed group. Cluster analysis also independently confirms the site groups defined in the MDS plot (fig. 6*A*) and preserves the rank ordering of sites originally defined by the calculated UII.

Undeveloped sites could be considered to be least disturbed conditions with respect to the five variables used to calculate the UII and were typified by Hillabahatchee Creek watershed (fig. 5*A*). This site was mostly forested with an UII value of 0.9 with only 2.8 percent developed land and 0.4 percent impervious surface within its basin. Within the undeveloped group of sites, percent developed land ranged from 2.3 to 7.3 percent, whereas percent forested land cover was greater than 55 percent (table 1).

Rural sites are transitional from near-reference and generally undeveloped conditions to somewhat more developed and were typified by the Beech Creek watershed (fig. 5*B*) which had an UII of 23.7. This site was about 16 percent developed, with about 38 percent forest and 5 percent impervious surface in the basin. Only small and disconnected areas of developed lands were present in the upland portions of this basin. Within the rural group of sites, the percent developed in the basin ranged from 11.0 to 25.7 percent, whereas the percent forest ranged from 37.9 to 58.0 percent. The amount of impervious surface in these watersheds was still relatively low, ranging from 2.4 to 6.8 percent (table 1).

Suburban sites are progressively more urban than the rural sites and have higher population densities and levels of infrastructure and urban development. Powder Springs Creek watershed (fig. 5*C*) typified this group of sites and had an UII of 37.7. Land use in the Powder Springs Creek basin consisted of highly distributed developed areas located in mixed forest and pasture areas. This basin was 35.6 percent developed, 8.9 percent covered by impervious surfaces, and only 39.6 percent forested. UII values of the suburban sites ranged from 37.7 to 46.4, whereas percent developed ranged from 35.6 to 43.2, percent impervious ranged from 8.9 to 14.6, and percent forest ranged from 34.8 to 40.8 (table 1).

Developed sites are composed of the most urbanized watersheds in the Metropolitan Atlanta area. These sites have the highest population and road densities in the region and consist of mostly developed urban areas. The Sope Creek watershed (fig. 5*D*) is typical of these highly developed watersheds and consists of 72.5 percent developed areas with 19.6 percent covered by impervious surfaces. Developed land cover in this group of watersheds ranged from 60.6 to 85.4 percent with percent imperviousness ranging from 16.9 to 38.2 percent. Percent forest in these watersheds ranged from only 11.3 in the most urbanized basin to 35.0 percent (table 1).

Water-Quality Response

With the exception of nutrients, the general response of stream water-quality properties to increasing urbanization was an increase in individual constituent levels across the gradient of urbanization. Spearman correlation values between all significant variables ($p<0.005$) are presented in table 4. Significant correlations were observed between the UII and water-quality properties in both the spring and late-summer synoptic surveys, with the spring synoptic having more significantly correlated properties (5) with the UII than the late-summer synoptic (4). The main differences between the seasonal response was observed with pesticides—both the sum of pesticides and the sum of herbicides metrics were correlated with the UII during the spring, whereas only a single herbicide, simazine, was significantly correlated with the UII during the late summer. Atrazine, while not significantly correlated with the UII in the spring, was correlated with components of the UII such as housing density, percent developed in the basin, and percent developed in the buffer as well as both measures of imperviousness during the spring synoptic. Of the significantly correlated water-quality variables, specific conductance consistently exhibited the highest correlation coefficients with the UII and its components as well as both measures of imperviousness. Specific conductance and chloride levels generally were higher in the late-summer synoptic when water levels were lower than in the spring when water levels were higher. Nutrient levels were not significantly correlated with the UII; however, nitrate-plus-nitrite and total nitrogen were inversely correlated with percent forest. Total nitrogen was not correlated with the UII, and only inversely with percent forest; it was correlated with percent impervious area in the basin during both spring and late-summer synoptic survey. Nutrient levels generally were higher during spring when surface runoff was a higher component of the streamflow.

To assess the degree to which seasonality would alter the interpretation of the water chemistry results, water samples were taken at 10 of the 30 sites (bolded sites in table 1) four times in addition to the two water-quality synoptic surveys (tables 1 and 3). These sites were distributed across the ranges of the urban gradient and were sampled bimonthly throughout the duration of the 2003 water year. Figures 7 and 8 illustrate the relations of selected chemical variables that were significantly correlated to the UII and seasonal variability of chemical constituents for all samples. In these plots, both synoptic events and the ranges of the four additional samples are included for the selected properties. Specific conductance, chloride, and sulfate each exhibit somewhat progressively higher levels in samples collected at sites with progressively higher UII values (figs. 7*A–C*). The pattern with respect to nutrient concentrations is not linear, with somewhat higher levels near the middle section of the gradient (fig. 7*D–E*). Phosphorus, although not significantly correlated with the UII, exhibited low concentrations at both low and high levels of urbanization. This pattern in respect to phosphorus was evident in the spring and late-summer synoptic as well as the bimonthly trend samples (fig. 7*F*). Concentrations of nutrients such as total phosphorus were highest near the middle of the urban gradient and may result from distributed septic systems, limited agriculture or land-disturbing activities related to suburban development.

Atrazine and simazine concentrations were relatively low at sites with low UII scores and increased as watersheds became progressively more urban (fig. 8*A*, *B*). Spring (wet-season) samples generally had higher concentrations of these constituents than the late-summer (dry-season) samples. A high degree of seasonal variability also was evident in several of the nutrients and pesticides, indicating that watersheds in the middle and upper portions of the urban gradient may be receiving higher constituent loads during times other than when the synoptic samples were collected. Both the SPMD assays and extract datasets exhibited significant ($p<0.005$) correlations with watershed urbanization.

Both pyrene and benzophenanthrene exhibited the highest correlations to the UII and to components of the index, except road density and percent forested. High negative correlations between these two constituents were observed, with percent forested ($r_s = -0.82$). Several other SPMD derived variables were strongly correlated with urbanization including both the Microtox and CYP1A1 induction bioassays. The highest correlation with these assay results were with percent developed in basin and buffer and percent impervious in the basin and buffer. The general response of SPMD derived data across the gradient of urbanization defined by the UII was low chemical extract levels and low assay response at low levels of urbanization, with a possible threshold response evident at UII values of between 20 and 30 (fig. 9*A*, *B*). A total of 14 chemicals extracted from the SPMDs were significantly correlated with the UII and all the constituent variables as well as both measures of percent imperviousness. Several other chemicals identified from SPMD extracts were also significantly correlated with various constituents of the UII and are related to increasing watershed urbanization and loss of forest, although not correlated to the UII. Plots illustrating the relations of some of the SPMD-derived compounds to the UII are shown in figure 9.

Table 4. Spearman rho (r_s) values for significant correlations ($p < 0.005$) between water-quality properties and the urban intensity index, components of the urban intensity index, and impervious surface estimates in the Metropolitan Atlanta study area, 2002–2003.

[km^2, square kilometer; n, number of sites used in analysis; r_s value in bold indicates mimimum level of significance after Bonforonni adjustment; semipermeable membrane devices (SPMD) values in parenthesis indicates number of isomers summed for constituent value used in analysis]

	Urban intensity index	[1]Housing density (units/km^2)	[1]Road density (km^2)	[1]Percent developed	[1]Percent developed (stream buffer)	[1]Percent forested	Percent impervious	Percent impervious (stream buffer)
High-baseflow (spring) synoptic (n = 30; r_s = |0.66|)								
Specific conductance	0.89	0.88	0.89	0.91	0.90	–0.83	0.89	0.89
Chloride	0.87	0.84	0.84	0.84	0.81	–0.82	0.81	0.80
Sulfate	0.81	0.80	0.78	0.82	0.83	–0.73	0.82	0.81
Sum of insecticides	0.76	0.68	0.69	0.74	0.75	–0.72	0.73	0.74
Sum of herbicides	0.66			0.67	0.67			0.69
Atrazine		0.66		0.67	0.68		0.67	0.69
Nitrite plus nitrate						–0.78		
Total nitrogen						–0.72		0.66
Low-baseflow (summer) synoptic (n = 30; r_s = |0.66|)								
Sulfate	0.85	0.84	0.82	0.85	0.86	–0.82	0.85	0.86
Chloride	0.81	0.78	0.76	0.82	0.80	–0.79	0.81	0.81
Simazine	0.78	0.80	0.75	0.83	0.83	–0.75	0.84	0.85
Specific conductance	0.78	0.78	0.77	0.81	0.79	–0.70	0.78	0.78
Total nitrogen						–0.77		0.67
Nitrite plus nitrate						–0.75		0.66
Semipermeable membrane device extracts (n = 30; r_s = |0.66|)								
Assays								
CYP1A1 induction bioassay[2]	0.87	0.89	0.86	0.91	0.91	–0.78	0.91	0.90
Fluoroscan[3]	0.86	0.86	0.84	0.89	0.89	–0.82	0.91	0.90
Chemistry								
Chlorpyrifos	0.81	0.76	0.81	0.78	0.75	–0.79	0.76	0.74
Benfluralin	0.81	0.78	0.77	0.81	0.82	–0.72	0.82	0.81
Trifluralin	0.80	0.79	0.76	0.81	0.82	–0.74	0.82	0.82
Trans-chlordane	0.79	0.79	0.76	0.79	0.77	–0.77	0.79	0.77
Chemistry[4]								
Pyrene	0.91	0.91	0.87	0.92	0.92	–0.82	0.93	0.92
Benzophenanthrene (sum of isomers)	0.90	0.90	0.87	0.92	0.92	–0.81	0.93	0.92
Fluoranthene	0.85	0.87	0.83	0.88	0.87	–0.74	0.88	0.87
Benzophenanthrene (2)	0.82	0.84	0.80	0.83	0.82	–0.68	0.84	0.81
X-methyl anthracene (3)	0.80	0.75	0.76	0.80	0.80	–0.86	0.82	0.82
Methyl dibenzofuran (1)	0.79	0.73	0.74	0.79	0.79	–0.84	0.79	0.78
Dibenzothiophene	0.76	0.76	0.75	0.77	0.76	–0.77	0.75	0.74
4H-cyclopenta[det]phenathrene	0.72	0.72	0.67	0.75	0.75		0.75	0.73
Methyl pyrene	0.71	0.69	0.69	0.71	0.74		0.72	0.71
Benzo(b)naptho [2,1]thiophene	0.70	0.69	0.67	0.72	0.76	–0.67	0.78	0.77
Fluorene				0.70	0.69	–0.67	0.68	0.65
Methyl-9H-fluorene (2)				0.67	0.73		0.69	0.71
1,2,3,4-tetramethyl napthalene					0.67	–0.69	0.67	0.70
Trimethyl napthalene (1)						–0.73		

[1]Variables used in calculating urban intensity index

[2]Screen for aryl hydrocarbon receptor (AhR) type compounds such as polychlorinated biphenyls (PCBs), polycyclic aromatic hydrocarbons (PAHs), dioxins, and furans (U.S. Army Corps of Engineers Environmental Laboratory in Vicksburg, Miss.; Murk and others, 1996)

[3]Screen for PAHs, which fluoresce under ultraviolet light (Johnson and others, 2004)

[4]Two SPMD samples lost prior to analysis for unknown compounds, therefore significance levels reset to |0.67| for n = 28 for this analysis group

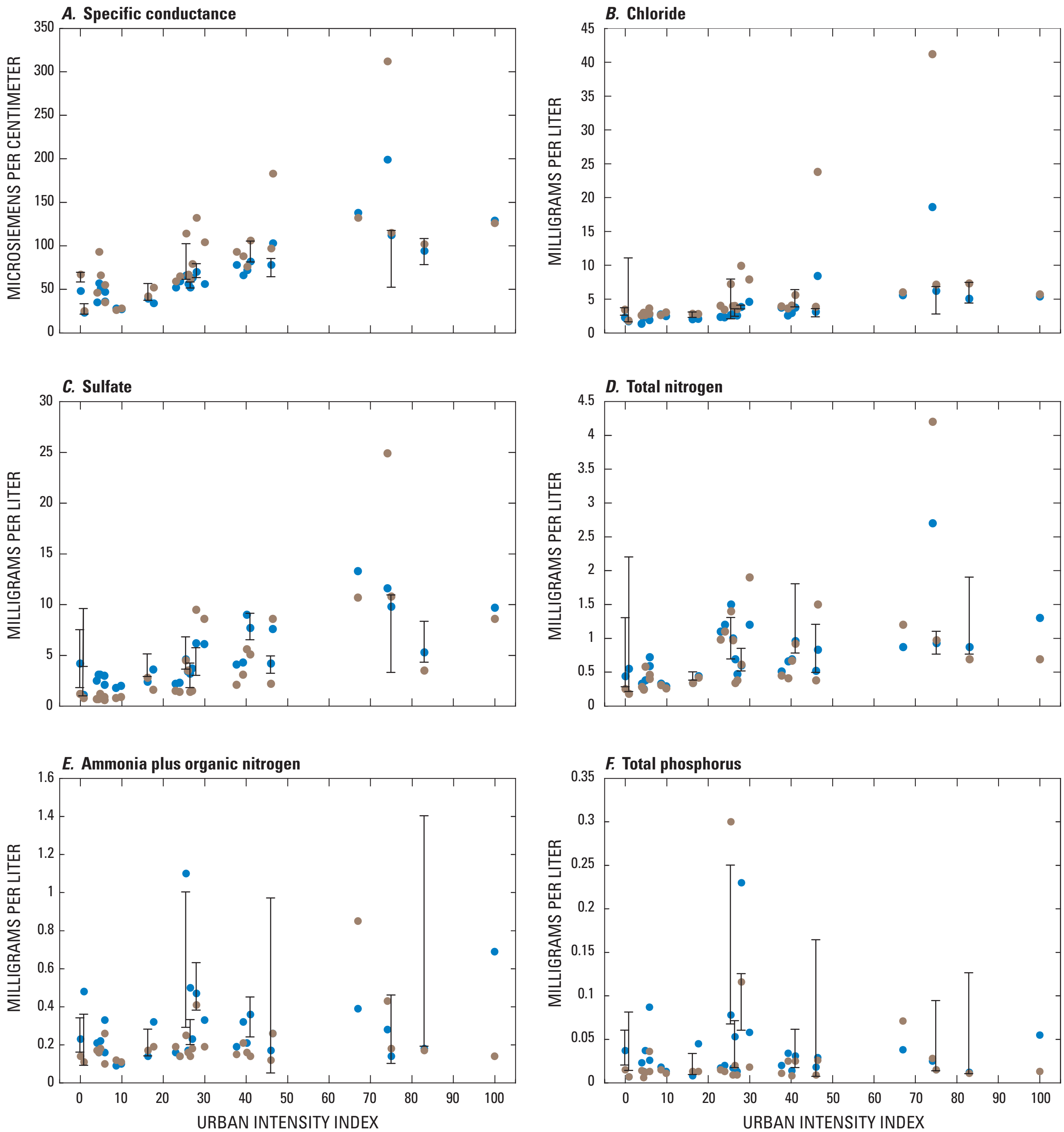


Figure 7. Scatter plots of selected variables along a gradient of urban intensity for 30 stream sites in the Piedmont Ecoregion of Georgia and Alabama, 2003: *(A)* specific conductance, *(B)* chloride, *(C)* sulfate, *(D)* total nitrogen, (E) ammonia plus organic nitrogen, and (F) total phosphorus.

EXPLANATION

- **Wet-season synoptic**
- **Dry-season synoptic**
- **Bimonthly sample range**

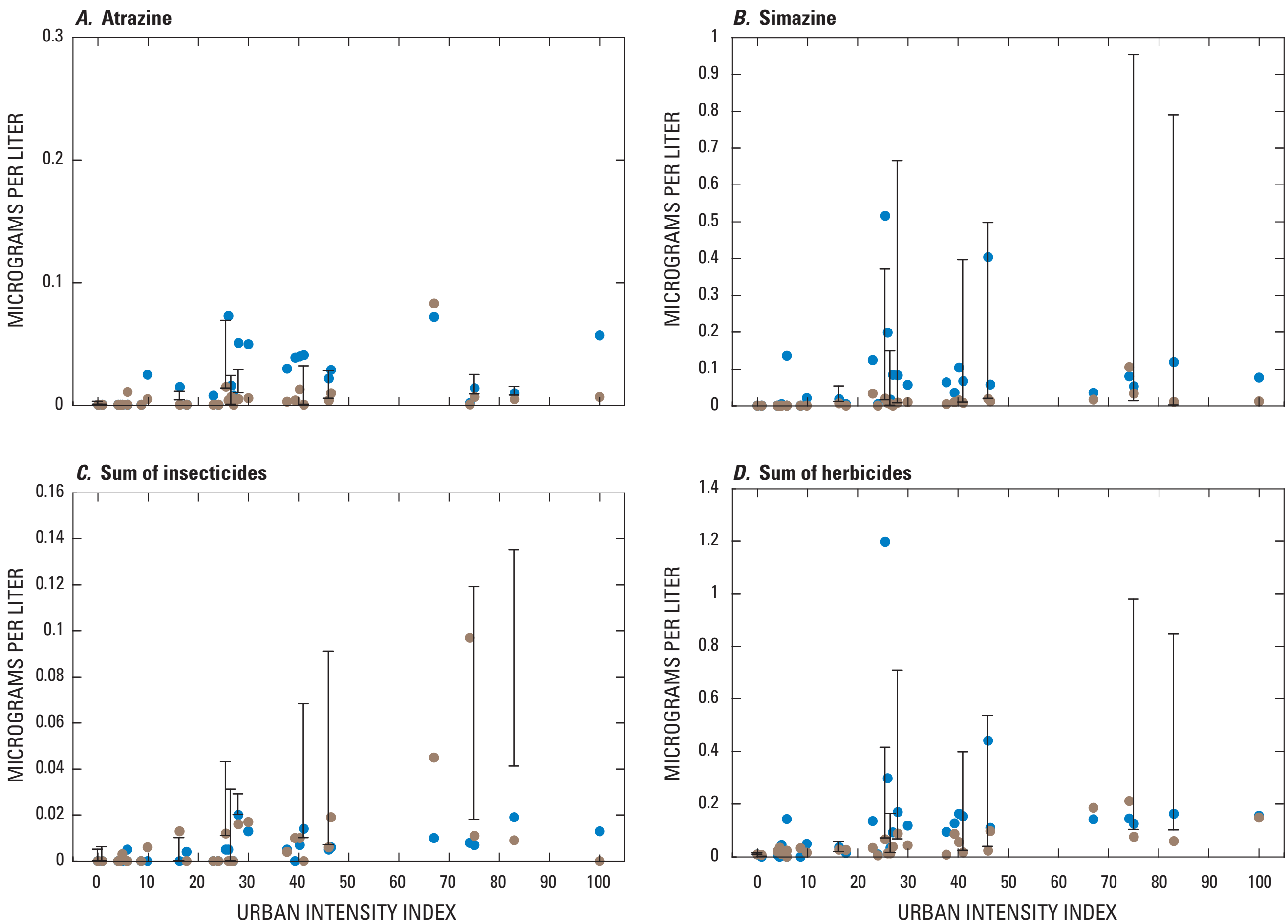


Figure 8. Scatter plots of selected pesticides and pesticide indices along a gradient of urban intensity for 30 stream sites in the Piedmont Ecoregion of Georgia and Alabama, 2003: *(A)* atrazine, *(B)* simazine, *(C)* sum of insecticides, and *(D)* sum of herbicides.

EXPLANATION

- **Wet-season synoptic**
- **Dry-season synoptic**
- **Bimonthly sample range**

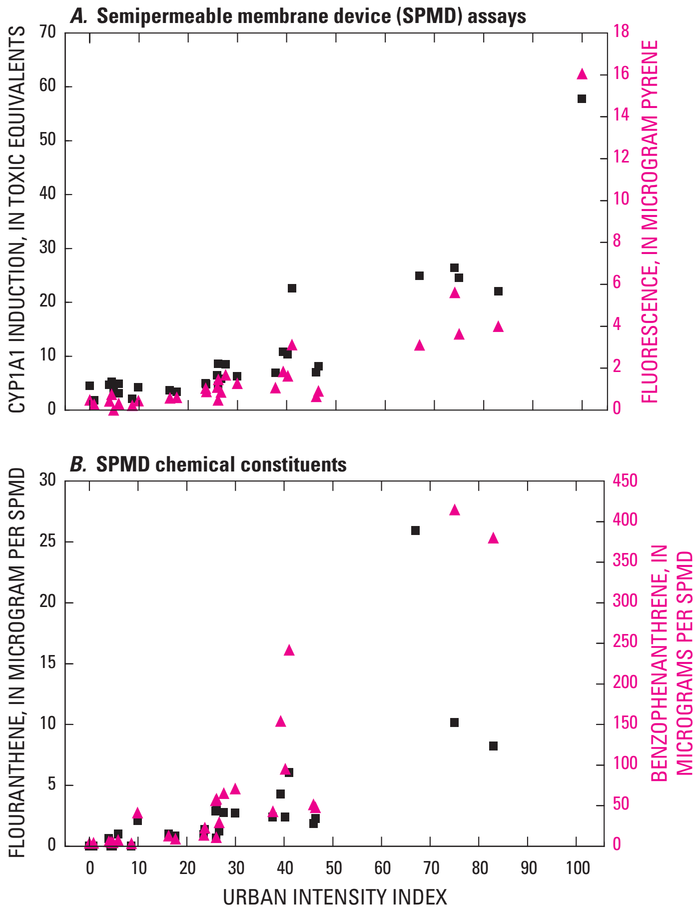


Figure 9. Selected semipermeable membrane device (SPMD) assay results and extracted chemical constituents along a gradient of urban intensity for 30 stream sites in the Piedmont Ecoregion of Georgia and Alabama, 2003: *(A)* CYP1A1 induction in toxic equivalents and pyrene fluorescence, and *(B)* flouranthene and benzophenanthrene.

Hydrologic Response

Significant correlations were observed between hydrologic variability metrics and watershed urbanization (table 5). In general, hydrologic variability metrics associated with increasing watershed urbanization were those that quantified the degree of flashiness and/or the duration of high flows in a basin. Of the 50 hydrologic variability metrics calculated for the 1 year period of record (POR), 11 showed significant ($p < 0.005$) correlations to the UII and/or the individual components of the UII in one or more of the periods of analyses (table 5). Streamflow during the fall was most influenced by the degree of urbanization in the watershed, as indicated by the high number of significantly correlated flow variables, whereas the response in winter was the weakest. The response to urbanization was significant in the spring and summer, with many of the same variables showing relations to urbanization; however, the magnitude of the r_s values was lower, indicting a weaker although still significant fit of the data across the gradient.

Hydrologic variability metrics based on water year POR indicated significant correlations with a metric, which indicates the most extreme periods of rising water (a_periodr9) with the highest r_s values between this metric and density of housing units and the percent of impervious in the basin (table 5). Other variables that were significant for the water-year analysis included several flashiness metrics, especially those which show the frequency of rising and falling events greater than 9 or 7 times the median rise or fall over the POR (a_periodf9, a_periodr7, and a_periodf7).

Analysis of the seasonal POR indicated greater significance in terms of number of variables during the fall, typically a low-flow period in the Southeastern United States, and the fewest in the winter when flows are normally the highest. The responses were similar to the water-year analysis with respect to the flashy nature of the more urban streams, but the seasonal analysis revealed negative correlations with respect to metrics, which measure the duration of high-flow pulses greater than the 95th 90th, or 75th percentile (a_mxh_95, a_mxh_90, and a_mxh_75). These negative correlations were significant with land use only during the summer and fall seasons indicating a potential seasonal component to land-use induced flow variation. This study indicated no evidence of a higher frequency of lower flows in more urban streams, although this relation has been demonstrated in other studies including recent findings in the Metropolitan Atlanta area (Rose and Peters, 2001; Calhoun and others, 2003).

Temperature Response

Maximum stream temperatures ranged from 18.3ºC to 25.1ºC during the fall, 16.2ºC to 20.5ºC during the winter, 20.6ºC to 26.2ºC during the spring, and from 21.3ºC to 33.0ºC during the summer. No significant correlations were observed between the UII and any of the components of the UII and maximum seasonal temperatures, maximum seasonal temperature ranges, seasonally accumulated degree days, or degree days accumulated for the entire water year. Often the highest temperatures were observed at streams with relatively low levels of urban intensity, suggesting that reach scale factors such as upstream canopy cover or aspect may be more important than land use at the basin scale in determining stream temperatures. Additional analysis of temperature records at sites with high levels of urbanization within the watershed and riparian zone did not indicate any evidence of changes in temperature due to individual rain events at critical times during the summer or fall. The maximum observed change was on the order of 1–2 degrees after storms and water temperatures sometimes decreased after a runoff event even during the summer months in highly developed watersheds.

Table 5. Spearman rho (r_s) values for significant correlations ($p < 0.005$) between hydrologic variability metrics and the urban intensity index, components of the urban intensity index and impervious surface estimates in the Metropolitan Atlanta study area, 2002–2003.

[km², square kilometer; n, number of sites used in analysis; r_s value in bold indicates mimimum level of significance after Bonforonni adjustment; detailed explanation of hydrologic variable names in Appendix B, table B2]

Hydrologic metric	Urban intensity index	[1]Housing density (units/km²)	[1]Road density (km²)	[1]Percent developed (basin)	[1]Percent developed (stream buffer)	[1]Percent forested (basin)	Percent impervious (basin)	Percent impervious (stream buffer)
Water year (n=26; r_s=|0.69|)								
a_periodr9	0.85	0.89	0.87	0.86	0.86	–0.74	0.87	0.84
a_periodr7	0.81	0.84	0.82	0.81	0.82	–0.72	0.83	0.80
a_periodf9	0.78	0.80	0.78	0.81	0.83	–0.66	0.82	0.80
a_periodf7	0.77	0.78	0.77	0.78	0.81		0.80	0.78
a_cummulative_change	0.71	0.73	0.70	0.75	0.76		0.76	0.76
a_periodr5	0.70	0.70	0.70				0.69	
Fall (n=28; r_s=|0.67|)								
a_periodr7	0.89	0.91	0.89	0.88	0.86	–0.80	0.87	0.86
a_periodf9	0.88	0.89	0.88	0.88	0.87	–0.82	0.89	0.87
a_periodr9	0.88	0.92	0.90	0.88	0.86	–0.77	0.88	0.85
a_periodf7	0.84	0.84	0.84	0.83	0.84	–0.78	0.85	0.84
a_cummulative_change	0.83	0.83	0.83	0.85	0.85	–0.71	0.83	0.84
a_day_pctchange	0.70	0.72	0.71	0.71	0.71		0.73	0.72
a_periodf5	0.70	0.68	0.69	0.68	0.71		0.71	0.72
a_mxh_95	–0.70			–0.68	–0.68	0.73	–0.69	–0.69
a_mxh_75	–0.73	–0.72	–0.75	–0.71	–0.69			–0.68
a_mxh_90	–0.87	–0.84	–0.85	–0.86	–0.86	0.85	–0.85	–0.86
Winter (n = 29; r_s = |0.66|)								
a_periodr9	0.68	0.72	0.68	0.71	0.70		0.74	0.69
a_cummulative_change		0.66		0.68			0.71	0.68
a_periodr7		0.68		0.66			0.71	
Spring (n=28; r_s=| 0.67|)								
a_periodr9	0.79	0.85	0.83	0.79	0.78	–0.69	0.80	0.75
a_periodf9	0.77	0.82	0.79	0.81	0.83		0.82	0.80
a_periodr7	0.76	0.82	0.80	0.77	0.76		0.77	0.73
a_periodf7	0.76	0.79	0.77	0.79	0.81		0.79	0.78
a_periodr5	0.69	0.75	0.73	0.69	0.68		0.70	
a_periodf5	0.68	0.70	0.67	0.72	0.74		0.71	0.71
Summer (n=27; r_s=|0.67|)								
a_cummulative_change	0.82	0.80	0.81	0.83	0.83	–0.79	0.83	0.83
a_periodr9	0.77	0.74	0.78	0.76	0.78	–0.76	0.78	0.77
a_periodf9	0.76	0.74	0.78	0.78	0.79	–0.73	0.79	0.79
a_periodf7	0.73	0.72	0.74	0.75	0.77	–0.67	0.76	0.76
a_periodr7	0.72	0.70	0.72	0.72	0.73	–0.71	0.75	0.74
a_periodf5	0.70		0.68	0.69	0.74		0.69	0.73
a_mxh_90	–0.75	–0.68	–0.75	–0.70	–0.69	0.71	–0.67	–0.67
a_mxh_95	–0.81	–0.77	–0.82	–0.79	–0.79	0.70	–0.75	–0.76

Algal Metric Responses

None of the algal metrics calculated from either the DTH or the RTH samples showed any significant correlations with the UII or to the individual components based on power to detect statistically significant relations. Since the lack of significant responses of the algal metric data set to urbanization may have been partly due to the loss of sites that resulted in a higher threshold for statistical significance (critical r_s |0.76| for DTH samples and |0.70| for RTH samples) the discussion of the algal metric responses to urbanization; therefore, is limited to only the algal metrics with the highest correlations to the UII and its components (table 6 and fig. 10*A–D*).

In general, the DTH samples were more responsive to increasing watershed urbanization, as indicated by the greater number of metrics correlated ($r_s > |0.60|$) and the higher correlation values. Two metrics, percent alkaliphilous taxa (pH4rp) and percent mesosaprobic taxa (SAPRO3rp), had the highest correlation values and responded negatively to increasing percent forest in the basin. The pH4rp taxa also responded positively to increasing housing density in the basin. Percentage of forest cover in the basin was linked to several other algal metrics including percent less pollution tolerant (PTOL3arp; $r_s = 0.74$), percent alkaliphilous taxa (pH4rp; $r_s = -0.75$), and percent mesosaprobic taxa (SAPRO3rp; $r_s = -0.75$) (table 6).

The only two RTH metrics that were positively correlated with increasing urbanization were percentage of meso/polysaprobic taxa (PTOL2arp) and number of meso/polysaprobic taxa (PTOL2ar) indicating pollution tolerance in the algal community. PTOL2arp had weak, but not statistically significant, positive correlations with percent developed in basin and the buffer and both impervious surfaces in the basin and in the buffer, whereas PTOL2ar responded only to percent development in the basin.

Individual variables from the environmental datasets were analyzed in relation to the algal metrics for algae collected from depositional habitats (DTH samples). The depositional algal community was selected based on indications from multivariate analyses that the depositional community responded more significantly to urbanization (discussed in more detail in Algal Community Response section).

Strongest correlations were found with the hydrologic variability metrics during the full water-year period. Maximum duration of consecutive rising and falling events (a_maxrise and a_maxfall) during several of the hydrologic periods analyzed—water year, fall, winter, and summer—correlated with indices measuring degree of tolerance of the algae to salinity, pH, levels of dissolved oxygen and oxygen demand, consistency of substrate inundation by water, and general categories of pollution tolerance (table 7). Other significant correlations

Table 6. Spearman rho (r_s) values $\geq |0.60|$ for the highest, but nonsignificant ($p < 0.005$), correlations between algal metrics and the calculated urban intensity index, components of the urban intensity index and impervious surface estimates in the Metropolitan Atlanta study area, 2002–2003.

[km^2, square kilometer; n, number of sites used in analysis; r_s value in bold indicates mimimum level of significance after Bonforonni adjustment; detailed explanation of algal metrics in Appendix D, table D1]

Algal metric	Urban intensity index	[1]Housing density (units/km^2)	[1]Road density (km^2)	[1]Percent developed (basin)	[1]Percent developed (stream buffer)	[1]Percent forested (basin)	Percent impervious (basin)	Percent impervious (stream buffer)
Episammic (depositional); n = 23; r_s = |0.76|)								
PTOL3arp						0.74	–0.60	
SAL1rp		–0.63				0.62		
ORGN1rp		–0.60				0.61		
pH2rp						0.60		
SAPRO3r						–0.61		0.61
SAPRO3ap	0.66	0.66	0.68	0.65	0.62	–0.61	0.63	0.62
OXTOL4ap						–0.62		
PTOL2ar				0.61		–0.66	0.63	0.66
pH4rp	0.67	0.70	0.65	0.65	0.61	–0.75	0.68	0.64
SAPRO3rp						–0.75		
PTOL2aap		0.60	0.62	0.63			0.61	
OXTOL3rp		0.64						
Snags; n = 29; r_s = |0.70|)								
PTOL2arp				0.62	0.61		0.61	0.64
PTOL2ar				0.60				

[1]Variables used in calculating urban intensity index

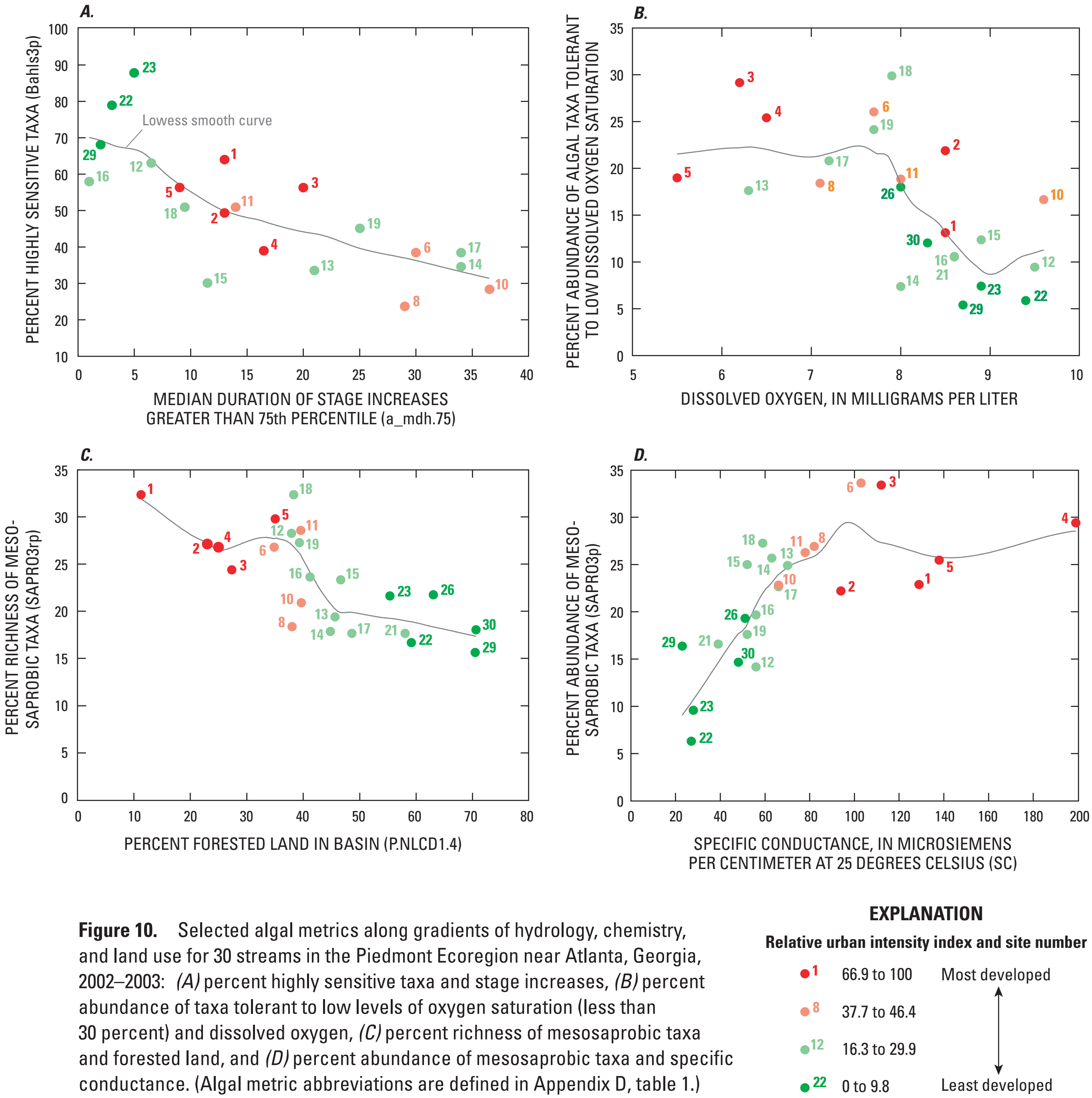


Figure 10. Selected algal metrics along gradients of hydrology, chemistry, and land use for 30 streams in the Piedmont Ecoregion near Atlanta, Georgia, 2002–2003: *(A)* percent highly sensitive taxa and stage increases, *(B)* percent abundance of taxa tolerant to low levels of oxygen saturation (less than 30 percent) and dissolved oxygen, *(C)* percent richness of mesosaprobic taxa and forested land, and *(D)* percent abundance of mesosaprobic taxa and specific conductance. (Algal metric abbreviations are defined in Appendix D, table 1.)

Table 7. Significant ($p < 0.005$) episammic diatom community metric responses to environmental variables in the Metropolitan Atlanta study area, 2002–2003.

[n, number of sites used on analysis; number in parenthesis in community metrics column indicates significant *r* value after Bonferonni adjustment; hydrological metric definitions in Appendix B2; algal community metric definitions in Appendix D1]

Variable group	Number of significant metrics (out of 229)	Community metrics with significant Spearman correlations (ranked list)
	Water quality	
High-baseflow (spring) synoptic ($n=23$; $r_s=\|0.76\|$)		
Dissolved oxygen	1	TROPH3rp (–0.77)
Specific conductance	1	SAPRO3p (0.78)
Carbon (dissolved organic)	1	pH1a (–0.78)
Low-baseflow (summer) synoptic ($n=23$; $r_s=\|0.76\|$)		
Turbidity	1	pH6p (–0.76)
Ammonia	1	TROPH5r (0.78)
Carbon (dissolved organic)	1	pH1a (–0.77)
Simazine	1	PTOL2ar (0.81)
	Semipermeable membrane device extracts	
Assays ($n=23$; $r_s=\|0.76\|$)	No significant correlations	
Chemistry ($n=23$; $r_s=\|0.76\|$)	No significant correlations	
	Hydrology	
Water year ($n=20$; $r_s=\|0.80\|$)		
a_mdh_75	2	SAL2ap (–0.85), Bahls3ap (–0.80)
a_ maxrise	9	NONDIArp (–0.88) OXTOL2r (0.80), NONFIXr (0.81), RICH (0.81), DIATOMr (0.82), SAL3r (0.82),MOTILEr (0.85), SAL4r (0.88), DIATOMrp (0.88)
a_maxfall	1	SAL2ap (–0.87)
Fall ($n=22$; $r_s=\|0.78\|$)		
a_skew	2	BLUGRNp (–0.81), Dom1 (–0.80)
a_mdh_75	1	SAL2ap (–0.79)
a_maxrise	3	SAL2ap (–0.86), Bahls2ap (–0.79), Bahls3ap (–0.80)
Winter ($n=22$; $r_s=\|0.78\|$)		
a_maxfall	2	SAL2ap (–0.83), SAL4ap (0.83)
Spring ($n=21$; $r_s=\|0.78\|$)		
a_skew	3	pH6ap (–0.83) PTOL2bap (–0.81), PTOL3aap (–0.80)
a_mdh_75	1	MOTILEr (0.78)
a_sum_95	1	Bahls2ap (–0.80)
Summer ($n=20$; $r_s=\|0.80\|$)		
a_mdh_75	1	SAL2ap (–0.80)
a_maxrise	2	SAL4rp (0.81), SAL4r (0.82)
	Habitat	
Reach habitat ($n=23$; $r_s=\|0.76\|$)		
Water surface gradient	1	TROPH6r (–0.77)
Percent riffle	1	TROPH5ap (–0.76)
Minumum wetted channel shape	1	Bahls1ap (–0.76)

of note were with water-quality conditions involving specific conductance during the high-baseflow spring sampling and concentrations of ammonia and of simazine during the fall, and with indices indicating eutrophic and pollution tolerant taxa, respectively. Weak, but significant, relations were observed between several habitat variables and algal metrics. Correlations between metrics generally indicative of eutrophic condition (TROPH6r and TROPH5p) were observed among habitat variables that indicated higher stream gradient (percent riffles and water-surface gradient) within the reach. No significant correlations were observed among algal metrics and SPMD assays and extracts between algal AFDM or chlorophyll *a* levels and water chemistry, land use, or the UII and its components.

Invertebrate Metric Responses

Invertebrate indices calculated from the QQ sample, which is a presence/absence composite of both the quantitative epidendric RTH sample (from woody debris) and the qualitative multihabitat sample responded strongly to the UII and components of the UII (table 8). The highest $|r_s|$ values were observed between the tolerance based richness (RichTOL) metric and the UII as well as its component variables except percent forest in the basin, indicating that tolerant species increase with increasing urbanization (table 8, fig. 11*A*). In contrast, metrics derived from the Ephemeroptera, Plecoptera, and Tricoptera (EPT) orders, generally considered sensitive to disturbance (Barbour and others, 1999), such as percent EPT richness (EPTRp) and percent richness of Plecoptera (PLECORp) were strongly negatively correlated with the urban intensity index and its components (table 8, fig. 11*B*). The ratio of EPT taxa to Chironomids (EPT_CHR) also was strongly correlated with the UII and its components. Percent developed land in the basin and stream buffer had the highest correlation coefficients ($r_s > |0.87|$) in relation to the invertebrate metrics, with negative correlations among all metrics, except percent Diptera taxa (DIPRp) and percent Chironomids (CHRp), both of which are represented mainly by tolerant taxa.

Table 8. Spearman rho (r_s) values for significant ($p < 0.005$) correlations between invertebrate metrics and calculated urban intensity index, components of the urban intensity index and impervious surface estimates in the Metropolitan Atlanta study area, 2002–2003.

[km^2, square kilometer; n, number is sites used in analysis; r_s value in bold indicates minimum level of significance after Bonferonni adjustment; detailed explanation of invertebrate metrics in Appendix D2]

Invertebrate metric	Urban intensity index	[1]Housing density (units/km^2)	[1]Road density (km^2)	[1]Percent developed (basin)	[1]Percent developed (stream buffer)	[1]Percent forested (basin)	Percent impervious (basin)	Percent impervious (stream buffer)
Multihabitat [2](QQ); n = 30; $r_s = \|0.66\|$)								
EPTRp	–0.82	–0.81	–0.82	–0.83	–0.83	0.71	–0.81	–0.80
EPT_CHR	–0.81	–0.79	–0.81	–0.82	–0.82	0.72	–0.81	–0.80
EPTR	–0.78	–0.77	–0.78	–0.80	–0.80		–0.77	–0.76
PLECORp	–0.77	–0.77	–0.77	–0.78	–0.80	0.68	–0.79	–0.78
PLECOR	–0.77	–0.75	–0.76	–0.78	–0.79	0.66	–0.77	–0.76
COLEOPR	–0.69			–0.71	–0.72	0.71	–0.69	–0.71
EPEMR	–0.69	–0.69	–0.70	–0.71	–0.71		–0.66	
DIPRp	0.69			0.68	0.69		0.68	0.69
CHRp	0.69		0.66	0.68	0.70		0.68	0.69
RichTOL	0.84	0.85	0.84	0.87	0.87	–0.70	0.85	0.84
COLEOPRp					–0.68	0.70		–0.67
Snags; n = 30; $r_s = \|0.66\|$)								
PLECOp	–0.82	–0.83	–0.79	–0.81	–0.81	0.81	–0.86	–0.82
EPTRp	–0.82	–0.81	–0.80	–0.82	–0.82	0.73	–0.82	–0.79
pPR_abund	–0.73	–0.75	–0.73	–0.76	–0.75		–0.79	–0.75
PLECO	–0.71	–0.74	–0.70	–0.71	–0.71	0.70	–0.76	–0.70
OLIGOp						–0.72	0.70	0.70
RichTOL	0.73	0.74	0.74	0.75	0.76		0.73	0.70

[1]Variables used in calculating urban intensity index

[2]Synthetic sample created by combining presence/absence information from snags and qualitative sample

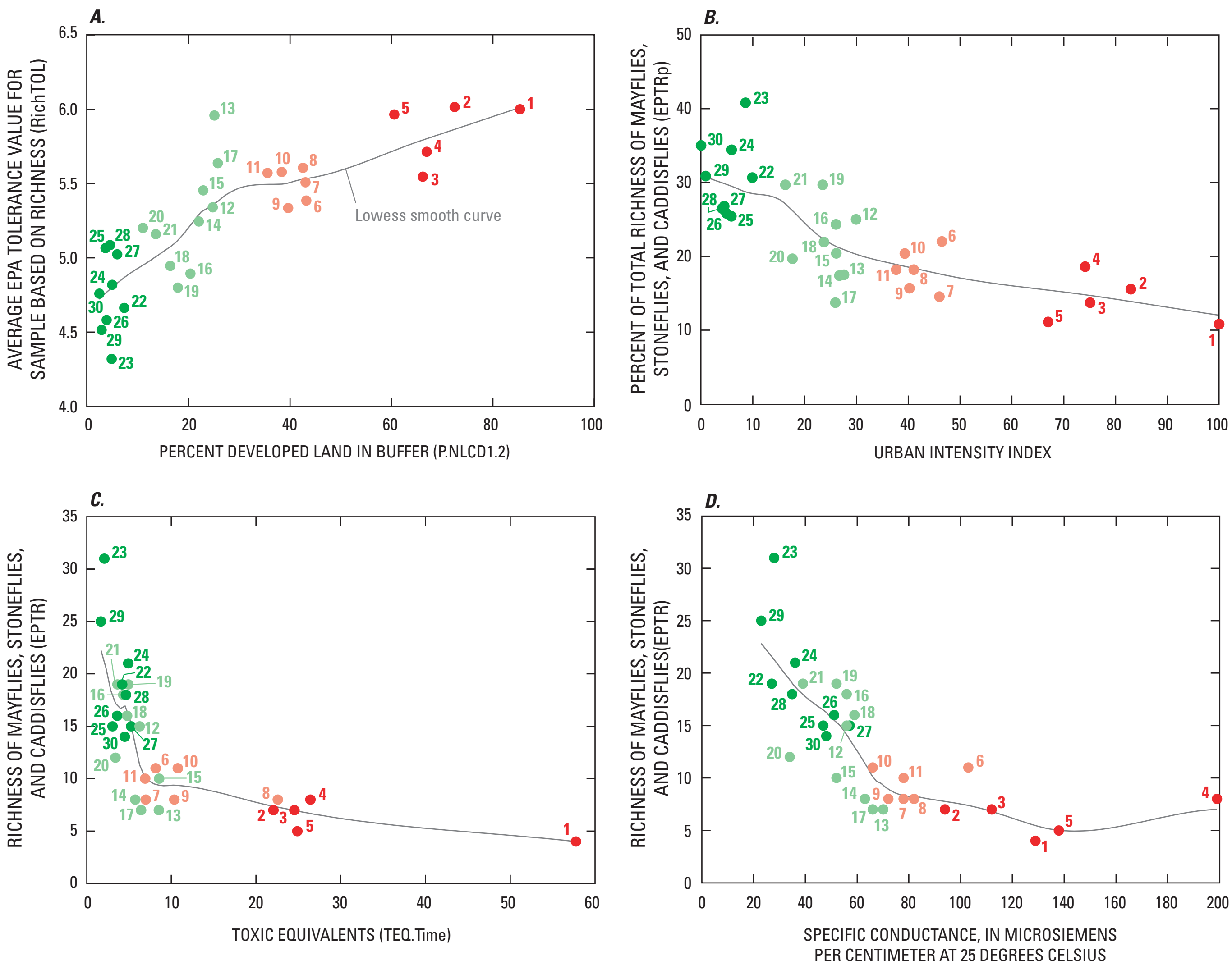


Figure 11. Selected invertebrate metrics along gradients of hydrology, chemistry, and land use for 30 streams in the Piedmont Ecoregion near Atlanta, Georgia, 2002–2003: *(A)* average EPA tolerance value for sample based on richness and developed land in buffer, *(B)* percent of total richness of mayflies, stoneflies, and caddisflies and urban intensity index, *(C)* richness of mayflies, stoneflies, and caddisflies and SPMD extract toxic equivalents, and *(D)* richness of mayflies, stoneflies, and caddisflies and specific conductance. (Invertebrate metric abbreviations are defined in Appendix D, table D2.)

EXPLANATION

Relative urban intensity index and site number

1	66.9 to 100	Most developed
8	37.7 to 46.4	
12	16.3 to 29.9	
22	0 to 9.8	Least developed

The general response from the semiquantitative RTH samples was similar to that of the QQ sample, with the percentage richness of EPT taxa (EPTRp) and percentage of Plecoptera (PLECOp) both responding negatively ($r_s = -0.82$) to increasing UII values as well as to its components. The strongest single taxa group indicator found during this analysis was the PLECOp in the samples taken from submerged woody debris (RTH), regressed against the percent imperviousness in the basin ($r_s = -0.86$). The RTH samples also showed significant response to changes in functional groups inhabiting submerged woody vegetation, with the percent predator abundance (pPR_abun) metrics being negatively correlated with the UII and all of its components except percent forest in the basin (table 8). Possible thresholds in the invertebrate responses can be observed in the relation between tolerance values and percent developed land in the buffer at about 30 percent developed (fig. 11*A*) and in the relation between percent EPT richness (EPTRp) and the UII at an urban intensity index value of approximately 15 (fig. 11*B*).

Other environmental variable sets including water quality, hydrology, and SPMD chemistry were analyzed in relation to the invertebrate metrics calculated from the QQ sample. This analysis indicated that water-quality variables, especially data from the SPMDs, had stronger correlations with invertebrate metrics than indicators of altered hydrology or habitat condition metrics (table 9). Specific conductance in spring and fall correlated with more invertebrate community metrics than any other of the water-quality variables. In general, metrics indicative of sensitive species such as EPT and Plecoptera-derived metrics decreased, whereas metrics of tolerant species (RichTOL) increased with increasing specific conductance. Similarly, the RichTOL metric was strongly correlated to the sum of insecticide concentration. Strongly correlated responses generally began to occur at low levels of urbanization, as illustrated by the response of richness of EPT taxa (EPTR) to the CYP1A1 assay and specific conductance (fig. 11*C*, *D*).

Many of the invertebrate metrics were strongly correlated with SPMD datasets, including both assay and chemical extract data. Richness of EPT taxa (EPTR), percent EPT (EPTp), and stonefly abundance (PLECOR), and ratio of EPT to midge taxa (EPT_CHR) consistently responded negatively to various chemical constituents identified in the SPMD extracts. The chemical variables shown in the SPMD section of table 9 mainly are composed of pesticides, herbicides, and PAHs, many of which have been shown to be toxic to aquatic life (Munn and Gilliom, 2001).

Invertebrate community metrics also were correlated with hydrologic variability metrics during all seasons, and primarily respond to variables that indicate frequency and duration of the most extreme hydrologic conditions. A metric that shows frequency of rising events greater than nine times median rise (a_periodr9) was negatively correlated with sensitive taxa metrics (such as the PLECOR, EPT metrics) during all seasons except summer and during the entire water year (table 9). Conversely, tolerant species (RichTOL) were positively correlated with the a_periodr9 metric. Other notable correlations were observed between the invertebrate community and relative cross-sectional area change metric (a_day_pctchange) in the winter and fall. Other significant responses between invertebrate community metrics and hydrologic variability metrics were observed in the fall (10 significant correlations) and winter (12 significant correlations) seasons rather than in the spring (3 significant correlations) when invertebrate sampling was conducted. The richness of tolerant taxa (RichTol) had the highest correlation coefficient of any of the metrics that responded to hydrologic variability metrics. No correlations were observed between any of the instream habitat variables and the invertebrate community.

Table 9. Significant ($p < 0.005$) invertebrate community metric responses to environmental variables in the Metropolitan Atlanta study area, 2002–2003.

[metric values calculated using data from both multihabitat and snag samples; n, number of sites used in comparison; number in parenthesis in community metrics column indicates minimum level of significance after Bonforonni adjustment; hydrologic variable definitions in Appendix B, tble B2; invertebrate metric definitions in Appendix D, table D2; numbers after semipermeable membrane device (SPMD) chemical variable names indicate number of isomers used in analysis]

Variable group	Number of significant metrics (out of 30)	Community metrics with significant Spearman correlations (ranked list)
	Water quality	
High-baseflow (spring) synoptic (n = 30; r_s = |0.66|)		
Specific conductance	10	EPTR (–0.84), EPTRp (–0.82), EPT_CHR (–0.80), PLECOR (–0.77), PLECOR (–0.76), PLECORp (–0.75), COLEOPR (–0.74), RICH (–0.72), PR_rich (–0.71), RichTOL (0.83)
Total nitrogen	1	COLEOPRp (–0.66)
Sum of insecticides	5	PLECOR (–0.74), EPTR (–0.72), PLECORp (–0.71), EPTRp (–0.69), RichTOL (0.76)
Sum of herbicides	2	EPTRp (–0.68), EPT_CHR (–0.66)
Low-baseflow (summer) synoptic (n = 30; r_s = |0.66|)		
Specific conductance	10	EPTR (–0.84), PLECOR (–0.79), RICH (–0.76), PLECORp (–0.75), EPTRp (–0.74), PR.rich (–0.74), EPT_CHR (–0.72), EPEMR (–0.71), COLEOPR (–0.70), RichTOL (0.81)
Simazine	1	RichTOL (0.67)
	Semipermeable membrane device extracts	
Assays (n = 30; r_s = |0.66|)		
CYP1A1 induction bioassay (TEQ)	11	EPTR (–0.83), COLEOPR (–0.79), RICH (–0.78), PLECOR (–0.78), EPT.CHR (–0.78), PLECORp (–0.76), PR.rich (–0.76), EPEMR (–0.74), DIPRp (0.67), CHRp (0.67), RichTOL (0.87)
Fluoroscan (UGPAH)	13	COLEOPR (–0.82), EPTR (–0.81), PLECOR (–0.81), PLECORp (–0.79), EPT_CHR (–0.78), EPTRp (–0.76), RICH (–0.74), COLEOPRp (–0.73), CHRp (–0.72), PR_rich (–0.72), EPEMR (–0.70), DIPRp (0.67), RichTOL (0.88)
Chemistry (n = 30; r_s = |0.66|)		
Trifluralin	6	EPT_CHR (–0.74), EPTRp (–0.69), EPTR (–0.68), DIPRp (0.67), CHRp (0.68), RichTOL (0.68)
Benfluralin	7	EPT_CHR (–0.79), EPTRp (–0.77), EPTR (–0.74), EPEMR (–0.71), CHRp (–0.71), DIPRp (0.67), RichTOL (0.73)
Chlorpyrifos	7	EPTRp (–0.76), EPT.CHR (–0.75), EPTR (–0.74), COLEOPR (–0.74), EPEMR (–0.70), PLECOR (–0.67), RichTOL (0.72)
Chemistry (n = 28; r_s = |0.67|)		
Fluoranthene	8	EPT_CHR (–0.76), EPTRp (–0.75), EPTR (–0.74), PLECOR (–0.73), PLECORp (–0.73), COLEOPR (–0.67), CHRp (0.72), RichTOL (0.86)

Table 9. Significant ($p < 0.005$) invertebrate community metric responses to environmental variables in the Metropolitan Atlanta study area, 2002–2003.—Continued

[metric values calculated using data from both multihabitat and snag samples; n, number of sites used in comparison; number in parenthesis in community metrics column indicates minimum level of significance after Bonforonni adjustment; hydrologic variable definitions in Appendix B, tble B2; invertebrate metric definitions in Appendix D,table D2; numbers after semipermeable membrane device (SPMD) chemical variable names indicate number of isomers used in analysis]

Variable group	Number of significant metrics (out of 30)	Community metrics with significant Spearman correlations (ranked list)
Pyrene	7	EPT_CHR (–0.77), EPTR (–0.75), EPTRp (–0.75), PLECOR (–0.75), COLEOPR (–0.69), CHRp (0.72), RichTOL (0.83)
Methyl dibenzofuran (1)	3	COLEOPR (–0.69), EPT_CHR (–0.68), COLEOPRp (–0.68)
4H cyclopenta[det]phenathrene	1	RichTOL (0.76)
X-methyl anthracene (3)	4	COLEOPR(–0.69), EPT_CHR (–0.69), EPTRp(–0.69), COLEOPRp (–0.67),
Benzo(b)naptho[2,1]thiophene	8	PLECOR (–0.81), PLECORp (–0.79), EPTR (–0.77), EPT_CHR (–0.73), EPTRp (–0.71), RICH (–0.68), PR.rich (–0.68), RichTOL (0.81)
Benzophenanthrene (2)	8	PLECOR (–0.81), PLECORp (–0.79), EPTR (–0.77), EPT_CHR (–0.73), EPTRp (–0.71), RICH (–0.68), PR_rich (–0.68), RichTOL (0.81)
Benzophenanthrene (3)	8	PLECOR (–0.79), EPT.CHR (–0.79), PLECORp (–0.79), EPTRp (–0.78), EPTR (–0.77), COLEOPR (–0.71), CHRp (0.72), RichTOL (0.84)
Sum of benzophenanthrene	9	EPT_CHR (–0.79), PLECOR (–0.78), PLECORp (–0.78), EPTRp (–0.78), EPTR (–0.76), COLEOPR (–0.71), DIPRp (0.67), CHRp (0.73), RichTOL (0.84)
	Hydrology	
Water year (n = 26; r_s = |0.69|)		
a_periodr9	5	PLECORp (–0.73), PLECOR (–0.71), EPTR (–0.71), EPTRp (–0.69), RichTOL (0.74)
Fall (n = 28; r_s = |0.67|)		
a_mxh_90	3	COLEOPR (–0.71), EPT_CHR (–0.70), EPTRp (–0.70)
a_day_pctchange	3	EPT_CHR (–0.70), EPTRp (–0.70), RichTOL (0.69)
a_periodr9	4	EPTR (–0.71), RICH (–0.71), EPTRp (–0.69), RichTOL (0.81)
Winter (n=29; r_s=|0.66|)		
a_day_pctchange	8	EPT_CHR (–0.73), DIPRp (–0.72), EPTR (–0.72), DIPRp (–0.72), EPEMR (–0.70), EPTRp (–0.70), CHRp (–0.68), RichTOL (0.71)
a_periodr9	4	PLECOR (–0.70), RICH (–0.69), PLECORp (–0.69), RichTOL (0.74)
Spring (n=28; r_s=|0.67|)		
a_periodr9	3	PLECOR (–0.73), PLECORp (–0.73), RichTOL (0.72)
Summer (n=27; r_s=|0.67|)		
a_cummulative_change	4	EPTRp (–0.70), EPTR (–0.68), EPT_CHR (–0.68), PR_rich (–0.68)
	Habitat	
Reach habitat (n = 30; r_s = |0.66|)	No significant correlations	

Fish-Metric Responses

The strongest relations between fish metrics and the UII were observed for the fish group classification that did not have tolerances reported (EPA_tol_Unknown), which was negatively correlated with the UII and all of its components, except percent forested (table 10). This relation may indicate that the species of fish in the Piedmont area that currently have unclassified tolerances compose a large percentage of taxa sensitive to some aspect of urbanization. Fish species that can live in a range of stream sizes (range of sizes) were positively correlated with the UII and its various components, except percent forest in basin. Because these species can survive in a range of stream sizes, this relation may indicate that habitat generalists are more likely to be found in urbanizing Piedmont streams. Although the Georgia IBI did not respond directly to the UII, percent cyprinids—a component of the Georgia IBI—did respond negatively to the UII, housing density, and road density in the basin (fig. 12*A*). Of these three variables, road density was the most correlated with proportion of cyprinids in the basin ($r_s = -0.69$) (fig. 12*B*).

Variables from the environmental variable groups analyzed in relation to the fish metrics showed strongest relations with spring and summer water-quality data and hydrologic alterations during the spring (table 11). The Georgia IBI scores declined with an increase in the frequency of events with rapid declines in stage (a_periodf9) (fig. 12*C*), whereas percent cyprinids was more closely correlated with total annual rise and fall of the hydrograph (a_cumulative_change) (fig. 12*D*). Weaker, but statistically significant, relations were found between fish metrics and SPMD datasets and instream habitat conditions. For example, percent simple nester (Simple.Nest) was correlated with the percent of woody debris in the reach (HabCvrPtWDPct), although the response is unrelated to watershed urbanization, as is evident from ordering of sites along the lowess smoothed curve (fig. 12*E*). Several of the most significantly correlated variables with the environmental datasets were broad metrics describing very general habitat preferences (Range_of_Sizes and Small_Creeks_to_Small_Rivers) or categories used to lump groups of fishes with no known tolerance data (EPA_tol_Unknown). These metrics did show significant responses to altered water quality, hydrologic characteristics, and habitat; however, these metrics provide little useful information on the response of Piedmont fishes to urbanization. Fishes categorized as being found in a range of stream sizes only indicated more general habitat preferences of these species, and positive correlations with urbanization indicate the generally more adaptive ability to tolerate a wider range of water-quality and hydrologic conditions that would be encountered naturally when moving from a small stream to a large river.

The response of fishes to changes in water quality was, in general, stronger during the spring, although weaker relations were observed during the summer. Other notable fish-metric responses to water quality included huggers (benthic dwellers) to particulate nitrogen ($r_s = -0.70$), total particulate carbon (–0.67), and dissolved organic carbon (–0.69); herbivores to suspended sediment concentration (–0.74); and bedrock associates to the herbicide prometon (–0.68) and to the sum of herbicides (–0.68). Metrics with highest r_s values included riffle dwellers, proportion of cyprinids, huggers, or bottom dwelling fishes. Riffle-dwelling fishes responded positively (increased) to increased skewness in the hydrograph during spring ($r_s = 0.80$), but negatively to maximum duration of highest flows (a_mxh_95) (table 11). One possible explanation is that higher skew values were more common at sites at the low end of the urban gradient, whereas the maximum duration of high flows was longer at sites with lower stream gradients and wider floodplains, which were more common at more urbanized sites. These sites are less suitable for riffle species even in the absence of altered hydrology caused by increased watershed urbanization.

Other negative correlations observed for the entire water year were between a_sum_5 and percent cyprinids ($r_s = -0.70$); a_periodf9 and number intolerant species ($r_s = -0.72$); a_maxrise and herbivores ($r_s = -0.71$), omnivores ($r_s = -0.69$), and simple nesters ($r_s = -0.70$). The only potential threshold in the response of the fish communities to urbanization occurred with respect to changes in water chemistry where percentage of cyprinids decline in response to specific conductance; the sharpest decline observed was between 50 and 75 microsiemens per centimeter (fig. 12*F*).

Table 10. Spearman rho (r_s) values for significicant (p<0.005) correlations between fish metrics and urban intensity index, components of the urban intensity index and impervious surface estimates in the Metropolitan Atlanta study area, 2002–2003.

[km², square kilometers; n, number of sites used in comparison; r_s value in bold indicates minimum level of significance after Bonforonni adjustment; detailed explanation of fish metrics in Appendix D3]

Fish metric	Urban index	[1]Housing density (units/km²)	[1]Road density (km²)	[1]Percent developed (basin)	[1]Percent developed (stream buffer)	[1]Percent forested (basin)	Percent impervious (basin)	Percent impervious (stream buffer)
Species traits (n=30; r_s=|0.66|)								
EPA_tol_Unknown [2]	–0.70	–0.71	–0.73	–0.72	–0.72		–0.66	–0.67
Pool (percent pool dwellers) [3]					0.67			
Range of sizes [3]	0.69	0.69	0.66	0.71	0.71		0.71	0.69
Georgia IBI metrics[4] (n=30; r_s=|0.66|)								
Percent cyprinids	–0.66	–0.66	–0.69					

[1] Variables used in calculating urban intensity index

[2] U.S. Environmental Protection Agency tolerance metric (Barbour and other, 1999)

[3] Goldstein and Meador, 2004

[4] Georgia Index of Biotic Integrity (IBI) (Georgia Department of Natural Resources, 2005)

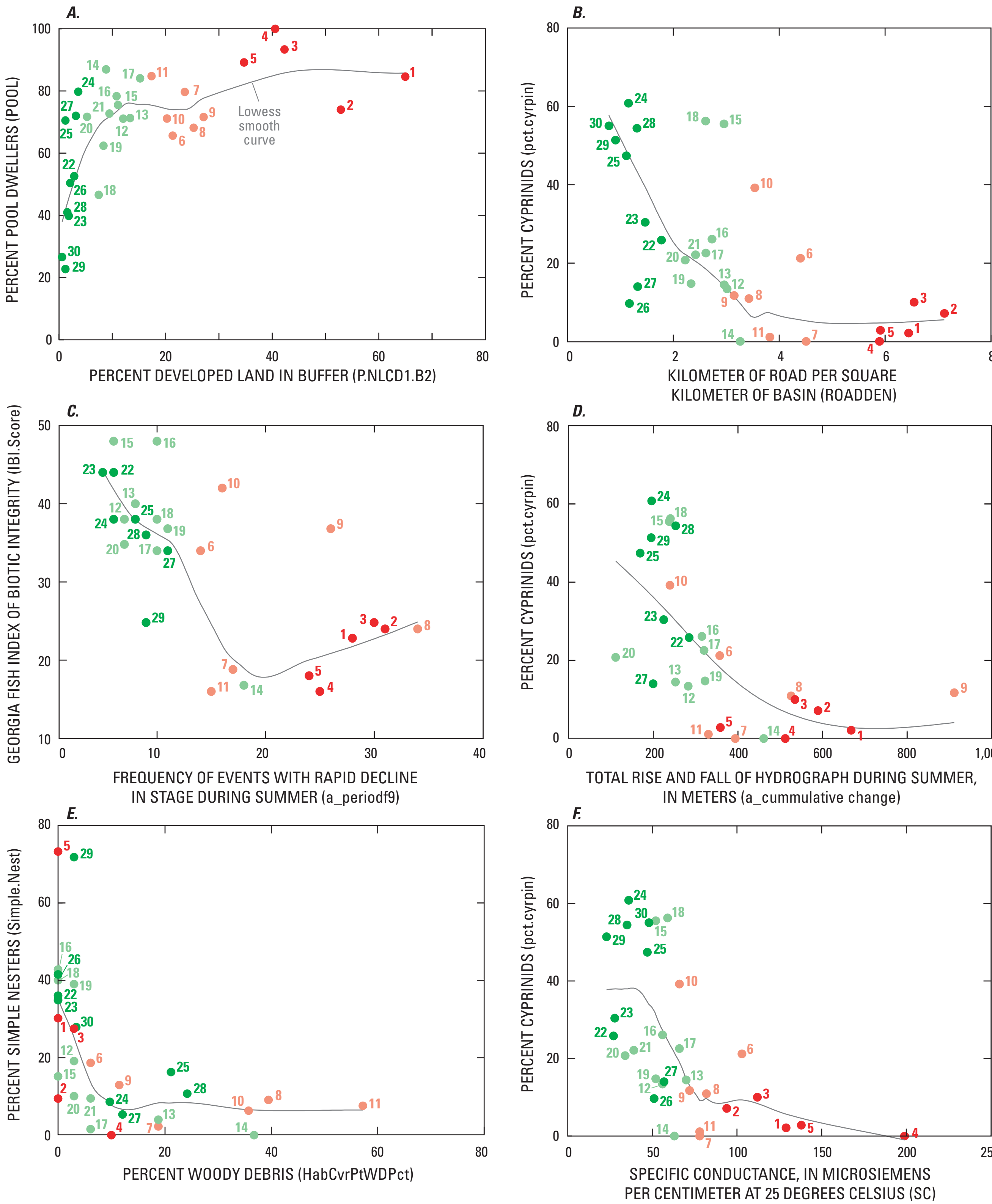


Figure 12. Selected fish metrics along gradients of hydrology, chemistry, and land use for 30 streams in the Piedmont Ecoregion near Atlanta, Georgia, 2002–2003: *(A)* percent pool dwellers and developed land, *(B)* percent cyprinids and roads, *(C)* fish index of biotic integrity and events with rapid decline in stage, *(D)* percent cyprinids and total rise and fall of hydrograph, *(E)* percent simple nesters and woody debris, and *(F)* percent cyprinids and specific conductance. (Fish metric abbreviations are defined in Appendix D, table D3.)

EXPLANATION

Relative urban intensity index and site number

1	66.9 to 100	Most developed
8	37.7 to 46.4	
12	16.3 to 29.9	
22	0 to 9.8	Least developed

Table 11. Spearman rho (r_s) values for significant ($p < 0.005$) correlations between fish metrics and environmental variables in the Metropolitan Atlanta study area, 2002–2003.

[n, number of sites used in analysis; number in parenthesis in community metrics column indicates minimimum significant r_s values after Bonferonni adjustment; hydrologic variable definition explanation in Appendix C, table C2; fish metric definitions in Appendix D, table D3]

Variable groups	Number of significant metrics (out of 57)	Ranked list of community metrics with significant Spearman correlations
	Water quality	
High-baseflow (spring) synoptic (n = 30; r_s = |0.66|)		
Specific conductance	3	EPA_tol_Unknown (–0.76), pct_cyprin (–0.68), Range_of_Sizes (0.70)
Nitrogen (particulate)	1	Hugger (–0.70)
Carbon (total particualte)	1	Hugger (–0.67)
Carbon (dissolved organic)	1	Hugger (–0.69)
Chlorophyll *a*	1	Boulders (0.67)
Sum of insecticides	1	Range_of_Sizes (0.76)
Low-baseflow (summer) synoptic (n = 30; r_s = |0.66|)		
Specific conductance	2	EPA_tol_Unknown (–0.76), Range_of_Sizes (0.72)
Suspended sediment	1	EPA_Herbivore (–0.74)
Prometon	2	EPA_tol_Unknown (–0.70), Bedrock (–0.68)
Simazine	2	EPA_tol_Unknown (–0.66), Range_of_Sizes (0.68)
Sum of herbicides	3	Bedrock (–0.68), EPA_tol_Unknown (–0.66), Range_of_Sizes (0.74)
	Semipermeable membrane device extracts	
Assays (n = 30; r_s = |0.66|)		
CYP1A1 induction bioassay	3	Range_of_Sizes (0.69), Small_Creeks_to_Small_Rivers (–0.67), EPA_tol_Unknown (–0.66)
Fluoroscan	1	Range_of_Sizes (0.71)
Chlorpyrifos	2	EPA_tol_Unknown (–0.66)
Chemistry (n = 28; r_s = |0.67|)		
Pyrene	1	Range_of_Sizes (0.67)
	Hydrology	
Water year (n = 26; r_s = |0.69|)		
a_sum_5	1	pct_cyprin (–0.70)
a_periodf9	1	num_intol (–0.72)
a_maxrise	3	Herbivore (–0.71), EPA_Omnivore (–0.69), Simple_Nest (–0.70)
Fall (n = 28; r_s = |0.67|)		
a_mdh_95	1	num_cyprin (0.69)
a_mxl_25	1	EPA_Piscivore (0.69)
Winter (n = 29; r_s = |0.66|)		
a_day_pctchange	1	Small_Creeks_to_Small_Rivers (–0.69)
Spring (n = 28; r_s = |0.67|)		
a_periodr9	2	pct_cyprin (–0.70), EPA_tol_Unknown (–0.69)
a_periodf9	1	num_intol (–0.69)
a_skew	1	Riffle (0.80)
a_ XA_90	1	Small_Creeks_to_Small_Rivers (–0.79),
a_ XA_75	1	Small_Creeks_to_Small_Rivers (–0.72)
a_ mxh_95	1	Riffle (–0.76)

Table 11. Spearman rho (r_s) values for significant ($p < 0.005$) correlations between fish metrics and environmental variables in the Metropolitan Atlanta study area, 2002–2003.—Continued

[n, number of sites used in analysis; number in parenthesis in community metrics column indicates minimimum significant r_s values after Bonferonni adjustment; hydrologic variable definition explanation in Appendix C, table C2; fish metric definitions in Appendix D, table D3]

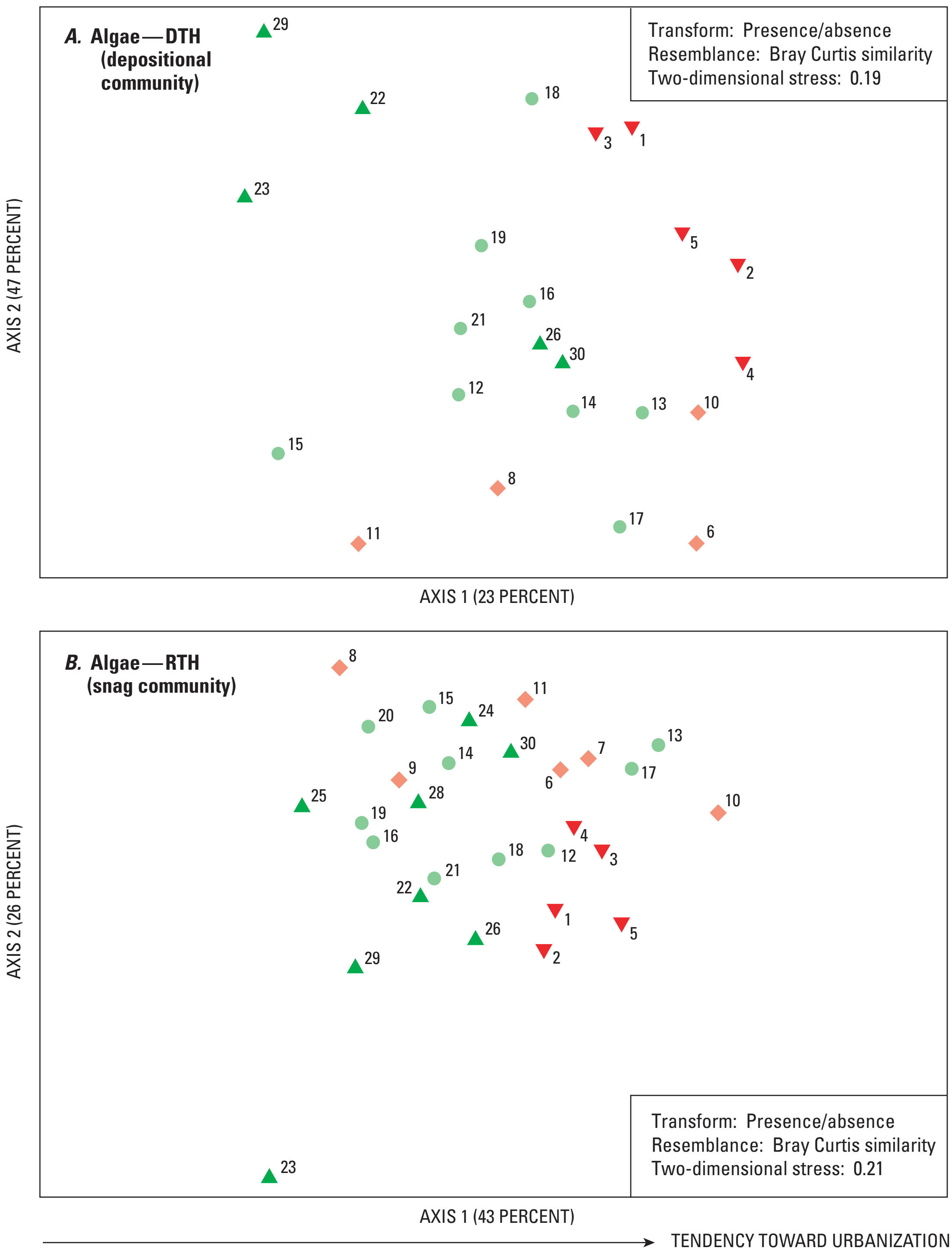
Variable groups	Number of significant metrics (out of 57)	Ranked list of community metrics with significant Spearman correlations
Summer (n = 27; r_s = |0.67|)		
a_cummulative_change	1	pct_cyprin (–0.75)
a_periodf9	2	pct_cyprin (–0.71), IBI Score (–0.71)
a_ XA_90	1	Small_Creeks_to_Small_Rivers (–0.71)
a_XA_75	1	Vegetation (0.67)
a_maxrise	1	Simple_Nest (–0.70)
a_day_pctchange	1	Vegetation (0.69)
Habitat		
Reach habitat (n = 30; r_s = |0.66|)		
mean embeddedness (percent)	1	Simple_Nest (–0.72)
cover of woody debris (percent)	2	Simple_Nest (–0.73), Herbivore (–0.66)
maximum open canopy angle	1	EPA_Herbivore (0.66)
minimum flow stability	1	Herbivore (–0.72)

Algal Community Responses

The RTH diatom communities collected from snag habitat were composed of a total of 233 taxa. These communities were comprised of between 32 and 93 species per site (mean 53 species per site). Of the species collected, eight were common and collected at more than 90 percent of sites and included the following species: *Achnanthidium minutissimum* (29 sites); *Encyonema minutum* Mann (29 sites); *Fragilaria vaucheriae* (27 sites); *Gomphonema angustatum* (29 sites); *Navicula cryptocephala* (27 sites); *Nitzschia palea* (27 sites); *Synedra ulna* (28 sites); and *Fragilaria aff. amphicephala* (28 sites). Of the total number of diatom taxa collected, 116 were considered rare taxa, occurring at less than 10 percent of the sites. Sites with the highest RTH diatom diversity included site 10 (83 species), site 7 (93 species), site 12 (83 species), and site 6 (74 species).

DTH diatom communities were composed of a total of 280 taxa, ranging from 15 to 112 taxa (mean 69.5). Eight species were common and collected at more than 90 percent of the sites. These common species included *Achnanthidium minutissimum* (30 sites), *Fragilaria vaucheriae* (28 sites), *Gomphonema angustatum* (29 sites), *Navicula cryptocephala* (29 sites), *Nitzschia palea* (30 sites), *Nitzschia recta* (28 sites), and *Synedra ulna* (27 sites). Of the total number of diatom taxa collected, 135 were considered rare taxa, occurring at less than 10 percent of the sites. Sites with the highest DTH diatom diversity included site 7 (103 taxa), site 15 (112 taxa), site 17 (102 taxa), and site 28 (101 taxa). An overview of diatom species collected and numbers of occurrences in RTH and DTH samples is summarized in Appendix E, table E1.

MDS plots of the algal communities indicate some separation of sites in species space for both the DTH and RTH species presence/absence with a general pattern of sites with higher intensity urban grouping on the right and sites with a lower-intensity grouping on the left of the figure (fig. 13*A*, *B*). MDS stress levels indicated that the two-dimensional representation of algal DTH communities (two-dimensional stress = 0.19) was slightly better than for the RTH samples (two-dimensional stress = 0.21). ANOSIM tests on groups indicated that the global separation of groups defined by cluster analysis of the components of the UII was significant in both communities, although significance was higher in the RTH communities ($p = 0.006$) than in the DTH communities ($p = 0.013$). Pairwise comparisons of ANOSIM test statistics show that the degree of separation among groups increased as the degree of urban intensity increased (fig. 14), with the highest degree of separation occurring between the developed sites and the undeveloped sites. The RTH community was better separated between rural and developed sites and undeveloped and developed sites, whereas the DTH community provided better separation between suburban and developed sites.



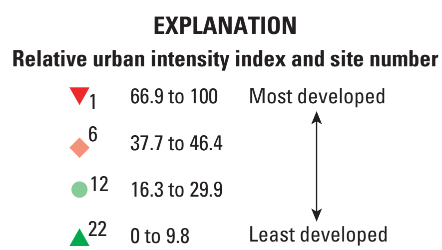


Figure 13. Two-dimensional representation of nonmetric multi-dimensional scaling analysis of algal community presence/absence in *(A)* depositional targeted habitat (DTH), ANOSIM (urban groups), $R=0.22$, $p<0.01$; and *(B)* richest targeted habitat (RTH) samples, ANOSIM (urban groups), $R=0.19$, $p<0.01$. Number in parentheses indicates amount of variance explained by each axis. Groups are based on cluster analysis (shown in fig. 5), and numbers are both site numbers and urban ranks used in analysis (fig. 1 and table 1). Boxed information indicates data handling options and two-dimensional stress value indicates adequacy of the multivariate ordination. [=, equals; < , less than]

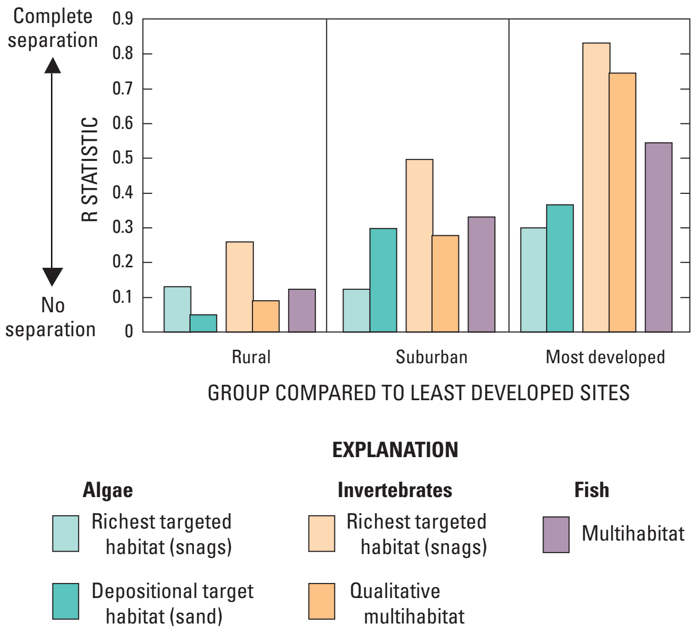


Figure 14. Pair-wise comparisons of analysis of similarity (ANOSIM) R statistics between least developed sites and sites with increasing levels of urbanization.

Another way to make distinctions among the land-use defined groups is by observing estimates of multivariate dispersion based on species composition among the groups of sites. Dispersion coefficients calculated from the algal community data (DTH and RTH samples) indicated that the group of sites with the lowest amount of urbanization had the highest amount of dispersion, whereas sites with the most urbanization had much lower dispersion values (fig. 15) indicating more similarity among communities with less variation in species assemblages. Groups with intermediate levels of urban development exhibited intermediate levels of dispersion with respect to both RTH and DTH algal communities, although dispersion values for both the RTH and DTH algal communities were higher in rural streams than in suburban streams.

The RELATE analysis indicated that the correlation with linear sequence along the urban gradient (that is, urban model) was only weakly significant for algal communities. IMS values were 0.14 ($p<0.05$) with algal species richness in RTH samples, 0.15 ($p<0.05$) algal species abundance and 0.25 ($p<0.01$) for algal species richness in the RTH samples. Species relative abundance from RTH samples exhibited no significant response to the UII (table 12). This analysis also indicated that algal communities were most strongly correlated with other environmental datasets, specifically between algal species richness in RTH samples and hydrology during the spring ($\rho=0.32$) and fall ($\rho=0.34$) as well as between species relative abundance in RTH samples and nutrients during the spring ($\rho=0.31$) and hydrology during the spring ($\rho=0.32$). Weaker, but significant, relations were noted between hydrology and species richness during the summer and between concentrations of nutrients and organic compounds and relative abundance from RTH samples (table 12). Algal relative abundance in RTH samples also exhibited a significant relation with stream habitat ($\rho=0.26$), although no relation with SPMD chemistry was observed.

Hydrologic relations with algal datasets demonstrated the most significant ($p<0.001$) links with RTH species richness during the fall ($\rho=0.34$) and spring ($\rho=0.32$). In general, however, hydrologic variation during the spring was most consistently related to RTH and DTH algal communities. Hydrologic variation pooled for the entire water year indicated weaker but still significant relations to both algal communities (table 12).

SIMPER analysis indicated that the diatom taxa most responsible for the observed multivariate patterns in DTH communities included nine species, which together accounted for about 10 percent of the total dissimilarity between the most urban and least urban sites. Of these nine most influential species *Achnanthes subhudsonis*, *Pinnularia gibba*, and *Nitzschia amphibia* were primarily found in streams draining undeveloped watersheds; whereas six species—including *Psammothidium chlidanos*, *Eunotia naegelii*, *Tabellaria flocculosa*, *Chamaepinnularia soehrensis* var. *muscicola*, *Eunotia incise*, and *E. minor*—were primarily found in streams draining developed watersheds.

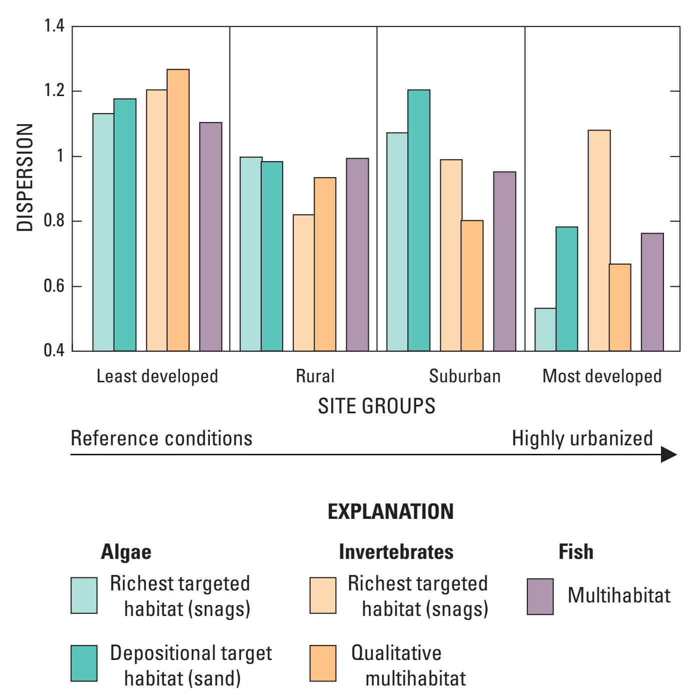


Figure 15. Multivariate dispersion within site cluster groups for algal, invertebrate, and fish communities with increasing levels of urbanization. The group dispersion value is proportional to the variability found in the community data—higher values mean more variability in terms of species composition, abundance, or both.

Table 12. Index of Multivariate Seriation (IMS) values, overall correlation coefficients (ρ) and significance levels between aquatic community sample types and explanatory variable data sets in the Metropolitan Atlanta study area, 2002–2003. Analysis conducted using RELATE (Primer) function.

[* denotes $p < 0.05$, ** $p < 0.01$, and *** $p < 0.001$]

Community and sample type	IMS (urban rank model)	Water quality							Hydrology					Stream habitat
		Spring high-baseflow synoptic			Summer low-base flow synoptic			SPMD extracts	Water year	Season				
		Field properties	Nutrients	Pesticides	Field properties	Nutrients	Pesticides			Fall	Winter	Spring	Summer	
Algae (Diatoms)														
Snag—abundance	0.15**	0.07	0.15	0.10	0.18*	0.16	0.19*	0.12	0.26**	0.19*	0.08	0.22*	0.09	0.14
Snag—relative abundance	0.10	0.16*	0.31***	0.18*	0.21*	0.31**	0.28**	0.08	0.21*	0.23*	0.13	0.32***	0.14	0.26**
Snag—richness	0.14*	0.14	0.19*	0.10	0.21*	0.17	0.11	0.10	0.26**	0.34***	0.19*	0.32***	0.21**	0.15
Episamic—richness	0.25**	0.23*	0.16	0.07	0.16	0.11	0.04	0.10	0.24*	0.17	0.24*	0.33**	0.30**	0.15
Invertebrates														
Snag—abundance	0.48***	0.28**	0.31**	0.38***	0.24*	0.12	0.22*	0.42***	0.16	0.12	0.04	0.21*	0.12	0.24**
Snag—relative abundance	0.51***	0.32**	0.27**	0.35***	0.21*	0.10	0.18	0.41***	0.23*	0.19	0.15	0.26**	0.18	0.23*
Multihabitat—richness	0.43***	0.23**	0.29**	0.26**	0.24*	0.16	0.20*	0.35***	0.17	0.15	0.02	0.23**	0.09	0.30***
Fish														
Reach—relative abundance	0.37***	0.34***	0.12	0.17	0.28**	0.28*	0.16	0.30**	0.27**	0.20	0.19	0.23*	0.09	0.18*
Reach—richness	0.30***	0.23**	0.12	0.14	0.22*	0.20	0.08	0.26**	0.15	0.10	0.12	0.18	0.03	0.14

The RTH diatom taxa most responsible for the observed multivariate patterns included seven species, which together accounted for about 10 percent of the total dissimilarity between the most developed and least developed sites. Of these seven species, four including *Nitzschia amphibia*, *N. intermedia*, an undescribed species (3 NAWQA MP), and *Achnanthes subhudsonis* var. *kraeuselii* were found primarily in streams draining developed watersheds whereas one species, *Synedra acus*, was found primarily in undeveloped conditions. *A. subhudsonis* and *N. amphibia* were selected as species that were most influential in structuring the urban diatom communities from both the depositional (DTH) and epidendric (RTH) samples.

Invertebrate Community Responses

A total of 50,998 individuals from 264 taxa of aquatic invertebrate were enumerated and identified in the 30 streams sampled for this study. Of the 264 taxa, 192 were found only in the RTH (snag habitat), whereas an additional 72 taxa were collected in multiple habitats other than snags. Of the 264 total species collected, 8 were ubiquitous and found at more than 90 percent of sites and included the following taxa: *Ablabesmyia* sp. (28 sites), *Ancyronyx variegate* (27 sites), *Brilla* sp. (27 sites), *Cheumatopsyche* sp. (28 sites), Naididae (26 sites), *Polypedilum* sp. (30 sites), *Rheotanytarsus* sp. (30 sites), and *Tanytarsus* sp. (27 sites). Of the 264 taxa collected, 111 were collected at less than 10 percent of sites.

Mean-density estimates of individual taxa collected from snags (across all sites) ranged from between 0.01 to 209 invertebrates per square meter (m^2) whereas maximum densities range from 0.23 to 2,378 invertebrates per m^2. Highest maximum densities in RTH samples were observed with *Rheotanytarsus* sp. (979 per m^2), Naididae (1,012 per m^2), *Simulium* sp. (1,069 per m^2), and Polypedilum (2,378 per m^2). Number of invertebrate taxa per site ranged from 39 to 84 (mean 58 taxa per site). Sites with the highest number of taxa included: site 29 (84 taxa), site 23 (79 taxa), site 16 (77 taxa), site 18 (74 taxa), and site 28 (71 taxa). An overview of invertebrate species collected, the numbers of occurrences and densities in RTH samples are summarized in Appendix E, table E2.

Results of MDS analysis show that RTH relative abundance and QQ species richness sample data were related to urban intensity, with more developed sites grouping on the right and the sites with less development and lower UII scores grouping on the left of the plots (fig. 16*A*,*B*). The two-dimensional representation of invertebrate RTH communities was stronger (MDS stress: 0.16) than for the QQ species richness samples (MDS stress: 0.20).

ANOSIM test results show that the global separation of groups defined by the UII was significant ($p < 0.001$) for both community types, but somewhat stronger for the RTH samples ($R = 0.51$) than for the QQ samples ($R = 0.43$). Similar to the algal community response, pair-wise comparisons of ANOSIM test statistics indicated that the degree of separation among groups increased as the degree of urban intensity increased (fig. 14) with the highest degree of separation occurring between the most developed group and the least

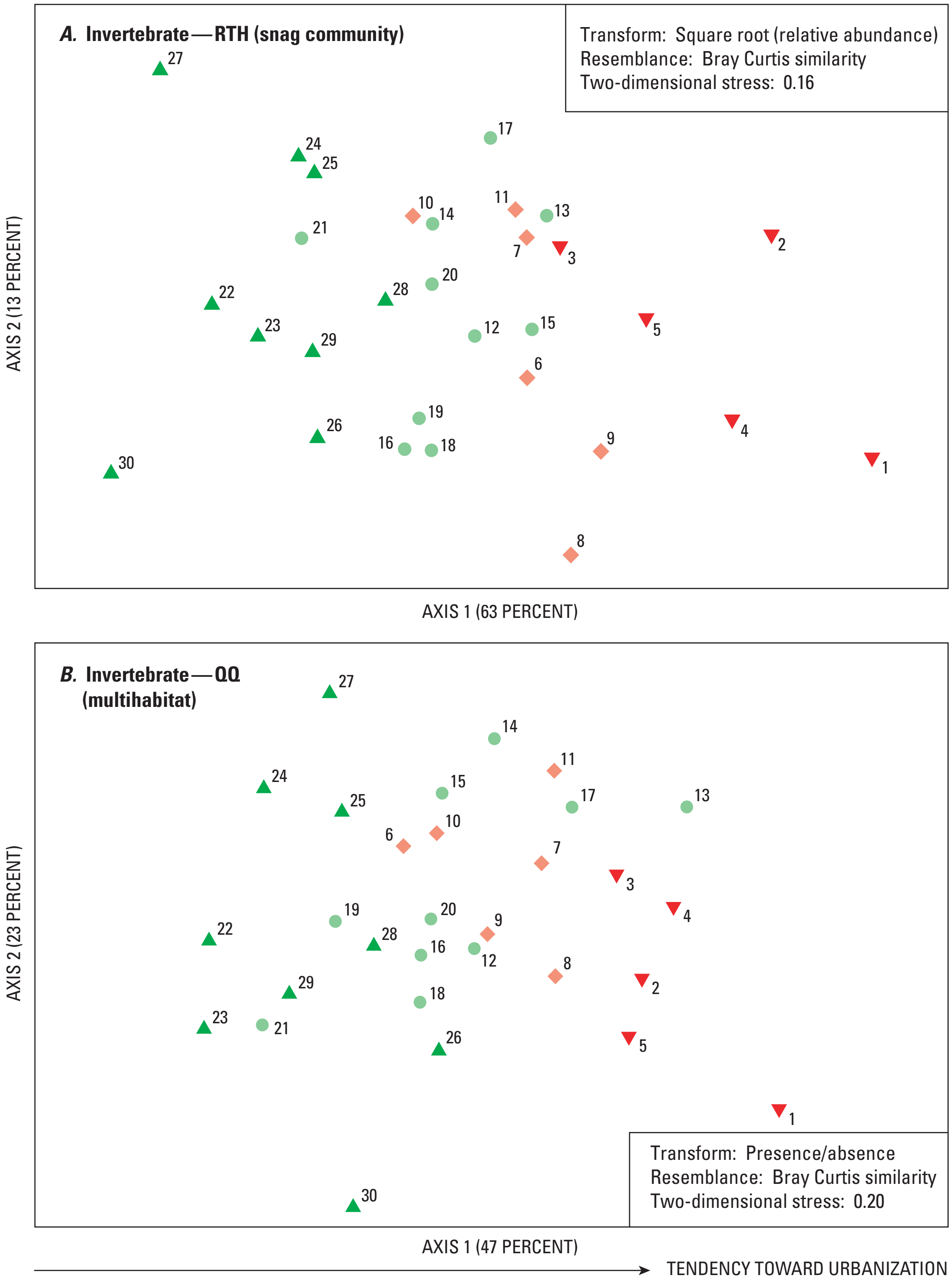


Figure 16. Two-dimensional representation of nonmetric multi-dimensional scaling analysis of invertebrate community relative abundance in *(A)* richest targeted habitat (RTH), ANOSIM (urban groups), $R = 0.39$, $p < 0.001$; and *(B)* multi-habitat qualitative (QQ) samples, ANOSIM (urban groups), $R = 0.25$, $p < 0.001$. Number in parentheses indicates amount of variance explained by each axis. Groups are based on based on cluster analysis (shown in fig. 5), and numbers are both site numbers and urban ranks used in analysis (fig. 1 and table 1). Boxed information indicates data handling options and two-dimensional stress value indicates adequacy of the multivariate ordination. [=, equals; < , less than]

EXPLANATION

Relative urban intensity index and site number

▼ 1	66.9 to 100	Most developed
◆ 6	37.7 to 46.4	
● 12	16.3 to 29.9	
▲ 22	0 to 9.8	Least developed

developed group of sites. In all pair-wise comparisons, the RTH invertebrate community had a higher R test statistic than the QQ sample, indicating a better distinction of group of sites based on species composition.

Multivariate dispersion coefficients calculated from the invertebrate community data (RTH and QQ samples) indicated that the least developed group of sites had the highest levels of dispersion (fig. 15) (that is, more variation in communities or species assemblages). Rural and suburban sites exhibited intermediate levels of dispersion with respect to the QQ sample. Dispersion values calculated from invertebrate RTH samples increased in the suburban and rural sites, although not to levels observed in the least developed group of sites.

Results from the RELATE analysis indicated that the correlation with linear sequence along the urban gradient was strongly significant with invertebrate RTH abundance (IMS = 0.48), RTH relative abundance (IMS = 0.51), and QQ species richness (IMS = 0.43) (table 12). This indicates that both invertebrate community samples responded strongly ($p < 0.001$) to the predefined land-use gradient using the urban intensity index. It should be noted that these IMS values were the highest observed for all biological communities, indicating that the invertebrate community is perhaps the most tightly linked to changes due to urbanization.

Datasets—including water quality, hydrologic variability, and stream habitat characteristics—also had strong relations with the invertebrate communities. During the spring, field properties, nutrients, and organics all showed significant ($p < 0.01$) relations to both the RTH and QQ samples, with the organic chemistry (for example, pesticides, pesticide degradates) exhibiting the highest ρ values (table 12). The water-quality datasets collected during the late summer exhibited weaker relations, along with the field properties and organics. In contrast, the relation between the invertebrate communities and the nutrients during the late summer was not significant. Unlike algal datasets, SPMD extract chemistry datasets were significantly ($p < 0.001$) related to both RTH and QQ invertebrate samples. Invertebrate RTH and QQ samples exhibited strong response to organics (pesticides) concentrations during the spring synoptic sampling. The QQ samples showed strongest relations with stream-habitat condition ($\rho = 0.30$). Invertebrate community data responded more consistently than fish or algae to water-quality datasets, especially during the spring high-baseflow synoptic when all relations among invertebrate community types and environmental datasets were moderately significant ($p < 0.001$). Field properties were significantly related during the late summer ($p < 0.05$).

The hydrologic variability metrics were related to the invertebrate RTH and QQ samples primarily during the spring. The RTH abundance ($\rho = 0.21$) samples showed weaker relations to hydrology than either the RTH relative abundance ($\rho = 0.26$) and the QQ samples ($\rho = 0.23$) (table 12). Only the RTH community showed any relation with hydrologic variability metrics calculated for the entire water year ($\rho = 0.23$; $p < 0.05$).

Analysis of the QQ samples using the SIMPER procedure indicated that the invertebrate taxa most responsible for the observed multivariate patterns included eight species, which together accounted for 10 percent of the total dissimilarity between the most developed and least developed sites. These eight species were found at more than 78 percent or less than 11 percent of all the sites in the most developed or least developed group, respectively, and typifies the community within each of these groups more than any other species in these samples. Of these eight taxa, four—including *Dannella simplex*, *Perlesta* sp., *Stenonema modestom*, and *Isonychia* sp.—were found primarily under near-reference conditions, whereas *Cricotopus bicinctus*, *Baetis flavistriga*, and *Hydropsyche depravata* (group) were found primarily in streams with highly developed watersheds.

Fish Community Responses

A total of 8,173 individual fish were collected during fish sampling and included 66 species. Fish communities in streams sampled for this study consisted of between 5 and 27 species and averaged 17 species per site. Sites with the highest fish species abundance included sites 13 and 22 (27 species) and site 10 (24 species). Of the species collected, three were ubiquitous and occurred at more than 90 percent of the sites (27 sites) and included *Lepomis auritus* (30 sites), *Lepomis macrochirus* (29 sites) and *Percina nigrofasciata* (28 sites). Of the 74 species collected, about 32 (43 percent) species were collected at less than 10 percent of the sites. An overview of fish species collected and numbers of occurrences in the two major drainages in the study area is summarized in Appendix E, table E3.

Due to biogeographical differences in the fish communities between the Atlantic slope (Altamaha River drainage) and Gulf slope (Apalachicola River drainage) streams sampled for this study, only the fish community data from Apalachicola drainages (Flint and Chattahoochee River Basins) were used in the community analysis ($n = 21$). Differences in these major river basins can be illustrated graphically using MDS analysis as in figure 17, which shows the sites outside of the Flint and Chattahoochee River drainages in the lower section of the graph. Although the more developed sites from the Altamaha River drainage tended to cluster with more developed sites in the Flint and Chattahoochee sites (sites 6, 9, and 4), the Altamaha River sites were different enough to group together as indicated by the sites encompassed by the shaded area on the graph. MDS stress levels indicated that the two-dimensional representation of fish community composition was adequate (stress = 0.16). The general response of the Piedmont stream fish communities also is illustrated as the more developed sites group together in the lower right section of the graph and undeveloped sites grouping toward the upper left (fig. 17).

Global ANOSIM test results indicated that the separation of cluster groups defined by the UII was significant for fish communities ($R = 0.32$; $p < 0.01$) (fig. 17) and that the strength of the analysis was improved through the reduction of the 30-site dataset ($R = 0.18$; $p < 0.01$). Pair-wise ANOSIM group comparisons indicated higher R values when comparing fish communities from near-reference watersheds to fish com-

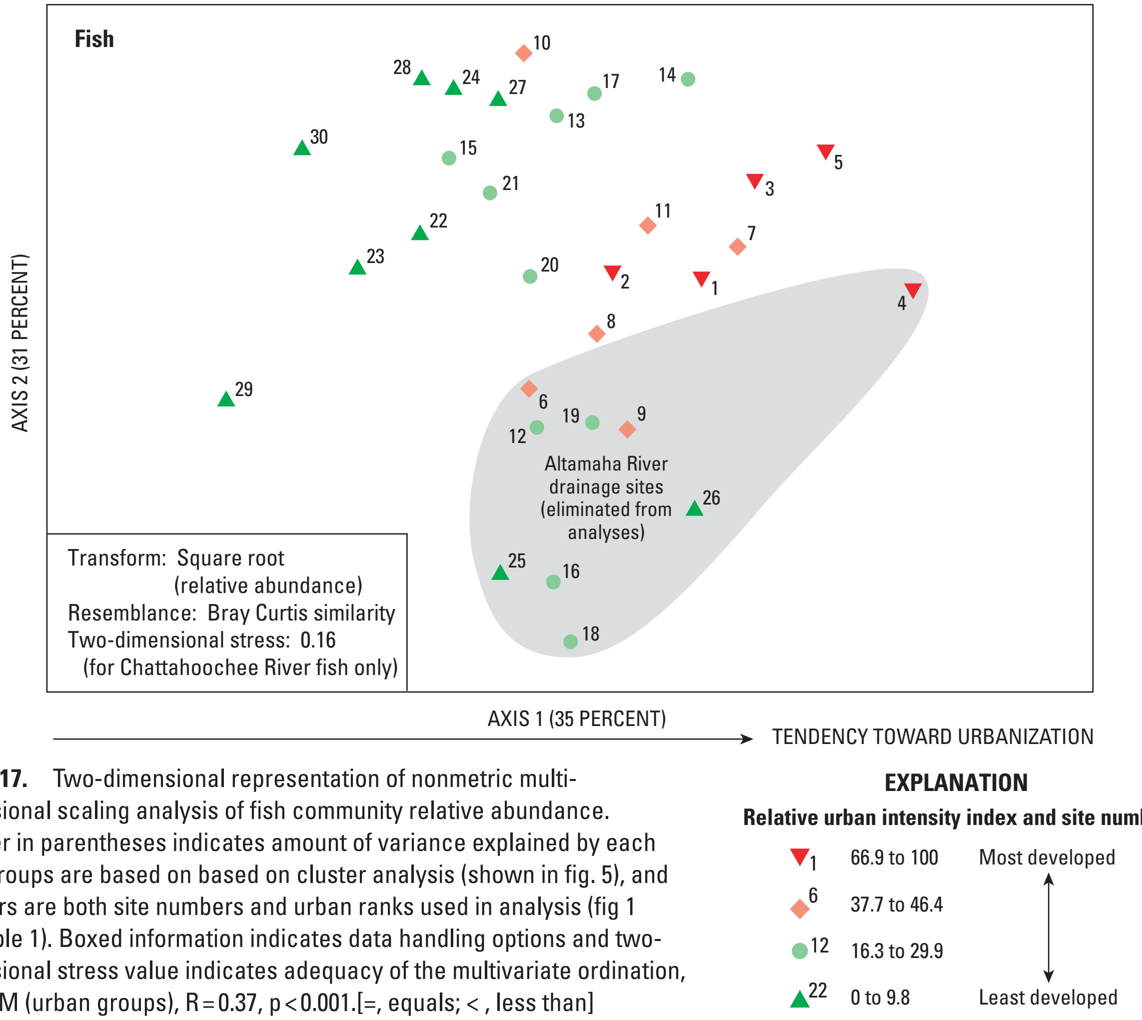


Figure 17. Two-dimensional representation of nonmetric multidimensional scaling analysis of fish community relative abundance. Number in parentheses indicates amount of variance explained by each axis. Groups are based on based on cluster analysis (shown in fig. 5), and numbers are both site numbers and urban ranks used in analysis (fig 1 and table 1). Boxed information indicates data handling options and two-dimensional stress value indicates adequacy of the multivariate ordination, ANOSIM (urban groups), $R = 0.37$, $p < 0.001$.[=, equals; < , less than]

munities from watersheds that are more developed (fig. 14). Multivariate dispersion values also were lower for fish communities in highly urbanized watersheds than for communities in near-reference watersheds, with these values declining progressively as watershed urbanization increases (fig. 15).

The RELATE function indicated that the correlation with linear sequence along the urban gradient is significant ($p < 0.001$) with respect to both fish relative abundance (IMS = 0.37) and species richness (IMS = 0.30; table 12). This significant correlation with linear sequence along environmental gradients defined by the urban rank model indicated that both fish community datasets responded in a strongly significant manner to the predefined land-use gradient. Fish communities also responded significantly to water quality, hydrology and stream habitat, although the strongest ($p \leq 0.001$) among these were between fish relative abundance and field properties collected during the spring synoptic ($\rho = 0.34$). Other, moderately significant ($0.05 > p > 0.01$) relations, were observed between SPMD chemistry and relative abundance ($\rho = 0.30$) and species richness ($\rho = 0.26$); field properties and species richness during spring ($\rho = 0.23$); field properties and relative abundance during summer ($\rho = 0.28$).

The hydrologic datasets exhibited only one weakly significant ($p < 0.05$) relation between fish abundance data during the spring ($\rho = 0.23$), but the relation between these two variable sets was stronger when hydrologic data were pooled for the entire water year ($\rho = 0.27$, $p < 0.01$). Other, weakly significant ($p < 0.05$) relations, were noted in summer between relative abundance and nutrients ($\rho = 0.28$) and stream habitat datasets ($\rho = 0.18$).

SIMPER analysis conducted on fish communities of the Chattahoochee and Flint drainages indicated that species most responsible for the observed multivariate community patterns included only three species. These three species together accounted for approximately 12 percent of the total dissimilarity between the most developed and least developed groups of sites and were found either at more than 75 percent or less than 25 percent of all the sites sampled within these groups. These species typify the community within each of these groups and included *Ichthyomzon gagei* found primarily under near-reference watersheds conditions and *Amerius natalis*, and *Cyprinella lutrensis* found primarily in urban watersheds. Other moderately influential species include *Nocomis leptocephalus* and the undescribed *Hybopsis,* both primarily found in near-reference conditions.

Summary and Conclusions

This study of 30 similarly sized, wadable streams conducted in four major drainages of the Georgia Piedmont links anthropogenic factors—such as population density, landscape, and infrastructure features—to altered hydrology, water quality, and stream biological communities.

The recent growth pattern of the Metropolitan Atlanta area can be described as "doughnut-shaped," with most of the new growth occurring as lower density urban and suburban outside a more densely developed older core area of the city. With no natural physical barriers to growth, this pattern is not expected to change in the near future and the total population of the Metropolitan Atlanta area is expected to grow to about 7 million by 2025. Much of this developing area was once dominated by intensive row-crop agriculture that severely altered the geomorphology of many of the region's smaller streams. Since the 1940s, these streams have begun to recover as former row-crop lands have converted to secondary forest; however, the legacy of the row-crop era can still be observed in the landscape and streams of the southern Piedmont. Studies conducted in this area should consider the legacy of historical agricultural practices that still affects stream habitat conditions even in nonurban areas. Even though the legacy effects of agriculture were not considered in this study, the general lack of correlation between the biological communities and stream-habitat conditions may be due partly to the hydrologic processes associated with urbanization occurring in streams that were previously impacted by hydrologic processes associated with the era of row-crop agriculture.

No relations were found between stream temperatures and the UII or to the individual components of the UII, which may be related to the subjective method used to select sites. Because care was taken to select sites that were as similar as possible in terms of instream and near-stream habitat conditions, all of these sites had fairly intact riparian cover. This fact alone may have mitigated temperature increases from proximate impervious cover or urban land use. Furthermore, the temperature probes were collocated with pressure transducers, which were generally placed upstream from the nearest bridge crossing to mitigate effects that bridge abutments would have on hydrographs during high flows. This placement criterion may have helped to mask any detectable effects on stream temperatures, especially after summer storms when the runoff entering the stream from a nearby road or impervious area would have been most noticeable.

In general, chemical and hydrologic characteristics responded to urban intensity as defined by the five variable UII (urban intensity index); however, physical characteristics of streams—such as instream habitat features and water temperature—exhibited no significant relations to increasing urban intensity. Due to the subjective methods used to select sampling sites, in which an attempt was made to minimize differences based on reach-scale habitat conditions, streams were selected for differing watershed characteristics but comparable reach-scale habitat conditions; therefore, habitat data were not used to correlate changes with the level of urbanization in the watershed. It may be appropriate, however, that habitat data collected for this study be used as a general guide to typical conditions found in the Piedmont near Atlanta, Ga.

The chemical response to urbanization shows that as watersheds become more urban, the mix of anthropogenic chemicals found in the watersheds becomes increasingly complex. These changes are apparent even at low levels of development. Chemicals or indicators of dissolved chemicals—such as specific conductance, chloride, sulfate, and species of nitrogen and phosphorus—strongly correlated with urban intensity and showed marked increases when the UII approached a value of about 10 or when the watershed has about 2.5-percent impervious cover. Streams with impervious values of more than 2.5 percent are not generally considered near-reference streams (least developed sites in this study); however, watersheds with this level of impervious surface represents fairly undeveloped watersheds in terms of population density and infrastructure.

Pesticides are significantly correlated with increasing urban development, although not as significantly correlated with watershed urbanization as the aforementioned chemicals. A threshold may be apparent with pesticides and with the total sums of pesticide categories where noticeable increases in concentrations at an UII value of about 25. An UII value of 25 corresponds to an estimated impervious cover value of about 6.5 percent. Interestingly, SPMD (semipermeable membrane device) assays as well as chemicals identified from SPMD extracts, such as benzophenanthrene and flouranthene, indicated weak thresholds in terms of concentration at about this same level of urban development. Chemical concentrations rarely exceeded criteria for the protection of human health or aquatic resources, although no standards currently exist for chemical data derived from the use of SPMDs.

Hydrologic variability metrics were particularly correlated with urban development and primarily comprise metrics that describe an increase in "flashy" streamflow conditions. Metrics that measured the most extreme flashy conditions were consistently the most highly correlated with the UII, although housing density, road density, and percent developed in the basin and the buffer also were highly correlated. Results from this study indicated that altered hydrology was apparent when analyzed for the entire water year; however, seasonal analysis indicated that the most pronounced departure from undeveloped hydrologic conditions occurs during the fall when these streams experience annual low flows. The impact of urbanization on hydrologic variability in small Piedmont streams was least apparent during the winter when flows generally are highest. This study indicated no evidence of a higher frequency of low flows in more urban streams than nonurban streams, although this relation has been demonstrated in other studies, including recent findings in the Atlanta area. The limited period of record for these 30 sites clearly affected the ability to determine alterations in baseflow conditions for these streams. The sampling year was one of the wettest on record and a more temporally extensive dataset might reveal a low-flow signature related to increasing watershed urbanization in these same streams.

The ramifications of altered hydrologic conditions in urban streams may be further complicated by the legacy of historical land use and resulting lack of geomorphic equilibrium in this part of the southern Piedmont. For instance, even if habitat conditions were different in urban and nonurban streams due to the effects of urbanization, urban stream habitat conditions actually may be more similar to historical prefarming conditions due to the accelerated rates of bank erosion and streambed coarsening that result from higher more flashy streamflow conditions. Although not an objective of this study, future studies would benefit from a better understanding of the relation between altered hydrology and geomorphic conditions in an historical context in the southern Piedmont.

Biological communities, especially invertebrates and to some extent fishes, responded significantly to increasing urbanization as defined by the UII. The diatom community response to the UII was relatively weaker particularly for individual diatom metrics. As these watersheds urbanized, the stream communities became more homogenous. The most developed sites lost the distinctive taxa of the least developed sites and exhibited less variation in terms of species composition.

Diatom community response to urbanization was relatively weak, but responded more strongly to specific hydrologic characteristics. Both sample types had weak responses to the urban intensity gradient as indicated by poor sample ordering in MDS (nonmetric multidimensional scaling) and weakly significant IMS (index of multivariate seriation) values. Although the UII was significant in explaining multivariate patterns in both diatom sample types, the hydrologic variability was the strongest explanatory factor in structuring the diatom composition. Hydrology during the spring was consistently the most significant predictor; this may indicate that nonurban-related hydrologic characteristics altered the algal communities prior to the biological sampling. Water chemistry was only weakly related to the diatom community composition. The strongest relations to nutrient chemistry were noted in the epidendric algal relative abundance, as were relations to pesticide chemistry in the late-summer samples. The nutrient response may reveal a primary agent of structuring the algal community that is not highly related to urbanization in these watersheds. Concentrations of nutrients, such as total phosphorus, were highest near the middle of the urban gradient and may result from distributed septic systems, limited agriculture, or land disturbing activities related to suburban development. Individual algal metrics showed no statistically significant responses to urbanization; however, antecedent hydrological conditions may have been a factor in this study. An abnormally wet spring and rain events during April 2003 just prior to sampling might have affected algal communities by reducing diversity and abundance across the study area.

Invertebrate community data from both snag and multihabitat samples were fairly well represented by MDS ordinations and were highly responsive to the gradient of increasing urbanization, although snag samples generally responded more strongly to the urban gradient. The UII and SPMD chemistry extract datasets were strong multivariate predictors of invertebrate community structure; whereas, water-quality and hydrologic variability measured in the spring were slightly less significantly related to multivariate patterns in the both the snags and multihabitat communities. Stream habitat data were only weakly related to invertebrate community structure in both the multihabitat and snag samples. The qualitative influence of significant environmental datasets on invertebrate relative abundance could be expressed as: SPMD chemistry > pesticide concentrations > water-quality properties (spring) > nutrient chemistry (spring) ≈ hydrology (spring) > instream habitat ≈ hydrology (water year) > water-quality properties (late summer).

Water-quality variables that best explained multivariate patterns in the invertebrate community data were specific conductance and the CYP1A1 (cytochrome P450) induction assay from the SPMD dataset. Hydrologic variables that best explained invertebrate community patterns included metrics that characterized both maximum and medium duration of high flows (greater than the 90th percentile) as well as metrics that characterized extremely rapid changes in water levels at a site (greater than nine times the median hydrologic response). Hydrologic variability metrics could explain patterns of change in the invertebrate community data during all seasons and over the entire water year. Percent boulders and percent riffles in the stream reach (habitat dataset) were significantly related to invertebrate communities. EPT (Ephemeroptera, Plecoptera, and Tricoptera) richness metrics were generally the most responsive indicators of the effect of increasing urbanization. Abundance metrics were not effective indicators, although one functional group abundance metric—percent predators in snag samples—responded to increasing urbanization. Responses were typically linear with little to no initial resistance to urbanization (no initial threshold). Strong threshold response was observed with the percent EPT richness metric. The general response indicated by invertebrate metric analysis was a loss of overall richness and increase in more tolerant species.

Biogeographic differences among fish communities in the Chattahoochee River and Flint River Basins (Gulf Slope) and the Ocmulgee River and Oconee River Basins (Atlantic Slope) were significant and prevented concurrent multivariate analysis on communities from both basins. Significant response to urbanization in the Chattahoochee River and Flint River Basins was indicated by acceptable MDS stress levels and the ordering of sites in terms of community similarity along an axis of increasing urbanization.

Relative abundance was more effective than presence/absence at predicting the responses of fish community structure, indicated by higher ρ values and more significance in pair-wise dataset comparisons. The UII was a strongly significant multivariate predictor of fish community structure in terms of relative abundance and presence/absence. The qualitative influence of significant environmental datasets on fish relative abundance could be expressed as field water-quality properties (spring) > SPMD chemistry > field water-quality properties (fall) ≈ hydrology (water year) > nutrients (late summer) ≈ hydrology (spring) ≈ stream habitat.

During the spring, summer, and entire water year, negative correlations were observed with cyprinids, the number of intolerant species, herbivore, omnivores, and simple nesters with variables that describe abnormally high flow and high-flow pulses. Bottom-dwelling species were negatively correlated to water quality during spring, whereas cyprinids, herbivores, and species that prefer bedrock were negatively correlated with water quality during the late summer. The Georgia Index of Biotic Integrity was negatively correlated with extreme stream flashiness.

Habitat variables—including flow stability, percent embeddedness, woody debris cover, and open canopy angle—were positively correlated with herbivores and simple nesters. The only family-level metric with a consistent response to altered flow and water quality were the cyprinids. Cyprinid richness was negatively correlated with the UII, housing density, and road density in the basin. The percentage of the community composed of pool-dwelling species increased in response to increased development in riparian buffer. Some overly general fish metrics—such as fishes that occupy a range of sizes, or fishes that occupy small creeks to small rivers—were correlated with environmental variables, but provided little useful information.

Fishes whose tolerances were unknown were negatively correlated with UII and increasing watershed urbanization; whereas fishes that are known to occupy a range of stream sizes were positively correlated with the UII. Fishes that prefer pool habitat were not correlated to the UII but were positively correlated with percent developed in the buffer. Percent cyprinids were negatively correlated with the UII.

The Metropolitan Atlanta area continues to be one of the fastest growing areas in the United States and issues related to water quantity and quality will continue to play a large role in local and regional planning agendas. This study provides a broad look at the effects of urbanization in terms of specific stressors and provides regionally specific analysis of the relation between increasing watershed urbanization and physical and biological changes that may occur in streams which drain these areas in the southern Piedmont.

References Cited

Atlanta Regional Commission, 2007, Envision 6 introduction presentation: Accessed August 2007 at *http://www.atlantaregional.com/cps/rde/xbcr/arc/looping2.ppt*

Barbour, M.T., Gerritsen, Jeroen., Snyder B.D., and Stribling, J.B., 1999, Rapid bioassessment protocols for use in streams and wadeable rivers—Periphyton, benthic macroinvertebrates and fish, EPA 841-B-99-002: Washington, D.C., U.S. Environmental Protection Agency.

Booth, D.B., and Hartely, David, 2002, Forest cover, impervious-surface area, and the mitigation of stormwater impacts: Journal of the American Water Resources Association, v. 38, no. 3, p. 835–846.

Booth, D.B., and Jackson, C.R., 1997, Urbanization of aquatic systems: Degradation thresholds, stormwater detention, and the limits of mitigation: Journal of the American Water Resources Association, v. 33, no. 5, p. 1077–1090.

Boschung, H.T., Jr., and Mayden, R.L., 2004, Fishes of Alabama: Washington, D.C., Smithsonian Books, 736 p.

Calhoun, D.L., Frick, E.A, and Buell, G.R., 2003, Effects of urban development on nutrient loads and streamflow, upper Chattahoochee River Basin, Georgia, 1976–2001, *in* Hatcher, K.J., ed., Proceedings of the 2005 Georgia Water Resources Conference, Athens, Ga., 5 p., CD–ROM, accessed August 2007 at *http://ga.water.usgs.gov/pubs/other/gwrc2003/pdf/Calhoun-GWRC2003.pdf*

Charles, D.F., Candia, Knowles, and Davis, R.S., eds., 2002, Protocols for the analysis of the algal collected as part of the U.S. Geological Survey National Water-Quality Assessment Program: The Academy of Natural Sciences, Report No. 02-06, 124 p., accessed August 2007 at *http://water.usgs.gov/nawqa/protocols/algprotocol/index.html*

Clarke, K.R., Warwick, R.M., and Brown, B.E., 1993, An index showing breakdown of seriation, related to disturbance, in a corral reef assemblage: Marine Ecology Progress Series, v. 102, p. 153–160.

Clarke, K.R., and Warwick, R.M., 2001, Changes in marine communities: an approach to statistical analysis and interpretation: Plymouth, United Kingdom, PRIMER_E Ltd, 174 p. -

Clarke, K.R., and Gorley, R.N., 2006a, Primer® user manual/tutorial: Plymouth, United Kingdom, PRIMER-E Ltd., 190 p.

Clarke, K.R., and Gorley, R.N., 2006b, Primer® software version 6: Plymouth, United Kingdom, PRIMER-E Ltd.

Coulter, C.B., Kolka, R.K., and Thompson, J.A., 2004, Water quality in agricultural, urban, and mixed land use watersheds: Journal of the American Water Resources Association, v. 40, no. 6, p. 1593–1601.

Cuffney, T.F., 2003, User's manual for the National Water-Quality Assessment Program invertebrate data analysis system (IDAS) software—Version 3: U.S. Geological Survey Open-File Report 03-172, p. 103.

Davis, N.M., Weaver, V., Parks, K., and Lydy, M.J., 2003, An assessment of water quality, physical habitat, and biological integrity of an urban stream in Wichita, Kansas, prior to restoration improvements (phase I): Archives of Environmental Contamination and Toxicology, v. 44, no. 3, p. 351–359.

Falcone, James, Stewart, J.S., Sobieszczyk, Steve, Dupree, J.A., McMahon, Gerard, and Buell, G,R., 2007, A comparison of natural and urban characteristics and the development of urban intensity indices across six geographic settings: U.S. Geological Survey Scientific Investigations Report 2007-5123, 43 p., accessed December 2007 at *http://pubs.usgs.gov/sir/2007/5123*

Fishman, M.J., 1993, Methods of analysis by the U.S. Geological Survey National Water Quality Laboratory—Determination of inorganic and organic constituents in water and fluvial sediments: U.S. Geological Survey Open-File Report 93-125, 217 p., accessed August 2007 at *http://pubs.er.usgs.gov/usgspubs/ofr/ofr93125*

Fishman, M.J., and Friedman, L.C., 1989, Methods for determination of inorganic substances in water and fluvial sediments: U.S. Geological Survey, Techniques of Water-Resources Investigation Reports, book 5, chap. A1, variously paged, accessed August 2007 at *http://pubs.usgs.gov/twri/twri5-a1/html/pdf.html*

Fitzpatrick, F.A., Waite, I. R. D'Arconte, P.J., Meador, M.R., Maupin, M.A., and Gurtz, M.E., 1998, Revised methods for characterizing stream habitat in the National Water-Quality Assessment Program: U.S. Geological Survey Water-Resources Investigations Report 98-4052, 67 p., accessed August 2007 at *http://water.usgs.gov/nawqa/protocols/WRI98-4052/index.html*

Freeman, P.L., and Schorr, M.S., 2004, Influence of watershed urbanization on fine sediment and macroinvertebrate assemblage characteristics in Tennessee Ridge and Valley streams: Journal of Freshwater Ecology, v. 19, no. 3, p. 353–362.

Garie, H.L., and McIntosh, Alan, 1986, Distribution of benthic macroinvertebrates in a stream exposed to urban runoff: Water Resources Bulletin, v. 22, no. 3, p. 447–455.

Geolytics, 2000, Census CD–ROM and Map Release 1.1 Geolytics, Inc.: East Brunswick, N.J.

Georgia Department of Natural Resources, 2005, Sampling protocols and SOP Part II: Scoring criteria for the index of biotic integrity and the index of well-being to monitor fish communities in wadeable streams in the Piedmont Ecoregion of Georgia: Atlanta, Ga., Georgia Department of Natural Resources, Wildlife Resources Division, Fisheries Management Section, 49 p., accessed August 2007 at *http://georgiawildlife.dnr.state.ga.us/content/displaycontent.asp?txtDocument=436*

Goldstein, R.M., and Meador, M.R., 2004, Comparisons of fish species traits from small streams to large rivers: Transactions of the American Fisheries Society, v. 133, p. 971–983.

Gray, Lawrence, 2004, Changes in water quality and macroinvertebrate communities resulting from urban stormflows in the Provo River, Utah, U.S.A.: Hydrobiologia, v. 518, p. 33–46.

Gregory, M.B., 2005, Microhabitat preferences by aquatic invertebrates influence bioassessment metrics in Piedmont streams of Georgia and Alabama, *in* Hatcher, K.J., ed., Proceedings of the 2005 Georgia Water Resources Conference, Athens, Ga., 6 p. CD–ROM, accessed August 2007 at *http://ga.water.usgs.gov/pubs/other/gwrc2005/pdf/GWRC05_Gregory.pdf*

Griffith, G.E., Omernik, J.M., Comstock, J.A., Lawrence, S., Martin, G., Goddard, A. Hulcher, V.J., Foster, T., 2001, Ecoregions of Alabama and Georgia (color poster with map, descriptive text, summary tables, and photographs): Reston, Va., U.S. Geological Survey, scale 1:1,700,000.

Hairston, J.B., and Tamman, Maurice, 2003, Atlanta swells into top 10 U.S. metro areas: Atlanta Journal-Constitution, May 21, 2003, p. A1.

Heimlich, R.E., and Anderson, W.D., 2001, Development at the urban fringe and beyond—Impacts on agriculture and rural land: U.S. Department of Agriculture, Economic Research Service, Agricultural Economic Report No. 803, 80 p.

Hewlett, J.D., 1967, A hydrologic response map for the State of Georgia: Contribution from the University of Georgia College of Agriculture Experiment Stations, College Station, Athens, Ga., Journal Series, Paper 59, p. 4–20.

Hickey, A.C., Kerestes, J.F., and McCallum, B.E., 2004, Continuous water-level, streamflow, water-quality data, and periodic water-quality data, water year 2003: USGS Water-Data Report GA-03-01, vol.1, p. 2338, CD–ROM, accessed August 2007 at *http://pubs.usgs.gov/wdr/wdr-ga-03-1/*.

Hopkins, E.H., 2003, Using a geographic information system to rank urban intensity of small watersheds for the Chattahoochee, Flint, Ocmulgee, and Oconee River Basins in the Piedmont Ecoregion of Georgia and Alabama, *in* Hatcher, K.J., ed., Proceedings of the 2003 Georgia Water Resources Conference, University of Georgia, Athens, Ga., CD–ROM, accessed August 2007 at *http://usgs.gov/pubs/other/gwrc2003/pdf/Hopkins-GWRC2003.pdf*

Huckins, J.N., Tubergen, M.W., and Manuweera, G.K., 1990, Semipermeable membrane devices containing model lipid—A new approach to monitoring the bioavailability of lipophilic contaminants and estimating their bioconcentration potential: Chemosphere, v. 20, no. 5, p. 533–552.

James, F.C., and McCulloch, C.E., 1990, Multivariate analysis in ecology and systematics—Panacea or Pandora's box: Annual Review of Ecology and Systematics, v. 21, p. 129–166.

Johnson, B.T., 1998, Microtox toxicity test system—New developments and applications, *in* Wells, P.G., Lee, Kenneth and Blaise, Christian, eds., Microscale testing in aquatic toxicology—Advances, techniques, and practice: Boca Raton, Fla., CRC Lewis Publishers, p.201–218.

Klien, R.D., 1979, Urbanization and stream quality impairment: Water Resources Bulletin, v. 15, no. 4, p. 948–963.

Kramer, Liz, 2006, Georgia Land Use Trends (GLUT), online report and database: University of Georgia, Institute of Ecology, accessed August 2007 at *http://narsal.ecology.uga.edu/glut.html*

LeBlanc, R.T., Brown, R.D., and FitzGibbon, J.E., 1997, Modeling the effects of land use change on the water temperature in unregulated urban streams: Journal of Environmental Management, v. 49, no. 4, p. 445–469.

McCune, Bruce, and Grace, J.B., 2002, Analysis of Ecological Communities: Gleneden Beach, Oreg., MjM software, 300 p.

McMahon, Gerard, and Cuffney, T.F., 2000, Quantifying urban intensity in drainage basins for assessing stream ecological conditions: Journal of the American Water Resources Association, v. 36, no. 6, p. 1247–1261, accessed August 2007 at *http://water.usgs.gov/nawqa/ecology/pubs/jawra2000.pdf*

McMahon, Gerard, Bales, J.D., Coles, J.F., Giddings, E.M.P., and Zappia, Humbert, 2003, Use of stage data to characterize hydrologic conditions in an urbanizing environment: Journal of the American Water Resources Association, v. 39, no.6, p. 1529–1546, accessed August 2007 at *http://water.usgs.gov/nawqa/ecology/pubs/index.html*

Moulton, S.R., II, Carter, J.L., Grotheer, S.A., Cuffney, T.F., and Short, T.M., 2000, Methods of analysis by the U.S. Geological Survey National Water Quality Laboratory—Processing, taxonomy, and quality control of benthic macroinvertebrate samples: U.S. Geological Survey Open-File Report 00-212, 49 p., accessed August 2007 at *http://nwql.usgs.gov/Public/pubs/OFR00-212.html*

Moulton, S.R., II, Carter, J.L., Grotheer, S.A., Cuffney, T.F., and Short, T.M.. 2002, Revised protocols for sampling algal, invertebrate, and fish communities as part of the National Water-Quality Assessment Program: U.S. Geological Survey Open-File Report 02-150, 75 p., accessed August 2007 at *http://water.usgs.gov/nawqa/protocols/OFR02-150/index.html*

Munn, M.D., and Gilliom, R.J., 2001, Pesticide toxicity index for freshwater aquatic organisms: U.S. Geological Survey Water-Resources Investigations Report 01-4077, 61 p.

Murk, A.J., Legler, J., Penison, M.S., Giesy, J.P., Van de Guchte, C., and Brouwer, A., 1996, Chemical activated luciferase gene expression (calux)—A novel in vitro bioassay for AH receptor active compounds in sediment and pore water: Fundamental and Applied Toxicology, v. 33, p. 149–160.

Murphy, J.F., and Davy-Bowker, John, 2005, Spatial structure in lotic macroinvertebrate communities in England and Wales—Relationship with physical, chemical and anthropogenic stress variables: Hydrobiologia, v. 534, p. 151–164.

Newall, Peter, and Walsh, C.J., 2005, Response of epilithic diatom assemblages to urbanization influences: Hydrobiologia, v. 532, p. 53–67.

Paul, M.J., Leigh, D.S., and Lo, C.P., 2001, Urbanization in the Etowah River Basin—Effects on stream temperature and chemistry, *in* Hatcher, K.J., ed., Proceedings of the 2001 Georgia Water Resources Conference, University of Georgia, Athens, Ga., p. 241–245.

Paul, M.J., and Meyer, J.L., 2001, Streams in the urban landscape: Annual Review of Ecology and Systematics, v. 32, p. 333–365.

Perneger, T.V., 1998, What's wrong with Bonferroni adjustments: BMJ, v. 316, p. 1236–1238.

Rehmel, Mike S., 2005, AreaComp software, U.S. Geological Survey.

Rose, Seth, and Peters, N.E., 2001, Effects of urbanization on streamflow in the Atlanta area (Georgia, USA)—A comparative hydrological approach: Hydrological Processes, v. 15, p. 1441–1457.

Roy, A.H., Rosemond, A.D., Leigh, D.S., Paul, M.J., and Wallace, B.J., 2003a, Habitat-specific responses of stream insects to land cover disturbance—Biological consequences and monitoring implications: Journal of North American Benthological Society, v. 22, no. 2, p. 292–307.

Roy, A. H., Rosemond, A. D., Paul, M. J., Leigh, D. S., and Wallace, J. B., 2003b, Stream macroinvertebrate response to catchment urbanisation (Georgia, U.S.A.): Freshwater Biology, v. 48, p. 329–346.

Sankoh, A.J., Huque, M.F., and Dubey, S.D., 1997, Some comments on frequently used multiple endpoint adjustment methods in clinical trials: Stat Med, v. 16, no. 22, p. 2529–2542.

Sauer, V.B., 2002, Standards for the analysis and processing of surface-water data and information using electronic methods: U.S. Geological Survey Water-Resources Investigations Report 01-4044, 92 p.

Simmons, D.L., and Reynolds, R.J., 1982, Effects of urbanization on base flow of selected south-shore streams, Long Island, New York: Water Resources Bulletin, v. 18, no. 5, p. 797–805.

Taylor, S.L., Roberts, S.C., Walsh, C.J., and Hatt, B.E., 2004, Catchment urbanization and increased benthic algal biomass in streams—Linking mechanisms to management: Freshwater Biology, v. 49, p. 835–851.

Trimble, S.W., 1969, Culturally accelerated sedimentation on the middle Georgia Piedmont, master's thesis, University of Georgia, 110 p.

U.S. Census Bureau, 2000, Census 2000 redistricting data summary file: U.S. Census Bureau Technical Documentation Public Law 94-171, 223 p.

U.S. Census Bureau, 2006, Decennial censuses of population and housing data: Accessed August 2007 at *http://www.census.gov/population/www/censusdata/hiscendata.html*

U.S. Environmental Protection Agency, 1994, National water quality inventory 1992 report to Congress: U.S. Environmental Protection Agency Office of Water, EPA841-F-94-002, 8 p.

U.S. Environmental Protection Agency, 2000, The quality of our Nation's waters—A summary of the national water quality inventory: 1998 Report to Congress, U.S. Environmental Protection Agency, Office of Water, EPA84-S-00-001, 20 p., accessed August 2007 at *http://www.epa.gov/305b/98report/98brochure.pdf*

U.S. Environmental Protection Agency, 2001, Our built and natural environments: U.S. Environmental Protection Agency, Community and Environment Division, EPA-231-R-01-002, Washington, D.C., 102 p., accessed August 2007 at *http://www.epa.gov/smartgrowth/built.htm*

U.S. Environmental Protection Agency, 2004, Protecting water resources with smart growth: U.S. Environmental Protection Agency, Eastern Research Group of the Development, Community, and Environmental Division, U.S. Environmental Protection Agency Office of Policy, Economics, and Innovation, EPA 231-R-04-002 Washington, D.C., p. 116, accessed August 2007 at *http://www.epa.gov/smartgrowth/pdf/waterresources_with_sg.pdf*

U.S. Environmental Protection Agency, 2005, Digital data files, accessed August 2007 at *http://www.epa.gov/wed/pages/ecoregions/level_iv.htm*, data extracted in 2005.

U.S. Geological Survey, 1992, National Land Cover Data, accessed December 2002 at *http://landcover.usgs.gov/landcoverdata.php*

U.S. Geological Survey, 1997 to present, National field manual for the collection of water-quality data: U.S. Geological Survey Techniques of Water-Resource Investigations, book 9, chaps. A1–A9, variously paged, accessed August 2007 at *http://pubs.water.usgs.gov/twri9A*

U.S. Geological Survey, 1999, The quality of our Nation's waters—Nutrients and pesticides: U.S. Geological Survey Circular 1225, 82 p., accessed August 2007 at *http://pubs.usgs.gov/circ/circ1225/*.

Walters, D.M., Leigh, D.S., and Bearden, A.B., 2003a, Urbanization, sedimentation, and the homogenization of fish assemblages in the Etowah River Basin, USA: Hydrobiologia, v. 494, no. 1, p. 5.

Walters, D.M., Leigh, D.S., Freeman, M.C., Freeman, B.J., and Pringle, C.M., 2003b, Geomorphology and fish assemblages in a Piedmont river basin, U.S.A.: Freshwater Biology, v. 48, no. 11, p. 1950–1970.

Wang, Lizhu, and Kanehl, Paul, 2003, Influences of watershed urbanization and instream habitat on macroinvertebrates in cold water streams: Journal of the American Water Resources Association, v. 39, no. 5, p. 1181–1196.

Wang, Lizhu, Lyons, John, Kanehl, Paul, and Bannerman, Roger, 2001, Impacts of urbanization on stream habitat and fish across multiple spatial scales: Environmental Management, v. 28, no. 2, p. 255–266.

Wilber, W.G., and Hunter, J.V., 1977, Aquatic transport of heavy metals in the urban environment: Water Resources Bulletin, v. 13, no.4, p. 721–734.

Williams, Michael, Hopkinson, Charles, Rastetter, Edward, Vallino, Joseph, and Claessens, Luc, 2005, Relationships of land use and stream solute concentrations in the Ipswich River Basin, northeastern Massachusetts: Journal of Water, Air, and Soil Pollution, v. 161, p. 55–74.

Zaugg, S.D., Sandstrom, M.W., Smith, S.G., and Fehlberg, K.M., 1995, Methods of analysis by the U.S. Geological Survey National Water-Quality Laboratory—Determination of pesticides in water by C-18 solid-phase extraction and capillary-column gas chromatography/mass spectrometry with selected ion monitoring: U.S. Geological Survey Open-File Report 95–181, 49 p.

Appendix A. GIS Variable Names, Abbreviations, and Descriptions

Table A1. Sources of geographic information system and digital information used to derive study variables.

[GIS, geographic information system; NED, National Elevation Dataset; USGS, U.S. Geological Survey; DRG, Digital Raster Graphics; WBD, Watershed Boundary Dataset; NRCS, Natural Resources Conservation Service; TIGER, Topologically Integrated Geographic Encoding and Referencing; NPDES, National Pollutant Discharge Elimination System; USEPA, U.S. Environmental Protection Agency; TRI, Toxics Release Inventory; NID, National Inventory of Dams; USACE, U.S. Army Corps of Engineers; MRLC, Multi-Resolution Land Characteristic Data; NLCD, National Land Cover Dataset; NHD, National Hydrography Dataset; NCAR, National Center for Atmospheric Research]

Basin characteristic	GIS data theme	Data theme source	Scale	Reference or data source
Watershed boundaries	NED	USGS	24,000	USGS, 1999, and USGS Seamless Data Distribution System Web site: *http://seamless.usgs.gov*; data extracted, 2005
	DRG	USGS and National Geographic Society	24,000	National Geographic Society TOPO!® Web site: *http://www.nationalgeographic.com/topo*, 2003
	National WBD	NRCS	24,000	NRCS Web site: *http://www.ncgc.nrcs.usda.gov/products/datasets/watershed/*; data extracted, 2004
Infrastructure	Census 2000 TIGER system Line® files	U.S. Census Bureau	100,000	Census TIGER Web site: *http://www.census.gov/geo/www/tiger/index.html*
	NPDES	USEPA	Unknown, assumed 24,000	USEPA Envirofacts Web site: *http://www.epa.gov/enviro/index_java.html*; data extracted, 2001
	TRI	USEPA	Unknown, assumed 24,000	USEPA Envirofacts Web site: *http://www.epa.gov/enviro/index_java.html*; data extracted, 2001
	NID	USACE	2,000,000	USACE NID Web site: *http://crunch.tec.army.mil/nid/webpages/nid.cfm*; data extracted, 2005
Land use/ land cover, including riparian	MRLC, 1992	USGS	100,000	USGS MRLC Data Web site: *http://gisdata.usgs.net/website/MRLC/*; data extracted, 2001
	NLCD, 2001	USGS	100,000	Falcone, 2005
	NHD	USGS	100,000	USGS NHD Web site: *http://nhd.usgs.gov/*; data extracted, 2005
Demography	Census Blocks and Block Groups 2000, short (SF1) and long forms (SF3)	U.S. Census Bureau	100,000	Geolytics Census 2000 Blocks short form CD and Census CD/DVD 2000 long form
Soil	State Soils Geographic (STATSGO) Database	NRCS	250,000	NRCS Web site: *http://www.ncgc.nrcs.usda.gov/products/datasets/statsgo/*; data extracted, 2002
Hydrologic landscape regions	Hydrologic soil groups	NRCS	250,000	NRCS Web site: *http://www.ncgc.nrcs.usda.gov/products/datasets/statsgo/*; data extracted, 2002
Hydrologic landscape regions	Hydrologic landscape regions	USGS	1,000,000	USGS Web site: *http://water.usgs.gov/GIS/metadata/usgswrd/XML/hlrus.xml*; data extracted, 2001; winter, 2001
Ecoregion	Ecoregions	USEPA	250,000 and 7,500,000	USEPA Web site: *http://www.epa.gov/wed/pages/ecoregions/level_iii.htm* and *http://www.epa.gov/wed/pages/ecoregions/level_iv.htm*; data extracted, 2001 and 2005; Omernik, 1987

Table A1. Sources of geographic information system and digital information used to derive study variables.—Continued

[GIS, geographic information system; NED, National Elevation Dataset; USGS, U.S. Geological Survey; DRG, Digital Raster Graphics; WBD, Watershed Boundary Dataset; NRCS, Natural Resources Conservation Service; TIGER, Topologically Integrated Geographic Encoding and Referencing; NPDES, National Pollutant Discharge Elimination System; USEPA, U.S. Environmental Protection Agency; TRI, Toxics Release Inventory; NID, National Inventory of Dams; USACE, U.S. Army Corps of Engineers; MRLC, Multi-Resolution Land Characteristic Data; NLCD, National Land Cover Dataset; NHD, National Hydrography Dataset; NCAR, National Center for Atmospheric Research]

Basin characteristic	GIS data theme	Data theme source	Scale	Reference or data source
Topography	NED	USGS	24,000	USGS, 1999, and USGS Seamless Data Distribution System Web site: *http://seamless.usgs.gov*; data extracted again, 2005
Segment	NED	USGS	24,000	USGS, 1999, and USGS Seamless Data Distribution System Web site: *http://seamless.usgs.gov*; data extracted again, 2005
	NHD	USGS	100,000	USGS NHD Web site: *http://nhd.usgs.gov/*; data extracted, 2005
	NID	USACE	2,000,000	USACE NID Web site: *http://crunch.tec.army.mil/nid/webpages/nid.cfm*; data extracted, 2005
	MRLC, 1992	USGS	100,000	USGS MRLC Data Web site: *http://gisdata.usgs.net/website/MRLC/*; data extracted, 2001
	NLCD, 2001	USGS	100,000	Falcone, 2005
	Census TIGER system Line® files	U.S. Census Bureau	100,000	U.S. Census Bureau TIGER Web site: *http://www.census.gov/geo/www/tiger/index.html*
Climate	Daymet Climatological Summaries for the Conterminous United States, 1980–97	University of Montana, Numerical Terradynamic Simulation Group and NCAR	1,000-meter grids	Daymet Web site: *http://daymet.ntsg.umt.edu/data/data.htm*; data extracted, 2005
Fragstats	NLCD, 2001	USGS	100,000	Falcone, 2005; FRAGSTATS Web site: *http://www.umass.edu/landeco/research/fragstats/fragstats.html*

Table A2. Basin variable abbreviations and definitions.

[USGS, U.S. Geological Survey; mi^2, square mile; km^2, square kilometer; ha, hectare; km, kilometer; TIGER, Topologically Integrated Geographic Encoding and Referencing; CFCC, census feature class code; USEPA, U.S. Environmental Protection Agency; NPDES, National Pollutant Discharge Elimination System; MRLC, Multi-Resolution Land Characteristic Data; NLCD, National Land Cover Dataset]

Variable code	Description
Basin identifier and area variables	
WS_CODE	Watershed identifier (integer)
STAID	USGS station identifier
SNAME	USGS station name
SQMI	Watershed area (mi^2)
COUNT	Cell count, from 30-meter resolution grid defining analysis area
SQKM	Watershed area (km^2)
HA	Watershed area (ha)
STREAMMI	Length of 1:100,000-scale stream centerline within watershed (km)
STREAMDN	Stream density (stream kilometers divided by watershed area)
Infrastructure variables	
RAWMILES	Cartographic road length in watershed (kilometers): length of 2000 TIGER roads within watershed (km)
RDLENGTH	Road network length in watershed (kilometers): road length i = SUM j (length ij multiplied by vehicle network weight ij) for watershed I and CFCC TIGER code j (km)
RDARINDX	Road area index in watershed (weighted kilometers): road area index i = SUM j (length ij multiplied by surface area weight ij) for watershed i and CFCC TIGER code j
RDTRINDX	Road traffic index in watershed (weighted kilometers): road traffic index i = SUM j (length ij multiplied by vehicular traffic weight ij) for watershed i and CFCC TIGER code j
ROADDEN	Road density in watershed = (RDLENGTH [kilometers] divided by watershed area [km^2])
RDARDEN	Road area index in watershed normalized by watershed area (index sum per square kilometer) = (RDARINDX divided by watershed area [km^2])
RDTRDEN	Road traffic index in watershed normalized by watershed area (index sum per square kilometer) = (RDTRINDX divided by watershed area [km^2])
PSCOUNT	Number of point source dischargers in watershed (USEPA database–NPDES)
DAMCOUNT	Number of dams in watershed
TRICOUNT	Number of Toxics Release Inventory sites in watershed
D_PSCOUNT	Number of point source dischargers in watershed per 100 km^2 (USEPA database–NPDES)
D_DAMCOUNT	Number of dams in watershed per 100 km^2
D_TRICOUNT	Number of Toxics Release Inventory sites in watershed per 100 km^2
NLCD 1992 riparian buffer variables	
BUF_MI2	Total watershed area within 90-meter buffer on each side of all 1:100,000-scale streams in watershed (km^2); stream is an additional 30-meter cell
MRLCBUF_1	Buffer area in MRLC level 1 category: water (km^2)
MRLCBUF_2	Buffer area in MRLC level 1 category: developed (km^2)
MRLCBUF_3	Buffer area in MRLC level 1 category: barren or transitional (km^2)
MRLCBUF_4	Buffer area in MRLC level 1 category: forest, upland (km^2)
MRLCBUF_5	Buffer area in MRLC level 1 category: shrub (km^2)

Table A2. Basin variable abbreviations and definitions.—Continued

[USGS, U.S. Geological Survey; mi^2, square mile; km^2, square kilometer; ha, hectare; km, kilometer; TIGER, Topologically Integrated Geographic Encoding and Referencing; CFCC, census feature class code; USEPA, U.S. Environmental Protection Agency; NPDES, National Pollutant Discharge Elimination System; MRLC, Multi-Resolution Land Characteristic Data; NLCD, National Land Cover Dataset]

Variable code	Description
MRLCBUF_6	Buffer area in MRLC level 1 category: orchard (includes all categories in level 1: nonnatural woody class) (km^2)
MRLCBUF_7	Buffer area in MRLC level 1 category: herbaceous upland/seminatural vegetation (grasslands) (km^2)
MRLCBUF_8	Buffer area in MRLC level 1 category: agricultural/urban grassland (includes all categories in level 1: planted/cultivated class) (km^2)
MRLCBUF_9	Buffer area in MRLC level 1 category: wetlands (km^2)
P_LCBUF_1	Buffer area in MRLC level 1 category: water (percentage of watershed riparian buffer)
P_LCBUF_2	Buffer area in MRLC level 1 category: developed (percentage of watershed riparian buffer)
P_LCBUF_3	Buffer area in MRLC level 1 category: barren or transitional (percentage of watershed riparian buffer)
P_LCBUF_4	Buffer area in MRLC level 1 category: forest, upland (percentage of watershed riparian buffer)
P_LCBUF_5	Buffer area in MRLC level 1 category: shrub (percentage of watershed riparian buffer)
P_LCBUF_7	Buffer area in MRLC level 1 category: herbaceous upland/seminatural vegetation (grasslands) (percentage of watershed riparian buffer)
P_LCBUF_8	Buffer area in MRLC level 1 category: agricultural/urban grassland (includes all categories in level 1: planted/cultivated class) (percentage of watershed riparian buffer)
P_LCBUF_9	Buffer area in MRLC level 1 category: wetlands (percentage of watershed riparian buffer)
NLCD 2001 riparian buffer variables	
NLCD1_B1	Buffer area in aggregated NLCD 2001 level 1 category: water (km^2)
NLCD1_B2	Buffer area in aggregated NLCD 2001 level 1 category: developed (km^2)
NLCD1_B3	Buffer area in aggregated NLCD 2001 level 1 category: barren (includes all level 2 barren and unconsolidated categories) (km^2)
NLCD1_B4	Buffer area in aggregated NLCD 2001 level 1 category: forest (km^2)
NLCD1_B5	Buffer area in aggregated NLCD 2001 level 1 category: shrubland (includes all level 2 shrub and scrub categories) (km^2)
NLCD1_B7	Buffer area in aggregated NLCD 2001 level 1 category: herbaceous upland natural/seminatural vegetation (includes all level 2 categories 70–79) (km^2)
NLCD1_B8	Buffer area in aggregated NLCD 2001 level 1 category: herbaceous planted/cultivated (km^2)
NLCD1_B9	Buffer area in aggregated NLCD 2001 level 1 category: wetlands (km^2)
NLCD_BIS	NLCD 2001 mean percentage impervious surface within buffer area
P_NLCD1_B1	Buffer area in aggregated NLCD 2001 level 1 category: water (percentage of watershed)
P_NLCD1_B2	Buffer area in aggregated NLCD 2001 level 1 category: developed (percentage of watershed)
P_NLCD1_B3	Buffer area in aggregated NLCD 2001 level 1 category: barren (includes all level 2 barren and unconsolidated categories (percentage of watershed)
P_NLCD1_B4	Buffer area in aggregated NLCD 2001 level 1 category: forest (percentage of watershed)

Table A3. FRAGSTATS variables and definitions.

FRAGSTATS variable	Definition
Patch	Discrete areas of homogeneous land-cover types that differ from their surroundings
Patch density	Number of patches per 100 hectares of watershed area
Largest patch index	Percent of basin area composed of the largest patch
Mean patch area	Mean patch area (square meter)
Shape index, mean	Measure of mean patch shape (dimensionless). Values range from 1 to infinity. Low values indicate compact shape (for example, perfectly square patch would have a value of 1, and higher values indicate more irregular shapes [for example, a very long, narrow patch might have a value of 3 or more])
Shape index, coefficient of variation	Variability as a percentage of the mean shape index
Proximity index, mean	Measure of isolation and fragmentation of patches (dimensionless). Large numbers mean many patches of the same type within the specified proximity (in this case, 1,000 meters); low numbers, the reverse.
Proximity, coefficient of variation	Variability as a percentage of the mean proximity index
Euclidean nearest neighbor distance, mean	Mean nearest neighbor distance for patches comprising the land-cover class (meter). Measure of how dispersed the patches are
Euclidean nearest neighbor distance, coefficient of variation	Variability as a percentage of the mean nearest neighbor distance
Proportion of like adjacencies	Percent of patch adjacencies that are the same land-cover class. If patches are surrounded by similar patches, this will be a high number. If patches are mostly surrounded by a different kind of patch, it will be a low number

Table A4. Variables used to calculate Urban Intensity Index used for site selection.

[km^2, square kilometer; MRLC, Multi-Resolution Land Characteristic Data]

Variable code	Description
ROADDEN	Road density in watershed = (RDLENGTH [kilometers] divided by watershed area [km^2])
RDARDEN	Road area index in watershed normalized by watershed area (index sum per square kilometer) = (RDARINDX divided by watershed area [km^2])
RDTRDEN	Road traffic index in watershed normalized by watershed area (index sum per square kilometer) = (RDTRINDX divided by watershed area [km^2])
P_LCBUF_2	Buffer area in MRLC level 1 category: developed (percentage of watershed riparian buffer)
P_MRLC_2	Aggregated MRLC 1992 level 1 category: developed (percentage of watershed)
P_MRLC_2	Aggregated MRLC 1992 level 1 category: forested (percentage of watershed)
P_MRLC_21	Watershed area in MRLC 1992: low-intensity residential (percentage of watershed)
P_MRLC_22	Watershed area in MRLC 1992: high-intensity residential (percentage of watershed)
P_MRLC_23	Watershed area in MRLC 1992: commercial/industrial/transportation (percentage of watershed)
P_MRLC_42	Watershed area in MRLC 1992: evergreen forest (percentage of watershed)
P_MRLC_85	Watershed area in MRLC 1992: urban/recreational grasses (percentage of watershed)
POP2000	2000 population (2000 census block based)
POP90_00	Proportional change in population from 1990–2000 (2000 census block based)
SEI_1_90	Socioeconomic index 1: indicating areas with relatively high income (1990 census block group based)
SEI_2_90	Socioeconomic index 2: indicating areas with relatively high population density and rental households (1990 census block group based)
ANNEX99	Average annual household expenditures, 1999 (dollars) (1990 census block group based)
MEDHHI89	Median household income, 1989 (dollars) (1990 census block group based)
P_OWN90	Percentage of occupied housing units that are owner occupied, 1990 (1990 census block group based)
PHHI_14	Percentage of households with income less than 14,999 (dollars), 1990 (1990 census block group based)

Appendix B. Chemical Variable Names and Descriptions

Table B1. Measured water-chemistry constituents, abbreviations, parameter codes and chemical classification.

[USGS, U.S. Geological Survey; ft^3/s, cubic feet per second; °C, degrees Celsuis; col/100 mL, colonies per 100 milliliters; mg/L, milligram per liter; µS/cm, microsiemens per centimeter; $CaCO_3$, calcium carbonate; mm, millimeter; N, nitrogen; P, phosphorus; µg/L, microgram per liter]

Variable code	Description	USGS parameter code	Chemical class	Use	Parent compound
INSTDIS	Discharge, instantaneous (ft^3/s)	P00061			
WTEMP	Temperature, water (°C)	P00010			
ECOLI	*Escherichia coli*, modified m-TEC membrane filtration method, water (col/100 mL)	P90902			
DISSOX	Dissolved oxygen, water, unfiltered (mg/L)	P00300			
PH	pH, water, unfiltered, field (standard units)	P00400			
SPCOND	Specific conductance, water, unfiltered (µS/cm)	P00095			
ALK	Alkalinity, dissolved, field, incremental titration (mg/L as $CaCO_3$)	P39086			
CARB	Carbonate, dissolved, field, incremental titration (mg/L)	P00452			
BICARB	Bicarbonate, dissolved, field, incremental titration (mg/L)	P00453			
PCTFINES	Suspended sediment, sieve diameter (percentage smaller than 0.063 mm)	P70331			
SUSSED	Suspended sediment concentration (mg/L)	P80154			
CHLOR	Chloride, water, filtered (mg/L)	P00940			
SULFA	Sulfate, water, filtered (mg/L)	P00945			
TKNITR	Ammonia plus organic nitrogen, water, unfiltered (mg/L as N)	P00625			
AMMON	Ammonia, water, filtered (mg/L as N)	P00608			
NITRATE	Nitrate, water, filtered (mg/L as N)	P00618			
NOX	Nitrite plus nitrate, water, filtered (mg/L as N)	P00631			
NITRITE	Nitrite, water, filtered (mg/L as N)	P00613			
ORTHOP	Orthophosphate, water, filtered (mg/L as P)	P00671			
PARTN	Particulate nitrogen, suspended in water (mg/L as N)	P49570			
TOTALP	Phosphorus, water, unfiltered (mg/L as P)	P00665			
TOTALN	Total nitrogen, water, unfiltered (mg/L as N)	P00600			
TPARTC	Carbon (inorganic plus organic), suspended sediment, total (mg/L)	P00694			
PINORGC	Inorganic carbon, suspended sediment, total (mg/L)	P00688			
PORGC	Organic carbon, suspended sediment, total (mg/L)	P00689			
DISORGC	Organic carbon, water, filtered (mg/L)	P00681			
NAPHT	1-naphthol, water, filtered, recoverable (µg/L)	P49295	Phenol	Degradate	Carbaryl, napropamide
DIETH	2,6-diethylaniline, water, filtered, recoverable (µg/L)	P82660	Degradate	Degradate	Aalachlor
PROPA	2-[(2-ethyl-6-methylphenyl)-amino]-1-propanol, water, filtered, recoverable (µg/L)	P61615	Aniline	Degradate	Metolachlor
CHLDI	2-chloro-2’,6’-diethylacetanilide, water, filtered, recoverable (µg/L)	P61618	Acetanilide	Degradate	Alachlor
CHLIS	2-chloro-4-isopropylamino-6-amino-s-triazine, water, filtered, recoverable (µg/L)	P04040	Triazine	Degradate	Atrazine

Table B1. Measured water-chemistry constituents, abbreviations, parameter codes and chemical classification.—Continued

[USGS, U.S. Geological Survey; ft^3/s, cubic feet per second; °C, degrees Celsuis; col/100 mL, colonies per 100 milliliters; mg/L, milligram per liter; µS/cm, microsiemens per centimeter; $CaCO_3$, calcium carbonate; mm, millimeter; N, nitrogen; P, phosphorus; µg/L, microgram per liter]

Variable code	Description	USGS parameter code	Chemical class	Use	Parent compound
ETHYL	2-ethyl-6-methylaniline, water, filtered, recoverable (µg/L)	P61620	Aniline	Degradate	Metolachlor
DICHL	3,4-dichloroaniline, water, filtered, recoverable (µg/L)	P61625	Aniline	Degradate	Diuron/propanil/ linuron/neburon
CHLME	4-chloro-2-methylphenol, water, filtered, recoverable (µg/L)	P61633	Phenol	Degradate	MCPA/MCPB
ACETO	Acetochlor, water, filtered, recoverable (µg/L)	P49260	Acetanilide	Herbicide	
ALACH	Alachlor, water, filtered, recoverable (µg/L)	P46342	Acetanilide	Herbicide	
ATRAZ	Atrazine, water, filtered, recoverable (µg/L)	P39632	Triazine	Herbicide	
AZMEO	Azinphos-methyl oxygen analog, water, filtered, recoverable (µg/L)	P61635	Organophosphate	Degradate	Azinphos-methyl
AZMET	Azinphos-methyl, water, filtered, recoverable (µg/L)	P82686	Organophosphate	Insecticide	
BENFL	Benfluralin, water, filtered, recoverable (µg/L)	P82673	Dinitroaniline	Herbicide	
CARBA	Carbaryl, water, filtered, recoverable (µg/L)	P82680	Carbamate	Insecticide	
CHLOX	Chlorpyrifos oxygen analog, water, filtered, recoverable (µg/L)	P61636	Organophosphate	Degradate	Chlorpyrifos
CHLOP	Chlorpyrifos, water, filtered, recoverable (µg/L)	P38933	Organophosphate	Insecticide	
PERME	*cis*-permethrin, water, filtered, recoverable (µg/L)	P82687	Pyrethroid	Insecticide	
CYFLU	Cyfluthrin, water, filtered, recoverable (µg/L)	P61585	Pyrethroid	Insecticide	
CYPER	Cypermethrin, water, filtered, recoverable (µg/L)	P61586	Ppyrethroid	Insecticide	
DCPA	DCPA, water, filtered, recoverable (µg/L)	P82682	Chlorobenzoic acid ester	Herbicide	
DESFI	Desulfinyl fipronil, water, filtered, recoverable (µg/L)	P62170	Phenyl pyrazole	Degradate	Fipronil
DIAZO	Diazinon oxygen analog, water, filtered, recoverable (µg/L)	P61638	Organophosphate	Degradate	Diazinon
DIAZI	Diazinon, water, filtered, recoverable (µg/L)	P39572	Organophosphate	Insecticide	
DICRO	Dicrotophos, water, filtered, recoverable (µg/L)	P38454	Organophosphate	Insecticide	
DIELD	Dieldrin, water, filtered, recoverable (µg/L)	P39381	Organochlorine	Insecticide/ degradate	Aldrin
DIMET	Dimethoate, water, filtered, recoverable (µg/L)	P82662	Organophosphate	Insecticide	
ETHIM	Ethion monoxon, water, filtered, recoverable (µg/L)	P61644	Organophosphate	Degradate	Ethion
ETHIO	Ethion, water, filtered, recoverable (µg/L)	P82346	Organophosphate	Insecticide	
FENSN	Fenamiphos sulfone, water, filtered, recoverable (µg/L)	P61645	Organophosphate	Degradate	Fenamiphos
FENSX	Fenamiphos sulfoxide, water, filtered, recoverable (µg/L)	P61646	Organophosphate	Degradate	Fenamiphos
FENAM	Fenamiphos, water, filtered, recoverable (µg/L)	P61591	Organophosphate	Nematocide	
DESAM	Desulfinylfipronil amide, water, filtered, recoverable (µg/L)	P62169	Phenyl pyrazole	Degradate	Fipronil
FIPSD	Fipronil sulfide, water, filtered, recoverable (µg/L)	P62167	Phenyl pyrazole	Degradate	Fipronil
FIPSN	Fipronil sulfone, water, filtered, recoverable (µg/L)	P62168	Phenyl pyrazole	Degradate	Fipronil
FIPRO	Fipronil, water, filtered, recoverable (µg/L)	P62166	Phenyl pyrazole	Insecticide	

Table B1. Measured water-chemistry constituents, abbreviations, parameter codes and chemical classification.—Continued

[USGS, U.S. Geological Survey; ft^3/s, cubic feet per second; °C, degrees Celsius; col/100mL, colonies per 100 milliliters; mg/L, milligram per liter; µS/cm, microsiemens per centimeter; $CaCO_3$, calcium carbonate; %, percent; mm, millimeter; N, nitrogen; P, phosphorus; µg/L, microgram per liter]

Variable code	Description	USGS parameter code	Chemical class	Use	Parent compound
FONOX	Fonofos oxygen analog, water, filtered, recoverable (µg/L)	P61649	Organophosphate	Degradate	Fonofos
FONOF	Fonofos, water, filtered, recoverable (µg/L)	P04095	Organophosphate	Insecticide	
HEXAZ	Hexazinone, water, filtered, recoverable (µg/L)	P04025	Triazine	Herbicide	
IPROD	Iprodione, water, filtered, recoverable (µg/L)	P61593	Dicarboximide	Fungicide	
ISOFE	Isofenphos, water, filtered, recoverable (µg/L)	P61594	Organophosphate	Insecticide	
MALAO	Malaoxon, water, filtered, recoverable (µg/L)	P61652	Organophosphate	Degradate	Malathion
MALAT	Malathion, water, filtered, recoverable (µg/L)	P39532	Organophosphate	Insecticide	
METAL	Metalaxyl, water, filtered, recoverable (µg/L)	P61596	Amino acid derivative	Fungicide	
METHI	Methidathion, water, filtered, recoverable (µg/L)	P61598	Organophosphate	Insecticide	
METPX	Methyl paraoxon, water, filtered, recoverable (µg/L)	P61664	Organophosphate	Degradate	Methyl parathion
METPT	Methyl parathion, water, filtered, recoverable (µg/L)	P82667	Organophosphate	Insecticide	
METOL	Metolachlor, water, filtered, recoverable (µg/L)	P39415	Acetanilide	Herbicide	
METRI	Metribuzin, water, filtered, recoverable (µg/L)	P82630	Triazine	Herbicide	
MYCLO	Myclobutanil, water, filtered, recoverable (µg/L)	P61599	Triazole	Fungicide	
PENDI	Pendimethalin, water, filtered, recoverable (µg/L)	P82683	Dinitroaniline	Herbicide	
PHOOX	Phorate oxygen analog, water, filtered, recoverable (µg/L)	P61666	Organophosphate	Degradate	Phorate
PHORA	Phorate, water, filtered, recoverable (µg/L)	P82664	Organophosphate	Insecticide	
PHOSO	Phosmet oxygen analog, water, filtered, recoverable (µg/L)	P61668	Organophosphate	Degradate	Phosmet
PHOSM	Phosmet, water, filtered, recoverable (µg/L)	P61601	Organophosphate	Insecticide	
PROME	Prometon, water, filtered, recoverable (µg/L)	P04037	Triazine	Herbicide	
PROMY	Prometryn, water, filtered, recoverable (µg/L)	P04036	Triazine	Herbicide	
PRONA	Pronamide, water, filtered, recoverable (µg/L)	P82676	Amide	Herbicide	
SIMAZ	Simazine, water, filtered, recoverable (µg/L)	P04035	Triazine	Herbicide	
TEBUT	Tebuthiuron, water, filtered, recoverable (µg/L)	P82670	Urea	Herbicide	
TERBO	Terbufos oxygen analog sulfone, water, filtered, recoverable (µg/L)	P61674	Organophosphate	Degradate	Terbufos
TERBF	Terbufos, water, filtered, recoverable (µg/L)	P82675	Organophosphate	Insecticide	
TERBU	Terbuthylazine, water, filtered, recoverable (µg/L)	P04022	Triazine	Herbicide	
TRIFL	Trifluralin, water, filtered, recoverable (µg/L)	P82661	Dinitroaniline	Herbicide	
DICHL	Dichlorvos, water, filtered, recoverable (µg/L)	P38775	Organophosphate	Insecticide, fumigant, degradate	Naled
TPCONC	Total pesticide concentration (µg/L)				
THCONC	Total herbicide concentration (µg/L)				
TICONC	Total insecticide concentration (µg/L)				
NUMP	Number of pesticides detected				
NUMH	Number of herbicides detected				
NUMI	Number of insecticides detected				

Table B2. Semipermeable membrane device chemical extract abbreviations, descriptions, and measurement techniques.

[na, not applicable; EI, electron ionization; ECNI, electron-capture negative ionization]

Variable code	Description	Ionization technique
SPMDTEQ	SPMD toxicity, CYP1A1 production (toxic equivalents)	na
SPMDUV	SPMD toxicity, ultraviolet fluourescence (micrograms pyrene)	na
SPMDEC50	SPMD toxicity, Microtox assay (EC50)	na
S_14DICH	1,4-dichlorobenzene	EI
S_1MENAP	1-methylnapthalene	EI
S_DMENAP	2,6-dimethylnapthalene	EI
S_2MBENZ	2-methyl benzothiophene	EI
S_2MENAP	2-methylnapthalene	EI
S_34DICH	3,4-dichlorophenyl isocyanate	EI
S_CUMYL	4-cumylphenol	EI
S_OCTYL	4-octylphenol	EI
S_TOCTYL	4-*tert*-octylphenol	EI
S_MHBENZ	5-methyl-1H-benzotriazone	EI
S_ACET	Acetophenone	EI
S_AHTN	Acetyl hexamethyl tetrahydronaphthalene (AHTN)	EI
S_ALDRIN	Aldrin	ECNI
S_AHCH	Alpha-HCH	ECNI
S_ANTHRC	Anthracene	EI
S_ANTHRQ	Anthraquinone	EI
S_BDE100	2,2’,4,4’,6-pentabromodiphenyl ether (BDE 100)	ECNI
S_BDE153	2,2’,4,4’,5,5’-hexabromodiphenyl ether (BDE 153)	ECNI
S_BDE154	2,2’,4,4’,5,6’-hexabromodiphenyl ether (BDE 154)	ECNI
S_BDE47	2,2´,4,4´-tetrabromodiphenyl ether (BDE 47)	ECNI
S_BDE99	2,2’,4,4’,5-pentabromodipenyl ether (BDE 99)	ECNI
S_BENFL	Benfluralin	ECNI
S_BAPYR	Benzo-(a)-pyrene	EI
S_BENZO	Benzophenone	EI
S_BCOPR	Beta-coprostanol	EI
S_BHCH	Beta-HCH	ECNI
S_BSITO	Beta-sitosterol	EI
S_BHA	3-*tert*-butyl-4-hydroxy anisole (BHA)	EI
S_BISPH	Bisphenol A	EI
S_BROMA	Bromacil	EI
S_BROMO	Bromoform	EI
S_CAFF	Caffeine	EI
S_CAMPH	Camphor	EI
S_CARBA	Carbaryl	EI
S_CARBAZ	Carbazole	EI
S_CHLOP	Chlorpyrifos	ECNI
S_CHOL	Cholesterol	EI
S_CCHLOR	*cis*-chlordane	ECNI
S_CNONAC	*cis*-nonachlor	ECNI
S_COTIN	Cotinine	EI
S_CUMEN	Cumene	EI
S_DCPA	Dacthal (DCPA)	ECNI
S_DHCH	Delta-HCH	ECNI

Table B2. Semipermeable membrane device chemical extract abbreviations, descriptions, and measurement techniques.—Continued

[na, not applicable; EI, electron ionization; ECNI, electron-capture negative ionization]

Variable code	Description	Ionization technique
S_DIAZI	Diazinon	EI
S_DIELD	Dieldrin	ECNI
S_DPHTA	Diethyl phtalate	EI
S_DHPHTA	Diethylhexyl phthalate	EI
S_DEET	N,N-diethyl-meta-toluamide (DEET)	EI
S_DPYRAZ	Diphenyl pyrazole	EI
S_LIMO	d-Limonene	EI
S_ENDOI	Endosulfan I	ECNI
S_ENDOII	Endosulfan II	ECNI
S_ENDOSF	Endosulfan sulfate	ECNI
S_ENDRN	Endrin	ECNI
S_ENDRNA	Endrin aldehyde	ECNI
S_ENDRNK	Endrin ketone	ECNI
S_ETHPH	Ethanol, 2-butoxy-, phosphosphate	EI
S_ECITR	Ethyl citrate	EI
S_FIPRO	Fipronil	ECNI
S_FLUOR	Fluoranthene	EI
S_GHCH	Gamma-HCH	ECNI
S_HCB	Hexachlorobenzene (HCB)	ECNI
S_HEPTEP	Heptachlor epoxide	ECNI
S_HHCB	Hexahydrohexamethylcyclopentabenzopyran (HHCB)	EI
S_INDOLE	Indole	EI
S_ISOBO	Isoborneol	EI
S_ISOPHO	Isophorone	EI
S_ISOQU	Isoquinoline	EI
S_MENTH	Menthol	EI
S_METAL	Metalaxyl	EI
S_MSALI	Methyl saliciylate	EI
S_METOL	Metolachlor	EI
S_MIREX	Mirex	ECNI
S_NAPTH	Napthalene	EI
S_NPEO1	Nonylphenol monoethoxylate (NPEO1)	EI
S_NPEO2	Nonylphenol diethoxylate (NPEO2)	EI
S_OPDDD	o,p’-DDD	ECNI
S_OPDDE	o,p’-DDE	ECNI
S_OPDDT	o,p’-DDT	ECNI
S_OCTSTY	Octachlorostyrene	ECNI
S_OPEO1	Octylphenol monoethoxylate (OPEO1)	EI
S_OPEO2	Octylphenol diethoxylate (OPEO2)	EI
S_OXYCHL	Oxychlordane	ECNI
S_PPDDD	p,p’-DDD	ECNI
S_PPDDE	p,p’-DDE	ECNI
S_PPDDT	p,p’-DDT	ECNI
S_PCRES	p-Cresol	EI
S_PNONYL	p-Nonylphenol, total	EI
S_PCA	Pentachloroanisole (PCA)	ECNI

Table B2. Semipermeable membrane device chemical extract abbreviations, descriptions, and measurement techniques.—Continued

[na, not applicable; EI, electron ionization; ECNI, electron-capture negative ionization]

Variable code	Description	Ionization technique
S_PCB70	2,3’4’,5-tetrachlorobiphenyl (PCB 70)	ECNI
S_PCB101	2,2’,4,5,5’-pentachlorobiphenyl (PCB 101)	ECNI
S_PCB110	2,3,3’,4’,6-pentachlorobiphenyl (PCB 110)	ECNI
S_PCB118	2,3’,4,4’,5-pentachlorobiphenyl (PCB 118)	ECNI
S_PCB138	2,2’,3,4,4’,4’,5-hexachlorobiphenyl (PCB 138)	ECNI
S_PCB146	2,2’,3,4’,5,5’-hexachlorobiphenyl (PCB 146)	ECNI
S_PCB149	2,2’,3,4’,5’,6-hexachlorobiphenyl (PCB 149)	ECNI
S_PCB151	2,2’,3,5,5’,6-hexachlorobiphenyl (PCB 151)	ECNI
S_PCB170	2,2’,3,3’,4,4’,5-heptachlorobiphenyl (PCB 170)	ECNI
S_PCB174	2,2’,3,3’,4,5,6’-heptachlororbiphenyl (PCB 174)	ECNI
S_PCB177	2,2’,3,3’,4,5’,6’-heptachlorobiphenyl (PCB 177)	ECNI
S_PCB180	2,2’,3,4,4’,5,5’-heptachlorobiphenyl (PCB 180)	ECNI
S_PCB183	2,2’,3,4,4’,5’,6- heptachlorobiphenyl (PCB 183)	ECNI
S_PCB187	2,2’,3,4’,5,5’,6-heptachlorobiphenyl (PCB 187)	ECNI
S_PCB194	2,2’,3,3’,4,4’,5,5’-octachlorobiphenyl (PCB 194)	ECNI
S_PCB206	2,2’,3,3’,4,4’,5,5’,6-nonachlorobiphenyl (PCB 206)	ECNI
S_PHENA	Phenanthrene	EI
S_PROME	Prometon	EI
S_PHENO	Phenol	EI
S_PYRE	Pyrene	EI
S_SKAT	3-methyl-1(H)-indole (skatole)	EI
S_STIG	Stigmastanol	EI
S_TOXAPH	Toxaphene	ECNI
S_TCHLOR	*Trans*-chlordane	ECNI
S_TNONAC	*Trans*-nonachlor	ECNI
S_TCPHOS	Tris (2-chloroethyl) phosphate	EI
S_TDPHOS	Tri (dichloroisopropyl) phosphate	EI
S_TBPHOS	Tributylphosphate	EI
S_TRICL	Triclosan	EI
S_TRIFL	Trifluralin	ECNI
S_TPPHOS	Triphenyl phosphate	EI

Appendix C. Physical Variable Names and Descriptions

Table C1. Stream reach habitat variables and definitions.

[m, meter; m/km^2, meter per square kilometer; m^2, square meter; m^2/km^2, square meter per square kilometer; m^3/s, cubic meter per second; mm, millimeter; >, greater than; m/s, meter per second; m^3, cubic meter]

Variable code	Description
BankErosN	Number of observations of whether bank erosion is occurring
BankErosCnt	Number of occurrences of bank erosion
BankErosPct	Occurrence of bank erosion (percent)
BankVegCovMin	Minimum bank vegetative cover (percent)
BankVegCovMax	Maximum bank vegetative cover (percent)
BankVegCovAvg	Mean bank vegetative cover (percent)
BankSub	Bank substrate type
BankAngle	Bank angle (degrees)
BankHt	Bank height (m)
BFWidthMin	Minimum bankfull width (m)
BFWidthMax	Maximum bankfull width (m)
BFWidthAvg	Mean bankfull channel width (m)
BFWidthDA	Mean bankfull channel width divided by drainage area (m/km^2) (excluding pools)
BFDepthMin	Minimum bankfull depth (m)
BFDepthMax	Maximum bankfull depth (m)
BFDepthAvg	Mean bankfull depth (m)
BFDepthDA	Mean bankfull depth divided by drainage area (m/km^2) (excluding pools)
BFWidthDepthMin	Minimum bankfull width-depth ratio
BFWidthDepthMax	Maximum bankfull width-depth ratio
BFWidthDepthAvg	Mean bankfull-channel width-depth ratio for reach
BFArea	Mean bankfull channel cross-sectional area (m^2)
BFAreaDA	Mean bankfull channel cross-sectional area divided by drainage area (m^2/km^2) (exclude pools)
DischM3Sec	Instantaneous discharge (m^3/s)
EmbedPctMin	Minimum embeddedness (percent)
EmbedPctMax	Minimum embeddedness (percent)
EmbedPctAvg	Mean embeddedness (percent)
FlowStbl	Flow stability = depth of water at low flow divided by bankfull depth (dimensionless)
FlowStblMin	Minimum flow stability ratio
FlowStblMax	Maximum flow stability ratio
FlowStblAvg	Mean flow stability ratio
CHStbl	Channel stability = ratio of mean bankfull to wetted cross-sectional areas
Froude	Froude number = mean flow velocity divided by [(acceleration due to gravity multiplied by mean depth of water) exponent 0.5]
GCULengthSum	Sum of the length of all geomorphic channel units in reach (m)
GCUTypePoolPct	Relative proportion of the total length of all geomorphic channel units that are comprised of pools (percent)
GCUTypeRiffPct	Relative proportion of the total length of all geomorphic channel units that are comprised of riffles (percent)
GCUTypeRunPct	Relative proportion of the total length of all geomorphic channel units that are comprised of runs (percent)

Table C1. Stream reach habitat variables and definitions.—Continued

[m, meter; m/km^2, meter per square kilometer; m^2, square meter; m^2/km^2, square meter per square kilometer; m^3/s, cubic meter per second; mm, millimeter; >, greater than; m/s, meter per second; m^3, cubic meter]

Variable code	Description
GCUTypePoolRiff	Ratio of the area of pool geomorphic units to the area of riffle geomorphic channel units
WaterSurfGrad	Reach water-surface gradient (dimensionless)
HydRadAvg	Mean wetted channel hydraulic radius (m)
HabCvrPtAnyPct	Percentage occurrence of transect points having at least one habitat cover feature
HabCvrPtAMPct	Percentage occurrence of aquatic macrophyte habitat cover feature for reach
HabCvrPtBOPct	Percentage occurrence of boulder habitat cover feature for reach
HabCvrPtMSPct	Percentage occurrence of man-made structure habitat cover feature for reach
HabCvrPtOVPct	Percentage occurrence of points having overhanging vegetation habitat cover feature for reach
HabCvrPtUBPct	Percentage occurrence of points having undercut bank habitat cover feature for reach
HabCvrPtWDPct	Percentage occurrence of woody debris instream habitat cover feature for reach
ManRoughAvg	Mean Manning's roughness for reach = (mean hydraulic radius exponent 2/3) multiplied by (water-surface gradient exponent 0.5) divided by mean reach velocity
RchLength	Total length of sampling reach (m)
CanClosrBnkMin	Minimum canopy closure, bank measurements (left bank shade, right bank shade) (percent)
CanClosrBnkMax	Maximum canopy closure, bank measurements (left bank shade, right bank shade) (percent)
CanClosrBnkAvg	Mean canopy closure, bank readings (left bank shade, right bank shade) (percent)
OCanAngleMin	Minimum open-canopy angle (degrees)
OCanAngleMax	Maximum open-canopy angle (degrees)
OCanAngleAvg	Mean open-canopy angle (degrees)
OCanAngleCv	Coefficient of variation of open-canopy angle
RipLU	Riparian land use = disturbed land cover in 30-meter buffer (percentage, out of 22 transect endpoints)
SiltCovPct	Percentage occurrence of transect points where silt layer was observed on streambed
DomSub1Pct	Percentage occurrence of transect points where the dominant substrate consists of smooth bedrock/concrete/hardpan
DomSub2Pct	Percentage occurrence of transect points where the dominant substrate consists of silt/clay/marl/muck/organic detritus
DomSub3Pct	Percentage occurrence of transect points where the dominant substrate consists of sand (>0.062–2 mm)
DomSub4Pct	Percentage occurrence of transect points where the dominant substrate consists of fine/medium gravel (>2–16 mm)
DomSub5Pct	Percentage occurrence of transect points where the dominant substrate consists of coarse gravel (>16–32 mm)
DomSub6Pct	Percentage occurrence of transect points where the dominant substrate consists of very coarse gravel (>32–64 mm)
DomSub7Pct	Percentage occurrence of transect points where the dominant substrate consists of small cobble (>64–128 mm) (percent occurrence)
DomSub8Pct	Percentage occurrence of transect points where the dominant substrate consists of large cobble (>128–256 mm) (percent occurrence)
DomSub9Pct	Percentage occurrence of transect points where the dominant substrate consists of small boulder (>256–512 mm)
DomSub10Pct	Percentage occurrence of transect points where the dominant substrate consists of large boulder, irregular bedrock, irregular hardpan, irregular artificial surface (>512 mm)

Table C1. Stream reach habitat variables and definitions.—Continued

[m, meter; m/km^2, meter per square kilometer; m^2, square meter; m^2/km^2, square meter per square kilometer; m^3/s, cubic meter per second; mm, millimeter; >, greater than; m/s, meter per second; m^3, cubic meter]

Variable code	Description
VelocMin	Minimum velocity (m/s)
VelocMax	Maximum streamflow velocity (m/s)
VelocAvg	Mean flow velocity (m/s)
VelocCv	Coefficient of variation of flow velocity
WidthWetMin	Minimum wetted channel width (m)
WidthWetMax	Maximum wetted channel width (m)
WidthWetAvg	Mean wetted channel width (m)
DepthMin	Minimum wetted channel depth (m)
DepthMax	Maximum wetted channel depth (m)
DepthAvg	Mean wetted channel depth (m)
DepthCv	Coefficient of variation of wetted channel depth
WidthDepthMin	Minimum wetted channel width-depth ratio
WidthDepthMax	Maximum wetted channel width-depth ratio
WidthDepthAvg	Mean wetted-channel width-depth ratio of reach
WetPerimMin	Minimum wetted channel perimeter (m)
WetPerimMax	Maximum wetted channel perimeter (m)
WetPerimAvg	Mean perimeter of wetted channel (m)
WetXAreaMin	Minimum wetted cross-sectional area of channel (m^2)
WetXAreaMax	Maximum wetted cross-sectional area of channel (m^2)
WetXAreaAvg	Mean cross-sectional area of wetted channel (m^2)
WetShape	Wetted channel shape = (wetted channel width divided by mean depth of water) exponent (mean depth of water divided by maximum depth of water) (dimensionless)
WetShapeMin	Minimum wetted channel shape (dimensionless)
WetShapeMax	Maximum wetted channel shape (dimensionless)
WetShapeAvg	Mean wetted channel shape (dimensionless)
RchArea	Wetted channel surface area of reach = reach length multiplied by mean wetted channel width (m^2)
RchVol	Reach wetted channel volume = reach length multiplied by mean channel width multiplied by mean depth (m^3)

Table C2. Hydrologic metric abbreviations and definitions.

[POR, period of record; m^2, square meter; <, less than; >, greater than; mi^2/d, square meter per day; ≥, greater than or equal to; hr, hour]

Variable code	Description
a_cv	Coefficient of variation of cross-sectional area during all hours in POR
a_skew	Skew of cross-sectional area during all hours in POR
a_cv_log	Coefficient of variation of hourly cross-sectional-area values, where cross-sectional-area values are equal to log of 1 plus cross-sectional area
a_coeff_disp	(75th-percentile cross-sectional area minus 25th-percentile cross-sectional area), divided by median cross-sectional area (dimensionless)
a_mean	Mean cross-sectional-area value during POR (m^2)
a_pct_50	Median (50th-percentile) cross-sectional-area value during POR (m^2)
a_pct_99n	99th-percentile cross-sectional-area value during POR, divided by median cross-sectional-area value during POR (dimensionless)
a_pct_95n	95th-percentile cross-sectional-area value during POR, divided by median cross-sectional-area value during POR (dimensionless)
a_pct_90n	90th-percentile cross-sectional-area value during POR, divided by median cross-sectional-area value during POR (dimensionless)
a_pct_75n	75th-percentile cross-sectional-area value during POR, divided by median cross-sectional-area value during POR (dimensionless)
a_pct_25n	25th-percentile cross-sectional-area value during POR, divided by median cross-sectional-area value during POR (dimensionless)
a_pct_10n	10th-percentile cross-sectional-area value during POR, divided by median cross-sectional-area value during POR (dimensionless)
a_pct_5n	5th-percentile cross-sectional-area value during POR, divided by median cross-sectional-area value during POR (dimensionless)
a_pct_99a	99th-percentile cross-sectional-area value during POR (m^2)
a_pct_95a	95th-percentile cross-sectional-area value during POR (m^2)
a_pct_90a	90th-percentile cross-sectional-area value during POR (m^2)
a_pct_75a	75th-percentile cross-sectional-area value during POR (m^2)
a_pct_25a	25th-percentile cross-sectional-area value during POR (m^2)
a_pct_10a	10th-percentile cross-sectional-area value during POR (m^2)
a_pct_5a	5th-percentile cross-sectional-area value during POR (m^2)
a_sum_5	Number of hours during POR with cross-sectional area < 5th-percentile cross-sectional-area value
a_sum_10	Number of hours during POR with cross-sectional area < 10th-percentile cross-sectional-area value
a_sum_25	Number of hours during POR with cross-sectional area < 25th-percentile cross-sectional-area value
a_sum_75	Number of hours during POR with cross-sectional area > 75th-percentile cross-sectional-area value
a_sum_90	Number of hours during POR with cross-sectional area > 90th-percentile cross-sectional-area value
a_sum_95	Number of hours during POR with cross-sectional area > 95th-percentile cross-sectional-area value
a_day_pctchange	Sum of the absolute value of the relative change in daily mean cross-sectional area, divided by the daily mean cross-sectional area (dimensionless)
a_rb_flash	Version of Richards-Baker flashiness index (Baker and others, 2004), calculated as the sum of the absolute value of the relative change in daily mean cross-sectional area, divided by the sum of the daily mean cross-sectional area for the POR (dimensionless)
a_cummulative_change	Sum of the absolute value of the total rise and fall in cross-sectional area during POR (m^2)
a_cumm_median	Sum of the absolute value of the total rise and fall in cross-sectional area during POR, divided by median cross-sectional area during POR (dimensionless)

Table C2. Hydrologic metric abbreviations and definitions.—Continued

[POR, period of record; m^2, square meter; <, less than; >, greater than; mi^2/d, square meter per day; ≥, greater than or equal to; hr, hour]

Variable code	Description
a_cumm_day	Sum of the absolute value of the total rise and fall in cross-sectional area during POR, divided by the number of days in record (m^2/d)
a_periodr1	Frequency of rising cross-sectional-area events, where hourly cross-sectional-area change is ≥1 multiplied by the median rise during POR (number of hourly time periods)
a_periodr3	Frequency of rising cross-sectional-area events, where hourly cross-sectional-area change is ≥3 multiplied by the median rise during POR (number of hourly time periods)
a_periodr5	Frequency of rising cross-sectional-area events, where hourly cross-sectional-area change is ≥5 times the median rise during POR (number of hourly time periods)
a_periodr7	Frequency of rising cross-sectional-area events, where hourly cross-sectional-area change is ≥7 multiplied by the median rise during POR (number of hourly time periods)
a_periodr9	Frequency of rising cross-sectional-area events, where hourly cross-sectional-area change is ≥9 multiplied by the median rise during POR (number of hourly time periods)
a_periodf1	Frequency of falling cross-sectional-area events, where hourly cross-sectional-area change is ≥1 multiplied by the median fall during POR (number of hourly time periods)
a_periodf3	Frequency of falling cross-sectional-area events, where hourly cross-sectional-area change is ≥3 multiplied by the median fall during POR (number of hourly time periods)
a_periodf5	Frequency of falling cross-sectional-area events, where hourly cross-sectional-area change is ≥5 multiplied by the median fall during POR (number of hourly time periods)
a_periodf7	Frequency of falling cross-sectional-area events, where hourly cross-sectional-area change is ≥7 multiplied by the median fall during POR (number of hourly time periods)
a_periodf9	Frequency of falling cross-sectional-area events, where hourly cross-sectional-area change is ≥9 multiplied by the median fall during POR (number of hourly time periods)
a_maxrise	Maximum duration of consecutive periods of rising cross-sectional area during POR (hr)
a_medianrise	Median duration of consecutive periods of rising cross-sectional area during POR (hr)
a_maxfall	Maximum duration of consecutive periods of falling cross-sectional area during POR (hr)
a_medianfall	Median duration of consecutive periods of falling cross-sectional area during POR (hr)
a_MXH_75	Maximum duration of high cross-sectional-area pulses during POR (hr); high cross-sectional area >75th percentile
a_MXH_90	Maximum duration of high cross-sectional-area pulses during POR (hr); high cross-sectional area >90th percentile
a_MXH_95	Maximum duration of high cross-sectional-area pulses during POR (hr); high cross-sectional area >95th percentile
a_MDH_75	Median duration of high cross-sectional-area pulses during POR (hr); high cross-sectional area >75th percentile
a_MDH_90	Median duration of high cross-sectional-area pulses during POR (hr); high cross-sectional area >90th percentile
a_MDH_95	Median duration of high cross-sectional-area pulses during POR (hr); high cross-sectional area >95th percentile
a_MXL_25	Maximum duration of low cross-sectional-area pulses during POR (hr); low cross-sectional area <25th percentile
a_MXL_10	Maximum duration of low cross-sectional-area pulses during POR (hr); low cross-sectional area <10th percentile
a_MXL_5	Maximum duration of low cross-sectional-area pulses during POR (hr); low cross-sectional area <5th percentile
a_MDL_25	Median duration of low cross-sectional-area pulses during POR (hr); low cross-sectional area <25th percentile
a_MDL_10	Median duration of low cross-sectional-area pulses during POR (hr); low cross-sectional area <10th percentile
a_MDL_5	Median duration of low cross-sectional-area pulses during POR (hr); low cross-sectional area <5th percentile

Appendix D. Biological Variable Names and Descriptions

Table D1. Algal metric names, abbreviations and definitions.

[bolded variable codes were listed as significant algal indicators from tables 6 and 7; <, less than; >, greater than; mg/L, milligram per liter; ppt, parts per thousand; N, nitrogen; ca., calculated]

	Metric code	Description
		Taxonomic metrics
Richness		
	RICH	Total taxa richness
	DIATOMr	Number of diatom taxa
	NONDIAr	Number of nondiatom taxa
	GREENr	Number of green algal taxa
	BLUGRNr	Number of blue-green algal taxa
	REDr	Number of red algal taxa
	YELLOWr	Number of yellow-green algal taxa
	CRYPTOr	Number of Cryptophyte algal taxa
	EUGLENr	Number of Euglenoid algal taxa
	DINOr	Number of Dinoflagellate algal taxa
	UNKNOWr	Number of alga taxa with unknown taxonomy
Percentage Richness		
	DIATOMrp	Percentage of total taxa richness composed of diatom taxa
	NONDIArp	Percentage of total taxa richness composed of nondiatom taxa
	GREENrp	Percentage of total taxa richness composed of green algal taxa
	BLUGRNrp	Percentage of total taxa richness composed of blue-green algal taxa
	REDrp	Percentage of total taxa richness composed of red algal taxa
	YELLOWrp	Percentage of total taxa richness composed of yellow-green algal taxa
	CRYPTOrp	Percentage of total taxa richness composed of Cryptophyte algal taxa
	EUGLENrp	Percentage of total taxa richness composed of Euglenoid algal taxa
	DINOrp	Percentage of total taxa richness composed of Dinoflagellate algal taxa
	UNKNOWrp	Percentage of total taxa richness composed of alga taxa with unknown taxonomy
Abundance		
	ABUND	Total abundance of algae
	DIATOM	Abundance of diatom taxa
	NONDIA	Abundance of nondiatom taxa
	GREEN	Abundance of green algal taxa
	BLUGRN	Abundance of blue-green algal taxa
	RED	Abundance of red algal taxa
	YELLOW	Abundance of yellow-green algal taxa
	CRYPTO	Abundance of Cryptophyte algal taxa
	EUGLEN	Abundance of Euglenoid algal taxa
	DINO	Abundance of Dinoflagellate algal taxa
	UNKNOW	Abundance of alga taxa with unknown taxonomy
Percentage Abundance		
	DIATOMp	Percentage of total abundance composed of diatom taxa
	NONDIAp	Percentage of total abundance composed of nondiatom taxa
	GREENp	Percentage of total abundance composed of green algal taxa
	BLUGRNp	Percentage of total abundance composed of blue-green algal taxa
	REDp	Percentage of total abundance composed of red algal taxa
	YELLOWp	Percentage of total abundance composed of yellow-green algal taxa
	CRYPTOp	Percentage of total abundance composed of Cryptophyte algal taxa
	EUGLENp	Percentage of total abundance composed of Euglenoid algal taxa
	DINOp	Percentage of total abundance composed of Dinoflagellate algal taxa
	UNKNOWp	Percentage of total abundance composed of alga taxa with unknown taxonomy

Table D1. Algal metric names, abbreviations and definitions.—Continued

[bolded variable codes were listed as significant algal indicators from tables 6 and 7; <, less than; >, greater than; mg/L, milligram per liter; ppt, parts per thousand; N, nitrogen; ca., calculated]

	Metric code	Description
		Dominance metrics
	Dom1	Percentage of total abundance represented by the most abundant taxon
	Dom1R	Number of taxa in Dom1 class
	Dom2	Percentage of total abundance represented by the two most abundant taxa
	Dom2R	Number of taxa in Dom2 class
	Dom3	Percentage of total abundance represented by the three most abundant taxa
	Dom3R	Number of taxa in Dom3 class
	Dom4	Percentage of total abundance represented by the four most abundant taxa
	Dom4R	Number of taxa in Dom4 class
	Dom5	Percentage of total abundance represented by the five most abundant taxa
	Dom5R	Number of taxa in Dom5 class
		Tolerance metrics
Richness		
	BENTHr	Number of benthic algal taxa
	SESTONr	Number of sestonic algal taxa
	BEN_SES_UNKN	Number of algal taxa not classified as benthic or sestonic
	BEN_SESr_CLASS	Percentage of algal taxa classified as benthic or sestonic
	MOTILEr	Number of motile algal taxa
	NONMOTr	Number of nonmotile algal taxa
	MOTILITY_UNKN	Number of algal taxa not classified as motile or nonmotile
	MOTILITYr_CLASS	Percentage of algal taxa classified as motile or nonmotile
	NFIXr	Number of nitrogen-fixing algal taxa
	NONFIXr	Number of nonnitrogen fixing algal taxa
	NFIX_UNKN	Number of algal taxa not classified as nitrogen-fixing or nonnitrogen fixing
	NFIXr_CLASS	Percentage of algal taxa classified as nitrogen-fixing or nonnitrogen fixing
	pH1r	Number of algal taxa in pH category 1: acidobiontic (optima < 5.5)
	pH2r	Number of algal taxa in pH category 2: acidophilous (optima generally < 7)
	pH3r	Number of algal taxa in pH category 3: circumneutral (optima around 7)
	pH4r	Number of algal taxa in pH category 4: alkaliphilous (optima generally > 7)
	pH5r	Number of algal taxa in pH category 5: alkalibiontic (optima always > 7)
	pH6r	Number of algal taxa in pH category 6: indifferent (no optimum)
	pH_UNKN	Number of algal taxa not classified as to pH preference
	pHr_CLASS	Percentage of algal taxa classified as to pH preference
	SAL1r	Number of algal taxa in salinity category 1: fresh (< 100 mg/L, < 0.2 ppt)
	SAL2r	Number of algal taxa in salinity category 2: fresh brackish (< 500 mg/L, < 0.9 ppt)
	SAL3r	Number of algal taxa in salinity category 3: brackish fresh (500–1,000 mg/L, 0.9–1.8 ppt)
	SAL4r	Number of algal taxa in salinity category 4: brackish (1,000–5,000 mg/L, 1.8–9 ppt)
	SAL_UNKN	Number of algal taxa not classified as to salinity preference
	SALr_CLASS	Percentage of algal taxa classified as to salinity preference
	ORGN1r	Number of algal taxa in nitrogen uptake category 1: N autotroph (low organic N)
	ORGN2r	Number of algal taxa in nitrogen uptake category 2: N autotrophic (high organic N)
	ORGN3r	Number of algal taxa in nitrogen uptake category 3: N heterotroph (high organic N, faculatative)
	ORGN4r	Number of algal taxa in nitrogen uptake category 4: N heterotroph (high organic N, obligate)
	ORGN_UNKN	Number of algal taxa not classified as to nitrogen uptake category
	ORGNr_CLASS	Percentage of algal taxa classified as to nitrogen uptake category

Table D1. Algal metric names, abbreviations and definitions.—Continued

[>, greater than; <, less than; bolded variable codes were listed as significant algal indicators from tables 6 and 7; mg/L, milligram per liter; ppt, parts per thousand; N, nitrogen; ca., calculated]

Metric code	Description
Tolerance metrics—Continued	
Richness—continued	
OXTOL1r	Number of algal taxa in oxygen requirements category 1: high oxygen requirements (ca. 100 percent saturation)
OXTOL3r	Number of algal taxa in oxygen requirements category 3: moderate oxygen requirements (> 50 percent saturation)
OXTOL4r	Number of algal taxa in oxygen requirements category 4: low oxygen requirements (> 30 percent saturation)
OXTOL5r	Number of algal taxa in oxygen requirements category 5: very low oxygen requirements (ca. 10 percent saturation)
OXTOL_UNKN	Number of algal taxa not classified as to oxygen requirement category
OXTOLr_CLASS	Percentage of algal taxa classified as to oxygen requirement category
SAPRO1r	Number of algal taxa in saprobic category 1: oligosaprobic
SAPRO2r	Number of algal taxa in saprobic category 2: B mesosaprobic
SAPRO3r	Number of algal taxa in saprobic category 3: a mesosaprobic
SAPRO4r	Number of algal taxa in saprobic category 4: a meso/polysaprobic
SAPRO5r	Number of algal taxa in saprobic category 5: polysaprobic
SAPRO_UNKN	Number of algal taxa not classified as to saprobic category
SAPPROr_CLASS	Percentage of algal taxa classified as to saprobic category
MOIST1r	Number of algal taxa in moisture category 1: in streams
MOIST2r	Number of algal taxa in moisture category 2: in streams, sometimes on wet or moist places
MOIST3r	Number of algal taxa in moisture category 3: in streams, often on wet or moist places
MOIST4r	Number of algal taxa in moisture category 4: on wet, moist, temporarily dry places
MOIST5r	Number of algal taxa in moisture category 5: exclusively outside water bodies
MOIST_UNKN	Number of algal taxa not classified as to moisture category
MOISTr_CLASS	Percentage of algal taxa classified as to moisture category
Bahls1r	Number of algal taxa in Bahls (1993) pollution class 1, most tolerant taxa
Bahls2r	Number of algal taxa in Bahls (1993) pollution class 2, less tolerant taxa
Bahls3r	Number of algal taxa in Bahls (1993) pollution class 3, most sensitive taxa
Bahls_UNKN	Number of algal taxa not classified as to Bahls pollution class
Bahlsr_CLASS	Percentage of algal taxa classified as to Bahls pollution class
PTOL1r	Number of algal taxa in pollution tolerance category 1: very tolerant (polysaprobic)
PTOL2ar	Number of algal taxa in pollution tolerance category 2a: tolerant (a-meso/polysaprobic)
PTOL2br	Number of algal taxa in pollution tolerance category 2b: tolerant (a-mesosaprobic)
PTOL3ar	Number of algal taxa in pollution tolerance category 3a: less tolerant (B-mesosaprobic)
PTOL3br	Number of algal taxa in pollution tolerance category 3b: less tolerant (oligosaprobic)
PTOL_UNKN	Number of algal taxa not classified as to pollution tolerance category
PTOLr_CLASS	Percentage of algal taxa classified as to pollution tolerance category
NU_BB_DPr	Number of algal taxa that are nuisance benthic bloom producers
NU_SB_DPr	Number of algal taxa that are nuisance sestonic bloom producers
NU_ALGr	Number of nuisance algal taxa (NU_BB_DPr + NU_SB_DPr)
NUr_Class	Percentage of algal taxa categorized as nusiance algae
Eutrophic_Softr	Number of algal taxa categorized as eutrophic soft algal taxa
Eutrophic_Soft_UNKN	Number of algal taxa not categorized as eutrophic soft algae
Eutrophic_Softr_CLASS	Number of algal taxa classified as eutrophic soft algae
BENTHrp	Percentage total taxa richness composed of benthic algal taxa
SESTONrp	Percentage of total taxa richness composed of sestonic algal taxa
BEN_SES_UNKN	Number of algal taxa not classified as benthic or sestonic

Table D1. Algal metric names, abbreviations and definitions.—Continued

[>, greater than; <, less than; bolded variable codes were listed as significant algal indicators from tables 6 and 7; mg/L, milligram per liter; ppt, parts per thousand; N, nitrogen; ca., calculated]

Metric code	Description
Tolerance metrics—Continued	
Richness—continued	
BEN_SES_CLASSr	Percentage of algal taxa classified as benthic or sestonic
MOTILErp	Percentage of total taxa richness composed of motile algal taxa
NONMOTrp	Percentage of total taxa richness composed of nonmotile algal taxa
MOTILITY_UNKN	Percentage of algal taxa not classified as motile or nonmotile
MOTILITYr_CLASS	Percentage of algal taxa classified as motile or nonmotile
NFIXrp	Percentage of total taxa richness composed of nitrogen-fixing algal taxa
Percentage Richness	
NONFIXrp	Percentage of total taxa richness composed of nonnitrogen fixing algal taxa
NFIX_UNKN	Percentage of algal taxa not classified as nitrogen-fixing or nonnitrogen fixing
NFIXr_CLASS	Percentage of algal taxa classified as nitrogen-fixing or nonnitrogen fixing
pH1rp	Percentage of total algal taxa richness in pH category 1: acidobiontic (optima < 5.5)
pH2rp	Percentage of total algal taxa richness in pH category 2: acidophilous (optima generally < 7)
pH3rp	Percentage of total algal taxa richness in pH category 3: circumneutral (optima around 7)
pH4rp	Percentage of total algal taxa richness in pH category 4: alkaliphilous (optima generally >7)
pH5rp	Percentage of total algal taxa richness in pH category 5: alkalibiontic (optima always >7)
pH6rp	Percentage of total algal taxa richness in pH category 6: indifferent (no optimum)
pH_UNKN	Percentage of algal taxa not classified as to pH preference
pHr_CLASS	Percentage of algal taxa classified as to pH preference
SAL1rp	Percentage of total algal taxa richness in salinity category 1: fresh (< 100 mg/L, < 0.2 ppt)
SAL2rp	Percentage of total algal taxa richness in salinity category 2: fresh brackish (< 500 mg/L, < 0.9 ppt)
SAL3rp	Percentage of total algal taxa richness in salinity category 3: brackish fresh (500–1,000 mg/L, 0.9–1.8 ppt)
SAL4rp	Percentage of total algal taxa richness in salinity category 4: brackish (1,000–5,000 mg/L, 1.8–9 ppt)
SAL_UNKN	Percentage of algal taxa not classified as to salinity preference
SALr_CLASS	Percentage of algal taxa classified as to salinity preference
ORGN1rp	Percentage of total algal taxa richness in nitrogen uptake category 1: N autotroph (low organic N)
ORGN2rp	Percentage of total algal taxa richness in nitrogen uptake category 2: N autotrophic (high organic N)
ORGN3rp	Percentage of total algal taxa richness in nitrogen uptake category 3: N heterotroph (high organic N, faculatative)
ORGN4rp	Percentage of total algal taxa richness in nitrogen uptake category 4: N heterotroph (high organic N, obligate)
ORGN_UNKN	Percentage of algal taxa not classified as to nitrogen uptake category
ORGNr_CLASS	Percentage of algal taxa classified as to nitrogen uptake category
OXTOL1rp	Percentage of total algal taxa richness in oxygen requirements category 1: high oxygen requirements (ca. 100 percent saturation)
OXTOL2rp	Percentage of total algal taxa richness in oxygen requirements category 2: fairly high oxygen requirements (>75 percent saturation)
OXTOL3rp	Percentage of total algal taxa richness in oxygen requirements category 3: moderate oxygen requirements (>50 percent saturation)

Table D1. Algal metric names, abbreviations and definitions.—Continued

[>, greater than; <, less than; bolded variable codes were listed as significant algal indicators from tables 6 and 7; mg/L, milligram per liter; ppt, parts per thousand; N, nitrogen; ca., calculated]

Metric code	Description
Tolerance metrics—Continued	
Percentage Richness—continued	
OXTOL4rp	Percentage of total algal taxa richness in oxygen requirements category 4: low oxygen requirements (>30 percent saturation)
OXTOL5rp	Percentage of total algal taxa richness in oxygen requirements category 5: very low oxygen requirements (ca. 10 percent saturation)
OXTOL_UNKN	Percentage of algal taxa not classified as to oxygen requirement category
OXTOLr_CLASS	Percentage of algal taxa classified as to oxygen requirement category
SAPRO1rp	Percentage of total algal taxa richness in saprobic category 1: oligosaprobic
SAPRO2rp	Percentage of total algal taxa richness in saprobic category 2: B mesosaprobic
SAPRO3rp	Percentage of total algal taxa richness in saprobic category 3: a mesosaprobic
SAPRO4rp	Percentage of total algal taxa richness in saprobic category 4: a meso/polysaprobic
SAPRO5rp	Percentage of total algal taxa richness in saprobic category 5: polysaprobic
SAPRO_UNKN	Percentage of algal taxa not classified as to saprobic category
SAPPROr_CLASS	Percentage of algal taxa classified as to saprobic category
MOIST1rp	Percentage of total algal taxa richness in moisture category 1: in streams
MOIST2rp	Percentage of total algal taxa richness in moisture category 2: in streams, sometimes on wet or moist places
MOIST3rp	Percentage of total algal taxa richness in moisture category 3: in streams, often on wet or moist places
MOIST4rp	Percentage of total algal taxa richness in moisture category 4: on wet, moist, temporarily dry places
MOIST5rp	Percentage of total algal taxa richness in moisture category 5: exclusively outside water bodies
MOIST_UNKN	Percentage of algal taxa not classified as to moisture category
MOISTr_CLASS	Percentage of algal taxa classified as to moisture category
PTOL1rp	Percentage of total algal taxa richness in pollution tolerance category 1: very tolerant (polysaprobic)
Bahls1rp	Percentage of algal taxa richness in Bahls (1993) pollution class 1, most tolerant taxa (percentage of taxa with a Bahls classifications)
Bahls2rp	Percentage of algal taxa richness in Bahls (1993) pollution class 2, less tolerant taxa (percentage of taxa with a Bahls classification)
Bahls3rp	Percentage of algal taxa richness in Bahls (1993) pollution class 3, most sensitive taxa (percentage of taxa with a Bahls classification)
Bahls_UNKN	Percentage of algal taxa not classified as to Bahls pollution class
Bahlsr_CLASS	Percentage of algal taxa classified as to Bahls pollution class
Bahls_TR	Bahls (1993) pollution index based on algal taxa richness: range 1 (all tolerant taxa) to 3 (all sensitive taxa)
PTOL2arp	Percentage of total algal taxa richness in pollution tolerance category 2a: tolerant (a-meso/polysaprobic)
PTOL2brp	Percentage of total algal taxa richness in pollution tolerance category 2b: tolerant (a-mesosaprobic)
PTOL3arp	Percentage of total algal taxa richness in pollution tolerance category 3a: less tolerant (B-mesosaprobic)
PTOL3brp	Percentage of total algal taxa richness in pollution tolerance category 3b: less tolerant (oligosaprobic)
PTOL_UNKN	Percentage of algal taxa not classified as to pollution tolerance category
PTOLr_CLASS	Percentage of algal taxa classified as to pollution tolerance category
NU_BB_DPrp	Percentage of algal taxa that are nuisance benthic bloom producers
NU_SB_DPrp	Percentage of algal taxa that are nuisance sestonic bloom producers

Table D1. Algal metric names, abbreviations and definitions.—Continued

[>, greater than; <, less than; bolded variable codes were listed as significant algal indicators from tables 6 and 7; mg/L, milligram per liter; ppt, parts per thousand; N, nitrogen; ca., calculated]

Metric code	Description
NU_ALGrp	Percentage of algal taxa categorized as nuisance algal taxa (NU_BB_DPr + NU_SB_DPr)
Tolerance metrics—Continued	
Percentage Richness—continued	
NUr_Class	Percentage of algal taxa categorized as nuisance algae
Eutrophic_Softr	Percentage of algal taxa categorized as eutrophic soft algal taxa
Eutrophic_Soft_UNKN	Percentage of algal taxa not categorized as eutrophic soft algae
Eutrophic_Softr_CLASS	Percentage of algal taxa classified as eutrophic soft algae
Abundance	
BENTHa	Abundance of benthic algae
SESTONa	Abundance of sestonic algal taxa
BEN_SES_UNKN	Abundance of algal taxa not classified as benthic or sestonic
BEN_SESa_CLASS	Percentage of algal abundance classified as benthic or sestonic
MOTILEa	Abundance of motile algal taxa
NONMOTa	Abundance of nonmotile algal taxa
MOTILITY_UNKN	Number of algal taxa not classified as motile or nonmotile
MOTILITYa_CLASS	Percentage of algal taxa classified as motile or nonmotile
MOTILITY_UNKN	Number of algal taxa not classified as motile or nonmotile
MOTILITYa_CLASS	Percentage of algal taxa classified as motile or nonmotile
NFIXa	Abundance of nitrogen-fixing algal taxa
NONFIXa	Abundance of nonnitrogen-fixing algal taxa
NFIX_UNKN	Abundance of algal taxa not classified as nitrogen-fixing or nonnitrogen fixing
NFIXa_CLASS	Percentage of algal abundance classified as nitrogen-fixing or nonnitrogen fixing
pH1a	Abundance in pH category 1: acidobiontic (optima < 5.5)
pH2a	Abundance in pH category 2: acidophilous (optima generally < 7)
pH3a	Abundance in pH category 3: circumneutral (optima around 7)
pH4a	Abundance in pH category 4: alkaliphilous (optima generally > 7)
pH5a	Abundance in pH category 5: alkalibiontic (optima always > 7)
pH6a	Abundance in pH category 6: indifferent (no optimum)
pH_UNKN	Abundance of algal taxa not classified as to pH preference
pHa_CLASS	Percentage of algal abundance classified as to pH preference
SAL1a	Abundance in salinity category 1: fresh (< 100 mg/L, < 0.2 ppt)
SAL2a	Abundance in salinity category 2: fresh brackish (< 500 mg/L, < 0.9 ppt)
SAL3a	Abundance in salinity category 3: brackish fresh (500–1,000 mg/L, 0.9–1.8 ppt)
SAL4a	Abundance in salinity category 4: brackish (1,000–5,000 mg/L, 1.8–9 ppt)
SAL_UNKN	Abundance of algal taxa not classified as to salinity preference
SALa_CLASS	Percentage of algal abundance classified as to salinity preference
ORGN1a	Abundance in nitrogen uptake category 1: N autotroph (low organic N)
ORGN2a	Abundance in nitrogen uptake category 2: N autotrophic (high organic N)
ORGN3a	Abundance in nitrogen uptake category 3: N heterotroph (high organic N, faculatative)
ORGN4a	Abundance in nitrogen uptake category 4: N heterotroph (high organic N, obligate)
ORGN_UNKN	Abundance of algal taxa not classified as to nitrogen uptake category
ORGNa_CLASS	Percentage of algal abundance classified as to nitrogen uptake category
OXTOL1a	Abundance in oxygen requirements category 1: high oxygen requirements (ca. 100 percent saturation)
OXTOL2a	Abundance in oxygen requirements category 2: fairly high oxygen requirements (> 75 percent saturation)
OXTOL3a	Abundance in oxygen requirements category 3: moderate oxygen requirements (> 50 percent saturation)
OXTOL4a	Abundance in oxygen requirements category 4: low oxygen requirements (> 30 percent saturation)

Table D1. Algal metric names, abbreviations and definitions.—Continued

[>, greater than; <, less than; bolded variable codes were listed as significant algal indicators from tables 6 and 7; mg/L, milligram per liter; ppt, parts per thousand; N, nitrogen; ca., calculated]

Metric code	Description
Tolerance metrics—Continued	
Abundance—continued	
OXTOL_UNKN	Abundance of algal taxa not classified as to oxygen requirement category
OXTOLa_CLASS	Percentage of algal abundance classified as to oxygen requirement category
SAPRO1a	Abundance in saprobic category 1: oligosaprobic
SAPRO2a	Abundance in saprobic category 2: B-mesosaprobic
SAPRO3a	Abundance in saprobic category 3: a mesosaprobic
SAPRO4a	Abundance in saprobic category 4: a meso/polysaprobic
SAPRO5a	Abundance in saprobic category 5: polysaprobic
SAPRO_UNKN	Abundance of algal taxa not classified as to saprobic category
SAPPROa_CLASS	Percentage of algal abundance classified as to saprobic category
MOIST1a	Abundance in moisture category 1: in streams
MOIST2a	Abundance in moisture category 2: in streams, sometimes on wet or moist places
MOIST3a	Abundance in moisture category 3: in streams, often on wet or moist places
MOIST4a	Abundance in moisture category 4: on wet, moist, temporarily dry places
MOIST5a	Abundance in moisture category 5: exclusively outside water bodies
MOIST_UNKN	Abundance of algal taxa not classified as to moisture category
MOISTa_CLASS	Percentage of algal abundance classified as to moisture category
Bahls1a	Abundance of algae in Bahls (1993) pollution class 1, most tolerant taxa
Bahls2a	Abundance of algae in Bahls (1993) pollution class 2, less tolerant taxa
Bahls3a	Abundance of algae in Bahls (1993) pollution class 3, most sensitive taxa
Bahls_UNKN	Abundance of algal taxa not classified as to Bahls pollution class
Bahlsa_CLASS	Percentage of algal abundance classified as to Bahls pollution class
PTOL1a	Abundance in pollution tolerance category 1: very tolerant (polysaprobic)
PTOL2aa	Abundance in pollution tolerance category 2a: tolerant (a-meso/polysaprobic)
PTOL2ba	Abundance in pollution tolerance category 2b: tolerant (a-mesosaprobic)
PTOL3aa	Abundance in pollution tolerance category 3a: less tolerant (B-mesosaprobic)
PTOL3ba	Abundance in pollution tolerance category 3b: less tolerant (oligosaprobic)
PTOL_UNKN	Abundance of algal taxa not classified as to pollution tolerance category
PTOLa_CLASS	Percentage of algal abundance classified as to pollution tolerance category
NU_BB_DPa	Abundance of algal taxa that are nuisance benthic bloom producers
NU_SB_DPa	Abundance of algal taxa that are nuisance sestonic bloom producers
NU_ALGa	Abundance of nuisance algal taxa that are categorized as nuisance algae (NU_BB_DPr + NU_SB_DPr)
NUr_Class	Percentage of algal abundance categorized as nuisance algae
Eutrophic_Softa	Abundance of algal abundance categorized as eutrophic soft algal taxa
Eutrophic_Soft_UNKN	Abundance of algal taxa not categorized as eutrophic soft algae
Eutrophic_Softa_CLASS	Percentage of algal abundance classified as eutrophic soft algae
Percentage Abundance	
BENTHap	Percentage of total algal abundance composed of benthic algal taxa
SESTONap	Percentage of total algal abundance composed of sestonic algal taxa
BEN_SES_UNKN	Abundance of algal taxa not classified as benthic or sestonic
BEN_SESap_CLASS	Percentage of algal abundance classified as benthic or sestonic
MOTILEap	Percentage of total algal abundance composed of motile algal taxa
NONMOTap	Percentage of total algal abundance composed of nonmotile algal taxa
MOTILITY_UNKN	Number of algal taxa not classified as motile or nonmotile
MOTILITYa_CLASS	Percentage of algal taxa classified as motile or nonmotile
NFIXap	Percentage of total algal abundance composed of nitrogen-fixing algal taxa
NONFIXap	Percentage of total algal abundance composed of nonnitrogen fixing algal taxa
NFIX_UNKN	Abundance of algal taxa not classified as nitrogen-fixing or nonnitrogen fixing

Table D1. Algal metric names, abbreviations and definitions.—Continued

[>, greater than; <, less than; bolded variable codes were listed as significant algal indicators from tables 6 and 7; mg/L, milligram per liter; ppt, parts per thousand; N, nitrogen; ca., calculated]

Metric code	Description
NFIXa_CLASS	Percentage of algal abundance classified as nitrogen-fixing or nonnitrogen fixing
	Tolerance metrics—Continued
Percentage Abundance—continued	
pH1ap	Percentage of total algal abundance in pH category 1: acidobiontic (optima < 5.5)
pH2ap	Percentage of total algal abundance in pH category 2: acidophilous (optima generally < 7)
pH3ap	Percentage of total algal abundance in pH category 3: circumneutral (optima around 7)
pH4ap	Percentage of total algal abundance in pH category 4: alkaliphilous (optima generally > 7)
pH5ap	Percentage of total algal abundance in pH category 5: alkalibiontic (optima always > 7)
pH6ap	Percentage of total algal abundance in pH category 6: indifferent (no optimum)
pH_UNKN	Percentage of algal abundance not classified as to pH preference
pHa_CLASS	Percentage of algal abundance classified as to pH preference
SAL1ap	Percentage of total algal abundance in salinity category 1: fresh (< 100 mg/L, < 0.2 ppt)
SAL2ap	Percentage of total algal abundance in salinity category 2: fresh brackish (< 500 mg/L, < 0.9 ppt)
SAL3ap	Percentage of total algal abundance in salinity category 3: brackish fresh (500–1,000 mg/L, 0.9–1.8 ppt)
SAL4ap	Percentage of total algal abundance in salinity category 4: brackish (1,000–5,000 mg/L, 1.8–9 ppt)
SAL_UNKN	Percentage of algal abundance not classified as to salinity preference
SALa_CLASS	Percentage of algal abundance classified as to salinity preference
ORGN1ap	Percentage of total algal abundance in nitrogen uptake category 1: N autotroph (low organic N)
ORGN2ap	Percentage of total algal abundance in nitrogen uptake category 2: N autotrophic (high organic N)
ORGN3ap	Percentage of total algal abundance in nitrogen uptake category 3: N heterotroph (high organic N, faculatative)
ORGN4ap	Percentage of total algal abundance in nitrogen uptake category 4: N heterotroph (high organic N, obligate)
ORGN_UNKN	Abundance of algal taxa not classified as to nitrogen uptake category
ORGNa_CLASS	Percentage of algal abundance classified as to nitrogen uptake category
OXTOL1ap	Percentage of total algal abundance in oxygen requirements category 1: high oxygen requirements (ca. 100 percent saturation)
OXTOL2ap	Percentage of total algal abundance in oxygen requirements category 2: fairly high oxygen requirements (> 75 percent saturation)
OXTOL3ap	Percentage of total algal abundance in oxygen requirements category 3: moderate oxygen requirements (> 50 percent saturation)
OXTOL4ap	Percentage of total algal abundance in oxygen requirements category 4: low oxygen requirements (> 30 percent saturation)
OXTOL5ap	Percentage of total algal abundance in oxygen requirements category 5: very low oxygen requirements (ca. 10 percent saturation)
OXTOL_UNKN	Percentage of algal abundance not classified as to oxygen requirement category
OXTOLa_CLASS	Percentage of algal abundance classified as to oxygen requirement category
SAPRO1ap	Percentage of total algal abundance in saprobic category 1: oligosaprobic
SAPRO2ap	Percentage of total algal abundance in saprobic category 2: B mesosaprobic
SAPRO3ap	Percentage of total algal abundance in saprobic category 3: a mesosaprobic
SAPRO4ap	Percentage of total algal abundance in saprobic category 4: a meso/polysaprobic
SAPRO5ap	Percentage of total algal abundance in saprobic category 5: polysaprobic
SAPRO_UNKN	Percentage of algal abundance not classified as to saprobic category
SAPPROa_CLASS	Percentage of algal abundance classified as to saprobic category
MOIST1ap	Percentage of total algal abundance in moisture category 1: in streams
MOIST2ap	Percentage of total algal abundance in moisture category 2: in streams, sometimes on wet or moist places

Table D1. Algal metric names, abbreviations and definitions.—Continued

[>, greater than; <, less than; bolded variable codes were listed as significant algal indicators from tables 6 and 7; mg/L, milligram per liter; ppt, parts per thousand; N, nitrogen; ca., calculated]

Metric code	Description
Tolerance metrics—Continued	
Percentage Abundance—continued	
MOIST3ap	Percentage of total algal abundance in moisture category 3: in streams, often on wet or moist places
MOIST4ap	Percentage of total algal abundance in moisture category 4: on wet, moist, temporarily dry places
MOIST5ap	Percentage of total algal abundance in moisture category 5: exclusively outside water bodies
MOIST_UNKN	Percentage of algal abundance not classified as to moisture category
MOISTa_CLASS	Percentage of algal abundance classified as to moisture category
Bahls1ap	Percentage of algal abundance in Bahls (1993) pollution class 1, most tolerant taxa (percentage of abundance with a Bahls classification)
Bahls2ap	Percentage of algal abundance in Bahls (1993) pollution class 2, less tolerant taxa (percentage of abundance with a Bahls classification)
Bahls3ap	Percentage of algal abundance in Bahls (1993) pollution class 3, most sensitive taxa (percentage of abundance with a Bahls classification)
Bahls_UNKN	Percentage of algal abundance not classified as to Bahls pollution class
Bahlsa_CLASS	Percentage of algal abundance classified as to Bahls pollution class
BahlsTA	Bahls (1993) pollution index based on abundance of algae in each Bahls pollution tolerance classes.
PTOL1ap	Percentage of total algal abundance in pollution tolerance category 1: very tolerant (polysaprobic)
PTOL2aap	Percentage of total algal abundance in pollution tolerance category 2a: tolerant (a-meso/polysaprobic)
PTOL2bap	Percentage of total algal abundance in pollution tolerance category 2b: tolerant (a-mesosaprobic)
PTOL3aap	Percentage of total algal abundance in pollution tolerance category 3a: less tolerant (B-mesosaprobic)
PTOL3bap	Percentage of total algal abundance in pollution tolerance category 3b: less tolerant (oligosaprobic)
PTOL_UNKN	Percentage of algal abundance not classified as to pollution tolerance category
PTOLa_CLASS	Percentage of algal abundance classified as to pollution tolerance category
NU_BB_DPap	Percentage of algal abundance that are nuisance benthic bloom producers
NU_SB_DPap	Percentage of algal abundance that are nuisance sestonic bloom producers
NU_ALGap	Percentage of nuisance abundance taxa (NU_BB_DPr + NU_SB_DPr)
NUr_Class	Percentage of algal abundance categorized as nuisance algae
Eutrophic_Softap	Percentage of abundance categorized as eutrophic soft algal abundance
Eutrophic_Soft_UNKN	Percentage of algal abundance not categorized as eutrophic soft algae
Eutrophic_Softap_CLASS	Percentage of algal abundance classified as eutrophic soft algae
Trophic metrics	
Richness	
TROPH1r	Number of taxa in trophic category 1: oligotraphentic (oligotrophic)
TROPH2r	Number of taxa in trophic category 2: oligo-mesotrohic
TROPH3r	Number of taxa in trophic category 3: mesotraphentic (mesotrophic)
TROPH4r	Number of taxa in trophic category 4: meso-eurtraphentic (meso-eutrophic)
TROPH5r	Number of taxa in trophic category 5: eutraphentic (eutrophic)
TROPH6r	Number of taxa in trophic category 6: hypertraphentic (hypereutrophic)

Table D1. Algal metric names, abbreviations and definitions.—Continued

[>, greater than; <, less than; bolded variable codes were listed as significant algal indicators from tables 6 and 7; mg/L, milligram per liter; ppt, parts per thousand; N, nitrogen; ca., calculated]

Metric code	Description
TROPH7r	Number of taxa in trophic category 7: indifferent
Trophic metrics—Continued	
Richness—continued	
TROPH_UNKN	Number of algal taxa not classified as to trophic category
TROPHICr_Class	Percentage of total taxa richness that was classified into a trophic category
Percentage Richness	
TROPH1rp	Percentage of total taxa richness in trophic category 1: oligotraphentic (oligotrophic)
TROPH2rp	Percentage of total taxa richness in trophic category 2: oligo-mesotrohic
TROPH3rp	Percentage of total taxa richness in trophic category 3: mesotraphentic (mesotrophic)
TROPH4rp	Percentage of total taxa richness in trophic category 4: meso-eurtraphentic (meso-eutrophic)
TROPH5rp	Percentage of total taxa richness in trophic category 5: eutraphentic (eutrophic)
TROPH6rp	Percentage of total taxa richness in trophic category 6: hypertraphentic (hypereutrophic)
TROPH7rp	Percentage of total taxa richness in trophic category 7: indifferent
TROPH_UNKN	Percentage of algal taxa not classified as to trophic category
TROPHICrp_Class	Percentage of total taxa richness that was classified into a trophic category
Abundance	
TROPH1a	Abundance in trophic category 1: oligotraphentic (oligotrophic)
TROPH2a	Abundance in trophic category 2: oligo-mesotrohic
TROPH3a	Abundance in trophic category 3: mesotraphentic (mesotrophic)
TROPH4a	Abundance in trophic category 4: meso-eurtraphentic (meso-eutrophic)
TROPH5a	Abundance in trophic category 5: eutraphentic (eutrophic)
TROPH6a	Abundance in trophic category 6: hypertraphentic (hypereutrophic)
TROPH7a	Abundance in trophic category 7: indifferent
TROPH_UNKN	Abundance of algal taxa not classified as to trophic category
TROPHICa_Class	Percentage of algal abundance that was classified into a trophic category
Percentage Abundance	
TROPH1ap	Percentage of total abundance in trophic category 1: oligotraphentic (oligotrophic)
TROPH2ap	Percentage of total abundance in trophic category 2: oligo-mesotrohic
TROPH3ap	Percentage of total abundance in trophic category 3: mesotraphentic (mesotrophic)
TROPH4ap	Percentage of total abundance in trophic category 4: meso-eurtraphentic (meso-eutrophic)
TROPH5ap	Percentage of total abundance in trophic category 5: eutraphentic (eutrophic)
TROPH6ap	Percentage of total abundance in trophic category 6: hypertraphentic (hypereutrophic)
TROPH7ap	Percentage of total Abundance in trophic category 7: indifferent
TROPH_UNKN	Percentage of algal abundance not classified as to trophic category
TROPHICap_Class	Percentage of algal abundance that was classified into a trophic category

Table D2. Invertebrate metrics names, abbreviations and definitions.

[bolded metric codes were significant invertebrate indicators from tables 8 and 9; EPT, Ephemeroptera, Plecoptera, and Tricoptera; USEPA, U.S. Environmental Protection Agency]

Metric code	Description
	Abundance metrics
ABUND	Total number of organisms in the sample
AMPHI	Abundance of Amphipoda
BIVALV	Abundance of Bivalvia
CHR	Abundance of midges
COLEOP	Abundance of Coleoptera
CORBIC	Abundance of Corbicula
DIP	Abundance of Diptera
EPEM	Abundance of mayflies
EPT	Abundance of EPT
EPT_CH	Ratio of EPT abundance to midge abundance
GASTRO	Abundance of Gastropoda
ISOPOD	Abundance of Isopoda
MOLCRU	Abundance of mollusks and crustaceans
NCHDIP	Abundance of nonmidge Diptera
NONINS	Abundance of noninsects
ODIPNI	Percentage of total abundance composed of nonmidge Diptera and noninsects
ODONO	Abundance of Odonata
OLOGO	Percentage of total abundance composed of Oligochaeta
ORTHO	Abundance of Orthocladiinae midges
ORTHO_CH	Ratio of Othrhoclad abundance to midge abundance
PLECO	Abundance of stoneflies
PTERY	Abundance of Pteronarcys
TANY	Abundance of Tanytarsini
TANY_CH	Ratio of Tanytarsini abundance to midge abundance
TRICH	Abundance of caddisflies
	Functional group abundance metrics
CG_Abund	Total abundance composed of collector-gatherers
FC_Abund	Total abundance composed of filtering-collectors
FG_ABUND_class	Percentage of total abundance that could be assigned a functional group
OM_Abund	Total abundance composed of omnivores
PA_Abund	Total abundance composed of parasites
pCG_Abund	Percentage of total abundance composed of collector gatherers
pFC_Abund	Percentage of total abundance composed of filtering collectors
PI_Abund	Total abundance composed of piercers
pOM_Abund	Percentage of total abundance composed of omnivores
pPA_Abund	Percentage of total abundance composed of parasites
pPI_Abund	Percentage of total abundance composed of piercers
pPR_Abund	Percentage of total abundance composed of predators
PR_Abund	Total abundance composed of predators
pSC_Abund	Percentage of total abundance composed of scrapers
pSH_Abund	Percentage of total abundance composed of shredders
SC_Abund	Total abundance composed of scrapers
SH_Abund	Total abundance composed of shredders
	Functional group richness metrics
CG_Rich	Richness composed of collector gatherers
FC_Rich	Richness composed of filtering collectors
FG_RICH_class	Percentage of richness that could be assigned a tolerance value
OM_Rich	Richness composed of omnivores
PA_Rich	Richness composed of parasites
pCG_Rich	Percentage of richness composed of collector gatherers
pFC_Rich	Percentage of richness composed of filtering collectors
PI_Rich	Richness composed of piercers
pOM_Rich	Percentage of richness composed of omnivores
pPA_Rich	Percentage of richness composed of parasites
pPI_Rich	Percentage of richness composed of piercers
pPR_Rich	Percentage of richness composed of predators
PR_Rich	Richness composed of predators
pSC_Rich	Percentage of richness composed of scrapers
pSH_Rich	Percentage of richness composed of shredders
SC_Rich	Richness composed of scrapers
SH_Rich	Richness composed of shredders
	Percentage abundance metrics
AMPHIp	Percentage of total abundance composed of Amphipoda
BIVALp	Percentage of total abundance composed of bivalves
CHp	Percentage of total abundance composed of midges
COLEOPp	Percentage of total abundance composed of Coleoptera
CORBICp	Percentage of total abundance composed of Corbicula
DIPp	Percentage of total abundance composed of Diptera
EPEMp	Percentage of total abundance composed of mayflies
EPT_CHp	Ratio of EPT and midge abundance
EPTp	Percentage of total abundance composed of EPT
GASTROp	Percentage of total abundance composed of Gastropoda
ISOPp	Percentage of total abundance composed of Isopoda
MOLCRUp	Percentage of total abundance composed of mollusks and crustaceans
NCHDIPp	Percentage of total abundance composed of nonmidge Dipterans
NONINSp	Percentage of total abundance composed of noninsects
ODIPNIp	Percentage of total abundance composed of nonmidge Diptera and noninsects
ODONOp	Percentage of total abundance composed of Odonata
OLIGOp	Percentage of total abundance composed of Oligochaeta
ORTHO_CH	Ratio of Othoclads to total midge abundance
ORTHOp	Percentage of total abundance composed of Orthocladiinae
PLECOp	Percentage of total abundance composed of stoneflies
PTERYp	Percentage of total abundance composed of Pteronarcys
TANY_CHp	Ratio of percentage Tanytarsini to percentage midge abundance
TANYp	Percentage of total abundance composed of Tanytarsini midges
THRICHp	Percentage of total abundance composed of caddisflies

Table D2. Invertebrate metrics names, abbreviations and definitions.—Continued

[EPT, Ephemeroptera, Plecoptera, and Tricoptera; USEPA, U.S. Environmental Protection Agency; bolded metric codes were significant invertebrate indicators from tables 8 and 9]

Metric code	Description
Percentage abundance of dominant taxa	
DOM1	Percentage of total abundance represented by the most abundant taxon
DOM2	Percentage of total abundance represented by the two most abundant taxa
DOM3	Percentage of total abundance represented by the three most abundant taxa
DOM4	Percentage of total abundance represented by the four most abundant taxa
DOM5	Percentage of total abundance represented by the five most abundant taxa
Percentage richness metrics	
AMPHIRp	Percentage of total richness composed of Amphipoda
BIVALRp	Percentage of total richness composed of Bivalvia
CHRp	Percentage of total richness composed of midges
COLEOPRp	Percentage of total richness composed of Coleoptera
CORBICRp	Percentage of total richness composed of Corbicula
DIPRp	Percentage of total richness composed of Diptera
EPEMRp	Percentage of total richness composed of mayflies
EPT_CHRp	Ratio of EPT and midge richness
EPTRp	Percentage of total richness composed of EPT
GASTRORp	Percentage of total richness composed of Gastropoda
ISOPODRp	Percentage of total richness composed of Isopoda
MOLCRURp	Percentage of total richness composed of mollusks and crustaceans
NCHDIPRp	Percentage of total richness composed of nonmidge Dipterans
NONINSRp	Percentage of total richness composed of noninsects
ODIPNIRp	Percentage of total richness composed of nonmidge Diptera and noninsects
ODONORp	Percentage of total richness composed of Odonata
OLOGORp	Percentage of total richness composed of Oligochaeta
ORTHO_CHRp	Ratio of Othoclads to total midge richness
ORTHORp	Percentage of total richness composed of Orthocladiinae
PLECORp	Percentage of total richness composed of stoneflies
PTERYRp	Percentage of total richness composed of Pteronarcys
TANY_CHRp	Ratio of percentage Tanytarsini to percentage midge richness
TANYRp	Percentage of total richness composed of Tanytarsini midges
TRICHRp	Percentage of total richness composed of caddisflies
Richness metrics	
AMPHIR	Richness composed of Amphipoda
BIVALVR	Richness composed of Bivalvia
CHR	Richness composed of midges
COLEOPR	Richness composed of Coleoptera
CORBICR	Richness composed of Corbicula
DIPR	Richness composed of Diptera
EPEMR	Richness composed of mayflies
EPT_CHR	Ratio of EPT richness to midge richness
EPTR	Richness composed of EPT
GASTROR	Richness composed of Gastropoda
ISOPODR	Richness composed of Isopoda
MOLCRUR	Richness composed of mollusks and crustaceans
NCHDIPR	Richness composed of nonmidge Diptera
NONINSR	Richness composed of noninsects
ODIPNIR	Richness composed of nonmidge Diptera and noninsects
ODONOR	Richness composed of Odonates
OLIGOR	Richness composed of Oligochaeta
ORTHO_CHR	Ratio of Orthoclad richness to midge richness
ORTHOR	Richness composed of Orthocladiinae midges
PLECOR	Richness composed of stoneflies
PTERYR	Richness composed of Pteronarcys
RICH	Total number of nonambiguous taxa
TANY_CHR	Ratio of Tanytarsini richness to midge richness
TANYR	Richness composed of Tanytarsini
TRICHR	Richness composed of caddisflies
Tolerance metrics	
ABUND_TOL_class	Percentage of abundance that could be assigned a tolerance value
ABUNDTOL	Abundance weighted USEPA tolerance value for sample
RICH_TOL_class	Percentage of richness that could be assigned a tolerance value
RICHTOL	Richness based average USEPA tolerance value for sample

Table D3. Fish metrics names, abbreviations and definitions.

[bolded metric codes were significant fish indicator metrics from table 11; IBI, Index of Biotic Integrity; USEPA, U.S. Environmental Protection Agency]

Metric code	Description
Georgia Department of Natural Resources, fish IBI metrics	
num_native	Number of native species
num_ben	Number of benthic invertivore species
num_sun	Number of native sunfish
num_cyprin	Number of insectivorous cyprinids
num_suck	Number of native round-bodied sucker species
num_intol	Number of intolerent/sensitive species
eveness	Measure of the proportion of each species in the sample
pct_lepom	Proportion of individuals as Lepomis
pct_cyprin	Proportion of individuals as insectivorous cyprinids
pct_carn	Proportion of individuals as top carnivores
pct_ben	Proportion os individuals as benthic fluvial specialists
num_200m	Number of individuals collected per 200 meters
IBI Score	Georgia Index of Biotic Integrity Score
USEPA fish metrics	
Trophic	
EPA_Piscivore	Percentage of community composed of piscivores
EPA_Herbivore	Percentage of community composed of herbivores
EPA_Omnivore	Percentage of community composed of omnivores
EPA_Insectivore	Percentage of commuity composed of insectivores
EPA_Filter	Percentage of community composed of herbivores
EPA_Generalist	Percentage of commuity composed of tropic generalists
EPA_Invertivore	Percentage of commuity composed of invertivores
EPA_Unknown	Percentage of commuity composed whose trophic status is unknown
EPA_C_Piscivore	Count of species classified as piscivores
EPA_C_Herbivore	Count of species classified as herbivores
EPA_C_Omnivore	Count of species classified as omnivores
EPA_C_insectivore	Count of species classified as insectivores
EPA_C_Filter	Count of species classified as filters
EPA_C_Generalist	Count of species classified as trophic generalists
EPA_C_Invertivore	Count of species classified as invertivores
Tolerance	
EPA_Intolerant	Percentage of community composed of intolerant
EPA_Intermediate	Percentage of community composed of species with intermediate tolerance
EPA_Tolerant	Percentage of community composed of tolerant taxa
EPA_tol_Unknown	Percentage of community composed of species with unknown tolerance
EPA_C_Intolerant	Count of intolerant taxa
EPA_C_Intermediate	Count of taxa with intermediate tolerance
EPA_C_Tolerant	Count of tolerant taxa

Metric code	Description
Goldstien and Meador fish trait metrics	
Trophic	
Herbivore	Percentage of commuity composed of herbivores
Planktivore	Percentage of commuity composed of planktivores
Detritivore	Percentage of commuity composed of detritovores
Invertivore	Percentage of commuity composed of invertivores
Carnivore	Percentage of commuity composed of carnivores
Unknown	Percentage of commuity composed of taxa with unknown tropic modes
Count herbivore	Count of taxa composed of herbivores
Count Planktivore	Count of taxa composed of planktivores
Count detritivore	Count of taxa composed of detritovores
Count invertivore	Count of taxa composed of invertivores
Count carnivore	Count of taxa composed of carnivores
Substrate	
Bedrock	Percentage of community whose substrate preference is bedrock
Boulders	Percentage of community whose substrate preference is boulders
Cobble/rubble (rocky)	Percentage of community whose substrate preference is cobble/rubble
Gravel	Percentage of community whose substrate preference is gravel
Sand	Percentage of community whose substrate preference is sand
Mud (silt, clay, detritus)	Percentage of community whose substrate preference is mud
Vegetation	Percentage of community whose substrate preference is vegetation
Variable	Percentage of community whose substrate preference is variable
Unknown	Percentage of community whose substrate preference is unknown
Count bedrock	Count of taxa whose substrate preference is bedrock
Count boulders	Count of taxa whose substrate preference is boulders
Count cobble/rubble (rocky)	Count of taxa whose substrate preference is cobble/rubble
Count gravel	Count of taxad whose substrate preference is gravel
Count sand	Count of taxa whose substrate preference is sand
Count mud (silt, clay, detritus)	Count of taxa substrate preference is mud
Count vegetation	Count of taxa whose substrate preference is vegetation
Count variable	Count of taxa whose substrate preference is variable

Table D3. Fish metrics names, abbreviations and definitions.—Continued

[IBI, Index of Biotic Integrity; USEPA, U.S. Environmental Protection Agency; bolded metric codes were significant fish indicator metrics from table 11]

Metric code	Description
Geomorphology	
Riffle	Percentage of community whose geomorphic preference is riffles
Pool	Percentage of community whose geomorphic preference is pool
Run or main channel	Percentage of community whose geomorphic preference is run or main channel
Backwater	Percentage of community whose geomorphic preference is backwater
Variable	Percentage of community whose geomorphic preference is variable
Unknown	Percentage of community whose geomorphic preference is unknown
Count riffle	Count of taxa whose geomorphic preference is riffles
Count pool	Count of taxa whose geomorphic preference is pool
Count run or main channel	Count of taxa whose geomorphic preference is run or main channel
Count backwater	Count of taxa whose geomorphic preference is backwater
Count variable	Count of taxa whose geomorphic preference is variable
Locomotion	
Cruiser	Percentage of community classified as cruisers
Accelerator	Percentage of community classified as accelerators
Hugger	Percentage of community classified as huggers
Creeper	Percentage of community classified as creepers
Maneuverer	Percentage of community classified as maneuverers
Specialist	Percentage of community classified as specialists
Unknown	Percentage of community with unknown locomation classification
Count cruiser	Count of taxa classified as cruisers
Count accelerator	Count of taxa classified as accelerators
Count hugger	Count of taxa classified as huggers
Count creeper	Count of taxa classified as creepers
Count maneuverer	Count of taxa classified as maneuverers
Count specialist	Count of taxa classified as specialists
Reproductive	
Broadcaster	Percentage of fish community that broadcast eggs
Simple nest	Percentage of fish community that constructs simple nests
Complex nest	Percentage of fish community that constructs complex nests
Bearer	Percentage of fish community that bears young live
Migratory	Percentage of fish community that migrates
Unknown	Percentage of fish community whose reproductive mode is unknown
Count broadcaster	Count of fish taxa that broadcast eggs
Count simple nest	Count of fish taxa that constructs simple nests
Count complex nest	Count of fish taxa that constructs complex nests
Count bearer	Count of fish taxa that bears young live
Count migratory	Count of fish taxa that migrates
Stream size	
Small creeks	Percentage of fish species whose stream size preference is small creeks
Small creeks to small rivers	Percentage of fish species whose stream size preference is small creeks to small rivers
Medium and large rivers	Percentage of fish species whose stream size preference is medium to large rivers
Large rivers	Percentage of fish species whose stream size preference is large rivers
Range of sizes	Percentage of fish species whose stream size preference is variable
Unknown	Percentage of fish species whose stream size preference is unknown
Count small creeks	Count of fish species whose stream size preference is small creeks
Count small creeks to small rivers	Count of fish species whose stream size preference is small creeks to small rivers
Count medium and large rivers	Count of fish species whose stream size preference is medium to large rivers
Count large rivers	Count of fish species whose stream size preference is large rivers
Count range of sizes	Count of fish species whose stream size preference is variable

Appendix E. Species Lists for Algal, Invertebrate, and Fish Communities

Table E1. Scientific names and number of occurrences of diatoms on snags (epidendric) and sand (episammic) habitat in 30 streams sampled in the Metropolitan Atlanta study area, 2003.

Scientific name/authority	Snag (epidendric)	Sand (episammic)
Achnanthes harveyi/Reimer		1
Achnanthes lanceolata var. *abbreviata*/Reimer	1	7
Achnanthes minutissima var. scotica/ (Carter) Lange-Bertalot		2
Achnanthes rupestoides/Hohn		1
Achnanthes sp. 1/ANS NAWQA EAM	18	20
Achnanthes stewartii/Patrick	3	5
Achnanthes subhudsonis var. *kraeuselii/*(Cholnoky) Cholnoky	5	7
Achnanthidium catenatum/(Bily et Marvan) Lange-Bertalot	3	3
Achnanthidium exiguum var. *heterov-alvum*/(Krasske) Czarnecki	6	19
Achnanthidium microcephalum/ Kützing		1
Achnanthidium minutissimum/ (Kützing) Czarnecki	29	30
Achnanthidium pyrenaicum/(Hustedt) Kobayasi	20	22
Achnanthidium saprophila/ (Kobayasi et Mayama) Round et Bukhtiyarova	4	
Amphipleura pellucida/(Kützing) Kützing	5	5
Amphora copulata/(Kützing) Schoeman et Archibald		4
Amphora holsatica/Hustedt		1
Amphora inariensis/Krammer		1
Amphora montana/Krasske		4
Amphora pediculus/(Kützing) Grun.	1	2
Asterionella formosa/Hassal	9	10
Aulacoseira ambigua/(Grunow) Simonsen	18	11
Aulacoseira granulata/(Ehrenberg) Simonsen	14	14
Bacillaria paradoxa/Gmelin	2	4
Brachysira brebissonii/Ross	1	
Brachysira microcephala/(Grunow) Compère	11	9
Caloneis bacillum/(Grunow) Cleve	3	8
Caloneis hyalina/Hustedt	11	16
Capartogramma crucicula/(Grunow ex Cleve) Ross	3	6
Cavinula cocconeiformis/(Gregory ex Greville) Mann et Stickle		5
Cavinula lacustris/(Gregory) Mann et Stickle		1
Cavinula lapidosa/(Krasske) Lange-Bertalot		2
Cavinula pseudoscutiformis/(Grunow ex Schmidt) Mann et Stickle		4
Chamaepinnularia mediocris/ (Krasske) Lange-Bertalot	1	
Chamaepinnularia soehrensis var. *muscicola*/(Petersen) Lange-Bertalot et Krammer		1
Cocconeis disculus/(Schumann) Cleve	3	6
Cocconeis fluviatilis/Wallace		1
Cocconeis neodiminuta/Krammer		1
Cocconeis placentula var. *lineata*/ (Ehrenberg) Van Heurck	9	8
Craticula cuspidata/(Kützing) Mann		1
Craticula halophila/(Grunow) Mann	2	2
Craticula molestiformis/(Hustedt) Lange-Bertalot	1	2
Craticula submolesta/(Hustedt) Lange-Bertalot		1
Ctenophora pulchella var. *lacerata*/ (Hustedt) Bukhtiyarova		1
Cyclotella atomus/Hustedt	1	
Cyclotella meneghiniana/Kützing	1	
Cyclotella pseudostelligera/Hustedt	1	1
Cyclotella stelligera/(Cleve et Grunow) Van Heurck	14	22
Cymbella affinis/Kützing	2	3
Cymbella mesiana/Cholnoky	7	3
Cymbella mexicana/(Ehrenberg) Cleve		1
Cymbella naviculiformis/Auerswald ex Héribaud	4	11
Cymbella sp./1 JCK		1
Cymbella tumida/(Brébisson ex Kützing) Van Heurck	9	3

Table E1. Scientific names and number of occurrences of diatoms on snags (epidendric) and sand (episammic) habitat in 30 streams sampled in the Metropolitan Atlanta study area, 2003.—Continued

Scientific name/authority	Snag (epidendric)	Sand (episammic)
Decussata placenta/(Ehrenberg) Lange-Bertalot et Metzeltin		2
Diadesmis confervacea/Kützing		2
Diadesmis contenta/(Grunow ex Van Heurck) Mann	22	22
Diatoma vulgaris/Bory	1	
Diploneis elliptica/(Kützing) Cleve	1	4
Diploneis ovalis/(Hilse ex Rabenhorst) Cleve	1	1
Diploneis parma/Cleve	2	4
Diploneis pseudovalis/Hustedt	1	
Encyonema lunatum/(Smith) Van Heurck	20	12
Encyonema minutum/(Hilse) Mann	29	23
Encyonema silesiacum/(Bleisch) Mann	18	16
Encyonema triangulum/(Ehrenberg) Kutzing	1	
Encyonopsis microcephala/(Grunow) Krammer	2	2
Epithemia adnata/(Kützing) Brébisson	1	1
Eunotia bilunaris/(Ehrenberg) Mills	10	16
Eunotia bilunaris var. *linearis*/(Okuno) Lang.-Bertalot et Nörpel	19	11
Eunotia diodon/Ehrenberg		1
Eunotia exigua/(Brébisson ex Kützing) Rabenhorst	16	22
Eunotia flexuosa/Brébisson ex Kützing	18	16
Eunotia formica/Ehrenberg	9	11
Eunotia implicata/Nörpel, Lange-Bertalot et Alles	2	3
Eunotia incisa/Smith ex Gregory	4	13
Eunotia minor/(Kützing) Grunow	12	14
Eunotia musicola var. *tridentula*/Nörpel et Lange-Bertalot	9	9
Eunotia naegelii/Migula	12	19
Eunotia paludosa/Grunow	1	1
Eunotia pectinalis var. *undulata*/(Ralfs) Rabenhorst	11	9
Eunotia praerupta/Ehrenberg	4	1
Eunotia soleirolii/(Kützing) Rabenhorst	6	1
Eunotia sp./9 NAWQA EAM		1
Fallacia indifferens/(Hustedt) Mann	1	1
Fallacia omissa/(Hustedt) Mann		1
Fistulifera pelliculosa/(Brébisson ex Kützing) Lange-Bertalot	1	
Fragilaria acutirostrata/Metzeltin et Lange-Bertalot	1	4
Fragilaria aff. amphicephala/ANS NAWQA EAM	28	25
Fragilaria capucina/Desmazières		1
Fragilaria capucina var. *distans*/(Grunow) Lange-Bertalot	9	1
Fragilaria capucina var. *gracilis*/(Oestrup) Hustedt	8	20
Fragilaria capucina var. *perminuta*/(Grunow) Lange-Bertalot	2	
Fragilaria capucina var. *rumpens*/(Kützing) Lange-Bertalot	4	3
Fragilaria crotonensis/Kitton	2	
Fragilaria nanana/Lange-Bertalot	17	8
Fragilaria pinnata var. *subcapitata*/Frenguelli	1	1
Fragilaria sp./11 NAWQA EAM	2	1
Fragilaria tenera/(Smith) Lange-Bertalot		3
Fragilaria vaucheriae/(Kützing) Petersen	27	28
Fragilariforma polygonata/(Cleve-Euler) Kingston, Sherwood et Bengston		3
Frustulia rhomboides/(Ehrenberg) De Toni	28	21
Frustulia saxonica/Rabenhorst	22	17
Frustulia sp./2 NAWQA EAM	3	4
Frustulia vulgaris/(Thwaites) DeT.	24	23
Frustulia weinholdii/Hustedt	18	10
Geissleria acceptata/(Hustedt) Lange-Bertalot et Metzeltin		3
Geissleria aikenensis/(Patrick) Torgan et Olivera	6	12
Geissleria decussis/(Hustedt) Lange-Bertalot et Metzeltin	14	23

Table E1. Scientific names and number of occurrences of diatoms on snags (epidendric) and sand (episammic) habitat in 30 streams sampled in the Metropolitan Atlanta study area, 2003.—Continued

Scientific name/authority	Snag (epidendric)	Sand (episammic)
Geissleria schoenfeldii/(Hustedt) Lange-Bertalot et Metzeltin		1
Gomphonema acuminatum/ Ehrenberg	4	1
Gomphonema acutiusculum O. Müller) Cleve-Euler	1	
Gomphonema affine/Kützing	9	7
Gomphonema americobtusatum/ Reichardt et Lange-Bertalot	12	10
Gomphonema angustatum/(Kütz.) Rabh.	29	29
Gomphonema aquamineralis/Krammer	1	
Gomphonema gracile/Ehr. emend. V. H.	8	10
Gomphonema innocens/Reichardt	17	7
Gomphonema kobayasii/Kociolek & Kingston	7	4
Gomphonema lagenula/Kützing	20	20
Gomphonema minutum/ (C.A. Agardh) C.A. Agardh		1
Gomphonema parvulum/ (Kütz.) Kütz.	15	17
Gomphonema patrickii/ Kociolek & Stoermer	8	3
Gomphonema sp./14 SAVANNAH EAM	1	
Gomphonema sp./32 NAWQA EAM	25	18
Gomphonema subclavatum/ (Grun.) Grun.		1
Gomphosphenia grovei/ (Schmid) Lange-Bertalot		1
Gomphosphenia lingulatiformis/ (Lange-Bertalot et Reichardt) Lange-Bertalot	1	2
Gyrosigma attenuatum/(Kütz.) Rabh.		1
Gyrosigma nodiferum/(Grun.) Reim.		5
Gyrosigma spencerii/(Quek.) Griff. & Henfr.	1	
Hantzschia amphioxys/(Ehr.) Grun.	11	21
Hippodonta capitata/(Ehrenberg) Lange-Bertalot, Metzeltin et Witkowski	2	11
Karayevia clevei/(Grunow) Kingston	1	4
Kobayasiella subtilissima/(Cl.) Lange-Bertalot	1	6
Luticola goeppertiana/(Bleisch) Mann	9	6
Luticola mutica/(Kutz.) Mann	9	22
Mastogloia smithii/Thw.		1
Mayamaea agrestis/(Hustedt) Lange-Bertalot	3	2
Mayamaea atomus/(Kützing) Lange-Bertalot	1	8
Melosira varians/Ag.	5	3
Meridion circulare var. *constrictum*/ (Ralfs) V. H.	9	17
Microcostatus maceria/(Schimanski) Lange-Bertalot	2	
Navicula aboensis/(Cl.) Hust.		9
Navicula angusta/Grunow		1
Navicula antonii/Lange Bertalot		1
Navicula arvensis/Hustedt	7	11
Navicula canalis/Patr.	6	8
Navicula cari/Ehrenberg	3	
Navicula catalanogermanica/ Lange-Bertalot et Hofmann	4	1
Navicula caterva/Hohn & Hellerm.	1	
Navicula cf. *harderii*/NAWQA EAM Hustedt	1	
Navicula cf. *kriegerii*/NAWQA KM Krasske	2	7
Navicula constans/Hustedt		1
Navicula cryptocephala/Kützing	27	29
Navicula cryptotenella/L.B. in Kramm. & L.-B.	8	5
Navicula difficillima/Hustedt	1	1
Navicula elginensis var. *neglecta*/ (Krass.) Patr.	1	
Navicula erifuga/Lange-Bert.		1
Navicula exilis/Kützing	1	
Navicula germainii/Wallace	11	16
Navicula globulifera/Hustedt	1	
Navicula gregaria/Donk.	16	20
Navicula hambergii/Hustedt	3	11
Navicula incertata/Hustedt	7	9

Table E1. Scientific names and number of occurrences of diatoms on snags (epidendric) and sand (episammic) habitat in 30 streams sampled in the Metropolitan Atlanta study area, 2003.—Continued

Scientific name/authority	Snag (epidendric)	Sand (episammic)
Navicula kotschyi/Grunow	1	2
Navicula lanceolata/(Ag.) Ehr.	1	1
Navicula lateropunctata/Wallace	4	11
Navicula longicephala/Hustedt	7	16
Navicula lundii/Reich.	4	3
Navicula minima/Grunow	20	26
Navicula mobiliensis/Boyer		1
Navicula notha/Wallace	25	23
Navicula ordinaria/Hustedt	1	
Navicula pseudoarvensis/Hustedt	1	1
Navicula radiosa/Kützing	1	1
Navicula radiosafallax/ Lange-Bertalot	1	1
Navicula reinhardtii/(Grun.) Grun.		1
Navicula rhynchocephala/Kützing	10	15
Navicula rostellata/Kützing	10	16
Navicula schadei/Krass.		4
Navicula schroeteri var. *escambia*/Patr.	14	12
Navicula sp./3 NAWQA MP		5
Navicula subadnata/Hustedt		3
Navicula subminuscula/Mang.	1	1
Navicula submuralis/Hustedt	6	11
Navicula tenelloides/Hustedt	2	2
Navicula trivialis/Lange-Bertalot	4	5
Navicula vaucheriae/Peters.		1
Navicula vilaplanii/(Lange-Bertalot et Sabater) Lange-Bertalot et Sabater	3	6
Navicula viridulacalcis/(Hustedt) Lange-Bertalot	2	5
Navicula vitabunda/Hustedt	1	1
Navicula wallacei/Reim.	1	
Neidium affine/(Ehr.) Pfitz.	1	2
Neidium alpinum/Hustedt		1
Neidium ampliatum/(Ehr.) Kramm.	3	14
Neidium bisulcatum/(Lagerst.) Cl.	1	1
Neidium densestriatum/(Oestrup) Krammer	1	
Neidium hercynicum/A. Mayer		3
Neidium hercynicum fo. *subrostratum*/Wallace		1
Neidium productum/(W. Sm.) Cl.		1
Nitzschia acicularis/(Kützing) Smith	6	6
Nitzschia agnita/Hustedt	1	1
Nitzschia amphibia/Grunow	8	11
Nitzschia archibaldii/Lange-Bertalot	13	20
Nitzschia aurariae/Choln.		1
Nitzschia biacrula/Hohn et Hellerman		4
Nitzschia bita/Hohn et Hellerman	1	2
Nitzschia brevissima/Grun. in V. H.		7
Nitzschia capitellata/Hustedt	5	10
Nitzschia clausii/Hantz.	10	12
Nitzschia dissipata/(Kützing) Grunow	20	22
Nitzschia dissipata var. *media*/ (Hantz.) Grun.		1
Nitzschia draveillensis/Coste & Ricard	5	12
Nitzschia dubia/W. Sm.	1	
Nitzschia filiformis/(W. Sm.) V. H.	5	3
Nitzschia fonticola/Grunow	17	20
Nitzschia fossilis/Grunow		1
Nitzschia frustulum/(Kützing) Grunow	5	11
Nitzschia gracilis/Hantz. ex Rabh.	14	22
Nitzschia heufleriana/Grunow	18	18
Nitzschia homburgienis/Lange-Bertalot	2	1
Nitzschia inconspicua/Grunow	1	
Nitzschia intermedia/Hantz. ex Cl. et Grun.	11	13
Nitzschia liebethruthii/Rabenhorst	1	
Nitzschia linearis var. *subtilis*/ Hustedt	11	13
Nitzschia lorenziana/Grunow	1	2
Nitzschia nana/Grun. in V. H.		2
Nitzschia palea/(Kützing) Smith	27	30
Nitzschia palea var. *debilis*/(Kützing) Grunow	22	25

Table E1. Scientific names and number of occurrences of diatoms on snags (epidendric) and sand (episammic) habitat in 30 streams sampled in the Metropolitan Atlanta study area, 2003.—Continued

Scientific name/authority	Snag (epidendric)	Sand (episammic)
Nitzschia paleacea/Grun. in V.H.	2	2
Nitzschia pellucida/Grunow	1	1
Nitzschia perspicua/Cholnoky	1	
Nitzschia pseudofonticola/Hustedt	1	1
Nitzschia pusilla/Grunow	4	9
Nitzschia recta/Hantz. ex Rabh.	23	28
Nitzschia sigma/(Kütz.) W.Sm.		2
Nitzschia sigmoidea/(Nitz.) W.Sm.		1
Nitzschia solita/Hustedt	19	18
Nitzschia suchlandtii/Hustedt		1
Nitzschia supralitorea/Lange-Bert.	1	
Nitzschia terrestris/(Peterson) Hust.		1
Nitzschia umbonata/Lange-Bert.		1
Nupela sp./3 NAWQA MP	6	8
Nupela sp./4 NAWQA EAM		5
Nupela wellneri/(Lange-Bertalot) Lange-Bertalot	1	3
Opephora aff. *olsenii*/ SAVANNAH EAM		2
Opephora cf. *schwartzii*/NAWQA EAM (Grunow) Petit		3
Opephora olsenii/M Moller		1
Pinnularia acidophila/Hofmann et Krammer	5	14
Pinnularia biceps/Greg.	1	1
Pinnularia borealis/Ehrenberg	1	2
Pinnularia borealis var. *rectangularis*/Carlson		1
Pinnularia braunii/(Grun.) Cl.		1
Pinnularia divergens/W. Sm.	16	18
Pinnularia gibba/Ehrenberg	4	5
Pinnularia interrupta/W. Sm.	2	
Pinnularia legumen/(Ehr.) Ehr.		1
Pinnularia lundii/Hustedt	1	2
Pinnularia maior/(Kütz.) Rabh.		1
Pinnularia meridiana/Metzeltin & Krammer	0	
Pinnularia microstauron/(Ehr.) Cl.	15	6
Pinnularia nodosa/(Ehr.) W. Sm.		1
Pinnularia obscura/Krass.	7	14
Pinnularia subcapitata/Greg.	9	2
Placoneis elginensis/(Greg.) Cox	1	3
Placoneis explanata/(Hust.) Cox		1
Planothidium apiculatum/(Patrick) Lange-Bertalot	2	7
Planothidium biporomum/(Hohn et Hellerman) Lange-Bertalot	1	1
Planothidium frequentissimum/ (Lange-Bertalot) Lange-Bertalot	5	14
Planothidium lanceolatum/(Brébisson ex Kützing) Lange-Bertalot	10	20
Planothidium minutissimum/ (Krasske) Lange-Bertalot	1	1
Planothidium peragalli/Brun et Heribaud	1	6
Planothidium rostratum/(Østrup) Lange-Bertalot	7	21
Pleurosira laevis/(Ehrenberg) Compere		1
Psammothidium chlidanos/(Hohn et Hellerman) Lange-Bertalot	5	13
Psammothidium grischunum f. *daonensis*/(L.-B. in L.-B. et Kram) Bukh. et Round	2	
Psammothidium helveticum/ (Hustedt) Bukhtiyarova et Round		1
Psammothidium marginulatum/ (Grun) Bukt. and Round	1	
Psammothidium subatomoides/ (Hustedt) Bukhtiyarova et Round	6	4
Psammothidium ventralis/(Kras.) Bukht. et Round		2
Pseudostaurosira pseudoconstruens/ (Marciniak) Williams et Round	0	
Reimeria sinuata/(Greg.) Kociolek & Stoermer	2	
Rhopalodia brebissonii/Kramm.		6
Rhopalodia gibberula/(Ehr.) O. Müll.	1	
Sellaphora bacillum/(Ehr.) Mann		1
Sellaphora laevissima/(Kutz.) Mann	4	3
Sellaphora pupula/(Kütz.) Meresckowsky	8	20
Sellaphora seminulum/(Grun.) Mann	16	22
Simonsenia delognei/(Grun.) Lange-Bert.		1

Table E1. Scientific names and number of occurrences of diatoms on snags (epidendric) and sand (episammic) habitat in 30 streams sampled in the Metropolitan Atlanta study area, 2003.—Continued

Scientific name/authority	Snag (epidendric)	Sand (episammic)
Stauroforma exiguiformis/Flower, Jones et Round	1	
Stauroneis anceps/Ehrenberg		6
Stauroneis anceps fo. gracilis/ Rabenhorst	1	6
Stauroneis kriegeri/Patr.		1
Stauroneis nana/Hustedt		1
Stauroneis phoenicenteron/(Nitz.) Ehr.	3	2
Stauroneis smithii/Grunow	1	15
Stauroneis sp./6 SAVANNAH EAM	3	13
Stauroneis sp./7 NAWQA DW	3	14
Stauroneis sp./8 NAWQA DW	2	2
Stauroneis thermicola/(Peters.) Lund	6	17
Staurosira construens var. *venter*/ (Ehr.) Hamilton	1	2
Staurosira elliptica/(Schumann) Williams et Round		1
Staurosirella pinnata/(Ehrenberg) Williams et Round	2	4
Stephanodiscus hantzschii/Grunow	1	
Surirella angusta/Kützing	16	24
Surirella minuta/Bréb.	3	6
Surirella robusta/Ehrenberg	1	1
Surirella stalagma/Hohn & Hellerm.		3
Synedra acus/Kützing	14	14
Synedra delicatissima/W. Sm.	24	21
Synedra parasitica/(W. Sm.) Hust.	1	2
Synedra ulna/(Nitz.) Ehr.	28	27
Tabellaria flocculosa/(Roth) Kütz.	13	15
Tabularia tabulata/(C. A. Ag.) Snoeijs		1
Tryblionella apiculata/Greg.		1
Tryblionella debilis/Arnott	1	1
Tryblionella hungarica/(Grun.) Mann		1
Tryblionella littoralis/(Grun. in Cl. and Grun.) Mann	1	1

Table E2. Scientific names, number of site occurrences of invertebrates in qualitative multihabitat and semi-qualitative snag samples and mean and maximum densities of individuals on snags collected from 30 streams in the Metropolitan Atlanta study area, 2002–2003.

[#, number; m^2, square meter]

Sceintific name/authority	Number of site occurences in sample types		Density (# per m^2) of individuals on snags	
	Qualitative	Snags	Mean density	Maximum density
Ablabesmyia sp.	28	10	2.41	37.08
Acari	22	22	7.14	32.77
Acentrella turbida/(McDunnough)	7	5	1.63	22.99
Acerpenna pygmaea/(Hagen)	1	1	0.19	5.63
Acroneuria sp.	5	5	0.53	10.33
Aedes sp.	1			
Aeshnidae	6	2	0.22	5.91
Alloperla sp.	1			
Amphinemura sp.	6	6	1.66	23.51
Amphipoda	1	1	0.05	1.64
Anchytarsus bicolor/(Melsheimer)	1			
Ancylidae	6	6	1.04	10.47
Ancyronyx variegata/(Germar)	27	27	13.91	67.66
Anisocentropus pyraloides/(Walker)	1	1	0.02	0.52
Anthopotamus sp.	1	1	0.12	3.55
Antocha sp.	10	10	8.06	69.11
Aquarius conformis/(Uhler)	15			
Aquarius nebularis/(Drake and Hottes)	1			
Argia fumipennis/(Burmeister)	1			
Argia sp.	13	1	0.01	0.27
Atrichopogon sp.	6	6	3.73	55.24
Baetis flavistriga/McDunnough	7	4	2.62	48.50
Baetis intercalaris/McDunnough	24	21	27.35	207.59
Baetis pluto/McDunnough	7	7	1.59	22.50
Baetis sp.	2	1	0.01	0.23
Baetisca rogersi/Berner	1	1	0.17	5.10
Bezzia/Palpomyia sp.	5	3	0.22	4.46
Bivalvia	1	1	0.08	2.49
Boyeria sp.	1	1	0.30	8.86
Boyeria vinosa/(Say)	14	6	0.69	12.94
Brachycentrus sp.	3	3	0.44	8.71
Brachycera	2	1	0.06	1.92
Brillia sp.	27	24	16.89	116.03
Bryophaenocladius sp.	1			
Bryozoa	4	1	0.08	2.49
Caecidotea sp.	5	4	0.98	20.95
Caenis sp.	6	5	5.42	109.43
Calopteryx maculata/(Beauvois)	9			
Calopteryx sp.	4			
Cambaridae	9	2	0.12	2.49
Cambarus sp.	1			
Capniidae	2	1	0.07	1.95
Cardiocladius sp.	12	8	7.79	119.55
Centroptilum/Procloeon sp.	9	7	2.08	20.95
Ceratopogonidae	9	3	0.34	5.96

Table E2. Scientific names, number of site occurrences of invertebrates in qualitative multihabitat and semi-qualitative snag samples and mean and maximum densities of individuals on snags collected from 30 streams in the Metropolitan Atlanta study area, 2002–2003.—Continued

[#, number; m², square meter]

Sceintific name/authority	Number of site occurences in sample types		Density (# per m²) of individuals on snags	
	Qualitative	Snags	Mean density	Maximum density
Ceratopsyche sp.	4	4	3.83	68.25
Chaetocladius sp.	4	3	0.65	13.37
Cheumatopsyche sp.	28	28	111.12	804.36
Chimarra sp.	6	5	0.53	6.47
Chironomus sp.	18	5	1.92	35.18
Chloroperlidae	1			
Cladotanytarsus sp.	2	1	0.13	3.87
Clinotanypus sp.	2			
Coenagrionidae	1			
Collembola	7	6	0.75	9.02
Corbicula sp.	21	11	3.13	46.58
Cordulegaster sp.	1			
Corduliidae	1			
Corydalus cornutus/(Linnaeus)	4			
Corynoneura sp.	7	6	6.21	86.36
Crangonyx sp.	7	3	0.24	4.43
Cricotopus bicinctus group	14	12	44.03	394.24
Cricotopus sp.	14	11	28.90	396.44
Cricotopus/Orthocladius sp.	24	24	40.25	313.27
Cryptochironomus sp.	5	2	0.10	2.10
Cybister fimbriolatus/(Say)	1			
Cymbiodyta sp.	2	1	0.05	1.50
Dannella simplex/(McDunnough)	18	17	8.03	42.10
Dannella sp.	1	1	0.18	5.42
Dasyhelea sp.	2	2	0.26	5.97
Diamesinae	3	3	1.32	27.81
Dicrotendipes sp.	13	13	3.91	31.84
Dineutus ciliatus/(Forsberg)	8			
Dineutus discolor/Aubé	11			
Dineutus sp.	6	5	0.29	2.96
Diploperla duplicata/(Banks)	2	2	0.09	1.95
Dixa sp.	1			
Drunella tuberculata/(Morgan)	1	1	0.66	19.84
Dubiraphia sp.	11	3	0.21	3.94
Eccoptura xanthenes/(Newman)	4	3	0.05	0.69
Ectopria sp.	1	1	0.04	1.31
Elimia sp.	1	1	0.71	21.22
Elliptio sp.	1			
Enallagma sp.	3	1	0.09	2.63
Enchytraeidae	17	14	8.98	136.57
Endochironomus sp.	1			
Epeorus sp.	2	1	0.16	4.94
Ephemerella dorothea/Needham	6	4	0.76	10.91
Ephemerella sp.	5	2	0.67	17.33
Ephydridae	1	1	0.05	1.59

Table E2. Scientific names, number of site occurrences of invertebrates in qualitative multihabitat and semi-qualitative snag samples and mean and maximum densities of individuals on snags collected from 30 streams in the Metropolitan Atlanta study area, 2002–2003.—Continued

[#, number; m², square meter]

Sceintific name/authority	Number of site occurences in sample types		Density (# per m²) of individuals on snags	
	Qualitative	Snags	Mean density	Maximum density
Epoicocladius sp.	1			
Eukiefferiella sp.	8	8	2.44	33.54
Eukiefferiella/Tvetenia sp.	1	1	0.27	8.04
Eurylophella sp.	4	3	3.28	50.69
Glyptotendipes sp.	1			
Gomphidae	6	2	0.11	2.49
Gomphus sp.	7			
Gyrinus marginellus/Fall	1			
Gyrinus sp.	3	1	0.14	4.21
Gyrinus woodruffi/Fall	1			
Hagenius brevistylus/Selys	1			
Hebrus sp.	1	1	0.03	0.77
Helichus basalis/LeConte	5	1	0.04	1.14
Helichus fastigiatus/(Say)	4	4	0.27	3.42
Helichus sp.	2	1	0.02	0.51
Hemerodromia sp.	3	3	0.80	10.05
Hemerodromiinae	7	7	1.47	17.33
Heptagenia sp.	2	2	0.11	2.34
Heptageniidae	2	1	0.15	4.46
Hetaerina sp.	1			
Heterocloeon sp.	1	1	0.21	6.24
Heteroptera	1	1	0.15	4.43
Hexagenia bilineata/(Say)	2			
Hexagenia limbata/(Serville)	2			
Hexagenia sp.	3			
Hexatoma sp.	4	1	0.01	0.27
Hyalella azteca/(Saussure)	9			
Hydra sp.	3	3	0.50	10.47
Hydroporini	4			
Hydropsyche demora/Ross	1			
Hydropsyche depravata group	12	6	1.92	28.93
Hydropsyche sp.	12	12	6.83	60.07
Hydropsyche venularis/Banks	1	1	0.16	4.86
Hydropsychidae	1			
Hydroptila sp.	2	1	0.04	1.16
Hydroptilidae	2	1	0.12	3.61
Isonychia sp.	14	14	3.08	17.71
Isoperla sp.	11	6	1.36	23.51
Labrundinia sp.	3	1	0.09	2.68
Lepidoptera	7	3	0.16	2.63
Lepidostoma sp.	2			
Leptophlebiidae	1			
Leucotrichia pictipes/(Banks)	1			
Leuctra sp.	3	1	0.18	5.54
Limnophyes sp.	14	12	2.90	28.14

Table E2. Scientific names, number of site occurrences of invertebrates in qualitative multihabitat and semi-qualitative snag samples and mean and maximum densities of individuals on snags collected from 30 streams in the Metropolitan Atlanta study area, 2002–2003.—Continued

[#, number; m², square meter]

Sceintific name/authority	Number of site occurences in sample types		Density (# per m²) of individuals on snags	
	Qualitative	Snags	Mean density	Maximum density
Limonia sp.	4			
Limoniinae	1	1	0.44	13.17
Lirceus sp.	7	5	8.85	164.60
Lopescladius sp.	1	1	0.13	3.89
Lumbriculidae	9	2	0.51	10.47
Lype diversa/(Banks)	4	3	0.54	10.57
Macromia sp.	4			
Macronychus glabratus/Say	25	25	18.36	95.15
Megadrile	19	8	0.69	10.47
Microcylloepus pusillus/(LeConte)	1	1	0.70	21.02
Micromenetus sp.	1	1	0.05	1.64
Micropsectra sp.	2			
Micropsectra/Tanytarsus sp.	12	6	0.90	10.21
Microtendipes sp.	13	8	2.90	60.39
Microvelia sp.	4	4	0.45	5.54
Mystacides sepulchralis/(Walker)	1			
Naididae	26	26	141.38	1,012.50
Nanocladius sp.	7	5	0.55	4.11
Nasiaeschna pentacantha/(Rambur)	1			
Natarsia sp.	3	3	0.89	21.26
Nematoda	21	18	6.82	46.58
Neoephemera youngi/Berner	3			
Neoperla sp.	1			
Neoporus sp.	8			
Neurocordulia sp.	1			
Nigronia fasciatus/(Walker)	1			
Nigronia serricornis/(Say)	2			
Nilothauma sp.	10	9	1.30	8.01
Oecetis persimilis/(Banks)	3	1	0.28	8.46
Oecetis sp.	5	4	0.42	4.21
Ophiogomphus sp.	2	1	0.13	3.81
Optioservus ovalis/(LeConte)	1			
Optioservus sp.	3	2	0.17	3.08
Orthocladius lignicola/(Kieffer)	12	12	2.20	13.50
Oulimnius latiusculus/(LeConte)	3	3	0.30	5.54
Oxyethira sp.	1	1	0.08	2.51
Pagastiella sp.	2	2	0.12	2.62
Parachironomus sp.	5	3	0.31	5.36
Paracladopelma sp.	1			
Paragnetina fumosa/(Banks)	7	3	0.41	10.33
Paragnetina sp.	1			
Parakiefferiella sp.	16	15	3.41	20.03
Paralauterborniella nigrohalterale/(Malloch)	1			
Paramerina sp.	6	1	0.10	2.90

Table E2. Scientific names, number of site occurrences of invertebrates in qualitative multihabitat and semi-qualitative snag samples and mean and maximum densities of individuals on snags collected from 30 streams in the Metropolitan Atlanta study area, 2002–2003.—Continued

[#, number; m^2, square meter]

Sceintific name/authority	Number of site occurences in sample types		Density (# per m^2) of individuals on snags	
	Qualitative	Snags	Mean density	Maximum density
Parametriocnemus sp.	22	16	8.41	48.24
Paranyctiophylax sp.	2	2	0.09	2.11
Paraphaenocladius sp.	2	1	0.27	8.04
Parapoynx sp.	1			
Paratanytarsus sp.	10	8	5.94	139.88
Paratendipes sp.	7	3	0.51	6.84
Peltodytes sp.	2			
Peltoperlidae	5	5	1.03	14.78
Pentaneurini	1	1	0.03	1.02
Pericoma/Telmatoscopus sp.	1	1	0.03	0.98
Perlesta sp.	22	19	31.15	175.95
Perlodidae	2	2	0.41	9.02
Phaenopsectra sp.	11	8	2.01	29.14
Phaenopsectra/Tribelos sp.	6	4	0.97	21.36
Phylocentropus sp.	2			
Physa sp.	1			
Physidae	2	2	0.25	5.91
Pisidium sp.	4	1	0.77	23.04
Plathemis lydia/(Drury)	1			
Plauditus sp.	14	11	7.41	48.94
Polypedilum sp.	30	30	209.31	2,378.03
Porifera	1			
Potthastia sp.	15	12	2.55	18.24
Probezzia sp.	1			
Procambarus sp.	8			
Procladius sp.	10	2	0.05	0.79
Progomphus obscurus/(Rambur)	4			
Progomphus sp.	4	1	0.22	6.47
Promoresia tardella/(Fall)	1	1	0.04	1.31
Prostoma sp.	1	1	0.06	1.82
Psectrocladius sp.	1	1	0.07	2.18
Psephenus herricki/(DeKay)	1	1	0.02	0.53
Pseudochironomus sp.	9	8	1.21	12.99
Pseudocloeon sp.	30	24	39.48	333.04
Pseudolimnophila sp.	4			
Pseudosmittia sp.	1	1	0.07	2.18
Pteronarcys sp.	6	5	2.22	38.47
Pycnopsyche sp.	5	2	0.04	0.77
Rhagovelia sp.	8	4	0.79	11.79
Rheocricotopus sp.	21	16	12.20	73.84
Rheosmittia sp.	2	2	3.23	86.36
Rheotanytarsus sp.	30	30	147.00	979.19
Rhyacophila sp.	1	1	0.06	1.88
Robackia sp.	7	2	0.37	9.22

Table E2. Scientific names, number of site occurrences of invertebrates in qualitative multihabitat and semi-qualitative snag samples and mean and maximum densities of individuals on snags collected from 30 streams in the Metropolitan Atlanta study area, 2002–2003.—Continued

[#, number; m^2, square meter]

Sceintific name/authority	Number of site occurences in sample types		Density (# per m^2) of individuals on snags	
	Qualitative	Snags	Mean density	Maximum density
Sciomyzidae	2			
Serratella deficiens/(Morgan)	6	4	1.86	31.96
Simuliidae	15	8	2.45	20.95
Simulium sp.	25	22	135.31	1,069.01
Smittia sp.	7	7	1.74	20.10
Sperchopsis tessellata/(Ziegler)	12	3	0.21	3.08
Sphaeriidae	2	2	0.19	3.65
Stactobiella sp.	2	2	0.27	4.46
Staphylinidae	6	3	0.86	14.78
Stelechomyia perpulchra/(Mitchell)	3	3	0.35	5.24
Stempellinella sp.	4	3	0.39	5.70
Stenacron interpunctatum/(Say)	6	1	0.05	1.58
Stenacron sp.	1	1	0.25	7.50
Stenelmis crenata/(Say)	2	2	0.15	4.21
Stenelmis mera/Sanderson	1			
Stenelmis sp.	10	6	1.44	14.92
Stenochironomus sp.	17	15	4.73	26.20
Stenonema modestum/(Banks)/ *smithae*/Traver	23	21	15.20	192.71
Stenonema sp.	5			
Stictochironomus sp.	4	1	0.07	2.13
Stylogomphus albistylus/(Hagen)	6	2	0.07	1.50
Stylurus sp.	1			
Sublettea coffmani/(Roback)	5	5	4.10	74.73
Tabanidae	1			
Taeniopteryx sp.	2	2	0.15	2.51
Tallaperla sp.	1	1	0.18	5.54
Tanypodinae	2	2	0.17	3.41
Tanytarsus sp.	27	27	15.66	81.71
Thienemanniella sp.	16	16	3.94	29.78
Thienemannimyia group sp./ (Coffman and Ferrington, 1996)	26	13	5.33	47.31
Tipula sp.	10	3	0.95	26.15
Tipulidae	4	2	0.36	9.10
Triaenodes sp.	5			
Tribelos sp.	18	8	3.28	60.39
Tropisternus sp.	1	1	0.05	1.50
Tubificidae	24	16	4.82	27.06
Tvetenia sp.	17	16	7.84	42.19
Unionidae	1			
Xestochironomus sp.	7	7	3.41	50.76
Xylotopus par/(Coquillett)	22	20	9.99	56.58
Zavrelimyia sp.	1			

Table E3. Scientific names, common names, basin distribution, numbers collected, and site occurrences of fishes collected from 30 streams in the Oconee–Ocmulgee and Chattahoochee–Flint River Basins in the Metropolitan Atlanta study area, 2002–2003.

Scientific name	Common name	Oconee–Ocmulgee	Chattahoochee–Flint	Number collected	Number of occurences
Ameiurus brunneus	Snail bullhead	x	x	230	21
Ameiurus natalis	Yellow bullhead	x	x	20	8
Ameiurus nebulosus	Brown bullhead	x		1	1
Ameiurus platycephalus	Flat bullhead		x	2	2
Ameiurus sp.	Unidentified bullhead	x	x	2	2
Amia calva	Bowfin		x	3	2
Aphredoderus sayanus	Pirate perch	x	x	21	4
Campostoma pauciradii	Bluefin stoneroller		x	113	10
Carassius auratus	Goldfish		x	1	1
Catostomus commersonii	White sucker	x	x	12	3
Centrarchus macropterus	Flier	x	x	4	2
Chaenobryttus gulosus	Warmouth	x	x	44	17
Cottus sp.[1]	Unidentified sculpin		x	14	1
Cyprinella callisema	Ocmulgee shiner	x		48	4
Cyprinella lutrensis	Red shiner		x	275	3
Cyprinella venusta	Blacktail shiner		x	338	12
Cyprinella xaenura	Altamaha shiner	x		46	5
Cyprinus carpio	Common carp	x		2	1
Esox americanus	Redfin pickerel	x	x	26	6
Esox niger	Chain pickerel	x	x	8	5
Etheostoma hopkinsi	Christmas darter	x		3	2
Etheostoma inscriptum	Turquoise darter	x		247	6
Etheostoma swaini	Gulf darter		x	34	4
Fundulus stellifera	Southern studfish		x	3	3
Gambusia affinis	Western mosquito fish	x	x	44	9
Gambusia sp.	Unidentified mosquito fish	x	x	2	2
Hybognathus regius	Eastern silvery minnow	x		42	1
Hybopsis sp. cf. H. winchelli	Undescribed chub		x	145	14
Hypentelium etowanum	Alabama hog sucker		x	127	11
Hypentelium nigricans	Northern hog sucker	x		14	2
Ichthyomyzon gagei	Southern brook lamprey		x	40	8
Ictalurus punctatus	Channel catfish	x		4	2
Labidesthes sicculus	Brook silverside		x	12	5

Table E3. Scientific names, common names, basin distribution, numbers collected, and site occurrences of fishes collected from 30 streams in the Oconee–Ocmulgee and Chattahoochee–Flint River Basins in the Metropolitan Atlanta study area, 2002–2003.—Continued

Scientific name	Common name	Oconee–Ocmulgee	Chattahoochee–Flint	Number collected	Number of occurences
Lepomis auritus	Redbreast sunfish	x	x	1,245	30
Lepomis cyanellus	Green sunfish	x	x	266	20
Lepomis macrochirus	Bluegill	x	x	1,170	29
Lepomis microlophus	Redear sunfish	x	x	4	4
Lepomis punctatus	Spotted sunfish		x	74	13
Luxilus zonistius	Bandfin shiner		x	220	7
Lythrurus atrapiculus	Blacktip shiner		x	2	1
Micropterus coosae	Redeye bass	x	x	24	4
Micropterus punctulatus	Spotted bass		x	6	5
Micropterus salmoides	Largemouth bass	x	x	88	25
Minytrema melanops	Spotted sucker	x	x	11	5
Moxostoma sp. cf. M. poecilurum	Undescribed redhorse		x	8	3
Nocomis leptocephalus	Bluehead chub	x	x	497	21
Notemigonus crysoleucas	Golden shiner	x	x	3	2
Notropis buccatus	Silverjaw minnow	x	x	104	13
Notropis cummingsae	Dusky shiner	x	x	2	2
Notropis hudsonius	Spottail shiner	x	x	104	11
Notropis hypsilepis	Highscale shiner		x	70	10
Notropis longirostris	Longnose shiner		x	212	10
Notropis lutipinnis	Yellowfin shiner	x	x	549	17
Notropis petersoni	Coastal shiner	x		1	1
Notropis rubrifrons	Rosyface chub	x		80	7
Notropis texanus	Weed shiner		x	246	8
Noturus funebris	Black madtom		x	15	2
Noturus insignis	Margined madtom	x		40	7
Noturus leptacanthus	Speckled madtom		x	67	10
Opsopoeodus emiliae	Pugnose minnow		x	2	1
Percina nigrofasciata	Blackbanded darter	x	x	1,022	28
Pimephales promelas	Fathead minnow		x	1	1
Pomoxis nigromaculatus	Black crappie	x	x	16	12
Scartomyzon lachneri	Greater jumprock		x	27	4
Scartomyzon rupiscartes	Striped jumprock	x		43	7
Semotilus atromaculatus	Creek chub		x	1	1

[1]Taxonomy of the species presently classified as "Cottus" in the Chattahoochee River Basin is currently under revision (Boshchung and Mayden, 2004)

Manuscript approved for publication, October 10, 2007

Prepared by USGS Georgia Water Science Center

Edited by Patricia L. Nobles

Graphics and layout by Caryl J. Wipperfurth

For more information concerning the research in this report, contact
USGS Georgia Water Science Center, Atlanta
telephone: 770-903-9100