National Water-Quality Assessment Program

A Comparison of Natural and Urban Characteristics and the Development of Urban Intensity Indices Across Six Geographic Settings

Scientific Investigations Report 2007–5123

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

A Comparison of Natural and Urban Characteristics and the Development of Urban Intensity Indices Across Six Geographic Settings

By James Falcone, Jana Stewart, Steven Sobieszczyk, Jean Dupree, Gerard McMahon, and Gary Buell

National Water-Quality Assessment Program

Scientific Investigations Report 2007–5123

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:
Falcone, James, Stewart, Jana, Sobieszczyk, Steven, Dupree, Jean, McMahon, Gerard, and Buell, Gary, 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., 7 apps.

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 our 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. From 1991–2001, the NAWQA Program completed interdisciplinary assessments and established a baseline understanding of water-quality conditions in 51 of the Nation's river watersheds and aquifers, referred to as Study Units *(http://water.usgs.gov/nawqa/studyu.html)*.

Multiple national and regional assessments are ongoing in the second decade (2001–2012) of the NAWQA Program as 42 of the 51 Study Units are reassessed. These assessments extend the findings in the Study Units by determining status and trends at sites that have been consistently monitored for more than a decade, and filling critical gaps in characterizing the quality of surface water and ground water. For example, increased emphasis has been placed on assessing the quality of source water and finished water associated with many of the Nation's largest community water systems. During the second decade, NAWQA is addressing five national priority topics that build an understanding of how natural features and human activities affect water quality, and establish links between ***sources*** of contaminants, the ***transport*** of those contaminants through the hydrologic system, and the potential ***effects*** of contaminants on humans and aquatic ecosystems. Included are topics on the fate of agricultural chemicals, effects of urbanization on stream ecosystems, bioaccumulation of mercury in stream ecosystems, effects of nutrient enrichment on aquatic ecosystems, and transport of contaminants to public-supply wells. These topical studies are conducted in those Study Units most affected by these issues; they comprise a set of multi-Study-Unit designs for systematic national assessment. In addition, national syntheses of information on pesticides, volatile organic compounds (VOCs), nutrients, selected trace elements, and aquatic ecology are continuing.

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

Figures

Tables

Conversion Factors

SI to Inch/Pound

Multiply	By	To obtain
	Length	
centimeter (cm)	0.3937	inch (in.)
meter (m)	3.281	foot (ft)
kilometer (km)	0.6214	mile (mi)
kilometer (km)	0.5400	mile, nautical (nmi)
meter (m)	1.094	yard (yd)
	Area	
hectare (ha)	2.471	acre
square meter (m^2)	0.0002471	acre
square kilometer (km^2)	247.1	acre
square meter (m^2)	10.76	square foot (ft^2)
hectare (ha)	0.003861	square mile (mi^2)
square kilometer (km^2)	0.3861	square mile (mi^2)

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

$$°F = (1.8 \times °C) + 32$$

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

$$°C = (°F - 32) / 1.8$$

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

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

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

A Comparison of Natural and Urban Characteristics and the Development of Urban Intensity Indices across Six Geographic Settings

By James Falcone, Jana Stewart, Steven Sobieszczyk, Jean Dupree, Gerard McMahon, and Gary Buell

Abstract

As part of the U.S. Geological Survey National Water-Quality Assessment Program, the effects of urbanization on stream ecosystems have been intensively investigated in six metropolitan areas in the United States. Approximately 30 watersheds in each area, ranging in size from 4 to 560 square kilometers (median is 50 square kilometers), and spanning a development gradient from very low to very high urbanization, were examined near Atlanta, Georgia; Raleigh, North Carolina; Denver, Colorado; Dallas-Fort Worth, Texas; Portland, Oregon; and Milwaukee-Green Bay, Wisconsin. These six studies are a continuation of three previous studies in Boston, Massachusetts; Birmingham, Alabama; and Salt Lake City, Utah. In each study, geographic information system data for approximately 300 variables were assembled to (a) characterize the environmental settings of the areas and (b) establish a consistent multimetric urban intensity index based on locally important land-cover, infrastructure, and socioeconomic variables. This paper describes the key features of urbanization and the urban intensity index for the study watersheds within each area, how they differ across study areas, and the relation between the environmental setting and the characteristics of urbanization. A number of features of urbanization were identified that correlated very strongly to population density in every study area. Of these, road density had the least variability across diverse geographic settings and most closely matched the multimetric nature of the urban intensity index. A common urban intensity index was derived that ranks watersheds across all six study areas. Differences in local natural settings and urban geography were challenging in (a) identifying consistent urban gradients in individual study areas and (b) creating a common urban intensity index that matched the site scores of the local urban intensity index in all areas. It is intended that the descriptions of the similarities and differences in urbanization and environmental settings across these study areas will provide a foundation for understanding and interpreting the effects of urbanization on stream ecosystems in the studies being conducted as part of the National Water-Quality Assessment Program.

Introduction

The effects of urbanization on stream hydrology, water quality, physical habitat, and stream temperature have been documented in numerous studies (Leopold, 1968; House and others, 1993; Booth and Jackson, 1997; U.S. Environmental Protection Agency, 1997; Paul and Meyer, 2001; Walsh and others, 2005). Anthropogenic impervious surfaces are a major influence: they increase the frequency and intensity of runoff, accelerate erosion and loss of riparian habitat, facilitate the transport of contaminants, and alter the natural heat flux within urban streams (Schueler, 1994; Center for Watershed Protection, 2003, Walsh and others, 2005). The effects of urbanization are influenced by a complex interaction of multiple factors, however, not just impervious surfaces (Karr and Chu, 2000), including housing, transportation infrastructure, population, landscape pattern, and socioeconomic factors. While responses to single-variable representations of urban intensity (for example roads, impervious surfaces or population density) are well documented, the effect of combined variables are less well understood, particularly when compared across diverse geographic settings (Paul and Meyer, 2001).

The U.S. Geological Survey (USGS) National Water-Quality Assessment (NAWQA) Program began a series of studies in 1999 that used a common design to examine the effects of urbanization on aquatic biota (fish, invertebrates, and algae), physical habitat, and water chemistry in different environmental settings (McMahon and Cuffney, 2000). The design used a multimetric urban intensity index (UII) that combines multiple urban characteristics to identify gradients of urbanization within relatively homogeneous environmental settings (McMahon and Cuffney, 2000; Tate and others, 2005). Initial studies were completed near Boston, Massachusetts; Birmingham, Alabama; and Salt Lake City, Utah (Tate and others, 2005). Subsequent studies centered around six additional metropolitan areas: Atlanta, Georgia; Raleigh, North Carolina; Denver, Colorado; Dallas-Fort Worth, Texas; Portland, Oregon; and Milwaukee-Green Bay, Wisconsin; and are described in this paper. These studies are part of the NAWQA Effects of Urbanization on Stream Ecosystems

(EUSE) program (U.S. Geological Survey, 2002). Future studies are scheduled for implementation in Seattle-Tacoma, Washington, and Sacramento, California (fig. 1).

In each study, the multimetric index was used both as a planning tool for identifying a gradient of final study watersheds, and as an explanatory factor for examining response variables (Cuffney and others, 2005; Meador and others, 2005; Potapova and others, 2005; Short and others, 2005). Multimetric indices can be used to characterize complex systems (Karr, 1981; Yoder and Rankin, 1995) and potentially provide distinct information about a system that may not be apparent from a single metric (McMahon and Cuffney, 2000). The UII used in this study combined characteristics of urbanization that correlated strongly to population density. Although a local index was derived separately for the group of approximately 30 final watersheds in each study area, the study design provided a mechanism by which multiple aspects of urbanization could be combined into a common urban intensity index (CUII) and compared across diverse settings, using the 175 final watersheds located in the 6 metropolitan study areas.

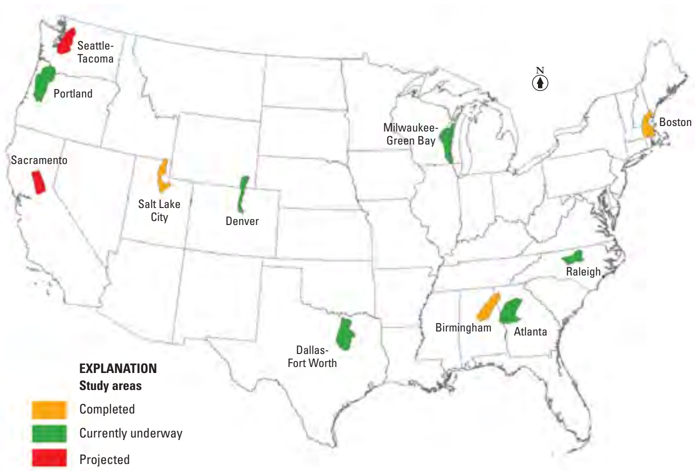


Figure 1. Location of study areas in the U.S. Geological Survey Effects of Urbanization on Stream Ecosystems (EUSE) program.

Purpose and Scope

Urban characteristics in six metropolitan study areas are discussed in this paper. The study areas are Atlanta, Georgia; Raleigh, North Carolina; Denver, Colorado; Dallas-Fort Worth, Texas; Portland, Oregon; and Milwaukee-Green Bay, Wisconsin.

The objectives of this paper are to (a) describe the data sources and methods used for characterizing urbanization in the study watersheds of these six study areas, (b) compare the environmental setting and key features of urbanization in these areas, and (c) discuss the issues and application of the UII, both within and across study areas. This description is designed to lay the foundation for hypothesis generation and testing of the effects of urbanization on stream ecosystems in ongoing concurrent NAWQA EUSE studies.

Methods

In the EUSE study, six geographic areas with large urban populations were identified. An attempt was made to identify urbanized areas with relatively homogeneous environmental settings to examine the effects of urbanization without the confounding effect of differing environmental conditions (for example, soils and climate). Metropolitan areas primarily within a single U.S. Environmental Protection Agency (USEPA) Level III ecoregion (Omernik, 1987) were identified to minimize natural variations among the study watersheds.

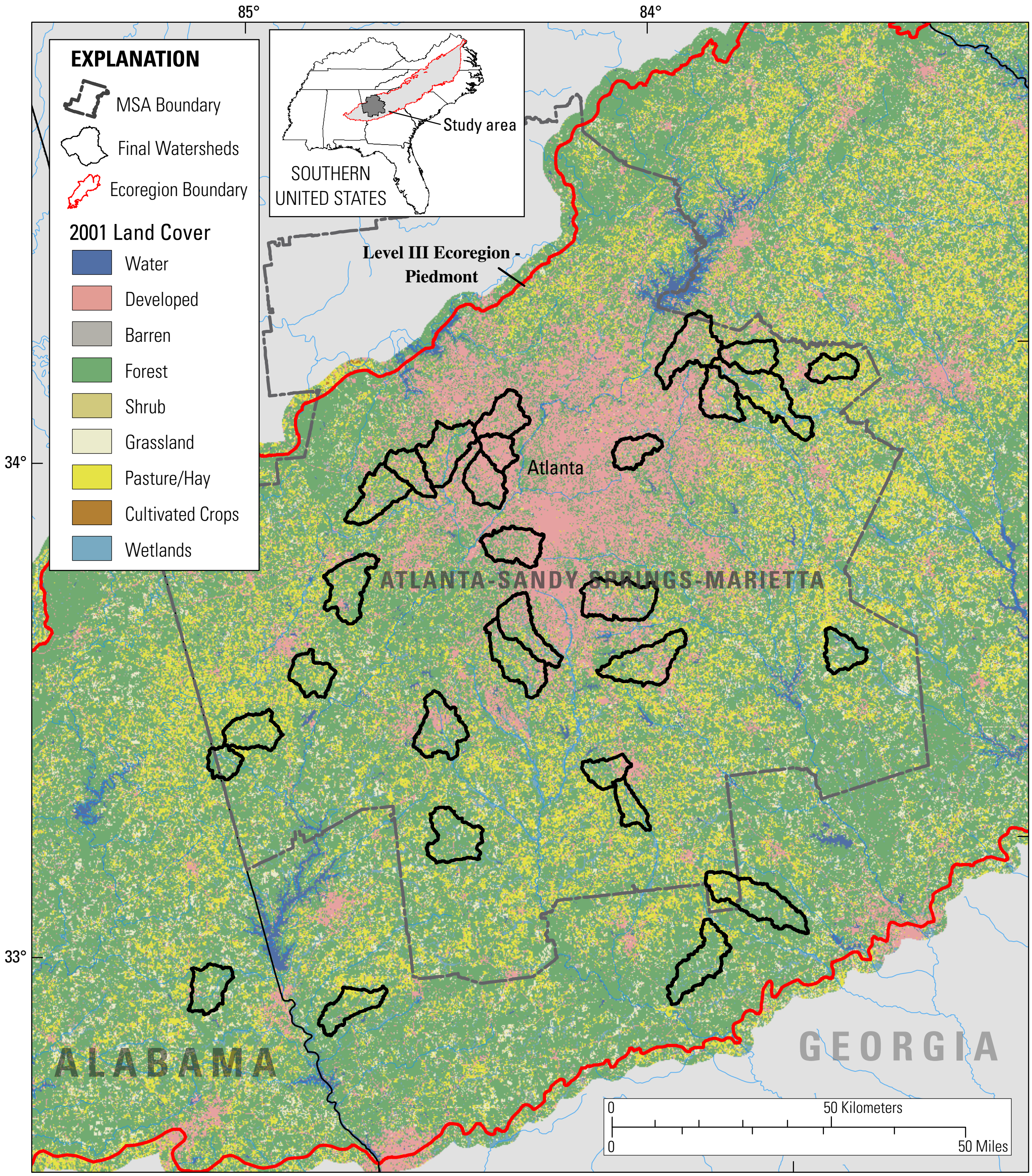
Study Areas

A general description of the six regional areas follows. Regional population statistics are based on Office of Management and Budget metropolitan statistical areas (MSAs), defined as core areas containing a population nucleus of at least 50,000 people together with adjacent communities having a high degree of economic and social integration within the core area (Office of Management and Budget, 2000; U.S. Census Bureau, 2006a). In two areas (Atlanta and Dallas-Fort Worth), study watersheds are centered around a single dominant MSA, but span the geographic extent of multiple MSAs in the other four areas (Raleigh, Denver, Portland, and Milwaukee-Green Bay).

Atlanta

The Atlanta (ATL) study area is located in north-central Georgia, and portions of eastern Alabama (fig. 2). The population of the MSA of Atlanta-Sandy Springs-Marietta in 2000 was 4,247,981, a 38.4 percent increase from the population in 1990 (table 1; U.S. Census Bureau, 2006c). Per capita income in the Atlanta-Sandy Springs-Marietta MSA in 2003 was $32,739, or 4 percent above the national average of $31,484 (Bureau of Economic Analysis, 2006). The economy is diversified and includes industrial, commercial, and service sectors (McKnight, 2001).

The ATL study watersheds are located entirely within the USEPA Piedmont Level III ecoregion (Omernik, 1987), specifically in the Southern Inner and Southern Outer Piedmont Level IV ecoregions (U.S. Environmental Protection Agency, 2006a). The study area is characterized by gently rolling topography and dissected irregular plains, with elevations ranging from about 100 to 500 meters (m) above



Base from digital files of:
Political boundaries, U.S. Department of Commerce,
Bureau of Census, 2003, 1:100,000 scale
River File 3, U.S. Environmental Protection Agency, 1:500,000 scale
National Land Cover Dataset, U.S. Geological Survey, 2001, 30-meter resolution
Ecoregion, Level III, U.S. Environmental Protection Agency, 2003, 1:250,000 scale
Map Projection, Albers Equal Area, North American Datum 1983

Figure 2. Locations of study watersheds and 2001 land-cover data for the Atlanta study area (U.S. Geological Survey, 2005c). Metropolitan statistical area (MSA) boundaries are based on June 6, 2003, MSA definitions (U.S. Census Bureau, 2006c).

Table 1. Summary of regional-scale characteristics of study areas.

[Population and income statistics are for the predominant metropolitan statistical areas (MSAs), as listed (U.S. Census Bureau, 2006c; Bureau of Economic Analysis, 2006). “Sprawl index” values (Sutton, 2003) are relative indicators of sprawl in urban clusters based on satellite night-light observations. Negative values suggest “more sprawl” (lower urban population density than expected); positive values suggest “less sprawl” (higher urban population density than expected). (See text under Discussion for more detail). Climate and topographic statistics (shaded rows) are for the area encompassing all study watersheds, a broader area than the MSA(s). USEPA, U.S. Environmental Protection Agency]

Characteristic	Study area (abbreviation)					
	Atlanta (ATL)	Raleigh (RAL)	Denver (DEN)	Dallas-Fort Worth (DFW)	Portland (POR)	Milwaukee-Green Bay (MGB)
Major Metropolitan Statistical Area(s) (MSAs)	Atlanta-Sandy Springs-Marietta	Raleigh-Cary	Denver-Aurora	Dallas-Fort Worth-Arlington	Portland-Vancouver-Beaverton	Milwaukee-Waukesha-West Allis
		Greensboro-High Point	Boulder		Salem	Green Bay
		Durham	Fort Collins-Loveland		Eugene-Springfield	Appleton
		Winston-Salem	Cheyenne		Corvallis	Racine
		Burlington				Oshkosh-Neenah
Population in combined MSAs, Census 2000	4,247,981	2,419,755	2,782,155	5,161,544	2,676,207	2,330,536
Population increase in combined MSAs, 1990–2000 (percent)	38.4	27.7	30.3	29.4	24.2	7.6% (14.7% Green Bay-Appleton-Oshkosh; 5.1% Milwaukee-Racine)
Combined MSAs 2003 Per Capita Personal Income	$32,739	$30,724	$38,544	$34,109	$30,797	$33,488
“Sprawl index”	–32	–8 (Raleigh); –21 Greensboro)	+7	–15	+13	–51 (Green Bay); +6 (Milwaukee)
Predominant USEPA Level III ecoregion	Piedmont	Piedmont	Western High Plains	Texas Blackland Prairies	Willamette Valley	Southeastern Wisconsin Till Plains
Study area mean annual air temperature (degrees Celsius)	16.6	15.0	8.1	18.2	11.1	7.5
Study area mean annual precipitation (centimeters)	131	118	43	105	145	85
Study area mean elevation (meters)	249	172	1,800	165	169	246
Study area mean slope (percent)	3.9	3.2	5.4	1.3	7.9	1.4

North American Vertical Datum of 1988 (NAVD 88; U.S. Geological Survey, 2005a). The climate is warm and humid, with mean annual precipitation of about 130 centimeters (cm), and mean annual air temperature of about 17 degrees Celsius (°C; Daymet, 2005). Streams in the area typically have low to moderate gradients with cobble, gravel, and sandy substrates. Streamflow in the southern Piedmont is generally highest in the winter and lowest in late summer and fall. Natural vegetation in the Piedmont ecoregion is oak-hickory-pine forest; however, current land use and land cover includes forested areas in silviculture and agricultural production of hay, cattle and poultry.

Raleigh

The Raleigh (RAL) study area is located in north-central North Carolina, and includes five predominant MSAs (fig. 3). The MSAs are Raleigh-Cary, with a population 797,071 in 2000, an increase of 47.3 percent since 1990; Greensboro-High Point, with a population of 643,430 in 2000, an increase of 19.1 percent since 1990; Durham, with a population of 426,493 in 2000, an increase of 23.8 percent since 1990; Winston-Salem, with a population of 421,961 in 2000, an increase of 16.7 percent since 1990; and Burlington, with a population of 130,800 in 2000, an increase of 20.9 percent since 1990 (table 1; U.S. Census Bureau, 2006c). The population for the combined MSAs increased by 27.7 percent from 1990 to 2000 (U.S. Census Bureau, 2006c). Per capita income in the combined five MSAs in 2003 was $30,724, or 2 percent below the national average of $31,484 (Bureau of Economic Analysis, 2006). The economy is diversified and has grown substantially in recent decades, in part as a result of the "Research Triangle" of Raleigh-Durham-Chapel Hill, a successful corporate research area associated with three nearby universities (McKnight, 2001). Heavier industry, primarily textiles, tobacco, chemicals, and furniture, dominate in the western part of the study area near Winston-Salem and Greensboro.

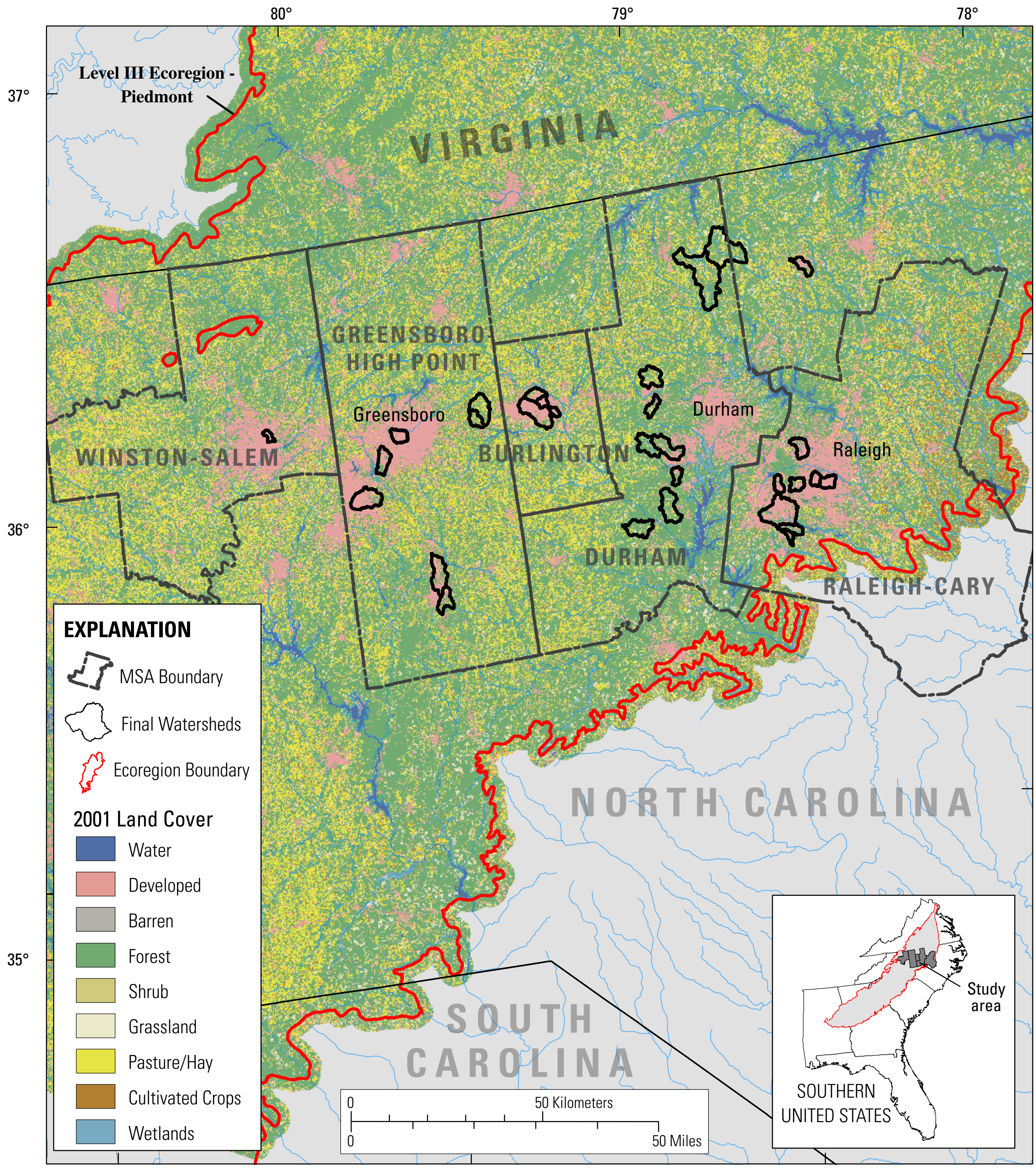
The RAL study watersheds are located entirely within the USEPA Piedmont Level III ecoregion (Omernik, 1987) and specifically are in the Northern Outer Piedmont, Southern Outer Piedmont, and Carolina Slate Belt Level IV ecoregions (U.S. Environmental Protection Agency, 2006a). The study area is characterized by irregular plains with some hills, and elevations ranging from about 50 to 330 m above NAVD 88 (U.S. Geological Survey, 2005a). The climate is warm and humid, with mean annual precipitation of about 118 cm, and mean annual air temperature of about 15 °C (Daymet, 2005). Rainfall is evenly distributed throughout the year, with slightly more rainfall in July and August and slightly less in October through December. Streams in all three subecoregions have low to moderate gradients and typically have gravel to cobble substrate. Streamflow typically is highest in the winter months, when deciduous vegetation is dormant, and lowest in late summer. Land use in the area has undergone major transformations, from oak-hickory-pine forests to agricultural lands, to forest again, and currently (2006) to urban and suburban lands. At one time, the region was heavily farmed in cotton, tobacco, corn, and wheat, and many areas underwent moderate to severe erosion of the silt/clay soils (Trimble, 1974).

Denver

The Denver (DEN) study area is located in north-central Colorado and southeastern Wyoming, and includes four predominant MSAs (fig. 4). The MSAs are Denver-Aurora, with a population 2,179,240 in 2000, an increase of 30.7 percent since 1990; Boulder, with a population of 269,814 in 2000, an increase of 29.1 percent since 1990; Fort Collins-Loveland, with a population of 251,494 in 2000, an increase of 35.1 percent since 1990; and Cheyenne, with a population of 81,607 in 2000, an increase of 11.6 percent since 1990 (table 1; U.S. Census Bureau, 2006c). The combined MSAs increased in population 30.3 percent from 1990 to 2000 (U.S. Census Bureau, 2006c). The economy is diversified and includes telecommunications, software, agriculture, mining, and heavy industry. Denver is a major regional center for U.S. Government offices, a transportation hub, and a tourist gateway to the mountain recreational areas of the southern Rockies (McKnight, 2001). Per capita income in the four combined MSAs in 2003 was $38,544, or 22 percent above the national average of $31,484 (Bureau of Economic Analysis, 2006).

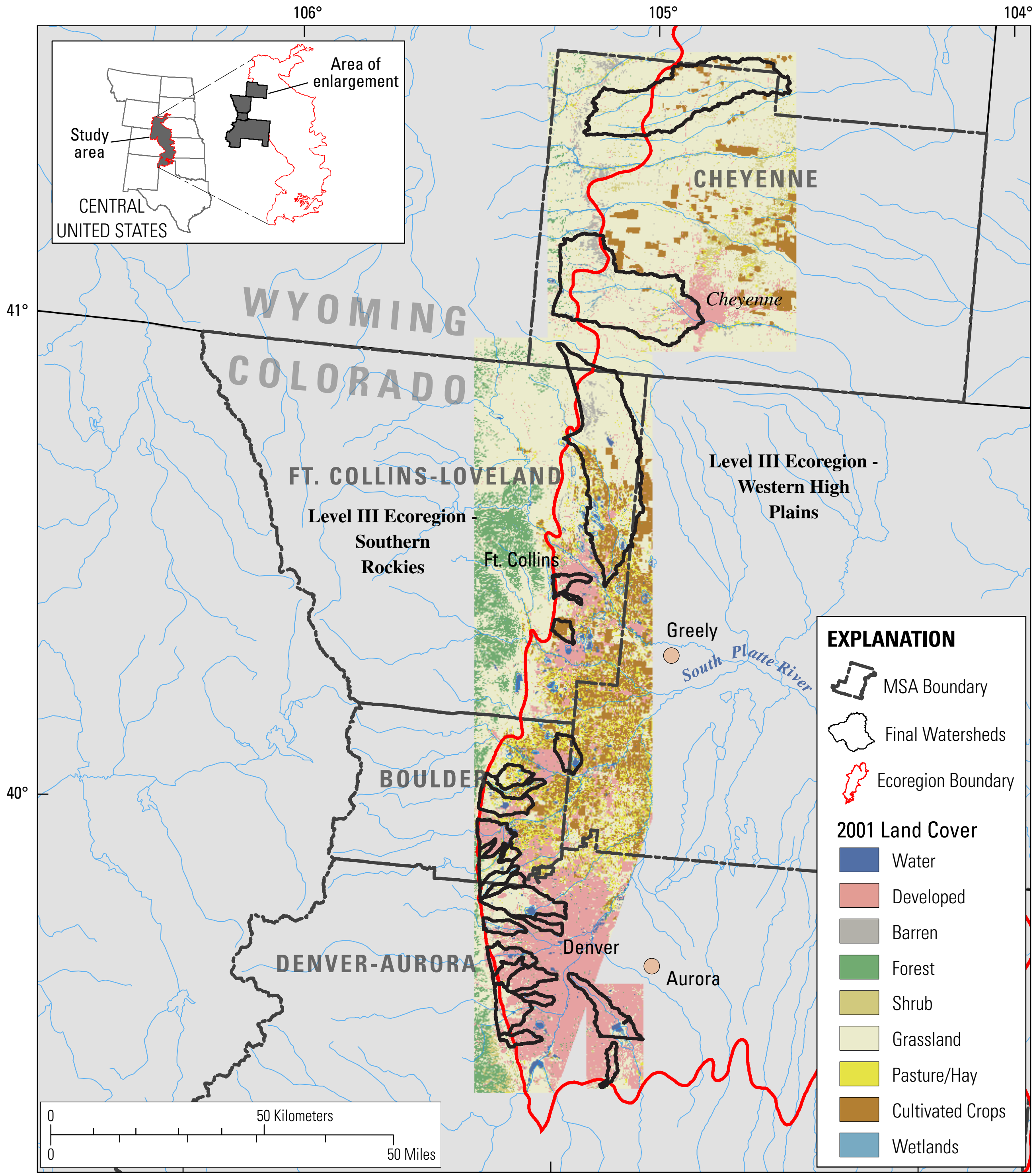
The major drainage in the DEN study area is the South Platte River. The study watersheds are located almost entirely within the USEPA Western High Plains Level III ecoregion (Omernik, 1987), except for western portions of a few watersheds, mainly in Wyoming, that are considered to be part of the Southern Rockies ecoregion[1]. Elevation in the study area ranges from about 1,500 to 2,500 m above NAVD 88 (U.S. Geological Survey, 2005a), although the study area is bordered on the west by the Southern Rockies ecoregion, where elevations are considerably higher. The climate is semiarid, and precipitation in the study area is affected considerably by topography. Most of the precipitation on the plains results from rainfall, primarily between April and September; however, perennial streamflow also is fed by snowmelt from the mountains, where snowfall occurs during the winter. Mean annual precipitation is about 43 cm, and mean annual air temperature is about 8 °C (Daymet, 2005). Smaller streams are often ephemeral, and a complex network of ditches and pipes moves water between different areas for domestic water supply, agricultural irrigation, and power generation (Sprague and others, 2006). Land cover in the study area is dominated by grassland and agriculture in the plains, and coniferous forest in the western mountains.

[1] Wyoming and Colorado Level III ecoregion boundaries were revised by the USEPA as the DEN study progressed.



Base from digital files of:
Political boundaries, U.S. Department of Commerce,
Bureau of Census, 2003, 1:100,000 scale
River File 3, U.S. Environmental Protection Agency, 1:500,000 scale
National Land Cover Dataset, U.S. Geological Survey, 2001, 30-meter resolution
Ecoregion, Level III, U.S. Environmental Protection Agency, 2003, 1:250,000 scale
Map Projection, Albers Equal Area, North American Datum 1983

Figure 3. Locations of study watersheds and 2001 land-cover data for the Raleigh study area (U.S. Geological Survey, 2005c). Metropolitan statistical area (MSA) boundaries are based on June 6, 2003, MSA definitions (U.S. Census Bureau, 2006c).



Base from digital files of:
Political boundaries, U.S. Department of Commerce,
Bureau of Census, 2003, 1:100,000 scale
River File 3, U.S. Environmental Protection Agency, 1:500,000 scale
National Land Cover Dataset, U.S. Geological Survey, 2001, 30-meter resolution
Ecoregion, Level III, U.S. Environmental Protection Agency, 2003, 1:250,000 scale
Map Projection, Albers Equal Area, North American Datum 1983

Figure 4. Locations of study watersheds and 2001 land-cover data for the Denver study area (Falcone and Pearson, 2006). Note: 2001 land-cover data were derived only for areas covering final study watersheds; therefore, land cover is not represented for entire Denver metropolitan area. Metropolitan statistical area (MSA) boundaries are based on June 6, 2003, MSA definitions (U.S. Census Bureau, 2006c).

Dallas-Fort Worth

The Dallas-Fort Worth (DFW) study area is in north-central Texas (fig. 5). The predominant metropolitan area, the MSA of Dallas-Fort Worth-Arlington, had a population in 2000 of 5,161,544, a 29.4 percent increase since 1990 (table 1; U.S. Census Bureau, 2006c). Dallas is a major regional center, and the economy includes finance, oil, transportation, aerospace, and electronics. Fort Worth, a twin city to Dallas, has an economic focus based on cattle, railways, and agricultural processing (McKnight, 2001). Per capita income in the Dallas-Fort Worth-Arlington MSA in 2003 was $34,109, or 8 percent above the national average of $31,484 (Bureau of Economic Analysis, 2006).

The DFW study area is located in the upper drainage of the Trinity River watershed and overlies, from west to east, the USEPA Texas Blackland Prairies and East-Central Texas Plains Level III ecoregions (Omernik, 1987). The study watersheds are located primarily in the Texas Blackland Prairies ecoregion, which is an area of generally rolling to level plains. Elevation in the study area ranges from about 80 to 270 m above NAVD 88 (U.S. Geological Survey, 2005a). The climate is semiarid, and precipitation occurs primarily in the spring and during summer thunderstorms. Mean annual precipitation is about 105 cm, and the mean annual air temperature is about 18 °C (Daymet, 2005). Surface-water in the study area consists primarily of reservoirs, intrawatershed transfers, diversions of water to municipalities, and wastewater effluent. Small streams in the area are generally intermittent. Land cover includes grasslands, pastures, row-crops, and urban land uses.

Portland

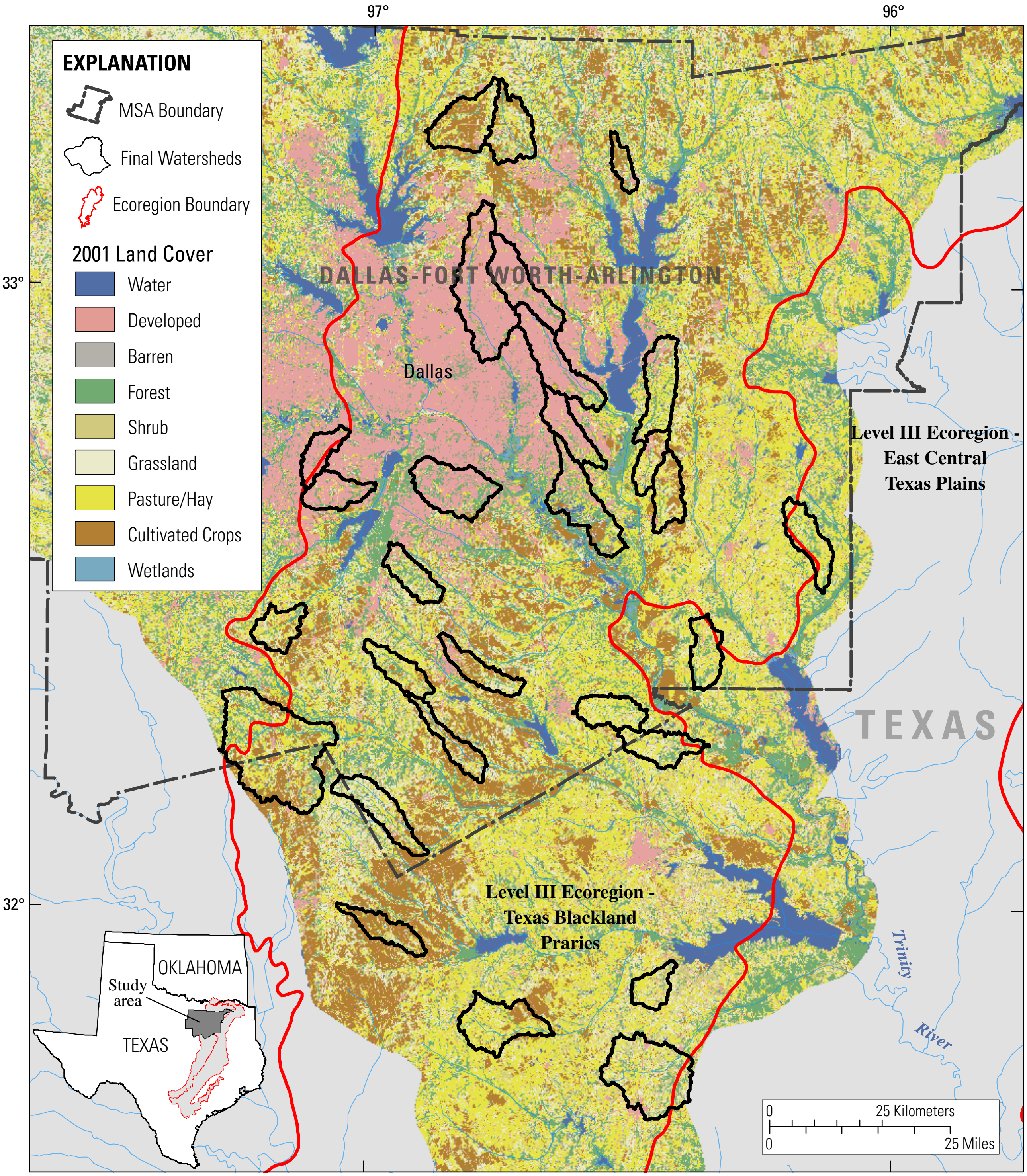
The Portland (POR) study area is located in western Oregon and southwestern Washington, and includes four predominant MSAs (fig. 6). The MSAs are Portland-Vancouver-Beaverton, with a population 1,927,881 in 2000, an increase of 26.5 percent since 1990; Salem, with a population of 347,214 in 2000, an increase of 24.9 percent since 1990; Eugene-Springfield, with a population of 322,959 in 2000, an increase of 14.2 percent since 1990; and Corvallis, with a population of 78,153 in 2000, an increase of 10.4 percent since 1990 (table 1; U.S. Census Bureau, 2006c). The combined MSAs increased in population 24.2 percent from 1990 to 2000 (U.S. Census Bureau, 2006c). Portland is the dominant commercial center of the study area, and includes extensive port facilities on the Columbia and Willamette Rivers, and is a center for extensive retail and consumer trade. The economy includes forestry and timber processing; fruit, wheat, and specialized farming; dairying; and food processing. Per capita income in the four combined MSAs in 2003 was $30,797, or 2 percent below the national average of $31,484 (Bureau of Economic Analysis, 2006).

The major drainage in the POR study area is the Willamette River. The study area is primarily in the USEPA Willamette Valley Level III ecoregion (Omernik, 1987). The Willamette Valley ecoregion is characterized by a broad, lowland valley with a patchwork of land-use types that include agriculture, evergreen forests, wetlands, and urban areas. Landforms consist of terraces and flood plains that are interlaced and surrounded by rolling hills. Elevation in the study area ranges from about 10 to 1,400 m above NAVD 88 (U.S. Geological Survey, 2005a), including the foothills of the Cascades mountain range. The climate is characterized by cool, wet winters and warm, dry summers. Mean annual precipitation in the study area is about 145 cm, and the mean annual air temperature is about 11 °C (Daymet, 2005). Most of the precipitation occurs between October and April. Highest streamflows generally occur from November through April, when either heavy winter rains or spring snowmelt causes rivers to swell. Lowest streamflows generally occur in summer and fall.

Milwaukee-Green Bay

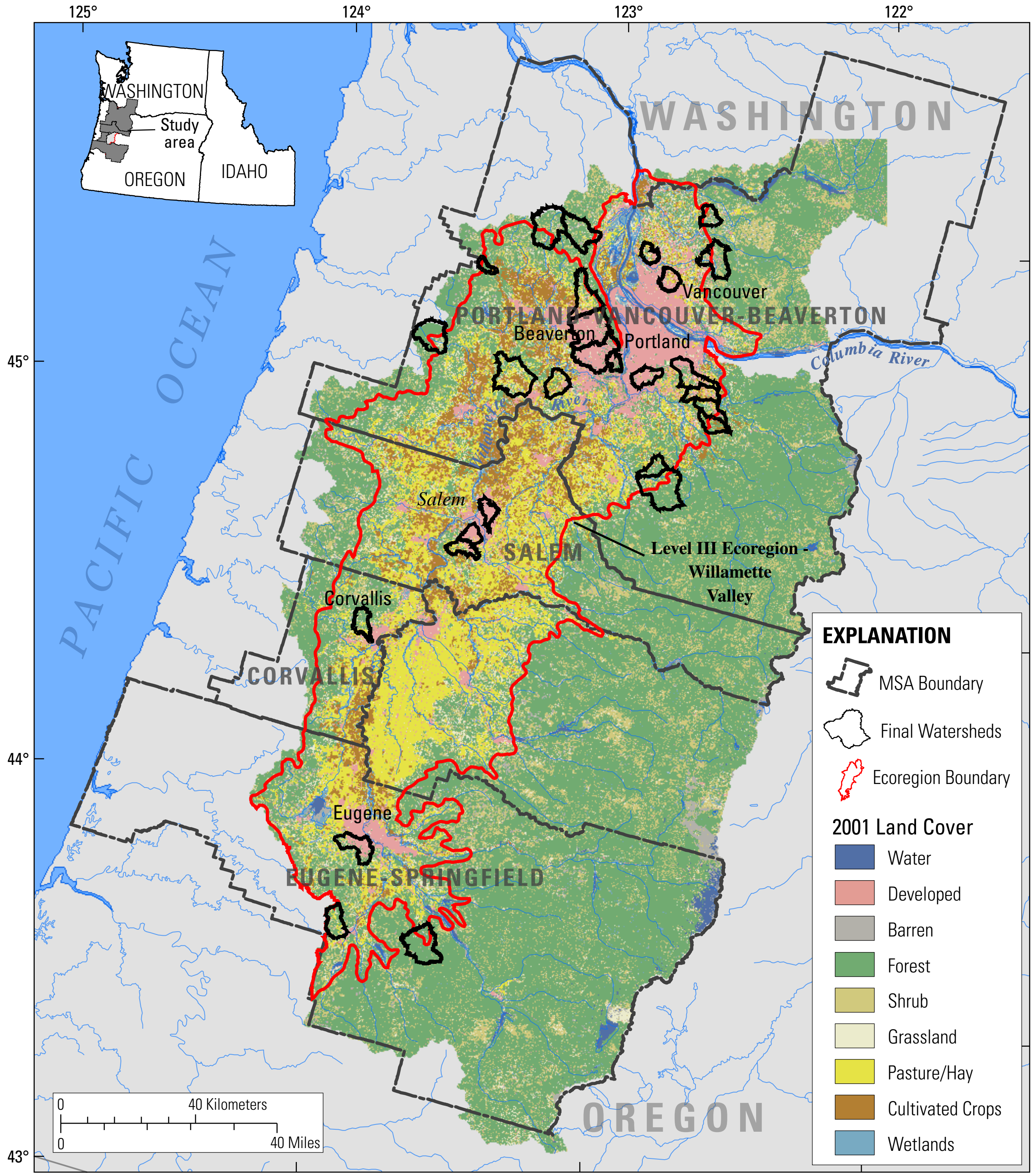
The Milwaukee-Green Bay (MGB) study area is located in southeastern Wisconsin, and includes five predominant MSAs (fig. 7). The MSAs are Milwaukee-Waukesha-West Allis, with a population 1,500,741 in 2000, an increase of 4.8 percent since 1990; Green Bay, with a population of 282,599 in 2000, an increase of 16.0 percent since 1990; Appleton, with a population of 201,602 in 2000, an increase of 15.3 percent since 1990; Racine, with a population of 188,831 in 2000, an increase of 7.9 percent since 1990; and Oshkosh-Neenah, with a population of 156,763 in 2000, an increase of 11.7 percent since 1990 (table 1; U.S. Census Bureau, 2006c). The population of the combined MSAs increased 7.6 percent from 1990 to 2000 (U.S. Census Bureau, 2006c). Milwaukee is the industrial and commercial hub of the MGB study area, and is a prominent industrial manufacturing center. Dairy and livestock farming and associated corn and soybean production represent the dominant land use in the region (Peters, 1997). Per capita income in the five combined MSAs in 2003 was $33,488, or 6 percent above the national average of $31,484 (Bureau of Economic Analysis, 2006).

The study area is located primarily in the USEPA Southeastern Wisconsin Till Plains Level III ecoregion (Omernik, 1987), although portions of the Central Corn Belt Plains and North Central Hardwood Forest ecoregions are also included. The Southeastern Wisconsin Till Plains ecoregion is characterized by a mixture of hardwood forests (north), oak savannas (west), and tall-grass prairies (south), based on presettlement vegetation types. Land surface is characterized by glacial outwash plains, lacustrine watersheds, level to rolling till plains, and extensive wetland areas. Elevation in the study area ranges from about 180 to 350 m above NAVD 88 (U.S. Geological Survey, 2005a). The climate is characterized by cool, dry winters and moderate summers. Mean annual precipitation in the area is about 85 cm, and the mean annual air temperature is about 7.5 °C (Daymet, 2005). Most of the precipitation occurs between May and September. Highest



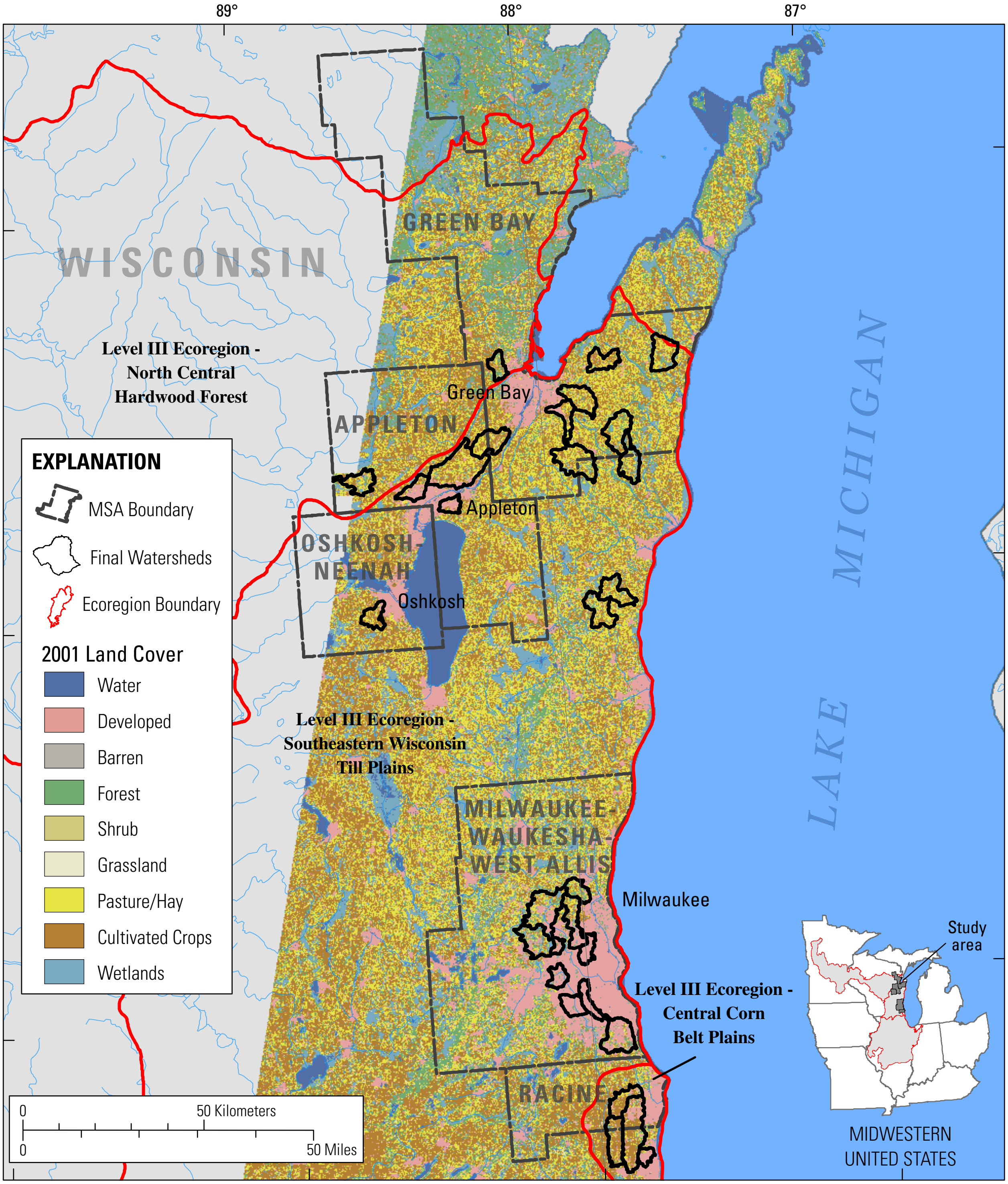
Base from digital files of:
Political boundaries, U.S. Department of Commerce, Bureau of Census, 2003, 1:100,000 scale
River File 3, U.S. Environmental Protection Agency, 1:500,000 scale
National Land Cover Dataset, U.S. Geological Survey, 2001, 30-meter resolution
Ecoregion, Level III, U.S. Environmental Protection Agency, 2003, 1:250,000 scale
Map Projection, Albers Equal Area, North American Datum 1983

Figure 5. Locations of study watersheds and 2001 land-cover data for the Dallas-Fort Worth study area (Falcone and Pearson, 2006). Metropolitan statistical area (MSA) boundaries are based on June 6, 2003, MSA definitions (U.S. Census Bureau, 2006c).



Base from digital files of:
Political boundaries, U.S. Department of Commerce, Bureau of Census, 2003, 1:100,000 scale
River File 3, U.S. Environmental Protection Agency, 1:500,000 scale
National Land Cover Dataset, U.S. Geological Survey, 2001, 30-meter resolution
Ecoregion, Level III, U.S. Environmental Protection Agency, 2003, 1:250,000 scale
Map Projection, Albers Equal Area, North American Datum 1983

Figure 6. Locations of study watersheds and 2001 land-cover data for the Portland study area (National Oceanic and Atmospheric Administration, 2005). Metropolitan statistical area (MSA) boundaries are based on June 6, 2003, MSA definitions (U.S. Census Bureau, 2006c).



Base from digital files of:
Political boundaries, U.S. Department of Commerce, Bureau of Census, 2003, 1:100,000 scale
River File 3, U.S. Environmental Protection Agency, 1:500,000 scale
National Land Cover Dataset, U.S. Geological Survey, 2001, 30-meter resolution
Ecoregion, Level III, U.S. Environmental Protection Agency, 2003, 1:250,000 scale
Map Projection, Albers Equal Area, North American Datum 1983

Figure 7. Locations of study watersheds and 2001 land-cover data for the Milwaukee-Green Bay study area (Falcone and Pearson, 2006). Metropolitan statistical area (MSA) boundaries are based on June 6, 2003, MSA definitions (U.S. Census Bureau, 2006c).

streamflows usually occur in March through May as a result of snowmelt or a combination of rain and snow; however, summer thunderstorms can produce flood peaks that exceed snowmelt peaks.

Compilation of Geographic Information System Data

Approximately 300 variables derived from a geographic information system (GIS) were calculated for this study (sources in Appendix 1; variable definitions in Appendix 2). Watershed boundaries were delineated in most cases from the USGS 30-m National Elevation Dataset (U.S. Geological Survey, 2005a), and in a small number of cases were refined from higher resolution data. Most variables were derived based on watershed boundaries (that is, watershed-level statistics); however, several categories of variables were calculated at the riparian-level and segment-level scale. These three extents (fig. 8) were used to characterize urbanization at different scales. Streams were based on the USGS 1:100,000 National Hydrography Dataset (NHD; U.S. Geological Survey, 2005b).

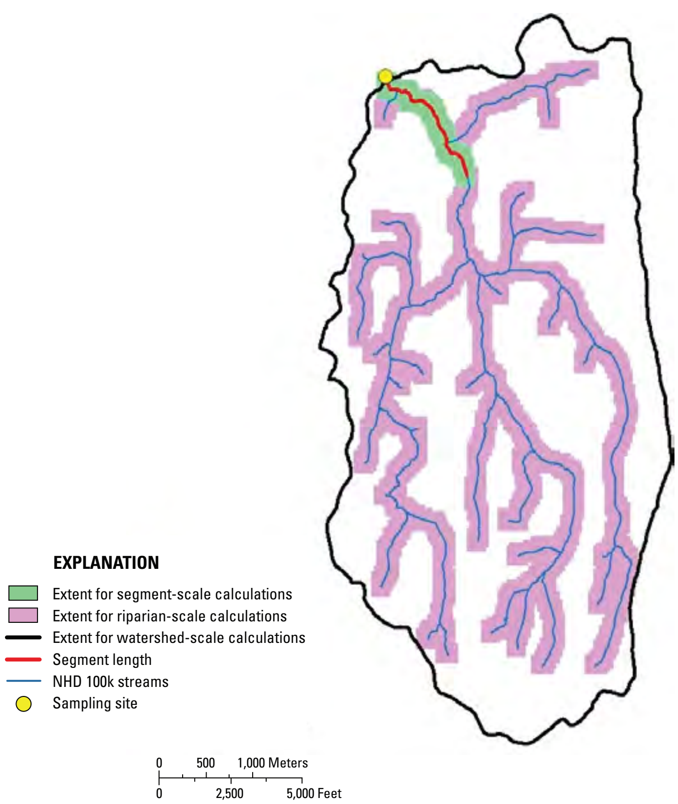


Figure 8. A geographic information system (GIS) was used to characterize urbanization at three spatial extents—watershed scale, riparian scale, and stream segment scale. Streamlines are based on U.S. Geological Survey 1:100,000 National Hydrography Dataset (NHD; U.S. Geological Survey, 2005b).

The variables derived from GIS fell into the broad categories of population and housing, climate, ecological and hydrological regions, infrastructure, watershed-scale 2001 land cover, watershed-scale National Oceanic and Atmospheric Administration (NOAA) 1-kilometer (km) imperviousness, riparian-scale 2001 land cover, segment-scale statistics, distance-weighted 2001 land cover, watershed-scale 1992 land cover, landscape pattern metrics, soils, and topography. These variables are summarized below.

A complete description of individual variable definitions is found in Appendix 2. Except where noted, calculations were performed at the watershed scale.

Population and Housing

Population counts and density were calculated for watersheds based on 2000 Census block data (GeoLytics, 2001). All other census variables (demographic, labor, income, and housing characteristics) were calculated based on 2000 Census block-group data. Four socioeconomic indices (SEI) were additionally derived for study watersheds based on principal component ordination of 63 Census variables, as described in McMahon and Cuffney (2000). Each SEI represented an association with a subset of the variables, and varied among the study areas (Appendix 3).

Climate

Watershed-level mean monthly and annual air temperature and precipitation statistics were derived from 1-km resolution Daymet (2005) model data, which represented 18-year (1980–1997) temperature and precipitation means obtained from terrain-adjusted daily climatological observations.

Ecological and Hydrological Regions

Ecological region boundaries were based on USEPA Level III ecoregions for all study areas (Omernik, 1987) and, in addition, level IV boundaries for the RAL, DFW, and MGB study areas. Hydrological landscape region boundaries were based on USGS hydrologic landscape regions (Wolock, 2003).

Infrastructure

Road data were based on Census 2000 TIGER roads (GeoLytics, 2001). The locations of point-source dischargers were derived from the USEPA National Pollutant Discharge Elimination System (NPDES; U.S. Environmental Protection Agency, 2005a). Toxic release locations were derived from the USEPA Toxic Release Inventory (U.S. Environmental Protection Agency, 2005b). Dam location data were based primarily on the U.S. Army Corps of Engineers national inventory of dams (U.S. Army Corps of Engineers, 1996).

Watershed-Scale 2001 Land Cover

All 2001 land-cover data were based on the National Land Cover Data 2001 (NLCD 2001) dataset classification scheme and protocols (U.S. Geological Survey, 2005c). Land-cover dataset sources varied by study area, but were comparable. Land-cover data for the ATL and RAL areas were based on the USGS NLCD 2001 program data; for the POR study, the data were based on data from the NOAA Coastal Change Analysis Program (National Oceanic and Atmospheric Administration, 2005), and for the DEN, DFW, and MGB study areas the data were derived in-house using identical methods and protocols as in the NLCD 2001 program (Falcone and Pearson, 2006). NOAA land-cover data for the POR study area were likewise produced using NLCD 2001 protocols, but the data contained slightly different class structures and were recoded for this project to match the NLCD 2001 classes (Appendix 4). The NLCD 2001 is a 16-class, 30-m resolution dataset based primarily on Landsat-7 Enhanced Thematic Mapper Plus data for the period 1999–2002 (U.S. Geological Survey, 2005c) and is designed to represent a composite of approximately the 2001 timeframe. (Coastal NLCD 2001 datasets, which affected the data only for the POR study area, contain additional coastal wetland classes beyond the base 16 classes.)

For most analyses in this study, the 16 classes were aggregated to 8 Anderson Level I classes (Anderson and others, 1976). For example, “Deciduous Forest,” “Evergreen Forest,” and “Mixed Forest” generally were aggregated to “Forest.” Although accuracy for the land-cover datasets was not assessed formally, aggregating the data from Anderson Level II to Level I classes generally improves classification accuracy considerably (Stehman and others, 2003) and, therefore, was thought to provide a superior dataset for analysis.

In addition to categorical land-cover data, the NLCD 2001 dataset contains an impervious-surface data layer, which estimates the percentage impervious surface for each 30-m pixel. Likewise, these data were acquired from the NLCD 2001 program for the ATL, RAL, and POR studies or derived in-house from imagery for the DEN, DFW, and MGB studies using NLCD 2001 methods. An accuracy assessment was performed on the impervious-surface datasets for the six study areas based on a random sample of 60 ground-truth plots digitized from concurrent high-resolution (0.3-m) orthoimagery in each area. General underestimation of impervious surfaces occurred in the ATL, RAL, and DFW datasets as compared to the DEN, POR, and MGB datasets (Falcone and Pearson, 2006). Because the accuracy of NLCD 2001 and in-house impervious-surface datasets varied considerably across study areas, these datasets were not used as a comparative variable in analyzing the data across the study areas in this paper.

Watershed-Scale 1-km Impervious Surface

Because of the inconsistencies in the NLCD 2001 imperviousness data, and because of the potential importance of imperviousness in this study, NOAA impervious-surface data for 1-km pixels were also acquired (National Oceanic and Atmospheric Administration, 2006). The NOAA data, although at a much coarser scale than the NLCD 2001 data (1-km compared to 30-m), were believed to be a consistent dataset that would be comparable among the study areas. The NOAA imperviousness data were estimates based on mid-1990s satellite night-light observations, 1992 land-cover data, and 2000 Census road-density data.

Riparian-Scale 2001 Land Cover

The NLCD 2001 land-cover statistics were derived for riparian zones based on NHD 100k stream lines for the entire watershed (fig. 8). The riparian zone is defined as the area approximately 100 m on each side of the stream centerline. Riparian-scale statistics were calculated for all streams in the watershed.

Segment-Scale Statistics

Segment-scale statistics were calculated for the riparian zone (approximately 100 m on each side of the stream centerline) for the length of stream approximately 2,000 m upstream from the sampling site on the main stem (fig. 8). The exact segment distance varied by watershed and was based on the log 10 distance of the drainage area. That is, for a 10-square kilometer (km^2) area watershed, the segment length was 1,000 m; for a 100-km^2 area watershed, the segment length was 2,000 m, and so forth.

Segment variables were calculated for only the 175 final watersheds. Median curvilinear segment stream length was approximately 2,100 m.

Segment statistics calculated were percent NLCD 2001 land cover, sinuosity, gradient (based primarily on 30-m NED data), mean distance to nearest road, and density of road and stream intersections along the length of the segment.

Distance-Weighted 2001 Land Cover

Observations indicated that land-cover data in a number of watersheds were not spatially distributed evenly throughout the watershed. For example, some watersheds had low levels of urbanization based on watershed-level statistics, but the urban land occurred disproportionately in the lowlands portion of the watershed and(or) near the sampling site. Proximity-based land-use models have, in some studies, been superior in explaining aquatic macroinvertebrate responses than watershed-level statistics (Wente, 2000); therefore, a “distance-weighted” land-cover metric was derived to capture the potential effect of disproportionately distributed urban land. The distance-weighted data were simply NLCD 2001 watershed data reweighted in relation to distance from the sampling site; that is, data for areas close to the sampling site were given a higher weight than data for areas farther away. The weight value assigned was the inverse distance from the sampling site, in meters. The mean watershed percentage of land cover for each class was then calculated using the distance-weighted data and normalized to 100 percent. The result was a watershed-scale percentage for each class but adjusted for spatial proximity to the sampling site. Distance-weighted statistics were calculated only for the 175 final watersheds.

Watershed-Scale 1992 Land Cover

Watershed-level land-cover statistics were derived from the 1992 NLCD (Vogelmann and others, 2001). The possibility of comparing the 1992 data to the 2001 NLCD was anticipated if the datasets were deemed compatible by the NLCD program.

Landscape-Pattern Metrics

Landscape-pattern metrics characterizing the shape, size, and spatial configuration of land-cover patches were derived by using the FRAGSTATS software package (McGarigal and Marks, 1995). Watershed land-cover data were reclassified to Anderson Level I classification, then FRAGSTATS metrics were calculated for patches (contiguous blocks) of each class type. The metrics calculated for each Anderson Level I land-cover class were number of patches, patch density, largest patch index, mean patch area, shape index, proximity index, Euclidean nearest-neighbor distance, and percentage of like adjacencies. An additional metric (watershed shape index) was calculated based on the entire watershed boundary. Landscape-pattern variables were calculated only for the 175 final watersheds.

Soils

Soil properties were derived from the U.S. Department of Agriculture State Soil Geographic (STATSGO) Database (U.S. Department of Agriculture, 1994). The soil properties included water capacity, erodibility, organic matter, permeability, soil type percentage, texture classification, hydrologic soil group, depth to water table, and organic carbon content.

Topography

Topographic characteristics were derived from the USGS 30-m National Elevation Dataset (U.S. Geological Survey, 2005a). These were minimum, maximum, and mean elevations, relief, midpoint, percentage of watershed that is flat, lowland and upland, mean slope, and wetness index.

Site Selection

The selection of final study watersheds was accomplished through an iterative process in a similar manner for each of the study areas. The general method is described by Tate and others (2005), and specifically in individual study reports (Gregory and Calhoun, 2006; Sprague and others, 2006; Waite and others, 2006); however, the site-selection method is summarized here. The goal was to use GIS data and site reconnaissance to identify approximately 30 final study watersheds in each geographic area. The final study watersheds were selected from a population of candidate watersheds and represent a gradient of urbanization (low to high urbanization) suitable for studying urbanization effects on stream ecosystems in each study area. The design was intended to minimize natural sources of variability among the study watersheds. Site selection was based on three major factors—variability in the natural landscape features, degree of urbanization, and suitability of local site conditions.

Variability in Natural Landscape Features

For each of the six study areas, GIS-derived data were used to identify a population of candidate watersheds having similar environmental characteristics in order to limit the variability of natural factors among the final study watersheds. Watershed boundaries were delineated based on the USGS 30-m National Elevation Dataset (U.S. Geological Survey, 2005a). The most general screening criteria for natural landscape features were ecoregions. The USEPA ecoregions (Omernik, 1987) provide a coarse framework of relatively homogeneous climate, elevation, soils, geology, and vegetation (Tate and others, 2005). The vast majority of delineated candidate watersheds in each study area was within a single USEPA Level III ecoregion. Cluster analysis was performed on the candidate watersheds to group them based on a number of environmental factors, including climate, elevation, slope, soils, vegetation, and geology. From the resulting clusters, a final set of candidate watersheds was identified from the most similar clusters. Each study area had a varying number of candidate watersheds (ATL-217, RAL-1245, DEN-162, DFW-57, POR-171, MGB-51); however, the same principle was used to identify watersheds with as little natural variability as possible.

Degree of Urbanization

A study-specific “planning” index that ranked candidate watersheds on a scale of 0–100 (low–high) according to their degree of urbanization was developed by using GIS-derived data. Index calculations generally were accomplished through the following steps (see also McMahon and Cuffney, 2000):

(A) Values for GIS variables were normalized: areas were converted to watershed percent, count values were converted to counts/area, and standardized to metric (SI) values. Variables that were considered for inclusion in local UIIs generally were all population and housing variables (described above), infrastructure, and 2001 land-cover variables for both watershed- and riparian-scale data.

(B) The Spearman's rank correlation coefficient (*rho* [*r*]) was calculated for each variable against both 2000 census population-density and drainage-area data. Population density was considered a core measure of urbanization; the variables that had at least moderate correlation to population density ($|r|$ greater than (>) 0.5), and did not correlate to drainage area ($|r|$ less than (<) 0.5) were identified.

(C) Values for these variables for each watershed were range-standardized according to the calculation:

$$val_{rs} = (val_{orig} - min/range) \quad (1)$$

where

val_{orig} = the original raw value for the variable,
min = the minimum value of all sites for the variable,
range = the range (max–min) value of all sites for the variable, and
val_{rs} = range-standardized (0–100) value.

(D) Values of variables with negative correlation to population density (for example, high values of "% forest" usually correlated negatively to urbanization) were subtracted from 100; values of variables with positive correlation were added to zero.

(E) The mean range-standardized value of all variables identified in (B) was calculated, then adjusted again to range from zero to 100. The result was a UII value calculated for each of the approximately 30 watersheds that ranged from zero (very low urbanization) to 100 (very high urbanization) based on the variables that correlated (negatively or positively) to population density in each area.

This basic method was modified in some of the individual studies based on local knowledge and judgment. In the POR study, a threshold value of 0.7 was used for *r* as opposed to 0.5. In the ATL, RAL, and DEN studies, a number of variables were eliminated selectively from the calculation because of judged redundancy with other variables.

Suitability of Local Site Conditions

The final set of watersheds in each study area was constrained by the requirements to limit natural variability and to have a suitable gradient of urban intensity among the final study watersheds. Candidate sites also needed to be screened in terms of site access, safety, the adequacy of streamflow, and other physical habitat conditions to permit the sampling of algae, invertebrates, fish, and chemistry. Some screening occurred in the office, but site reconnaissance was required to identify local-scale issues that could have confounded the implementation of the study design. Watersheds were eliminated from consideration if the streams were ephemeral or if access permissions could not be obtained from land-owners. Site reconnaissance resulted in adjusting some sampling locations to minimize the effects of upstream diversions or wastewater-treatment plants or in locating stream reaches with similar substrates or other local habitat conditions. In some cases new sampling sites and associated watersheds were identified in the field; in other cases, candidate watershed boundaries had to be adjusted to represent a modified sampling location. GIS data were recalculated for the new set of selected watersheds; new UII values were calculated, and the iterative process resulted in the identification of a final set of watersheds. For each study, approximately 30 watersheds were selected: ATL-30, RAL-30, DEN-28, DFW-29, POR-28, MGB-30. The 175 final watersheds are identified in Appendix 5.

Because of difficulties in identifying watersheds that met screening requirements or local decisions to focus on a specific range of urbanization, the gradient of urban intensity was not evenly distributed across the 30 watersheds in all the study areas. Therefore, the final set of 30 watersheds in each study cannot be considered an ideal representation of a gradient of urbanization because of these constraints.

Common Index Calculation

The UIIs calculated individually for each study area (the six "local" UIIs) were developed to reflect the conditions of urbanization in the representative region. However, the variables composing each local index differed from study to study, making index scores not directly comparable across study areas. To create a common basis for comparing study watersheds across all environmental settings, a common urban intensity index (CUII) was developed based on five variables—the core variable population density and four others that strongly correlated to population density in every study area (table 2)—and across all study areas. The CUII calculation was performed on the set of 175 watersheds spanning all 6 study areas. Table 2 lists all variables that had the strongest correlation to population density ($|r| > 0.8$) in every study area and across study areas.

The five variables included as components of the CUII were population density, housing-unit density, road density, percentage of urban land cover in the watershed, and largest urban patch index. In addition to being strongly related to population density, these variables were believed to be good representations of major categories of urbanization—**population** (population density), **housing infrastructure** (housing-unit density), **road infrastructure** (road density), **urban land cover** (percentage of urban land cover in the watershed), and **spatial concentration** (largest urban patch index). The largest urban patch index is the percentage of land in the watershed that represents the largest contiguous urban patch; that is, a measure of the concentration of urban land in one place in the watershed.

Table 2. Spearman rank correlation coefficients for variables with strongest correlation to population density in every study area.

[Variables in table all had |*r*| values > 0.8 within each of the six study areas, as well as across all study areas. Significance level p-value < 0.05. The five variables used for the common urban intensity index (CUII) are highlighted in bold italics. Coefficients for each study area are based on the approximately 30 final watersheds in each local study; coefficients in the final column are based on the total set of 175 study watersheds]

Variable	Variable abbreviation	ATL	RAL	DEN	DFW	POR	MGB	Across all study areas
Percent urban land cover in watershed	***pNLCD1_2***	***0.976***	***0.935***	***0.945***	***0.910***	***0.982***	***0.978***	***0.908***
Mean urban patch area	PAM_C2	0.933	0.894	0.870	0.906	0.974	0.943	0.911
Percent urban land cover in riparian zone	pNLCD1_B2	0.955	0.903	0.911	0.845	0.969	0.943	0.916
Percent population living in rural area	PPRURAL	-0.952	-0.935	-0.860	-0.921	-0.915	-0.954	0.925
Percent population living in urban areas	PPURBAN	0.961	0.929	0.860	0.917	0.915	0.954	0.926
Percent distance-weighted urban land cover	pURBANdw	0.978	0.933	0.942	0.856	0.965	0.961	0.927
Road density	***ROADDEN***	***0.982***	***0.960***	***0.955***	***0.943***	***0.954***	***0.943***	***0.941***
Proportion of like adjacencies (urban patches)	PLA_C2	0.946	0.886	0.940	0.910	0.972	0.974	0.941
Largest Patch Index - urban	***LPI_C2***	***0.975***	***0.925***	***0.944***	***0.888***	***0.978***	***0.955***	***0.951***
Percent impervious surface in watershed	NLCD_IS	0.967	0.804	0.940	0.927	0.980	0.968	0.952
Housing-unit density	***HUDEN***	***0.986***	***0.987***	***0.985***	***0.985***	***0.989***	***0.991***	***0.986***
Household density	HHDEN	0.983	0.986	0.986	0.986	0.989	0.993	0.992
Population density 2000	***POPDENOO***	***1.000***	***1.000***	***1.000***	***1.000***	***1.000***	***1.000***	***1.000***

Data Analysis

Spearman rank correlation *(r)* was used to examine the strength of relations between population density and other variables. Spearman rank correlation is a method suitable for nonparametric data distributions (Burt and Barber, 1996), which primarily was the case in the datasets examined here. Regression analysis (R^2) was used to examine the relations between UIIs and population density, and between the UIIs and the CUII. Unless otherwise stated, significance level of statistical tests (*p*-value) was 0.05.

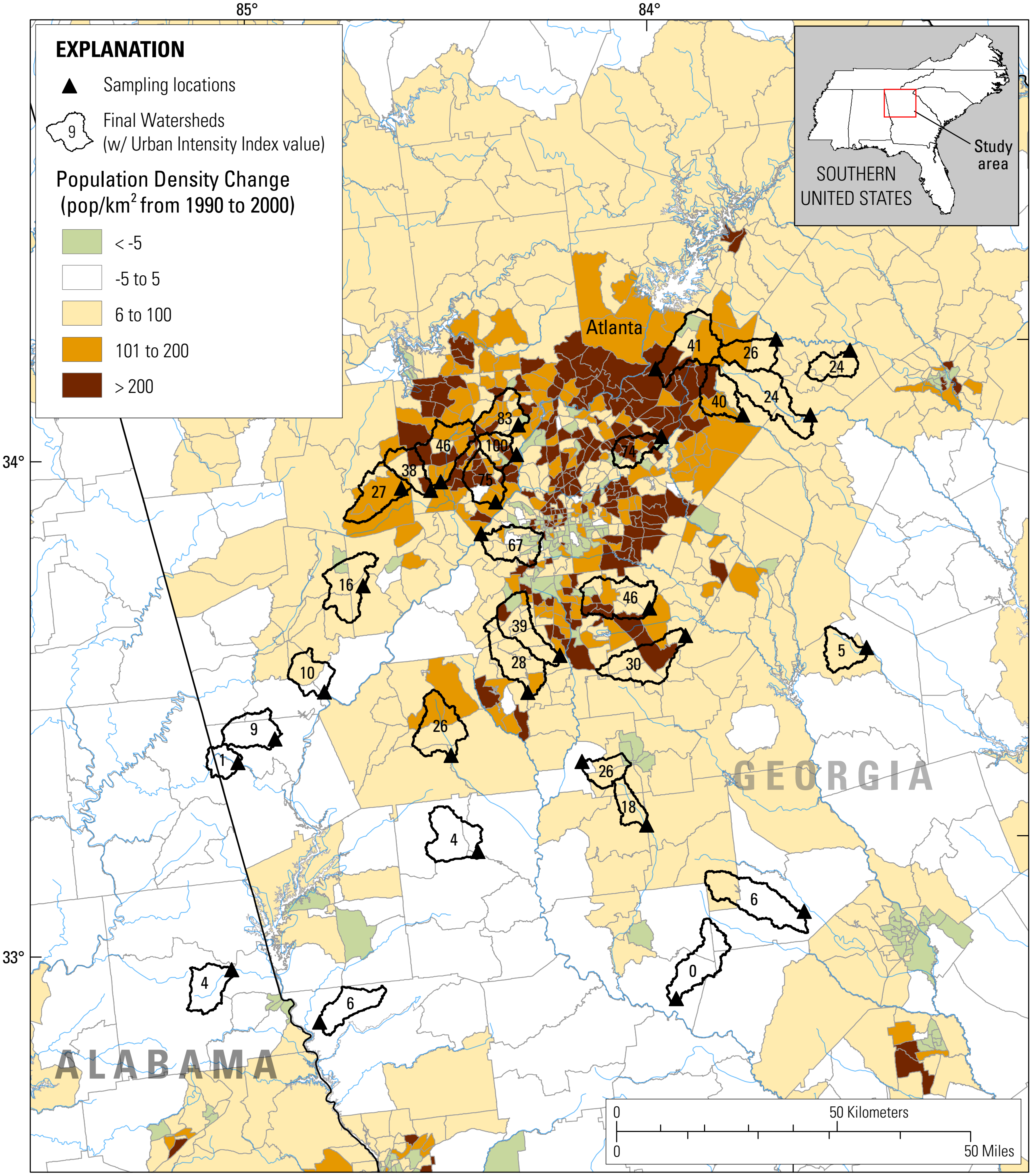
Results

Three broad areas of analysis were conducted for this report, based on the GIS-derived data described above. These were comparison of patterns of urban growth in the study areas, comparison of variability in environmental settings and urbanization in the final watersheds, and comparison of urban index components and results.

Pattern of Urban Growth in Study Areas

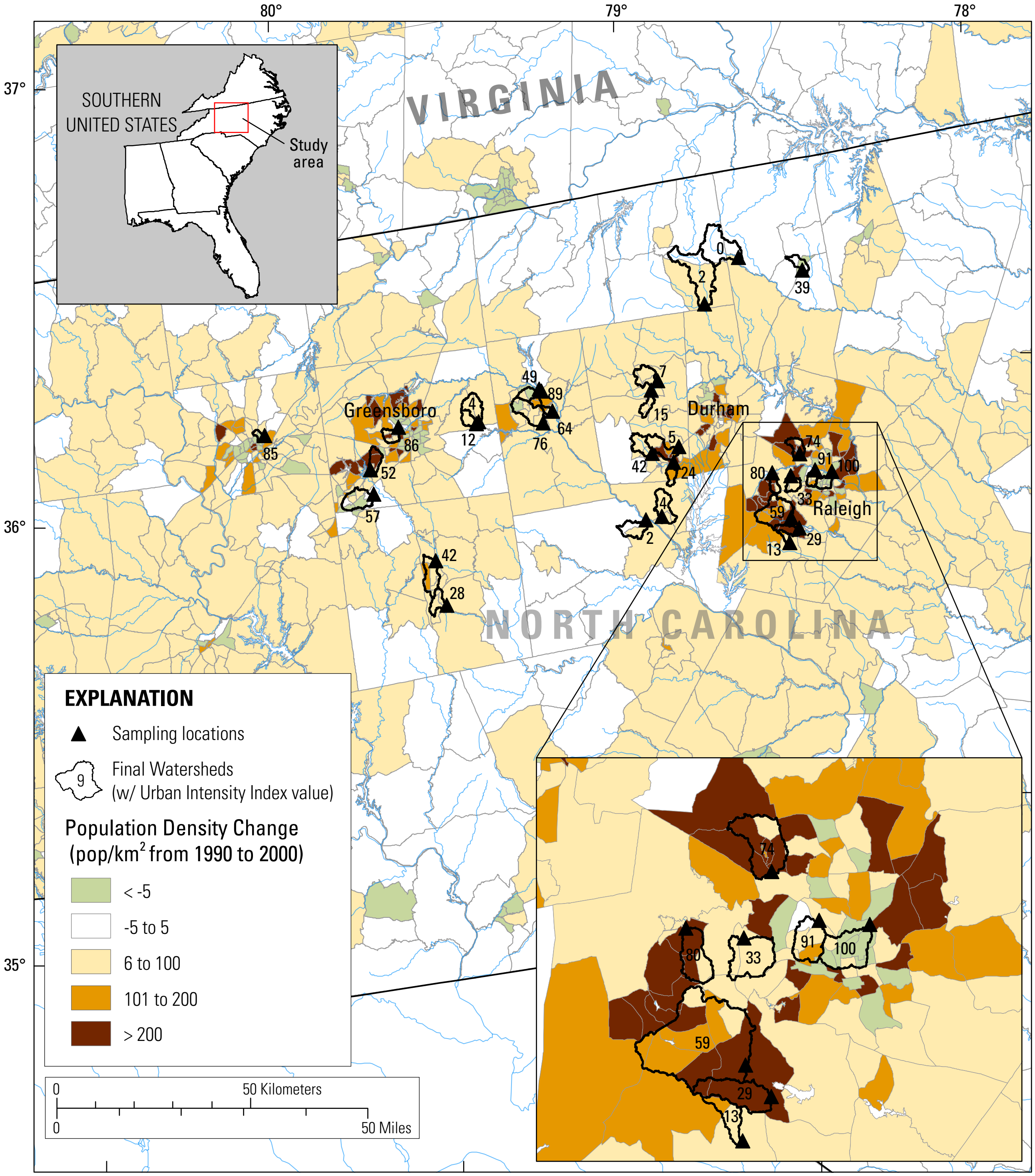
In the six regional areas, urban population growth was highest in the ATL area (38.4 percent, 1990–2000; table 1), as defined by aggregated MSAs. Only the individual MSA of Raleigh-Cary had a higher percentage population growth at 47.3 percent. These were some of the highest large-city growth areas in the United States—of the 88 MSAs in the Nation with populations greater than 500,000, Raleigh-Cary ranked 4th, and Atlanta-Sandy Springs-Marietta ranked 6th in 1990–2000 percentage population growth (U.S. Census Bureau, 2006c). Population growth was lowest in the MGB area (combined MSAs 7.6 percent).

Overall patterns of urbanization in the six study areas varied (figs. 9A–F). In the ATL study area, because of a lack of natural barriers that might preclude development, urbanization generally has occurred in a radial pattern outward from the original city limits and in some cases followed major interstate highways to the north and south (fig. 9A). The RAL area has seen tremendous growth in the Raleigh-Cary area, in parts of Greensboro, and along the general east-west I–40 corridor (fig. 9B). The DEN area is constrained from growth in the west by the Rocky Mountains (although it has occurred, particularly along the I–70 and U.S. 285 corridors west), and has grown primarily along a longitudinal axis from Fort Collins to about 50 km south of Denver (fig. 9C). The DFW area developed primarily northward from the original urban cores (fig. 9D), and to the southwest. Development in the POR area is limited by law to specific boundaries by a predefined "Urban Growth Boundary," governed by a special metropolitan government agency (Metro, 2006), and urbanization largely was constrained to those boundaries (fig. 9E). Development in the MGB area is constrained to the east by Lake Michigan, and growth in this area occurred westward and longitudinally along the Lake Michigan shoreline south to Kenosha. Similar to the other MSAs, development in this area often occurred near major highways, which is also the case in Green Bay, where growth occured longitudinally following transportation routes along the Fox River corridor. (fig. 9F).



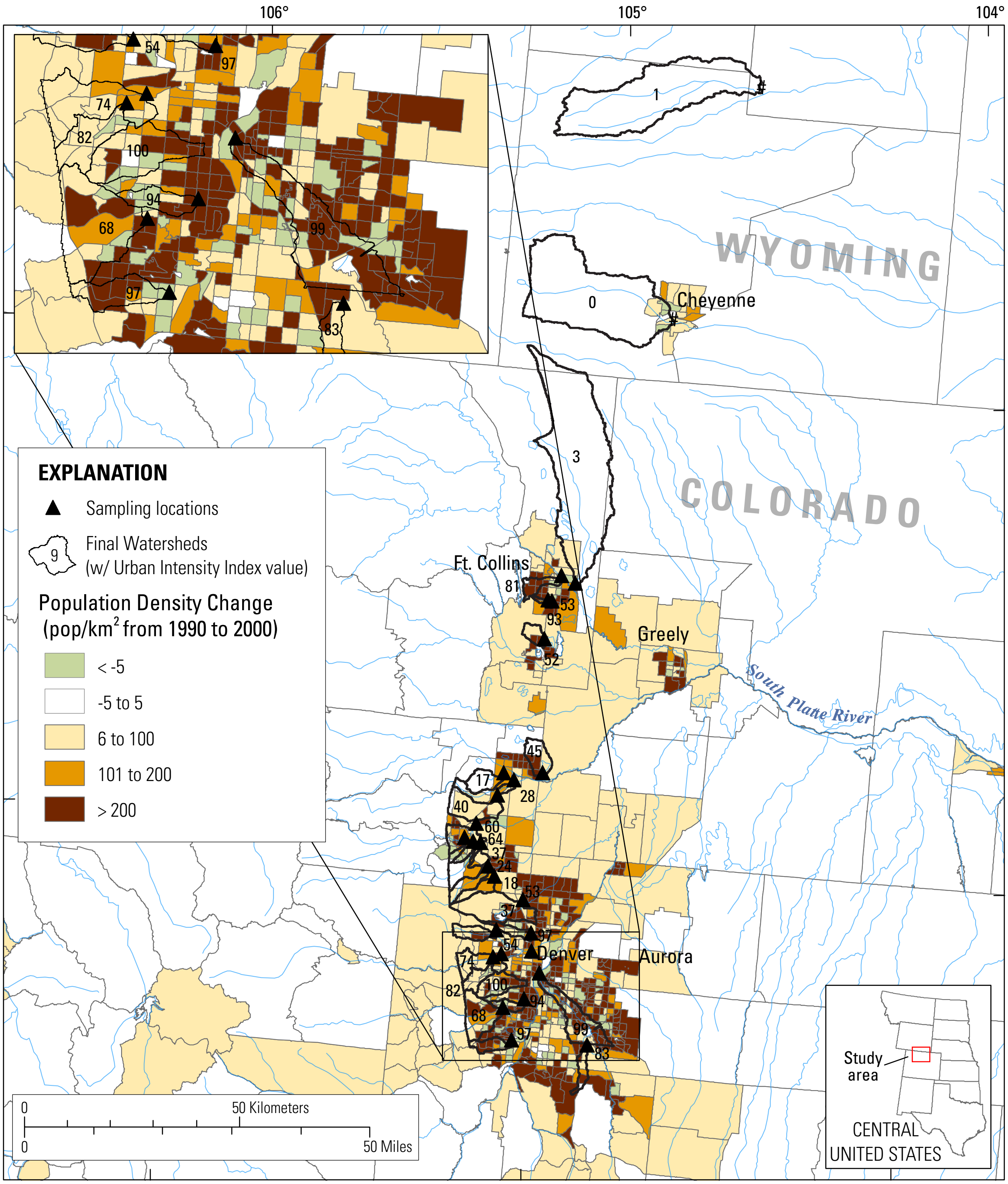
Base from digital files of:
Political boundaries, 2003, Census tract boundaries, 1990, 2000,
U.S. Department of Commerce, Bureau of Census, 1:100,000 scale
River File 3, U.S. Environmental Protection Agency, 1:500,000 scale
Map Projection, Albers Equal Area, North American Datum 1983

Figure 9A. Local urban intensity index values and urban change during 1990–2000 in the Atlanta study area. Population-density changes in population per square kilometer (pop/km²) are based on 1990 and 2000 Census tract boundaries from GeoLytics (2001).



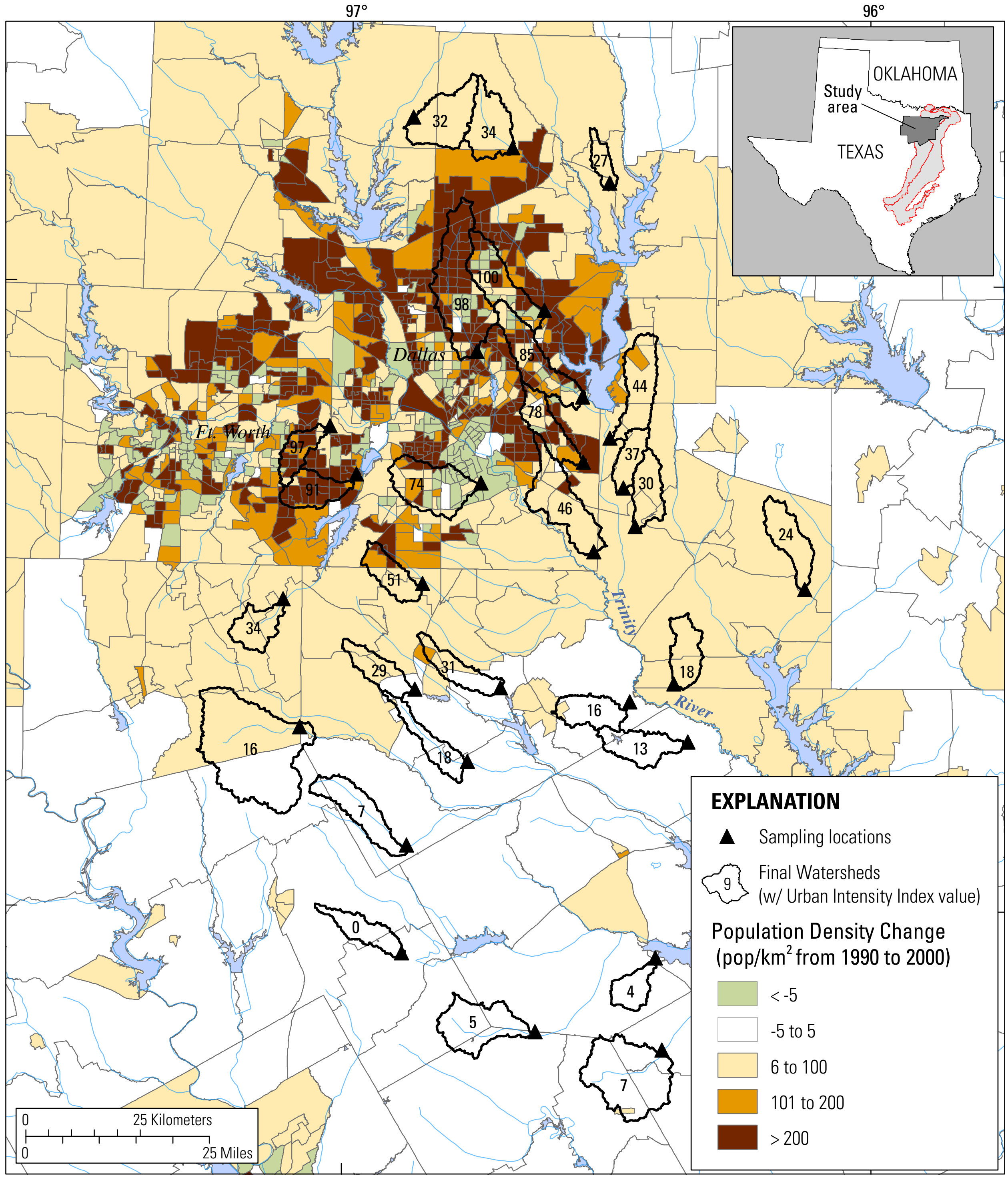
Base from digital files of:
Political boundaries, 2003, Census tract boundaries, 1990, 2000,
U.S. Department of Commerce, Bureau of Census, 1:100,000 scale
River File 3, U.S. Environmental Protection Agency, 1:500,000 scale
Map Projection, Albers Equal Area, North American Datum 1983

Figure 9B. Local urban intensity index values and urban change during 1990–2000 in the Raleigh study area. Population-density changes in population per square kilometer (pop/km^2) are based on 1990 and 2000 Census tract boundaries from GeoLytics (2001).



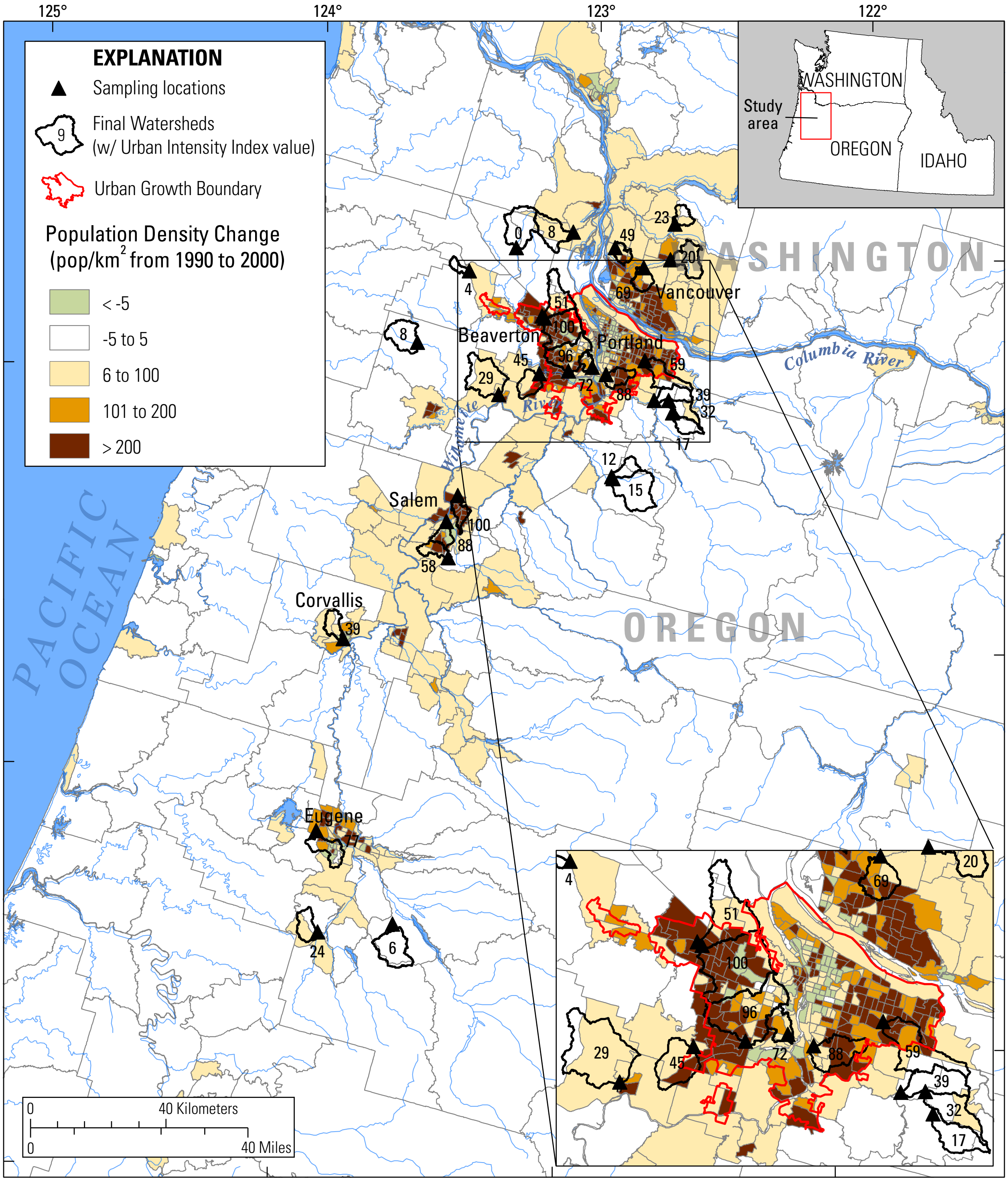
Base from digital files of:
Political boundaries, 2003, Census tract boundaries, 1990, 2000,
U.S. Department of Commerce, Bureau of Census, 1:100,000 scale
River File 3, U.S. Environmental Protection Agency, 1:500,000 scale
Map Projection, Albers Equal Area, North American Datum 1983

Figure 9C. Local urban intensity index values and urban change during 1990–2000 in the Denver study area. Population-density changes in population per square kilometer (pop/km²) are based on 1990 and 2000 Census tract boundaries from GeoLytics (2001).



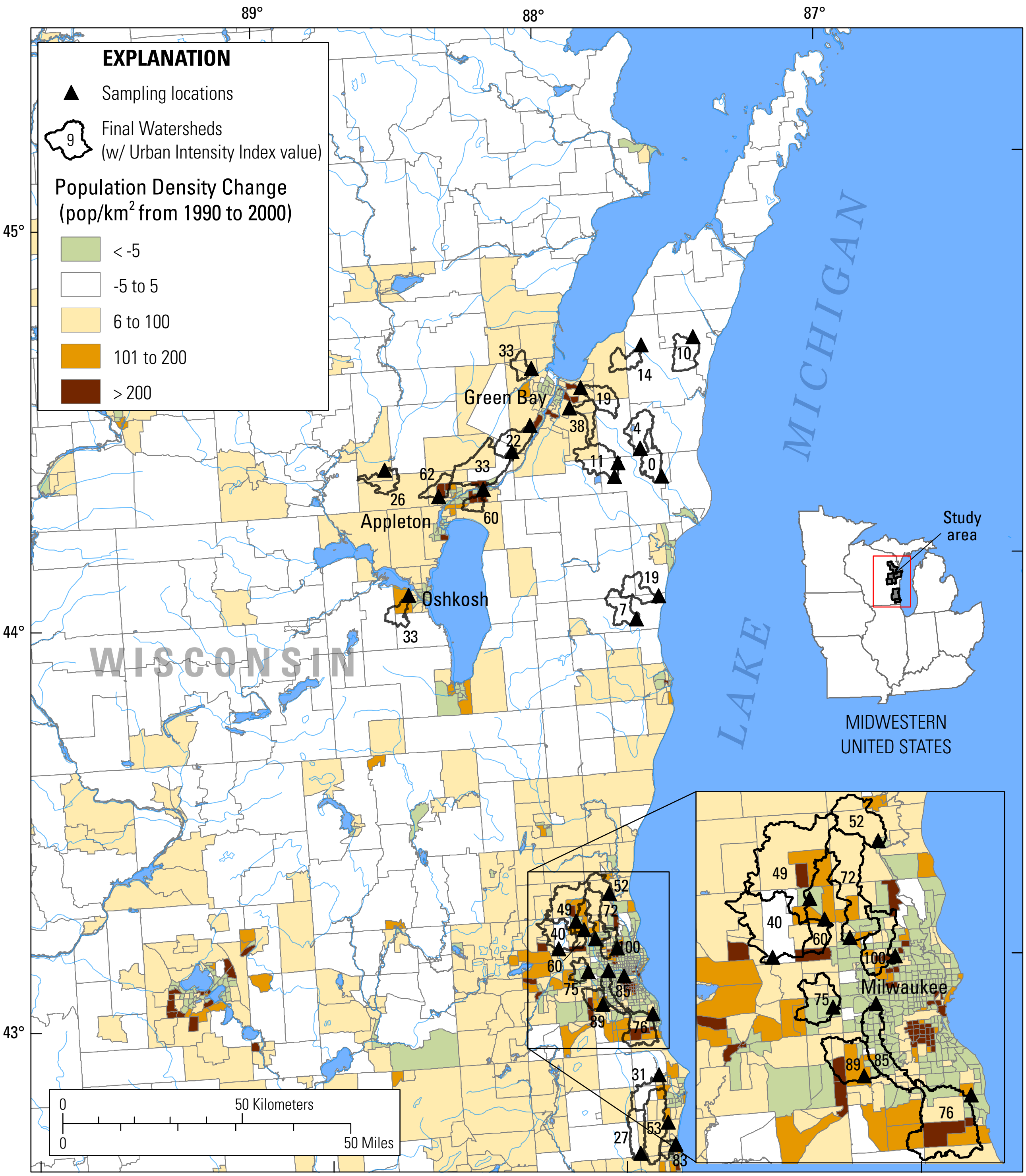
Base from digital files of:
Political boundaries, 2003, Census tract boundaries, 1990, 2000,
U.S. Department of Commerce, Bureau of Census, 1:100,000 scale
River File 3, U.S. Environmental Protection Agency, 1:500,000 scale
Map Projection, Albers Equal Area, North American Datum 1983

Figure 9D. Local urban intensity index values and urban change during 1990–2000 in the Dallas-Fort Worth study area. Population-density changes in population per square kilometer (pop/km^2) are based on 1990 and 2000 Census tract boundaries from GeoLytics (2001).



Base from digital files of:
Political boundaries, 2003, Census tract boundaries, 1990, 2000,
U.S. Department of Commerce, Bureau of Census, 1:100,000 scale
River File 3, U.S. Environmental Protection Agency, 1:500,000 scale
Map Projection, Albers Equal Area, North American Datum 1983

Figure 9E. Local urban intensity index values and urban change during 1990–2000 in the Portland study area. Population-density changes in population per square kilometer (pop/km²) are based on 1990 and 2000 Census tract boundaries from GeoLytics (2001).



Base from digital files of:
Political boundaries, 2003, Census tract boundaries, 1990, 2000,
U.S. Department of Commerce, Bureau of Census, 1:100,000 scale
River File 3, U.S. Environmental Protection Agency, 1:500,000 scale
Map Projection, Albers Equal Area, North American Datum 1983

Figure 9F. Local urban intensity index values and urban change during 1990–2000 in the Milwaukee-Green Bay study area. Population-density changes in population per square kilometer (pop/km²) are based on 1990 and 2000 Census tract boundaries from GeoLytics (2001).

Variability in Environmental Settings

Environmental characteristics of the watersheds in this study can be compared among study areas and within a study area at two levels (table 3)—that of the candidate watersheds and of the final watersheds. The set of candidate watersheds provided broader geographic and environmental characteristics; the set of final watersheds provided a more focused grouping to minimize environmental variability and included watersheds on an urban gradient.

The ability to minimize environmental variability varied somewhat among the study areas. The DEN study included several large (>500 km^2) watersheds, because the arid conditions required inclusion of some large watersheds for adequate streamflow. Watershed area varied the most in the two study areas (DEN and DFW) where water availability

Table 3. Comparative summary of key environmental variables for study watersheds.

[Candidate and final (shaded) watersheds alternate rows for each variable. Values are given as median (min–max). Values for all computed variables are given in Appendix 7; sq km, square kilometer; N, north; °C, degrees Celsius; cm, centimeter; m, meter; %, percent; cm/hr, centimeter per hour]

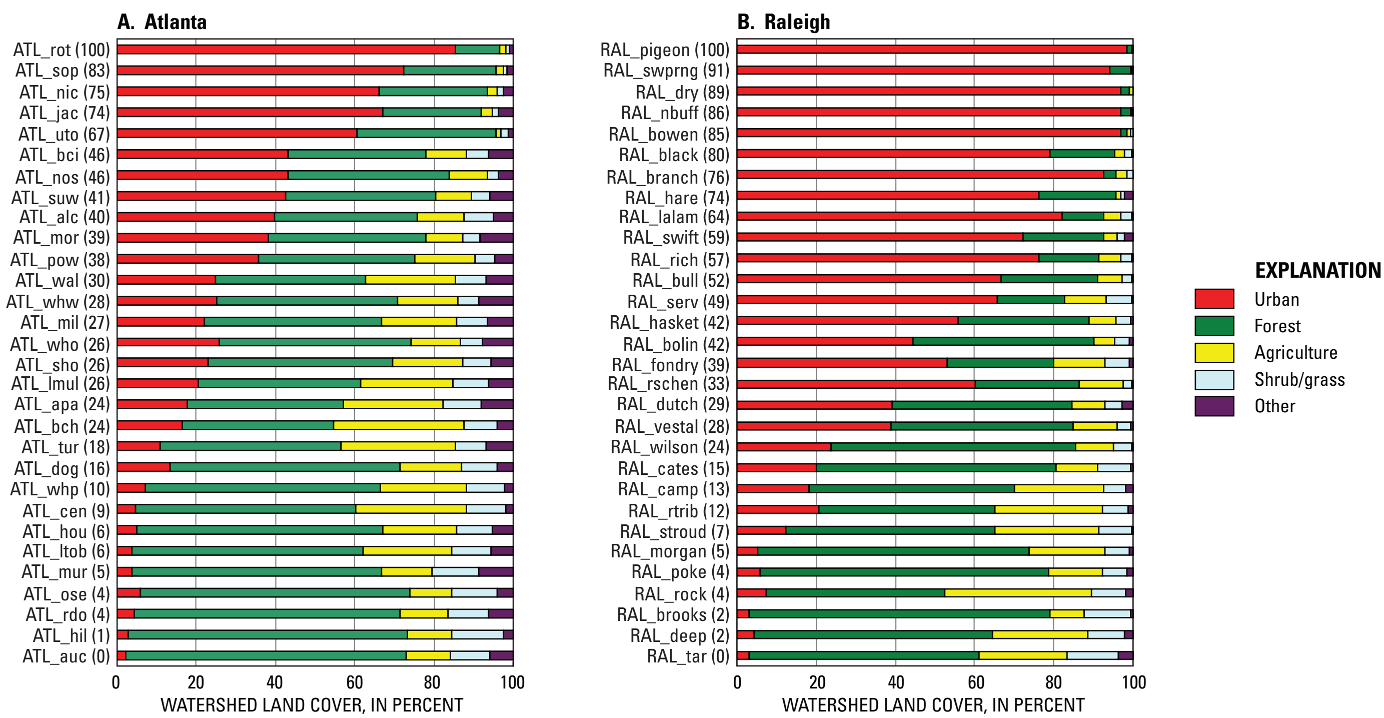
Variable [abbreviation]	Metropolitan area					
	Atlanta	Raleigh	Denver	Dallas-Fort Worth	Portland	Milwaukee-Green Bay
Number of candidate basins	217	1,245	162	57	171	51
Number of final basins	30	30	28	29	28	30
Candidate basins: Drainage area (sq km) [SQKM]	73.0 (15.2 – 187.4)	23.6 (5.7 – 108.0)	31.8 (14.3 – 375.4)	60.6 (12.2 – 321.8)	30.2 (5.5 – 113.2)	39.9 (7.0 – 117.4)
Final basins: Drainage area (sq km) [SQKM]	81.7 (43.2 – 146.3)	14.4 (4.9 – 82.5)	28.6 (4.1 – 558.6)	64.6 (26.8 – 291.4)	38.5 (12.6 – 103.8)	43.5 (11.2 – 118.8)
Candidate basins: Latitude [degrees N]	33.6 (32.6 – 34.7)	36.1 (34.8 – 38.5)	40.2 (39.1 – 41.2)	32.6 (31.7 – 33.6)	44.9 (43.7 – 45.9)	43.8 (42.5 – 44.6)
Final basins: Latitude [degrees N]	33.5 (32.8 – 34.2)	36.0 (35.6 – 36.4)	39.9 (39.5 – 41.3)	32.6 (31.7 – 33.3)	45.3 (43.8 – 45.9)	43.7 (42.6 – 44.6)
Candidate basins: Mean annual air temperature (°C) [MAAT]	16.7 (14.4 – 17.7)	14.9 (13.1 – 16.5)	9.2 (5.6 – 10.3)	18.4 (17.3 – 18.7)	11.0 (8.4 – 11.9)	7.2 (6.8 – 8.7)
Final basins: Mean annual air temperature (°C) [MAAT]	16.1 (15.6 – 17.6)	14.9 (14.3 – 15.5)	9.4 (6.5 – 9.9)	18.4 (17.7 – 18.7)	11.1 (8.9 – 11.8)	7.4 (6.8 – 8.7)
Candidate basins: Annual precipitation (cm) [MAP]	131 (117 – 165)	118 (108 – 146)	38 (33 – 53)	104 (95 – 116)	146 (110 – 267)	84 (80 – 91)
Final basins: Annual precipitation (cm) [MAP]	134 (122 – 141)	119 (115 – 125)	43 (38 – 47)	104 (96 – 111)	149 (116 – 205)	85 (79 – 91)
Candidate basins: Basin elevation (m) [MEANELEV]	248 (135 – 463)	143 (49 – 317)	1,597 (1,369 – 2,221)	167 (117 – 242)	382 (13 – 1,183)	246 (201 – 293)
Final basins: Basin elevation (m) [MEANELEV]	283 (178 – 35)	176 (89 – 284)	1,720 (1,535 – 2,024)	169 (121 – 220)	184 (53 – 621)	234 (202 – 273)
Candidate basins: Basin slope (%) [SLOPE_X]	5.9 (3.1 – 12.1)	5.4 (1.1 – 11.9)	3.1 (0.6 – 26.4)	2.1 (1.2 – 4.2)	13.4 (0.4 – 49.1)	2.1 (0.9 – 4.2)
Final basins: Basin slope (%) [SLOPE_X]	5.9 (4.2 – 11.0)	5.1 (2.9 – 8.8)	5.8 (1.7 – 12.5)	2.1 (1.3 – 3.7)	11.8 (1.0 – 32.9)	2.1 (1.0 – 3.3)
Candidate basins: Sandy soils (%) [SNDH]	53 (44 – 63)	49 (11 – 85)	60 (30 – 87)	20 (17 – 48)	25 (19 – 61)	33 (18 – 63)
Final basins: Sandy soils (%) [SNDH]	53 (51 – 55)	44 (39 – 52)	44 (35 – 68)	21 (17 – 48)	26 (18 – 46)	33 (18 – 62)
Candidate basins: Soil permeability (cm/hr) [PERH]	5.9 (4.7 – 9.8)	5.2 (1.1 – 13.2)	9.5 (1.7 – 41.9)	0.6 (0.2 – 2.5)	2.1 (1.0 – 10.6)	2.3 (1.6 – 9.8)
Final basins: Soil permeability (cm/hr) [PERH]	6.0 (5.5 – 9.3)	4.2 (2.1 – 5.2)	6.0 (2.4 – 16.9)	0.6 (0.2 – 2.1)	2.1 (1.0 – 7.8)	2.2 (1.7 – 7.8)

was the biggest issue. Elevation and slope varied the most in the POR study, because of site selection of some watersheds in the Cascades ecoregion, which likewise led to the greatest variability in precipitation. Soils varied the most in the DEN study. In every study area, variability in environmental settings was less in almost every case in the set of final watersheds compared with those of the candidate watersheds. Variability among study areas was an expected result of conducting studies across diverse settings.

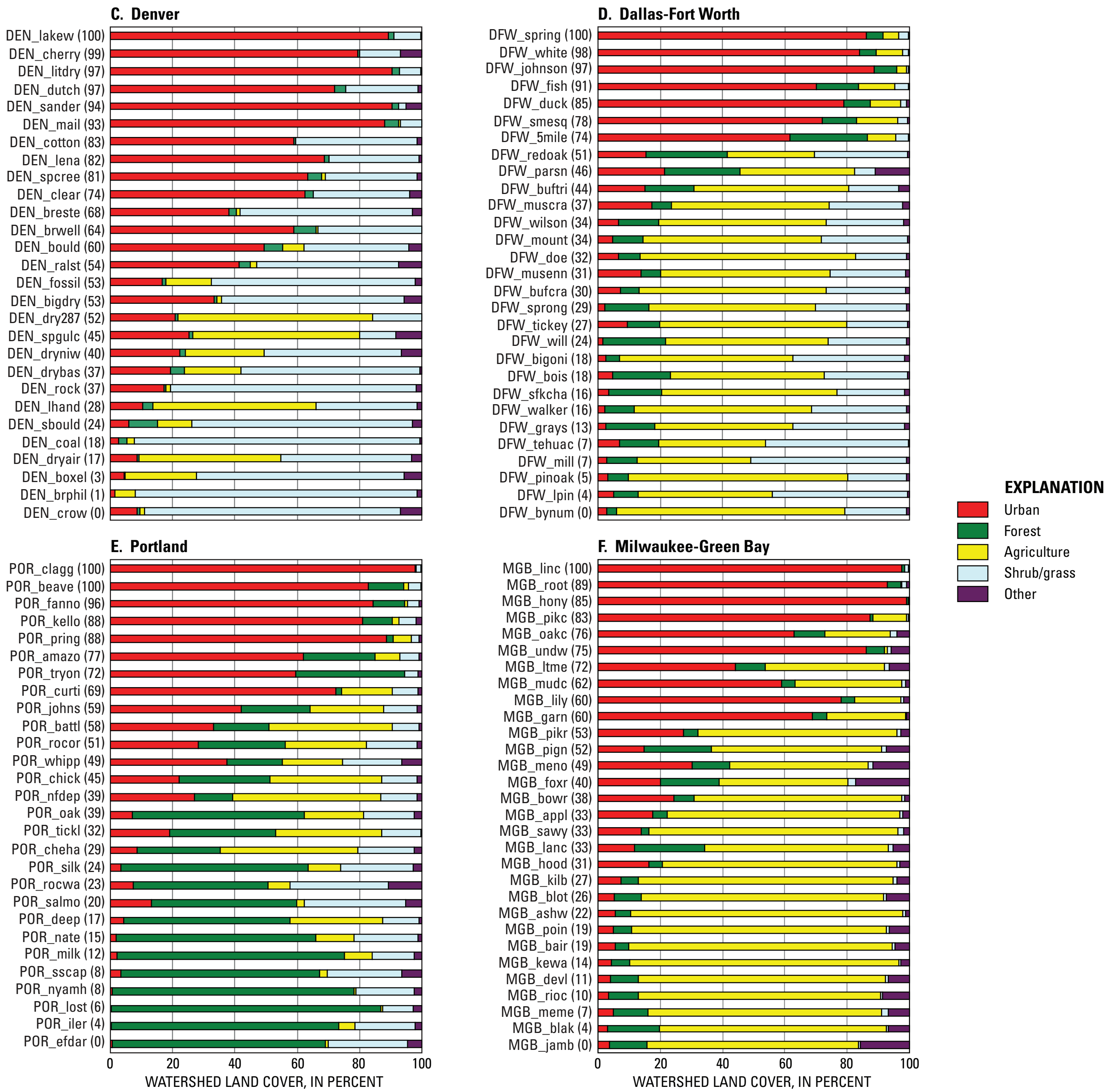
A graphic representation of the variability of land cover in the final watersheds is given in figures 10A–F. "Background" land cover of nondeveloped land varied considerably. In the humid east (RAL and ATL), forest predominated, and agriculture was a secondary component. In the DEN area, shrub and grasslands were the primary background vegetation followed by agriculture. The proportions of those land covers in the DFW study area were reversed: agriculture (predominantly pasture) was the primary background land cover, and shrub/grasslands was the secondary land-cover category. In the MGB area, agriculture was almost exclusively the background land cover. The POR watersheds had the most heterogeneous mix: background land cover was generally a mixture of forest, agriculture, and shrub/grass. Wetlands were a significant component (>10 percent) in only a few watersheds, all of which were in the MGB area.

Variability in Aspects of Urbanization

As with environmental setting variables, aspects of urbanization, such as population, housing, infrastructure, and land cover, can be compared at both the candidate-watershed scale and the final-watershed scale, both within and among the study areas (table 4).



Figures 10A–B. 2001 land cover for watersheds of each study area. Sites are ordered by local urban intensity index value (in parentheses). (Land-cover sources: Atlanta and Raleigh—U.S. Geological Survey, 2005c.)



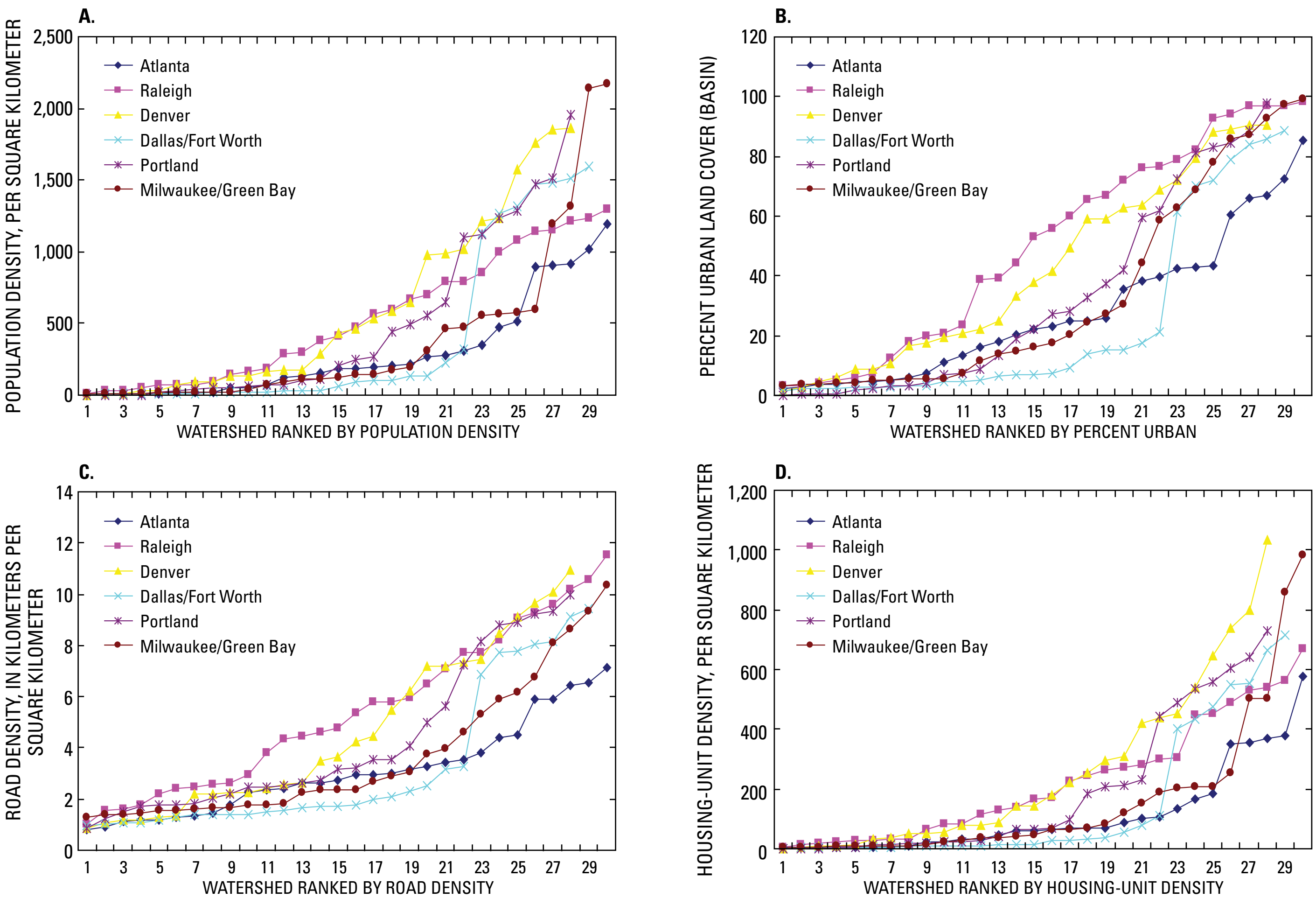
Figures 10C–F. 2001 land cover for watersheds of each study area. Sites are ordered by local urban intensity index value (in parentheses). (Land-cover sources: Denver, Dallas-Fort Worth, and Milwaukee-Green Bay—Falcone and Pearson, 2006; Portland—National Oceanic and Atmospheric Administration, 2005.)

Table 4. Comparative summary of key population, infrastructure, and land-cover-derived variables for study area watersheds.

[Candidate and final (shaded) watersheds alternate rows for each variable. Unless otherwise indicated, values are given as median (min–max). Values for all computed variables are given in Appendix 7; sq km, square kilometer; %, percent; km/sq km, kilometer per square kilometer; >, greater than; m, meter]

Variable [abbreviation]	Metropolitan area					
	Atlanta	Raleigh	Denver	Dallas-Fort Worth	Portland	Milwaukee-Green Bay
Candidate basins: 2000 population density (persons/sq km) [POPDEN00]	44 (1 – 1,559)	31 (0 – 1,435)	2 (0 – 2,398)	23 (3 – 3,097)	20 (0 – 2,001)	35 (9 – 2,111)
Final basins: 2000 population density (persons/sq km) [POPDEN00]	186 (5 – 1,197)	440 (9 – 1,293)	361 (0 – 1,860)	64 (3 – 1,591)	162 (1 – 1,958)	131 (10 – 2,175)
Candidate basins: Population change, 1990–2000 (%) [POP90_00]	27 (–15 – 479)	20 (–91 – 973)	44 (–83 – 1,498)	23 (–4 – 76)	8 (–1 – 485)	12 (–13 – 99)
Final basins: Population change, 1990–2000 (%) [POP90_00]	32 (–11 – 166)	33 (0 – 232)	24 (–12 – 2,338)	24 (0 – 60)	28 (–17 – 167)	17 (–16 – 138)
Candidate basins: Median household income (1,000) [MEDHHI]	$42.7 (17.5 – 103.8)	$39.9 (18.8 – 163.9)	$45.0 (33.5 – 157.6)	$46.4 (20.4 – 90.7)	$50.3 (34.7 – 80.5)	$55.3 (40.3 – 100.0)
Final basins: Median household income (1,000) [MEDHHI]	$51.8 (24.9 – 76.1)	$50.0 (20.7 – 94.2)	$67.0 (51.1 – 99.6)	$47.7 (31.7 – 81.1)	$56.9 (36.9 – 82.2)	$57.0 (36.9 – 82.2)
Candidate basins: Road density (km/sq km) [ROADDEN]	1.8 (0.4 – 8.6)	1.8 (0.0 – 9.6)	0.9 (0.0 – 10.4)	1.6 (0.9 – 12.8)	1.8 (0.8 – 10.2)	1.7 (1.1 – 9.0)
Final basins: Road density (km/sq km) [ROADDEN]	2.9 (0.8 – 7.1)	5.1 (1.0 – 11.5)	3.6 (0.9 – 10.9)	1.7 (0.9 – 9.5)	3.0 (0.9 – 10.0)	2.4 (1.3 – 10.4)
Candidate basins: Houses >60 years old (%) [PHU_G60]	6.7 (10.1 – 25.6)	8.0 (0 – 27.6)	18.6 (0 – 38.2)	5.0 (0.0 – 23.6)	12.7 (0.1 – 37.1)	24.6 (0.5 – 45.7)
Final basins: Houses >60 years old (%) [PHU_G60]	3.6 (1.2 – 17.4)	7.1 (0 – 33.4)	4.6 (0 – 19.7)	4.1 (0.3 – 23.7)	8.2 (2.2 – 22.7)	13.5 (2.7 – 45.4)
Final basin data only:						
Final basins: Urban land cover in basin (%) [P_NLCD1_2]	22.5 (2.3 – 85.4)	54.5 (3.0 – 98.4)	35.6 (1.5 – 90.4)	6.9 (1.6 – 88.8)	20.5 (0.2 – 97.8)	17.0 (3.2 – 99.1)
Final basins: Urban land cover in riparian zone (%) [P_NLCD1_B2]	11.0 (0.6 – 65.0)	45.3 (1.8 – 98.4)	37.6 (1.3 – 89.2)	2.8 (0.0 – 64.3)	14.5 (0.0 – 97.4)	13.5 (2.8 – 99.2)
Final basins: Forest land cover (%) [P_NLCD1_4]	43.0 (11.3 – 70.6)	29.9 (1.1 – 75.8)	2.0 (0.0 – 9.4)	9.9 (3.3 – 26.2)	31.7 (0.1 – 86.8)	5.8 (0.6 – 22.6)
Final basins: Agriculture land cover (%) [P_NLCD1_8]	12.4 (1.4 – 33.0)	8.5 (0.2 – 37.1)	1.6 (0.0 – 62.5)	49.6 (3.1 – 73.3)	8.3 (0.0 – 47.5)	65.3 (0.0 – 87.3)
Final basins: Persons per sq km of urban land [from POP2000 and P_NLCD1_2]	748 (180 – 1,516)	909 (303 – 1,783)	1,031 (15 – 2,336)	863 (64 – 1,881)	1,250 (231 – 2,363)	725 (284 – 2,229)
Final basins: Housing unit density (per sq km) [HUDEN]	63 (3 – 577)	168 (7 – 668)	143 (0 – 1,033)	16 (2 – 717)	65 (1 – 731)	56 (4 – 985)
Final basins: Percentage of basin comprised of largest urban patch [LPI_C2]	20.4 (0.2 – 85.2)	52.8 (0.7 – 98.5)	33.0 (0.6 – 90.2)	2.4 (0.2 – 88.7)	15.3 (0.0 – 97.7)	12.5 (0.2 – 99.1)
Final basins: Mean distance of segment to nearest road (m) [SEG_RMD]	247 (91 – 778)	120 (20 – 611)	98 (13 – 654)	250 (72 – 937)	88 (38 – 309)	123 (30 – 410)
Final basins: Basins with disproportionate distribution of urban land in lowlands (near sampling site) (%) [from pURBANdw]	10 of 30 (33%)	13 of 30 (43%)	26 of 28 (93%)	8 of 29 (28%)	18 of 28 (64%)	26 of 30 (87%)
Final basins: riparian urban as percent of basin urban (%) (P_NLCD1_B2/P_NLCD1_2)	0.53 (0.26 – 0.76)	0.84 (0.30 – 1.37)	1.02 (0.62 – 1.51)	0.49 (0.0 – 0.87)	0.92 (0.0 – 2.51)	0.87 (0.39 – 1.31)

Urbanization, as represented by the Census 2000 population density and other individual urban variables, did not follow the same distribution in the final watersheds when compared across study designs (fig. 11A). Although every study area had watersheds with very low and very high urbanization, certain ranges of urbanization were not represented in some study areas compared with others. Focusing on certain ranges of urbanization was, in some cases, an intentional decision by individual investigators in some studies (to capture more data at sites in the lower end of urbanization where ecological health may be in jeopardy) and, in some cases, simply because of the difficulties in site selection noted earlier and the lack of suitable candidate watersheds. In general, steep increases of lines in figures 11A–E represent ranges of urbanization that were not represented in the study design. For example, a large gap occurred in the DFW population density line between 300 and 1,100 persons per square kilometer (fig. 11A), that is, there were no watersheds representing that range of urbanization, which was a result of difficulty in finding candidate watersheds in that range. The RAL watersheds had



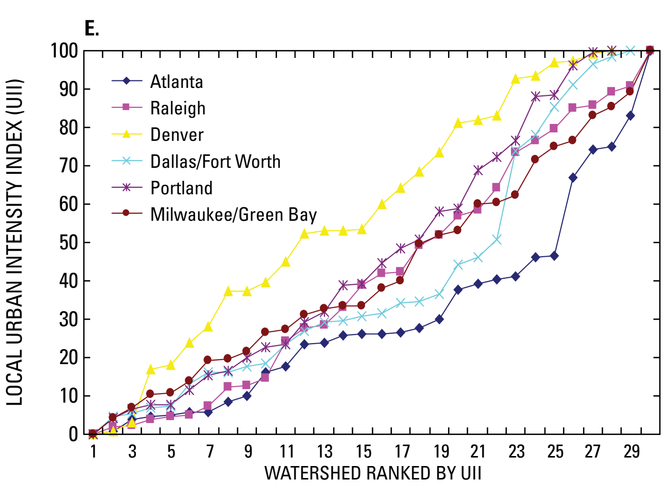


Figure 11. Distribution of (A) population density, (B) percent urban land cover in watershed, (C) road density, (D) housing-unit density, and (E) local Urban Intensity Index (UII) for final watersheds. X-axis is the relative ranking of watersheds for each variable. Steep slope in a line indicates a gap in representing a continuous range for that variable.

the smoothest continuous urban gradient as represented by the single variables of population density, percent urban land cover, road density, and housing-unit density, with no major unrepresented gaps (fig. 11A–D). It is noteworthy that gaps in urbanization are smoothed considerably by the UII (fig. 11E) for all study areas. It also is noteworthy that for a number of study areas, road density had the similar effect of being the individual variable that reduced variability in gaps of urbanization (compare, for example, the MGB population density line in figure 11A to the MGB road density line in figure 11C).

The distribution of urbanization in the final watersheds for the same four urban variables and the local UII is shown by study area in figures 12A–E: population density, percent urban land cover in watershed, road density, housing-unit density,

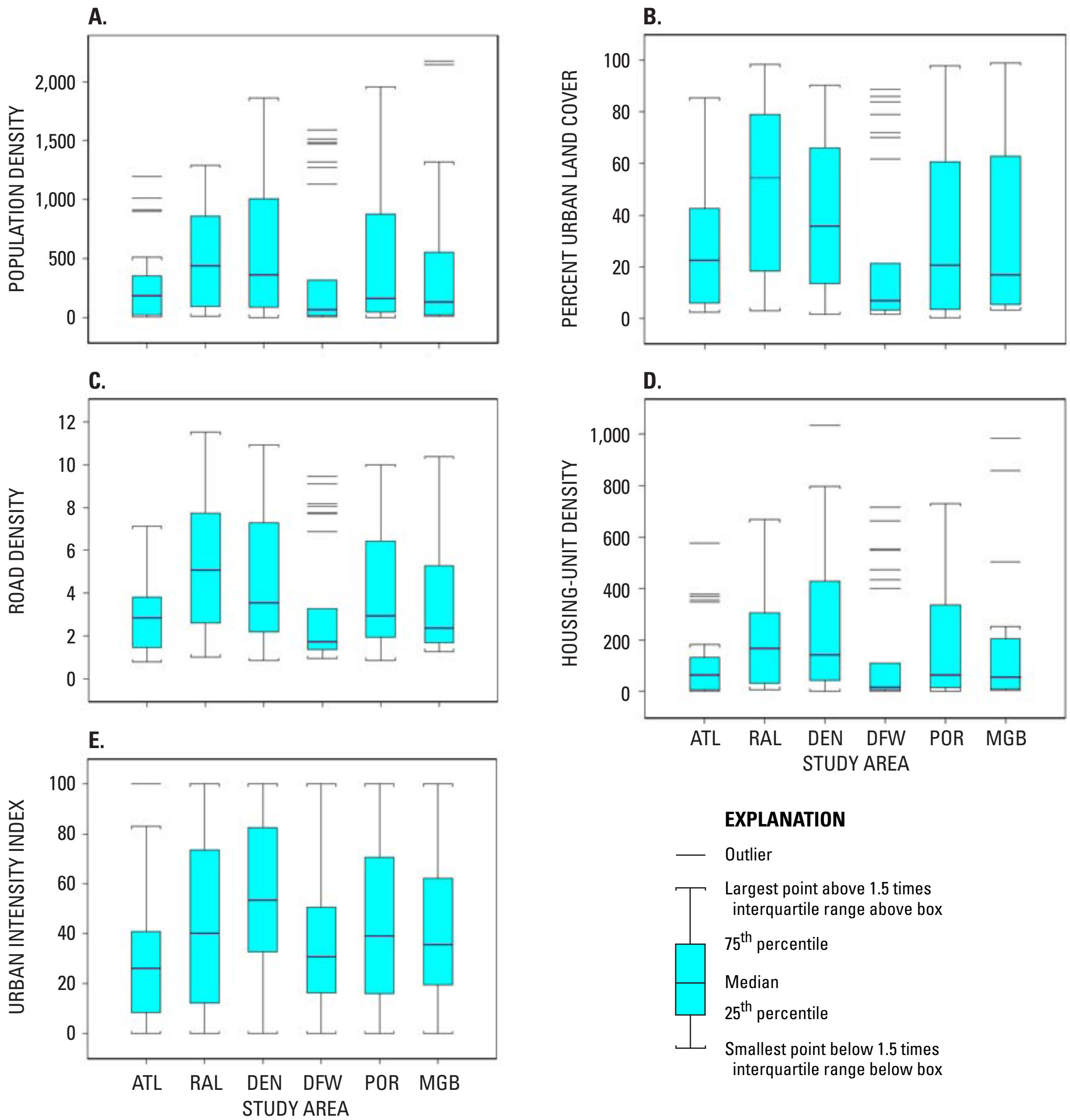


Figure 12. Distribution of (A) population density, (B) percent urban land cover in watershed, (C) road density, (D) housing-unit density, and (E) local Urban Intensity Index (UII) for final watersheds.

and local UII, respectively. The box plots match the visual pattern in figures 11A–E: median and interquartile range values were higher in the RAL and DEN watersheds than in the other study areas, and ranges of urbanization varied, as measured by these four variables. Once again the UII has a smoothing effect, giving a more consistent spread over the entire range, as a result of its multimetric nature.

Comparison of Index Components of the Six Study Areas

The variables composing the UII for each study area were selected primarily based on their relation to the Census 2000 population density. All component variables had a Spearman's rank correlation coefficient $|r| > 0.5$ to population density and < 0.5 to drainage area. Investigators in each study area, however, had the ability to use local judgment in subsetting the component variables based on the strength of the relation (for example, using a higher *r* threshold), eliminating variables deemed to be redundant in nature, or using population density itself as part of the index. The final number of variables used in each index varied (table 5), and represented somewhat different approaches to building the local UII but with relatively uniform methodologies.

Results of Local Urban Intensity Index Calculations

Each local index calculation provided a score ranging from zero to 100 for the watersheds in that study (figs. 9A–F, figs. 10A–F, and Appendix 6). The UII was calculated from variables that correlated to population density (and in the case of RAL included population density); however, the UII did not necessarily show a 1:1 association with population density (figs. 13A–F). As was noted by Tate and others (2005), the UII may allow differentiation between sites with very low levels of urbanization. For example, differences in values of individual variables are difficult to see at low levels of urbanization (figures 11A–D), however, are more distinct when scaled from zero to 100 on the UII (fig. 11E). Linear correlation (R^2) between the UII and population density was high in four of the six study areas (ATL = 0.95, RAL = 0.94, DFW = 0.89, and POR = 0.88), but only moderately high in DEN (0.70) and MGB (0.69).

Table 5. Spearman rank correlation coefficients for variables correlated with 2000 population density that were used in the urban intensity indices.

[Variables with correlation coefficients in blue (positive correlation) or red (negative correlation) were included as components of that study area's urban intensity index. —, variable not considered for inclusion; >, greater than]

Variable	Abbreviation	ATL	RAL	DEN	DFW	POR	MGB
Land-cover variables							
percent urban in watershed	P_NLCD1_2	0.976	0.935	0.945	0.910	0.982	0.978
percent barren in watershed	P_NLCD1_3	–0.154	–0.673	–0.429	0.349	–0.794	–0.040
percent forest in watershed	P_NLCD1_4	–0.906	–0.849	0.291	0.013	–0.909	–0.468
percent shrubland in watershed	P_NLCD1_5	–0.683	–0.883	–0.176	–0.817	–0.852	0.732
percent grassland in watershed	P_NLCD1_7	–0.847	–0.886	–0.808	–0.698	–0.313	–0.362
percent pasture/agriculture in watershed	P_NLCD1_8	–0.581	–0.901	–0.695	–0.621	–0.003	–0.855
percent impervious surface in watershed	NLCD_IS	0.967	0.804	0.940	0.927	0.980	0.968
percent urban in riparian zone	P_NLCD1_B2	0.955	0.903	0.911	0.845	0.969	0.943
percent barren in riparian zone	P_NLCD1_B3	0.050	–0.404	–0.440	0.310	–0.816	–0.005
percent forest in riparian zone	P_NLCD1_B4	–0.825	–0.823	0.268	0.081	–0.831	–0.341
percent shrubland in riparian zone	P_NLCD1_B5	–0.572	–0.796	–0.198	–0.821	–0.874	0.750
percent grassland in riparian zone	P_NLCD1_B7	–0.635	–0.662	–0.824	–0.703	–0.315	–0.311
percent pasture/agriculture in riparian zone	P_NLCD1_B8	–0.298	–0.844	–0.685	–0.623	–0.008	–0.819
percent herbaceous wetlands in watershed	P_NLCD2_95	—	—	–0.520	—	—	—
percent impervious surface in riparian zone	NLCD_BIS	0.951	0.789	0.908	0.861	0.967	0.929
Infrastructure variables							
road area index in watershed	RDARDEN	—	—	0.946	—	—	0.940
road area index in watershed (miles)	RDARINDX	0.840	0.434	—	0.939	0.666	0.592
road traffic index in watershed (miles)	RDTRINDX	0.824	0.438	—	0.933	0.726	0.580
road density in watershed	ROADDEN	0.982	0.960	0.955	0.943	0.954	0.943
density of Toxics Release Inventory sites	D_TRICOUNT	0.724	0.438	—	0.767	0.557	0.263

Table 5. Spearman rank correlation coefficients for variables correlated with 2000 population density that were used in the urban intensity indices. — Continued

[Variables with correlation coefficients in blue (positive correlation) or red (negative correlation) were included as components of that study area's urban intensity index. —, variable not considered for inclusion; >, greater than]

Variable	Abbreviation	ATL	RAL	DEN	DFW	POR	MGB
Socioeconomic variables							
SE Index 2	SEI_2	0.948	0.797	—	0.864	0.544	–0.902
SE Index 3	SEI_3	0.870	–0.024	—	–0.842	0.915	0.123
SE Index 4	SEI_4	0.192	0.223	—	–0.689	–0.644	0.729
Population and housing variables							
household density	HHDEN	0.983	0.986	0.986	0.986	0.989	0.993
density of housing units	HUDEN	0.986	0.987	0.985	0.985	0.989	0.991
median non-family household income	MNFAMINC	0.673	0.215	–0.162	0.586	0.211	0.353
percent housing units that have three bedrooms	P_HU3RM	—	—	–0.567	—	—	—
percent occupied housing units	P_OCCUPY	0.792	0.186	0.352	0.637	0.416	0.129
percent housing units that are owner occupied	P_OWN	–0.137	–0.634	–0.413	–0.399	–0.507	–0.597
percent housing units that are renter occupied	P_RENT	0.137	0.634	0.413	0.399	0.508	0.597
percent housing units that are vacant	P_VACANT	–0.792	–0.186	–0.348	–0.658	–0.416	–0.191
percent population >25 that have Bachelor's degree	PBCH_G25	0.848	0.253	–0.117	0.500	0.480	0.594
percent citizens born in state of residence	PC_INSTAT	–0.839	–0.344	0.239	–0.733	–0.565	–0.788
percent citizens not born in the United States	PC_NONUS	0.595	0.268	0.336	0.489	0.640	0.671
percent citizens born in other states in the United States	PC_OUTST	0.838	0.150	–0.402	0.591	0.198	0.721
percent living in same state > 5 years (since 1995)	PP_SH95	–0.268	–0.405	0.626	–0.256	0.489	0.019
percent citizens born in the United States	PC_US	–0.805	–0.650	–0.380	–0.522	–0.815	–0.796
percent females gt than 16 that are employed	PF_GT16E	0.585	–0.197	–0.196	0.468	0.225	–0.518
percent households occupied by two persons	PH_2PERS	–0.219	–0.389	–0.540	–0.595	–0.396	–0.230
percent housing units using electricity as fuel	PHEL	–0.338	–0.453	0.314	0.284	0.008	0.621
percent two-person households	PHH2	—	—	–0.576	—	—	—
percent population race = Asian	PPASIA	0.648	0.423	0.358	0.769	0.738	0.837
percent population race = black	PPBLACK	0.123	–0.134	0.472	0.401	0.638	0.750
percent population race = white	PPWHITE	–0.257	0.000	–0.258	–0.534	–0.620	–0.798
percent population that is female	PPFEMALE	–0.021	0.083	0.409	0.203	0.295	0.589
percent population that is male	PPMALE	0.014	–0.085	–0.419	–0.260	–0.297	–0.600
percent housing units using liquid propane gas as fuel	PHLP	–0.943	–0.919	–0.583	–0.934	–0.782	–0.892
percent households of less than three people	PHO_L3P	–0.012	–0.773	–0.412	–0.629	–0.154	–0.323
percent housing units using oil as fuel	PHOIL	–0.297	–0.302	–0.290	–0.090	–0.409	–0.823
percent population >25 that have high school degree	PHS_G25	–0.574	–0.364	0.077	–0.701	–0.646	–0.816
percent houses built prior to 1959 (1939–1959)	PHU_G40	–0.551	0.292	–0.053	–0.482	–0.247	–0.298
percent houses built prior to 1949 (1939–1949)	PHU_G50	–0.706	0.242	–0.423	–0.790	–0.585	–0.739
percent houses built prior to 1939	PHU_G60	–0.825	0.092	–0.541	–0.861	–0.726	–0.803
percent housing units using utility gas as fuel	PHUT	0.876	0.841	0.469	0.640	0.775	0.808
percent housing units using wood as fuel	PHWOOD	–0.858	–0.830	–0.648	–0.726	–0.895	–0.906
percent males >16 working in retail	PMRETAIL	—	—	0.535	—	—	—
percent houses occupied by persons age >65	POCC_G65	–0.534	0.157	0.477	–0.570	0.117	0.240
percent change in population, 1990–2000	POP90_00	0.029	–0.327	0.707	0.003	0.244	0.211
population density 2000	POPDEN00	—	1.000	—	—	—	—
percent population living in same house as 1995	PP_SH95	–0.539	–0.524	–0.241	–0.622	–0.804	–0.780
percent population living in rural area	PPRURAL	–0.952	–0.935	–0.860	–0.921	–0.915	–0.954
percent population living in urban areas	PPURBAN	0.961	0.929	0.860	0.917	0.915	0.954
Total number of variables in index:		5	5	16	40	24	35

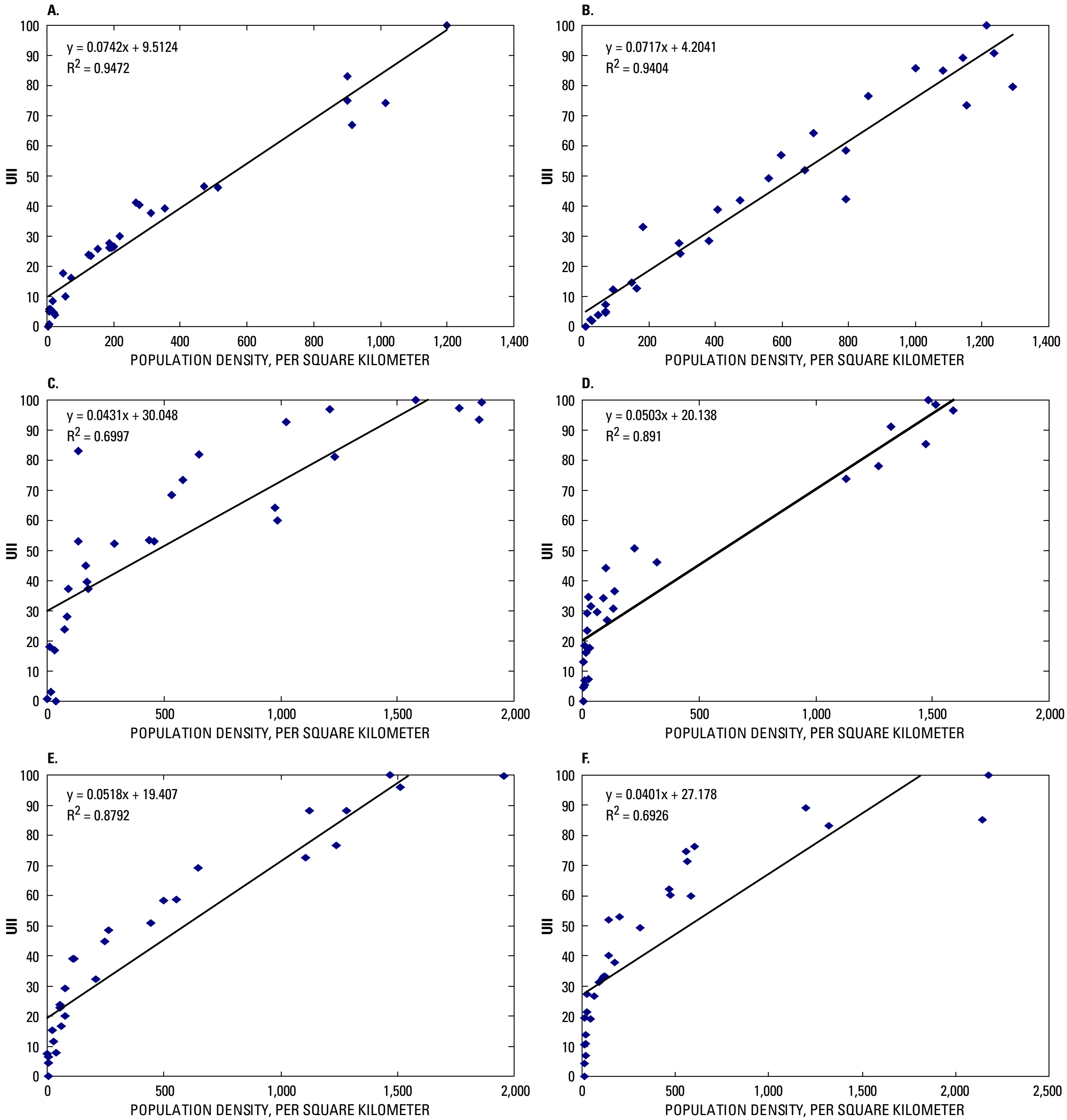
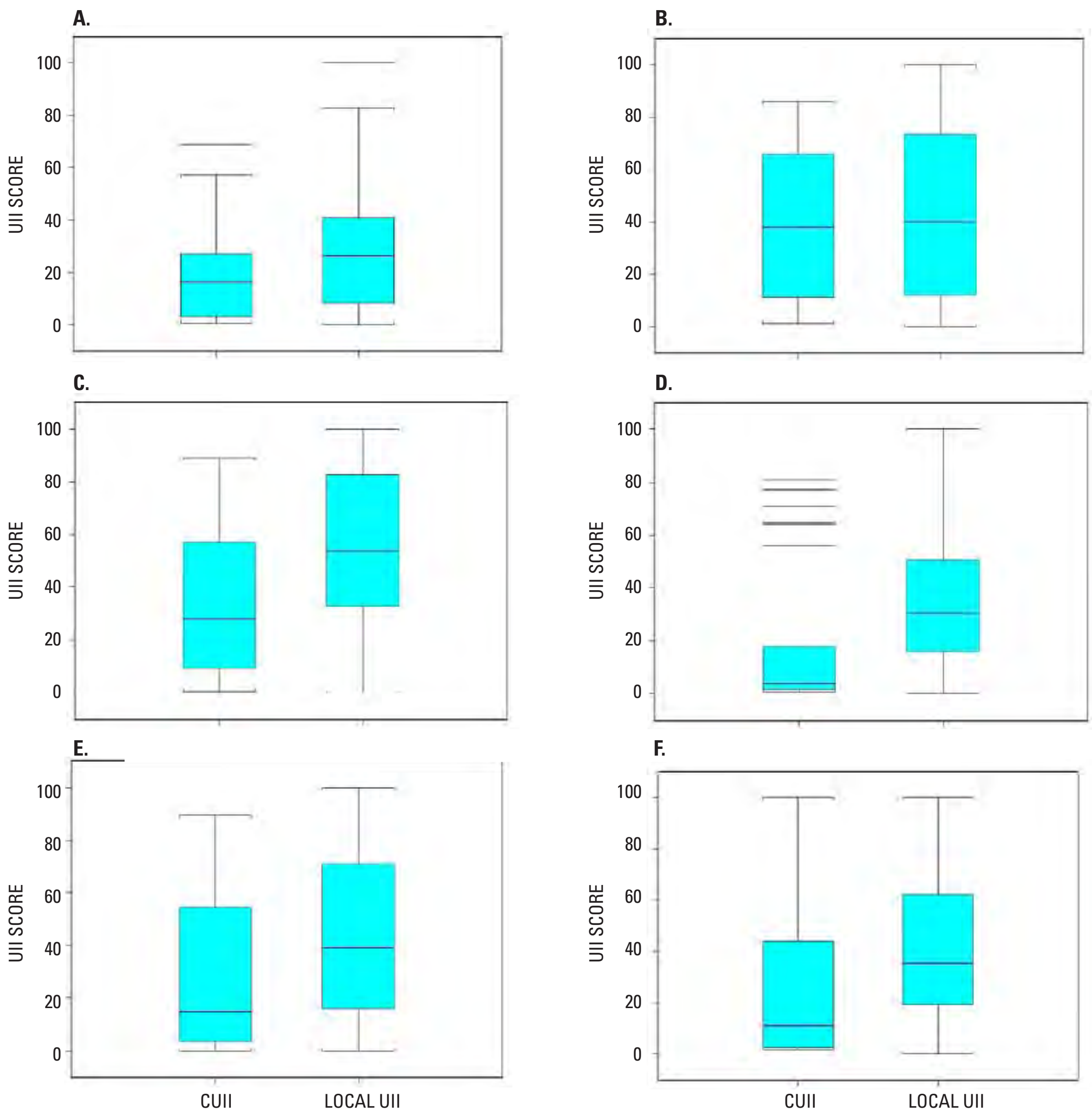


Figure 13. Relation of local urban intensity index (UII) to population density in the (A) Atlanta, (B) Raleigh, (C) Denver, (D) Dallas-Fort Worth, (E) Portland, and (F) Milwaukee-Green Bay study areas.

Results of Common Urban Intensity Index Calculation

The two factors that control the UII value of a site are the type and number of variables included in the calculation and the range of values the variables have. The range of values will increase with an increasing number of watersheds included in the study. As noted previously, the CUII was based on the final set of 175 watersheds from all study areas, and a set of variables that all had strong correlation to population density and the population density variable itself.

In Appendix 6, CUII values can be compared to the local UII values. Placing the sites for an individual study area in a larger context and standardizing variable input to a small set of five variables changed the scores of many sites considerably (generally lower) from the local UII scores (fig. 14), particularly those at the low end of the UII gradient. However, given the nature of the index calculation, this was not entirely



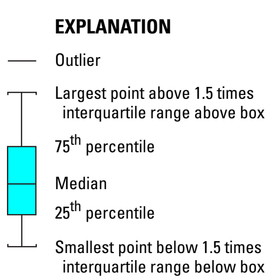


Figure 14. Distribution of common urban intensity index (CUII) and local urban intensity index scores for (A) Atlanta, (B) Raleigh, (C) Denver, (D) Dallas-Fort Worth, (E) Portland, and (F) Milwaukee-Green Bay.

unexpected. Because the index is a range-standardized number, increasing the range (including sites with much higher urbanization) forces site scores on the low end of the scale to decrease. Likewise, decreasing the number of variables incorporated in the calculation also results in site score changes.

Although the site scores could change considerably from UII to CUII, their relative ranking within each study had less change. The CUII was strongly related to the UII in most study areas: R^2 = 0.99 (ATL), 0.99 (RAL), 0.84 (DEN), 0.90 (DFW), 0.93 (POR), and 0.83 (MGB). In general, the distribution of site scores for a particular study area matched the CUII scores most closely when the component variables of the UII and CUII were most similar, as was the case in the RAL and ATL study areas. The DFW, MGB, and DEN study areas had the largest change in rankings when comparing UII and CUII rankings. The mean change in ranking by study area was as follows: 1.00 (ATL), 0.47 (RAL), 1.57 (DEN), 3.45 (DFW), 0.79 (POR), and 1.70 (MGB).

Discussion

Urban Growth and Land Use

For decades the extent of urbanized land area in the United States has exceeded the percentage of population growth (Fellmann and others, 1992; Theobald, 2005). In 147 of the 175 watersheds in this study (84 percent), this pattern was duplicated; that is, the percent increase in urbanized land-cover area between 1992 and 2001 exceeded the percent population increase (1990 to 2000). Most of the watersheds where this pattern did not occur were already highly urbanized. “Urban sprawl,” generally considered an undesirable growth pattern (Theobald, 2005), is typically characterized by a relatively small population consuming a disproportionate amount of natural land for development. Sutton (2003) proposed a metric that quantified sprawl as a measure of expected population density and reported results that can be compared to the metropolitan areas in this study. For 244 urban areas with greater than 50,000 people, this measure of sprawl ranged from a value of –95 (most sprawl) to +56 (least sprawl). On this scale, the Green Bay MSA had the most sprawl (value of –51), followed by Atlanta (–32), Greensboro (–21), Dallas-Fort Worth (–15), Raleigh (–8), Milwaukee (+6), Denver (+7), and Portland, which had the least sprawl (value of +13; table 1). These values conform generally to other studies. For example, Portland is regularly cited as a model for progressive urban planning (Dieleman and Wegener, 2004).

Urban land-use efficiency and sprawl also can be represented by the number of persons occupying a unit of urban land. High numbers of persons per unit of urban land generally are recognized as being a desirable characteristic, because land is used more efficiently (The Brookings Institution, 2006). In that regard, the final watersheds for the six study areas generally matched the results of the Sutton (2003) sprawl index (table 1) for the metropolitan areas; the POR watersheds had the highest median measure of persons per urban square kilometer (1,250), followed by the DEN watersheds (1,031), with the ATL and MGB watersheds exhibiting the lowest values (748 and 725, respectively, fig. 15).

The concepts of urban sprawl and urban growth are complex, with multiple definitions (Torrens and Alberti, 2000), and are tied to the physiography of the region, natural barriers, climate, transportation corridors, job growth, commuting patterns, and the political/development environment. Sutton (2003) noted that the idea of what constitutes sprawl, or even what constitutes an urban area, is being redefined as rapidly increasing housing prices have caused “commuter-sheds” to grow; that is, workers are willing or forced to travel farther distances. For example, the number of workers commuting 90 minutes or more one way between home and job nearly doubled between 1990 and 2000 (U.S. Census Bureau, 2006b). This raises the question of whether Census-defined population density (individuals residing in the Census area) is the best single metric to define “what is urban.” Theobald (2005) likewise suggested exurban growth—rural residential development—occupies 5–10 times more land use than urban or suburban densities and, although of lower intensity, may have important ecological implications. McKnight (2001) also noted that cities are no longer the favored locales for many manufacturing and retail firms, and it is commonplace for a firm to purchase a rural tract and build a single-story facility with parking lots covering a vast area. This trend likewise argues the need to consider alternate or changing paradigms of what is considered “urban,” and how to measure it.

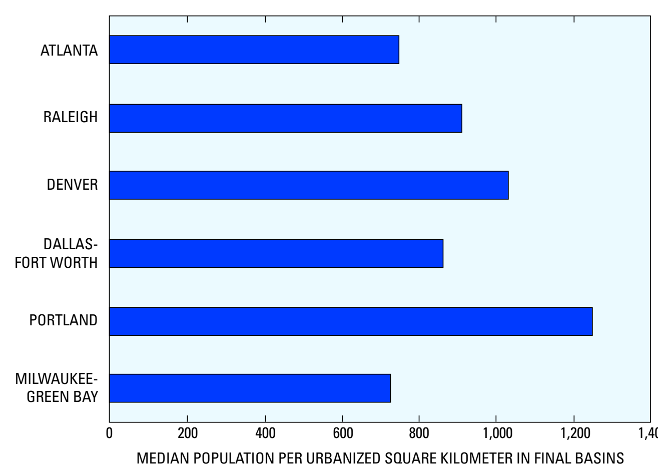


Figure 15. Median values of population per square kilometer of urban land in the final study watersheds. High values generally are thought of as characteristics of “less sprawl” in urban areas (The Brookings Institution, 2006).

Variability in Urbanization

Variability in urbanization is best looked at together with variability in environmental settings. Table 6 contains coefficient of variation (CV) values for key environmental and urban variables. The CV (standard deviation divided by mean) allows a method for comparing the relative variability of frequency distributions with differing means (Burt and Barber, 1996). Low CV values indicate less variability in the sample; high CV values indicate more variability. The study design supported minimizing differences in local environmental settings; thus, environmental setting variables had lower CV values and urban intensity variables had higher CV values.

Values in table 6 indicate the following:

- Of the environmental setting variables, a fairly consistent level of variability occurred within each study area. For example, the variability in precipitation within the 30 ATL watersheds is very low (CV = 0.04) and very low within the 30 RAL watersheds (0.02), and so on. The two exceptions to this, both of which were noted earlier regarding the values in table 3 are DEN, which has considerably more variability in drainage areas (CV = 1.78) than in the other study areas, and POR, which has more variability in elevation and slope (CV = 0.62 and 0.58, respectively) than the other study areas (fig. 16).
- Of the urban variables (fig. 17), DFW generally has the most variability among the final study watersheds, and RAL generally the least. For example, population density variability is greatest in DFW (CV = 1.53) and least in RAL (0.83); urban land-cover variability greatest in DFW (CV = 1.30) and least in RAL (0.69), and so forth. This also is confirmed by the box plots presented in figure 12; that is, DFW had the greatest number of outliers.

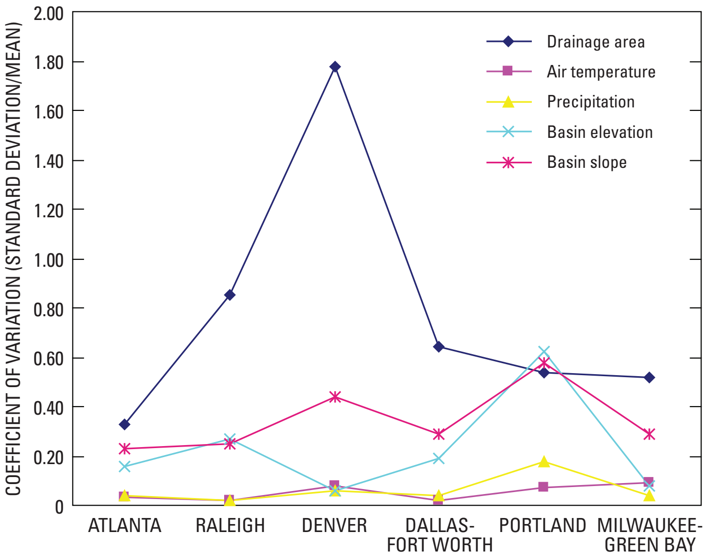


Figure 16. Coefficient of variation (CV) values for selected environmental variables for the final watersheds. Note the high variation for drainage area in DEN watersheds compared to other study areas, and high variation in topographic variables (elevation, slope) in the POR watersheds.

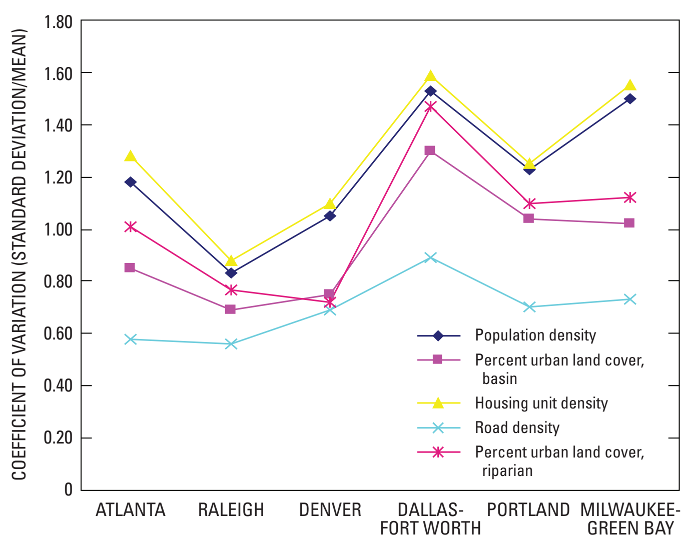


Figure 17. Coefficient of variation (CV) values for selected urban variables for the final watersheds.

Table 6. Coefficient of variation (CV) values for selected environmental and urban variables.

[CV calculated as standard deviation/mean for the set of final watersheds. Low CV values indicate lower variability among the final watersheds for that study; high values indicate higher variability. The "Across all study areas" column contains CV values for the complete set of 175 final watersheds. Values referenced in the text are bolded]

Variable [abbreviation]	ATL	RAL	DEN	DFW	POR	MGB	Across all study areas
Environmental setting variables							
drainage area [SQKM]	0.33	0.85	**1.78**	0.64	0.54	0.52	1.14
mean annual air temperature [MAAT]	0.03	0.02	0.08	0.02	0.07	0.09	0.31
mean annual precipitation [MAP]	0.04	0.02	0.06	0.04	0.18	0.04	0.35
mean basin elevation [MEANELEV]	0.16	0.27	0.06	0.19	**0.62**	0.08	1.22
mean basin slope [SLOPE_X]	0.23	0.25	0.44	0.29	0.58	0.29	0.87
segment sinuosity [SINUOUS]	0.18	0.12	0.14	0.13	0.14	0.20	0.16
percent clay soils [CLAYAVE]	0.02	0.06	0.22	0.11	0.27	0.17	0.23
percent sandy soils [SNDH]	0.01	0.09	0.18	0.36	0.22	0.37	0.34
soil permeability [PERH]	0.14	0.24	0.55	0.46	0.58	0.52	0.71
Urban variables							
population density [POPDEN00]	1.18	**0.83**	1.05	**1.53**	1.23	1.50	1.21
percent urban land cover, basin [P_NLCD1_2]	0.85	**0.69**	0.75	**1.30**	1.04	1.02	0.92
housing unit density [HUDEN]	1.28	0.88	1.10	1.59	1.25	1.55	**1.26**
road density [ROADDEN]	0.58	0.56	0.69	0.89	0.70	0.73	0.71
percent impervious surfaces, basin [NLCD_IS]	1.04	0.88	0.80	1.49	1.14	1.12	1.08
largest patch index, urban [LPI_C2]	0.95	0.79	0.80	1.51	1.16	1.18	1.04
percent urban land cover, riparian [P_NLCD1_B2]	1.01	0.77	0.72	1.47	1.10	1.12	1.04
Urban Intensity Index [UII]	0.84	0.77	0.57	0.79	0.73	0.66	1.01

- It is noteworthy that the variability in road density among study areas is less than in population density and percentage urban land cover, two variables commonly used in urban studies. This may be a result of a certain minimum level of road infrastructure existing even in very rural areas. The low variability in roads—in a study area and across study areas—also is confirmed by the graphs in figure 11 and box plots in figure 12.
- For urban variables, approximately the same level of variability occurs in the entire set of 175 study basins as in any individual study area. For example, the CV value for housing-unit density was 1.26, which was about the average CV value for individual study units. This differed from the environmental setting variables, which tended to have much higher variability across study areas than in any individual study area.

Impervious Surfaces

Impervious surfaces are clearly a key indicator of human presence (Schueler, 1994), although this variable was not used extensively as a variable in this analysis. Two imperviousness datasets were available for this study. The first was the NLCD 2001 datasets of 30-m spatial resolution (U.S. Geological Survey, 2005c). Although the scale of these datasets was ideal for this study, the accuracy-assessment results indicated considerable variability among the study areas and, in particular, significant underestimation in three of the six areas. The second imperviousness source was NOAA data available at 1-km spatial resolution (National Oceanic and Atmospheric Administration, 2006). This dataset was derived by a single group of developers for the conterminous United States based on national data layers and was believed to be a consistent representation of impervious surfaces for the appropriate timeframe of this study. However, concerns were raised as to the appropriateness of the coarse spatial scale of the NOAA data with regard to the size of the watersheds in this study, which were as small as 4 km^2. For this reason, the NOAA data were not relied on extensively in this study. Despite this, the NOAA data showed strong correlation to other individual variables used (population density, percentage of urban land cover, road density), and to the local UIIs and CUII (fig. 18), and provide good supportive data.

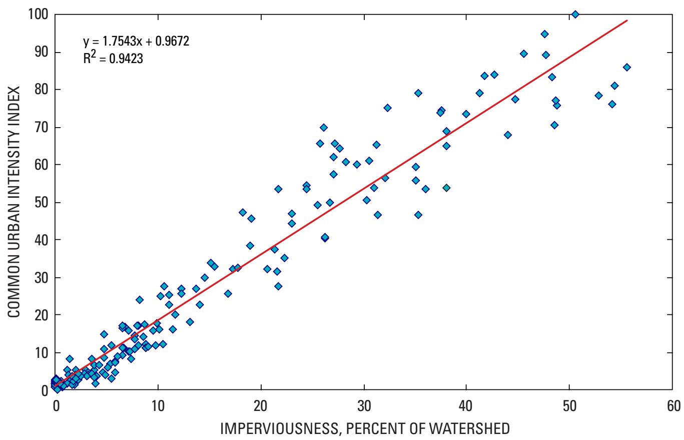


Figure 18. Relation of common urban intensity index (CUII) values to impervious surfaces, in percent, for all 175 watersheds (from National Oceanic and Atmospheric Administration, 2006). Linear regression line and equation are shown.

Other Variables with Strong Correlations to Population Density

The urban indices were derived based on the correlations of variables to population density. In addition to the variables that had uniformly strong correlation to population density in every area (table 2), a number of variables had strong correlation to population density in a subset of the study areas (also see table 5). Those that had strong correlation ($|r| > 0.8$) in at least three, but not all, study areas are noted here.

Background Land Cover

Forest land cover (at all scales—watershed, riparian, and segment) had strong negative correlation to population density in ATL (–0.906), RAL (–0.849), and POR (–0.909), but weak or no correlation in the other study areas. Because forest is the primary "natural" background land cover in those three areas, this confirms the notion that urbanization is likely to replace the major natural land cover. In general, the predominant background natural land cover had strong negative correlation to population density in each study (for example, grassland in DEN = –0.808). It is worth noting, however, that some categories of natural land cover were very sparse in some areas. For example, shrub and grassland in MGB or wetlands in DFW generally make up zero to 2 percent of a typical watershed. Therefore, interpreting *r* values for those variables was, and should be, approached with some caution.

Measures of Home Heating

Two Census-derived variables that describe the manner of home heating (liquid propane gas (PHLP) and wood (PHWOOD)) had strong negative correlation to population density in most, but not all, study areas (table 5). Conversely, use of utility gas as fuel (PHUT) had a strong positive correlation in most areas. This was expected, given the greater likelihood that urban homes in the United States are heated primarily by "city gas" (piped utility gas) instead of wood or liquid propane gas. The relative sparseness of homes being heated by wood as primary fuel (most values < 1 percent) or liquid propane gas (< 8 percent) also should be noted when considering the potential use of home-heating fuels as explanatory variables concerning stream ecosystems.

Age of Housing

Generally, an increase in negative correlation occurred with older homes and population density. That is, 40-year-old homes had weak negative correlation to population density; 50-year-old homes had a somewhat stronger negative correlation, and the negative correlation of 60-year-old homes was stronger still (>–0.8 in ATL, DFW, and MGB). The greater likelihood of older homes being in rural areas also is a relatively sparse variable; the percentage of homes more than 60 years old generally was less than 6 percent in most watersheds, and was at its maximum in rural areas in the MGB study area.

Spatial Position or Orientation of Urban Land

The spatial pattern and scale of urbanization in a watershed has long been recognized as a potential factor in the disturbance effect of urbanization (Alberti, 1999; Neel and others, 2004). Although considerable opportunity exists for further analysis regarding the spatial pattern metrics calculated for this study, three notable trends occurred.

Proximity of Development to Sampling Sites

The calculation of a "distance-weighted" measure of land cover—assigning a weight to land cover according to its proximity to the sampling site—allowed for identification of watersheds that had an unusually low or high percentage of urbanization close to the sampling site (fig. 19). There is evidence that the proximity of land cover affects the interpretation of response data in stream ecosystem studies in certain settings (Wente, 2000), and the conditions that influence where development takes place (topography, geographic barriers, historical patterns) also may play a role.

In this study the DEN and MGB study watersheds had a pattern of disproportionate development close to the sampling site (table 4). Urban development was disproportionately near the sampling sites at 26 of the 28 watersheds in the DEN study area and in 26 of the 30 watersheds in the MGB study area. The DFW study area had the least number of watersheds with this characteristic (8 of 29). Analysis of the topography in the DEN study area would suggest that the range of steep slopes

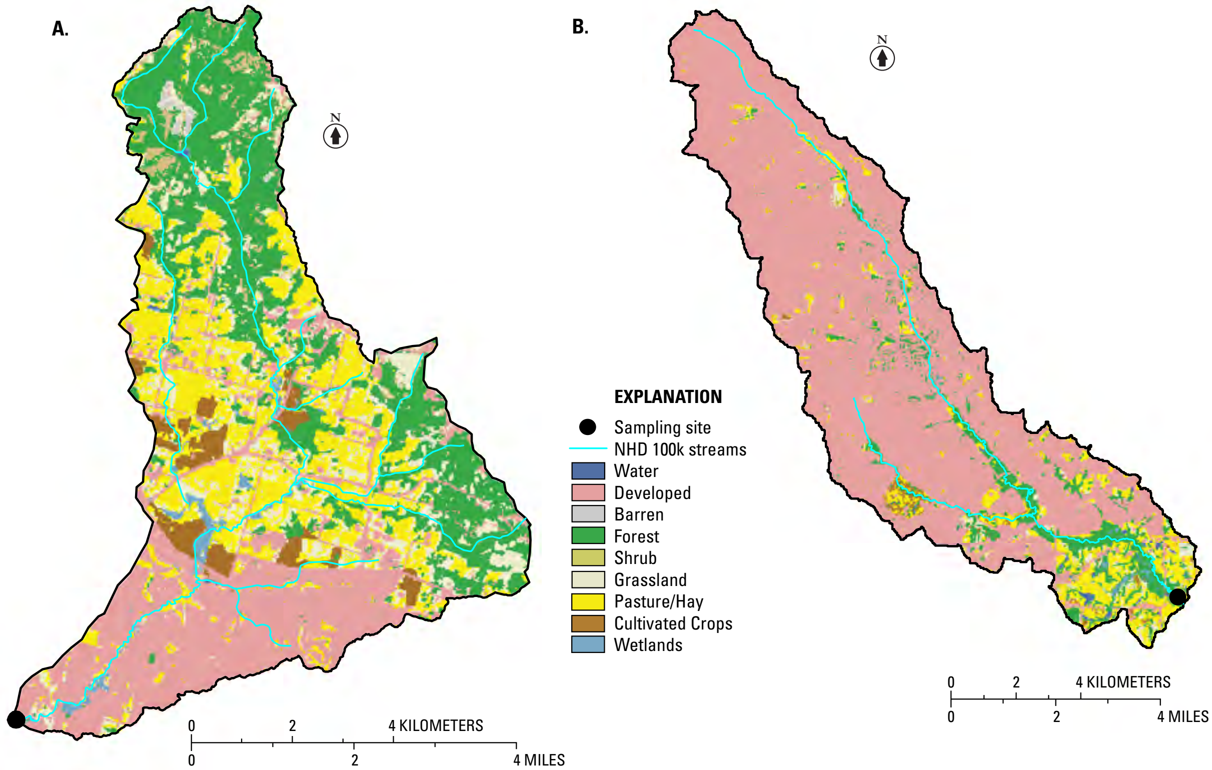


Figure 19. Examples of watersheds with differing spatial patterns of urbanization. (A) Watershed has proportionately more urbanization near the sampling site (POR_rocor). (B) Watershed has proportionately less urbanization near the sampling site (DFW_duck).

and high elevations in the uplands portions of the watersheds may be the reason for less development there than in areas of more favorable topography closer to the sampling site. An important factor in the MGB study area is likely historical development—settlements historically originated near Lake Michigan or Green Bay, and along the lower Fox River, the most downstream point of many watersheds in that area, and spread outward from there. It is not clear to what extent these spatial patterns may or may not affect ecological sampling results, but it is worth noting.

Riparian-Scale Compared to Watershed-Scale Development

Development can be measured at the riparian scale as well as the watershed scale. The potential benefits of wetlands and forested buffers near stream ecosystems are well recognized (U.S. Environmental Protection Agency, 2006b), and riparian-zone protection in some manner is recommended or mandated by many counties. Therefore, it is likely that in many areas "percent urban in riparian zone" would be less than "percent urban in watershed," as was the case in this study. Of the 175 study watersheds, the median ratio of "percent riparian urban" to "percent watershed urban" was 0.77; that is, the riparian zone had 23 percent less urbanization than the watershed as a whole.

Two study areas stood out particularly in this regard (table 4). For the DFW watersheds, the median ratio of riparian urban to watershed urban was 0.49, and for the ATL watersheds the ratio was 0.53. A value of 1.0 indicates identical amounts of riparian and watershed urbanization; the DEN study area was the one area in which the median riparian/watershed urbanization ratio crossed that threshold (1.02). These ratios indicate that there may be factors (physical or political) in the DFW and ATL watersheds that reduce the amount of development in riparian zones in a way that is different from other areas.

Landscape Fragmentation

Three landscape-pattern metrics had strong linear correlation to population density in every area (table 2)—largest patch index of urban patches, mean urban patch area, and proportion of like adjacencies of urban patches. The largest patch index is a measure of urban concentration in a single place, and this metric increased monotonically with increasing urbanization in the watershed. The proportion of like adjacencies of urban patches, a measure of whether an urban patch is surrounded by other urban patches or dissimilar land cover, and mean urban patch area likewise both increased monotonically with increasing urbanization. It is possible that metrics describing urban spatial pattern may not have linear response to increasing urbanization; therefore, the method of linear correlation to population density may be an insufficient analysis technique. For example, patch density (the number of urban patches per unit area) generally had a pattern similar to that shown in figure 20. That is, at low levels of urbanization, patches are small and scattered. As urbanization increases, patch density increases. However, at some threshold (for example, at approximately 400 persons per square kilometer (persons/km^2) in figure 20), patch density begins to decrease as patches get larger and coalesce. Eventually, at high levels of urbanization, patch density becomes very low as a watershed may become a single contiguous patch of urbanization.

Quantifying the independent or joint effects of landscape-pattern metrics on stream ecosystems is a nontrivial goal (Neel and others, 2004). In this paper the largest patch index metric was adopted in a simplistic fashion as one of the components of the CUII, in that it had a strong linear relation to urbanization in every study area and potentially captured a measure of urbanization concentration in the watershed. However, further analysis of the entire suite of landscape-pattern metrics may yield additional or superior ways of quantifying these or similar pattern effects.

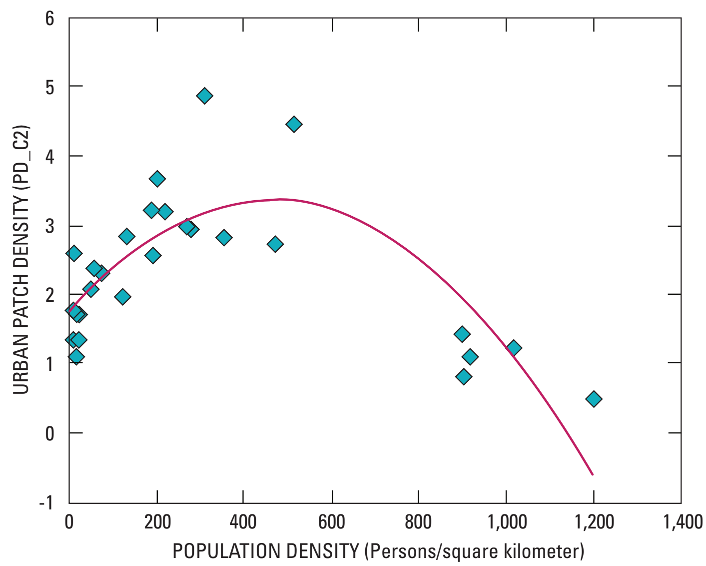


Figure 20. Urban patch density (number of urban patches per hectare) compared to population density for RAL watersheds.

Derivation of a Common Index

As noted previously, the CUII (derived from five variables that had very strong correlation to population density in every study area and for all 175 watersheds) had generally lower values than the local UII (fig. 21; Appendix 6). This was partially the effect of the reduced number of variables and partially the effect of an increased maximum in the calculation for the entire set. The effect was less for the RAL and ATL studies, in which the UII component variables were most similar to the CUII variables (figs. 14A–F).

In this study, attempts were made initially to create a CUII that would closely match local UII scores from every study area. This was found to be difficult eventually, because of the variation in UII scores based on varying input parameters. The decision then was made to create the CUII based simply on the strength of across-study-area variables, specifically variables that had strong links to urbanization in every setting and represented major categories of urbanization (population, road infrastructure, housing infrastructure, land cover, and urban concentration). The CUII represents a consistent way of ranking watersheds from diverse geographic settings that includes multiple aspects of urbanization. In the absence of additional information about the relation of component variables to stream conditions (such as which response variables react most strongly to which independent variables in those specific settings), the CUII is a reasonable measure of urbanization across study areas.

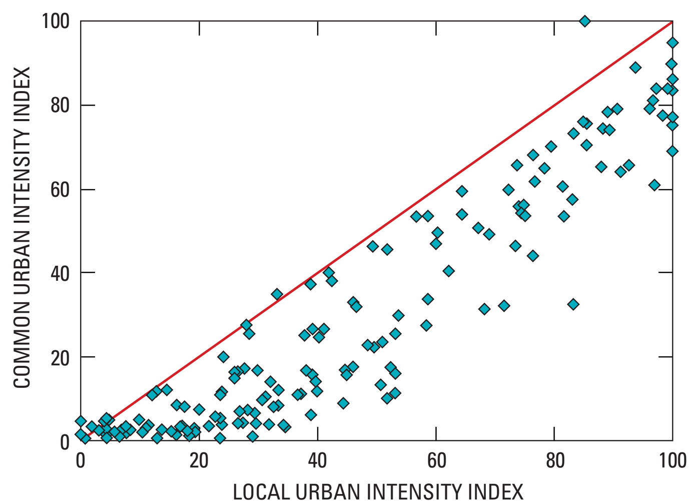


Figure 21. Common urban intensity index (CUII) values compared to local urban intensity index (UII) values for all 175 watersheds. 1:1 line is shown. Note: CUII values are almost universally lower than corresponding UII values.

Road Density as a Surrogate for Urban Intensity Index

As noted earlier, road density was not only one of the variables with the strongest correlation to population density in every area and across study areas (table 2), it was the variable that most closely had a “smoothing effect” (reducing the variability of individual variables) of the UII. Road density also had a strong correlation to the UII and, in some cases, was stronger than population density itself, for the study watersheds (fig. 22). This is noteworthy in that population density was the foundation variable used to identify variables included in the UII.

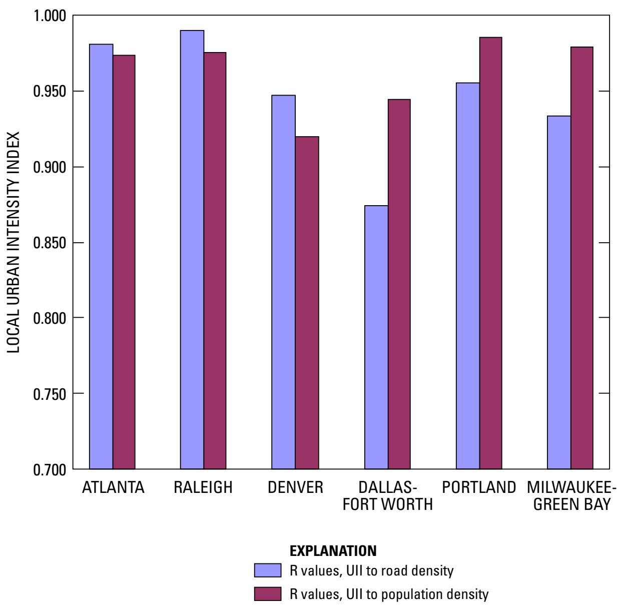


Figure 22. Spearman rank correlation coefficients (r values) for local urban intensity index (UII) to road density and population density for final watersheds.

This indicates that road density (and, by inference, roads in general) may capture many of the same effects as a multimetric index composed of dozens of individual variables. There is no doubt that roads are a factor in the effects of urbanization on stream ecosystems. They represent a large proportion of the impervious surface in a watershed (along with the attendant landscape features that are virtual extensions of roads, such as parking lots, driveways, and so forth). Roads act as the temporary resting place from which hydrocarbons, solvents and other detrimental substances gain accelerated access to the stream system (U.S. Environmental Protection Agency, 2006c). Also, roads are a reliable indicator of human presence in general. Given the difficulties of accurate measurement of wall-to-wall land cover and(or) impervious surfaces over large areas (Tate and others, 2005), roads provide a good alternative as a measure of the urban landscape. To some degree then, if urban studies have the resources to measure or acquire only a single landscape variable, these results indicate that road density would be a good choice.

Summary of Distinguishing Differences

The 30 final study watersheds were selected by using a combination of objective criteria (limiting variability in environmental setting and representing a gradient of urban development intensity) and expert judgment (adequacy for biological/chemical/physical sampling, including adequate streamflow and sampling access). The final watersheds are not necessarily representative, in a statistical sense, of the population of similarly sized watersheds in the region in which they are located. Thus, it is not possible to make statistically valid generalizations about the study watersheds relative to all other watersheds in the region or to compare urbanization in the six regional areas from the characteristics of the 30 final watersheds in each area.

Nevertheless, it is instructive to compare the major differences in environmental and urban variables in the study watersheds across the six studies. The following list summarizes noteworthy differences in environmental (ENV) and urban or land-cover (URB) variables among the final study watersheds. Descriptive terms used (“high,” “low,” “most,” “least,” and so forth) generally refer to median values from the set of 30 final watersheds compared to final watersheds from other areas. (Summary statistics for all variables are provided in Appendix 7.) It is intended that this list may aid in hypothesis generation in analyzing response variables for across-study-area studies within the NAWQA Program.

ATL

URB: High population growth, 1990–2000 (table 4)
URB: Lowest urbanization in high range of UII, by most measures (figs. 11A–E)
URB: Low ratio of percentage riparian urban to percentage watershed urban (table 4)
URB: Most forest as natural background land cover (table 4)

RAL

URB: High population growth, 1990–2000 (table 4)
URB: Most urbanized watersheds, by most measures (figs. 12A–D; table 4)
URB: Highest variation in household income (table 4)
ENV: Smallest drainage areas (table 3)
ENV: Low variability in precipitation (fig. 16; table 3)

DEN

URB: High urban intensity, by most measures (figs. 12A–D; table 4)
URB: Highest household income (table 4)
URB: Most shrub/grassland as natural background land cover (figs. 10A–F)
URB: High ratio of persons per square kilometer of urban land (fig. 15; table 4)
ENV: Most variability in drainage areas (fig. 16; table 3)
ENV: Least variability in precipitation (fig. 16; table 3)

DFW

URB: High variability of urbanization by most measures (figs.12A–D; table 4)
URB: Lowest urbanization, and very low urbanization at mid-range of UII (figs. 11A–D)
URB: Lowest ratio of percent riparian urban to percent watershed urban (table 4)
ENV: Least variability in air temperature (fig. 16; table 3)

POR

URB: Highest ratio of persons per square kilometer of urban land (fig. 15; table 4)
ENV: Highest variability in precipitation, watershed elevation and slope (fig. 16; table 3)

MGB

URB: Lowest population growth, 1990–2000 (table 4)
URB: High variability in population density and housing-unit density (fig. 17; table 4)
URB: Lowest ratio of persons per square kilometer of urban land (fig. 15; table 4)
URB: Most agriculture as background land cover (figs. 10A–F; table 4)
URB: Most wetlands as natural background land cover (figs. 10A–F)
URB: High percentage of older homes (>60 years old; table 4)

Conclusion

Data sources and methods for characterizing environmental settings and urbanization in six metropolitan study areas were described, and the issues and applications of the UII and CUII within and across the study areas were evaluated. Study watersheds were selected for their suitability with respect to minimizing natural variability and producing a gradient of urbanization. However, because of the requirements of site selection, or local decisions to focus on specific ranges, the gradients of urbanization varied among the study areas. Substantial variability among distributions of urban variables for some study areas may require careful attention when comparing response data. The local UIIs in each study area had the effect of reducing the variability of individual urban variables by aggregating them. The single individual variable that most closely mimicked that effect was road density.

Although features of urbanization had less variability across geographic settings than natural features, observed differences were noted in the nature of "urban" in the watersheds examined here that may not be dependent on the gradient of urbanization, such as lower ratios of urban land use per capita in the POR and DEN study areas, lower riparian development in the DFW and ATL study areas, faster growth in the RAL and ATL study areas, and more development closer to the sampling site in the DEN and MGB study areas. These may be considerations in hypothesis generation regarding response data.

The CUII presented here provides an *a priori* way of ranking watersheds on a national scale by combining multiple features of urbanization that have common strong association with population density. Because many local variables did not have strong correlation to population density in every area, the list of component variables was reduced to a small subset. It should not be concluded, however, that these are necessarily the only important features of urbanization that span geographic settings. There is considerable opportunity for identifying other features of urbanization that also may play important roles in every setting—at different scales, from nonlinear correlation to population density, or from an association with a variable other than population density.

The urban intensity index may be a useful tool for characterizing urbanization at local, regional, or national scales. Additional information about other metropolitan areas and a broader range of watersheds in each area would be valuable in placing the results given here in a larger context.

Acknowledgments

The authors wish to acknowledge the tremendous work that went into the development of the datasets described in this paper and, in particular, for the generous efforts of Daniel Pearson, Silvia Terziotti, Evelyn Hopkins, Jennifer Lanning-Rush, and Ronald Zelt.

References Cited

Alberti, M., 1999, Urban patterns and environmental performance—What do we know?: Journal of Planning Education and Research, v. 19, no. 2, p. 151–164.

Anderson, J.R., Hardy, E.E., Roach, J.T., and Witmer, R.E., 1976, A land use and land cover classification system for use with remote sensor data: U.S. Geological Survey Professional Paper 964, 41 p.

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

Bureau of Economic Analysis, 2006, Regional economic accounts: U.S. Department of Commerce, Bureau of Economic Analysis; accessed in April 2006 at *http://www.bea.gov/bea/regional/bearfacts/* .

Burt, J.E., and Barber, G.M., 1996, Elementary statistics for geographers: New York, NY, The Guildford Press, 640 p.

Center for Watershed Protection, 2003, Impacts of impervious cover on aquatic ecosystems: Ellicott City, MD, Center for Watershed Protection, Watershed Protection Research Monograph No. 1.

Cuffney, T.F., Zappia, Humbert, Giddings, E.M.P., and Coles, J.F., 2005, Effects of urbanization on benthic macroinvertebrate assemblages in contrasting environmental settings—Boston, Massachusetts; Birmingham, Alabama; and Salt Lake City, Utah, *in* Brown, L.R., Hughes, R.M., Gray, R., and Meador, M.R., eds., Effects of urbanization on stream ecosystems: Bethesda, MD, American Fisheries Society Symposium 47, p. 361–407.

Daymet, 2005, Numerical Terradynamic Simulation Group: Missoula, MT, University of Montana; accessed in December 2005 at *http://www.daymet.org* .

Dieleman, F., and Wegener, M., 2004, Compact city and urban sprawl: Built Environment, v. 30, no. 4, p. 308–323.

Falcone, J.A., and Pearson, D.K., 2006, Land-cover and imperviousness data for regional areas near Denver, Colorado; Dallas-Fort Worth, Texas; and Milwaukee-Green Bay, Wisconsin—2001: U.S. Geological Survey Data Series 221, 17 p.

Fellmann, J., Getis, A., and Getis, J., 1992, Human geography—Landscapes of human activities: Dubuque, IA, Wm. C. Brown Publishers, 523 p.

GeoLytics, 2001, Census 2000 and street 2000: East Brunswick, NJ, GeoLytics, Inc., 2 CDROMS.

Gregory, M.B., and Calhoun, D.L., 2006, Chapter B. Physical, chemical, and biological responses of streams to increasing watershed urbanization in the Piedmont ecoregion of Georgia and Alabama, 2003: U.S. Geological Survey Scientific Investigations Report, 2006–5101–B.

House, M.A., Ellis, J.B., Herricks, E.E., Hvitved-Jacobsen, T., Seager, J., Lijklema, L., Aalderink, H., and Clifforde, I.T., 1993, Urban drainage—Impacts on receiving water quality: Water Science and Technology, v. 27, no. 12, p. 117–158.

Karr, J.R., 1981, Assessment of biotic integrity using fish communities: Fisheries, v. 6, p. 21–27.

Karr, J.R., and Chu, E.W., 2000, Sustaining living rivers: Hydrobiologia, v. 422, p. 1–14.

Leopold, L.B., 1968, The hydrologic effects of urban land use—Hydrology for urban land planning—A guidebook of the hydrologic effects of urban land use: U.S. Geological Survey Circular 554, 18 p.

McGarigal, Kevin, and Marks, B.J., 1995, FRAGSTATS—Spatial pattern analysis program for quantifying landscape structure: Portland, OR, U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station, General Technical Report PNW–GTR–351, 122 p.

McKnight, T.L., 2001, Regional geography of the United States and Canada: Upper Saddle River, NJ, Prentice Hall, 525 p.

McMahon, Gerard, and Cuffney, T.F., 2000, Quantifying urban intensity in drainage watersheds for assessing stream ecological conditions: Journal of the American Water Resources Association, v. 36, p. 1247–1261.

Meador, M.R.., Coles, J.F., and Zappia, Humbert, 2005, Fish assemblage responses to urban intensity gradients in contrasting metropolitan areas—Birmingham, Alabama and Boston, Massachusetts, *in* Brown, L.R., Hughes, R.M., Gray, R., and Meador, M.R., eds., Effects of urbanization on stream ecosystems: Bethesda, MD, American Fisheries Society Symposium 47, p. 409–423.

Metro, 2006, [Portland] Metro; accessed in April 2006 at *http://www.metro-region.org/* .

National Oceanic and Atmospheric Administration, 2005, Coastal Change Analysis Program (CCAP): National Oceanic and Atmospheric Administration; accessed in December 2005 at *http://www.csc.noaa.gov/crs/lca/ccap.html* .

National Oceanic and Atmospheric Administration, 2006, Impervious surface area of the United States: National Oceanic and Atmospheric Administration; accessed in July 2006 at *http://dmsp.ngdc.noaa.gov/html/download_isa2000_2001.html* .

Neel, M.C., McGarigal, Kevin, and Cushman, S.A, 2004, Behavior of class-level landscape metrics across gradients of class aggregation and area: Landscape Ecology, v. 19, p. 435–455.

Office of Management and Budget, 2000, Standards for defining metropolitan and micropolitan statistical areas: Washington, D.C., Federal Register, part IX, 12 p.; accessed in August 2006 at *http://www.census.gov/population/www/estimates/11-34997.pdf* .

Omernik, J.M., 1987, Ecoregions of the conterminous United States, Annals: Association of American Geographers, v. 77, no. 1, p. 118–125.

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

Peters, C.A. ed., 1997, Environmental setting and implications for water quality in the Western Lake Michigan drainages: U.S. Geological Survey Water-Resources Investigations Report 97–4196, 79 p.

Potapova, Marina, Coles, J.F., Giddings, E.M., and Zappia, Humbert, 2005, A comparison of the influences of urbanization on stream benthic algal assemblages in contrasting environmental settings, *in* Brown, L.R., Hughes, R.M., Gray, R.H., and Meador, M.R., eds., Effects of urbanization on stream ecosystems: Bethesda, MD, American Fisheries Society Symposium 47, p. 333–359.

Schueler, T.R., 1994, The importance of imperviousness: Watershed Protection Techniques, v. 1, no. 3, p. 100–111.

Shirazi, M.A., Boersma, Larry, Haggerty, P.K., and Johnson, C.B., 2001a, Spatial extrapolation of soil characteristics using whole-soil particle size distributions: Journal of Environmental Quality, v. 30, p. 101–111.

Shirazi, M.A., Boersma, Larry, and Johnson, C.B., 2001b, Particle-size distributions—Comparing texture systems, adding rock, and predicting soil properties: Soil Science Society of America Journal, v. 65, p. 300–310.

Shirazi, M.A., Boersma, Larry, Johnson, C.B., and Haggerty, P.K., 2001c, Predicting physical and chemical water properties from relationships with watershed soil characteristics: Journal of Environmental Quality, v. 30, p. 112–120.

Short, T.M., Giddings, E.M.P., Zappia, Humbert, and Coles, J.F., 2005, Urbanization effects on stream habitat characteristics in Boston, Massachusetts; Birmingham, Alabama; and Salt Lake City, Utah, *in* Brown, L.R., Hughes, R.M., Gray, R., and Meador, M.R., eds., Effects of urbanization on stream ecosystems: Bethesda, Maryland, American Fisheries Society Symposium 47, p. 317–332.

Sprague, L.A., Zuellig, R.E., and Dupree, J.A., 2006, Chapter A. Effects of urbanization on stream ecosystems in the South Platte River basin, Colorado and Wyoming: U.S. Geological Survey Scientific Investigations Report, 2006–5101–A, 139 p.; available online at *http://pubs.er.usgs.gov/usgspubs/sir/sir20065101A* .

Stehman, S.V., Wickham, J.D., Smith, J.H., and Yang, L., 2003, Thematic accuracy of the 1992 National Land-Cover Data for the eastern United States—Statistical methodology and regional results: Remote Sensing of Environment, v. 86, no. 4, p. 500–516.

Sutton, P.C., 2003, A scale-adjusted measure of “urban sprawl” using nighttime satellite imagery: Remote Sensing of Environment, v. 86, no. 13, p. 353–369.

Tate, C.M., Cuffney, T.F., McMahon, Gerard, Giddings, E.M.P., Coles, J.F., and Zappia, Humbert, 2005, Use of an urban intensity index to assess urban effects on streams in three contrasting environmental settings, *in* Brown, L.R., Hughes, R.M., Gray, R., and Meador, M.R., eds., Effects of urbanization on stream ecosystems: Bethesda, MD, American Fisheries Society Symposium 47, p. 291–315.

The Brookings Institution, 2006, Center on Urban and Metropolitan Policy—Who sprawls most? How growth patterns differ across the U.S.; accessed in April 2006 at *http://www.brook.edu/es/urban/publications/fulton.pdf* .

Theobald, D.M., 2005, Landscape patterns of exurban growth in the USA from 1980 to 2020: Ecology and Society, v. 10, no. 1, p. 34.

Torrens, P.M., and Alberti, Marina, 2000, Measuring sprawl: London, UK, University College, Centre for Advanced Spatial Analysis (CASA) Working Paper 27; accessed in April 2006 at *http://www.casa.ucl.ac.uk/publications/workingPaperDetail.asp?ID=27* .

Trimble, S.W., 1974, Man-induced soil erosion on the Southern Piedmont, 1700–1970: Ankeny, IA, Soil Conservation Society of America.

U.S. Army Corps of Engineers, 1996, Water control infrastructure, National inventory of dams, 1995–1996: Arlington, VA, U.S. Federal Emergency Management Agency [CDROM].

U.S. Census Bureau, 2006a, About metropolitan and micropolitan statistical areas: U.S. Census Bureau; accessed in July 2006 at *http://www.census.gov/population/www/estimates/aboutmetro.html* .

U.S. Census Bureau, 2006b, Journey to work 2000: U.S. Census Bureau, Census 2000 Brief, 16 p.; accessed in April 2006 at *http://www.census.gov/prod/2004pubs/c2kbr-33.pdf* .

U.S. Census Bureau, 2006c, Population in metropolitan and micropolitan statistical areas in alphabetical order and numerical and percent change for the U.S. and Puerto Rico, 1990–2000: U.S. Census Bureau, Census 2000 PHC–T–29, 27 p.; accessed in July 2006 at *http://www.census.gov/population/cen2000/phc-t29/tab01a.pdf* .

U.S. Department of Agriculture, 1994, State Soil Geographic (STATSGO) Data Base, data use information: U.S. Department of Agriculture, Natural Resources Conservation Service, National Soil Survey Center, Miscellaneous Publication 1492; accessed in July 2006 at *http://www.nrcd.usda.gov/technical/techtools/statsgo_db.pdf* .

U.S. Environmental Protection Agency, 1997, Urbanization and streams—Studies of hydrologic impacts: Washington D.C., U.S. Environmental Protection Agency, Office of Water, Report 841–R–97–009, 18 p.

U.S. Environmental Protection Agency, 2005a, National Pollutant Discharge Elimination System (NPDES): U.S. Environmental Protection Agency; accessed in December 2005 at *http://cfpub.epa.gov/npdes/* .

U.S. Environmental Protection Agency, 2005b, Toxics Release Inventory (TRI): U.S. Environmental Protection Agency; accessed in December 2005 at *http://www.epa.gov/tri/* .

U.S. Environmental Protection Agency, 2006a, EPA Level IV ecoregions: U.S. Environmental Protection Agency; accessed in April 2006 at *http://www.epa.gov/wed/pages/ecoregions/level_iv.htm* .

U.S. Environmental Protection Agency, 2006b, Landscape ecology, introduction: U.S. Environmental Protection Agency; accessed in August 2006 at *http://www.epa.gov/esd/land-sci/intro.htm* .

U.S. Environmental Protection Agency, 2006c, Polluted runoff (nonpoint source pollution)—Management measures for urban areas—1. Introduction: U.S. Environmental Protection Agency; accessed in August 2006 at *http://www.epa.gov/nps/MMGI/Chapter4/ch4-1.html* .

U.S. Geological Survey, 2002, Effects of urbanization on stream ecosystems: U.S. Geological Survey Fact Sheet FS–042–02, 2 p.; accessed in April 2006 at *http://water.usgs.gov/nawqa/ecology/pubs/ulug_fs.pdf* .

U.S. Geological Survey, 2005a, National Elevation Dataset (NED): U.S. Geological Survey; accessed in December 2005 at *http://ned.usgs.gov/* .

U.S. Geological Survey, 2005b, National Hydrography Dataset (NHD): U.S. Geological Survey; accessed in December 2005 at *http://nhd.usgs.gov/* .

U.S. Geological Survey, 2005c, National Land Cover Database 2001 (NLCD 2001): U.S. Geological Survey; accessed in December 2005 at *http://www.mrlc.gov/mrlc2k_nlcd.asp* .

Vogelmann, J.E., Howard, S.M., Yang, L., Larson, C.R., Wylie, B.K., and Van Driel, N., 2001, Completion of the 1990s national land cover data set for the conterminous United States from Landsat Thematic Mapper data and ancillary data sources: Photogrammetric Engineering and Remote Sensing, v. 67, p. 650–662.

Waite, I.R., Sobieszczyk, Steven, Carpenter, K.D., Hughes, C.A., Rinella, F.A., Arnsberg, A.J., Sarantou, M.J., and Johnson, H.M., 2006, Chapter F. Effects of urbanization on stream ecosystems in the Willamette Valley ecoregion, Oregon and Washington: U.S. Geological Survey Scientific Investigations Report 2006–5101–F.

Walsh, C.J., Roy, A.H., Feminella, J.W., Cottingham, P.D., Groffman, P.M., and Morgan, R.P., II, 2005, The urban stream syndrome—Current knowledge and the search for a cure: Journal of the North American Benthological Society, v. 24, p. 706–723.

Wente, S.P., 2000, Proximity-based measure of land use impacts to aquatic ecosystem integrity: Environmental Toxicology and Chemistry, v. 19, no. 4(2), p. 1148–1152.

Wolock, D.M., 2003, Hydrologic landscape regions of the United States: U.S. Geological Survey Open-File Report 2003–145; accessed in May 2005 at *http://water.usgs.gov/GIS/metadata/usgswrd/XML/hlrus.xml* .

Yoder, C.O., and Rankin, E.T., 1995, Biological response signatures and the area of degradation value—New tools for interpreting multimetric data, p. 263–286, *in* Davis, W.S. and Simon, T.P., eds., Biological assessment and criteria—Tools for water resource planning and decision making: Boca Raton, FL, Lewis Publishers.

Prepared by:
USGS Enterprise Publishing Network
Raleigh Publishing Service Center
3916 Sunset Ridge Road
Raleigh, NC 27607

For additional information regarding this publication, contact:
James Falcone
U.S. Geological Survey
NAWQA—Ecological Synthesis
413 National Center
Reston, VA 20192
phone: 703-648-5008
email: jfalcone@usgs.gov

Or visit the Ecological National Synthesis Project website at:
http://water.usgs.gov/nawqa/ecology/index.html

Falcone and others—**Natural and Urban Characteristics and Development of Urban Intensity Indices Across Six Geographic Settings**—Scientific Investigations Report 2007–5123

Printed on recycled paper