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National Water-Quality Assessment Program

Relation of Urbanization to Stream Habitat and Geomorphic Characteristics in Nine Metropolitan Areas of the United States

Scientific Investigations Report 2010–5056

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

Cover. **Photographs clockwise from top:**

Lincoln Creek, Milwaukee, Wisconsin *(photograph by Michelle Lutz, U.S. Geological Survey)*
Pigeon House Branch, Raleigh, North Carolina *(photograph by Elise Giddings, formerly U.S. Geological Survey)*
Mill Creek, Salt Lake City, Utah *(photograph by Elise Giddings, formerly U.S. Geological Survey)*

Center image:

Map showing locations of nine metropolitan areas of the United States sampled as part of the U.S. Geological Survey National Water-Quality Assessment Program study on the effects of urbanization on stream ecosystems.

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By Faith A. Fitzpatrick and Marie C. Peppler

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Foreword

The U.S. Geological Survey (USGS) is committed to providing the Nation with reliable 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, 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 quality of our Nation's streams and groundwater? How are conditions changing over time? How do natural features and human activities affect the quality of streams and groundwater, 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 to 2001, the NAWQA Program completed interdisciplinary assessments and established a baseline understanding of water-quality conditions in 51 of the Nation's river basins and aquifers, referred to as Study Units (*http://water.usgs.gov/nawqa/studies/study_units.html*).

National and regional assessments are ongoing in the second decade (2001–2012) of the NAWQA Program as 42 of the 51 Study Units are selectively reassessed. These assessments extend the findings in the Study Units by determining water-quality 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 groundwater. 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 studies 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. In addition, national syntheses of information on pesticides, volatile organic compounds (VOCs), nutrients, 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.

Matthew C. Larsen
Associate Director for Water

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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)
	Area	
square meter (m^2)	0.0002471	acre
square kilometer (km^2)	247.1	acre
square meter (m^2)	10.76	square foot (ft^2)
square kilometer (km^2)	0.3861	square mile (mi^2)
	Volume	
cubic meter (m^3)	264.2	gallon (gal)
cubic meter (m^3)	0.0002642	million gallons (Mgal)
cubic meter (m^3)	35.31	cubic foot (ft^3)
cubic meter (m^3)	0.0008107	acre-foot (acre-ft)
	Flow rate	
meter per second (m/s)	3.281	foot per second (ft/s)
	Hydraulic gradient	
meter per kilometer (m/km)	5.27983	foot per mile (ft/mi)

Inch/Pound to SI

Multiply	By	To obtain
	Length	
inch (in.)	2.54	centimeter (cm)
inch (in.)	25.4	millimeter (mm)
foot (ft)	0.3048	meter (m)
meter (m)	3.281	foot (ft)
mile (mi)	1.609	kilometer (km)
	Area	
square mile (mi^2)	2.590	square kilometer (km^2)
	Flow or precipitation rate	
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
inch per hour (in/h)	2.54	centimeter per hour (m/h)

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

$$°F = (1.8 \times °C) + 32$$

Relation of Urbanization to Stream Habitat and Geomorphic Characteristics in Nine Metropolitan Areas of the United States

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Abstract

The relation of urbanization to stream habitat and geomorphic characteristics was examined collectively and individually for nine metropolitan areas of the United States—Portland, Oregon; Salt Lake City, Utah; Denver, Colorado; Dallas–Forth Worth, Texas; Milwaukee–Green Bay, Wisconsin; Birmingham, Alabama; Atlanta, Georgia; Raleigh, North Carolina; and Boston, Massachusetts. The study was part of a larger study conducted by the U.S. Geological Survey from 1999 to 2004 to examine the effects of urbanization on the physical, chemical, and biological components of stream ecosystems. The objectives of the current study were to determine how stream habitat and geomorphic characteristics relate to different aspects of urbanization across a variety of diverse environmental settings and spatial scales. A space-for-time rural-to-urban land-cover gradient approach was used. Reach-scale habitat data and geomorphic characteristic data were collected once during low flow and included indicators of potential habitat degradation such as measures of channel geometry and hydraulics, streambed substrate, low-flow reach volume (an estimate of base-flow conditions), habitat complexity, and riparian/bank conditions. Hydrologic metrics included in the analyses were those expected to be altered by increases in impervious surfaces, such as high-flow frequency and duration, flashiness, and low-flow duration. Other natural and human features, such as reach-scale channel engineering, geologic setting, and slope, were quantified to identify their possible confounding influences on habitat relations with watershed-scale urbanization indicators. Habitat and geomorphic characteristics were compared to several watershed-scale indicators of urbanization, natural landscape characteristics, and hydrologic metrics by use of correlation analyses and stepwise linear regression.

Habitat and geomorphic characteristics were related to percentages of impervious surfaces only in some metropolitan areas and environmental settings. The relations between watershed-scale indicators of urbanization and stream habitat depended on physiography and climate, hydrology, pre-urban channel alterations, reach-scale slope and presence of bedrock, and amount of bank stabilization and grade control. Channels increased in size with increasing percentages of impervious surfaces in southeastern and midwestern metropolitan areas regardless of whether the pre-existing land use was forest or agriculture. The amount of enlargement depended on annual precipitation and frequency of high-flow events. The lack of a relation between channel enlargement and increasing impervious surfaces in other metropolitan areas was thought to be confounded by pre-urbanization hydrologic and channel alterations. Direct relations of channel shape and streambed substrate to urbanization were variable or lacking, probably because the type, amount, and source of sediment are dependent on the phase of urbanization. Reach-scale slope also was important for determining variations in streambed substrate and habitat complexity (percentage of riffles and runs). Urbanization-associated changes in reach-scale riparian vegetation varied geographically, partially depending on pre-existing riparian vegetation characteristics. Bank erosion increased in Milwaukee–Green Bay and Boston urban streams, and bank erosion also increased with an increase in a streamflow flashiness index. However, potential relations likely were confounded by the frequent use of channel stabilization and bank protection in urban settings. Low-flow reach volume did not decrease with increasing urbanization, but instead was related to natural landscape characteristics and possibly other unmeasured factors. The presence of intermittent bedrock in some sampled reaches likely limited some geomorphic responses to urbanization, such as channel bed erosion. Results from this study emphasize the importance of including a wide range of landscape variables at multiple scales as well as detailed information about historical channel alterations, such as watershed drainage alterations for stormwater design or agriculture, and engineered or natural channel stabilizations upstream and downstream from the reach sampled for habitat.

Introduction

Stream physical responses to urbanization are dependent on temporal changes in hydrologic conditions and sediment fluxes associated with increases in impervious surfaces, construction practices, and stormwater management (Paul and Meyer, 2001; Brabec and others, 2002; Miltner and others, 2004). Generally, major hydrologic changes associated with urbanization include decreases in the duration of floods and base flow and increases in total runoff volume, magnitude and frequency of floods, and flashiness (Leopold, 1968; Dunne and Leopold, 1978; Finkenbine and others, 2000; Konrad, 2003; McMahon and others, 2003). Changes in sediment fluxes typically are related to phases of urbanization, with increased sediment from overland sources during early construction and increased channel erosion after build-out (Wolman, 1967; Wolman and Schick, 1967; Guy, 1970; Owens and others, 2000; Chin, 2006). Channel erosion in urban streams may contribute more than two-thirds of the total sediment load after sediment delivery from construction sites ceases (Trimble, 1997). Bedload transport capacity, a major factor affecting channel shape, also may increase (Whipple and DiLouie, 1981). These physical changes in water/sediment fluxes and geomorphic responses associated with urbanization have potentially negative effects on habitat conditions (Paul and Meyer, 2001; Brabec and others, 2002; Walsh and others, 2005).

Habitat degradation can be assessed in terms of qualitative or quantitative indicators of channel size and shape, substrate size and stability, low-flow habitat conditions (such as reach volume and maximum depth), habitat complexity and cover, and bank/riparian conditions (Barbour and others, 1999; Kaufman and others, 1999; Somerville and Pruitt, 2004). Channel enlargement, which is an increase in channel size through widening or downcutting, and erosion are the most commonly measured responses to urbanization in a variety of environments worldwide (Guy, 1970; Hammer, 1972; Graf, 1975; Whipple and DiLouie, 1981; Roberts, 1989; Gregory and others, 1992; Booth and Jackson, 1997; Trimble, 1997; Doll and others, 2002; Center for Watershed Protection, 2003; Fitzpatrick and others, 2005; Leopold and others, 2005; Chin, 2006). Changes in channel size have been documented in watersheds with as little as 10 percent connected impervious surface (Booth and Jackson, 1997). In the Seattle, Washington area, urbanization-altered hydrology also caused increased bank erosion and larger streambed substrate sizes (Booth, 1991; Finkenbine and others, 2000; Konrad and others, 2005). The spatial connectivity of urban land, the timing, phase, and location of urbanization, and riparian land use also may affect channel size, shape, and substrate conditions (Leopold and others, 2005; McBride and Booth, 2005; Chin, 2006; Colosimo and Wilcock, 2007). Some urban streams have more uniform, less complex habitat structure in the form of less riffles and loss of pools (Pizzuto and others, 2000). Local geologic setting may have some mitigating effects; urban streams with relatively steep slopes and rocky substrates are more likely to have good habitat quality and biotic integrity than streams with relatively flat slopes and fine-grained substrates (Wang and others, 1997; Fitzpatrick and others, 2005). Geomorphic responses to urbanization are dependent on the erodibility of channel bottom and banks, mode of sediment transport, local geologic setting, history of channel modifications, geomorphic position within the drainage network, and geomorphic thresholds (Schumm, 1977; Bledsoe and Watson, 2001; Chin, 2006; Fitzpatrick and others, 2006; Fitzpatrick and Peppler, 2007).

This study of the relation of urbanization to stream habitat and geomorphic characteristics was part of a larger study by the National Water-Quality Assessment (NAWQA) Program of the U.S. Geological Survey (USGS) of the effects of urbanization on stream ecosystems (Couch and Hamilton, 2002). The primary objectives of the larger study were to (1) examine the physical, chemical, and biological responses to urbanization across a range of environmental settings, (2) determine the most important landscape features associated with the responses, and (3) describe the physical and chemical characteristics associated with biological responses (Giddings, and others, 2009). The study was conducted from 1999 to 2004 in nine metropolitan areas in the United States—Portland, Oregon; Salt Lake City, Utah; Denver, Colorado; Dallas–Forth Worth (hereafter referred to as Dallas), Texas; Milwaukee–Green Bay (hereafter referred to as Milwaukee), Wisconsin; Birmingham, Alabama; Atlanta, Georgia; Raleigh, North Carolina; and Boston, Massachusetts (fig. 1). As many as 30 streams in each metropolitan area were characterized for hydrology, habitat, water chemistry, fish, macroinvertebrates, and algae. The Boston, Birmingham, and Salt Lake City studies were conducted in 1999–2000; Atlanta, Denver, and Raleigh in 2002–2003; and Dallas, Milwaukee, and Portland in 2003–2004. Associations among urbanization, hydrology, and habitat were previously examined for Salt Lake City and Boston as part of a NAWQA urban-effects pilot study (Short and others, 2005).

The purpose of this report is to describe the relations among urbanization and stream habitat and geomorphology across a variety of diverse environmental settings. As many as 30 streams in 9 metropolitan areas in the United States were examined. Environmental variables included urban, landscape, and reach-scale natural and anthropogenic factors operating at several scales that have a high potential for affecting water and sediment fluxes and subsequently altering stream physical characteristics. Hydrologic metrics that represent flashiness, frequency and duration of high-flow events, and duration of low-flow events were included. Reach-scale habitat characteristics included commonly measured and representative indicators of channel geometry and hydraulics, streambed substrate, low-flow habitat conditions, habitat complexity, and bank/riparian conditions. Spearman correlation analysis and stepwise linear regression were used to determine the importance of the various watershed- and reach-scale features on habitat and geomorphic characteristics collectively and individually for the nine metropolitan areas.

Figure 1. Locations of nine metropolitan areas of the United States sampled as part of the U.S. Geological Survey National Water-Quality Assessment Program study on the effects of urbanization on stream ecosystems.

Methods

This study involved collection of urban indicators, landscape characteristics, hydrologic metrics, and habitat and geomorphic characteristics for about 30 watersheds in 9 metropolitan areas. Details on the study design, field methods, and data analyses techniques are described in the following sections.

Study Design

As many as 30 streams were selected from mainly separate watersheds in each of the 9 metropolitan areas using a rural-to-urban land-cover gradient design (McMahon and Cuffney, 2000; Tate and others, 2005; Falcone and others, 2007; Sprague and others, 2007). For site selection, a multimetric urban intensity index (UII) was developed with a geographic information system (GIS) from a study-area specific combination of mainly watershed-scale urban characteristics from census, land-cover, infrastructure, and socioeconomic data that highly correlated with population density (Tate and others, 2005; Falcone and others, 2007; Cuffney and Falcone, 2009). A national common urban intensity index (MA_NUII) also was developed from standardized values of watershed urban land, housing density, and road density (table 1; fig. 2). Land cover for the selected streams in the low urban, or rural, part of the gradient varied among forest, agriculture, and grassland. Four metropolitan areas in the eastern United States—Birmingham, Atlanta, Raleigh, and Boston—had forested rural portions. The other five metropolitan areas had either rural portions of agriculture (Milwaukee), grassland (Denver), a mix of agriculture and grassland (Dallas and Salt Lake City), or a mix of forest, agriculture, and grassland (Portland). The small number of candidate streams in the Salt Lake City area required sampling some streams from the same watershed.

Within each metropolitan area, investigators attempted to hold watershed- and reach-scale environmental setting, such as climate, geology, soils, and topography, relatively constant (Tate and others, 2005; Falcone and others, 2007). Collectively, the selected metropolitan areas represented a range of environmental settings and hydrologic conditions (table 1; fig. 3). Climatic conditions across the metropolitan areas ranged from warm and dry to cool and wet. Soils ranged from fine (Portland, Dallas, Milwaukee, and Atlanta) to moderately coarse (Boston) (U.S. Department of Agriculture, 1994; Shirazi, Boersman, and Johnson, 2001; Shirazi and others, 2001a,b; Falcone and others, 2007). Watershed slopes were lowest in Dallas and Milwaukee and highest in Salt Lake City.

Stream reaches with watersheds of less than 100 square kilometers (km^2) were preferred for sampling (fig. 3). Delineation of drainage areas was problematic in Salt Lake City because a large portion of streamflow can be transferred among different watersheds using canals located upstream from sampling locations (Short and others, 2005). In addition, drainage delineation of highly urban watersheds was limited by lack of detail about storm sewer networks, which may span topographic highs.

Selected stream reaches for habitat sampling generally were meandering and single thread, with perennial flow and riffle/pool morphology. Concrete-lined channels were avoided. Reaches with riffles were preferred for consistent invertebrate and algae sampling.

Table 1. Selected urban, landscape, and hydrologic characteristics used to determine the relation of urbanization to stream geomorphic and habitat characteristics for nine metropolitan areas of the United States.

[Min, Minimum; Max, Maximum; %, percent; m, meter; km^2, square kilometer; km, kilometer; >, greater than; °C, degrees Celsius; cm, centimeter; h, hour; USDA, U.S. Department of Agriculture; <, less than; m^2, square meter; POR, period of record; m/m, meter per meter; m^3, cubic meter; m/s, meters per second; °, degrees]

Variable name (unit)	Abbreviation	Median	Min	Max
Watershed-scale urban, channel-alteration, and land-cover characteristics				
National urban intensity index (rank)	MA_NUII	24	0	100
Watershed total urban land (%)	NLCD_2	27	0	99
Watershed developed land (%)	NLCD22_23_24	17	0	89
Watershed developed open space (%)	NLCD_21	8	0	75
Urban patch nearest neighbor mean distance (m)	EDM_C2	93	60	450
Watershed total impervious surface (%)	NLCD_IS	9	0	55
Population density in 2000 (people/km^2)	POPDEN00	254	0	2,174
Population change 1990–2000 (%)	POP90_00	0.20	–0.19	234
Housing units built prior to 1939 (proportion)	PHU_G60	0.07	0.00	0.45
Road area density (km/km^2)	RDARDEN	3.7	0.0	15.0
Watershed urban land, distance weighted (%)	URBANdw	32.2	0.0	99.4
Nearest upstream engineered channel (m)	ENG_HYDd	>23,000	1	>23,000
Dam density (dams/100 km^2)	DAMd	2.2	0.0	130.4
Watershed agriculture (%)	NLCD_8	10	0	87
Watershed forest (%)	NLCD_4	22	0	87
Watershed-scale landscape characteristics				
Drainage area (km^2)	DA	52	4	184
Mean annual air temperature (°C)	MAAT	11	4	19
Mean annual precipitation (cm)	MAP	119	38	205
Watershed mean low range permeability (cm/h)	PERL	1	0	19
Watershed mean high range sand (%)	SNDH	42	0	88
USDA soil texture classification – fine (%)	TEXTURE5	29	0	100
Mean watershed elevation (m)	MEANELEV	227	31	2,353
Watershed area with slope <1% (proportion)	P_FLAT	0.06	0.0	0.77
Watershed slope (m/km)	WAT_SLOPE	5.8	1.0	57.8
Basin shape index (unitless)	BAS_SHAP_INDX	1.7	1.3	2.9
Drainage density (km/km^2)	DRAINDEN	0.8	0.0	1.7
Hydrologic metrics				
Richards-Baker flashiness index (m^2)	RB_FLASH	0.084	0.004	0.589
Number of time periods when total rise is greater than or equal to 7 times the median total rise (count)	PERIODR7	20	0	175
Max duration of rising cross-sectional area over POR (h)	MAX_DURRISE	10	2	32
Max duration of falling cross-sectional area over POR (h)	MAX_DURFALL	14	1	69
Max duration of high cross-sectional area (90th percentile) pulses over POR (h)	MXH_90	120	24	558
Median duration of high cross-sectional area (90th percentile) pulses over POR (h)	MDH_90	8	1	286
Max duration of low cross-sectional area (10th percentile) pulses over POR (h)	MXL_10	103	0	593
Reach-scale channel alterations and geologic setting				
Percent of channelized reach length (%)	ChannelizedPct	0	0	100
Percent of reach with bank stabilization (%)	BankStabPct	0	0	100
Number of grade-control structures (count)	GradeControl	1	0	4
Bedrock present in reach (presence or absence)	Bedrock	0	0	1

Table 1. Selected urban, landscape, and hydrologic characteristics used to determine the relation of urbanization to stream geomorphic and habitat characteristics for nine metropolitan areas of the United States.—Continued

[Min, Minimum; Max, Maximum; %, percent; m, meter; km^2, square kilometer; km, kilometer; >, greater than; °C, degrees Celsius; cm, centimeter; h, hour; USDA, U.S. Department of Agriculture; <, less than; m^2, square meter; POR, period of record; m/m, meter per meter; m^3, cubic meter; m/s, meters per second; °, degrees]

Variable name (unit)	Abbreviation	Median	Min	Max
Reach-scale channel geometry and hydraulics				
Reach slope (%)	ReachSlope	0.39	0.01	16.61
Average bankfull channel area (m^2)	BFArea	12.8	1.2	197.1
Average bankfull channel area/drainage area (m^2/km^2)	BFArea.DA	0.34	0.04	4.47
Average bankfull channel width/depth (ratio)	BFWidthDepth	7.7	2.7	26.2
Flow stability index (m/m)	FlowStblAvg	0.26	0.06	0.68
Reach-scale streambed substrate				
Types of depositional bars present in reach (count)	Bar	0	0	3
Dominant substrate size sand, silt and clay (%)	DomSubFine	24	0	100
Dominant substrate size sand (%)	DomSubSand3	9	0	100
Dominant substrate size cobble (%)	DomSubCobble78	18	0	100
Substrate stability (ratio)	DomSubStab	1	0.0002	56
Embeddedness (%)	EmbedPctAvg	58	4	100
Reach-scale low-flow conditions				
Average reach volume (m^3)	RchVol	265	6	2,535
Average reach volume/drainage area (m^3/km^2)	RchVol.DA	7.1	0.6	41.0
Maximum depth (m)	DepthMax	0.7	0.2	2.7
Average velocity (m/s)	VelocAvg	0.157	0.000	0.691
Reach-scale habitat complexity				
Riffle (%)	GCUTypeRiffPct	26	0	78
Pool (%)	GCUTypePoolPct	14	0	88
Run (%)	GCUTypeRunPct	56	0	100
Reach-scale riparian/bank characteristics				
Disturbed land cover within 30-meter buffer (% of transect endpoints)	RipLUDis	41	0	100
Open canopy angle (°)	OCanAngleAvg	25	0	148
Bank vegetative cover (%)	BankVegCovAvg	47	4	100
Presence/absence of bank erosion (%)	BankErosPct	50	0	100

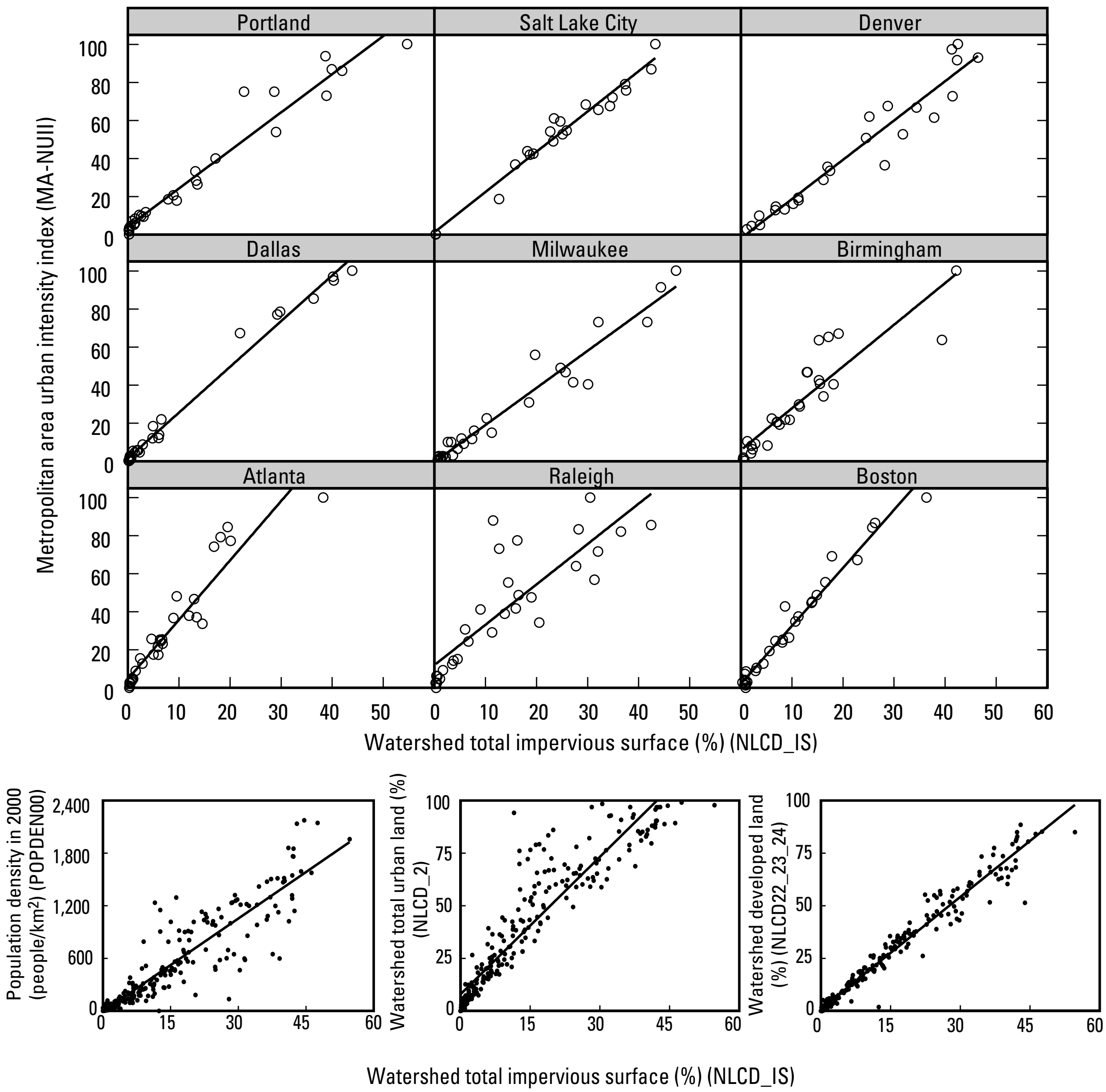

Figure 2. Comparison of urban indicators for nine metropolitan areas of the United States.

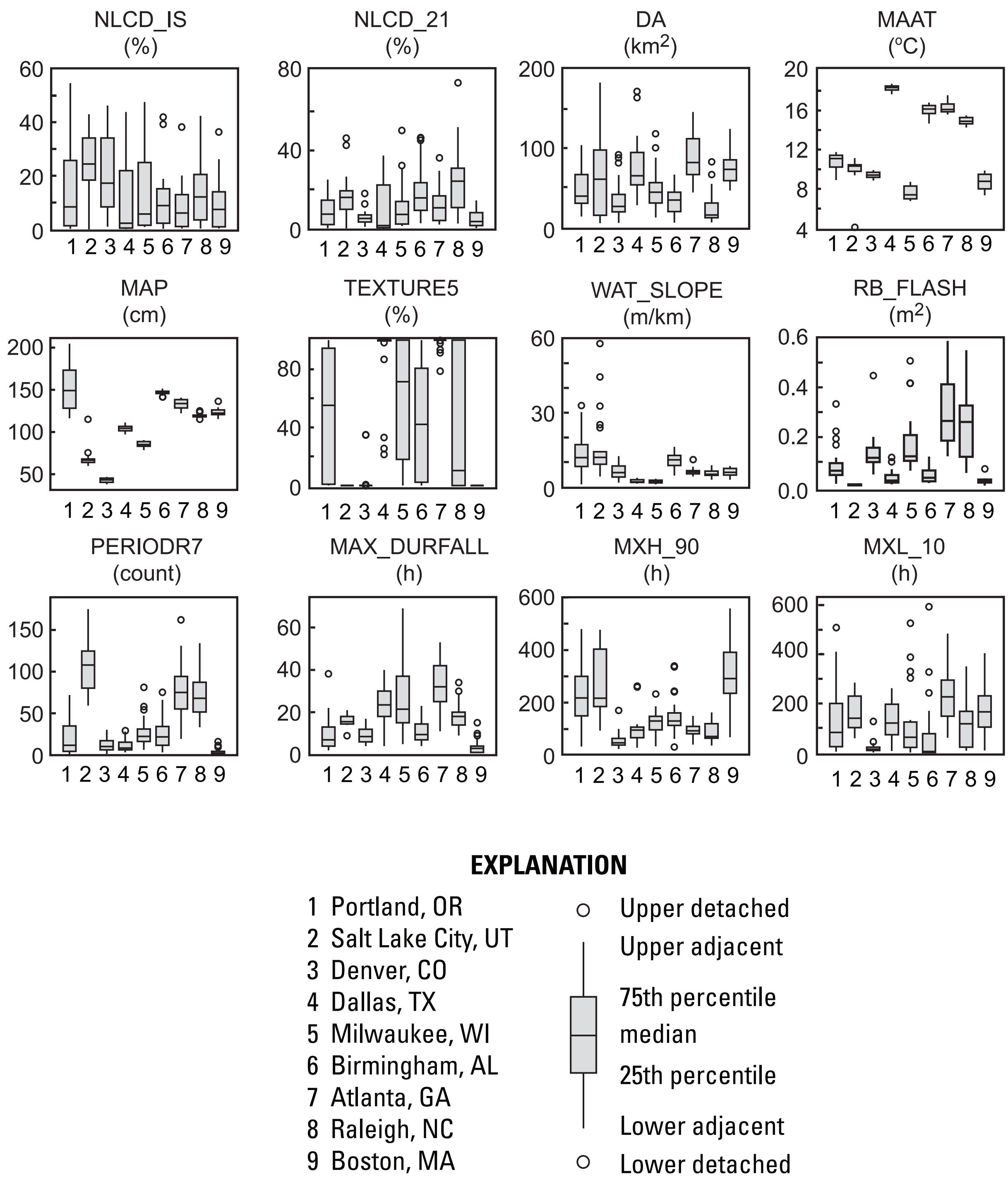

Figure 3. Boxplots of urban, landscape, and hydrologic characteristics for nine metropolitan areas of the United States. (See table 1 for definitions of abbreviations. Boxplots are listed for metropolitan areas from west to east.)

Urban Indicators and Landscape Characteristics

Urban indicators and landscape characteristics mainly were derived from overlays of thematic maps using a GIS (Falcone and others, 2007; table 1). Watershed-based land-cover and total impervious surface statistics were based on the 2001 National Land-Cover Data (NLCD; U.S. Geological Survey, 2005, 2006). The four NLCD Level 2 urban land-cover categories were based on percentage of total impervious surface: less than 20 percent open space, 20 to less than 50 percent low-intensity development, 50 to less than 80 percent medium-intensity development, and 80 percent or greater high-intensity development. Developed open space included mowed grassy areas associated with large-lot residential development, golf courses, lawns, airports, schools, parks, and roadsides and medians (James Falcone, U.S. Geological Survey, written commun., 2006). The separation of developed open space from the group of three developed categories is important in determining the intensity of urbanization and the potential effects on streams (fig. 2). One landscape pattern metric that describes the dispersion of urban patches within a watershed (EDM_C2) was included. This EDM_C2 metric was derived from FRAGSTATS software calculations of the land cover data and is a representation of the connectivity of impervious surfaces (Falcone and others, 2007).

Census data included 2000 population density, change in population density from 1990 to 2000, and housing age (Falcone and others, 2007). One housing age measure, the proportion of houses built prior to 1939 (PHU_G60), was selected for this study to represent older urban areas. Road density was based on Census 2000 TIGER data. Distance to nearest upstream engineered channel (ENG_HYDd), such as canals, ditches, and pipelines, was derived from the NHDPlus Dataset (Horizon Systems Corporation, 2006; Kelly Ruhl, U.S. Geological Survey, written commun., 2007). Density of dams in the watershed (DAMd) was derived from the National Inventory of Dams (U.S. Army Corps of Engineers, 2006; Kelly Ruhl, U.S. Geological Survey, written commun., 2007).

Landscape characteristics included descriptions of watershed-scale soils, topography, slope, basin shape, and drainage density (table 1; Falcone and others, 2007). Soils data were derived from the U.S. Department of Agriculture State Soil Geographic (STATSGO) Data Base (U.S. Department of Agriculture, 1994; Shirazi, Boersman, and Johnson, 2001; Shirazi and others, 2001a,b). Elevation, relief, and watershed slopes were calculated from USGS 30-meter (m) National Elevation Data (U.S. Geological Survey, 2005).

Hydrologic Metrics

Hydrologic metrics can provide a direct link between urban-caused changes in floods and low-flow characteristics and habitat conditions (McMahon and others, 2003; Booth and others, 2004). For six of the nine metropolitan areas, hydrologic metrics were calculated from hourly records of changes in flow cross-sectional area from stage recorders (McMahon and others, 2003; Giddings and others, 2009). For the other three metropolitan areas (Salt Lake City, Birmingham, and Boston), hydrologic metrics were calculated from records of hourly changes in stage (McMahon and others, 2003). Stage recorders were operated at Salt Lake City, Birmingham, Atlanta, and Raleigh for about a year (table 2). Stage recorders were operated at Milwaukee and Boston for less than a year, but the period included the nonwinter period of potential flooding from snowmelt or rainfall. Portland, Denver, and Dallas had periods of record that were less than a full year. The measured period for Birmingham coincided with extreme drought; consequently, several perennial streams were intermittent. Records of 10 years or more are recommended to identify site-specific trends over longer periods of time (U.S. Water Resources Council, 1981; Konrad and Booth, 2002). However, hydrologic metrics calculated from short-term hourly stage data were useful for comparisons of streamflow variability and flashiness caused by increased urbanization (McMahon and others, 2003).

Based on annual or near annual periods of record for hourly stage or cross-sectional area data, 54 hydrologic condition metrics were calculated, including indicators of the variability in the frequency and duration of high and low flows (McMahon and others, 2003; Giddings and others, 2009). Frequency metrics included the number of rising or falling flows, where the stream rise or fall is equal to or greater than three, five, seven, or nine times the median flow rise or fall. Duration metrics included median and maximum durations of rising or falling high or low flows as well as total duration of high and low flows. A flashiness index similar to the Richards-Baker flashiness index was calculated on the basis of daily changes in flow cross-sectional area (Baker and others, 2004). A low flashiness index typically indicates small shifts in flow cross-sectional area, and a high value indicates large shifts in flow cross-sectional area.

Table 2. Physiographic region, precipitation occurrence, time period for hydrologic data collection, and unusual conditions during habitat sampling for nine metropolitan areas of the United States.

Metropolitan area	Physiographic provinces (Fenneman and Johnson, 1946)	Precipitation occurrence (Falcone and others, 2007)	Noteworthy conditions during hydrologic data collection	Hydrologic data time period (mm/dd/yy)
Portland	Pacific Mountain, Pacific Border, Cascade–Sierra Mountains	Snowmelt in spring, rainfall October–April	None	03/01/04–12/01/04
Salt Lake City	Rocky Mountain System, Middle Rocky Mountains; Intermontane Plateaus, Basin and Range	Snowmelt in winter/spring is major runoff source, scattered light thunder-storms in summer	Flow affected by reservoirs, interbasin transfers, and diversions	04/26/00–03/29/01
Denver	Interior Plains, Great Plains; Rocky Mountain System, Southern Rocky Mountains	Snowmelt in spring, rainfall April–September	Flow affected by reservoirs, interbasin transfers, and diversions	05/01/03–09/30/03
Dallas–Fort Worth	Atlantic Plain, Coastal Plain	Rainfall spring and summer	None	10/15/03–02/15/04
Milwaukee–Green Bay	Interior Plains, Central Lowland	Snowmelt March–May, rain-fall May–September	None	03/16/04–10/30/04
Birmingham	Appalachian Highlands; Valley and Ridge, Plateaus, Piedmont	Rainfall—frontal systems in winter, thunderstorms in summer/fall	Severe drought	07/08/00–07/28/01
Atlanta	Appalachian Highlands, Piedmont	Rainfall—frontal systems in winter, thunderstorms in summer/fall	None	10/01/02–09/30/03
Raleigh	Appalachian Highlands, Piedmont	Rainfall distributed through-out the year	None	11/16/02–11/15/03
Boston	Appalachian Highlands, New England	Snowmelt March–May, rain-fall May–September	Drought	05/02/00–06/22/00, 09/11/00–12/07/00, 03/09/01–06/16/01

Habitat and Geomorphic Characteristics

Field-based reach-scale habitat assessments were conducted once during low flow on wadeable streams (Fitzpatrick and others, 1998). Data included qualitative and quantitative observations and measurements collected at 11 equidistant transects (table 1; fig. 4; Giddings and others, 2009). The measured reach was generally 20 times the channel width or a minimum of 150 m. A short description of how the habitat and geomorphic characteristics were measured and calculated in this study follows.

Measurements of channel geometry and hydraulics included surveyed low-flow water-surface slope (hereafter referred to as reach slope) and bankfull channel dimensions (table 1; fig. 4). Morphologic indicators were used to estimate bankfull stage and included variations in bank-face slope and riparian vegetation, undercut banks, and particle-size changes associated with point bars (Fitzpatrick and others, 1998). Sampling teams received national and in-house training to aid in consistent measurement techniques. Bankfull channel dimensions were calculated from riffle and run transects only (no pools). A flow-stability index was calculated from the ratio of the average depth and bankfull depth. Three point observations of dominant streambed substrate size from each of the 11 transects were summarized into percentage of points with fine (sand sized or smaller), sand, gravel, cobble and boulder, or bedrock substrate. A relative bed stability index was calculated on the basis of the ratio of the median particle size and the critical particle size potentially mobilized at bankfull flow (Kaufman and others, 1999). Percentage of embedded particles at each transect point was measured to the nearest 10 percent. Measurements of low-flow habitat conditions included wetted channel dimensions, maximum depth, discharge, and velocity. Habitat complexity included length-based measurements of riffle, runs, and pools in the reach. Habitat-cover data were not included in this analysis because many of the small streams had water depths of less than 30 centimeter (cm). Measures of bank/riparian conditions included percentage of disturbed riparian land cover within a 30-m buffer, open canopy angle, percentage of bank-face vegetative cover, and presence/absence of bank erosion at transect endpoints. Disturbed land cover included cropland, pasture, farmsteads, residential, commercial, or transportation. Undisturbed land cover included grassland, shrubs and woodland, or wetland.

After the field surveys, additional information was needed about potential reach-scale channel alterations and natural controls that might affect habitat conditions and geomorphic responses. Using a combination of remarks on field forms, notes on field-drawn reach maps, photographs of

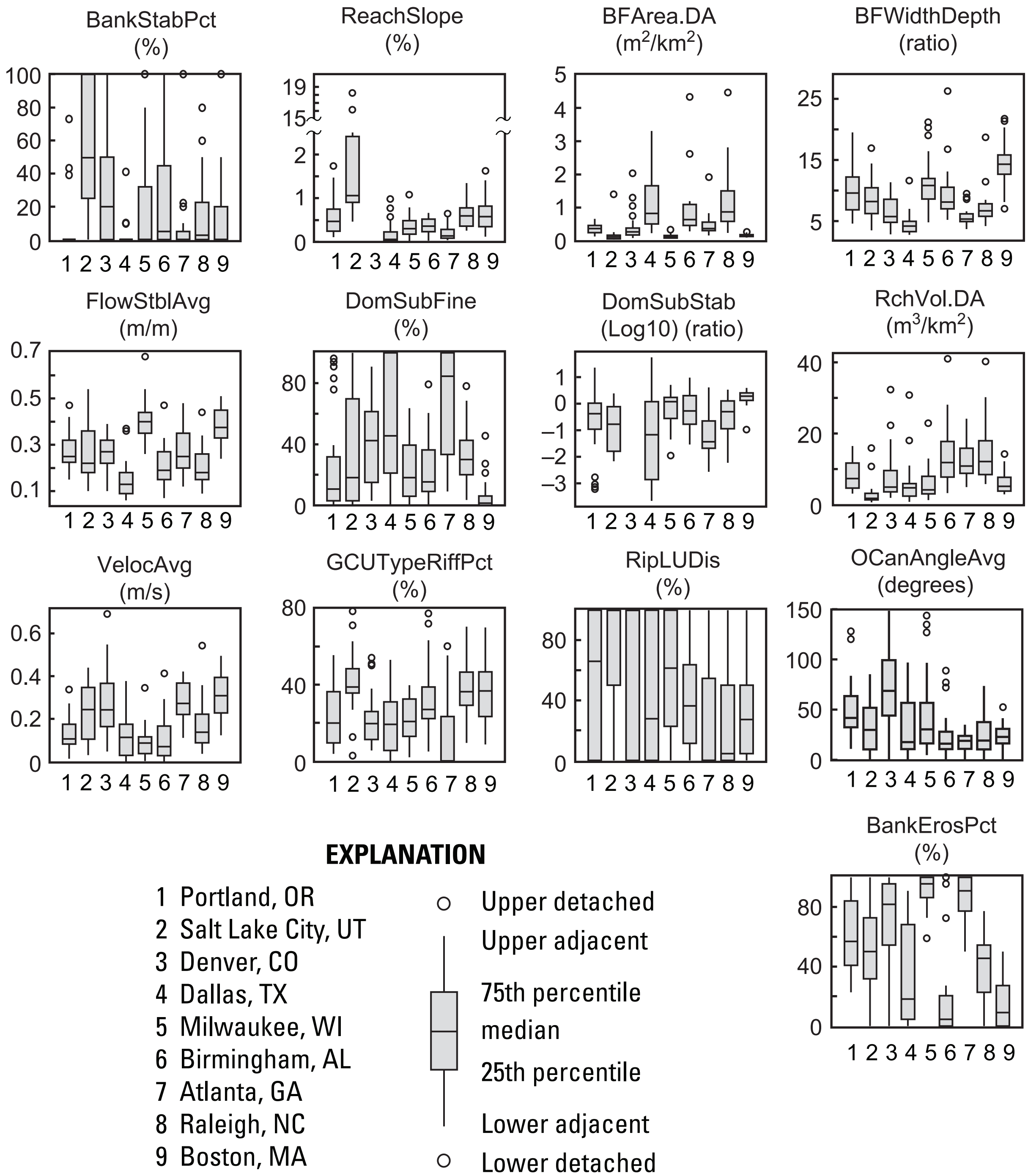

Figure 4. Boxplots of selected reach-scale channel controls, channel geometry, streambed substrate, low-flow habitat conditions, habitat complexity, and riparian/bank characteristics for nine metropolitan areas of the United States. (See table 1 for definitions of abbreviations. Boxplots are listed for metropolitan areas from west to east.)

the reach, and aerial photographs, the percentage of the reach with bank stabilization or channelization, number of grade-control structures (weirs, low-head dams, culverts) within the reach and within a distance of one reach length upstream or downstream, presence/absence of bedrock cropping out in the channel, and presence/absence of depositional bar features (lateral, mid, or point bars) were estimated (table 1). The degree of confidence in these techniques varied by metropolitan area depending on the level of details included on field forms and maps and the number of field photos. The calculated values represent a minimum for each type of reach-scale modification or natural control.

Data Analyses

The number of sites used for the habitat and geomorphic analyses was reduced from 262 to 249 by eliminating 13 sites with drainage areas much greater than 200 km^2 because a large range in watershed sizes can add to the complexity of geomorphic settings and possible responses (Ritter and others, 2002). Omitted sites included nine from Salt Lake City, three from Denver, and one from Dallas. Some sites were dropped from hydrologic comparisons if more than 30 percent of the hydrologic record was missing. Several hydrologic metrics were dropped if the data ranges were affected by whether they were based on flow cross-sectional area or stage. Bankfull channel areas and low-flow reach volumes were normalized by drainage area to account for differences in channel size.

Distributions of urban indicators, landscape characteristics, hydrologic metrics, and habitat/geomorphic characteristics were examined for the combined dataset and for individual metropolitan areas using scatterplots, boxplots, and histograms produced with S-Plus (Insightful Corporation, 2005) collectively for the entire dataset. Relations among urban indicators, landscape and hydrologic characteristics, and habitat and geomorphic characteristics were examined using Spearman rank correlation analysis (Iman and Conover, 1983) for overall relations as well as for each metropolitan area. Univariate linear regressions were performed. Urban indicators, landscape characteristics, and hydrologic metrics were considered independent variables. Reach slope and riparian disturbed land cover also were considered independent variables. All other reach-scale habitat and geomorphic characteristics were considered dependent variables. Spearman correlation coefficients (rho) with P-values of less than 0.001 were considered statistically significant for individual correlations. Bonferroni-adjusted coefficients for multiple tests also were taken into account.

Initial analysis of boxplots, scatterplots, and Spearman correlations included approximately 250 urban indicators and landscape characteristics, approximately 50 hydrologic metrics, and approximately 120 habitat/geomorphic characteristics. The final subset of variables used for this study was reduced by a combination of eliminating intercorrelated characteristics after examination of boxplots, correlation tables, and scatterplots. Remaining variables were predictor or response factors commonly included in other studies of urban stream habitat conditions and determined to be of general interest for urban stream studies.

Stepwise multiple linear regressions (Velleman, 1997) were performed on the collective dataset for the selected subset of habitat and geomorphic characteristics. Data were checked for normal distributions and transformed if necessary prior to regression.

The sites were subdivided into four categories of watershed-scale total impervious surface (NLCD_IS) representative of rural (less than 6 percent NLCD_IS), urbanizing (6 to less than 12 percent NLCD_IS), urban (12 to less than 18 percent NLCD_IS), and highly urban (greater than or equal to 18 percent NLCD_IS) streams. The categorical breaks were selected on the basis of past experience, previous literature, and maintaining a relatively similar number of sites per grouping. Histograms of the categorical data were used to explore for potential nonlinear patterns in streambed substrate and riparian vegetation characteristics.

Relations among Watershed-Scale Urban, Landscape, and Hydrologic Characteristics

Many urban indicators were highly correlated with each other in the combined dataset of all nine metropolitan areas (rho > 0.92) (table 3; fig. 2). Watershed total impervious surface (NLCD_IS) was used as a surrogate for the highly correlated urban indicators because of its common use in literature for research and management and its direct link to infiltration and runoff. Although highly correlated, the exact relation between the urban intensity index (MA_NUII) and NLCD_IS varied somewhat among the metropolitan areas depending on regional patterns in the density of urban development (Cuffney and Falcone, 2009). In most metropolitan areas, sites at the upper end of the urban gradient had 40 to 50 percent NLCD_IS except for Birmingham, Atlanta, and Boston, which had two or fewer sites above 30 percent NLCD_IS (fig. 2). In general, watersheds with about 10 percent NLCD_IS, a common percentage above which watersheds are considered to be influenced by urban development (Schueler, 1994), had about 25 percent watershed total urban land (NLCD_2). The relation between NLCD_2 and NLCD_IS improved if the proportion from the Level II category of developed open space (NLCD_21) was removed from the total urban land. Population density change (POP90_00), distance upstream to engineered channels (ENG-HYDd), or dam density (DAMd) did not relate to NLCD_IS (table 3).

Landscape characteristics were not related to NLCD_IS as part of the study design, but correlations among landscape characteristics, distance to engineered channels, dam density,

Table 3. Spearman rank correlations among selected watershed-scale urban, channel-alteration, and land-cover characteristics for combined data from nine metropolitan areas of the United States.

[Abbreviations for characteristics are defined in table 1. Statistically significant correlation coefficients with a P ≤ 0.001 and correlation coefficients with an absolute value greater than 0.34 are shown in bold]

	MA_NUII	NLCD_2	NLCD_21	EDM_C2	NLCD_IS	POPDEN00	POP90_00	PHU_G60	RDARDEN	URBANdw	ENG_HYDd	DAMd	NLCD_8	NLCD_4
MA_NUII	**1.00**													
NLCD_2	**0.97**	**1.00**												
NLCD_21	**0.78**	**0.84**	**1.00**											
EDM_C2	**–0.57**	**–0.57**	**–0.49**	**1.00**										
NLCD_IS	**0.95**	**0.97**	**0.73**	**–0.57**	**1.00**									
POPDEN00	**0.97**	**0.95**	**0.74**	**–0.56**	**0.94**	**1.00**								
POP90_00	–0.15	–0.15	–0.07	0.04	–0.15	–0.14	**1.00**							
PHU_G60	**–0.42**	**–0.44**	**–0.45**	0.32	**–0.40**	**–0.43**	**–0.37**	**1.00**						
RDARDEN	**0.96**	**0.95**	**0.76**	**–0.55**	**0.94**	**0.95**	–0.19	**–0.38**	**1.00**					
URBANdw	**0.93**	**0.96**	**0.77**	**–0.52**	**0.94**	**0.92**	–0.15	**–0.39**	**0.92**	**1.00**				
ENG_HYDd	–0.21	–0.22	0.08	0.01	–0.30	–0.26	0.00	0.23	–0.25	–0.29	**1.00**			
DAMd	–0.13	–0.06	–0.01	0.08	–0.05	–0.09	–0.17	0.08	–0.07	–0.03	0.16	**1.00**		
NLCD_8	**–0.63**	**–0.58**	**–0.43**	0.26	**–0.55**	**–0.57**	0.29	0.19	**–0.58**	**–0.59**	0.20	0.10	**1.00**	
NLCD_4	**–0.47**	**–0.56**	–0.24	0.33	**–0.61**	**–0.50**	0.06	0.24	**–0.49**	**–0.59**	**0.51**	–0.08	0.07	**1.00**

and agricultural land cover for the combined data indicate the close association and influence of natural landscape characteristics on human activities (tables 3, 4). For example, watersheds with high precipitation, low elevation, clayey soils, and high percentages of agricultural land had engineered channels near the sampling reach. Previous studies have shown that drainage density increases with urbanization (Graf, 1977); however, drainage density did not increase with urbanization in this study, probably because the scale of the stream network data was too coarse to discern changes in the networks of ditches and pipes related to stormwater management. Watershed size, drainage density, and basin shape did not correlate with urban indicators or other landscape characteristics.

Hydrologic metrics were related to both urban indicators and landscape characteristics (table 5). An increase in the frequency of high-flow events (PERIODR7) is a common feature of urbanized streams regardless of their environmental setting. Developed open space had the highest correlation with PERIODR7 out of all the urban indicators; mowed grassy areas or soil compaction from heavy equipment could have unknown aspects of stormwater management (Pitt and others, 2002). Comparatively, streams with a long MAX-DURFALL had a high percentage of clayey surficial deposits and gentle watershed slopes, and had relatively high mean annual air temperature.

Table 4. Spearman rank correlations of selected watershed-scale urban and channel-alteration characteristics with landscape characteristics for combined data from nine metropolitan areas of the United States.

[Abbreviations for characteristics are defined in table 1. Statistically significant correlation coefficients with a P ≤ 0.001 and correlation coefficients with an absolute value greater than 0.34 are shown in bold]

	NLCD_IS	ENG_HYDd	DAMd
DA	–0.12	0.06	–0.20
MAAT	–0.06	0.24	–0.06
MAP	–0.27	**0.56**	0.05
PERL	0.04	–0.19	–0.34
SNDH	–0.01	–0.14	**–0.49**
MEANELEV	0.10	**–0.49**	0.11
TEXTURE5	–0.18	**0.40**	0.12
P_FLAT	0.05	0.07	–0.05
WAT_SLOPE	–0.05	–0.13	0.07
BAS_SHAP_INDX	0.00	–0.06	–0.11
DRAINDEN	–0.14	–0.09	–0.10

Table 5. Spearman rank correlations of selected hydrologic characteristics with watershed-scale urban, channel-alteration, and landscape characteristics for combined data from nine metropolitan areas of the United States.

[Abbreviations for characteristics are defined in table 1. Number of sites for the subsets ranged from 222 to 249. Statistically significant correlation coefficients with a P ≤ 0.001, with Bonferroni adjustments, are shown in bold]

	RB_FLASH	PERIODR7	MAX_DURRISE	MAX_DURFALL	MXH_90	MXL_10
MA_NUII	0.20	**0.42**	–0.13	0.05	–0.24	–0.06
NLCD_IS	0.20	**0.38**	–0.17	0.05	–0.24	–0.13
NLCD_21	0.32	**0.63**	–0.04	0.23	–0.26	–0.09
EDM_C2	–0.30	–0.31	–0.05	–0.16	0.15	–0.06
POP90_00	0.23	0.02	0.16	0.20	–0.14	0.07
PHU_G60	–0.27	**–0.36**	–0.09	–0.33	**0.49**	0.08
ENG_HYDd	0.08	0.08	0.11	0.14	0.16	0.21
DAMd	0.04	0.03	–0.11	0.09	0.03	–0.22
DA	–0.13	–0.10	**0.51**	0.22	0.24	**0.40**
MAAT	0.03	0.29	0.18	**0.41**	–0.28	0.10
MAP	–0.08	0.02	–0.02	–0.16	0.31	0.12
PERL	–0.18	–0.05	0.01	**–0.37**	0.28	0.13
SNDH	0.02	0.02	0.17	–0.21	0.15	0.27
TEXTURE5	0.29	0.33	0.19	**0.49**	–0.28	0.15
P_FLAT	0.10	–0.14	0.21	0.19	0.08	0.12
WAT_SLOPE	–0.17	0.02	–0.22	**–0.38**	0.20	–0.10
BAS_SHAP_INDX	–0.33	**–0.35**	0.00	–0.26	0.25	0.03
DRAINDEN	0.20	–0.12	–0.17	–0.25	–0.03	–0.22

Relations Among Reach-Scale Habitat/Geomorphic Characteristics and Watershed-Scale Urban, Landscape, and Hydrologic Characteristics

There were no statistically significant correlations among habitat characteristics and NLCD_IS for the combined dataset of all nine metropolitan areas (table 6). However, streams near a large proportion of houses older than 60 years had relatively wide channels and coarse-grained substrates. The amount of older houses decreased with increasing urbanization in this study, indicating that watersheds with high amounts of urban land had relatively young residential areas (table 3). These combined relations among channel shape and streambed substrate for the spatial gradient are supportive of similar channel changes measured in temporal studies (Leopold and others, 2005; Colosimo and Wilcock, 2007). Reaches near engineered channels (ENG_HYDd) had relatively large bankfull channel areas. The amount of disturbed land cover within the 30-m reach buffer (RipLUDis) was not related to any watershed land cover or landscape characteristics.

Watershed-scale landscape characteristics influenced channel geometry, streambed substrate, and low-flow reach volume (table 6). Mean annual air temperature was a surrogate for north-to-south regional differences in environmental settings included in this study, in that southern metropolitan areas had more fine-grained soil texture, more gentle reach slopes, larger and deeper channels, less flow stability, and finer, more embedded streambed substrates than the northern metropolitan areas. Streams with high mean annual precipitation had relatively large bankfull channel areas and low-flow reach volumes. Streams with gentle topography had relatively low reach slopes, high flow stability, and more run. The strength of correlation coefficients among soil texture (PERL, SNDH, and TEXTURE5), topographic relief (P_FLAT and WAT_SLOPE), and habitat characteristics varied, making it useful to examine more than one characteristic reflective of surficial deposits and topography.

The interrelations among landscape characteristics were further reflected in the relations among habitat characteristics and hydrologic metrics (table 5). The hydrologic metric MAX_DURFALL, which correlated with the most landscape characteristics, also correlated with the most habitat characteristics. Reach slope had a higher correlation coefficient with MAX_DURFALL than did watershed slope, indicating the importance of local setting as well as watershed setting for hydrologic influences. Streams with high flashiness indexes and frequent high-flow events had high percentages of bank erosion and fine-grained streambed substrates. Streams with longer MXH_90 had wide channels and relatively small bankfull channel areas and reach volume (normalized by drainage area).

Table 6. Spearman rank correlations of reach-scale habitat/geomorphic characteristics with selected watershed-scale urban, channel-alteration, landscape, and hydrologic characteristics for combined data from nine metropolitan areas of the United States.

[Abbreviations for characteristics are defined in table 1. Statistically significant correlation coefficients with a P ≤ 0.001, with Bonferroni adjustments, are shown in bold]

	ReachSlope	BFArea	BFArea.DA	BFWidthDepth	FlowStblAvg	DomSubFine	DomSubCobble78	DomSubStab	EmbedPctAvg	RchVol	RchVol.DA	DepthMax	VelocAvg	GCUTypeRiffPct	GCUTypePoolPct	GCUTypeRunPct	BankVegCovAvg	BankErosPct
MA_NUII	0.07	–0.01	0.10	–0.09	–0.02	0.13	–0.08	–0.03	0.08	0.02	0.20	0.05	0.05	–0.04	0.08	–0.02	–0.10	0.03
NLCD_IS	0.07	–0.11	0.02	–0.07	0.01	0.11	–0.05	–0.01	0.10	–0.07	0.11	–0.01	–0.02	–0.07	0.07	0.01	–0.08	0.08
PHU_G60	0.07	–0.12	–0.24	**0.42**	0.24	–0.32	**0.36**	0.32	–0.33	0.06	–0.09	–0.03	–0.04	0.18	–0.09	–0.02	0.02	–0.09
ENG_HYDd	–0.27	**0.35**	0.26	0.05	–0.05	–0.11	–0.09	0.09	–0.09	0.33	0.31	0.23	–0.20	–0.01	0.01	–0.05	–0.10	–0.03
DAMd	–0.07	–0.14	0.02	0.08	–0.05	–0.14	0.01	0.08	–0.01	–0.18	0.01	–0.12	**–0.36**	0.05	0.16	–0.11	–0.03	0.13
DA	–0.24	**0.38**	**–0.42**	0.12	0.21	–0.05	0.04	0.04	0.19	**0.58**	–0.28	**0.40**	0.30	–0.18	–0.29	0.27	–0.01	0.03
MAAT	**–0.40**	**0.75**	**0.66**	**–0.54**	**–0.57**	**0.35**	**–0.50**	–0.31	**0.44**	0.26	0.28	0.32	–0.11	–0.17	0.07	–0.01	0.07	–0.17
MAP	–0.07	**0.46**	0.33	0.15	–0.10	–0.11	–0.07	0.05	–0.15	**0.42**	**0.42**	0.21	–0.01	0.01	–0.02	–0.02	0.10	–0.20
TEXTURE5	**–0.42**	**0.47**	**0.36**	**–0.39**	–0.25	0.24	**–0.49**	–0.28	0.32	0.22	0.21	0.31	–0.13	–0.26	–0.04	0.16	–0.12	0.28
P_FLAT	**–0.43**	–0.09	–0.28	0.12	**0.37**	0.07	–0.03	0.08	0.23	0.15	–0.10	0.13	–0.08	–0.32	–0.24	**0.36**	0.10	0.15
BAS_SHAP_INDX	0.01	–0.09	–0.27	0.20	0.20	–0.15	0.24	0.14	0.00	0.09	–0.18	0.08	0.09	0.02	–0.10	0.06	0.13	–0.07
DRAINDEN	0.11	–0.18	0.03	0.04	0.10	0.03	0.11	0.08	–0.19	–0.07	0.14	–0.12	0.12	–0.01	0.02	0.03	0.18	0.11
RB_FLASH	–0.18	0.02	0.12	–0.27	–0.02	**0.36**	–0.31	–0.21	0.11	0.07	0.26	0.04	0.01	–0.24	–0.03	0.17	–0.2	**0.47**
PERIODR7	–0.08	0.19	0.25	–0.3	–0.19	0.33	–0.34	–0.28	0.16	0.11	**0.36**	0.05	–0.09	–0.14	0.06	0.05	**–0.36**	0.34
MAX_DURRISE	**–0.37**	0.26	–0.17	–0.13	0.15	0.24	–0.15	–0.25	0.27	**0.4**	–0.01	0.3	0.08	–0.33	–0.17	0.28	–0.2	0.16
MAXDURFALL	**–0.52**	0.33	0.14	**–0.42**	–0.15	**0.48**	**–0.48**	**–0.39**	**0.47**	0.21	0.09	0.25	–0.18	**–0.39**	–0.03	0.24	–0.26	**0.36**
MXH_90	0.27	–0.18	**–0.41**	**0.46**	0.32	–0.34	0.29	0.23	–0.27	0.09	–0.2	–0.01	0.02	0.11	–0.11	0.01	–0.06	–0.16
MXL_10	–0.11	0.23	–0.14	0	0.19	0.02	–0.02	–0.01	0.02	**0.41**	0.08	0.33	0.21	–0.12	–0.19	0.15	–0.13	0.06

Results from stepwise linear regression analysis indicate that a wide range of watershed- and reach-scale natural and human factors influence reach-scale habitat and geomorphic characteristics (table 7). Landscape characteristics accounted for the most variability in bankfull channel area, flow stability, and percentage of cobble in streambed substrate. Precipitation

Table 7. Results of stepwise linear regression analysis of selected reach-scale habitat/geomorphic characteristics with watershed-scale urban, channel-alteration, landscape, and hydrologic characteristics for combined data from nine metropolitan areas of the United States.

[Abbreviations for characteristics are defined in table 1]

Habitat characteristics	Variables included in linear regression model	R^2	F-ratio	Standard error of the residuals
BFArea	MAAT	0.54	286	0.28
(log transformed)	MAAT, DA	0.63	209	0.25
	MAAT, DA, (-)NLCD_21	0.63	138	0.24
	MAAT, DA, (-)NLCD_21, MAP	0.65	110	0.24
	MAAT, DA, (-)NLCD_21, (-) MAP, NLCD_IS	0.68	105	0.22
	MAAT, DA, (-)NLCD_21, (-) MAP, NLCD_IS, EDM_C2	0.69	89	0.22
	MAAT, DA, (-)NLCD_21, (-) MAP, NLCD_IS, MXH_90	0.70	85	0.21
FlowStblAvg	(-)MAAT	0.31	112	0.10
	(-)MAAT, MAX_DURRISE	0.45	91.7	0.09
	(-)MAAT, MAX_DURRISE, MXL_10	0.48	69.1	0.09
	(-)MAAT, MAX_DURRISE, MXL_10, P_FLAT	0.50	55.0	0.08
	(-)MAAT, MAX_DURRISE, MXL_10, P_FLAT, MDH_90	0.51	46.9	0.08
	(-)MAAT, MAX_DURRISE, MXL_10, P_FLAT, MDH_90, MAP	0.52	40.8	0.08
DomSubFine	(-)ReachSlope	0.23	55.6	0.42
(log transformed)	(-)ReachSlope, PERIODR7	0.34	43.7	0.37
	(-)ReachSlope, PERIODR7, MAAT	0.38	35.4	0.36
	(-)ReachSlope, PERIODR7, MAAT, POP90_00	0.39	24.2	0.36
	(-)ReachSlope, PERIODR7, MAAT, POP90_00, (-)MAP	0.42	22.5	0.35
	(-)ReachSlope, PERIODR7, MAAT, POP90_00, (-)MAP, (-)ENG_HYDd	0.44	20.4	0.34
DomSubCobble78	SNDH	0.16	37.2	0.41
(log transformed)	SNDH, (-)PERIODR7	0.25	29.2	0.39
	SNDH, (-)PERIODR7, ReachSlope	0.29	22.1	0.38
	SNDH, (-)PERIODR7, ReachSlope, (-)NLCD_21	0.32	18.6	0.37
	SNDH, (-)PERIODR7, ReachSlope, (-)NLCD_21, (-)POP90_00	0.36	15.8	0.36
RchVol	DA	0.29	102	0.34
(log transformed)	DA, MAP	0.42	90.5	0.31
	DA, MAP, RB_FLASH	0.45	62.0	0.28
	DA, MAP, RB_FLASH, PERL	0.47	49.3	0.27
	DA, MAP, RB_FLASH, PERL, MAAT	0.48	41.8	0.27
GCUTypeRunPct	(-)ReachSlope	0.17	45.2	23.4
	(-)ReachSlope, (-)MAAT	0.21	29.6	22.8
	(-)ReachSlope, (-)MAAT, DA	0.24	23.8	22.4
	(-)ReachSlope, (-)MAAT, DA, NLCD_8	0.25	18.6	22.3
	(-)ReachSlope, (-)MAAT, DA, NLCD_8, PERL	0.28	17.8	21.6
	(-)ReachSlope, (-)MAAT, DA, NLCD_8, PERL, PERIODR7	0.30	15.3	21.6
BankErosPct	RB_FLASH	0.20	54.7	33.2
	RB_FLASH, (-)MAAT	0.23	34.8	32.4
	RB_FLASH, (-)MAAT, MAX_DURFALL	0.32	36.2	30.5
	RB_FLASH, (-)MAAT, MAX_DURFALL, RipLUDis	0.39	25.1	30.0
	RB_FLASH, (-)MAAT, MAX_DURFALL, RipLUDis, POP90_00	0.44	21.4	28.9
	RB_FLASH, (-)MAAT, MAX_DURFALL, RipLUDis, POP90_00, SNDH	0.46	19.5	28.3

accounted for the most variability in low-flow reach volume after accounting for drainage area. Reach slope accounted for the most variability for percentage of fine-grained streambed substrate and run percentage. The flashiness index accounted for the most variability in bank erosion, although the amount of variability explained was small. Urban indicators of developed open space, impervious surface, urban patch distance, and population density change accounted for a small amount of variability in bankfull channel area, streambed substrate size, and bank erosion.

Regional Variations in Relations Among Reach-Scale Habitat/Geomorphic Characteristics and Watershed-Scale Total Impervious Surface

Relations among reach-scale habitat and geomorphic characteristics and NLCD_IS were few and variable for individual metropolitan areas (table 8). Relations between hydrologic metrics and urbanization did not necessarily

Table 8. Spearman rank correlations among watershed-scale total impervious surface (NLCD_IS) and selected hydrologic and habitat/geomorphic characteristics for individual data from nine metropolitan areas in the United States.

[nd, no data. Number of sites for the study unit subsets ranged from 8 to 30. Abbreviations for characteristics are defined in table 1. Statistically significant correlation coefficients with a P ≤ 0.01 are shown in bold]

	Portland	Salt Lake City	Denver	Dallas–Fort Worth	Milwaukee–Green Bay	Birmingham	Atlanta	Raleigh	Boston
Hydrologic metrics									
RB_FLASH	**0.49**	–0.07	0.37	0.43	0.35	0.34	**0.59**	0.38	0.12
PERIODR7	**0.59**	–0.41	0.29	**0.81**	**0.86**	**0.70**	**0.93**	**0.82**	0.39
MAX_DURRISE	0.23	0.11	0.00	–0.19	**–0.56**	–0.36	0.39	**–0.54**	0.15
MAX_DURFALL	0.67	**0.74**	0.40	–0.07	0.00	–0.11	0.22	–0.27	0.05
MXH_90	–0.06	0.36	0.16	**–0.54**	–0.37	–0.26	**–0.61**	**–0.62**	0.27
MDH_90	0.37	–0.36	0.02	0.46	**-0.71**	**–0.62**	–0.29	**–0.69**	0.36
MXL_10	0.37	0.24	–0.10	0.21	–0.36	0.19	–0.26	–0.19	–0.33
Channel geometry and hydraulics									
ReachSlope	–0.44	**–0.53**	nd	0.13	–0.16	0.06	–0.27	0.02	–0.20
BFArea	–0.09	**0.58**	0.06	0.25	0.21	0.44	0.12	0.43	0.27
BFArea.DA	0.18	–0.33	0.26	0.06	**0.58**	**0.51**	0.09	**0.77**	–0.05
BFWidthDepth	–0.30	0.17	–0.22	0.48	0.08	–0.05	–0.22	**–0.52**	**–0.62**
FlowStblAvg	0.04	0.25	–0.48	0.47	–0.02	–0.46	0.19	**–0.60**	0.34
Bottom substrate									
DomSubFine	0.37	0.05	0.07	–0.13	–0.10	–0.16	0.08	**0.49**	**0.48**
DomSubCobble78	–0.05	0.35	–0.24	0.15	–0.32	–0.17	–0.08	**–0.46**	–0.38
DomSubStab	–0.26	0.44	nd	0.32	–0.09	0.32	–0.24	–0.33	0.04
EmbedPctAvg	**0.49**	–0.22	0.09	nd	–0.03	0.40	0.18	0.29	0.41
Low-flow habitat conditions									
RchVol	0.03	**0.70**	–0.08	**0.51**	0.09	–0.03	0.08	–0.28	0.36
RchVol.DA	0.24	0.00	0.07	**0.49**	0.38	0.17	0.05	0.18	0.19
DepthMax	0.01	0.39	–0.15	**0.49**	0.22	–0.18	0.14	0.07	**0.62**
VelocAvg	–0.47	0.00	–0.10	0.23	0.19	–0.06	–0.05	–0.27	0.33
Habitat complexity									
GCUTypeRiffPct	**–0.61**	–0.41	–0.16	–0.12	0.22	0.05	–0.15	0.02	–0.11
GCUTypePoolPct	–0.33	–0.44	0.14	0.33	–0.16	–0.08	0.24	0.11	0.15
GCUTypeRunPct	**0.58**	**0.56**	0.11	–0.34	0.03	0.12	0.04	–0.23	0.04
Riparian/bank characteristics									
RipLUDis	0.08	**0.52**	–0.23	–0.06	**0.51**	0.23	0.24	**0.50**	**0.56**
BankVegCovAvg	0.16	0.05	–0.18	0.17	–0.42	–0.18	–0.09	–0.04	**–0.50**
BankErosPct	0.14	0.18	0.01	0.06	0.19	0.05	0.01	–0.27	0.23

extend to habitat and geomorphic characteristics. Out of the nine metropolitan areas, Raleigh had the most and strongest correlation coefficients for channel geometry and streambed substrate with NLCD_IS. A few of the more notable relations are discussed in the following paragraphs.

Bankfull channel area (normalized by drainage area) increased with increasing NLCD_IS in Milwaukee, Birmingham, and Raleigh (fig. 5). Both previously forested and agricultural areas had urbanization related channel enlargement. Milwaukee, Birmingham, and Raleigh also had high correlation coefficients between PERIODR7 and NLCD_IS, potentially indicating that the increase in frequency of high-flow events may be the hydrologic process responsible for the enlarged channels. Raleigh's channel sizes increased at the highest rate of response with increasing NLCD_IS, and Milwaukee's channel sizes increased the least, likely due to differences in precipitation amounts and frequency of events (figs. 3, 5). Variability in channel sizes also increased with increasing impervious surface in these metropolitan areas. Atlanta streams showed no channel enlargement with increasing urbanization, even though Atlanta is in the same physiographic setting as Raleigh and had similar hydrologic responses to urbanization (table 8; fig. 5). The lack of association between channel size and urbanization in Atlanta perhaps is an artifact that Atlanta streams had larger watershed sizes relative to the other metropolitan areas (fig. 3) or that bankfull indicators were missing. Dallas-area rural streams had the largest channels, which were almost 10 times as large as rural channels near Milwaukee and Boston (fig. 5).

Correlations among bankfull width/depth ratios and NLCD_IS were different than for bankfull area for Milwaukee, Birmingham, and Raleigh (table 8). Out of the three metropolitan areas with bankfull area associations, only Raleigh showed an increase in narrow and deep channels with increasing urbanization. In addition, Boston channels became more narrow and deep with increasing urbanization, yet did not increase in size. This finding suggests that a variety of geomorphic processes, such as widening, narrowing, or deepening, can happen in urban streams depending on water/sediment fluxes (including bedload), geomorphic setting, grade control, and relative erosion resistance of streambed and bank materials. In a previous study of Seattle-area streams, urban channels were larger and generally were 1–1.5 m wider than their rural counterparts (Booth and Jackson, 1997); however, the same trends were not observed for regionally similar Portland streams, perhaps because of the wide precipitation range for the sampled Portland streams (fig. 3).

Relations between low-flow habitat characteristics and NLCD_IS were few, contrary to expected decreases in low flow with increasing urbanization (Paul and Meyer, 2001)

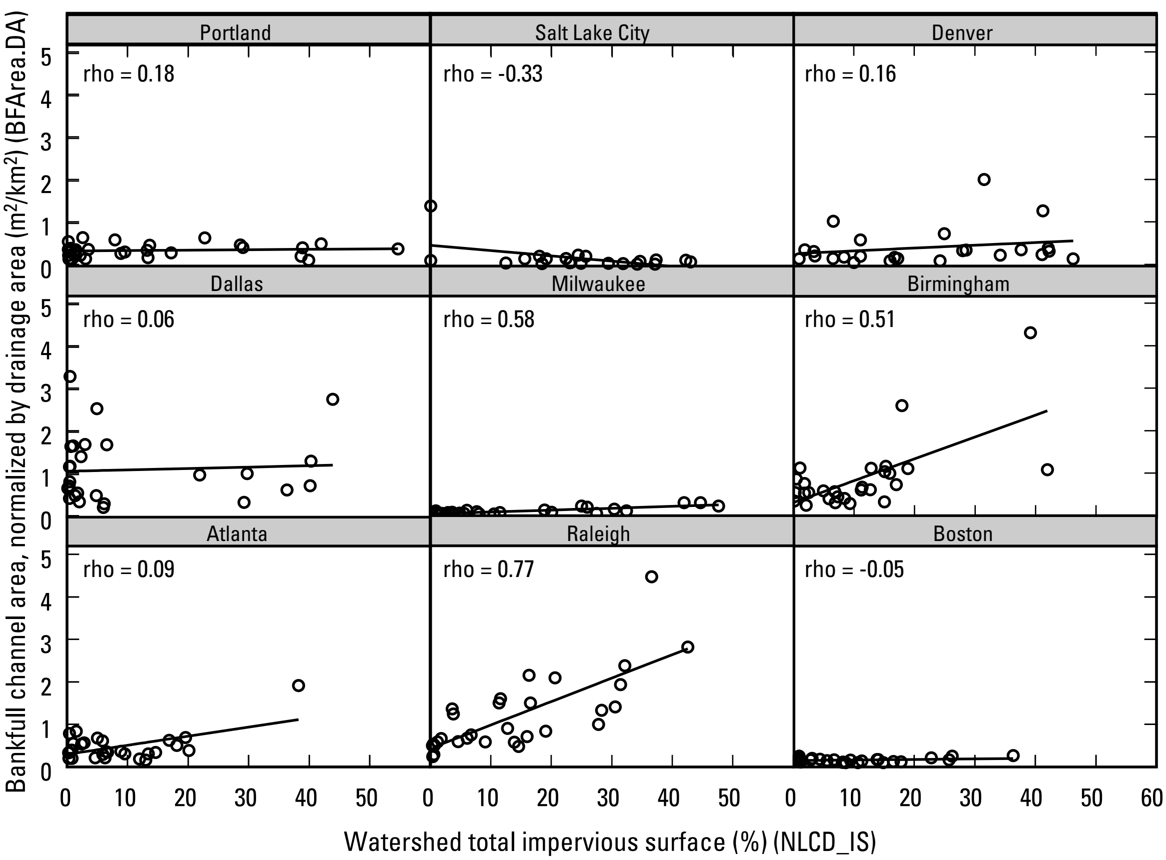

Figure 5. Bankfull channel area, normalized by drainage area, compared to watershed total impervious surface for nine metropolitan areas of the United States. [rho, Spearman correlation coefficient]

(table 8). The habitat measurement of reach volume (RchVol) and the hydrologic metric used as a surrogate for low flow (MXL_10) correlated with each other for the combined dataset (table 6), indicating some agreement between the hydrologic and habitat measurement techniques, yet neither showed any consistent relation with NLCD_IS in the individual metropolitan areas. Only in Salt Lake City and Dallas did urban streams have more RchVol than rural streams, yet there was not a comparable increase in MXL_10. Augmentation from wastewater discharges should not be an issue for streams in any of the metropolitan areas because sampled reaches were chosen to be upstream from known discharge points. Urban streams in Dallas and Boston had higher maximum low-flow depths than rural streams had, again contrary to what is expected from urbanization (Center for Watershed Protection, 2003).

Few relations were found among reach-scale riparian/bank characteristics and NLCD_IS for the individual metropolitan areas (table 8). Only Milwaukee, Raleigh, and Boston had increasing RipLUDis with increasing NLCD_IS. The lack of correlations in other metropolitan areas may be caused in part by sampling streams from different stages of urbanization or different rural endpoints. Leopold and others (2005) noted that the previously open agricultural riparian zone along the Watts Branch in Maryland was lined with trees and brush 30–40 years after urban development. Temporal changes in riparian vegetation along the spatially derived gradient may be inferred by grouping streams from the nine metropolitan areas into four categories of NLCD_IS—rural (less than 6 percent), urbanizing (6 to less than 12 percent), urban (12 to less than 18 percent), and highly urban (greater than or equal to 18 percent), with rural representing the initial stages of urban development and highly urban representing old urban (fig. 6). The Milwaukee spatial trend in open canopy angle shown in the histograms somewhat mirrors the Watts Branch findings with streams becoming more shaded and wooded as agricultural riparian lands are transformed into unmanaged public spaces or floodways in urban settings (fig. 6). Only Birmingham shows the expected trend of more open streams with the highest percentages of NLCD_IS.

Reach-Scale Controls on Habitat and Geomorphic Responses to Urbanization

Reach-scale channel alterations and geology, in some cases, may overwhelm or moderate a response caused by increases in NLCD_IS. Channel alterations were numerous for most of the sampled streams; almost 70 percent of rural streams and more than 90 percent of highly urban streams had at least one type of channel alteration (fig. 7). On average, more than 50 percent of the stream lengths were channelized for Salt Lake City, Denver, Milwaukee, and Birmingham, indicating a possible mix of ongoing geomorphic adjustments from variably aged pre-urban agriculture-related and urban channelization. Salt Lake City had more streams with bank stabilization (56 percent on average) and a greater number of grade-control structures (an average of 1.6 per reach) than any

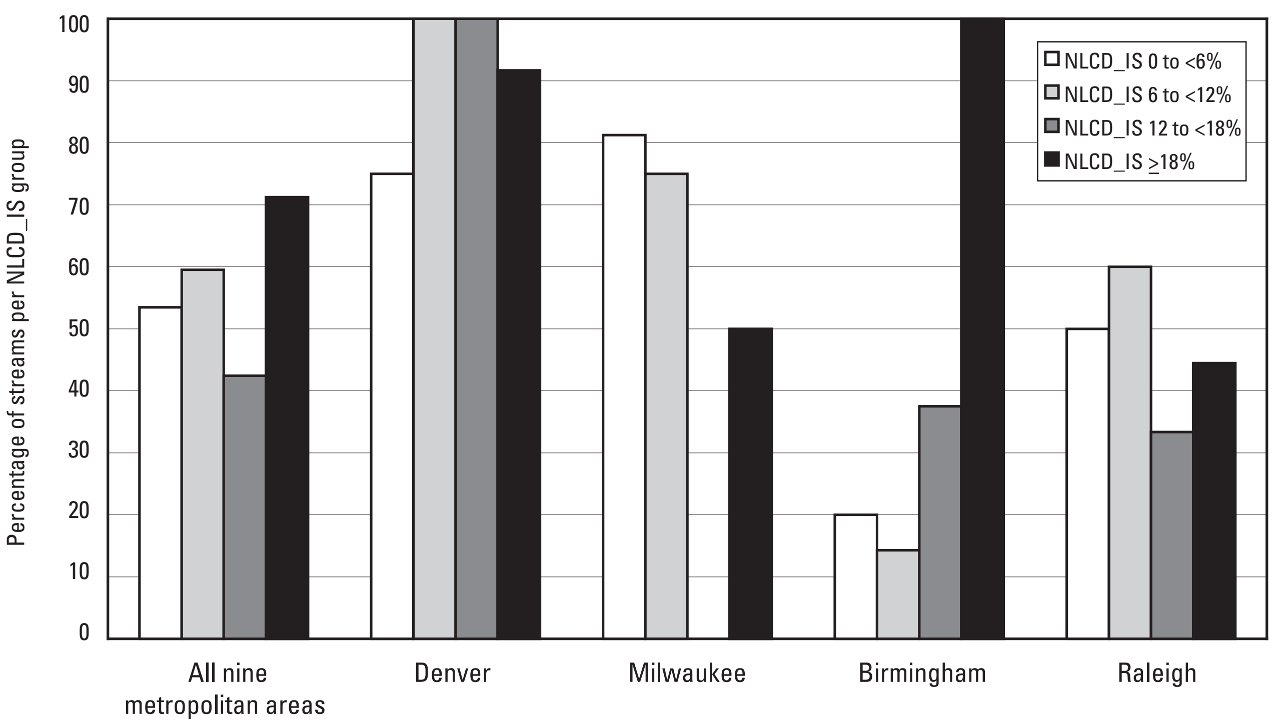

Figure 6. Percentage of streams with open canopy angle greater than 20 degrees for the percentage of watershed total impervious surface (NLCD_IS) groups for all nine and selected individual metropolitan areas of the United States.

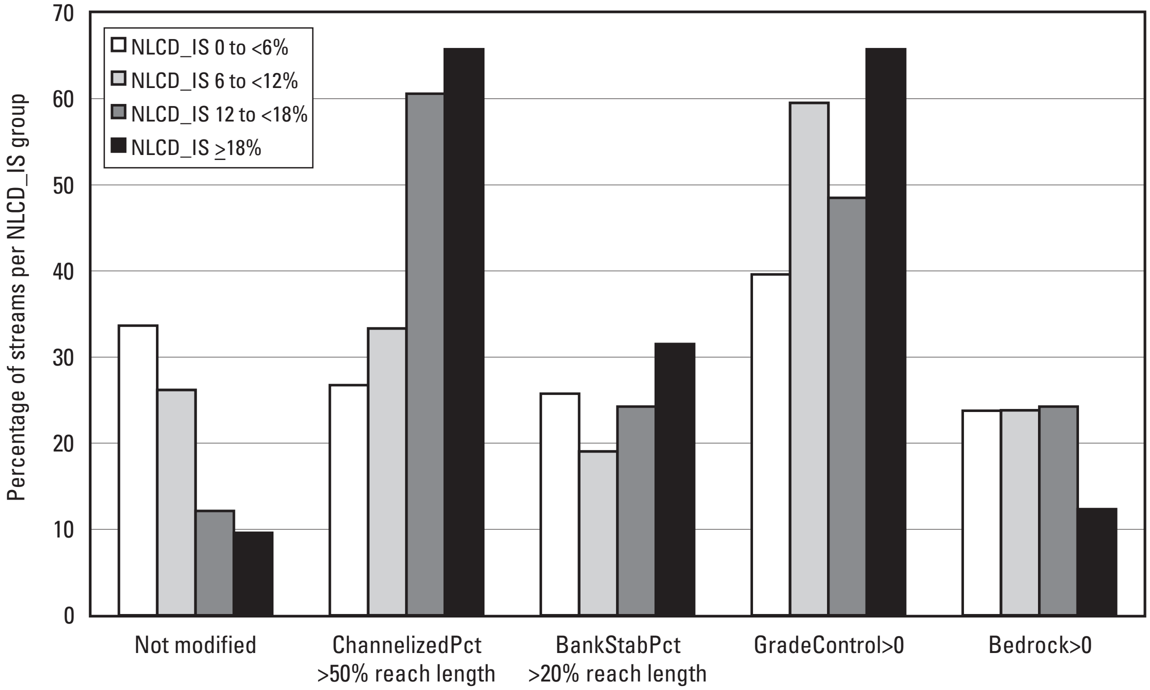

Figure 7. Percentage of streams with selected reach-scale channel alterations grouped by percentage of watershed total impervious surface (NLCD_IS) for combined data from nine metropolitan areas of the United States. (See table 1 for characteristic abbreviation definitions.)

other metropolitan area. Bank stabilization was 30 percent or less, and grade-control structures were one or fewer for the rest of the metropolitan areas. Unfortunately, the number of sites without channel modifications was inadequate for separate analysis of urbanization effects on unmodified streams.

Reach slope was measured in eight of the nine metropolitan areas and correlated with many habitat characteristics (table 9). Reach slope did not correlate with NLCD_IS and was more important than urbanization or watershed slope for determining streambed substrate size and habitat complexity; these results are similar to results from previous studies in Chicago, Illinois, and Milwaukee (Fitzpatrick and others, 2005; Fitzpatrick and Peppler, 2007; table 6). Reach-scale slope is assumed to be most affected by natural or human engineered factors, such as geologic setting, geomorphic position within the drainage network, and proximity to grade- or base-level controls. In this study, streams with relatively steep reach slopes generally had smaller cross-sectional areas and wider channels, more coarse and less embedded streambed substrates, less depth and reach volume, higher low-flow velocity, more riffle substrate, and less run than streams with relatively gentle slopes. Five of the eight metropolitan areas had significant correlations among reach slope and streambed substrate. Seven of the eight metropolitan areas had significant correlations between reach slope and riffle percentage, indicating that small variations in reach slope have a substantial influence on habitat complexity and streambed substrate. These findings are important for examining the possible confounding reach-scale factors that affect physical and biological responses to urbanization, especially responses of benthic invertebrates, which are dependent on streambed substrate type and sedimentation history (Waters, 1995). The amount of riparian disturbance and bank erosion was not related to reach slope.

Stream reaches with some outcrops of bedrock typically have less bank erosion and incision than alluvial streams, even in urban environments with high stream power and steep reach slopes (Allen and others, 2002; Fitzpatrick and others, 2006). Many streams with drainage areas less than 50 km^2, such as a large number included in this study, are likely affected by local geologic controls. For all of the metropolitan areas in this study, at least 20 percent of the sampled reaches had outcrops of bedrock (fig. 7). Half of the streams in Birmingham and Raleigh had bedrock outcrops. Comparisons of correlations from a subset of nonbedrock streams with the full dataset are not compelling (table 10); however, correlations were stronger among some habitat characteristics and landscape characteristics, hydrologic metrics, or reach slope for a subset of streams without bedrock outcrops compared to all streams.

Table 9. Spearman rank correlations among reach-scale slope and selected habitat/geomorphic characteristics for combined and individual data from eight metropolitan areas of the United States.

[nd, no data. Abbreviations for characteristics are defined in table 1. Number of sites for the study unit subsets ranged from 21 to 30. Statistically significant correlation coefficients with a P ≤ 0.01 are shown in bold. Reach slope (ReachSlope) data were not collected for the Denver metropolitan area]

	All eight areas	Portland	Salt Lake City	Dallas–Fort Worth	Milwaukee–Green Bay	Birming-ham	Atlanta	Raleigh	Boston
Channel geometry and hydraulics									
BFArea	**–0.39**	–0.06	–0.18	0.04	–0.15	0.09	0.31	–0.05	–0.44
BFWidthDepth	**0.33**	**0.59**	0.22	–0.18	0.19	0.13	–0.09	–0.07	–0.06
BFArea.DA	–0.16	0.03	–0.05	0.00	–0.04	0.14	0.39	0.22	–0.01
FlowStblAvg	0.00	–0.26	–0.33	–0.33	–0.09	0.08	**–0.52**	–0.25	–0.17
Bottom substrate									
DomSubFine	**–0.43**	–0.43	–0.50	–0.20	–0.43	–0.18	**–0.65**	–0.28	–0.29
DomSubCobble78	**0.43**	0.47	0.27	–0.09	**0.58**	–0.01	**0.57**	0.33	–0.07
DomSubStab	**0.19**	0.33	–0.03	–0.20	0.19	0.10	0.29	0.36	**–0.52**
EmbedPctAvg	**–0.59**	**–0.73**	—0.37	nd	**–0.56**	–0.19	**–0.67**	–0.06	–0.33
Low-flow habitat conditions									
RchVol	**–0.36**	–0.40	–0.41	–0.13	–0.16	–0.02	–0.06	–0.28	–0.41
RchVol.DA	**–0.18**	–0.35	–0.25	–0.07	–0.15	0.08	0.13	–0.01	–0.15
DepthMax	**–0.41**	–0.32	–0.36	–0.37	0.03	0.07	–0.12	–0.43	–0.18
VelocAvg	**0.28**	**0.56**	0.13	**0.61**	0.12	0.20	0.25	0.29	0.35
Habitat complexity									
GCUTypeRiffPct	**0.68**	**0.81**	**0.84**	**0.52**	**0.51**	0.08	**0.69**	**0.61**	**0.72**
GCUTypePoolPct	0.13	0.23	0.11	**–0.49**	0.30	0.04	0.18	–0.32	–0.16
GCUTypeRunPct	**–0.49**	**–0.72**	**–0.63**	0.23	**–0.50**	–0.19	**–0.57**	–0.08	**–0.65**
Riparian/bank characteristics									
RipLUDis	0.06	–0.35	–0.40	–0.09	0.13	–0.12	0.25	–0.08	–0.05
BankVegCovAvg	–0.26	0.21	–0.30	–0.38	–0.14	–0.28	0.24	0.14	–0.33
BankErosPct	–0.22	–0.38	–0.23	–0.15	–0.29	0.15	–0.18	–0.17	–0.11

Table 10. Spearman correlations for selected urban indicators, landscape characteristics, hydrologic metrics, and habitat characteristics for all streams and streams without bedrock outcrops for combined data from nine metropolitan areas of the United States.

[Abbreviations for characteristics are defined in table 1. Numbers of sites for the subsets ranged from 177 to 249. Statistically significant correlation coefficients with a P ≤ 0.001 and with Bonferroni adjustments range from the absolute value of 0.32 to 0.37. Correlation coefficients with an absolute value greater than 0.37 are shown in bold]

	BFArea.DA		DomSubFine		GCUTypeRunPct		BankErosPct	
	All	No bedrock	All	No bedrock	All	No bedrock	All	No bedrock
NLCD_IS	0.02	–0.09	0.11	0.03	0.01	–0.03	0.08	0.07
NLCD_21	0.24	0.11	0.18	0.07	–0.12	–0.10	0.04	0.07
MAAT	**0.66**	**0.67**	0.35	**0.48**	–0.01	0.06	–0.17	–0.17
TEXTURE5	0.36	**0.45**	0.24	0.27	0.16	0.21	0.28	0.24
RB_FLASH	0.12	0.08	0.36	**0.38**	0.17	0.29	**0.47**	**0.55**
PERIODR7	0.25	0.15	0.33	0.30	0.05	0.16	0.34	0.40
MAX_DURFALL	0.14	0.14	**0.48**	**0.55**	0.24	0.33	0.36	0.36
ReachSlope	–0.16	–0.23	**–0.43**	**–0.49**	**–0.49**	**–0.52**	–0.22	–0.22

Nonlinear Relations of Depositional Bars, Channel Shape, and Streambed Substrate with Urbanization

The source and amount of transported sediment affect channel shape and streambed substrate size and bed configuration (Leopold and Maddock, 1953; Schumm, 1960; Brierley and Fryirs, 2005). Because sediment fluxes temporally vary in magnitude and source with urban development, spatial patterns in channel shape and streambed substrate should not necessarily follow a linear trend along an urban gradient. For example, in Watts Branch near Rockville, Maryland, a 40-year study of channel change showed initial changes within the first one to two decades of the channel being overloaded with sediment and narrowing, followed in the next two decades by channel widening as sediment production from construction sites decreased (Leopold and others, 2005). Descriptive measures of in-channel storage of sediment, such as the development and build-up of lateral and mid-channel bars in single-thread meandering channels, can be used as indicators of channel change caused by changes in the mode or magnitude of sediment loads (Thorne, 1998; Brierley and Fryirs, 2005; Colosimo and Wilcock, 2007). Potential indicators of channel change were plotted for the four NLCD_IS groups, including channel shape (bankfull width/depth ratio), presence/absence of depositional bars, streambed substrate size and stability, embeddedness, and bank erosion (fig. 8).

The initial qualitative measurement of the presence or absence of lateral and mid-channel depositional bars, although tentative, shows an expected response with increasing urbanization (fig. 8). Rural streams had the fewest bars, whereas urbanizing streams with 6 to 12 percent NLCD_IS had the most. More than 30 percent of rural streams had depositional bars, indicating a possible pre-urban excess of sediment or a nearby downstream constriction for bedload transport, such as an undersized culvert. The percentage of streams with depositional bars decreased slightly with higher levels of urbanization. Comparatively, the percentage of wide streams (width/depth ratios greater than 10) and the percentage of streams with fine-grained streambed substrate increased initially with urbanization but then decreased at higher levels of urbanization. The percentage of streams with sandy, embedded substrates increased with increasing urbanization. In general, approximately 50 percent of all the streams, both rural and urban, had embedded substrate and evidence of bank erosion, indicating potential issues with fine-grained sediment deposition and local bank sources for sediment in all land-cover settings.

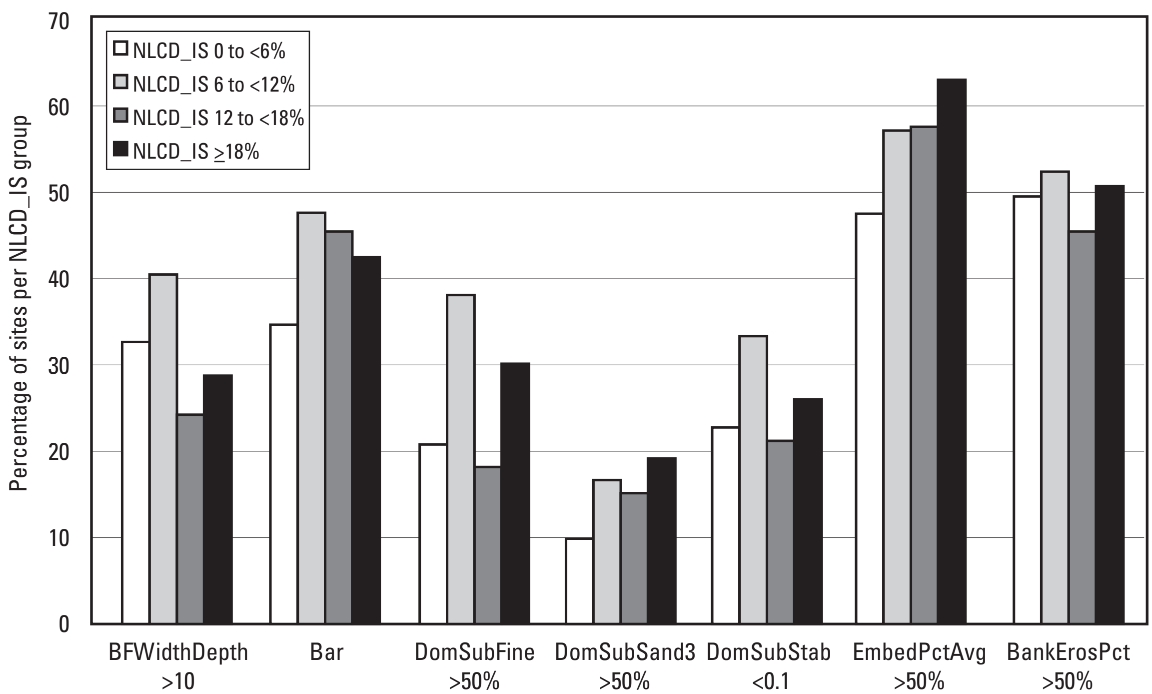

Figure 8. Percentage of streams with selected characteristics of channel shape, bar formation, and streambed substrate characteristics, grouped by watershed total impervious surface (NLCD_IS) for combined data from all nine metropolitan areas of the United States. (See table 1 for characteristic abbreviation definitions.)

Implications

The regional variability of habitat and geomorphic relations to urbanization found in this study facilitated further exploration of three issues. First, in order to adequately determine the potential rate and direction of geomorphic responses, multiple spatial scales of urban, landscape, and hydrologic characteristics are needed. Second, the occurrence and rate of reach-scale geomorphic responses are controlled by reach-scale channel boundary conditions. Third, as the amount of urbanization increases, geomorphic responses are not always linear, mainly because urban-related changes in sediment flux are likely nonlinear with time and spatial gradients. Overriding all three issues are influences of historical and ongoing reach- to watershed-scale channel alterations, in terms of unmeasured drainage network expansions or changes associated with stormwater management practices and grade control, bank stabilization, habitat improvement, and stream rehabilitation. Effects from reach-scale channel controls seem to be more important than pre-urban watershed-scale land cover (agriculture compared to forest). The spatial and temporal complexity of these issues has limited the development of simple indicators of habitat quality or habitat degradation, such as those needed for regional and national assessments of habitat conditions and similarly developed for biological integrity (H. John Heinz III Center for Science, Economics, and the Environment, 2002).

Watershed-scale indicators of urbanization generally were highly intercorrelated, including impervious surface, the urban intensity index, watershed total urban land, population density, road-area density, and distance to nearest urban land. Use of any of these variables in a spatial gradient analysis would have given similar results. Some of the unexplained variability in hydrologic metrics and habitat/geomorphic characteristics may have been more interpretable with additional quantitative data on connectivity of impervious surfaces, possibly through further analysis of land-cover patchiness and road-density data or higher resolution GIS data. This assessment would have benefited from additional data on drainage network changes associated with pre-urban water use (irrigation, diversion storage, and interbasin transfers) and urban stormwater management (conveyance, connectivity, and detention). Streams in metropolitan areas in the semiarid Western United States, such as Salt Lake City and Denver, had highly regulated systems prior to urbanization from agricultural uses. Quantitative data for pre-urban channel alterations for the northeastern United States are probably equally important because of abundant dams and mill ponds that are more than 100 years old (Walter and Merritts, 2008).

General conclusions for major habitat and geomorphic responses and adjustments to urbanization are summarized in figure 9 and discussed in the next paragraphs. The diagram in figure 9 illustrates expected responses of habitat/geomorphic characteristics from this study supplemented with insights from previous studies. Dashed lines for some characteristics indicate that there is some uncertainty in the relation, either through lack of conclusive results in this study or previous studies. The magnitude and direction of the relational lines in figure 9 are arbitrary and realistically will depend on climatic and physiographic setting, as well as pre-urban and urban-related watershed-scale human modifications of drainage network patterns. The streams are assumed to be alluvial with no bedrock or base-level control and are not limited by any reach-scale channel modifications, such as bank stabilization, grade control, or habitat improvements.

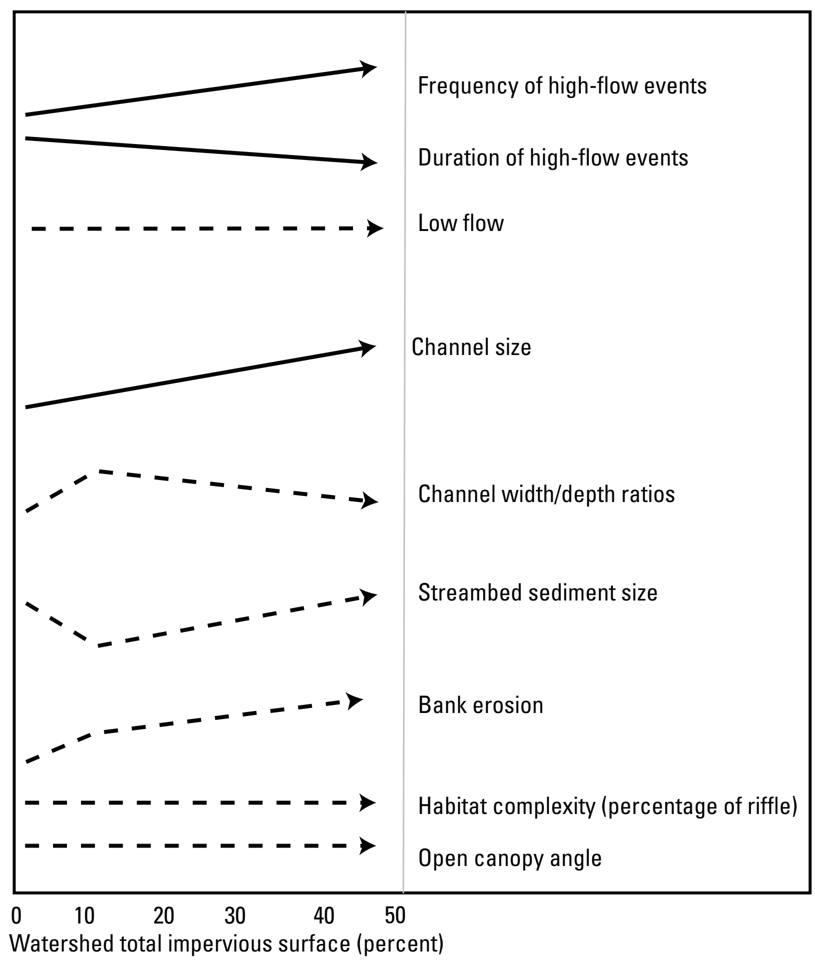

Figure 9. Generalized hydrologic and habitat/geomorphic relations to urbanization. [Relations are based on watershed total impervious surface (NLCD_IS) for the nine metropolitan areas across the United States. Solid lines are relations typically observed in this study and other studies. Dashed lines are potential relations. All relations are dependent on watershed climatic and physiographic setting. Channels are assumed to be alluvial, nonbedrock, and not influenced by historical or recent changes in stormwater management, bank stability, or grade control.]

Increased frequency of high-flow events was the most widespread change in hydrologic conditions associated with urbanization (fig. 9). Duration of high-flow events probably decreases with increased urbanization, but this aspect is moderated by regional variations in climate and physiography. Both our data and the literature suggest unidirectional changes in the frequency and duration of high-flow events, both spatially and temporally. Low-flow characteristics were not related to urbanization. Other studies have shown that base flow likely decreases with urbanization (Finkenbine and others, 2000), but patterns are likely dependent on watershed-scale climate, physiography, and water use (Roesner and Bledsoe, 2003), as well as reach-scale geologic and geomorphic setting and hydrologic modifications.

Increased channel size is the most predictable geomorphic response of channels to urbanization (fig. 9), most likely because channel size mainly is determined by flow characteristics and erosion potential (excess shear stress). The results from this study supported previous worldwide studies (Hammer, 1972; Graf, 1975; Knight, 1979; Whipple and DiLouie, 1981; Roberts, 1989; Gregory and others, 1992; Doll and others, 2002; Fitzpatrick and others, 2005; Leopold and others, 2005; Chin, 2006). Channel size may increase through widening, downcutting, or both, depending on the erosion-resistance potential of the banks and channel bottom and temporal/spatial variations in sediment-flux type and magnitude (Roberts, 1989; Allen and others, 2002; Brierley and Fryirs, 2005; Cianfrani and others, 2006). In this study, six metropolitan areas—Portland, Dallas, Milwaukee, Birmingham, Atlanta, and Raleigh—had increased frequency of high-flow events. Of these six areas, Milwaukee, Birmingham, and Raleigh had corresponding increases in channel size, indicating that the frequency aspect of floods is an important hydrologic factor for channel size; however, additional factors were more important indicators of channel size for Portland, Dallas, and Atlanta. The lack of increases in channel size from urbanization for Portland and Dallas is unexpected, given that in previous studies of urbanization effects in Seattle and Dallas, there was evidence for channel incision (Booth, 1990; Allen and others, 2002). It is possible that indicators of bankfull stage were difficult to identify in Portland, Dallas, and Atlanta. The large range in annual precipitation among sampled streams in Portland may be another complicating factor. Rural channels near Dallas were large relative to other rural channels in this dataset, suggesting that historical land use or channel modification may have influenced channel size and the ability to determine bankfull indicators more so than hydrologic conditions.

Sediment-related habitat characteristics, such as channel width/depth ratios, streambed sediment size, and bank erosion, likely respond to urbanization in a nonlinear pattern. Previous studies in the Eastern United States have generally shown that suspended-sediment loads do not follow a linear increase with increasing urbanization, but instead peak early in the urbanization process when construction and land clearing peak (Wolman, 1967; Wolman and Schick, 1967; Guy, 1970; Chin, 2006; fig. 9). These nonlinear patterns would likely happen in previously forested or agricultural watersheds. Typical hydrologic responses to urbanization combine to increase the potential for excess shear stress, channel erosion, and bedload transport (Graf, 1975; Whipple and DiLouie, 1981; Roberts, 1989; Trimble, 1997; Roesner and Bledsoe, 2003; Rohrer and Roesner, 2007; Pomeroy and others, 2008). Exploratory results from this study and previous temporal studies in the Eastern United States (Leopold and others, 2005; Colosimo and Wilcock, 2007) indicate that with increasing amount of time since urbanization, channels widen initially and then narrow, fine sediment increases and then decreases, and depositional bar formation increases then wanes. Spatial and temporal fluctuations in source and amount of suspended sediment and bedload could cause these varying outcomes for channel shape, bar formation, and streambed substrate size. Measuring the amount and type of depositional features may help explain the relative influences on streambed substrate from changes in the sources, sizes, and amounts of transported sediment in urban streams.

Whether the channel widens or deepens (or both) during enlargement can vary, mainly depending on phase of urbanization and the relative strength of the banks and channel bottom (fig. 9). A combination of flow energy (slope) and sediment flux, which changes as urbanization increases through time or space, affects the balance between erosional and depositional processes acting on channel banks and bottoms (Brierley and Fryirs, 2005; Cianfrani and others, 2006). Streambed substrate size and stability may follow similar trends because they also are affected by sediment availability. Local channel boundary conditions are highly influential on channel-shape responses, including engineered grade control, bank stabilization, and riparian vegetation (Hession and others, 2003; Cianfrani and others, 2006). The balance between erosional and depositional processes is mostly dependent on slope; however, the balance may be influenced by nearby upstream or downstream flow constrictions, such as culverts, that may reduce bedload transport, confounding predictions of channel shape or substrate adjustments.

Embeddedness is generally thought to increase in early phases of urbanization but eventually decreases as the amount of fine sediment decreases or as streams stabilize in old urban areas (May and others, 1997; Finkenbine and others, 2000; Scholz and Booth, 2001; Center for Watershed Protection, 2003). In this study, reach slope was related to embeddedness more so than NLCD_IS (table 9), although a relation with urbanization is perhaps more apparent if the number of streams with more than 50 percent embedded substrate is compared to amount of urbanization (fig. 8). Some of the variability likely was due to known subjectivity problems in measuring embeddedness in different stream types with different sizes of substrates (Wang and others, 1996; Sylte and Fischenich, 2002; McHugh and Budy, 2005).

Bank erosion was not correlated with watershed urbanization for the combined dataset (table 6), and few conclusive studies exist on urbanization effects on bank erosion (Booth, 1991; Center for Watershed Protection, 2003; Fitzpatrick and others, 2005) perhaps because of the many, highly variable reach-scale factors that can influence bank erosion, such as geology and riparian vegetation (Pizzuto and others, 2000; Hession and others, 2003). Bank erosion for the combined dataset correlated with flashiness and duration metrics, similar to findings by Julian and Torres (2006) that indicated that flow variability is important. The amount of observed bank erosion is particularly sensitive to grade control, the presence of erosion-resistant bedrock, or bank stabilization structures, many of which are well hidden by techniques that emphasize natural-looking channels. If length of erosion along a transect is measured instead of just noting the presence or absence of erosion and if bank stabilization is assessed as part of the reach-scale habitat assessments, a response between bank erosion and urbanization may be seen, such as that seen in the Milwaukee study by Fitzpatrick and Peppler (2007). The trendline in figure 9 for bank erosion mainly is based on the Milwaukee study, which had a steep increase in length of bank erosion between 0 and 15 percent NLCD_IS and a continuing increase for streams with greater than 15 percent NLCD_IS.

Decreases in habitat complexity from urbanization could not be detected in this study, but some evidence from other studies suggests that complexity decreases and pool depth increases with urbanization (fig. 9; Scholz and Booth, 2001; Walsh and others, 2005). For streams in this study, the measure of habitat complexity (percent riffle, run, pool) was primarily related to reach slope, with lesser influences from north-south regional differences, watershed size, amount of watershed agricultural land, soil permeability, and frequency of high-flow events (tables 7, 9). Reach slope should be considered as an important independent factor for studying effects of land-cover disturbance because changes in reach slope are caused by century- to millennial-scale changes in climatic conditions and basinwide network development, not decadal changes in land cover (Sear and others, 2003). Thus, the extra time taken to accurately measure reach water-surface slope provides information for describing the most explanatory variable in predicting substrate size and habitat complexity. Perhaps a more sensitive measurement for habitat complexity would be within-reach variability of velocity/depth combinations. Additionally, it may be important to investigate habitat complexity in terms of varying flow conditions instead of point-in-time low-flow conditions.

Responses of low flow to urbanization in this study were hampered by its confounding relation to stream size. The hydrologic metric that was used as a surrogate for low-flow conditions, MXL_10, was affected by stream size. No conclusive evidence from other studies shows that reach volume decreases with increasing urbanization (Walsh and others, 2005), potentially because this measurement also is affected by channel modifications within the reach. The trend line for low flow is flat in figure 9 because reach volume is more likely to be affected by other factors than by urbanization.

Finally, the space-for-time approach for determining habitat/geomorphic responses to urbanization was adequate for showing changes in hydrology and channel size, but it may miss subtle and cumulative effects caused by historical events and nonlinear temporal trends in sediment sources and loads. Temporally, a stream reach may be experiencing ongoing geomorphic adjustments from natural and human modifications prior to urbanization, including large floods, flood control, channel rehabilitation, grade control, and road crossings. During the 1990s, channel restoration projects increased for small and large streams across the United States in urban and rural areas (Cunningham, 2002; Schueler, 2004; ICF Consulting, 2005). Recent Federal guidelines for stream mitigation have further promoted extensive channel rehabilitation (U.S. Environmental Protection Agency, 1995; U.S. Army Corps of Engineers and others, 2003). Recent channel stabilization efforts look much more natural than older efforts and can be difficult to detect even after a few years because hard structures typically are hidden by vegetation. In this study, the possibility of channel modifications was high for all streams along the urban gradient; more than 60 percent of rural streams had channel modifications, and about 90 percent of urban streams had modifications. Furthermore, geomorphic adjustments within a reach may be the result of channel modifications upstream or downstream. Knowledge of historical channel modifications within and surrounding the reach is an important part of any assessment of habitat conditions related to urbanization.

Summary and Conclusions

Habitat and geomorphic responses to urbanization were dependent on regional variations in climatic and physiographic conditions, as well as effects from reach-scale channel alterations, slope, and geologic setting. Total impervious surface was a useful watershed-scale indicator of urbanization, although the study would have benefited from more detailed data on stormwater management practices and connectivity of impervious surfaces. Reach-scale human and natural controls on channel-boundary conditions, including amount of channel alterations (bank stabilization, channelization, and grade control), bedrock/parent material, and reach slope also were important. Inclusion of reach slope in analyses was necessary for describing reach-scale controls on hydrologic conditions and habitat responses, especially for streambed substrate and habitat complexity. Hydrologic metrics that described various aspects of frequency and duration of high-flow events were helpful in describing the continuity between watershed urbanization and habitat changes.

Channel enlargement (channel widening or downcutting) and increases in disturbed riparian vegetation only occurred in three metropolitan areas in the Midwestern and Eastern United States. The frequency of large high-flow events was the hydrologic characteristic most closely related with the channel enlargement. Streams with pre-urban hydrologic alterations from interbasin transfers and diversions or dams and reservoirs, such as the streams found in the semiarid West and Northeast, did not show channel enlargement. Changes in amounts of disturbed riparian vegetation associated with urbanization vary regionally and with the amount of urbanization. The amount of riparian shading may increase along previously agricultural streams, or may remain the same or decrease along previously forested streams.

Channel shape and streambed substrate size were not correlated with watershed urbanization, likely because these characteristics are affected by temporal changes in the type and source of sediment load associated with phases of urbanization and controls on channel-boundary conditions within the sampled reach. Bank erosion increased with an increasing index of hydrologic flashiness in Milwaukee and Boston, but no trends were observed in other metropolitan areas. Lack of observed responses for bank erosion with watershed urbanization may have been caused by the abundance of channel and bank stabilizations in urban reaches or simply by the high percentage of streams with bank erosion in both rural and urban settings.

Results of this study were inconclusive for responses of habitat complexity and low-flow habitat conditions to urbanization. Instead, habitat complexity, in terms of percentage of riffle, run, and pool, mainly depended on variations in reach slope. Responses of low-flow habitat conditions, such as reach volume, likely were masked by precipitation variations, within-reach channel modifications, and stream size.

The multitude of within-reach channel modifications, such as channelization, bank stabilization, and grade control; the presence of bedrock in urban streams from a variety of environmental settings; and the importance of reach slope emphasize that reach-scale data are needed to adequately describe controls on channel-boundary conditions and potential geomorphic responses. This is an especially important issue as the popularity of channel rehabilitation continues and as bank stabilization and grade control efforts are designed to appear natural.

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