Changes in Aquatic Habitat and Geomorphic Response to Urbanization, with Implications for Assessing Habitat Degradation

F.A. Fitzpatrick[1] and M.C. Peppler[2]

[1]U.S. Geological Survey, 8505 Research Way, Middleton, WI 53562; PH (608)821-3818; email: fafitzpa@usgs.gov

[2]U.S. Geological Survey, 8505 Research Way, Middleton, WI 53562; PH (608)821-3821; email: mpeppler@usgs.gov

Abstract

In 2004, an agricultural to urban land-cover gradient approach was used in a study of habitat and geomorphic responses to urbanization for 30 streams in Milwaukee and Green Bay, Wisconsin. Multiple scales of land-cover and landscape (reflecting glacial geologic setting) characteristics were compared to reach-scale habitat/geomorphic characteristics using correlation analysis. Urban streams had enlarged channels and more bank erosion than agricultural streams. However, geomorphic channel units and substrate characteristics mainly were related to subtle variations in reach slope. Hydrologic metrics, including flashiness, were of limited use for explaining habitat variations or geomorphic response. Bank stabilization, and historical channel modifications potentially confounded relations, emphasizing the need to recognize historical bank and channel stabilizations for site selection and habitat assessment. Studies of geomorphic processes and responses to the complex interaction of changes in watershed runoff and sediment with local geologic and anthropogenic controls would be needed to adequately predict habitat degradation associated with urbanization.

Introduction

Stream habitat degradation in urbanizing areas is caused by complex geomorphic responses and ongoing adjustments to changes in runoff and sediment inputs (Gregory and Madew 1982, Wolman 1967, Wolman and Schick 1967, Colosimo 2002). Channel erosion (through incision or widening) or sedimentation may result from urban development (Wolman 1967, Wolman and Schick 1967, Guy 1970, Graf 1975, Roberts 1989, Booth 1990, Gregory et al. 1992, Booth and Jackson 1997, Trimble 1997, Colosimo 2002). Channel enlargement (increase in channel size through incision or widening) is the most common geomorphic response to urbanization in a wide variety of environments (Hammer 1972, Doll et al. 2002, Center for Watershed Protection 2003, Coles et al. 2004, Fitzpatrick et al. 2005). However, the response is dependent on stream power (representing combined effects of discharge and slope), erodibility potential of the channel bed and banks, riparian conditions, local sediment transport, and geomorphic thresholds (Bledsoe and Watson 2001).

Some studies show relations among stream habitat characteristics and urban development, whereas other studies do not (Booth and Jackson 1997, Paul and Meyer 2001, Wang et al. 2001, Rogers et al. 2002, Coles et al. 2004, Fitzpatrick et al. 2004, Short et al 2005, Fitzpatrick et al 2005, Sprague et al. 2006). Habitat indexes are not always a good indicator of geomorphic responses to urbanization possibly because the component metrics are not unique in describing geomorphic processes and (or) metrics are not sensitive enough to quantify urban-related geomorphic change (Fitzpatrick et al. 2004). Some studies looked at individual metrics forming a habitat index, including measures of riffle/pool quality, bank stability, embeddedness, amount of fine substrate, and amount of large woody debris (Finkenbine et al. 2000, Paul and Meyer 2001, Center for Watershed Protection 2003). In the Pacific Northwest, increased bank erosion and lack of large woody debris corresponded to increases in urbanization (Booth 1991, Finkenbine et al. 2000). The amount of fine substrate also decreased from altered hydrology in Pacific Northwest streams (Finkenbine et al. 2000). The spatial connectivity of urban land, location of road crossings, and amount of forested riparian buffer may also affect physical conditions (McBride and Booth 2005). Urban streams with relatively steep slopes and rocky substrates were more likely to have good habitat quality and biotic integrity than streams with relatively flat slopes and fine-grained substrates (Wang et al. 1997, Fitzpatrick et al. 2005).

Few studies have been able to integrate watershed scales of environmental setting and urban characteristics with geomorphic and habitat characteristics to distinguish cause and effect from simple correlations (Roesner and Bledsoe 2003). Previous national evaluations of relations among watershed-scale landscape and land-cover characteristics and stream habitat were limited by inadequate data on national- and local-scale geologic setting, historical river-engineering practices and water regulation, and unusual drought conditions during sampling (Short et al. 2005, Goldstein et al. 2006, Sprague et al. 2006).

The purpose of this study was to examine spatial patterns in expected geomorphic responses and changes in habitat associated with urbanization within the context of multiple scales of urban indicators and landscape features. Habitat and geomorphic data were examined in 30 streams from the metropolitan areas of Milwaukee and Green Bay, Wis. (Figure 1) by the U.S. Geological Survey (USGS) National Water-Quality Assessment Program (NAWQA) in 2004 as part of a larger national study of the effects of urbanization on stream ecosystems (Couch and Hamilton 2002).

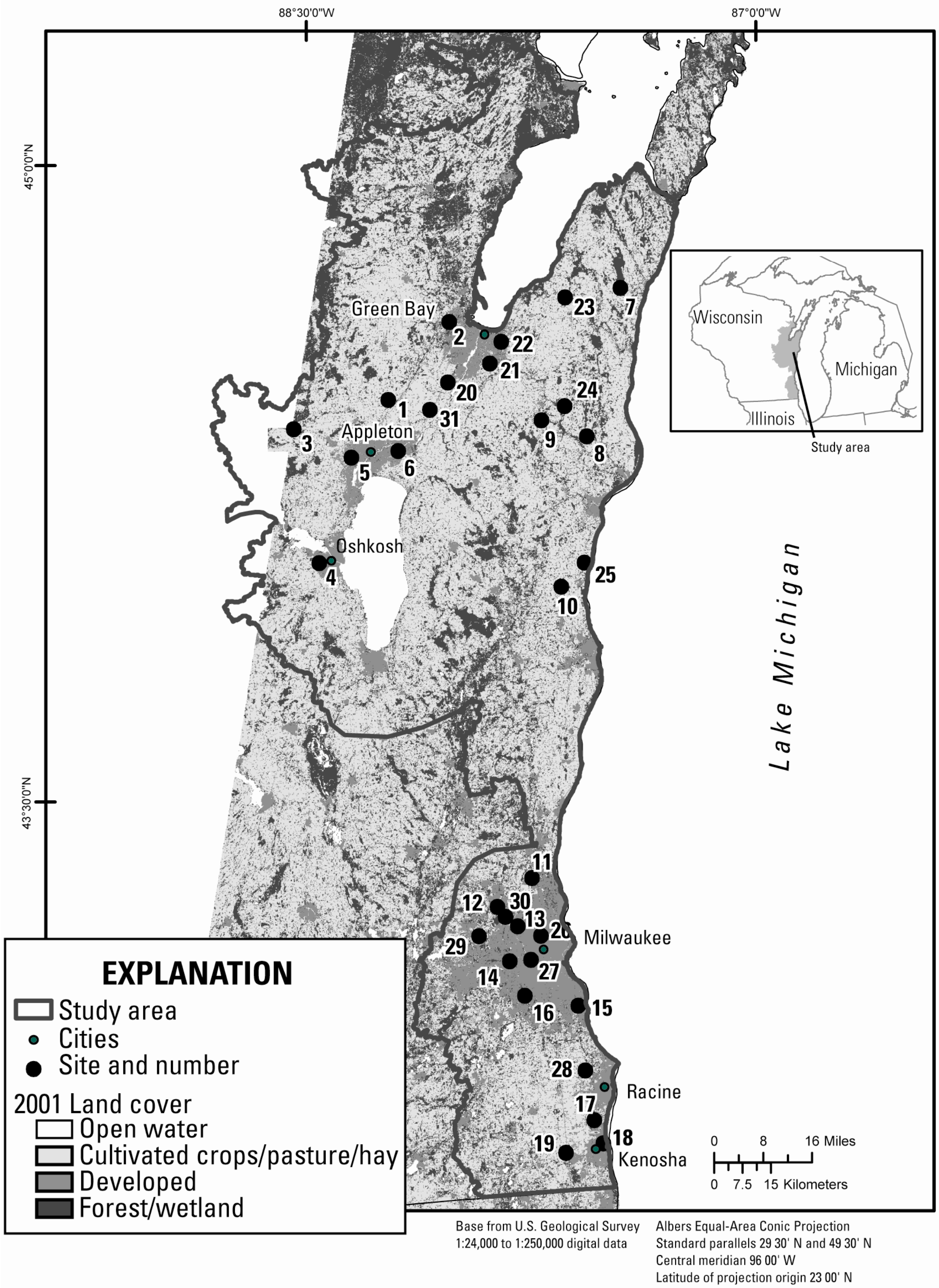

Figure 1. Location of study area, land-cover characteristics, and stream sites sampled in the Milwaukee/Green Bay, Wis., area.

Study Area

Sampled streams were western tributaries to Lake Michigan, near Milwaukee and Green Bay, Wisconsin, metropolitan areas (Figure 1) (Table 1). Streams were primarily in the Southeastern Wisconsin Till Plains ecoregion (Omernik 1987) and had a physiographic setting of the Interior Plains Division, Central Lowland Province, Eastern Lakes Section (Martin 1965). Bedrock geology mainly was Silurian dolomite in the Milwaukee area and Ordovician dolomite and shale in the Green Bay area (Mudrey et al. 1982). The bedrock was buried by unconsolidated Quaternary glacial deposits ranging in thickness from 0 to over 120 m (Soller 1998). Glacial landforms include outwash, lake, and till plains (Richmond and Fullerton 1983, 1984).

The climate of the study area is temperate continental with a mean annual air temperature of 7.5^{o}C and mean annual precipitation of 85 cm (Daymet 2005). High streamflow usually occurs in March through May and is caused by snowmelt or a mix of rainfall and snowmelt.

Land cover in the study area (2001) consisted of mainly agriculture and urban land with some forest and wetland, mainly occurring in county forest preserves (U.S. Geological Survey 2006a) (Figure 1, Table 1). Percent watershed urban land ranged from 3 to 99%, and percent agriculture (row crops and hay) ranged from 0 to 87%. Forest and wetland within a 100-m riparian zone along the entire stream network ranged from 0 to 49%.

Methods

This study was part of a larger study by the NAWQA program of urbanization effects on stream ecosystems. From 2003–2004, the USGS collected biological, chemical, hydrological, and physical data for 30 wadeable streams in the Green Bay/Milwaukee area. The NAWQA program conducted similar studies in five major urban areas of the U.S. during the same time period (Couch and Hamilton 2002). Differences among sites in natural environmental settings were minimized by selecting streams with small watersheds (11–119 km^2) and clayey surficial deposits (glacial or glaciolacustrine) based on Quaternary deposit maps (Richmond and Fullerton 1983, 1984). A previous study in the Chicago area found that streams with clayey surficial deposits potentially were more responsive to urbanization than streams with more loamy surficial deposits (Fitzpatrick et al. 2005).

Description of Urbanization Indicators and Landscape Characteristics. Urban indicators and landscape-scale characteristics mainly were derived from overlays of thematic maps with watershed boundaries using a geographic information system (J. Falcone, J. Stewart, S. Sobieszczyk, J. Dupree, G. McMahon, G., and G. Buell, USGS, written commun.—report in progress, 2006) (Table 1). Urban indicators discussed in this paper include percent urban land and impervious area for watersheds, and stream-network buffers (approximately 100 m on each side of the stream).

Table 1. Map reference number, site name, drainage area, watershed land cover, and impervious area for 30 streams in the Milwaukee/Green Bay, Wis., area. Land-cover and impervious area data are from 2001 (U.S. Geological Survey 2005, 2006). Historical channel modification: C, channelization; B, bank stabilization; G, grade control, -- none.

Map reference number (see Figure 1)	Site name	Drainage area (km^2)	Watershed urban land (%)	Watershed impervious area (%)	Watershed agricultural land (%)	Forest/ wetland in 100-m stream-network buffer (%)	Reach slope (%)	Historical channel modification
1	Lancaster Br at Shawano Ave at Howard, WI (LANC)	26	11.7	2.9	58.8	43.9	0.34	--
2	Black Otter Cr nr Hortonville, WI (BLOT)	41	5.4	1.9	77.8	24.7	0.25	C, B
3	Sawyer Cr at Westhaven Rd at Oshkosh, WI (SAWY)	31	13.8	4.8	79.9	3.8	0.26	--
4	Mud Cr at Spencer Rd at Appleton, WI (MUDC)	33	58.8	30.3	34.2	7.1	0.18	--
5	Garners Cr at Park St at Kaukauna, WI (GARN)	21	68.9	25.9	25.4	10.8	0.3	B, G
6	Apple Cr at Sniderville, WI (APPL)	119	17.6	7.6	74.5	10.8	0.48	--
7	Ashwaubenon Cr at S Bridge Rd nr De Pere, WI (ASHW)	52	5.7	2.4	87.3	14.2	0.042	C
8	Bower Cr Trib at Lime Kiln Rd nr Bellevue, WI (BOWR)	34	24.4	8.0	66.6	18.8	0.49	C, B, G
9	Baird Cr at Superior Rd at Green Bay, WI (BAIR)	52	5.5	1.6	84.4	23.2	0.6	C, B?, G?
10	Rio Cr at Pheasant Rd nr Rio Creek, WI (RIOC)	56	3.5	0.9	77.6	30.0	0.19	B
11	Kewaunee R Trib @ Lowell Rd nr Luxemburg, WI (KEWA)	37	4.4	1.1	86.3	15.5	0.39	--
12	Jambo Cr at Jambo Creek Rd nr Mishicot, WI (JAMB)	49	3.7	0.9	67.9	37.7	0.34	--
13	Black Cr at Curran Rd nr Denmark, WI (BLAK)	56	3.2	0.9	72.7	25.1	0.31	--
14	Devils R at Rosencrans Rd nr Maribel, WI (DEVL)	76	4.0	1.0	79.3	24.6	0.63	C
15	Point Cr at Ucker Point Rd nr Newton, WI (POIN)	46	5.0	1.4	81.7	16.9	0.55	--
16	Meeme R at Washington Rd nr Cleveland, WI (MEME)	50	5.0	1.4	75.2	19.4	0.07	--
17	Pigeon Cr at Williamsburg Dr at Theinsville, WI (PIGN)	30	14.9	3.5	54.8	42.8	0.52	C, B
18	Lincoln Cr at 47th St at Milwaukee, WI (LINC)	26	97.6	44.6	0.0	2.0	0.22	C, B, G
19	Menomonee R at Menomonee Falls, WI MENO)	88	30.4	10.5	44.4	38.2	0.51	C, B, G
20	Lily Cr at Good Hope Rd nr Menomonee Falls, WI (LILY)	11	78.0	24.9	14.8	13.4	0.79	C, B, G
21	Little Menomonee R at Milwaukee, WI (LTME)	52	44.3	18.8	38.2	34.7	0.02	C
22	Underwood Cr at Elm Grove, WI (UNDW)	25	86.0	20.0	0.8	19.3	0.21	C, B
23	Honey Cr nr Portland Ave at Wauwatosa, WI (HONY)	28	99.1	47.6	0.0	0.0	1.08	C, B, G
24	Oak Cr at South Milwaukee, WI (OAKC)	67	62.9	27.4	21.0	21.7	0.17	C, G
25	Root R at Layton Ave at Greenfield, WI (ROOT)	31	92.8	32.4	0.3	15.6	0.21	C
26	Hoods Cr at Brook Rd nr Franksville, WI (HOOD)	39	16.3	6.0	75.2	15.8	0.36	--
27	Pike R at Cty Hwy A nr Kenosha, WI (PIKR)	100	27.3	11.5	64.0	17.1	0.18	--
28	Pike Cr at 43rd St at Kenosha, WI (PIKC)	16	87.2	41.9	10.8	1.7	0.09	--
29	Kilbourn Ditch at 60th St nr Kenosha, WI (KILB)	54	7.4	3.9	81.8	11.8	0.1	B
30	Fox R at River Rd nr Sussex, WI (FOXR)	61	20.2	5.5	41.5	49.2	0.31	B

Land-cover statistics were based on the National Land-cover Data 2001 (NLCD01) dataset classification scheme and protocols (U.S. Geological Survey 2005, 2006). The NLCD01 is a 16-class, 30-meter resolution dataset based primarily on LANDSAT-7 Enhanced Thematic Mapper data from the period 1999 through 2002. The NLCD01 data set contains four categories that encompass urban land—open space, and low-, medium-, and high-density development. These categories are based on percent imperviousness with open space having less than 20% imperviousness, low density having 20 to less than 50%, medium density having 50 to less than 80%, and high density having 80% or greater imperviousness. Urban open space includes grassy areas (not forested or wetland) associated with golf courses, lawns, airports, parks, and roads (J. Falcone, USGS, written commun., 2006). The NLCD01 data set also contained 30-m pixel estimates for percent total (connected and unconnected) impervious area.

Landscape characteristics included descriptions of watershed-scale glacial geology, topography, and segment-scale slope and sinuosity. The definition of a segment used for this study was GIS-derived and represented a length of stream upstream of the sampled reach, the length determined to be equal to the $\log_{10}$ of the watershed area. Texture and characteristics of surficial deposits were derived from two data sets—Quaternary deposit maps (Richmond and Fullerton 1983, 1984) and soils maps from the U.S. Department of Agriculture State Soil Geographic (STATSGO) Data Base (U.S. Department of Agriculture 1994; Shirazi et al. 2001a, 2001b, 2001c). Watershed and segment slopes were calculated from USGS 30-meter National Elevation Data (U.S. Geological Survey 2005).

Description of Hydrologic Characteristics. Hydrologic data came from four sources (E. Giddings, USGS, written commun., 2006; J. Steuer, USGS, written commun., 2006; McMahon et al. 2003). Four hydrologic metrics were based on hourly changes in channel cross-sectional area from stage-recorder data (Table 2). Stage recorders were installed at 22 of the 30 streams in October 2003 and operated through September 2004. Eight of the 30 streams already were active USGS streamflow-gaging stations. Data were divided into pre-ice and post-ice periods because the streams were frozen from December through February. The pre-ice period (October through November 2003) included a few small rainfall events, whereas the post-ice period (March 2004 through September 2004) included multiple snowmelt and rainfall events. Streams were dropped from further analysis if more than 25% of the record was missing. This limited the number of streams to 24 for pre-ice and 25 for post-ice periods. Hydrologic metrics were calculated for each time period based on hourly changes in hydrologic variability and rate, magnitude, frequency, and duration. In addition, a flashiness metric was calculated, based on daily changes in cross-sectional area and similar to the Richards-Baker Flashiness Index (Baker et al. 2004). A low flashiness value typically indicates small shifts in area (less flashy) and a high value indicates large shifts in area (more flashy). (E. Giddings, USGS, written commun., 2006; J. Steuer, USGS, written commun., 2006).

Secondly, bankfull flow was estimated for all 30 streams by use of HEC-RAS flow routing modeling of data from channel cross section and slope surveys and habitat measurements (J. Steuer, USGS, written commun., 2006) (Table 2). Bankfull flow was normalized by drainage area.

Table 2. Selected urban indicators, landscape, and hydrologic characteristics used to determine urbanization effects on the geomorphic and habitat characteristics of 30 streams in the Milwaukee/Green Bay, Wis., area.

Characteristic	Abbreviation	Median	Mean	Minimum	Maximum
Urban indicators and land cover					
Watershed impervious area (%)	IMPERV	6	13	1	48
Watershed urban land (%)	URBAN	17	34	3	99
Watershed open urban land (%)	OPENURB	7	11	1	50
Watershed agriculture (%)	AGRIC	65	55	0	87
Watershed forest (%)	FOREST	6	8	1	23
Watershed wetland (%)	WETLAND	4	5	0	15
Forest and wetland within 100-m stream-network buffer (%)	BUFFOWE	18	20	0	49
Disturbed land cover within 30-m reach buffer (% of transect endpoints)	RCHBUFDIS	61	59	0	100
Average open canopy angle within reach (°)	CANANG	31	44	5	144
Landscape characteristics					
Watershed clayey surficial deposits (based on Quaternary deposits) (%)	WATCLAY	100	91	9	100
Watershed mean low range permeability (cm/hr)	PERL	0.5	0.6	0.3	2.4
Drainage area (km^2)	DRAIN	43.5	46.8	11.2	118.8
Watershed slope (%)	WATSLOP	2.1	2.2	1.0	3.3
Segment slope (%)	SEGSLOP	0.23	0.26	0.01	1.04
Reach slope (%)	RCHSLOP	0.31	0.34	0.02	1.08
Sinuosity (ratio)	SINUOUS	1.3	1.3	1.0	2.2
Hydrologic characteristics					
Flashiness index (pre-ice record of hourly cross section area, sites = 24)	FLASH_PRE	0.1	0.1	0.04	0.2
Flashiness index (post-ice record of hourly cross section area, sites = 25)	FLASH_PST	0.1	0.2	0.06	0.5
Frequency of rising cross-sectional area events, where total rise is greater than or equal to 9 times the median total rise (number of rising events, post ice record of hourly cross section area, sites = 24)	PERIODR9_PST	19	24	7	71
Frequency of falling cross-sectional area events, where total fall is greater than or equal to 3 times the median total fall (number of falling events, pre-ice record of hourly cross section area, sites = 25)	PERIODF3_PRE	6	8	1	25
Bankfull flow/drainage area, from HEC-RAS models ($m^3/s/km^2$)	BFFLOWDA	0.03	0.04	0.01	0.13
Instantaneous maximum discharge/drainage area, from daily streamflow data ($m^3/s/km^2$)	FLOWMAXDA	0.24	0.30	0.08	0.97
Median discharge/drainage area, from daily streamflow data ($m^3/s/km^2$)	FLOW50DA	0.01	0.01	0.01	0.04
Discharge with a 90% exceedance probability, from daily streamflow data (m^3/s)	FLOW90	0.02	0.03	0.00	0.23
Discharge at the time of habitat sampling	FLOWXS	0.04	0.10	0.00	1.12
Reach geomorphic/habitat characteristics					
Average bankfull channel area/drainage area (m^2/km^2)	BFAREADA	0.11	0.14	0.06	0.34
Average bankfull channel depth/drainage area (m/km^2)	BFDEPDA	0.02	0.02	0.01	0.05
Average bankfull channel width/drainage area (m/km^2)	BFWIDDA	0.16	0.19	0.09	0.48
Average length of bank erosion along transect endpoints (m)	BKEROSLEN	1.5	1.5	0.1	3.6
Average wetted width/depth ratio	WETWDRAT	30	32	13	65
Average wetted volume (m^3)	WETVOL	213	242	63	646
Average wetted volume/ drainage area (m^3/km^2)	WETVOLDA	4.1	5.9	1.2	22.9
Average wetted depth (m)	WETDEP	0.24	0.25	0.11	0.56
Riffle (%)	RIFFLE	21	22	2	40
Pool (%)	POOL	9	12	0	39
Fine substrate (%)	FINE	18	24	0	64
Silt coverage (%)	SILT	84	74	0	100
Bank vegetative cover (%)	BKVEG	32	39	9	89
Presence/absence of bank erosion (% of transect endpoints)	BKEROSPCT	96	91	59	100

Thirdly, annual summary statistics were calculated based on daily discharge data for all 30 streams. Stage/discharge relations and estimation of missing values were done with traditional USGS procedures (J. Steuer, USGS, written commun., 2006; U.S. Geological Survey 2006b). Three annual metrics were included in this paper.

Lastly, discharge was measured in August 2004 at the time of the ecological and reach-scale habitat assessments.

Collection of Reach-Scale Habitat and Geomorphic Characteristics. Field-based reach-scale habitat assessments were conducted in August–September 2004 during low flow by use of NAWQA protocols (Fitzpatrick et al. 1998). Bank vegetation was at its maximum extent toward the end of the growing season. A few of the streams had slightly elevated stages from isolated thunderstorms.

Data included qualitative and quantitative observations of channel, substrate, bank, and riparian conditions at 11 transects distributed equally along the reach; data were also collected at five points (two bank and three in-stream) along each transect (Table 2).

Channel measurements included the identification of channel geomorphic units (riffles, runs, and pools), water-surface slope, bankfull channel dimensions, and wetted channel dimensions. Morphologic indicators were used to estimate bankfull stage and included variations in bank slope and riparian vegetation, undercut banks, and substrate changes associated with point bars (Fitzpatrick et al. 1998). Bankfull data from riffle and run transects only (no pools) were used to calculate reach-averaged dimensions. Bankfull dimensions were normalized by drainage area.

Observations of dominant substrate size were summarized into percent of transect points with fine substrate (sand-sized or smaller). Percent of transect points with loose silt coverage was calculated.

Bank vegetative cover and presence/absence of erosion were determined at each transect endpoint according to the NAWQA habitat protocol (Fitzpatrick et al. 1998). In addition, the length of bare ground on the bank was measured (running perpendicular to the channel and following the transect line). This measurement represented the length of bank erosion along transect endpoints. Bare surfaces, devoid of vegetation, were interpreted as erosional. Thus, some recent depositional units, such as those that occur in point bars and longitudinal bars, were included in these observations and measurements.

Dominant riparian land cover within a 30-m buffer was recorded for each transect endpoint. The percentage of endpoints with disturbed riparian land cover was calculated for each reach. Disturbed land cover included cropland, pasture, farmsteads, residential, commercial, or transportation. Undisturbed land cover was considered to be grassland, shrubs and woodland, or wetland.

Open riparian canopy angle was calculated for each transect by combining angles measured from the center of the channel to the tallest object on each bank. Small angles (close to 0 degrees) represented shaded channels with tree-lined banks whereas large angles (close to 180 degrees) represented open channels with grassy banks.

Data Analysis. Relations among urban indicators, landscape and hydrologic characteristics, and habitat and geomorphic characteristics were examined using scatterplots and Spearman rank correlation analysis (Iman and Conover 1983).

Multi-scale land-cover, landscape, and hydrologic characteristics were considered independent variables (including reach slope). Reach-scale habitat and geomorphic characteristics were considered dependent variables. Spearman correlation coefficients (ρ) with *P*-values of $\leq$0.01 were considered statistically significant for individual correlations. Bonferroni-adjusted coefficients for multiple tests also were taken into account.

Results

Urbanization, Land Cover, Landscape, and Channel Modifications. Watershed urban land ranged from 3 to 99% and watershed imperviousness (total) ranged from 1 to 48% (Table 2). In general, 10–15% watershed imperviousness equated with 25–38% watershed urban land (Figure 2). The large difference in imperviousness among streams with greater than 30% urban land was caused by differences in the amount of urban open space, which can be highlyvariable (Figure 2). A good example of the range in variability is the comparison of Underwood Creek (UNDW) with 20% imperviousness and 50% urban open space, to Pike Creek (PIKC) with 42% imperviousness and 16% urban open space. Thus, it is important to take into account the types of urban land that go into total urban area calculations within a watershed.

Watersheds for most of the sampled streams (27) had greater than 80% clayey surficial deposits based on Quaternary deposits (WATCLAY) (Richmond and Fullerton 1983, 1984) (Figure 3A, Table 2). However, the Quaternary-deposits-based clay percentages were substantially higher than clay percentages in soils from the STATSGO database (percent of material less than 2 mm) (U.S. Department of Agriculture 1994) (Figure 3A). STATSGO watershed mean minimum permeability rates ranged from 0.29–2.42 cm/hr and also did not relate to Quaternary-deposits-based clay percentages (Figure 3B). Based on previous habitat/geomorphic studies of Wisconsin tributaries to Lakes Michigan and Superior by the authors, it was found that STATSGO under-represented the clay content of glacially modified clayey lacustrine deposits that rim the two Great Lakes. Even though the published scale of the STATSGO data is larger than the Quaternary deposits maps (1:250,000 compared to 1:1,000,000), it is possible that some detail was lost in the national generation or averaging of STATSGO data, especially for characteristics that may represent end members of a range.

The topographic setting of the streams was generally gentle with watershed slopes of 1.0–3.3%, and segment and reach slopes of 0.01–1.08% (Table 2). This is reflective of the glacial landscape, with streams draining end moraines having more slope than those draining glacial lake plains, ground moraine, or outwash fans. The streams were straight to sinuous (segment sinuosity from 1 to 2.2) (Table 2), reflective of natural meandering and channelization. Valley development at reaches included none, confined, entrenched, or oversized (relict from glacial meltwater). Most reach slopes are related to local geologic setting and history instead of alluvial features

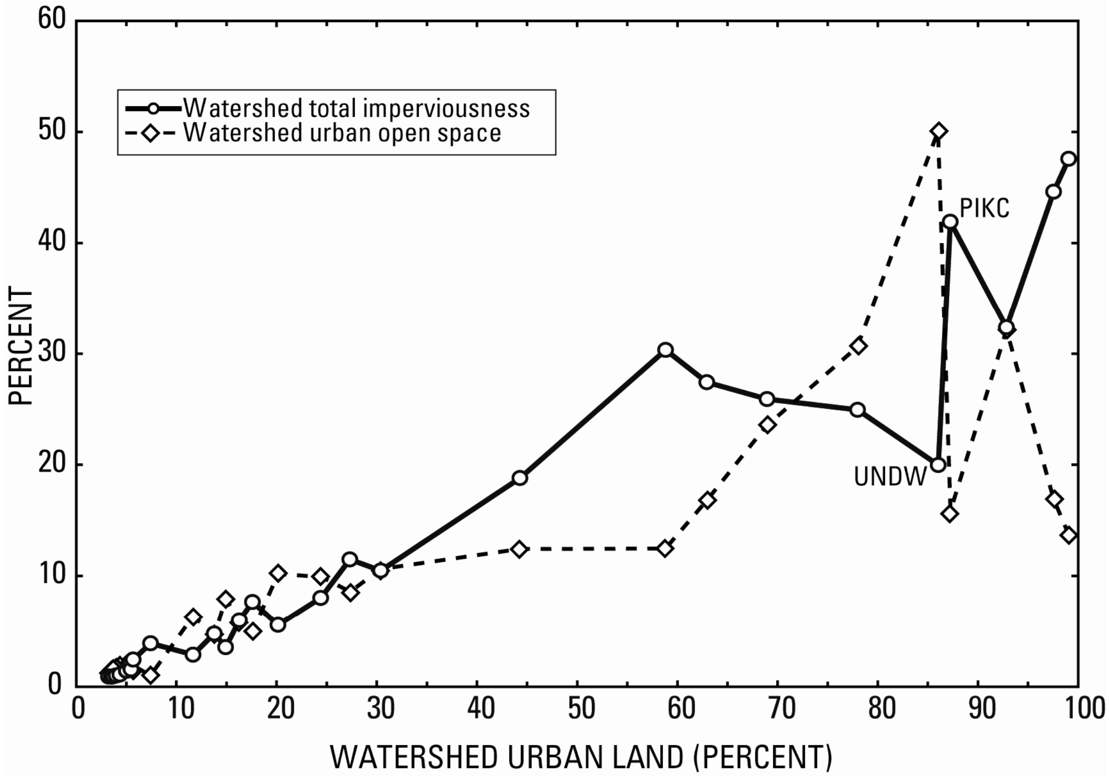

Figure 2. Comparison of watershed urban land, imperviousness, and urban open space for 30 streams in the Milwaukee/Green Bay Wis., area. See table 1 for stream abbreviation explanation.

because of the young age of stream network development (less than about 14,000 years). Even with the small variation in watershed, segment, and reach slope, topographic setting can still affect land-cover development, as shown in the plot of amount of forest/wetland in the 100-m stream-network buffer and watershed slope (Figure 4). In the Midwest, flat areas with fine-grained soils are preferentially developed into agriculture or urban, with steeper-sloped areas left in more natural vegetation (Fitzpatrick et al. 2001, 2005). This makes it difficult to separate land-cover effects from geologic setting, even in geologic settings with subtle topographic differences.

Many of the streams (18) had historical channel modifications (Table 1, Figure 5). Original clearing of forest or prairie vegetation for agriculture likely occurred more than 150 years ago. Only 12 out of the 30 streams were not modified, and only 2 of the 12 were urban (greater than 40% watershed urban land). Two rural, urbanizing, and urban streams were lightly affected and had some limited bank stabilization in parts of the reach, whereas stabilized streams (mainly urban) had bank stabilization and (or) grade control that affected most of the banks or the substrate. The age of the channel modifications ranged from several decades to less than 1 year.

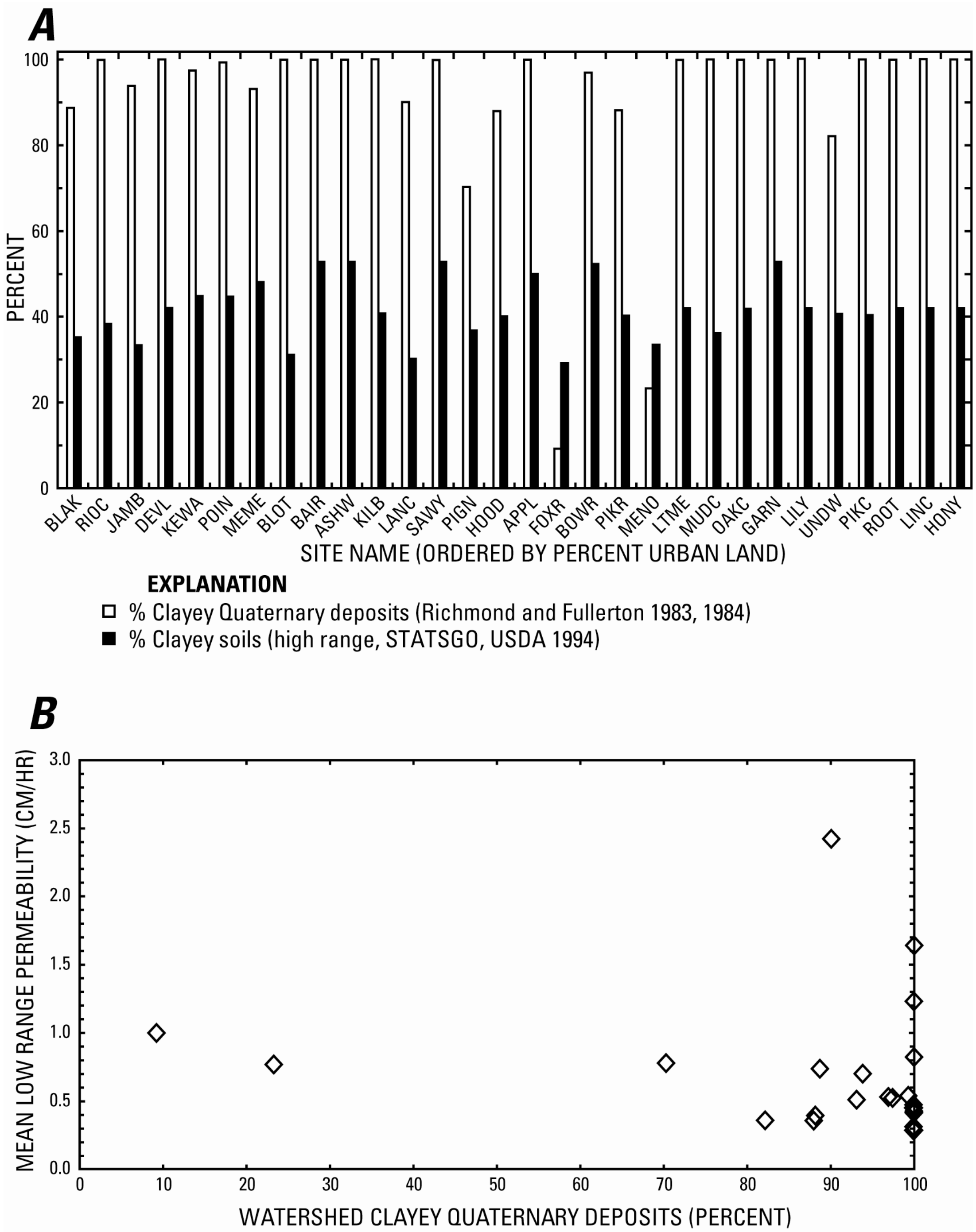

Figure 3. Comparison of characteristics of texture of surficial deposits derived from Quaternary deposits (Richmond and Fullerton 1983, 1984) and State Soil Geographic Data Base (STATSGO) (U.S. Department of Agriculture 1994). **A**, Site by site comparison of percent clay, **B**, comparison of clayey Quaternary deposits and soil permeability. See table 1 for stream abbreviation explanation.

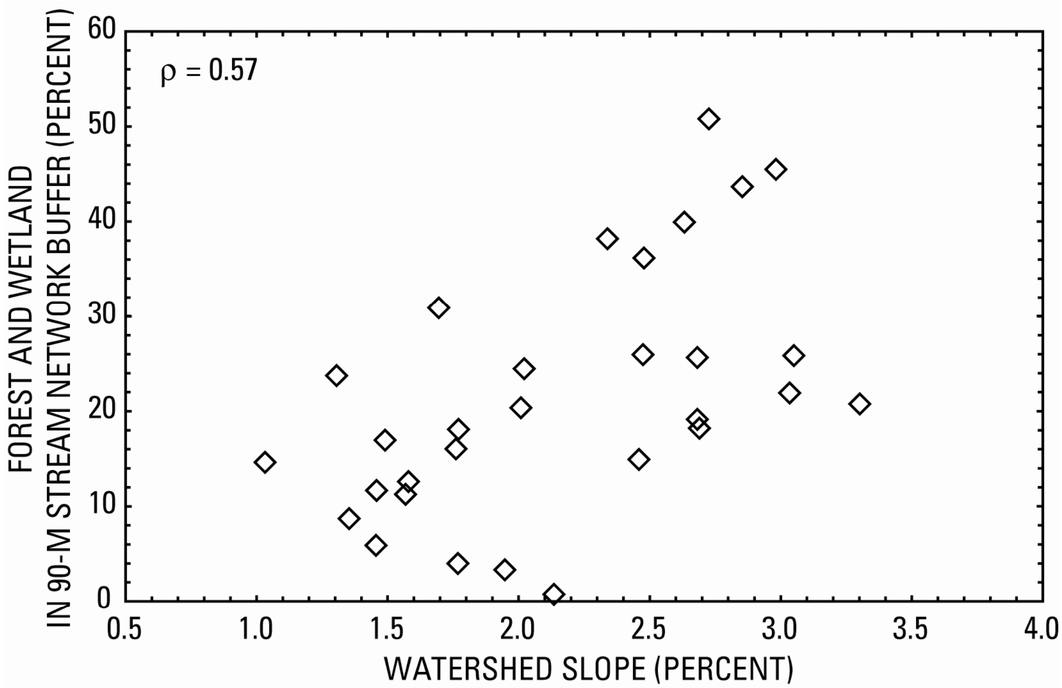

Figure 4. Comparsion of watershed slope and percent forest and wetland in the 100-m stream-network buffer for 30 streams in the Milwaukee/Green Bay, Wis., area. (ρ, Spearman correlation coefficient)

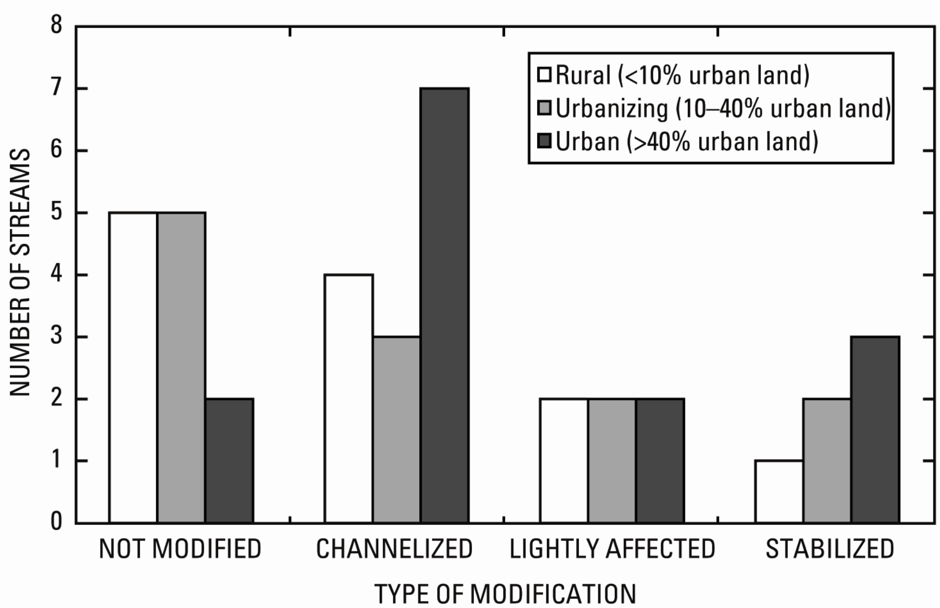

Figure 5. Comparison of channel modification for 30 rural, urbanizing, and urban streams in the Milwaukee/Green Bay, Wis., area.

Reach Habitat and Geomorphology. Reach habitat and geomorphology for the sampled streams was typical for Upper Midwest streams flowing on glacial parent material (Table 2). Most of the reaches were shallow (average wetted depths of 0.11 to 0.56 m) and had run habitat. Riffles ranged from 2 to 40% of the reach length and 10 streams had no pools. Bed substrates ranged from sand to large cobble and typically were covered with silt (mean of 74% per reach). Banks had mainly fine-grained deposits with low percentages of bank vegetative cover (mean of 39% per reach). Most banks had evidence of some bank erosion (mean of 91% per reach) and average bank erosion length was 1.5 m.

Relations Among Habitat/Geomorphology and Hydrology, Urbanization, and Landscape Characteristics. Results from Spearman correlations of habitat with urban characteristics indicated that only unit-area bankfull channel dimensions and length of bank erosion were related to imperviousness and watershed urban land (Table 3) (Figure 6). The negative correlation of unit-area bankfull channel area with agricultural land ($\rho = -0.71$) is an artifact of the sampling design because agricultural land represents the lower end of the urban gradient. These relations were similar for bankfull characteristics that included or excluded pools; however, correlation coefficients were higher for calculations that excluded pools. Bankfull channel area also correlated with wetted channel volume ($\rho = 0.74$); however, wetted channel volume did not correlate with urban indicators and thus is not an appropriate surrogate for bankfull channel area (Table 3).

Bankfull width and depth both correlated with bankfull area, indicating that channel enlargement occurred through both widening and incision. However, Spearman correlation coefficients were stronger for width and area ($\rho = 0.84$) than depth and area ($\rho = 0.68$). This may indicate that the streams were more prone to widening than incision, or that the streams were following basic hydraulic geometry relations in which width increases faster than depth with increasing discharge or drainage area (Leopold and Maddock 1953).

Increases in bankfull channel dimensions have been documented in other urbanization studies across the U.S. (Konrad et al. 2005, Fitzpatrick et al. 2005, Gregory et al. 1992, Hammer 1972, Paul and Meyer 2001, Center for Watershed Protection 2003). In general, as urbanization increases in previously agricultural areas, bankfull channel area increases, reflecting increases in flood frequency and duration related to increased imperviousness. The hydrologic characteristics that most closely related to imperviousness were post-ice frequency of rising events (PERIODR9_PST), frequency of pre-ice falling events (PERIODF3_PRE), and unit-area (drainage-area normalized) annual median flow (FLOW50DA) (Table 3). These characteristics, however, were not statistically related to the bankfull channel dimensions, indicating that the relations among hydrologic and geomorphic characteristics cannot be reduced to one or two specific hydrologic metrics. Low-flow characteristics (FLOW90, FLOWXS) did not correlate with imperviousness.

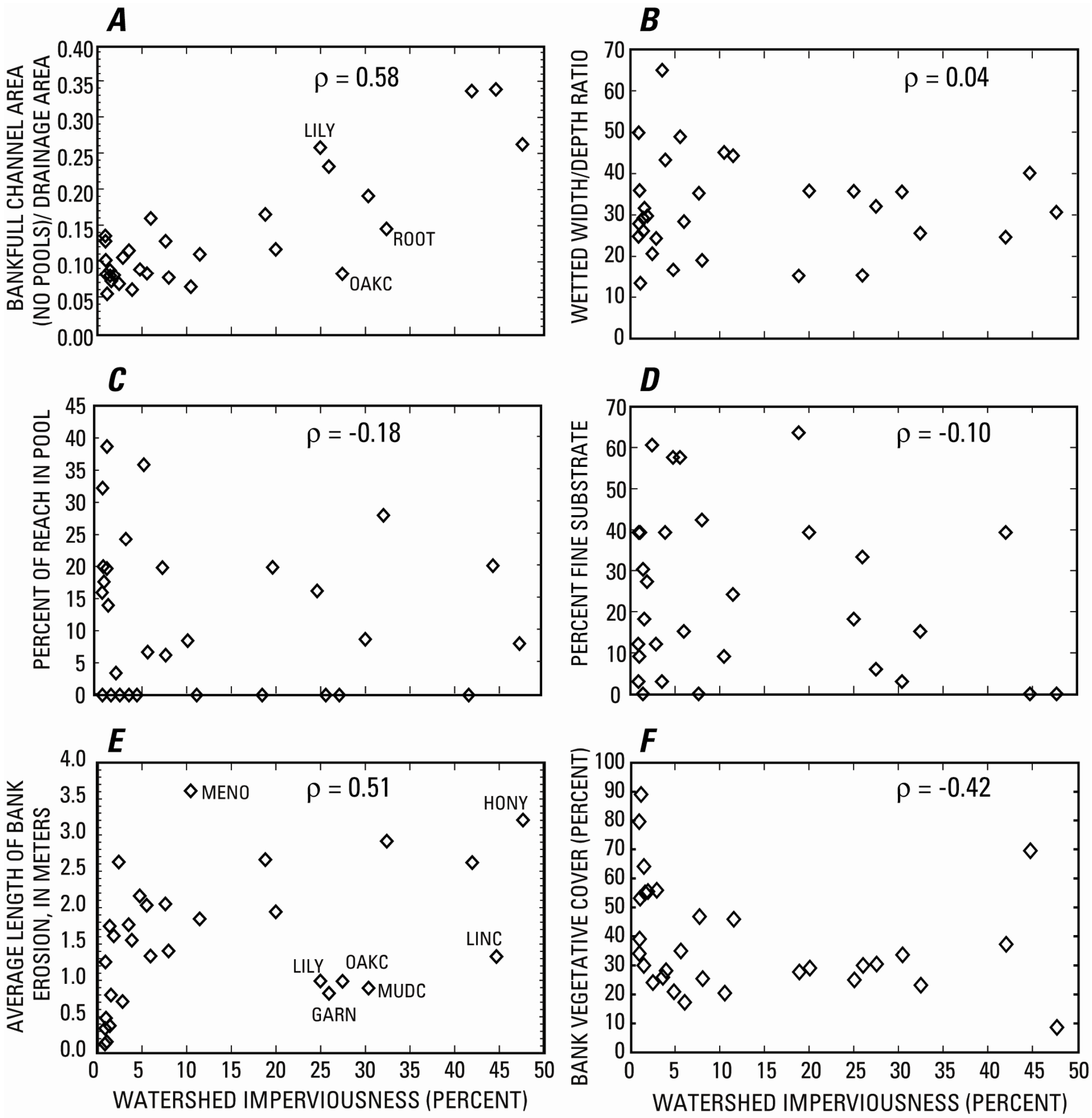

Figure 6. Scatterplots of watershed imperviousness and, **A**, unit-area bankfull channel area without pools, **B**, wetted width-to-depth ratio, **C**, percent of reach in pool, **D**, percent fine substrate, **E**, average length of bank erosion and, **F**, average bank vegetative cover, for 30 streams in the Milwaukee/Green Bay, Wis., area. (ρ, Spearman correlation coefficient)

Table 3. Spearman rank correlations among selected multiscale geomorphic, habitat, and hydrologic characteristics and watershed characteristics for 30 streams in the Milwaukee/Green Bay, Wis., area. See table 2 for abbreviation definitions. Bolded correlation coefficients have $P \leq 0.01$ unadjusted for multiple comparisons; bolded and asterisked correlation coefficients have $P \leq 0.01$ based on Bonferroni adjustments. [n = 30 for urban, landscape, habitat, and geomorphic characteristics; n = 24 for pre-ice (_PRE) hydrologic characteristics; n = 25 for post-ice (_PST) hydrologic characteristics]

	Urban indicators and land cover							Landscape characteristics							Hydrologic characteristics									Reach geomorphic/habitat characteristics										
	IMPERV	URBAN	OPENURB	AGRIC	BUFFOWE	RCHBUFDIS	CANANG	WATCLAY	PERL	DRAIN	WATTSLOP	SEGSLOP	RCHSLOP	SEGSINU	FLASH_PRE	FLASH_PST	PERIODR9_PST	PERIODF3_PRE	BFFLOWDA	FLOWMAXDA	FLOW50DA	FLOW90	FLOWXS	BFAREADA	BFDEPDA	BFWIDDA	BKEROSLEN	WETWDRAT	WETVOL	WETVOLDA	RIFFLE	POOL	FINE	BKVEG
IMPERV	**1.00**																																	
URBAN	**0.99***	**1.00**																																
OPENURB	**0.89***	**0.93***	**1.00**																															
AGRIC	**-0.82***	**-0.85***	**-0.88***	**1.00**																														
BUFFOWE	**-0.54**	**-0.47**	-0.26	0.16	**1.00**																													
RCHBUFDIS	**0.52**	**0.50**	0.41	-0.38	-0.18	**1.00**																												
CANANG	-0.22	-0.24	-0.20	0.15	0.07	-0.10	**1.00**																											
WATCLAY	0.30	0.23	0.07	-0.06	**-0.64**	0.11	0.02	**1.00**																										
PERL	**-0.57**	**-0.58**	-0.43	0.37	**0.53**	-0.19	0.12	-0.36	**1.00**																									
DRAIN	-0.43	**-0.47**	**-0.52**	**0.46**	0.40	-0.03	0.05	-0.20	0.18	**1.00**																								
WATTSLOP	-0.13	-0.04	0.14	-0.28	**0.57**	0.07	-0.02	-0.43	0.28	-0.10	**1.00**																							
SEGSLOP	-0.09	-0.12	-0.11	0.19	-0.03	-0.02	0.18	0.06	0.26	-0.03	-0.24	**1.00**																						
RCHSLOP	-0.16	-0.11	-0.01	0.07	0.10	0.16	-0.08	-0.07	0.22	-0.08	0.09	**0.52**	**1.00**																					
SEGSINU	**-0.54**	**-0.54**	**-0.52**	**0.46**	0.21	-0.34	-0.08	-0.13	0.43	0.32	-0.05	0.05	0.19	**1.00**																				
FLASH_PRE	0.56	0.51	0.42	-0.29	-0.41	0.35	-0.38	0.44	-0.27	-0.11	-0.21	-0.20	-0.26	-0.07	**1.00**																			
FLASH_PST	0.39	0.39	0.31	-0.33	-0.30	0.43	-0.22	0.16	-0.30	-0.28	0.03	**-0.53**	-0.21	-0.19	**0.75***	**1.00**																		
PERIODR9_PST	**0.90***	**0.88***	**0.76***	**-0.74**	-0.42	0.39	-0.20	0.23	**-0.57**	-0.19	-0.17	-0.30	**-0.57**	-0.48	0.49	0.37	**1.00**																	
PERIODF3_PRE	**0.71**	**0.65**	0.49	-0.44	-0.50	0.30	-0.43	0.18	-0.44	0.02	-0.25	0.15	-0.34	-0.14	**0.53**	0.22	**0.89***	**1.00**																
BFFLOWDA	0.42	0.40	0.42	**-0.48**	-0.32	0.29	-0.15	0.33	-0.19	-0.43	-0.03	0.07	0.12	-0.22	0.19	0.31	0.23	0.30	**1.00**															
FLOWMAXDA	0.20	0.20	0.10	-0.17	-0.01	0.29	0.08	-0.20	-0.16	-0.07	-0.02	-0.14	-0.04	-0.25	0.09	0.43	0.31	-0.12	0.02	**1.00**														
FLOW50DA	**0.46**	0.44	**0.49**	**-0.53**	0.07	0.38	-0.13	-0.09	0.08	-0.20	0.27	0.11	-0.06	-0.14	0.23	0.03	0.37	0.36	**0.47**	0.23	**1.00**													
FLOW90	0.06	0.03	0.07	-0.22	0.29	0.12	0.00	-0.07	0.27	0.46	0.27	0.07	-0.09	0.16	0.14	-0.14	0.21	0.33	0.13	-0.15	**0.53**	**1.00**												
FLOWXS	0.19	0.14	0.12	-0.23	0.14	0.12	-0.08	-0.01	-0.08	0.40	0.16	0.08	-0.19	-0.12	0.13	-0.27	0.30	**0.51**	0.11	-0.17	0.42	**0.77***	**1.00**											
BFAREADA	**0.58**	**0.58**	**0.58**	**-0.71***	-0.38	0.19	-0.19	0.25	-0.41	**-0.51**	-0.05	-0.23	-0.05	-0.32	0.20	0.23	0.49	0.33	**0.65**	0.16	0.43	0.03	0.18	**1.00**										
BFDEPDA	**0.52**	**0.53**	**0.57**	**-0.53**	**-0.48**	-0.01	-0.01	0.31	-0.32	**-0.94***	-0.05	0.03	-0.03	-0.37	0.13	0.16	0.33	0.06	**0.49**	0.01	0.22	-0.41	-0.23	**0.68**	**1.00**									
BFWIDDA	**0.50**	**0.53**	**0.58**	**-0.73***	-0.22	0.21	-0.09	0.15	-0.18	**-0.72***	0.23	-0.16	0.05	-0.40	0.06	0.25	0.35	0.11	**0.56**	0.21	0.44	-0.04	-0.04	**0.84***	**0.74***	**1.00**								
BKEROSLEN	**0.51**	**0.54**	0.37	-0.31	-0.20	0.36	**-0.54**	-0.06	-0.33	-0.03	0.05	-0.28	-0.09	-0.25	0.38	0.41	**0.62**	**0.52**	-0.11	0.32	0.16	0.05	0.18	0.12	-0.01	0.06	**1.00**							
WETWDRAT	0.04	0.06	0.04	-0.19	0.22	**0.54**	-0.07	-0.11	0.11	0.34	0.25	-0.01	0.23	-0.17	-0.05	0.17	0.08	0.16	0.19	0.16	0.17	0.43	0.24	0.00	-0.44	0.11	0.05	**1.00**						
WETVOL	0.09	0.06	0.10	-0.28	0.19	-0.19	0.09	-0.06	-0.02	0.37	-0.01	0.06	-0.16	0.05	0.00	-0.33	0.29	0.31	0.06	-0.05	0.42	**0.75***	**0.72***	0.32	-0.18	0.10	-0.06	0.12	**1.00**					
WETVOLDA	0.38	0.38	0.44	**-0.63**	-0.10	-0.15	0.07	0.15	-0.23	-0.35	0.07	-0.07	-0.18	-0.28	0.02	-0.03	0.38	0.13	0.39	0.05	0.46	0.30	0.34	**0.74***	**0.51**	**0.70***	-0.06	-0.11	**0.67**	**1.00**				
RIFFLE	0.23	0.25	0.26	-0.29	0.05	0.44	-0.21	0.08	0.06	0.06	0.10	0.34	**0.50**	-0.14	0.05	-0.05	0.02	0.25	0.38	-0.06	0.13	0.29	0.32	0.12	-0.07	0.09	0.05	**0.57**	0.05	-0.06	**1.00**			
POOL	-0.18	-0.10	0.01	-0.06	0.16	-0.11	-0.05	-0.17	0.11	0.03	0.28	-0.04	0.31	0.13	-0.22	-0.13	-0.10	0.06	-0.19	-0.18	-0.19	0.11	0.09	-0.03	-0.11	0.08	-0.06	0.24	0.14	0.09	0.19	**1.00**		
FINE	-0.10	-0.07	-0.09	0.22	0.08	-0.24	0.20	-0.16	-0.05	-0.08	-0.08	-0.21	-0.43	-0.06	-0.12	0.08	0.07	-0.40	**-0.54**	0.11	-0.27	-0.35	-0.36	-0.32	0.03	-0.22	0.17	**-0.47**	-0.20	-0.05	**-0.61**	-0.20	**1.00**	
BKVEG	-0.42	-0.43	-0.32	0.24	0.21	-0.27	**0.53**	0.07	0.34	0.20	0.08	-0.01	-0.14	0.31	-0.18	-0.24	-0.33	-0.28	0.01	-0.35	-0.10	0.27	0.10	-0.13	-0.15	-0.22	**-0.64**	-0.02	0.26	0.03	-0.02	0.17	-0.10	**1.00**

The relation between bankfull channel area and imperviousness for Milwaukee/Green Bay streams was more variable for urban sites with greater than 20% imperviousness (Figure 6A). Two urban streams, Oak Creek (OAKC) and Root River (ROOT), had smaller channel areas than expected. These streams had more forested land (forest preserves and parks) along their 100-m stream-network buffers and less channel modifications than other urban streams and are located within the forest preserve network of Milwaukee. In contrast, Lily Creek (LILY) had slightly less imperviousness than Oak Creek, 15% forest/wetland within its 100-m stream-network buffer, but had a riprap lined, trapezoidal channel. The larger bankfull channel area for Lily Creek may be due to greater uncertainty in measuring bankfull channel dimensions (a common problem for recently stabilized or engineered channels).

The relation between bank erosion and urbanization was strongest for streams with less than 20–25% imperviousness (Figure 6E). The relation appears curvilinear and streams with greater than 5% imperviousness had more than 0.75 m of bank erosion. Some urban streams, such as Lily Creek, Garners Creek, Oak Creek, Mud Creek, and Lincoln Creek, had lower than expected bank-erosion lengths. Lily and Lincoln Creeks are engineered channels with abundant riprap associated with bank protection and grade control (Table 1). Garners, Oak, and Mud Creeks had low average bank-erosion lengths and had no evidence of bank stabilization or grade control. However, Mud Creek banks are lined with residential lawns on both sides, suggesting historical bank protection. Oak Creek was channelized and has rock riffles that may have provided historical grade control. The Menominee River and Honey Creek had high average bank-erosion lengths and failing bank stabilizations. These results indicate that is important to know the history of stabilization for the sampled reach as well as upstream and downstream areas.

Average length of bank erosion significantly correlated with imperviousness, whereas percent bank vegetative cover did not, indicating that length measurements more accurately represented bank erosion than measurements based on percent coverage (Figure 6E and 6F, Table 3). Channels with high lengths of bank erosion and less bank vegetation also had small canopy angles (Table 3), suggesting that tree-lined banks had less herbaceous bank vegetation. However, the lack of bank vegetation is not a direct surrogate for erosion rates. Tree-lined banks tend to be less vegetated on the surface but tree roots have more resistance to erosion by extending deeper in the bank than herbaceous vegetation (Simon and Collison 2002). In addition, slumping along grassy banks is quickly masked by new vegetation growth. Thus, assumptions of erosion amounts only based on vegetative cover may be erroneous.

Wetted channel dimensions were not related to urbanization or any landscape characteristics but were instead related to low flow measured at the time of sampling (FLOWXS) and annual discharge with a 90% exceedance probability (traditionally, this statistic is used to represent low-flow conditions) (FLOW90) (Table 3; Figure 6B). Reaches with wide channels (high wetted width/depth ratios) (WETWDRAT) had a high amount of riffles (RIFFLE), a low amount of fine streambed sediment (FINE), and a high amount of disturbed land cover in the reach riparian buffer (RCHBUFDIS) (Table 3).

Urban indicators were poorly correlated with geomorphic channel units or substrate (Table 3). Instead, the percentage of riffles correlated with reach slope and streams with higher percentages of riffles had fewer fines in channel bed substrates (Figure 7, Table 3). Relatively subtle (0.5%) changes in slope affected the amount of riffles, similar to Chicago-area streams (Fitzpatrick et al. 2005). Other studies in Wisconsin and across the U.S. had similar findings (Wang et al. 2000, Wang et al. 2001, Wang et al. 1997, Walters et al. 2005). There also is a high probability that riffles were caused by relict glacial deposits and processes rather than modern alluvial processes because of their geologically young age (less than 14,000 years old), general lack of alluvium and valley development, and small stream size.

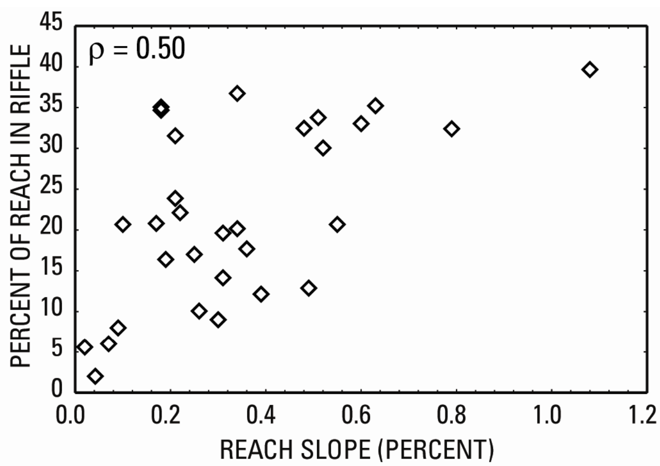

Figure 7. Plot of reach slope and percent riffles for 30 streams in the Milwaukee/Green Bay, Wis., area. (ρ, Spearman correlation coefficient)

Discussion and Conclusions

The general lack of strong correlations of habitat characteristics with urbanization in the Milwaukee/Green Bay areas further supports the findings of other studies that suggest commonly measured habitat metrics, except those related to bankfull channel size, are inadequate for detecting geomorphic responses caused by urbanization (Booth and Jackson 1997, Fitzpatrick et al. 2005, Short et al. 2005, Walters et al. 2005). Variations in geomorphic channel units and substrate for Upper Midwest streams are more likely caused by local geologic setting, slope, and watershed topography rather than land-cover disturbance. A complex combination of other environmental factors, in addition to changes in hydrology—slope, position within the stream network, base level, phase of development, channel-boundary conditions, local sediment-transport characteristics, proximity to geomorphic thresholds, and disturbance history—are usually responsible for determining whether the response to urbanization is erosional or depositional (Knight 1979; Bledsoe and Watson 2001; Fitzpatrick et al. 2006).

Geomorphic responses to urbanization are highly variable in space and time (Gregory and Madew 1982). A plot of possible geomorphic responses to various disturbance mechanisms, in terms of spatial and temporal scales, illustrates important fluvial geomorphology concepts of responsiveness, feedback mechanisms, thresholds, and history (Figure 8, Newson and Sear 1993). For example, river-engineering practices such as channelization may cause changes in channel dimensions over short time scales and local lengths of the stream network. Watershed land-cover changes can take decades or centuries and require significant lengths of the stream network to cause changes in coarse-bed substrates or channel types, such as a switch between meandering and braided channel type. Century to millennial climatic variations are responsible for altering slopes and changing longitudinal profiles of streams. It is important to keep these scales of geomorphic response in mind when looking for complex responses.

Schumm (2005) recently summarized the major concerns with applied studies of geomorphic responses to disturbance, which highlight the complexity and variability inherent in river systems. First, studies need to extend beyond the reach of interest and include conditions upstream and downstream. Secondly, the sensitivity of reaches may differ significantly, even within the same river system or close proximity. Third, studies of river responses should use an approach that includes multiple hypotheses because the first hypothesis may often be incorrect. One of the pieces of information lacking in our design and analysis is an understanding of downstream processes and controls that may affect our sampled reach. These data are typically not generated in studies designed on watershed characteristics because they incorporate types, scales, and time periods of data not readily available from geographic information systems or

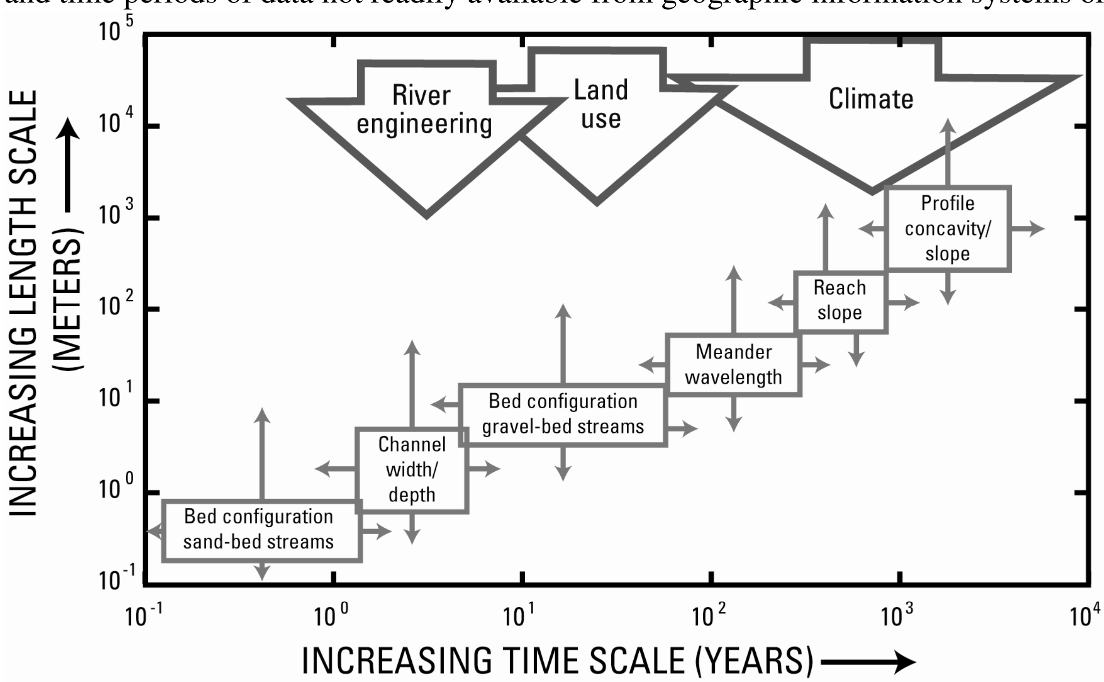

Figure 8. The importance of spatial and temporal scale in determining possible geomorphic response (modified from Newson and Sear 1993).

in a computerized format. In addition, a trained person familiar with the area and history needs to decide how far downstream is adequate to depict the important conditions.

The significant difference between watershed percentage of clayey deposits based on Quaternary deposit maps (Richmond and Fullerton 1983, 1984) and soils (STATSGO, U.S. Department of Agriculture 1984) for Milwaukee/Green Bay streams illustrates the usefulness of using multiple regional or national data sets for accounting for natural landscape variability. For this study, represented geologic characteristics may be too generalized in the soils database, and the scale of both data sets may be too coarse for small watersheds. Additional data on local geologic setting, probably at a segment buffer scale, also would have been useful.

An alternative design approach to examine habitat and geomorphic responses to urbanization is to sample and measure multiple reaches within the same watershed or conduct repeated measurements at the same reach as watershed urbanization or imperviousness increases. It is important to be able to identify the dominant geomorphic processes occurring in a reach as an overriding function of stream network position, age, geologic setting, and climate. Geomorphic responses to watershed land-cover change are often an acceleration of natural long-term processes of episodic erosion or deposition (Fitzpatrick and Knox 2000). A study of potential geomorphic response and sensitivity to disturbance of Duluth, Minn., area streams was done by selecting stream segments along the stream network with differing geologic settings (glacial and bedrock) and valley development (Fitzpatrick et al. 2006). This study gave some idea how habitat and geomorphic characteristics changed in concert with the balance between upstream and local sources of runoff and sediment and resistive forces of boundary conditions. It also provided some perspective on variations and outliers caused by local historical disturbance (something as simple as culvert type or replacement) that may alter channel hydraulics and sediment transport both upstream and downstream of the disturbance.

During reach selection and reconnaissance, the type, amount, and age of channel modifications need to be recognized because of the important ramifications that river engineering techniques have for affecting the geomorphic response potential of streams to urbanization. For this study, field comments regarding channel modifications were supplemented after sampling with additional evidence from USGS quadrangle maps, aerial photographs, photographs of the reach and transects taken during the sampling, and occurrence of riprap/irregular bedrock for bank and channel-bed substrate. Biostabilization is a popular technique for controlling bank erosion, which is purposefully made to look as natural as possible and becomes a further challenge for field crews to detect. The most obvious bank stabilization and grade-control features in this study were either less than 2 years or likely more than a few decades old. For future studies, it would be helpful for field crews to receive awareness training for identifying stabilization techniques. Additionally, it would be helpful to have information on grade controls immediately upstream or downstream of the reach, which also may affect the geomorphic response potential of the stream.

In conclusion, it is difficult or impossible to predict urbanization effects on habitat characteristics and geomorphic responses to urbanization with models based only on watershed-derived land cover and natural features. Some variability may be explained using this approach because it accounts for watershed inputs of runoff and possibly sediment, but local boundary conditions and history of channel modifications, as well as upstream/downstream geologic controls and anthropogenic channel alterations, may explain as much, if not more, of the variability. Hydrologic metrics are useful in explaining runoff changes associated with urbanization, but cannot be used alone to predict geomorphic response. In addition, the age and type of bank stabilization and grade control influence not only habitat conditions, but also the ability to recognize and record anthropogenic features (such as distinguishing between riprap and glacial boulders). Stream stabilization history (at the reach, upstream, and downstream) needs to be properly identified to assist in the interpretation of habitat characteristics and geomorphic responses to urbanization. A better understanding of habitat degradation associated with urbanization can be attained by studying how geomorphic processes are affected by watershed and local changes in runoff and sediment in the context of local geologic and anthropogenic controls on geomorphic sensitivity to response.

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