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Effects of Urbanization on the Geomorphology, Habitat, Hydrology, and Fish Index of Biotic Integrity of Streams in the Chicago Area, Illinois and Wisconsin

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Abstract.—Effects of urbanization on geomorphic, habitat, and hydrologic characteristics and fish biotic integrity of 45 streams in the Chicago area were examined by the U.S. Geological Survey from 2000 to 2001. An agricultural to urban land-cover gradient approach was used. Landscape characteristics such as texture of surficial deposits, slope, riparian land cover, and stream network position also were examined to determine if these factors influenced the effects of urbanization. Among geomorphic characteristics, channel enlargement occurred in urban streams with a high percent of watershed clayey surficial deposits. Other geomorphic and habitat characteristics such as stream power, fine substrate, and amount of riffles did not correlate with percent watershed urban land but instead correlated with reach slope. Bank erosion, habitat variability, and two habitat indexes did not correlate with watershed urban land. Below 30% watershed urban land, the unit area discharge for a 2-year flood increased with increasing urban land; however, above 30% urban land, unit area discharges for a 2-year flood were variable, most likely due to variations in stormwater management practices, point-source contributions, and the transport index. Streams with greater than 33% watershed urban land had low base flow, but the effects of urbanization on base flow were offset by point-source contributions. Fish index of biotic integrity (IBI) scores were low in streams with greater than 25% watershed urban land. Fish IBI scores also were low in streams with high percentages of watershed clayey surficial deposits and enlarged channels. The amount of riparian forest/wetland buffer had no moderating effect on geomorphic/habitat/hydrologic characteristics and fish IBI scores. Variations in the texture and topography of glacial landforms affected reach slope and some habitat characteristics. Longitudinal profiles were useful for distinguishing differences in local geologic settings among sampled sites.

Introduction

Urbanization is a major concern for water-resource managers, engineers, geomorphologists, and aquatic ecologists (Leopold 1968; American Society of Civil Engineers, Urban Hydrology Research Council 1969; Spieker 1970; The H. John Heinz II Center for Science, Economics and the Environment 2002). Urban development affects stream hydraulics and sediment input, transport, and deposition, thereby altering aquatic habitat and the resident community of aquatic organisms (Garie and McIntosh 1986; Yoder and Rankin 1997; Kennen 1999; Paul and Meyer 2001; and references within). Few studies have been able to integrate multiple spatial scales of landscape characteristics and urban indicators with reach-scale geomorphic, hydrologic, habitat, and aquatic biota characteristics in order to distinguish cause and effect from simple correlations (Roesner and Bledsoe 2003).

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Land-cover gradient and space-for-time approaches have been used to examine urbanization effects on aquatic communities, habitat, geomorphic, and hydrologic conditions (Booth and Reinelt 1993; Dreher 1997; Wang et al. 2001). Various measures have been used to represent urbanization, including imperviousness (total and effective), amount of urban land, population density, and combinations of urban indicators (Schueler 1994; Booth and Jackson 1997; McMahon and Cuffney 2001; Gergel et al. 2002). Past studies of streams showed that biotic integrity degrades at relatively low levels of urbanization (Booth and Reinelt 1993; Booth and Jackson 1997; Maxted and Shaver 1997; Wang et al. 2000, 2001). Near the Chicago area, fish index of biotic integrity (IBI) scores tended to be low in watersheds with greater than 10–20% urban land and about 100–200 people/km^2 (Dreher 1997; Wang et al. 1997; Fitzpatrick et al. 2004). Urbanization in the Chicago area is occurring on previously agricultural land; thus, urbanized streams are potentially affected by historical agricultural practices. The percent watershed agricultural land is a major factor affecting fish, macroinvertebrate, and habitat integrity in previously forested watersheds (Richards et al. 1996; Roth et al. 1996; Wang et al. 1997; Fitzpatrick et al. 2001; Stewart et al. 2001). However, some agricultural streams near the Chicago area have high biotic integrity (Dreher 1997; Wang et al. 1997; Fitzpatrick et al. 2004). Agricultural 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 sandy substrates (Wang et al. 1997). The steep, rocky streams also were less likely to be channelized than flat, sandy streams.

In urban development, impervious surface area (roads, sidewalks, driveways, parking areas, rooftops) increases, which decreases infiltration and increases the rate and volume of surface runoff. Pervious surfaces are compacted by construction equipment and removal of topsoil. Drainage networks are extended through ditching and construction of storm sewers. These factors result in changes in the frequency, duration, and size of floods (Hollis 1975; Booth 1990; Booth and Jackson 1997; Konrad 2003). Flood peaks in northeastern Illinois potentially have increased threefold due to urbanization (Allen and Bejcek 1979), and relative increases may be greater for small, frequent floods than for large, infrequent floods (Krug and Goddard 1986; Konrad 2003). Decreases in infiltration may result in decreases in the water table and ultimately decreases in base flow (Finkenbine et al. 2000). However, these offsets may be compensated for by contributions from point sources (LaTour 1993). In the Chicago area, point-source discharges may originate from outside the watershed (beyond both surface- or groundwater contributing areas) because the major source for drinking water is Lake Michigan. Although storm-water detention basins and other control measures are common in urban areas, they may not meet their design goals of controlling surface runoff (Booth and Jackson 1997; Finkenbine et al. 2000).

Early in urbanization, upland sources and available sediment may increase due to clearing of vegetation. Sediment loads may increase during initial construction and decrease to predevelopment loads after construction (Wolman 1967; Wolman and Schick 1967; Colosimo 2002). In Wisconsin, sediment loads were 10 times larger from watersheds with residential construction than from rural or urban watersheds (Owens et al. 2000). Channel and flood-plain processes of sediment erosion, transport, and deposition also may change to accommodate changes in the size, duration, and frequency of floods.

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) commonly occurs in urbanizing streams (Hammer 1972; Doll et al. 2002; Center for Watershed Protection 2003). However, geomorphic processes following urbanization are highly variable both in space and time (Gregory and Madew 1982) and stability cannot be predicted by the magnitude of urbanization or the rate of ongoing land-cover change (Henshaw and Booth 2000). Channel and watershed slope, stream network position, base level, phase of urban development, distance to urban land, riparian conditions, erodibility potential of the channel bed and banks, local sediment transport characteristics, proximity of geomorphic thresholds, and history of past disturbances influence whether and where hydrologic changes associated with urbanization lead to channel erosion or sedimentation (Knight 1979; Bledsoe and Watson 2001). In addition, geomorphic conditions may or may not stabilize after one or two decades of constant land cover (Finkenbine et al. 2000; Henshaw and Booth 2000; Bledsoe and Watson 2001).

Some studies show relations among stream habitat indexes and metrics and urban development, whereas other studies do not (Booth and Jackson 1997; Paul and Meyer 2001; Wang et al. 2001; Rogers et al. 2002; Fitzpatrick et al. 2004). 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 may decrease from altered hydrology (Finkenbine et al. 2000). The Center for Watershed Protection (2003) noted that little data are available for urbanization effects on riparian shading, wetted perimeter, velocity/depth regimes, riffle frequency, and sediment deposition in pools.

A major goal of our study was to integrate geomorphic, habitat, hydrologic, fish, landscape, and urban-indicator data from a range of spatial scales to better understand how the interactions of these factors affect channel conditions and biotic integrity of Chicago area streams (Figure 1). A major hypothesis for the study was that reach-scale geomorphic, habitat, and hydrologic characteristics are affected by urbanization. Landscape characteristics or physiographic setting possibly moderate these effects. A second hypothesis is that fish biotic integrity is ultimately affected by urbanization through proximate effects from changes in geomorphic, habitat, and hydrologic characteristics.

Study Area

Sampled streams are within the Des Plaines and Fox River watersheds, two major tributaries to the upper Illinois River (Figures 1 and 2). The Des Plaines River basin contains the intensely urban downtown area, older suburbs of Chicago, and some expanding suburbs and rural areas. The Fox River drains the western suburbs of Chicago where rapid expansion of residential areas has been occurring since the early 1980s. The northern parts of the Des Plaines and Fox River basins are in expanding suburbs of the Milwaukee, Wisconsin metropolitan area. The climate of the study area is humid continental with an average annual temperature (1961–1990) of 9°C and average annual precipitation of 89 mm.

The physiographic setting of the study area is composed of two sections: the Great Lakes section, which encompasses all of the Des Plaines River basin and the northern half of the Fox River basin; and the Till Plains section, which covers the southern half of the Fox River basin (Fenneman 1938; Leighton et al. 1948; Arnold et al. 1999). Bedrock geology mainly consists of limestone and dolomite in both basins (Willman et al. 1975; Wisconsin Geological and Natural History Survey 1981) and is buried by unconsolidated Quaternary deposits ranging in thickness from 0 to more than 120 m (Soller and Packard 1998). Deposits are thin or absent along the upper parts of the Fox River in Wisconsin, the lower valley of the Fox River upstream of its confluence with the Illinois River, and in portions of the lower Des Plaines River, the Chicago River, and the Calumet basins. The distribution of Quaternary deposits is highly variable and complex, but the deposits generally consist of clayey till in the Des Plaines River basin, glacial lake clay in the Chicago River and Calumet basins, sandy and loamy till and outwash sand and gravel in the upper Fox River basin, and loamy till in the lower Fox River basin (Willman 1971; Richmond et al. 2001) (Figure 2). Outwash sand and gravel are found along the main stem of the Des Plaines River. Streams sampled in both basins have relatively low slopes (0.01–0.8%).

Land cover in the study area consists of mainly agricultural and urban land with small amounts of forest and wetland, mainly occurring in county forest preserves (Figure 1). For the 45 sampled streams, percent watershed urban land ranged from 0% to 92% and agricultural land ranged from 0% to 99% (Table 1). Forest preserves are common in the Chicago area and forest and wetland within a 60-m riparian zone along the entire stream network ranged from 2% to 49% (Table 1).

Potentially impaired water uses (Illinois Environmental Protection Agency 2002) occurred in urban streams in the Des Plaines River basin with greater than about 30% watershed urban land, although there were exceptions (Table 1). Hickory Creek and Sugar Run have impairments and less than 30% watershed urban land. Sawmill Creek, East Branch Du Page River, and Poplar Creek (74%, 73%, and 38% watershed urban land, respectively) had no listed impairments. Impairment in the urban streams

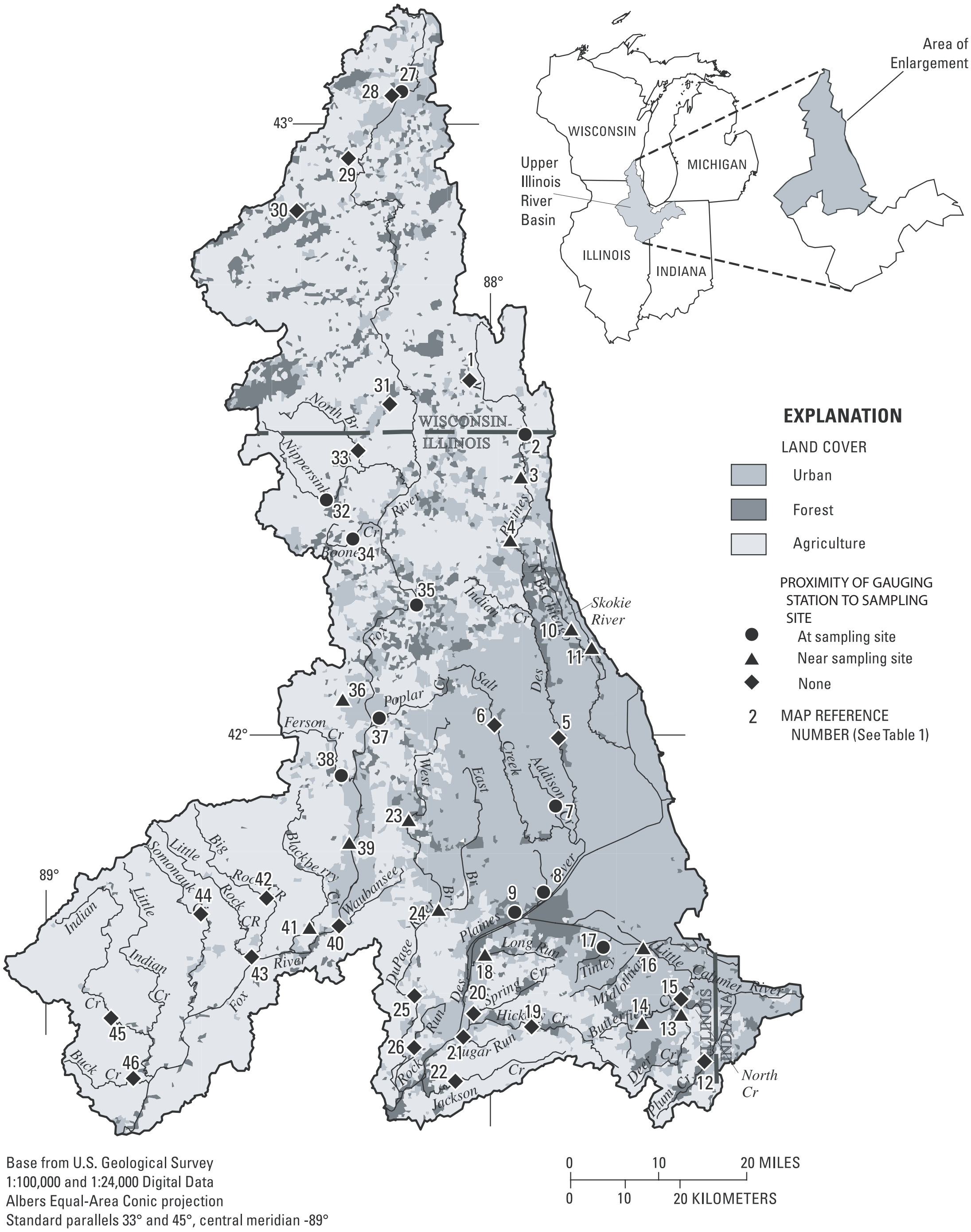


FIGURE 1. Location of study area, land-cover characteristics, and stream sites sampled in the Chicago, Illinois metropolitan area.

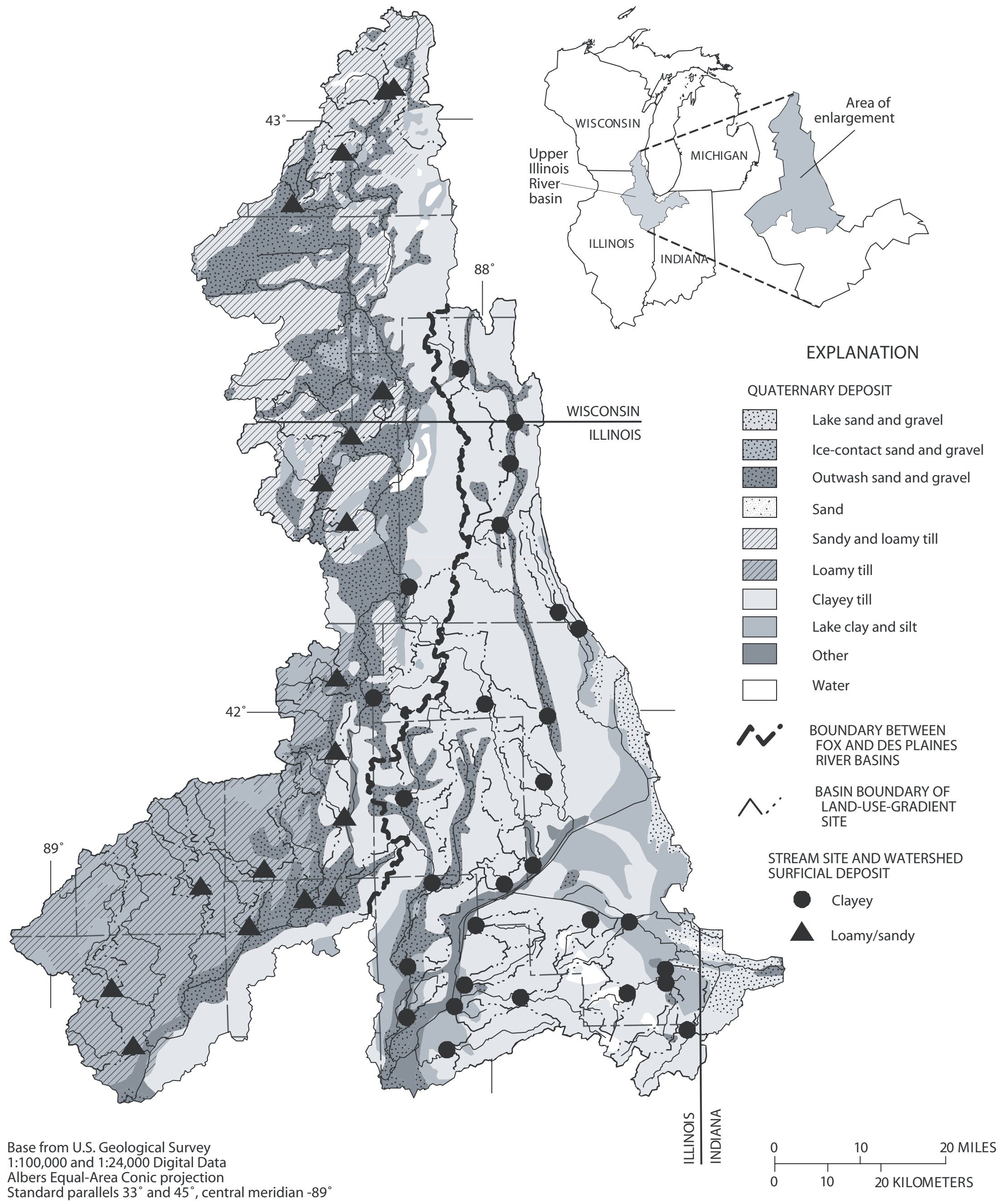


FIGURE 2. Quaternary deposits and sites grouped by texture of surficial deposits for streams in the Chicago area.

most commonly occurred from municipal point sources, construction, land development, urban run-off/storm sewers, hydromodification, channelization, habitat modification, and bank modification. No impairments were listed Fox River tributaries in Illinois, and no impairment data were available for Wisconsin streams.

A variety of storm-water controls are used in the Chicago area. Wet and dry storm-water detention ponds of various sizes are numerous because of the

TABLE 1. Map reference number, site name, drainage area, watershed land cover, population density, and potential causes for physical impairments (Illinois Environmental Protection Agency 2002) for sampled sites in the Chicago area. Sites with U.S. Geological Survey (USGS) streamflow gauging stations are **bolded.** Impairment data are not available for Wisconsin streams.

Map reference number (see Figure 1)	Site name	Drainage area (km^2)	Watershed urban land (%)	Watershed agriculture land (%)	Forest/ wetland in 60-m stream network buffer (%)	1980 population density (people/ km^2)	1990 population density (people/ km^2)	2000 population density (people/ km^2)	Potential causes for impairments[a]
1	Brighton Cr.	66	7	62	28	52	80	100	na
2	**Des Plaines R.**	**318**	**5**	**78**	**17**	**50**	**52**	**70**	**None**
3	Mill Cr. (Des Plaines)	169	10	68	21	164	164	311	None
4	Bull Cr.	20	27	52	31	238	337	453	None
5	Willow Cr.	56	86	0	9	555	454	510	1, 5
6	Salt Cr.	128	73	5	17	1,029	1,159	1,236	1, 5, 6, 7, 8, 9
7	**Addison Cr.**	**47**	**92**	**0**	**7**	**1,609**	**1,597**	**1,689**	**1, 4, 5, 6, 7, 8, 10, 11, 12**
8	**Flag Cr.**	**43**	**87**	**0**	**14**	**1,130**	**1,205**	**1,299**	**1, 2, 3, 5, 6, 7, 10, 11**
9	**Sawmill Cr.**	**33**	**74**	**1**	**33**	**706**	**850**	**900**	**None**
10	**N Br Chicago R.**	**48**	**33**	**21**	**49**	**342**	**252**	**334**	**1, 4, 5, 6, 7, 10, 11**
11	**Skokie R.**	**62**	**60**	**11**	**25**	**752**	**678**	**756**	**1, 2, 3, 4, 5, 7, 8, 9, 10, 11**
12	Plum Cr.	85	8	64	35	69	72	88	None
13	**Deer Cr**	**62**	**26**	**51**	**32**	**341**	**302**	**311**	**1, 5, 6, 7**
14	**Butterfield Cr.**	**48**	**38**	**40**	**16**	**537**	**606**	**667**	**2, 3, 5, 6, 7, 10, 11, 12**
15	North Cr.	58	35	44	24	678	679	710	2, 3, 5, 6, 7, 10, 11
16	**Midlothian Cr.**	**51**	**72**	**13**	**16**	**1077**	**1346**	**1451**	**2, 3, 5, 6, 7, 10, 11, 12**
17	**Tinley Cr.**	**29**	**57**	**10**	**35**	**826**	**1005**	**1115**	**2, 3, 5, 6, 7, 10, 11, 12**
18	**Long Run**	**61**	**29**	**45**	**34**	**183**	**343**	**473**	**None**
19	Hickory Cr.	127	21	59	25	211	260	352	1, 2, 3, 4, 5, 6, 9
20	Spring Cr.	47	11	59	36	186	149	204	None
21	Sugar Run	33	17	77	13	192	214	253	2, 3, 5, 14
22	Jackson Cr.	113	4	93	5	75	76	133	None
23	**W Br. Du Page R.**	**157**	**58**	**23**	**18**	**800**	**1,036**	**1,289**	**1, 2, 3, 5, 13**
24	E Br. Du Page R.	206	73	5	22	1,054	1,202	1,300	None
25	Lily Cache Cr.	114	19	69	10	366	377	636	na

TABLE 1. Continued.

Map reference number (see Figure 1)	Site name	Drainage area (km^2)	Watershed urban land (%)	Watershed agriculture land (%)	Forest/wetland in 60-m stream network buffer (%)	1980 population density (people/km^2)	1990 population density (people/km^2)	2000 population density (people/km^2)	Potential causes for impairments[a]
26	Rock Run	37	52	33	25	594	717	909	1, 2, 3, 5
27	Fox R.	203	30	44	30	244	268	320	na
28	Pewaukee R.	98	19	56	17	188	193	290	na
29	Genesee Cr.	72	7	62	31	66	94	110	na
30	Jericho Cr.	32	3	72	34	69	66	96	na
31[b]	Bassett Cr.	–	–	–	–	–	–	–	–
32	Nippersink Cr.	219	4	87	9	72	81	100	None
33	N Br. Nippersink Cr.	167	6	75	20	46	64	83	None
34	Boone Cr.	40	3	61	26	54	47	56	None
35	Flint Cr.	96	31	32	36	210	303	341	None
36	Tyler Cr.	81	3	87	12	29	39	49	None
37	**Poplar Cr.**	**94**	**38**	**40**	**22**	**541**	**748**	**881**	**None**
38	**Ferson Cr.**	**134**	**17**	**70**	**19**	**84**	**142**	**242**	**None**
39	Mill Cr. (Fox)	80	16	74	14	196	174	311	None
40	Waubansee Cr.	77	21	72	7	205	317	646	None
41	**Blackberry Cr.**	**174**	**7**	**83**	**15**	**98**	**103**	**155**	**None**
42	Big Rock Cr.	273	1	95	7	24	22	24	None
43	Little Rock Cr.	196	4	92	10	23	53	60	None
44	Somonauk Cr.	96	1	94	9	24	16	18	None
45	Indian Cr.	326	1	93	12	15	14	16	None
46	Buck Cr.	103	0	99	2	6	5	5	None

[a] Causes for impairment: 1, Municipal point source; 2, construction; 3, land development; 4, combined sewer overflow; 5, urban runoff/storm sewers; 6, hydromodification; 7, channelization; 8, upstream impoundment; 9, flow regulation/modification; 10, habitat modification; 11, bank modification/destabilization; 12, riparian vegetation removal; 13, highway/road/bridge construction; 14, agriculture/nonirrigated crop production

[b] Site 31, Bassett Creek, was dropped from analysis because of close proximity to a waste-water treatment plant.

low permeability of clayey surficial deposits. Combined-sewer systems are used in the city of Chicago and in many of the suburbs. Historically, the capacity of combined-sewer systems was often exceeded resulting in releases of untreated sewage to streams. To avoid this, Chicago's Tunnel and Reservoir Plan (TARP) system was developed and consists of drop shafts, tunnels, and reservoirs designed to capture and hold overflows from combined sewers and convey them to wastewater treatment plants (Terrio 1994). Six study streams are part of the TARP system: Willow Creek, Salt Creek, Addison Creek, Flag Creek, North Creek, and Midlothian Creek. There are five major wastewater treatment plants for the Metropolitan Water Reclamation District of Greater Chicago. Two of these are located in the watersheds of Willow Creek and Salt Creek.

Methods

Study Design

Our study was part of a larger study of urbanization effects on stream ecosystems conducted by the National Water-Quality Assessment (NAWQA) Program of the U.S. Geological Survey (USGS). From 2000 to 2001, we examined the effects of urbanization on biological, chemical, hydrologic, geomorphic, and habitat characteristics of 46 streams in the Chicago area in the Des Plaines and Fox River basins (Table 1; Figure 1) (Adolphson et al. 2002). The NAWQA program also conducted similar studies in other major urban areas of the United States during the same time period (Couch and Hamilton 2002).

Streams with historical streamflow or biological data were preferred. Streams without point sources were desirable, but in intensive urban areas point sources could not be avoided. However, one rural stream, Bassett Creek (site 31), was dropped because a wastewater treatment plant was located immediately upstream of the sampling location; thus, the data set was reduced to 45 streams. Drainage areas ranged from 20 to 326 km^2 (Table 1).

Streams were grouped into two categories based on texture of watershed surficial deposits. Streams with greater than 60% clayey till, lake clay, and silt were grouped as clayey streams (n = 28). Streams with greater than 60% loam, sand, or gravel deposits were classified as loamy/sandy streams (n = 17). All 26 streams in the Des Plaines River basin and 2 eastern tributaries to the Fox River were grouped as clayey streams (Figure 2). The remaining 17 streams in the Fox River basin were loamy/sandy streams.

The 45 streams also were grouped into three categories based on percentage of watershed urban land and population density (U.S. Bureau of the Census 2001) (Figure 3). Rural streams had less than 9% watershed urban land and population densities less than 150 people/km^2 (n = 16). Rural/urbanizing streams had 9–33% watershed urban land and population densities of 150–600 people/km^2 (n = 15). Urban streams had greater than 33% watershed urban land and greater than 600 people/km^2 (n = 14). Only clayey streams had greater than 33% watershed urban land.

Data Collection

Urban 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 (GIS). Urban indicators included percent watershed urban land, estimated imperviousness, upstream distance to urban land from sampling site, population density, road density, and point-source discharge information. Percent watershed land cover was calculated from 1993 30-m Multi-Resolution Land Cover (MRLC) data (Vogelmann et al. 2001) using a GIS. The land-cover data included four categories of urban land cover: low intensity residential, high intensity residential, commercial/industrial/transportation, and urban/recreational grasses. Percent forest and wetland for a 60-m buffer on each side of the stream along the entire stream network upstream of the sampling site was calculated from MRLC data. The MRLC land-cover data were used to calculate distance from the sampling site to the nearest upstream urban land. An estimate of total impervious area was calculated using U.S. Department of Agriculture, Soil Conservation Service (1986) estimates of percent impervious area for different types of urban land uses.

Population density data were from the U.S. Bureau of Census 1980, 1990, and 2000 population data (U.S. Bureau of the Census 1985, 1991, 2001). Changes in population density (as raw values and as percent change) were calculated.

The 1999 Topologically Integrated Geographic Encoding and Referencing (TIGER) system line files (U.S. Bureau of the Census 1999) were used to estimate road area and length (Adolphson et al. 2002). Road density was calculated by dividing road area by drainage area.

Point-source discharge data were obtainable only

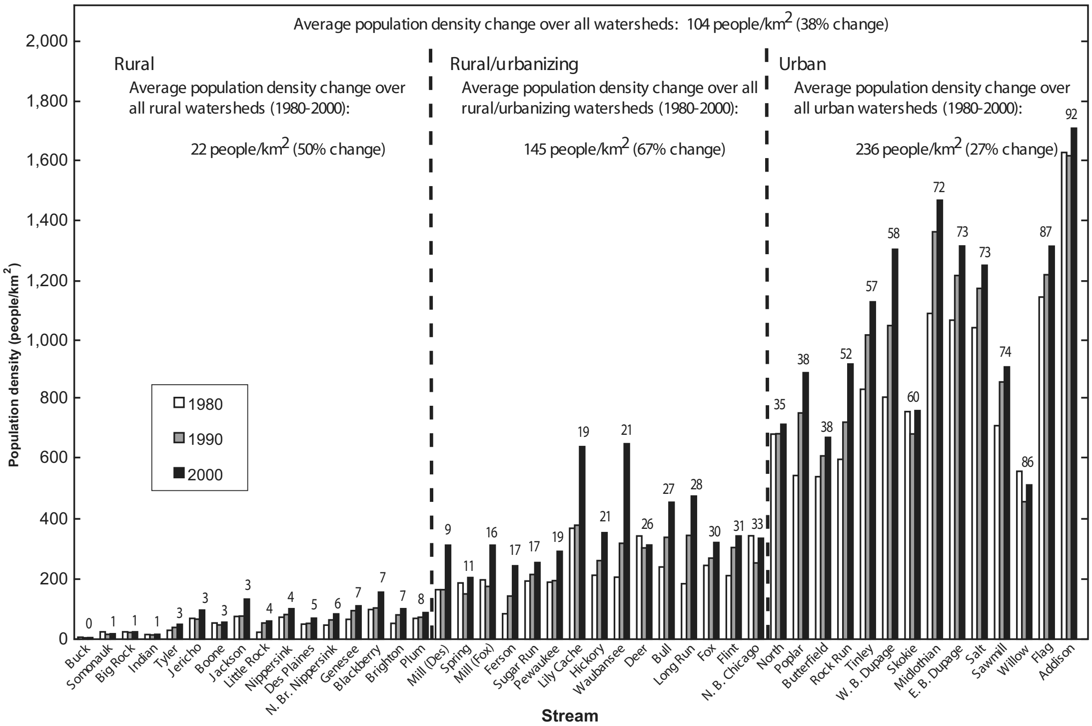


FIGURE 3. Changes in population density from 1980 to 2000 (U.S. Bureau of the Census 1985, 1991, 2001) and percent urban land (values given above histograms) in 1993 (Vogelmann et al. 2001) for 45 streams in the Chicago area.

for Illinois streams. Average monthly discharges for 2000 were obtained for each watershed (Charles Avery, U.S. Geological Survey, personal communication).

Data for landscape characteristics, which included Quaternary deposits (texture of surficial deposits), bedrock geology, bedrock depth less than 15 m, drainage area, stream slope (calculated for the length of stream between 10% and 85% of total stream length in the basin), drainage density, relief ratio (minimum elevation subtracted from maximum elevation in the watershed, divided by watershed length), cumulative stream length, and a transport index (drainage density × relief ratio), were obtained from Adolphson et al. (2002, and references within). Similar to land cover data, percentages for surficial deposits, bedrock geology, and bedrock depth were calculated for a 60-m buffer on each side of the stream along the entire stream network upstream of the sampling site. The 1:24,000 National Elevation Dataset (NED) Digital Elevation model (DEM) (U.S. Geological Survey 2001), GIS, and the BasinSoft Program were used to delineate stream networks and calculate selected watershed-scale geomorphic characteristics (Harvey and Eash 1996; Fitzpatrick et al. 1998). Sinuosity for a segment encompassing the sampled reach was measured from 1:24,000 NED DEM (U.S. Geological Survey 2001) data.

Longitudinal profiles were constructed for a subset of streams. Profiles extend from the headwaters to the first major confluence downstream of the sampled reach. Stream lengths were measured with a map measurer between contour lines on USGS 7.5-min topographic maps. Longitudinal profiles were used to identify changes in slope usually related to glacial landforms or spatial position within the stream network.

Geomorphic characteristics.—Channel geometry and water-surface slope were surveyed once between November 2000 and May 2001 at three generally equidistant cross sections in a stream reach using an electronic Total Station or an auto-level. Reach length was 20 times the channel width, or a minimum of 150 m, and cross sections generally were located in runs. Approximately 20 points were surveyed along each transect. End points for cross sections extended into the flood plain or above bank-full stage. A combination of field indicators were used to identify bank-full stage along each reach and included the top of coarse deposits associated with point bars (minimum elevation); occurrence of a sharp break in slope of the bank above the low-flow water surface where slope changes from vertical to more horizontal; changes in vegetation, such as a change from herbaceous to tree species; and for undercut banks, the top of the undercut (minimum bank-full elevation) (Harrelson et al. 1994; Fitzpatrick et al. 1998).

Channel roughness was estimated in the field using Coon's (1998) adaptation of Cowan's (1956) method. Comparison with photos in Hicks and Mason (1998), Coon (1998), Arcement and Schneider (1987), and Barnes (1967) provided additional guidance.

The U.S. Army Corps of Engineers' HEC-RAS (v. 3.0) computer program (Brunner 2001) was used to estimate average bank-full channel area, width, depth, velocity, shear stress, and unit-channel-area stream power. Inputs to the HEC-RAS model include channel geometry, roughness, and reach water-surface slope. Bank-full area was normalized by drainage area prior to analysis because of its dependence on watershed size.

Stream competence describes the maximum particle size (D) that a stream is capable of transporting under a given flow and was calculated by the formula $D = T_c/4$, for coarse, noncohesive beds where D is mean grain diameter (ft) that can be transported and T_c is critical shear stress (lb/ft^2) (Anderson et al. 1970; Chang 1992). Critical shear stress values were calculated from HEC-RAS hydraulic models for cross-section data from the stream reach. An estimate of erosivity potential of the channel at bank-full flow was calculated as the ratio of maximum particle size (mm) transported at bank-full flow divided by average substrate particle size (mm) measured for the reach from transect-point data from the habitat assessments.

Habitat characteristics.—Habitat assessments were conducted in July 2000 along the same reach used for the surveys of channel geometry and slope using NAWQA protocols (Fitzpatrick et al. 1998). Data included both qualitative and quantitative observations of channel, substrate, bank, and habitat cover conditions at 11 transects distributed equally along the reach; data were also collected at five points (two bank and three instream) along each transect. Bank-full width and depth were measured and bank-full area and bank-full width/depth ratios were calculated for each transect and averaged. Coefficient of variation of bank-full width/depth ratio was calculated and gives an indication of variability in the shape of the channel. Presence/absence of erosion at the intersection of each transect with the bank was noted and the length of bank erosion occurring along the transect line was measured. Presence and depth of loose silt was measured at each transect point.

Dominant riparian land cover within a 30-m buffer was recorded for each transect endpoint, and the open canopy angle was measured at the center of each transect. 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.

Metrics of wetted channel shape and shape variability were calculated. A channel-shape index (CHANSH) was calculated for each transect by the equation CHANSH = $(W/D)^{(D/D\text{max})}$, where W = wetted width, D = average depth, and Dmax = maximum depth (Armantrout 1998). Smaller values of CHANSH indicate relatively narrow/deep or pool-like conditions, whereas larger values indicate more wide/shallow or riffle-like conditions. This index provides a measure of relative occurrence of macrohabitat conditions (Terry Short, U.S. Geological Survey, personal communication). Coefficient of variation of channel-shape index provides a measure of habitat variability.

Presence/absence of instream habitat cover for fish, including woody debris, was recorded at each of three in-channel points along transects. In shallow streams, woody debris in less than 0.3 m of water was not considered habitat cover. Many shallow streams had abundant woody debris; thus, the percent woody debris was a small fraction of the possible total.

Two habitat indexes were calculated, the USEPA's rapid bioassessment protocol (RBP; Barbour et al. 1999) and Wisconsin Department of Natural Resources (WDNR) habitat index; (WIHAB; Simonson et al. 1994). These indexes are commonly used in other habitat studies of Midwestern streams. The RBP index is intended to quantify the quality of habitat for the broader aquatic community, whereas the WDNR index is intended to quantify the quality of habitat for fish. Each index contained multiple metrics (10 in the RBP and 7 in the WDNR) that were combined to give a cumulative assessment of habitat quality for wadeable streams. Scores range from 0 to 170 for the RBP index and from 0 to 100 for the WDNR index. High scores reflect excellent habitat quality for both indexes. The RBP incorporates adjustments for streams with high and low slopes. Minor modifications were made to the calculation techniques for WIHAB because NAWQA data collection varied from WDNR protocols (archives are available as unpublished files, U.S. Geological Survey, Middleton, Wisconsin, 2002). For example, the riffle:riffle ratio metric for the WIHAB index was not measured; instead, the relative number of geomorphic channel units in a reach (riffle, run, pools) was substituted.

Hydrologic characteristics.—Hydrologic data included discharge measurements at all sites at the time of ecological sampling in July 2000, HEC-RAS modeled bank-full and base flow, and daily streamflow data from 1985 to 2000 for 15 streams with USGS streamgauges (Table 1). Bank-full flows were modeled in HEC-RAS by adjusting discharge to match observed bank-full stage indicators. Bank-full flows were normalized by drainage area.

Of the 15 gauged sites, 13 are on clayey streams (12 in the Des Plaines River basin and 1 in the Fox River basin). The time period 1985–2000 was selected for analysis of gauging-station data because it reflects recent urbanization. Flood-frequency analyses of gauging-station data followed guidelines in Interagency Advisory Committee on Water Data (1982) to fit logarithms of annual peak flows to a Pearson Type III distribution. Estimates of flood peaks with a 2-year recurrence interval were used because past studies showed that small, frequent floods were increased more by urbanization than large, infrequent floods (Krug and Goddard 1986). Streamflow data from the gauges were used to estimate base flow in 2001.

Discharge was measured in streams during ecological sampling; however some streams were sampled during falling stages following summer thunderstorms and thus did not represent base flow. By matching water-surface elevations during base flow conditions obtained from cross-section surveys, HEC-RAS was used to estimate base flow for streams sampled at falling stages. HEC-RAS estimates were compared to discharge measurements collected during ecological sampling and to base flow discharges from the 15 gauging stations. The base flow variable was estimated from comparisons of the three sources. Flow variability was calculated as the ratio of HEC-RAS derived bank-full flow to estimated base flow. Flow data were normalized by drainage area to remove effects of watershed size on relations with other characteristics. In Illinois streams with point sources, monthly point-source discharges for 2000 were subtracted from estimated base flow to calculate an adjusted base flow variable that more closely reflected groundwater contributions.

Fish index of biotic integrity.—Fish-assemblage data were collected during low flow by three agencies: the USGS (2 sites sampled in 2000 and 22 sites sampled in 2001), the Illinois Department of Natural Resources (IDNR) (17 sites sampled during the period from 1995 to 1999), and the WDNR (5 sites sampled in July 1997). The USGS used a barge or backpack electroshocker to sample one pass of the entire stream reach and then conducted supplementary riffle kicks and seine hauls (Meador et al. 1993). The IDNR collected fish in a single pass using a backpack electroshocker, barge electroshocker, or electric seine (Bertrand et al. 1996). The WDNR used a barge or backpack electroshocker to sample all major habitats in a stream reach. The reach length for WDNR sampling was determined by stream size, which is based on stream width (Lyons 1992). Fish data for the Addison Creek site were collected near but not at the same reach as the other samples.

A revised fish IBI is being reviewed for use in Illinois (Hite and Bertrand 1989; Roy Smogor, Illinois Environmental Protection Agency, personal communication). A draft version of the revised Illinois IBI was used in our study. Ten metrics are used in the revised IBI, of which six are based on richness, three on trophic or reproductive structure, and one on tolerance. Metric values are scaled according to geographic region, stream size, and slope; scores for the revised IBI can range from 0 to 60. High scores reflect high fish biotic integrity.

Statistical Analyses

Statistical analyses included correlation and redundancy analysis. When examining relations among physical characteristics at multiple spatial scales, reach-scale geomorphic, habitat, and hydrologic characteristics and fish IBI scores were considered dependent variables and urban indicator, landscape characteristics, and reach-scale riparian land-cover data were considered independent variables. Reach-scale slope was considered an independent variable because most Chicago area streams are not alluvial and flow on glacial deposits, bedrock, or thin fluvial deposits in poorly developed valleys.

Spearman rank correlation and principle components analysis (PCA) (Iman and Conover 1983) were used to reduce the number of variables (Table 2). Some geomorphic and habitat characteristics were retained for analysis, such as bank erosion, canopy angle, and occurrence of woody debris, because little is known about how they respond to urbanization (Table 2).

TABLE 2. Selected urban indicators and landscape characteristics used to determine urbanization effects on the geomorphic, habitat, and hydrologic characteristics and fish index of biotic integrity of 45 Chicago area streams.

Type of variable	Abbreviation	Median	Minimum	Maximum	Correlated variables
Urban indicators					
Watershed urban land (%) (square-root transformed)	URBANLU	19	0	92	Watershed industrial lands; population density, impervious area, road density
Population density change, 1980–2000 (%)	POPDENP	158	–117	1,266	Population density change by area
Mean upstream distance of urban land (km)	URBANDIS	10.2	2.4	25.3	Road area, road length
Landscape characteristics					
Drainage area (km^2) (log-10 transformed)	DRAIN	81.2	20.1	326.1	Stream order, cumulative stream length
Watershed clayey surficial deposits (%)	WATCLAY	71	0	100	Soil permeability
Drainage density (km/km^2)	DRAINDEN	1.34	1.08	1.44	None
Watershed slope (%)	WATSLOP2	1.31	0.20	3.36	None
Transport index *1,000 (km^{-1}) (log-10 transformed)	TRANSIN	4.77	1.23	10.05	Relief ratio
Sinuosity (ratio)	SINUOS	1.3	1.1	2.0	None
Coarse deposits within 60-m stream network buffer (%) (log-10 transformed)	BUFCOARS	2	0	96	Coarse deposits in watershed
Forest and wetland within 60-m stream network buffer (%)	BUFFOWE	19	2	49	None
Disturbed land cover in 30-m buffer (%) (log-10 trans.)	RIPLU	5	0	100	None
Average open canopy angle (°)	CANOPY	48	2	145	None
Geomorphic characteristics					
Reach slope, low-flow water surface (%) (square-root transformed)	SLOPELO	0.20	0.01	0.79	Segment and bank-full slope, velocity, power, stress, bank-full flow/drainage area, competence
Bank-full channel area/drainage area (m^2/km^2) (square-root transformed)	BFAREADA	0.11	0.030	0.43	Channel area, bank-full flow
Stream power (N/(m s))	POWER	12	0.097	149	None
Erosivity potential at bank-full flow (ratio) (inverse square-root transformed)	EROSBF	1.5	0.4	88.7	None
Habitat characteristics					
Fine substrate (%) (log-10 transformed)	FINES	27	3	100	Amount and type of geomorphic units, substrate texture, embeddedness, silt depth, roughness, Wisconsin habitat index
Average bank-full channel width/depth (ratio) (log-10 transformed)	BWDRAT	11	2	31	Shape index, bank-full surface area, wetted width/depth ratio, coefficient of variation of canopy

TABLE 2. Continued.

Type of variable	Abbreviation	Median	Minimum	Maximum	Correlated variables
Coefficient of variation of average bank-full channel width/depth (ratio)	BWDRATCO	25	9	86	None
Average bank erosion (m) (square-root transformed)	EROSION	2.6	0.0	11.3	Bank stability index, coefficient of variation of silt depth
Amount if riffle in reach (%)	RIFFLE	20	0	59	None
Coefficient of variation of wetted channel shape index	CHANSHCO	36	13	87	None
Woody debris (%)	WOODDEBR	11	0	71	None
USEPA rapid bioassessment protocol habitat index	RBPHABIN	118	67	154	Wisconsin habitat index
Wisconsin habitat index	WIHAB	45	20	68	RBPHABIN
Hydrologic characteristics					
Bank-full flow/drainage area ($m^3/s/km^2$) (square-root transformed)	BFLOWDA	0.10	0.011	0.42	None
Estimated base flow at time of cross section surveys (m^3/s) (log-10 transformed)	FLOWXS	0.42	0.06	2.4	None
Estimated base flow/drainage area ($m^3/s/km^2$) (log-10 transformed)	FLOWXSDA	0.0044	0.00061	0.030	None
Bank-full flow/estimated low flow (ratio) (square-root transformed)	FLOWVAR1	24.0	2.0	153.8	None
Estimated base flow - average 2000 point source flow (m^3/s) (log-10 transformed)	FLOWXS_P	0.31	–0.45	2.3	None
2-year flood peak (m^3/s)	Q2	20	6.7	28	None
2-year flood peak/drainage area ($m^3/s/ km^2$) (log-10 transformed)	Q2DA	0.27	0.081	0.68	None
Fish					
Revised fish index of biotic integrity	FISHIBI	33	6	57	None

Spearman correlation analysis was used to identify relations among the remaining 34 variables for all 45 streams. For individual correlations the critical ρ is 0.29 for P = 0.05, but with Bonferroni adjustments for multiple tests, the critical ρ is 0.55 for P = 0.05.

Spearman correlation analysis was conducted separately for groups of clayey and loamy/sandy streams. The 17 loamy/sandy streams all had less than 33% urban land, so only the 15 clayey streams with less than or equal to 33% watershed urban land were included in these comparisons. With Bonferroni adjustments for multiple tests, the critical ρ values for 17 and 15 streams, 34 variables, and P = 0.05, are 0.81 and 0.84, respectively.

Redundancy analysis (RDA) was used to determine the relative effects of urban indicators and landscape characteristics on geomorphology, habitat, hydrology, and fish biotic integrity. Redundancy analysis is a direct gradient analysis that describes variation between a linear response data set (in this case the geomorphic, habitat, and hydrologic characteristics and fish IBI) and a predictor data set (urban indicators and landscape characteristics) (Hill 1979; Ter Braak 1986; Ter Braak and Smilauer 1998). Characteristics with nonnormal distributions were transformed prior to the RDA (Table 2). A subset of 11 urban indicators and landscape characteristics; 10 geomorphic, habitat, and hydrologic characteristics; and the revised fish IBI were selected for the RDA based on correlation analysis and the need recognized in the literature for more information about their response to urbanization. Response characteristics were plotted in ordination diagrams (biplots) with vectors representing gradients for selected predictor characteristics using a symmetric focus for scaling. Length and direction of the arrows on a biplot indicate relative strength of relations among characteristics. Arrows that plot closely to each other are positively correlated. Arrows that plot directly opposite each other are negatively correlated. Arrows that plot at right angles to each other are not correlated. Thus, proximity of a geomorphic, habitat, or hydrologic characteristic to certain urban or landscape characteristics in an RDA biplot represent relative influences of the independent variable on the dependent variable. Proximity of dependent variables to each other identifies those that behave similarly. Monte Carlo permutation tests were used to determine whether the RDA axes were significant ($P \leq 0.05$).

Results

Urban Indicators

For all 45 streams, watershed urban land, total imperviousness, and 1980, 1990, and 2000 population density were positively correlated ($\rho \geq 0.95$). Watershed urban land also positively correlated with road density ($\rho = 0.88$). Thus, watershed urban land was used as a surrogate variable to represent the amount of urbanization. Two other urban indicator variables did not correlate with watershed urban land—percent change in population density from 1980 to 2000 and mean upstream distance to urban land (Table 3). Urban sites had the highest numerical change in population density (236 people/km^2), but rural/urbanizing sites had the highest percent change in population density (67%) (Figure 3).

Landscape Characteristics

There was a general lack of correlations between urban indicators and landscape characteristics (Table 3). The positive relation between clayey surficial deposits and watershed urban land was an artifact of having a full agricultural to urban land-cover gradient (0–92%) for clayey streams and only a partial gradient (0–31%) for loamy/sandy streams. Upstream distance to nearest urban land was positively correlated with drainage area; thus, this variable was dependent on watershed size. Streams with steep watershed slopes had high percent forest/wetland in the stream network buffer (Figure 4). This relation was affected by the amount of urbanization, with rural streams showing more of a relation than urban streams. There was no relation between percent of disturbed riparian land cover in the sampled reach and percent forest/wetland within the full stream network buffer or percent watershed urban land (Table 3). Instead, streams with less than 5% and greater than 80% watershed urban land appeared to have more disturbed riparian buffers (Figure 5A). Correlation analyses for separate groups of clayey and loamy/sandy streams (standardized for range of percent watershed urban land) showed similar results to correlations when all streams were grouped together (Tables 4 and 5).

Geomorphic/Habitat Characteristics

In general, there was a lack of correlations among urban indicators, landscape characteristics, and geomorphic/habitat characteristics. Only unit-area bank-full channel area (normalized by drainage area) positively correlated with watershed urban land and clayey surficial deposits and negatively correlated with watershed size (Table 3; Figure 5B). The two habitat indexes did not correlate with watershed urban land (the RBP index is shown in Figure 5C). For the subgroup of clayey streams, only the amount of woody debris negatively correlated with the transport index (Table 4).

Relations among geomorphic and habitat characteristics were more numerous for the group of all streams (Table 3) compared to the subgroups of clayey or loamy/sandy streams (Tables 4 and 5). Stream power positively correlated with reach slope for all groups. For the group of all streams, streams with high percent fine-grained substrate had flat reach slopes, low stream power, and high erosivity potential. Streams with relatively high reach slopes had high percentages of riffles (Figure 6). The two habitat indexes correlated with each other and the WIHAB correlated with percent fines, which is a metric included in the index (Simonson et al. 1994).

Hydrologic Characteristics

Hydrologic characteristics did not correlate with any urban indicators for the group of all streams or sub-

TABLE 3. Spearman rank correlations among selected multi-scale geomorphic, habitat, and hydrologic characteristics and watershed characteristics for 45 streams in the Chicago area. Correlation coefficients shown have $P \leq 0.05$ unadjusted for multiple comparisons; bolded correlation coefficients have $P \leq 0.05$ based on Bonferroni adjustments.

	Urban indicators			Landscape characteristics										Geomorphic characteristics				Habitat characteristics									Hydrolgoic characteristics							Fish
	URBANLU	POPDENP	URBANDIS	DRAIN	WATCLAY	DRAINDEN	WATSLOP2	TRANSIN	SINUOS	BUFCOARS	BUFFOWE	RIPLU	CANOPY	SLOPELO	BFAREADA	POWER	EROSBF	FINES	BWDRAT	BWDRATCO	EROSION	RIFFLE	CHANSHCO	WOODDEBR	RBPHABIN	WIHABIN	BFLOWDA	FLOWXS	FLOWXSDA	FLOWVAR1	FLOWXS_P	Q2	Q2DA	FISHIBI
URBANLU	1.00																																	
POPDENP	–	1.00																																
URBANDIS	–	–	1.00																															
DRAIN	–0.39	–	**0.73**	1.00																														
WATCLAY	**0.58**	–	–	–0.38	1.00																													
DRAINDEN	–	–	–	–	–	1.00																												
WATSLOP2	–	0.30	–	–	–	0.34	1.00																											
TRANSIN	–	–	–0.32	–	–0.42	–	0.54	1.00																										
SINUOS	–	–	–	–	–	–	–	–	1.00																									
BUFCOARS	–	0.40	–	–	–0.47	–	–	0.30	–0.32	1.00																								
BUFFOWE	–	–	–	–0.39	0.31	–	**0.56**	–	–0.32	–	1.00																							
RIPLU	–	–0.34	–	–	–	–	–	–	–	–	–	1.00																						
CANOPY	–	–	–	0.39	–	–	–	–	–	–	–0.31	–	1.00																					
SLOPELO	–	0.29	–0.42	–0.45	–	–	–	0.44	–	–	–	–	–	1.00																				
BFAREADA	**0.59**	–0.30	–0.35	**–0.64**	**0.59**	–	–	–	–	–0.40	–	–	–0.37	–	1.00																			
POWER	–	–	–	–	–	–	–	–	0.29	–	–	–	–	**0.84**	–	1.00																		
EROSBF	–	–	–	–0.34	–	–	–0.35	–0.30	–	–	–	–	–	–	–	–	1.00																	
FINES	–	–0.36	–	–	–	–	–	–0.29	–0.29	–	–	–	–	**–0.56**	–	**–0.65**	**0.60**	1.00																
BWDRAT	–0.33	–	0.37	0.53	–0.40	–	–	–	–	–	–0.34	–	–	–	–0.45	–	–	–	1.00															
BWDRATCO	–	–	–	–	–	–	–	0.39	–	–	–	–	–	0.48	–	0.35	–	–	0.40	1.00														
EROSION	–	–	–	–	0.39	–	–0.30	–0.44	–	–0.44	–	–	–	–	–	–	–	–	–0.35	–0.35	1.00													
RIFFLE	–	–	–	–	–	–	–	–	–	–	–0.30	–	–	**0.71**	–	**0.70**	–	**–0.66**	–	0.30	–	1.00												
CHANSHCO	–0.33	–	–	–	–	0.34	–	–	–	–	–	–	–	0.30	–	–	–	–	–	0.39	–	0.38	1.00											
WOODEBR	–	–	–	–	–	–	–	–0.31	–	–	–	–	–0.49	–0.30	–	–	–	–	–	–	–	–0.33	–	1.00										
RBPHABIN	–	0.38	–	–	–	–	0.42	0.49	–	0.29	–	–0.36	–	0.38	–	0.39	–0.45	–0.53	0.36	0.52	–0.39	0.45	–	–	1.00									
WIHABIN	–	0.46	–		–	0.30	–	–	–	–	–	–0.42	–	0.34	–	–	–0.35	**–0.58**	–	0.31	–	0.43	–	–	**0.60**	1.00								
BFLOWDA	0.46	–	–0.38	**–0.66**	0.35	–	–	–	–	–0.32	–	–	–0.36	0.46	**0.87**	**0.60**	–	–	–0.34	–	–	–	–	–	–	–	1.00							
FLOWXS	–	–	0.40	**0.69**	–	–	–	–	–	–	–0.40	–	0.33	–0.42	–0.30	–0.29	–0.33	–	0.53	–	–	–	–	–	–	–	–0.41	1.00						
FLOWXSDA	–	–	–	–	–	–0.32	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	**0.72**	1.00					
FLOWVAR1	–	–	–	–0.52	–	–	–	–	–	–0.34	–	–	–0.37	0.45	0.54	0.54	–	–	–0.42	–	0.29	0.34	–	–	–	–	**0.71**	**–0.81**	**–0.65**	1.00				
FLOWXS_P	–0.51	–	–	0.54	–	–	–	–	0.34	–	–0.29	–	–	–	–0.37	–	–	–	0.49	–	–	–	–	–	–	–	–0.40	**–0.69**	0.46	**–0.60**	1.00			
Q2	–0.31	0.31	–	–	–0.48	**0.69**	**0.61**	**0.70**	0.49	0.50	–	–	0.39	–	–	0.42	–0.42	–	0.50	**0.61**	**–0.68**	–	–	–0.30	**0.78**	0.37	–	0.39	–	–	–	1.00		
Q2DA	0.48	–0.35	–0.87	**–0.89**	0.35	0.52	–	0.44	–	–0.51	0.29	–	–	0.41	**0.85**	0.33	–	–	–0.34	–	–	–	–	–	–	–	**0.90**	**–0.65**	–	**0.79**	–0.35	–	1.00	
FISHIBI	**–0.81**	0.29	–	0.43	**–0.57**	–	–	–	–	–	–0.33	–	–	–	–0.49	–	–	–	0.37	–	–	–	0.39	–	0.36	–	–0.31	–	–	–	0.47	0.40	–	1.00

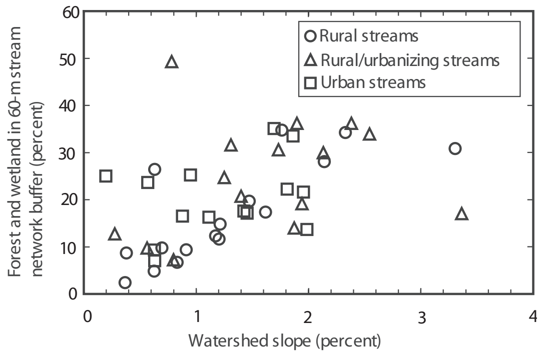


FIGURE 4. Plot of watershed slope and percent forest and wetland in the 60-m stream network buffer for 45 rural, rural/urbanizing, and urban streams in the Chicago area.

groups of clayey or loamy/sandy streams (Tables 3, 4, and 5; Figures 5D, E). Unit-area bank-full flow was negatively correlated with watershed size and positively correlated to unit-area bank-full channel area, stream power, flow variability, and unit-area 2-year flood peaks. Two-year flood peaks positively correlated with drainage density, watershed slope, and transport index. Unit-area 2-year flood peaks were positively correlated with stream power and negatively correlated with drainage area.

Examination of the effects of urbanization on base flow is complicated because most urban streams in the Chicago area have point source contributions that augment base flow (Figure 7). A scatter plot of streams with less than 3% of base flow resulting from point-source contributions and watershed urban land illustrates that rural and rural/urbanizing streams with both clayey and loamy/sandy surficial deposits have variable base flow, whereas urban streams have consistently low base flow (Figure 5D). Tinley Creek, Midlothian Creek, and Sawmill Creek are representative examples of urban streams (greater than 50% watershed urban land) with small base flows and little or no point-source contributions (Figure 7).

The scatter plot of unit-area 2-year flood peaks and urban land illustrates the complexity of the relation between percent urban land and the size of small, frequent floods (Figure 5E). From 0% to about 30% urban land, unit-area 2-year flood peaks increase linearly with percent urban land. Above 30% urban land, streams split into two groups of relatively small and large unit-area 2-year flood peaks. This change at about 30% urban land occurs near the boundary between rural/urbanizing streams and urban streams and may be caused by the extent or type of hydrologic modifications implemented in urban streams (e.g., combined sewers and storm-water detention). Of the 10 gauged streams with greater than 30% urban land, 5 have point-source discharges (N. Br. Chicago River, Skokie River, W. Br. Du Page River, Addison Creek, and Flag Creek) and 3 are in the TARP system (Flag Creek, Addison Creek, and Midlothian Creek). Physiographic setting may play a role because the urban streams with relatively large unit-area 2-year flood peaks have higher transport indexes than the urban streams with small unit-area 2-year flood peaks (Figure 5E).

Fish IBI Scores

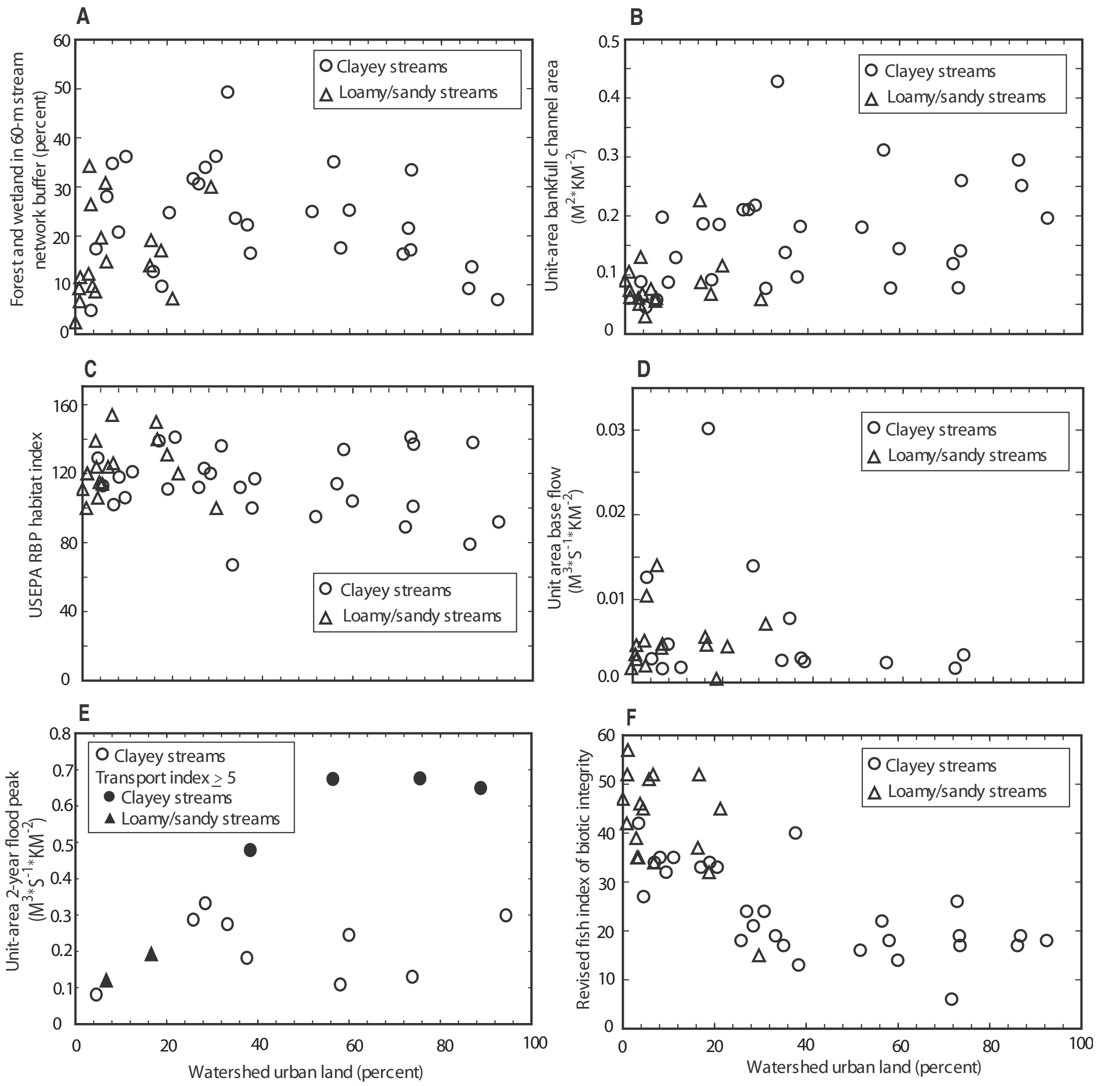
For all 45 streams, revised fish IBI scores had a higher correlation with watershed urban land than with any other geomorphic, habitat, or hydrologic characteristic (Table 3). High IBI scores occurred in streams with less than 25% watershed urban land, similar to Fitzpatrick et al. (2004) (Figure 5F). At 40% watershed urban land, all streams had IBI scores below 30. However, one clayey stream, Poplar Creek, had a relatively high IBI score of 40 with 38% watershed urban land.

In the revised fish IBI, 8 of the 10 metrics are expected to decrease with disturbance and 2 metrics are expected to increase. Nine of the 10 metrics responded as expected and had significant correlation coefficients with percent urban land. One metric reflecting the abundance of native sunfish did not correlate with percent urban land. The IBI had a stronger negative correlation with watershed urban land than did the individual metrics.

The fish IBI scores did not correlate with any landscape, geomorphic, habitat, or hydrologic characteristic except for a negative correlation with percent watershed clayey surficial deposits (Table 3). The total lack of correlation between fish IBI scores and watershed urban land for loamy/sandy streams compared to a relatively high (but not significant based on Bonferroni adjustments) correlation coefficient of –0.74 for clayey streams (Tables 4 and 5) suggests that fish IBI scores may respond more to urbanization in clayey streams than in loamy/sandy streams.

Redundancy Analysis

The RDA was used to examine the complex interrelations among revised fish IBI scores and geomorphic/habitat/hydrologic characteristics, as well as urban indicators and landscape characteristics. The RDA in-



FFGURE 5. Plots of percent watershed urban land and (A) percent forest and wetland in the 60-m stream network buffer for the 45 sampled streams, (B) bank-full channel area (normalized by drainage area) for the 45 sampled streams, (C) USEPA's rapid bioassessment protocol (RBP) habitat index for the 45 sampled streams, (D) estimated base flow (normalized by drainage area) for 30 streams with less than 3% of their base flow from point-source contributions, and (E) 2-year flood peaks (normalized by drainage area) for 15 streams with streamflow-gaging stations, and (F) revised fish index of biotic integrity scores for the 45 sampled streams in the Chicago area.

cluded 40 of the 45 streams. Five large, agricultural, loamy/sandy streams (sites 42–46) with less than 5% urban land were dropped from the RDA because they exaggerated the correlation among watershed urban land and surficial deposits. The streams also are in a separate physiographic province, which added to the potential for more natural variability in landscape and geomorphic/habitat characteristics. With the five sites removed, the Spearman correlation coefficient between watershed urban land and clayey surficial deposits dropped from 0.58 to 0.45.

As observed with the correlation results, the RDA biplot shows differing and overlapping responses of revised fish IBI and geomorphic, habitat, and hydrologic characteristics to urban indicators and landscape characteristics (Figure 8). The first two axes of the

TABLE 4. Spearman rank correlations among selected multi-scale geomorphic, habitat, and hydrologic characteristics and watershed characteristics for 15 streams with clayey surficial deposits and ≤ 33% watershed urban land in the Chicago area. Correlation coefficients shown have $P \leq 0.05$ unadjusted for multiple comparisons; bolded correlation coefficients have $P \leq 0.05$ based on Bonferroni adjustments.

	Urban indicators			Landscape characteristics										Geomorphic characteristics				Habitat characteristics									Hydrolgoic characteristics							Fish
	URBANLU	POPDENP	URBANDIS	DRAIN	WATCLAY	DRAINDEN	WATSLOP2	TRANSIN	SINUOS	BUFCOARS	BUFFOWE	RIPLU	CANOPY	SLOPELO	BFAREADA	POWER	EROSBF	FINES	BWDRAT	BWDRATCO	EROSION	RIFFLE	CHANSHCO	WOODDEBR	RBPHABIN	WIHABIN	BFLOWDA	FLOWXS	FLOWXSDA	FLOWVAR1	FLOWXS_P	Q2	Q2DA	FISHIBI
URBANLU	1.00																																	
POPDENP	–	1.00																																
URBANDIS	–	–	1.00																															
DRAIN	–	–	**0.87**	1.00																														
WATCLAY	–	–	–	–	1.00																													
DRAINDEN	–	–	–	–	–	1.00																												
WATSLOP2	–	–	–	–	–	0.73	1.00																											
TRANSIN	–	–	–	–	–	0.62	0.57	1.00																										
SINUOS	–	–	–	–	–	–	–	–	1.00																									
BUFCOARS	–	–	–	–	–0.80	–	–	–	–0.54	1.00																								
BUFFOWE	0.59	–	–	–	–	–	0.60	–	–	–	1.00																							
RIPLU	–	–	–	–	–	–	–	–	–	–	–	1.00																						
CANOPY	–0.51	–	–	0.65	–	0.56	–	–	–	–	–	–	1.00																					
SLOPELO	–	–	–0.60	–	–	–	–	0.66	–	–	–	–	–	1.00																				
BFAREADA	0.63	–	–0.52	–0.66	–	–	–	–	–	–	–	–	–0.83	–	1.00																			
POWER	–	–	–	–	–	–	–	–	–	–	–	–	–	**0.86**	–	1.00																		
EROSBF	–	–0.52	–	–	–	–	–	–	–0.63	–	–	–	–	–	–	–	1.00																	
FINES	–	–	–	–	–	–	–	–0.62	–0.56	–	–	–	–	–0.77	–	–0.82	0.75	1.00																
BWDRAT	–	–	0.53	0.53	–	–	–	–	–	–	–	–0.58	–	–	–0.55	–	–	–	1.00															
BWDRATCO	–	–	–	–	–	–	–	0.56	–	–	–	–	–	–	–	–	–0.57	–0.63	0.74	1.00														
EROSION	–	–	–	–	–	–	–	–	–	–	–	0.62	–	–	0.52	–	–	0.52	–0.79	–0.76	1.00													
RIFFLE	–	–	–	–	–	–	–	–	0.63	–	–	–	–	0.68	–	0.74	–0.74	–0.72	–	–	–	1.00												
CHANSHCO	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	0.52	–	–	–	–	1.00											
WOODDEBR	–	–0.51	–	–	–	–0.65	–0.69	**–0.84**	–	–	–	–	–	–0.57	–	–	0.64	0.65	–	–	–	–	–	1.00										
RBPHABIN	–	0.58	–	–	–	–	–	–	–	–	–	–	–	0.51	–	–	–0.72	–0.64	–	–	–	0.58	–	–	1.00									
WIHABIN	–	–	–	–	–	–	–	–	0.82	–	–	–	–	0.54	–	0.76	–0.71	–0.78	0.60	0.64	–	0.80	–0.60	–	0.52	1.00								
BFLOWDA	0.57	–	–0.61	–0.70	–	–	–	–	–	–	–	–	**–0.84**	–	**0.84**	0.57	–	–	–	–	–	–	–	–	–	–	1.00							
FLOWXS	–	–	–	0.55	–	–	–0.51	–	–	–	–0.70	–	–	–	–	–	–	–	0.72	–	–	–	–	–	–	0.56	–	1.00						
FLOWXSDA	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	0.59	–	–	–	–	–	0.66	–	–	–	0.63	–	0.76	1.00					
FLOWVAR1	0.57	–	–	–0.57	–	–	–	–	–	–	0.78	–	–0.57	–	0.74	–	–	–	–0.63	–	–	–	–	–	–	–	0.52	–0.81	–0.52	1.00				
FLOWXS_P	–	–	–	0.52	–	–	–0.52	–	–	–	–0.61	–	–	–	–	–	–	–	0.63	–	–	–	–	–	–	–	–	**0.97**	0.77	–0.78	1.00			
Q2	–0.80	0.60	–	0.80	–0.63	–	0.80	–	–	0.63	–0.80	**–0.95**	–	–	–0.80	–	–0.80	–	–	–	–	–	–0.80	–0.80	0.80	0.80	–0.80	0.78	–	–0.80	–	1.00		
Q2DA	–	–	–0.80	–	0.63	–	–	0.80	0.74	–0.63	–	–	–	**0.95**	–	–	–	–0.80	–	–	–	0.78	–	–	–	–	–	–0.78	**–0.89**	–	–	–	1.00	
FISHIBI	–0.74	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	0.80	–	1.00

TABLE 5. Spearman rank correlations among selected multi-scale geomorphic, habitat, and hydrologic characteristics and watershed characteristics for 17 streams with loamy/sandy surficial deposits in the Chicago area. Correlation coefficients shown have $P \leq 0.05$ unadjusted for multiple comparisons; bolded correlation coefficients have $P \leq 0.05$ based on Bonferroni adjustments.

	Urban indicators			Landscape characteristics										Geomorphic characteristics				Habitat characteristics									Hydrolgoic characteristics							Fish
	URBANLU	POPDENP	URBANDIS	DRAIN	WATCLAY	DRAINDEN	WATSLOP2	TRANSIN	SINUOS	BUFCOARS	BUFFOWE	RIPLU	CANOPY	SLOPELO	BFAREADA	POWER	EROSBF	FINES	BWDRAT	BWDRATCO	EROSION	RIFFLE	CHANSHCO	WOODDEBR	RBPHABIN	WIHABIN	BFLOWDA	FLOWXS	FLOWXSDA	FLOWVAR1	FLOWXS_P	Q2	Q2DA	FISHIBI
URBANLU	1.00																																	
POPDENP	0.63	1.00																																
URBANDIS	–	–	1.00																															
DRAIN	–	–	0.60	1.00																														
WATCLAY	–	–	–	–	1.00																													
DRAINDEN	–	–	–	–	–	1.00																												
WATSLOP2	0.52	–	–	–	–	–	1.00																											
TRANSIN	–	–	–	–	–	–	0.71	1.00																										
SINUOS	–	–	0.64	0.55	–	–	–	–	1.00																									
BUFCOARS	0.48	0.58	–	–	–	–	–	–	–0.52	1.00																								
BUFFOWE	–	–	–	–	–	–	0.74	0.74	–0.56	–	1.00																							
RIPLU	–	–	–	–	–	–	–	–	–	–	–	1.00																						
CANOPY	–	–	–	–	–	–	–	–	–	–	–	–	1.00																					
SLOPELO	–	–	–	–0.60	–	–	–	–	–	–	–	–	–	1.00																				
BFAREADA	–	–	–	–	–	–	–	–	–	–	–	–	–	–	1.00																			
POWER	–	–	–	–	–	–	–	–	–	–	–	–	–	**0.82**	0.52	1.00																		
EROSBF	–	–	–	–0.49	–	–	–	–	–	–	–	–	–	0.60	–	0.51	1.00																	
FINES	–	–0.68	–	–	–	–	–	–	–	–	–	–	–	–0.53	–	–0.48	–	1.00																
BWDRAT	–	–	–	–	–	0.51	–	–	–	–	–	–	–	–	–	–	–	–	1.00															
BWDRATCO	–	–	–	–0.53	–	–	–	–	–	–	–	–	–	0.60	–	–	0.79	–	–	1.00														
EROSION	–	–	0.57	0.64	–	–	–0.58	–0.60	0.48	–	–0.68	–	–	–	–	–	–	–	–	–	1.00													
RIFFLE	–	–	–	–	–	–	–	–	–	–	–	–	–	0.80	–	0.70	–	–0.52	–	–	–	1.00												
CHANSHCO	–	–	–	–	–	0.63	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	1.00											
WOODDEBR	–0.48	–	–	–	–	–	–	–	–	–	–	–	–0.50	–	–	–	–	–	–	–	–	–	–	1.00										
RBPHABIN	–	0.61	–	–	–	–	–	–	–0.54	–	–	–	–	0.51	–	–	–	–0.64	–	–	–	–	–	–	1.00									
WIHABIN	–	0.61	–	–	–	–	0.61	0.54	–	–	–	–	–	–	–	–	–	–	–	0.48	–0.5	–	–	–	0.55	1.00								
BFLOWDA	–	–	–	–	–	–	–	–	–	–	–	–	–	0.63	**0.86**	**0.85**	0.60	–	–	–	–	–	–	–	–	–	1.00							
FLOWXS	–	–	–	0.76	–	–	–	–	–	–	–	–0.72	–	–0.65	–	–0.49	–	–	–	–	–	–0.61	–	–	–	–	–	1.00						
FLOWXSDA	–	–	–	–	0.65	–	–	–	–	–	–	–	–	–	–	–0.48	–	–	–	–	–	–0.53	–	–	–	–	–	0.61	1.00					
FLOWVAR1	–	–	–	–	–	–	–	–	–	–	–	–	–	0.69	0.52	**0.90**	–	–	–	–	–	0.58	–	–	–	–	0.79	–0.64	–0.67	1.00				
FLOWXS_P	–	–	–	0.74	–	–	–	–	–	–	–	–0.70	–	–0.63	–	–	–	–	–	–	–	–0.61	–	–	–	–	–	**0.99**	0.63	–0.62	1.00			
Q2	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	1.00		
Q2DA	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	1.00	
FISHIBI	–	–	–	–	–	0.59	–	–	–	–	–	–	0.48	–	–	–	–	–	–	–	–	–	–	–0.50	–	–	–	–	–	–	–	–	–	1.00

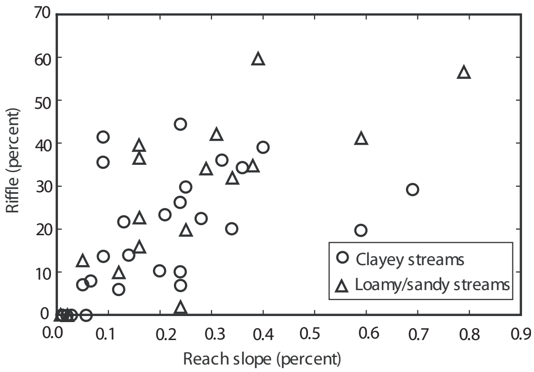


FIGURE 6. Plot of reach slope and percent riffles for clayey streams in the Chicago area.

RDA explained 68% of the variance, with the first axis explaining 55%. Monte Carlo permutation tests indicated that both axes were significant ($P = 0.002$). The first RDA axis is mainly a reflection of watershed urban land, drainage area, and clayey surficial deposits (correlation coefficients of –0.68, 0.63, and –0.46, respectively). The second RDA axis reflects a combination of features including population density change, watershed urban land, reach slope, clayey surficial deposits, coarse deposits in the 60-m stream network buffer, watershed slope, and transport index (correlation coefficients of 0.56, –0.53, 0.47, –0.46, 0.45, 0.41, and 0.40, respectively).

Among geomorphic and habitat characteristics, unit-area bank-full channel area was the strongest response variable and plotted closely to watershed urban land and clayey surficial deposits, whereas bank-full width/depth ratios plotted directly opposite watershed urban land and clayey surficial deposits (Figure 8). Thus, clayey urban streams had relatively large, narrow channels. Amount of fine substrate plotted closely along RDA axis 2, and opposite to the coefficient of variation of the bank-full width/depth ratio (a measurement of habitat variability), watershed and reach slope, and transport index. Thus, slope and runoff appear to be the main determinates of the amount of fine substrate and habitat variability. The RBP habitat index plotted near population density change and coarse surficial deposits in the 60-m stream network buffer and opposite erosion, indicating that these factors potentially were most influential on the habitat index.

Flow variability plotted opposite the amount of base flow (accounting for point sources) and drainage

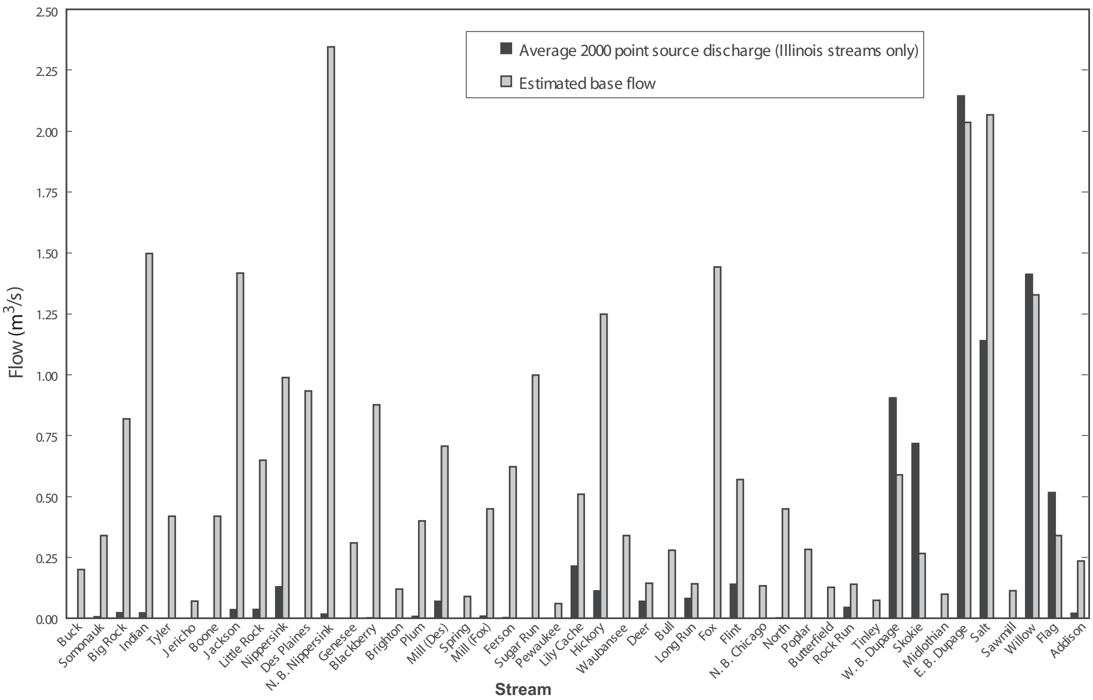


FIGURE 7. Average flow from point sources in 2000 and estimated base flow for 45 streams in the Chicago area.

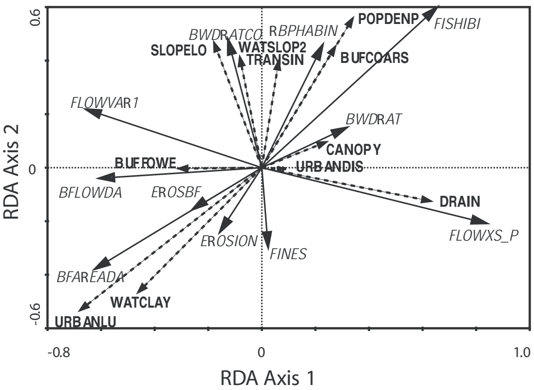


FIGURE 8. Redundancy analysis (RDA) biplot of representative landscape characteristics in relation to geomorphic, habitat, and hydrologic characteristics and revised fish IBI scores for 40 streams in the Chicago area. Refer to Table 2 for definition of abbreviations. Arrows are dashed and abbreviations are bolded for the independent variables (urban indicators and landscape characteristics).

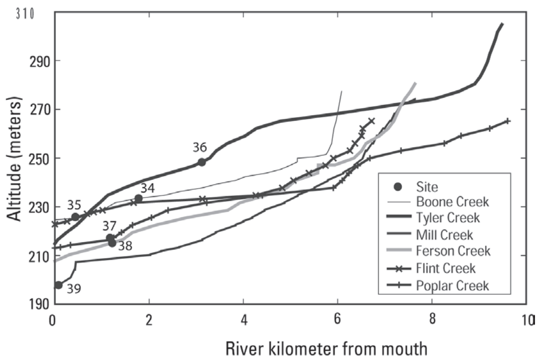


FIGURE 9. Longitudinal profiles for six tributaries to the Fox River in the Chicago area. Sampling sites with map reference numbers from Figure 1 are shown as circles on the profiles.

area. This suggests that small streams with high flow variability tended to have low base flow.

Fish IBI scores plotted opposite watershed urban land and clayey surficial deposits, indicating that IBI scores for clayey streams were negatively influenced by the amount of urbanization. Unit-area bank-full channel area plotted directly opposite fish IBI scores as well, indicating that channel enlargement may be the best reflection of physical disturbance to fish habitat associated with urbanization in clayey streams.

Longitudinal Profiles, Local Geologic Setting, and Stream Network Position

Longitudinal profiles and local geologic setting for six tributaries to the Fox River illustrate the complexity of how glacial landforms may influence geomorphic, habitat, hydrologic, and fish characteristics (Figures 2 and 9; Table 6). The six streams are located near each other (within about a 50-km radius) and represent three pairs of streams with similar percentages of watershed urban land (3%, 16–17%, and 31–38%). In general, reaches with steep slopes on the longitudinal profile are prone to incision, whereas reaches with flat slopes are prone to deposition. Reaches in a transition from steep to flat slopes may be erosional or depositional depending on upstream inputs of water and sediment. For Chicago area streams, transitions in slope and shape of longitudinal profiles mainly are caused by spatial distribution of glacial landforms such as end moraines, outwash plains, lake plains, melt-water valleys, or bedrock outcrops.

Some of the variability in geomorphic and habitat characteristics can be explained by location of sampled reach in relation to local glacial and fluvial landforms (Figure 9). Boone and Tyler Creeks are rural streams with similar reach slopes (Table 6). However, the Boone Creek Reach (site 34) is flat and located in a sandy outwash plain, and the Tyler Creek Reach (site 36) is located in a transition zone in slope where the stream is flowing through end moraine and esker deposits. Boone Creek has finer substrate (sand included) and fewer riffles than Tyler Creek, even though overall it has less watershed clay than Tyler Creek. The eskers near Tyler Creek contribute sand and gravel that, along with the locally steep slope, promote development of riffles.

Mill (site 39) and Ferson Creek (site 38) are both rural/urbanizing streams with large changes in population density. Both have similar drainage areas, longitudinal profiles, and local glacial landforms but different reach slopes, bank-full areas, stream power, unit-area bank-full flows, and revised fish IBI scores. The Mill Creek Reach is downstream from a dam and is on the steep slope of the Fox River valley side, which consists of limestone bedrock. This local setting results in a steeper reach slope, higher power, and larger bank-full area for Mill Creek compared to Ferson Creek. The high scour potential at Mill Creek may be affecting the IBI scores. Ferson Creek's IBI scores may be elevated because of channel restoration and habitat improvements in recent years.

Flint and Poplar creeks both are clayey tributaries to the Fox River with similar drainage areas (Table 6).

TABLE 6. Values of watershed, geomorphic, habitat, hydrologic characteristics and revised fish IBI scores for six tributaries to the Fox River in the Chicago area.

Characteristic	Abbreviation	Boone Creek	Tyler Creek	Mill Cr. (Fox)	Ferson Creek	Flint Creek	Poplar Creek
Urban indicators							
Watershed urban land (%)	URBANLU	3	3	16	17	31	38
Population density change, 1980–2000 (%)	POPDENP	6	50	298	411	339	880
Landscape characteristics							
Drainage area (km^2)	DRAIN	40	81	80	134	96	94
Watershed clayey surficial deposits (%)	WATCLAY	18	49	39	17	93	87
Watershed slope (%)	WATSLOP2	0.6	1.2	1.9	1.9	2.4	1.8
Transport index *1,000 (km^{-1})	TRANSIN	7.1	5.8	7.2	8.5	5.6	4.0
Coarse deposits within 60-m stream network buffer (%)	BUFCOARS	25	0	29	39	7	4
Forest and wetland within 60-m stream network buffer (%)	BUFFOWE	26	12	14	19	36	22
Disturbed land cover in 30-m buffer (%)	RIPLU	27	9	0	9	0	68
Average open canopy angle (°)	CANOPY	75	77	25	87	82	12
Geomorphic characteristics							
Slope, low-flow water surface (%)	SLOPELO	0.24	0.25	0.59	0.34	0.36	0.28
Bank-full channel area/drainage area (m^2/km^2)	BFAREADA	0.13	0.06	0.23	0.09	0.08	0.10
Stream power ($N/(m\ s)$)	POWER	10.6	6.7	148.8	34.9	14.7	31.1
Habitat characteristics							
Fine substrate (%)	FINES	79	24	13	6	12	3
Average bank-full channel width/depth (ratio)	BWDRAT	10	9	17	16	29	8
Average bank erosion (m)	EROSION	0.5	0.2	0.2	0.7	0.2	0.8
Amount of riffle in reach (%)	RIFFLE	2	20	41	32	34	22
Coefficient of variation of wetted channel shape index	CHANSHCO	32	64	36	63	42	29
USEPA rapid bioassessment protocol (RBP) habitat index	RBPHABIN	106	139	150	140	136	100
Hydrologic characteristics							
Bank-full flow/drainage area ($m^3/s/km^2$)	BFLOWDA	0.11	0.04	0.39	0.11	0.07	0.10
Estimated base flow at time of cross-section surveys (m^3/s)	FLOWXS	0.42	0.42	0.45	0.62	0.57	0.28
Estimated base flow/drainage area ($m^3/s/km^2$)	FLOWXSDA	0.0105	0.0052	0.0056	0.0047	0.0060	0.0030
Bank-full flow/estimated low flow (ratio)	FLOWVAR1	10.1	8.4	69.2	22.7	12.4	35.0
Estimated base flow - average 2000 point source flow (m^3/s)	FLOWXS_P	0.42	0.42	0.44	0.62	0.43	0.28
Fish							
Revised fish index of biotic integrity	FISHIBI	35	39	37	52	24	40

Poplar Creek (site 37) has slightly more watershed urban land and larger population density but maintains a higher revised fish IBI score than Flint Creek. In headwater areas, both flow off of a large end moraine of clayey till. Near the sampled reaches, Poplar Creek flows across an outwash plain and has a more defined valley than Flint Creek (site 35). The Poplar Creek Reach is located in a transition zone from steep to flat slope, and the Flint Creek Reach is located in a zone of relatively steep slope (Figure 9). Bank-full area, bank-full flow, and bank erosion are slightly higher, and bank-full width/depth ratio is slightly lower in Poplar Creek compared to Flint Creek. This may be caused by the slightly higher watershed urban land and population density change in Poplar Creek. It is not known what is causing the higher fish IBI scores in Poplar compared to Flint Creek. The longitudinal profile and sampling reach location for Ferson Creek is similar to that for Poplar Creek, and Ferson Creek had one of the highest revised fish IBI scores.

These example comparisons show that, in some cases, local factors of geologic setting and landforms and the boundaries and transitions between them can explain some of the variability in geomorphic and habitat characteristics and fish IBI scores. These factors are not easy to quantify, and are difficult to explore through typical multivariate statistical techniques.

Discussion and Conclusions

Clayey streams with high percent urban land had large bank-full channel areas and low fish IBI scores. Bank-full channel area (normalized by drainage area) showed the highest positive correlation to percent watershed urban land of all geomorphic, habitat, and hydrologic characteristics analyzed. There are multiple geomorphic processes by which a channel can enlarge, including incision, widening, and overbank deposition. As the magnitude of frequent floods increase with increasing imperviousness, channels with noncohesive banks, low slopes, base-level control, or armored substrates may be more likely to widen, whereas channels with cohesive banks, steep slopes, no base-level control, and erodible substrate may be more likely to incise. In our study, streams with large bank-full channel areas tended to have deeper channels (low bank-full width/depth ratios). When streams were split into two groups based on watershed surficial deposits, only clayey streams showed a positive correlation between enlarged bank-full channel areas and watershed urban land, an indication that geomorphic conditions in clayey streams may be more responsive to urbanization than loamy/sandy streams. Booth (1990) also found that, in the Pacific Northwest, a combination of steep slopes and clayey deposits resulted in streams susceptible to incision. Our study was limited by only having loamy/sandy streams with less than or equal to 31% urban land. The potential moderating effects of watershed surficial deposits should be examined at loamy/sandy streams with higher percent urban land.

Geomorphic and habitat characteristics such as stream power, fine substrate, bank erosion, woody debris, and habitat indexes were most related to reach slope, surficial deposits, and transport index. Compared to the studies of Pacific Northwest streams (Booth 1991; Finkenbine et al. 2000), the relations in Chicago-area streams among urbanization and the amount of woody debris and bank erosion were subtle. Only clayey streams in our study had a statistically significant negative correlation between woody debris and the transport index. Bank erosion and erosivity at bank-full flow did not directly correlate with watershed urban land but the two characteristics plotted closely to percent watershed urban land and clayey deposits on the RDA biplot (Figure 8). The complexity of relations observed in these streams compared to the Pacific Northwest streams could be because the land-cover gradient used in our study ranged from agriculture to urban, and the streams potentially have had multiple historical human alterations.

Habitat index scores showed little or no response to urbanization; instead, they appeared to increase with increasing slope. Based on RDA results, high RBP habitat index scores were related to high slope, population density change, and percentage of coarse deposits in the 60-m stream network buffer; and low percentages of clayey surficial deposits and watershed urban land. In a forest-to-agricultural gradient study in eastern Wisconsin, the WDNR habitat index correlated with fish IBI scores and amount of undisturbed riparian buffer, as well as slope (Fitzpatrick et al. 2001). In the Chicago area, local geologic setting and glacial landforms determine reach slope for the most part, not modern fluvial geomorphic processes. In addition, the range of reach slopes in studied streams was relatively small, with all reaches having slopes of less than 1%.Results from our study indicate that the habitat indexes are less useful in accounting for urbanization-caused habitat degradation. This may reflect complex geomorphic processes that vary both spatially and temporally during urbanization. Habitat indexes combine characteristics from different geomorphic processes and, thus, can be insensitive to substantial changes of individual processes. Habitat indexes that have mainly been developed and used on streams impacted by agricultural practices may need refinement when used on streams impacted by urban development.

Hydrologic effects from urbanization were confounded by differences in stormwater control and sewering practices (presence of combined-sewer systems and TARP) and point-source contributions. For streams with less than 30% watershed urban land, there was a positive relation between unit-area 2-year flood peaks and percent watershed urban land. For streams with greater than 30% watershed urban land, effects from point sources, combined sewer overflows, TARP, and physiographic setting confounded the positive relation. In watersheds with a high transport index (high relief and dense drainage pattern), storm-water control efforts may be less effective at moderating small, frequent flood peaks. Effectiveness of storm-water control measures and hydrologic alterations for decreasing peak flows of small, frequent floods is variable (Finkenbine et al. 2000; Booth and Jackson 1997). Detention basins may cause more incision because they increase the duration of high flows (McCuen and Moglen 1988). Culvert placement is another important aspect influencing flood peaks and geomorphic stability (Whipple and DiLouie 1981). No information for these local factors that affect stormwater was gathered during our study.

Base flow (adjusted for point sources) in our study was consistently low in streams with more than about 33% watershed urban land (roughly equal to 10% total impervious area). Below 33% watershed urban land, base flow was variable. Near Vancouver, British Columbia, base flow was low in streams with watersheds that had more than 40% total impervious area (Finkenbine et al. 2000). Streams in the Chicago area with greater than 33% watershed urban land had low base flow, but the effects of urbanization were offset by point-source contributions.

More local information regarding stormwater practices, as well as historical stream stabilization and channelization projects, is needed to better explain the hydrologic variability for Chicago-area streams. More insight into how hydrologic conditions change for urbanizing streams could be obtained by evaluating other types of streamflow data from gauging stations in urban or urbanizing areas, such as total annual flow, seasonality of flow, base flow, flow duration, annual/seasonal flow volumes, and annual/seasonal precipitation. In addition to comparisons among gauges, historical analysis of data from a single gauging station could be performed to identify changes in hydrologic conditions for specific historical land development, storm-water control, or sewerage practices.

Revised fish IBI scores had the highest correlation with watershed urban land of all characteristics examined. The IBI scores also were negatively correlated to watershed clayey deposits and bank-full channel area. Historical data for the Chicago area show that IBI scores most strongly relate to population density and watershed urban land cover and possibly to the amount of clayey surficial deposits (Fitzpatrick et al. 2004; no historical data were available for bank-full channel area or base flow). Correlations indicated that fish IBI scores were affected by early stages of urbanization more so in clayey streams than in loamy/sandy streams. Relations among channel enlargement and increasing urban land were more pronounced in clayey streams. However, these relations are still tentative and may be artifacts of historical alterations from agricultural land use. In addition, historical data from some clayey sites suggest that IBI scores may be dependent on fish passage issues (Fitzpatrick et al. 2004).

Geomorphic and hydrologic responses to urbanization generally were continuous among the streams; only fish IBI scores showed a possible degradation threshold, with low scores occurring in watersheds with more than 25% watershed urban land and no high scores in watersheds with greater than 40% watershed urban land. Data from other studies of aquatic communities and urbanization have not shown a threshold response, but suggest that degradation occurs as a continuum (Booth and Jackson 1997; Fitzpatrick et al. 2004). Booth and Jackson (1997) suggest that the abrupt transition (or threshold) for urban-related degradation of aquatic communities is based on human "perception of" and "tolerance for" degradation. The revised IBI used in this study may better reflect the level and scope of aquatic-community degradation tolerated and perceived as negative by humans.

Presence of stream buffers with forest and wetland did not influence geomorphic, habitat, or hydrologic characteristics, or IBI scores. Lack of correlation among forest/wetland in the stream network buffer, fish IBI scores, and base flow is in contrast to relations observed in a study of eastern Wisconsin streams along a forest-to-agriculture land-cover gradient, where the amount of forest/wetland/grassland vegetation in the stream network buffer was positively correlated with fish IBI scores and base flow (Fitzpatrick et al. 2001). This suggests that forested riparian buffers are less able to moderate the influence of urbanization on geomorphic, habitat, and hydrologic characteristics and biotic integrity of streams probably because of hydrologic alterations (such as storm sewers, detention basins, and point-source discharges) that directly bypass riparian buffers.

The range in spatial-scale of urban indicator, landscape, geomorphic, habitat, and hydrologic data used in this study helped to infer geomorphic processes in urbanizing streams and describe the response of fish biotic integrity to urbanization. However, these data were not detailed enough to confirm the geomorphic processes at work in each stream reach. Geomorphic processes at a particular reach may be influenced by present and historical upstream or downstream disturbances, such as watershed land-use and past agricultural practices, knickpoint migration, channelization, or restoration/rehabilitation projects. Longitudinal profiles were useful for distinguishing differences in local geologic settings among sampled sites. The longitudinal profiles helped to distinguish the proximity of reaches to transitions in slope that are caused by glacial landforms and gave an indication of whether erosion, transport, or deposition was dominant. Additional information on local geomorphic processes can be gained through a variety of methods, including (1) more detailed geomorphic assessments oriented toward geomorphic processes with a historical and watershed approach, such as Thorne's (1998) geomorphic reconnaissance surveys, (2) sampling at many locations within stream networks, (3) collecting temporal data (monitoring) during urban development in the watershed, and (4) collecting historical information on past land-use practices and channel alteration.

In conclusion, for Chicago-area streams, some geomorphic, habitat, and hydrologic characteristics and fish biotic integrity were affected by urbanization. However, the percent watershed slope and clayey surficial deposits influenced the effects, as did other more local factors such as reach slope, glacial landforms, and hydrologic alterations (stormwater practices and point sources), and historical and present channel alterations. Specific local-scale and temporal data on geomorphic processes are needed to distinguish the cause and effect relations between urbanization and habitat characteristics.

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