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Urbanization Effects on Stream Habitat Characteristics in Boston, Massachusetts; Birmingham, Alabama; and Salt Lake City, Utah

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Abstract.—Relations between stream habitat and urban land-use intensity were examined in 90 stream reaches located in or near the metropolitan areas of Salt Lake City, Utah (SLC); Birmingham, Alabama (BIR); and Boston, Massachusetts (BOS). Urban intensity was based on a multi-metric index (urban intensity index or UII) that included measures of land cover, socioeconomic organization, and urban infrastructure. Twenty-eight physical variables describing channel morphology, hydraulic properties, and streambed conditions were examined. None of the habitat variables was significantly correlated with urbanization intensity in all three study areas. Urbanization effects on stream habitat were less apparent for streams in SLC and BIR, owing to the strong influence of basin slope (SLC) and drought conditions (BIR) on local flow regimes. Streamflow in the BOS study area was not unduly influenced by similar conditions of climate and physiography, and habitat conditions in these streams were more responsive to urbanization. Urbanization in BOS contributed to higher discharge, channel deepening, and increased loading of fine-grained particles to stream channels. The modifying influence of basin slope and climate on hydrology of streams in SLC and BIR limited our ability to effectively compare habitat responses among different urban settings and identify common responses that might be of interest to restoration or water management programs. Successful application of land-use models such as the UII to compare urbanization effects on stream habitat in different environmental settings must account for inherent differences in natural and anthropogenic factors affecting stream hydrology and geomorphology. The challenge to future management of urban development is to further quantify these differences by building upon existing models, and ultimately develop a broader understanding of urbanization effects on aquatic ecosystems.

Introduction

Despite the fact that urbanization represents a relatively small component of human-caused landscape change (U.S. Environmental Protection Agency 2000), urban development has a profoundly degrading influence on stream ecosystems (Grimm et al. 2000; Paul and Meyer 2001). The disproportionately large influence of urbanization on surface water systems can be attributed to dramatic changes in land surface characteristics, such as soil properties, vegetative cover, and runoff potential as impervious surface area increases,

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and to changes in water management practices implemented to offset adverse effects of population growth on domestic water resources (McDonnell et al. 1997; Grimm et al. 2000). Physical properties of streams are particularly vulnerable to landscape disturbance caused by urbanization, and the detrimental effects of urban development on stream hydrology and geomorphology have been documented in numerous studies (Hammer 1972; Klein 1979; Gregory et al. 1992; Booth and Jackson 1997; Finkenbine et al. 2000). However, relatively few studies have examined differences in the effects of urbanization on stream habitat in widely contrasting land-use settings, where differences in climate, physiography, and geology could modify how hydrologic and geomorphic conditions are changing in response to urban development (Paul and Meyer 2001). Landscape disturbances in these complex and heterogeneous environments are highly variable (McDonnell and Pickett 1990; Zipperer et al. 2000), and it is unclear whether urbanization affects stream habitat similarly in different environmental settings.

To characterize the effects of urbanization on stream ecology in contrasting environmental settings, the National Water-Quality Assessment (NAWQA) Program of the U.S. Geological Survey investigated the relations between urbanization and the physical, chemical, and biological conditions of streams in the metropolitan areas of Boston, Massachusetts; Birmingham, Alabama; and Salt Lake City, Utah. These urban areas provided contrasting conditions of climate, physiography, geological setting, vegetation types, and soils (Tate et al. 2005, this volume). This study presents results of the effects of urbanization on stream physical habitat. The objectives were to (1) characterize and compare habitat conditions in urban streams in different urban areas, (2) examine relationships between stream habitat and urbanization using a multi-metric index of urban intensity, and (3) compare physical responses to urbanization in contrasting environmental settings to identify common indicators of urbanization effects on stream habitat.

Study Areas

Study sites consisted of stream reaches located in the metropolitan and surrounding areas of Boston (BOS), Birmingham (BIR), and Salt Lake City (SLC). Sites in each urban area were selected from a pool of candidate watersheds representing a gradient of urbanization defined by an urban intensity index (UII) described in McMahon and Cuffney (2000). The UII is a multimetric index that combines measures of watershed land use, infrastructure (e.g., numbers of sewers, roads, and stormwater drains), population and socioeconomic condition (e.g., income levels and home ownership) into a single measure of urban intensity. Values for each measure are standardized and scaled to a numerical range of urban intensity from 0 (low intensity) to 100 (high intensity). Additional details describing the calculation of the urban intensity index for each of the three urban areas, and maps of the study sites and basin boundaries, are provided in Tate et al. (2005).

Sites were located primarily on 3rd- to 5th-order streams (Strahler 1957), although a few 2nd- and 6th-order streams were included. Boundaries for each candidate watershed were delineated using 30-m digital elevation model (DEM) data in conjunction with geographic information system (GIS) programs (U.S. Geological Survey 2000). It was possible in the BOS study area to locate sites in each of 30 different drainage basins. Severe drought conditions occurred in the southeast during the summer of 2000, and as a result, 2 of the 30 candidate sites in BIR went dry and were excluded from the study. Owing to the relative paucity of perennial flowing streams in the SLC study area, it was necessary to locate more than one site within some drainage basins. This resulted in 30 sites being located in 17 different drainages. Streams in the SLC area have their headwaters in the Wasatch and Uinta Mountains and flow westerly to their eventual terminus in Great Salt Lake (Tate et al. 2005). The mountainous terrain adjacent to the Salt Lake City metropolitan area resulted in study sites having a relatively wide range of water-surface gradients (0.4% to 16.6%) compared to streams in BOS and BIR where basin slopes were generally lower and considerably less variable (Table 1).

Median reach lengths were similar among study areas and ranged from 150 to 163 m. While it was possible to establish reaches of 150 m for all sites in BOS, reach lengths varied for BIR (140–300 m) and SLC (81–295 m). Median basin areas for SLC streams were small (4.5 km^2) compared to streams in BOS (72.0 km^2) and BIR (33.5 km^2). Much of the water contributing to streamflows in SLC was diverted prior to entering the study area. The relatively small basin sizes for streams in SLC (Table 1) resulted from the use of modified basin boundaries that more accurately reflected catchment contributions to streamflow in the urban area (see Tate et al. 2005 for details). In spite of the fact that drainage basin areas were generally larger in BIR than SLC, drought conditions in BIR resulted in relatively low median flows (0.086 m^3/s). Median discharge for BOS streams (0.680 m^3/s) was the highest of the three study areas.

TABLE 1. Characteristics of study sites in the Boston (BOS), Birmingham (BIR), and Salt Lake City (SLC) areas. Median values with ranges given in parentheses.

Study area	Sites	Basin area (km^2)	Basin elevation range (m)	Segment length (m)	Reach length (m)	Reach gradient (%)	Discharge (m^3/s)
BOS	30	73.0	156	1,203	150[a]	0.54	0.680
		(45.8–124.7)	(76–485)	(200–5,871)		(0.12–1.62)	(0.018-2.847)
BIR	28	33.5	205	1,567	160	0.36	0.086
		(4.7–66.1)	(85–428)	(260–5,320)	(140–300)	(0.03–0.67)	(0.001–1.723)
SLC	30	4.5[b]	222	1,352	163	1.01	0.242
		(0.3–29.0)	(33–1,351)	(131–3,507)	(81–295)	(0.40–16.6)	(0.002–3.874)

[a] All reach lengths were 150 m.
[b] Basin areas based on modified boundary delineations (see Tate et al. 2005).

In order to minimize local-scale differences in physical properties that might confound interpretation of broader-scale urbanization effects, sampling locations were limited to reaches that were free-flowing for at least 150 m, showed no evidence of recent anthropogenic modification, and had relatively well-defined banks with at least 50% mature vegetation cover. In addition, biological sampling was facilitated by selecting reaches with natural substrates and riffle habitats. The presence of riffles for biological sampling was necessary to reduce among-site variability in substrate size and composition of benthic habitats, thereby minimizing substrate-dependent effects on invertebrate and algae community richness (Ward 1992; Burkholder 1996; Cuffney et al. 2005; Potapova et al. 2005; both this volume).

Methods

Habitat Parameters

Habitat assessments were conducted in the three study areas during June to August 2000. Base flow conditions were predominant for most streams during this period. Lowest flows typically occur in the BOS area in July through September (Flanagan et al. 1999), and in June through September in BIR (Johnson et al. 2002). Flow regimes for streams in BIR were altered by drought conditions resulting in flows below the long-term (>50 year) average (Atkins et al. 2004). Streams in the SLC area generally experience lowest flows during October to March (Baskin et al. 2002); however, many of the smaller streams become intermittent during this period, and sampling during June to August ensured that flows would be sufficient for completing habitat and biological assessments. Sampling during base flow conditions was desirable because it represented a period of relative hydrologic stability that allowed for greater consistency in application of habitat and biological survey methods.

Determinations of hydraulic parameters, channel morphology, bank characteristics, substrate particle size, and instream cover were based on methods described in Fitzpatrick et al. (1998). Eleven equidistant transects perpendicular to the direction of flow were established within the longitudinal boundaries of each reach. Bank-full width, bank-full depth, and wetted channel width were measured at each transect location. In addition, wetted depth and flow velocity were recorded at three locations along each transect. Aspect of stream flow (compass heading in degrees) was determined at mid-channel between adjacent transects. Standard deviation of average stream aspect was used as a relative measure of reach sinuosity, with higher values representing greater sinuosity. At each transect, the presence of a habitat cover type (overhanging vegetation, undercut banks, woody debris, boulders, macrophytes, artificial structures) that could provide refuge for fish or other organisms was recorded at channel margins near the edge of water and at three other locations in the main channel (limited to woody debris, boulders, macrophytes, and artificial structures). Twenty-four types of habitat cover were possible at each transect location. The proportion of cover types occurring within a stream reach was calculated as percent cover.

Visual estimates of dominant substrate particle size, percent siltation, and percent embeddedness were conducted at three locations along each transect. Particle size was based on a categorical scale of 1–10, with 1 representing the smallest particles (silt/clay) and 10 representing the largest (large boulder). Percent composition of the substrate consisting of sand and smaller-sized particles was used as an estimate of percent fines. Percent composition of sand and smaller-sized particles were summed as percent fines. The presence or absence of predominantly silt- and clay-sized particles (<1 mm) on bottom surfaces was recorded at each location, averaged for all locations in the reach, and reported as percent siltation. Embeddedness (nearest 10%) was determined for gravel and larger-sized particles, and averaged for each reach. The ratio of dominant particle size to wetted depth was used as an estimate of streambed roughness, with higher values indicating greater hydraulic roughness (Leopold et al. 1992).

Riparian vegetation density (percent) was measured near stream channel margins at each transect location using a hemispherical densiometer (Platts et al. 1987). Bank characteristics were determined at each transect, and consisted of bank angle, bank height, dominant substrate size (as described for bed substrate), and percent vegetative cover. These variables were used to calculate a multimetric index of bank stability (Fitzpatrick et al. 1998). Index values ranged from 4 to 22, with higher values representing greater bank instability.

Change in water surface elevation between reach boundaries was determined by surveying and used to calculate reach gradient. Lengths of major fluvial geomorphic features (riffles, runs, pools) were measured and used to determine the proportion of these features in each reach. Occurrences of riffles and runs are not reported in this study. Average reach discharge was calculated based on measurements of wetted cross-sectional area and flow velocities taken at each transect (Gordon et al. 1993). Additional calculated variables were wetted volume, flow stability, and stream power. Wetted volume represents a gross measure of total hydrologic habitat available in each of the study reaches (Church 1995) and was calculated as the product of the mean wetted-channel width, mean depth of water, and reach length. The ratio of maximum wetted depth to bank-full depth was used as an estimate of relative flow stability. As the ratio becomes larger, stability increases, and presumably the stream channel is less subject to hydrologic disturbance that might arise from storm runoff or other related events (Leopold et al. 1992). Stream power was calculated for each reach as an indication of general channel stability (Gordon et al. 1993), where higher values indicate increased potential for channel scouring.

Data Analysis

Habitat conditions were described based on a total of 28 measured and derived physical variables. Variables were selected to represent conditions of physical habitat relating to channel properties (15), hydraulic properties (5), and streambed properties (6). Additional variables were percent cover and percent pool habitat. A description of these variables is provided in Appendix 1.

Discriminant function analysis (DA) was conducted to identify physical variables most responsible for discriminating site conditions among urban areas. Discriminant analysis can be useful for classifying observations into one of several groups (e.g., urban areas) according to which group they most closely resemble with respect to a set of measurements, such as those related to physical habitat variables (ter Braak 1995). Stepwise forward-selection discriminant analysis was used to select the best subset of predictive variables. All variables were standardized prior to analysis by transforming site measurements into z-scores (mean = 0, SD = 1). Separation of groups was evaluated based on Wilk's lambda (l), which ranges from zero (perfect separation of groups) to one (no separation of groups). Significance of group separations was tested with a chi-square approximation (Manley 1986). Correct classification of canonical variable scores was evaluated using a jackknifed classification data matrix. Calculations were performed using SYSTAT 9 (SPSS 1999).

Relations between physical variables and the urban intensity index were examined using Spearman's rank correlation analysis (r_s). Principal components analysis (PCA; ter Braak 1995) was used to identify gradients of physical habitat characteristics within urban areas. Habitat variables that were highly correlated (Spearman's Rho greater than |0.4|) were reduced in number to a single variable that we felt best characterized conditions for a given physical property (e.g., channel morphology, hydraulics, streambed condition). This resulted in a total of 19 variables used for PCA (see Table 4). Results are based on standardized data (correlation matrix) and reported for axes having eigenvalues greater than one (Legendre and Legendre 1983). Habitat variables accounting for the greatest variance for each axis were identified as those having absolute loading scores greater than 0.3. Relations between PCA axes scores and the UII were examined using Spearman's rank correlation analysis.

Results

Habitat Conditions in Study Areas

Discriminant analysis identified three site clusters that corresponded to differences in habitat conditions in BOS, BIR, and SLC (Figure 1). Urban areas differed

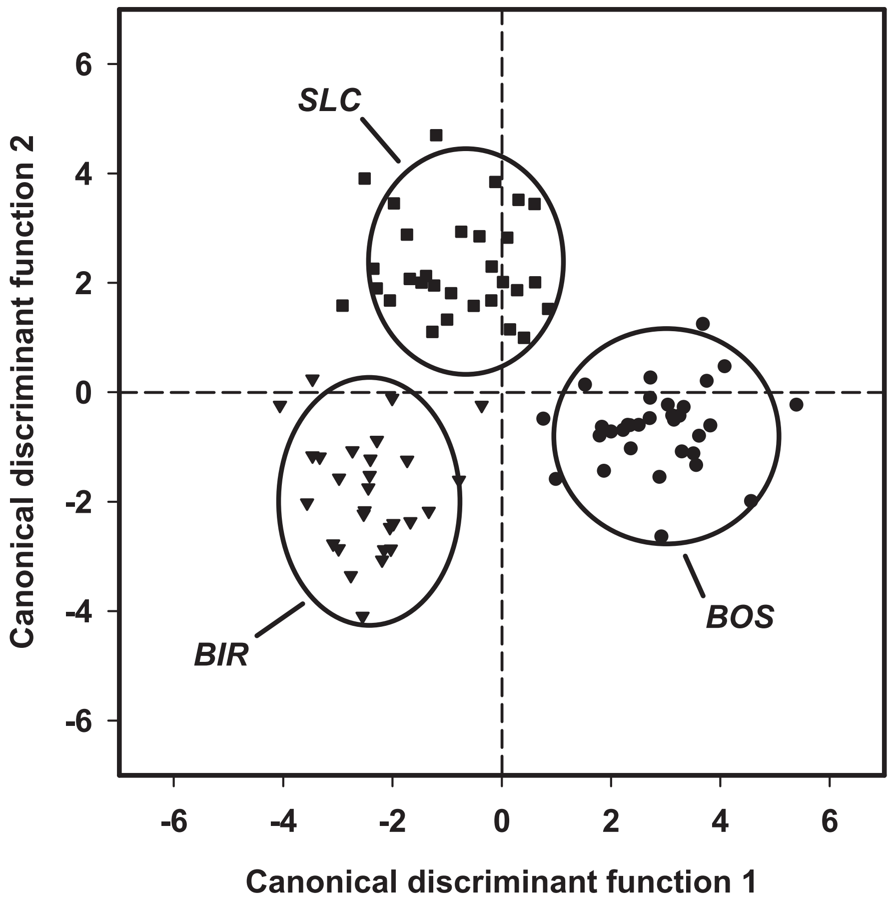

FIGURE 1. Canonical discriminant function biplot based on stepwise forward-selection analysis of physical characteristics of sites in the Boston (BOS), Birmingham (BIR), and Salt Lake City (SLC) areas. Site groups are enclosed within 90% confidence ellipses. Description of variables accounting for site-group separations is provided in Table 2.

primarily in channel size (based on bank-full cross-sectional area) and shape (based on bank-full width to depth ratio), discharge, stream power, flow stability, percent siltation, heterogeneity of substrate particle size (based on coefficient of variation of particle size), percent embeddedness, and riparian vegetation density (Table 2). The first and second canonical functions accounted for 62% and 38%, respectively, of the total variance associated with site group dispersion. A low Wilk's Lambda (0.038) indicated that these habitat variables were highly effective in discriminating among study areas. Classification analysis of jackknifed site-variable scores indicated that 97% of BOS sites, 93% of BIR sites, and 97% of SLC sites were classified correctly.

Average bank-full cross-sectional area of BIR streams was approximately twice that of streams in BOS and SLC (Table 3). Bank-full area was not related to discharge at the time of sampling for streams in BIR (r_s = 0.198; P = 0.115), but discharge was significantly correlated with bank-full area for streams in BOS (r_s = 0.496; P = 0.015) and SLC (r_s = 0.704; P < 0.001). Average stream power was relatively low in all urban areas (2.53–7.63 W/m) and probably reflected low-flow conditions prevalent during summer sampling. Flow stability was lowest for streams in BIR, suggesting that streams in this urban area were the least hydrologically stable, although drought conditions likely contributed to low stability values. Siltation was low in BOS (22.4%), intermediate in SLC (53.1%), and high in BIR (86.3%). Substrates in BOS streams consisted primarily of small cobble-sized particles (mean size = 7.2, where category 7 = small cobble; Fitzpatrick et al. 1998) with relatively homogeneous distributions (CVSUB = 17.9%). Gravel-sized particles were prevalent in BIR and SLC streams (mean

TABLE 2. Standardized discriminant function coefficients for habitat variables accounting for site separations among urban study areas shown in Figure 1. Results based on stepwise forward-selection analysis. Evaluation of group separation was based on Wilk's lambda[a] and tested for significance using a chi-square approximation[b].

Variable[c]	Discriminant function 1	Discriminant function 2
BFWD	0.657	0.427
BFAREA	–0.244	–0.766
DSCHR	0.341	0.721
POWER	–0.741	0.000
FLOSTAB	0.291	–0.394
SILT	–0.456	–0.063
CVSUB	–0.408	0.250
EMBED	–0.100	0.382
VEG	0.330	–0.779
Eigenvalues	5.236	3.257
Variance explained (%)	61.7	38.3

[a] Wilk's lambda = 0.038.
[b] $F_{18,158} = 36.448$; $P < 0.001$.
[c] Variables described in Appendix 1.

size = 5.4 and 4.3, respectively, where categories 4–5 = medium to coarse gravel). However, heterogeneity of particle size was relatively high for sites in BIR (CVSUB = 45.6%) and SLC (CVSUB = 57.4%). Substrates were less embedded in BOS streams (35.7%) than in BIR (62.2%) and SLC (62.0%). Streambanks in BOS and BIR were relatively well vegetated (VEG = 91.1% and 87.9%, respectively) compared to SLC (VEG = 62.9%).

Habitat Variables and UII

Numbers and types of habitat variables that significantly correlated with the UII varied among urban areas. None of the variables was significantly correlated with the UII in all three study areas (Table 4). Moreover, the number of significant correlations between habitat variables and the UII was markedly greater for the BOS study (46%) compared to BIR (7%) and SLC (11%). Effects of drought conditions on instream flows in BIR, and the necessity of nesting some site locations within the same drainages in SLC, may have weakened correlations between the UII and variables characterizing channel and hydraulic properties for these areas.

Channel properties.—Several channel variables were significantly correlated with the UII in the BOS study area (Table 4). Segment sinuosity and bank-full width to depth ratios decreased with increasing urbanization. Significant correlations between the UII and bank-full depth, wetted depth, and maximum wetted depth indicated that stream channels were deepening with increasing urbanization in the BOS area. In contrast, changes in channel size did not appear to be a significant effect of urbanization in BIR or SLC. Reach sinuosity decreased in BIR streams with increasing urban intensity; however, correlations between variability in bank-full cross-sectional area (CVBFAREA) and the UII for all study areas were not significant suggesting that urbanization effects on stream channelization were not pronounced. The lack of significant correlations in all three study areas between riparian vegetation density and the UII was not unexpected given that sites were chosen on the basis of having relatively well-established riparian vegetation. Ability to identify urbanization effects on riparian vegetation was limited because vegetation density was high (>60%) in all urban areas, and the range of vegetation density among sites was relatively narrow (Table 3).

Hydraulic properties.—Responses of stream hydraulic properties to urbanization were evident only in BOS streams (Table 4). Wetted volume and discharge increased with increasing urban intensity, consistent with concomitant changes in channel deepening. Wetted volume and discharge were not significantly correlated to basin area ($r_s = 0.326$, $P = 0.081$; $r_s = 0.287$, $P = 0.110$, respectively), suggesting that flow regimes in the BOS area may be under the influence of more local controls, such as inputs from wastewater treatment facilities or interbasin transfers (see Tate et al. 2005). Even though bank-full depth increased significantly with urbanization in BOS streams, accompanying higher discharge and flow volume resulted in lower wetted depth to bank-full depth ratios, suggesting that flow stability also increased.

In contrast, flow stability for streams in BIR was negatively correlated ($r_s = -0.344$, $P = 0.085$) with the UII, although atypically low flow conditions during sampling may have accentuated differences between base flow and bank-full discharge. Hydraulic properties of streams in BIR were poorly correlated with the UII (Table 4). Wetted volume was highly correlated to basin area ($r_s = 0.621$, $P < 0.001$), although discharge was not ($r_s = 0.210$, $P = 0.107$). Discharge at 50% of the sites in the BIR area was less than 0.09 m^3/s (Table 1), and differences in discharge among sites may not have been sufficient to support a

TABLE 3. Means of habitat variables (ranges in parenthesis) for study sites in the Boston (BOS), Birmingham (BIR), and Salt Lake City (SLC) areas.

Variables[a]	BOS (N = 30)	BIR (N = 28)	SLC (N = 30)
Channel properties			
SEGSINU	1.14 (1.01–1.54)	1.23 (1.00–1.57)	1.18 (1.00–1.36)
RCHSINU	23.7 (8.8–57.8)	15.8 (0–54.4)	21.2 (7.6–59.3)
GRAD (%)	0.62 (0.12–1.62)	0.38 (0.03–0.67)	2.25 (0.40–16.6)
BFD (m)	0.96 (0.64–1.52)	1.67 (0.84–2.81)	1.04 (0.36–1.83)
CVBFD (%)	16.5 (6.9–35.5)	20.5 (7.8–36.0)	18.6 (4.2–42.9)
BFW (m)	12.55 (8.13–16.39)	13.76 (5.86–26.59)	9.42 (2.81–21.76)
BFWD	13.9 (7.0–21.7)	3.7 (1.4–9.1)	9.2 (3.5–16.9)
BFAREA (m^2)	9.05 (6.17–17.02)	18.39 (5.29–47.19)	7.98 (0.71–25.83)
CVBFAREA (%)	22.5 (12.8–62.7)	29.1 (13.9–89.3)	28.2 (9.6–68.6)
WETD (m)	0.30 (0.11–0.62)	0.25 (0.05–0.44)	0.25 (0.06–0.56)
MAXWETD (m)	0.38 (0.15–0.77)	0.34 (0.12–0.56)	0.34 (0.08–0.75)
WETW (m)	9.24 (4.75–12.53)	8.29 (3.92–15.11)	5.78 (1.22–13.49)
VOL (m^3)	425 (80–1,127)	395 (94–991)	390 (6–1,581)
BANK	11.6 (8.5–14.8)	16.5 (14.4–18.6)	12.3 (9.2–14.8)
VEG (%)	91.1 (77.8–99.7)	87.9 (50.6–100)	62.9 (40.1–80.1)
Hydraulic properties			
DSCHR (m^3/s)	0.720 (0.018–2.847)	0.229 (0.001–1.723)	0.714 (0.002–3.874)
VEL (m/s)	0.294 (0.050–0.496)	0.127 (0.002–0.557)	0.299 (0.026–0.671)
CVVEL (%)	71.3 (31.8–127.3)	136.7 (0–387.9)	86.2 (38.9–228.5)
FLOSTAB	0.37 (0.16–0.51)	0.22 (0.10–0.47)	0.34 (0.10–0.78)
POWER (W/m)	4.45 (0.07–12.89)	2.53 (0.01–20.65)	7.63 (0.16–53.91)
Streambed properties			
FINE (%)	5.3 (0–45.5)	23.0 (0–79.3)	20.8 (0–100)
EMBED (%)	35.7 (15.8–86.4)	62.2 (8.8–100)	62.0 (26.1–100)
SILT (%)	22.4 (0–84.8)	86.3 (30.3–100)	53.1 (0–100)
SUB	7.2 (5.1–8.6)	5.4 (2.3–8.8)	4.3 (0.5–8.0)
CVSUB (%)	17.9 (4.8–49.1)	45.6 (15.0–123.4)	57.4 (17.2–148.1)
ROUGH	35.2 (11.5–71.5)	45.6 (18.0–140.8)	53.3 (6.7–204.2)
Cover and pools			
COVER (%)	11.3 (2.9–23.8)	7.4 (0–21.7)	12.2 (2.1–20.8)
POOL (%)	11.1 (0–36.4)	19.3 (0–73.5)	14.1 (0–45.5)

[a] Definitions provided in Appendix 1.

stronger correlation. None of the hydraulic properties of streams in SLC was significantly correlated with the UII. Stream discharge and wetted volume were strongly related to basin area (r_s = 0.698, P < 0.001; r_s = 0.808, P < 0.001, respectively).

Streambed properties.—Variables related to streambed condition were among the most responsive to urbanization, and significant relationships with the UII were found for streams in all study areas (Table 4). Average substrate particle size decreased with increasing urbanization for sites in SLC, but particle size was not highly correlated with the UII for sites in BOS and BIR. In spite of relatively low variability of substrate particle sizes in BOS streams (CVSUB = 17.9%), particle size variability significantly increased with increasing urbanization. Particle size variability was not significantly correlated with the UII for streams in BIR and SLC. Percent fines significantly increased with increasing urbanization for sites in BOS and SLC. The increase in percent fines was due primarily to increases in the relative abundance of sand-size particles. Sand comprised 91% of fine-grained substrates in BOS and 78% in SLC; however, fines comprised a greater percentage of the overall substrate composition in SLC streams (20.8% compared to 5.3% in BOS). Although the relative abundance of fines increased with urban-

TABLE 4. Correlations (Spearman's Rho) between urbanization intensity index values (UII) and selected physical habitat variables for the Boston (BOS), Birmingham (BIR), and Salt Lake City (SLC) areas. Asterisks indicate significance of correlation analysis (*, $P < 0.05$; **, $P < 0.01$; ***, $P < 0.001$). Bolded variables were used in principal components analysis.

Variables[a]	BOS (N = 30)	BIR (N = 28)	SLC (N = 30)
Channel properties			
SEGSINU	–0.421*	–0.362	0.098
RCHSINU	–0.236	–0.456*	0.178
GRAD	–0.199	0.067	–0.187
BFD	0.581***	0.245	–0.127
CVBFD	0.347	–0.039	0.309
BFW	–0.231	0.282	–0.147
BFWD	–0.504**	–0.050	–0.067
BFAREA	0.147	0.293	–0.114
CVBFAREA	0.055	–0.093	0.234
WETD	0.626***	–0.214	0.022
MAXWETD	0.553**	–0.235	0.002
WETW	–0.159	0.101	–0.053
VOL	0.419*	–0.043	–0.003
BANK	–0.030	–0.128	0.036
VEG	0.023	–0.134	–0.122
Hydraulic properties			
DSCHR	0.481**	0.025	–0.141
VEL	0.433*	0.027	–0.299
CVVEL	–0.210	–0.187	0.106
FLOSTAB	0.415*	–0.344	0.060
POWER	0.221	0.027	–0.291
Streambed properties			
FINE	0.542**	–0.174	0.433*
EMBED	0.292	0.410*	–0.017
SILT	–0.111	0.099	0.475**
SUB	–0.196	0.134	–0.437*
CVSUB	0.450**	0.118	0.352
ROUGH	–0.703***	0.160	–0.137
Cover and pools			
COVER	0.451**	0.029	0.089
POOL	0.034	–0.206	0.129

[a] Definitions provided in Appendix 1.

ization at sites in BOS and SLC, significant increases in substrate embeddedness were observed only for streams in the BIR area. With increasing urban development increases in runoff potential can result in greater channel erosion and sedimentation (Booth and Jackson 1997; Trimble 1997). It was expected that increases in streambed siltation would be a common response to urbanization; however, a significant increase in siltation was observed only for sites in SLC. A decline in relative roughness was highly correlated with increasing urban intensity at sites in BOS (Table 4), but was not significantly related to urbanization in BIR and SLC. Streambed roughness increases with increasing substrate particle size and decreasing depth of water. Since average substrate particle size for streams in BOS did not increase with urbanization intensity, the decline in roughness in this study area is likely due to the significant increase in wetted depth.

Instream cover and pools.—Abundance of habitat cover types was poorly correlated with the UII for streams in BIR and SLC (Table 4). However, habitat cover significantly increased in BOS streams with increasing urbanization. Most of this increase was due to greater numbers of boulder-size rocks in the stream channel (boulders comprised 54% of all habitat cover types). Percent of pool habitats was not significantly correlated with the UII for streams in any of the study areas.

Multivariate Gradients and UII

For BOS and BIR, the primary PCA axis site scores were strongly correlated with the UII (Table 5), suggesting that urban intensity was likely a factor affecting the variance in these data. Urbanization effects were most apparent for BOS where the gradient described by the habitat data was relatively strong (eigenvalue = 6.630). The greatest proportion of the variance described by axis 1 (34.9%) was accounted for by trends in maximum wetted depth, discharge, percent fines, and relative roughness. Each of these variables was significantly correlated with the UII (Table 4), which in part accounts for the strong relationship between the UII and the gradient defined by the primary axis of the habitat ordination. Secondary axes scores were poorly correlated with the UII, suggesting that these habitat gradients were not strongly influenced by urbanization. The physical gradient defined by axis 1 for BIR was somewhat weaker (eigenvalue = 3.787). Trends in bank-full width, bank-full cross-sectional area, substrate particle size, embeddedness, and relative roughness accounted for most of the variance (21.0%). Although PCA axis 1 scores for sites in BIR significantly correlated with the UII, the strength of the association appears to be driven largely by the significant relationship between the UII and embeddedness (Table 4). Moreover, strengths of the habitat-site gradients defined by secondary axes were similar to that of the primary axis (secondary axes eigenvalues ranged from 2.206 to 3.600), suggesting that habitat gradients for BIR were not strongly influenced by urbanization.

The gradients defined by the primary and secondary axes for the site-habitat ordinations for SLC were relatively strong (eigenvalues = 7.209 and 5.053), and together account for 61.3% of the total variance. Channel properties (bank-full width, bank-full depth, and bank-full cross-sectional area) and discharge were the primary physical variables defining the habitat gradient for axis 1, whereas streambed properties (substrate particle size, percent fines, embeddedness, relative roughness) and bank stability accounted for most of the variance defining the axis 2 gradient. Component scores from either axis were not significantly related to the UII. Urbanization intensity was significantly

TABLE 5. Spearman rank correlations between PCA axes scores for site-habitat[a] ordinations and the urban intensity index (UII). Asterisks indicate significance of correlation analysis (*, $P < 0.05$; **, $P < 0.01$; ns, $P > 0.1$).

Study area	Parameters	Axis 1	Axis 2	Axis 3	Axis 4
BOS	Eigenvalues	6.630	4.218	1.779	1.413
	Variance explained (%)	34.9	22.2	9.4	7.4
	Variables with component loadings > |0.3|	MAXWETD, DSCHR, FINE, ROUGH	POOL, VEL, CVVEL, SILT	GRAD, SUB, RCHSINU, POOL, CVBFD	RCHSINU, BFW, BFAREA, SILT
	Correlation with UII	–0.63**	–0.19 ns	0.01 ns	0.08 ns
BIR	Eigenvalues	3.787	3.600	2.574	2.206
	Variance explained (%)	21.0	19.9	14.3	12.3
	Variables with component loadings > |0.3|	BFW, BFAREA, SUB, EMBED, ROUGH	DSCHR, VEL, FLOSTAB, SILT, COVER	MAXWETD, BFD, CVVEL, CVSUB	GRAD, VEL, CVVEL, BANK, COVER
	Correlation with UII	–0.47*	0.03 ns	–0.13 ns	0.03 ns
SLC	Eigenvalues	7.209	5.053	2.289	1.173
	Variance explained (%)	36.0	25.3	11.5	5.9
	Variables with component loadings > |0.3|	BFW, BFD, BFAREA, DSCHR	SUB, FINE, EMBED, ROUGH, BANK	CVBFD, VEL, FLOSTAB, SILT	GRAD, SILT, RCHSINU, CVSUB, EMBED, BANK
	Correlation with UII	–0.12 ns	0.29 ns	0.12 ns	–0.44*

[a] Definitions provided in Appendix 1.

correlated with component scores for axis 4 (Table 5); however, the strength of the gradient was relatively weak (eigenvalue = 1.173), and the primary physical variables defining the gradient (reach gradient, percent siltation, reach sinuosity, variation in substrate particle size, embeddedness, and bank stability) accounted for only 5.9% of the total variance. Based on these results, it appeared that urbanization was not having a significant effect on stream habitat in the SLC study area.

Discussion

Urbanization Effects on Channel Properties

Increase in impervious area and surface runoff can result in more frequently occurring extreme flow events (Hammer 1972; Arnold and Gibbons 1996) and contribute to channel enlargement. There was no strong evidence that channel enlargement was occurring in response to urbanization in any of the three study areas. Structural reinforcement of streambanks using riprap or wire netting was not extensive but may have confined lateral expansion of stream channels in some areas. Bank stability was not significantly correlated with the UII, and it appeared that urbanization effects on bank erosion and channel widening were minimal at most. Changes in channel morphology in response to urbanization were most apparent for streams in the BOS area. Although bank-full area for these streams did not significantly increase, channels tended to become more incised (narrower and deeper) with increasing urbanization, which is consistent with urbanization effects reported for other areas (Hammer 1972; Arnold et al. 1982; Booth 1990).

Channelization is a common practice in urban areas to reduce flooding and facilitate transport of water and sediments (Paul and Meyer 2001). If channel straightening was occurring, there would be corresponding increase in reach gradient and flow velocity (Pizzuto et al. 2000). Based on measurements of reach sinuosity, water-surface gradient, and flow velocity, it did not appear that urbanization was contributing to marked increases in channelization in BOS and SLC. The best evidence of urbanization effects on channel straightening was for streams in BIR where reach sinuosity significantly declined with increasing urbanization intensity. Reach gradient and flow velocity did not increase with decreasing sinuosity, but extremely low flows at the time of sampling may have masked these effects.

Although it has been argued that the majority of disturbances to streams in urban environments may be more local in scale (Kemp and Spotila 1997; Wang et al. 2001; Townsend et al. 2003), in BOS we found that segment-level sinuosity was more highly correlated to urbanization (i.e., significant decline) than reach-level sinuosity. Despite the fact that segment and reach sinuosity were not markedly different among study areas (Table 3), reach sinuosity was more highly correlated to urbanization for streams in BIR. These differences between reach- and segment-level responses to urbanization may be indicative of differences among urban areas in water-management infrastructures, specifically controls on water movement and storage that may alter connectivity of stream networks and contribute to increase variability in segment length and relative linear shape of stream channels (Hirsch et al. 1990; Paul and Meyer 2001).

Urbanization Effects on Hydraulic Properties

Flow regimes can be dramatically altered in urbanized watersheds due to increases in runoff potential as land surfaces become increasingly impervious (Seaburn 1969; Booth and Jackson 1997; Moscrip and Montgomery 1997). Groundwater recharge can decrease with increasing impervious surface area resulting in a reduction of base flow discharge (Barringer et al. 1994). A decline in base flow discharge with increasing urbanization was evident only for streams in SLC, but the relationship was weak ($r_s = -0.141$). Flow modifications from diversions, impoundments, and groundwater abstraction were pervasive in the SLC study area (see Tate et al. 2005) and likely contributed to the high variability in average discharge among sites (CV = 154%) and to the corresponding weak relations between urbanization intensity and stream hydraulic properities. Although effects of these modifications on flow characteristics were difficult to quantify, it was expected that severe alterations of flow patterns would result in poor correlation between drainage basin size and discharge (Petts and Bravard 1996). Discharge was highly correlated with basin area ($r_s = 0.698$) for streams in SLC, suggesting that flow modification effects were probably local in scope (reach level) and of low to moderate intensity. Elevation changes among SLC streams corresponded to changes in land use along a gradient of urban intensity with lower intensity urbanization occurring in the higher elevation foothills and higher urbanization in the lower elevation valley floor. Consequently, it was difficult to separate the effects of elevation change on hydraulic properties of discharge and velocity from urbanization effects. Similar results were observed for BIR streams where none of the hydraulic variables was significantly correlated with the UII; however, unseasonably low flows in this study area limited the range of flow conditions with which to test relationships with the UII.

Urbanization appeared to be more closely linked to flow regimes for streams in the BOS area. In this urban setting, discharge increased significantly with urbanization intensity and varied in magnitude independent of basin area. These findings suggest that urbanization in BOS was affecting flow conditions, perhaps by increasing surface runoff from rainfall and irrigation, increasing input volume from wastewater treatment facilities, or augmenting flows by interbasin transfers (Hirsch et al. 1990; Dennehy et al. 1998). The increase in base flow discharge with urbanization intensity resulted in a significant increase in flow stability; however, flow regimes can be highly unpredictable over short time scales (Leopold et al. 1992), and inferences about long-term flow conditions based on short-term estimates of flow stability are speculative at best.

Urbanization Effects on Streambed Properties

Effects of urbanization on stream habitat were most evident in responses of the streambed substrate, particularly substrate size, embeddedness, and siltation; however, responses were not consistent among urban areas. Although the site selection process favored reaches with riffles and coarser-grained substrates, we felt that variability in substrate size among sites was sufficient to determine if urbanization was affecting substrate composition (see Table 3). An increase in percent fines significantly correlated with increasing urbanization intensity for streams in BOS and SLC, and similar results have been reported for other urban studies (Finkenbine et al. 2000; Pizzuto et al. 2000). Although results were similar for streams in BOS and SLC, it is likely that the factors responsible for the increase in percent fines were different between the two urban areas. For example, urban development in SLC proceeds along an increasing elevation gradient from the valley floor to the foothills. Accordingly, surface water gradients and flow velocities tend to decrease with decreasing elevation, resulting in a natural sorting of particles with finer-grained particles being deposited in the more downstream reaches (Leopold et al. 1992). In contrast, elevation differences among sites for BOS streams were not great and would not account for site differences in sediment composition. Sand comprised a relatively large proportion (median = 34%) of the soil volume for drainages in BOS (see Tate et al. 2005), and increases in sand-based fines in more urbanized areas could reflect local differences in sediment sources to stream channels. Differences in substrate properties may also be indicative of differences in the age of urban development. Introduction of fine sediments to stream channels can result from construction activities in the watershed during early stages of urban development (Wolman and Schick 1967; Waters 1995), whereas in older urban areas (corresponding to higher UII), increases in surface runoff and peak flows as a result of more impervious surfaces could increase inputs of coarser-grained sediments (Klein 1979; Arnold and Gibbons 1996). Percent siltation did not increase with urbanization intensity in BOS streams, which is consistent with results expected for older urban areas. The propensity of streambed materials to be mobilized and displaced by elevated flow velocities decreases as substrate particle size becomes smaller or larger than sand-size materials (Leopold et al. 1992); accordingly, streambed stability may also have declined with urbanization in the BOS area, owing to the introduction of predominantly sand-size particles to the stream channel.

Substrate embeddedness has been reported to increase in urban areas as a result of increased sediment loading to stream channels (Wolman and Schick 1967; Klein 1979). Significant increases in embeddedness were found only for streams in the BIR area. Low correlation (r_s = 0.181) between percent fines and embeddedness suggested that sediment loading was not a primary factor responsible for increased embeddedness. Instead, greater embeddedness in more urbanized areas may reflect remnant conditions of bed armoring and channel incision caused by high discharge flows during nondrought conditions (Montgomery and Buffington 2001).

Urbanization Effects on Instream Cover and Pools

The complexity and stability of the biotic environment are in large part a function of the numbers and types of habitat structures occurring within the stream channel (Cummins 1979; Maddock 1999; Rosenfeld 2003). A decline in the richness of habitat structures in urban and urbanizing landscapes could significantly alter the structure of stream biotic assemblages. Previous studies have shown that the types and availability of habitat structures and channel features that can act as cover for aquatic biota may diminish in some urban settings as channel complexity is reduced through modifications to facilitate water transfer and mitigate local flooding (Booth and Jackson 1997; Wang et al. 1997; Finkenbine et al. 2000; Pizzuto et al. 2000). We found no evidence that urbanization significantly reduced percent cover in any of the study areas. To the contrary, percent cover increased with urbanization in BOS streams, owing primarily to greater numbers of boulder-size rocks and concrete pieces in the more highly urbanized areas. Abundance of cover in study reaches was low (average = 7% to 12%), and the relative paucity of these features likely contributed to poor correlations with the UII.

Channel enlargement through widening or deepening of the stream channel can alter the relative abundance and distribution of fluvial habitat features such as riffles and pools (Gregory et al. 1994). There were no significant effects of urbanization on the occurrence of pool habitats, even for streams in the BOS area where channel deepening occurred. Urbanization effects may have been less pronounced because of the low number of sites with pools (72% of all sites) and the relatively low number of pools at each site (median ≤ 2 for all sites).

Habitat Properties as Indicators of Urbanization Effects

These results illustrate the physical complexities of urban streams and the difficulties in comparing urbanization effects on stream habitat in contrasting urban environments. The magnitude and type of hydrologic and geomorphic responses vary within a stream network according to differences in age of development, drainage basin slope, surficial geology, sediment characteristics, type of urbanization, and land use history (Gregory et al. 1992). The model of urban intensity described by McMahon and Cuffney (2000) and discussed in Tate et al. (2005) incorporates elements of these landscape features into a common index that accounts for these differences by providing a scale of landscape intensity that can be used as a comprehensive measure of urbanization effects. Despite the fact that study site locations were based on a common model of land-use intensity that constrained natural variability in hydrologic and geomorphic conditions, streams in the three urban study areas differed in channel shape and size, discharge, and substrate type and composition. For streams in SLC and BIR, these differences are less indicative of urbanization effects and probably reflect the overwhelming influences of basin slope (SLC) and prolonged drought (BIR) on flow regimes. The influence of these natural factors on modifying the hydrology of streams in SLC and BIR limited our ability to effectively compare habitat responses among different urban settings and identify common responses as targets for restoration or water management programs.

Flow regimes in the BOS study area were not unduly influenced by climate and physiography, and habitat conditions in these streams were more responsive to urbanization. Strong relations between urbanization and stream habitat were evident from correlations between PCA axes scores and the UII. Urbanization in the BOS area contributed to higher baseflows, channel deepening, and increased loading of fine-grained particles.

Despite some successes in applying the urban intensity model to identify habitat responses to urbanization, our study would have benefited from a better understanding of factors affecting hydrologic connectivity of streams in the study areas. Human modification to flow regime, resulting from dams, diversions, and surface- and groundwater abstractions are commonplace in urban settings and can fragment stream networks by disrupting linkages between streams, tributaries, and drainage basins. Although it is recognized that alteration of flow regimes is a fundamental outcome of landscape change, there is a general lack of a more predictive understanding of the ecological implications of hydrologic connectivity in urban systems (Pringle 2003). Difficulties in characterizing urbanization effects on habitat for the BIR and SLC studies underscore the need to supplement this understanding. While the urban intensity model developed by McMahon and Cuffney (2000) provides a relatively comprehensive means with which to characterize urban land use, identification of habitat responses to urbanization across multiple landscapes and scales must account for inherent differences in natural and anthropogenic factors affecting stream hydrology and geomorphology at basin and site scales. The challenge to future management of urban development is to further quantify these differences by building upon existing models and ultimately develop a broader understanding of urbanization effects on aquatic ecosystems.

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APPENDIX 1. Selected habitat variables measured at or calculated for each study reach.

Variables	Description
Channel properties	
Segment sinuosity (SEGSINU)	Ratio of curvilinear channel length to valley centerline length (Platts et al. 1983).
Reach sinuosity (RCHSINU)	Standard deviation of mean difference in streamflow direction (degrees) measured at mid-channel between reach transects; increasing values represent increasing sinuosity.
Reach gradient (GRAD)	Percent change in elevation (m) between lower and upper reach boundaries.
Bank-full depth (BFD)	Average depth (m) at deepest part of stream channel to top of bank at bank-full stage; calculated from 11 transects.
Coefficient of variation in bank-full depth (CVBFD)	Percent variation of reach-averaged bank-full depth.
Bank-full width (BFW)	Average width (m) of stream channel at bank-full stage from top edge of left bank to top edge of right bank; calculated from 11 transects.
Bank-full width to depth ratio (BFWD)	Average bank-full width to depth ratio; calculated from 11 transects.
Bank-full cross-sectional area (BFAREA)	Average area (m^2) based on product of bank-full depth and bank-full width; calculated from 11 transects.
Coefficient of variation in bank-full cross-sectional area (CVBFAREA)	Percent variation of reach-averaged bankfull cross-sectional area.
Wetted depth (WETD)	Average depth (m) of wetted channel; measured at three locations at each of 11 transects.
Maximum wetted depth (MAXWETD)	Average depth (m) at deepest part of wetted channel; calculated from 11 transects.
Wetted width (WETW)	Average width (m) of wetted channel; calculated from 11 transects.
Wetted volume (VOL)	Stream volume (m^3) based on product of reach length, average wetted width, and average wetted depth.
Bank stability (BANK)	Multimetric index representing average bank stability; based on combination of characteristics consisting of bank angle, bank height, dominant substrate (ordinal), and percent vegetative cover (Fitzpatrick et al. 1998); index values range from 4 to

APPENDIX 1. Continued.

Variables	Description
	22, with scores 4–7 = stable, 8–10 = at risk, 11–15 = unstable, 16–22 = highly unstable; calculated from 11 transects.
Percent vegetation density (VEG)	Percent riparian vegetation density near wetted channel margins (see Methods); measured at two locations at each of 11 transects.
Hydraulic properties	
Discharge (DSCHR)	Average discharge (m^3/s) based on product of wetted cross-sectional area and mean velocity (Gordon et al. 1993); calculated from 11 transects.
Velocity (VEL)	Average velocity (m/s) measured at six-tenths depth at three locations at each of 11 transects.
Coefficient of variation in velocity (CVVEL)	Percent variation of reach-averaged velocity.
Flow stability (FLOSTAB)	Average ratio of maximum wetted depth to bank-full depth; values range from 0 to 1, with increasing values representing more hydrologically stable conditions; calculated from 11 transects.
Stream power (POWER)	Power per unit of stream length (W/m) (Gordon et al. 1993).
Streambed properties	
Percent fines (FINE)	Average percent of total substrate composition (categorical) consisting of sand and smaller-sized particles; calculations based on visual determinations at three locations at each of 11 transects.
Percent embeddedness (EMBED)	Average percentage (nearest 10%) to which larger substrate particles (≥ coarse gravel) are surrounded or covered by fine sediment (< 2 mm); calculations based on visual determinations at three locations at each of 11 transects.
Percent siltation (SILT)	Proportion (presence or absence) of fine sediment (<1 mm) on bottom surfaces; calculations based on visual determinations at three locations at each of 11 transects.
Substrate size (SUB)	Average substrate particle size (ordinal) with size categories ranging from 1 to 10, where 1 = smooth bedrock and 10 = large boulder (Fitzpatrick et al. 1998); calculations based on visual determinations at three locations at each of 11 transects.
Coefficient of variation in substrate size (CVSUB)	Percent variation in reach-averaged substrate size.
Relative roughness (ROUGH)	Average ratio of dominant particle size (categorical) to wetted depth; higher values represent increasing hydraulic roughness of streambed; calculations based on measurements at three locations at each of 11 transects.
Cover and pools	
Percent cover (COVER)	Percent occurrence (based on total number of observations) of habitat cover (overhanging vegetation, undercut banks, woody debris, boulders, macrophytes, artificial structures) at five locations (two for undercut banks and overhanging vegetation) at each of 11 transects; a maximum of 24 cover types was possible at each transect.
Percent pool (POOL)	Proportion of total pool length to reach length, for pools comprising ≥ 50% of wetted channel width.