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URBAN IMPACTS ON PHYSICAL STREAM CONDITION: EFFECTS OF SPATIAL SCALE, CONNECTIVITY, AND LONGITUDINAL TRENDS[1]

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ABSTRACT: An assessment of physical conditions in urban streams of the Puget Sound region, coupled with spatially explicit watershed characterizations, demonstrates the importance of spatial scale, drainage network connectivity, and longitudinal downstream trends when considering the effects of urbanization on streams. A rapid stream assessment technique and a multimetric index were used to describe the physical conditions of multiple reaches in four watersheds. Watersheds were characterized using geographic information system (GIS) derived landscape metrics that represent the magnitude of urbanization at three spatial scales and the connectivity of urban land. Physical conditions, as measured by the physical stream conditions index (PSCI), were best explained for the watersheds by two landscape metrics: quantity of intense and grassy urban land in the subwatershed and quantity of intense and grassy urban land within 500 m of the site (R^2 = 0.52, $p < 0.0005$). A multiple regression of PSCI with these metrics and an additional connectivity metric (proximity of a road crossing) provided the best model for the three urban watersheds (R^2 = 0.41, $p < 0.0005$). Analyses of longitudinal trends in PSCI within the three urban watersheds showed that conditions improved when a stream flowed through an intact riparian buffer with forest or wetland vegetation and without road crossings. Results demonstrate that information on spatial scale and patterns of urbanization is essential to understanding and successfully managing urban streams.
(KEY TERMS: urbanization; rivers/streams; geomorphology; land use/land cover; spatial scale; habitat.)

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INTRODUCTION

Urban development, coupled with human population growth, threatens local and global ecosystems (Zipperer *et al.,* 2000). Urbanization of the Puget Sound region has dramatically altered the natural streamflow regime and the physical and geomorphic conditions within stream systems (Booth, 1990; May *et al.,* 1997). As a result of development, once forested land has been replaced with buildings, roads, and lawns. These land cover changes, as well as the extensive changes to the soil profile and the native vegetation community, have altered conditions and processes in lowland streams, which in turn have impaired stream health (Booth, 1991).

The altered physical and geomorphic conditions in urban streams are diverse and complex (Hammer, 1972; Neller, 1988; Booth, 1990; Booth and Jackson, 1997; May *et al.,* 1997; Caraco, 2000; Pizzuto *et al.,* 2000; Hession *et al.,* 2003). In general, urban streams tend to have enlarged cross-sectional dimensions (Hammer, 1972; Caraco, 2000; Pizzuto *et al.,* 2000; Booth and Henshaw, 2001; Hession *et al.,* 2003), accelerated bed and bank erosion (Neller, 1988; Roesner and Bledsoe, 2003), decreased amounts of large woody debris (LWD) and other roughness elements (May *et al.,* 1997; Finkenbine *et al.,* 2000), and simplified morphology (Pizzuto *et al.,* 2000). The grain size distribution commonly shifts to smaller sizes in urban streams (Booth and Jackson, 1997); conversely, smaller grain sizes may be selectively removed in highly urbanized systems where transport capacity greatly exceeds sediment supply (Pizzuto *et al.,* 2000; Finkenbine *et al.,* 2000).

Assessments of the complex physical or biological conditions of urban streams are often attempted by using multimetric indices, measures that integrate

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multiple components to indicate an overall condition (Plafkin *et al.,* 1989; Rankin, 1995; Raven *et al.,* 1998; Barbour *et al.,* 1999; Karr and Chu, 1999). This integrative approach to measuring conditions can help diagnose causes of degradation in complex ecological systems (Karr and Chu, 1999). Another benefit of multimetric indices is their statistical versatility. Because multimetric indices are continuous and can be normally distributed, familiar tests can be applied to identify significant differences in index values (Karr and Chu, 1999).

There is a need for dependable, statistically sound tools to evaluate the amount, location, and distribution of urban land in watersheds. Quantitative methods that link landscape patterns and ecological processes are considered critical to basic ecological research (Turner and Gardner, 1991). Measures of urbanization that go beyond single watershed scale numbers will help to understand and predict the severity and extent of urban effects on stream systems. With better information on the interaction of land cover change and stream ecosystems, it should be possible to improve policies and management strategies for protecting stream integrity in developing areas (Wear *et al.,* 1998). Based on these assumptions, this study had three main objectives: (1) to assess instream physical and geomorphic conditions and their variability within individual urban streams; (2) to measure urbanization using a range of alternative landscape metrics; and (3) to identify relationships between physical stream conditions and various spatial scales and degrees of urbanization.

METHODS

Study Streams

Multiple stream reaches were studied within four watersheds in the Puget Sound Lowland region with similarities in watershed size, surface geology, and relief ratio (Figure 1). In total, 70 sites were sampled: 7 in Juanita Creek, 28 in Swamp Creek, 22 in Little Bear Creek, and 13 in Thorndyke Creek. The watersheds range from approximately 17 to 60 km^2 and are predominantly underlain by glacial till (Table 1). The relief ratios, defined as the difference in elevation between the highest and lowest points of the watershed divided by the length of the watershed (Dunne and Leopold, 1978), range from 11 to 23 m/km.

The study watersheds were selected to span a range of urban land cover (Table 1). Thorndyke Creek, on the western side of the remote Olympic Peninsula (Figure 1), served as a reference stream. Thorndyke Creek's watershed has very little development and is predominantly forested, although some logging has occurred in the watershed. Approximately 20 percent of the upland areas of Thorndyke Creek's watershed were logged at the time of this study. The watershed of Juanita Creek, which flows into the northwest side of Lake Washington, is highly urbanized. Little Bear Creek and Swamp Creek, also tributaries in the Lake Washington watershed system, both have moderate levels of urbanization. Forested areas in all watersheds are predominantly second-growth or third-growth forests.

Field Methods

Physical conditions in the study streams were sampled using a rapid assessment technique during the summer of 2000. The assessments were based on average conditions within 100 m reaches. Assessment reaches were randomly located approximately every 300 to 500 m along the mainstem channel, except where access was prohibited, in wetlands, or in nonalluvial reaches (e.g., reaches constrained by bank armoring). The location of the downstream end of each sample reach was located using a Garmin 12XL global positioning system (GPS) unit. These point locations are hereinafter referred to as sites.

Quantitative and qualitative measures were taken to describe channel morphology, estimate channel dimensions, and characterize bed substrate. Bed morphology was classified as cascade, step-pool, plane bed, pool-riffle, or dune-ripple (Montgomery and Buffington, 1998). The presence of sediment storage bars was recorded (Knighton, 1998). Channel planform was classified as straight, meandering, or braided (Leopold and Wolman, 1957). Gradient was measured at each site using a clinometer and stadia rod. Bankfull width and average bankfull depth were measured at one representative riffle and pool feature for each site, using a tape and stadia rod. An estimate of bankfull cross-sectional area was derived from the product of average bankfull width and depth. An enlargement ratio was then calculated as the ratio of the measured channel size to an expected channel size determined from a regional regression of bankfull cross-sectional area to watershed size for nonurban streams (Booth, 1990). Streambank stability was visually evaluated and ranked as stable, slightly unstable, moderately unstable, or unstable (Henshaw and Booth, 2000). Channel spanning pools with a residual depth greater than one-fourth of the bankfull depth were tallied (Montgomery *et al.,* 1995). Large woody debris pieces were tallied within the active bankfull channel if LWD was at least 25 cm in diameter and 3 m in

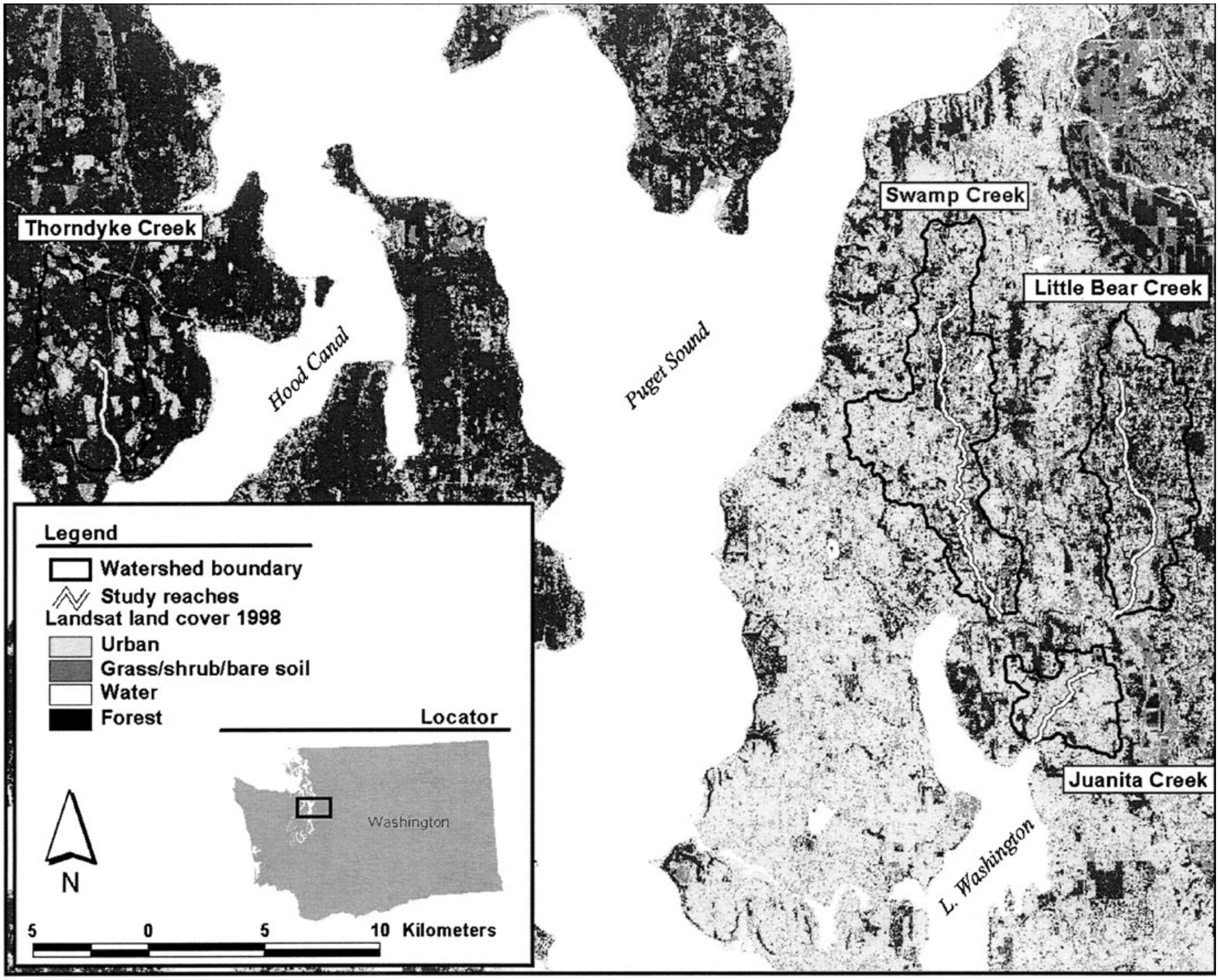

Figure 1. Locator Map With Study Watersheds and 1998 Land Cover (Center for Water and Watershed Studies, 1998) Using a Classification Simplified From Hill *et al.,* 2003.

length (Scholz and Booth, 2001). The structural complexity of the stream was visually assessed and ranked in four classes from excellent/complex to poor/simple. The structural complexity rank was based on the sites' diversity in channel geometry, planform, types of pool and riffle features, and overall structure (McBride, 2001). Substrate size of active riffles or bar features was determined using the pebble count method, where 100 clasts were selected randomly from the riffle or bar surface (Wolman, 1954). Both substrate embeddedness (Barbour *et al.,* 1999) and substrate cementation of riffle features (McBride, 2001) were each ranked in four visual classes (poor, fair, good, and excellent). The substrate embeddedness rank was based on an assessment of the embeddedness of approximately 10 randomly selected individual clasts. All measurements were made by the same observer and under similar base flow conditions between July and September 2000.

Spatial Methods

A GIS based spatial analysis was used to characterize the landscape contributing to each sampled site. Several spatial data sources were employed to characterize the study watersheds, including land cover (30 m, Landsat; Center for Water and Watershed Studies, 1998; Hill *et al.,* 2003); elevation (10 m, 1:24,000 digital elevation model; University Libraries, 1999); wetlands (1:24,000, National

TABLE 1. Watershed Sizes and Land Cover Distributions.

Stream	Watershed Size (km^2)	Land Cover Distribution: Intense Urban (percent)	Grassy Urban (percent)	Forested Urban (percent)	Grass/ Shrub (percent)	Bare Soil (percent)	Forested (percent)	Wetland (percent)	Surface Geology: Glacial Till (percent)	Glacial Outwash (percent)	Alluvium (percent)	Other (percent)
Juanita	17.4	9	32	39	6	0	13	2	45	46	0	9
Swamp	58.8	11	27	28	8	1	21	4	79	16	4	1
Little Bear	40.3	5	15	32	7	1	37	2	68	29	3	1
Thorndyke	31.0	2	7*	11*	5	0	72	3	77	20	2	0

*Recently logged areas in Thorndyke Creek appear as grassy urban and forested urban.

Wetlands Inventory; U.S. Fish and Wildlife Service, 1987-1989); and roads (1:24,000; Puget Sound Regional Council, 1997, unpublished, data). The land cover classification is a 30 m grid that distinguished a total of seven categories, three of which were "urban" categories – intense urban land, grassy urban land, and forested urban land. Intense urban lands are areas with the highest amounts of pavement, and total impervious area (TIA) is approximately 92 percent in this category (Hill *et al.,* 2003). Grassy urban lands areas distinguish areas with high amounts of pavement and moderate amounts of grassy or shrub vegetation, and TIA is approximately 74 percent (Hill *et al.,* 2003). Forested urban lands are areas with high percentages of pavement and moderate amounts of forest vegetation, and TIA is approximately 34 percent (Hill *et al.,* 2003).

Three landscape zones were delineated for each sampled site to characterize the magnitude and potential hydraulic connectivity of urban land at different spatial scales. Often, the primary zone of interest is the watershed, the total contributing area of the landscape. Subwatersheds were delineated for each sampled site using GIS. A second delineated zone was the "buffer," which was defined as the total riparian area upstream from the site location (Figure 2). Two buffer zones of different widths, 100 m and 200 m, were created. The third zone of interest was the "local" zone, defined as that portion of the total watershed uphill from the site location and within a specified distance (Figure 2). Two local zones of different sizes, with boundaries 500 m and 1,000 m from the sampling site, were created. Both buffer and local zone boundaries were determined along topographic flow paths. The areas of the buffer and local zones were not extracted from the subwatershed zones, a method preferred by some researchers (Fitzpatrick *et al.,* 2001; Wang and Kanehl, 2003). The methodologies used in this study for buffer and local zones are similar to other spatial analyses (Roth *et al.,* 1996; Allan *et al.,* 1997; Schuft *et al.,* 1999), particularly those of Morley and Karr (2002).

Following the delineation of the three spatial zones (subwatershed, buffer, and local), landscape metrics that characterize both the magnitude of urban development and the connectivity of urban land were defined. Magnitude metrics included the fractions of urban land categories in a given spatial zone (Table 2). Connectivity is broadly defined as "how spatially or functionally continuous a patch, corridor, network or matrix of concern is" (Zipperer *et al.,* 2000, page 687). The connectivity metrics (road density, median flow path length, and upstream distance to road) specifically addressed the hydraulic connectivity of urban land to the channel network within a particular spatial zone, as listed and described in Table 2.

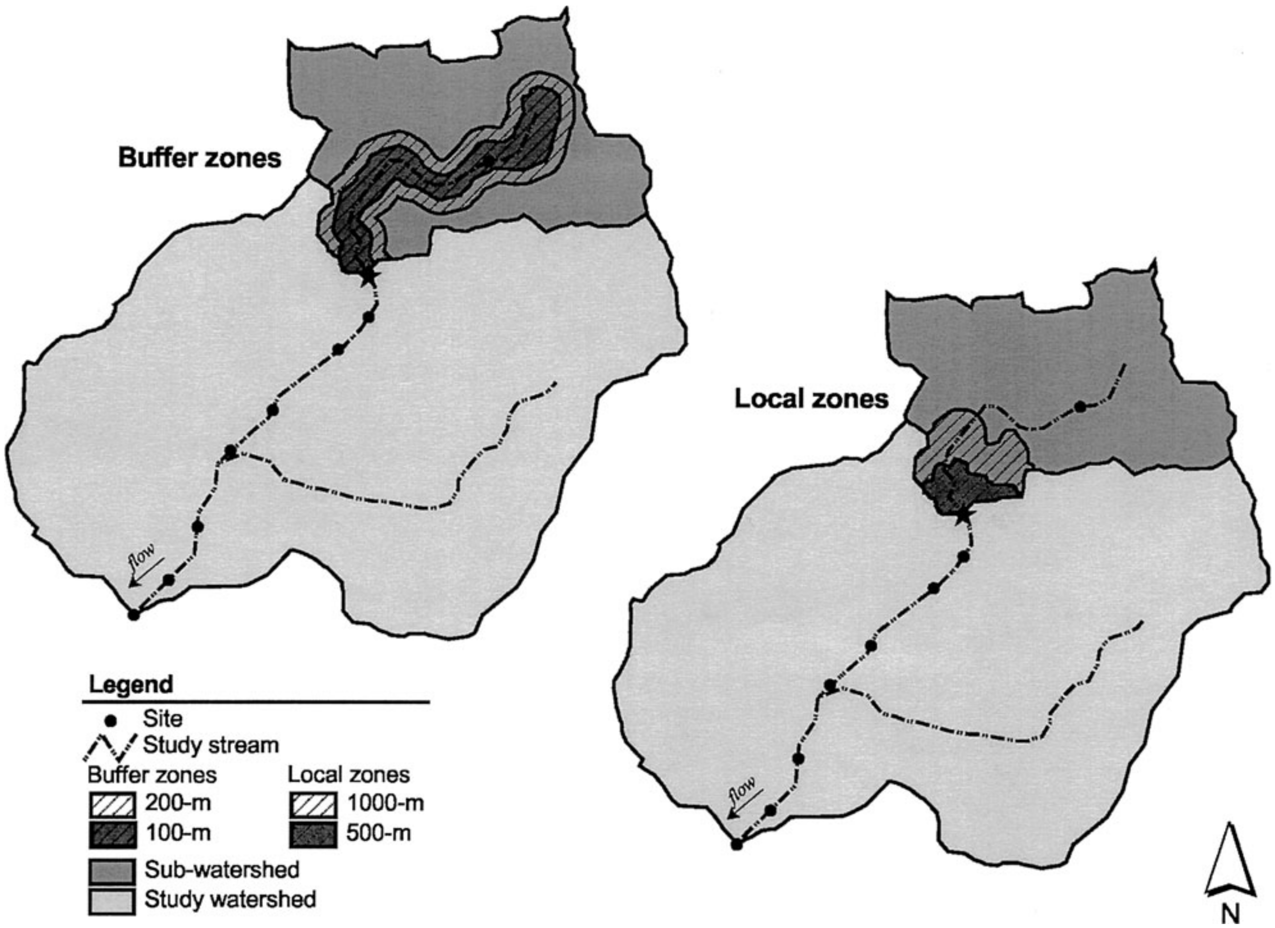

Figure 2. Conceptual Illustration of the Types of Spatial Scales Used in This Study.

TABLE 2. A List of Landscape Metrics, Their Units, and Detailed Descriptions.

Name	Unit	Description
	Magnitude Metrics	
Intense Urban Land (IU)	Percent	Proportion of intense urban land
Intense and Grassy Urban Land (IGU)	Percent	Proportion of intense urban land and grassy urban land
Total Urban Land (TU)	Percent	Proportion of all three urban land categories (intense, grassy, forested)
	Connectivity Metrics	
Road Density (RDD)	km/km^2	Total road length within a zone divided by the area of the zone
Median Flow Path Length (MFPL)	m	Median value of all flow path distances from each pixel of urban land to the closest stream channel
Upstream Distance to Road (UPRD)	m	Distance between a site and the closest upstream road crossing

The road density metric (RDD) represents the overall connectedness of the landscape regardless of the type of land cover. Roads are typically conduits for stormwater either via pipes or roadside ditches. The median flow path length metric (MFPL) is a measure of the proximity between urban areas and the stream channel network, regardless of the road network. The upstream distance to road metric (UPRD) represents how connected a particular stream site is to the nearest significant road crossing, which usually coincides with a point source of storm water runoff from the road or an adjacent urban area.

The intactness of the riparian buffer between consecutive sites was described via spatial analysis to evaluate longitudinal downstream trends. The intactness of the riparian buffer was defined by two measures: (1) the proportion of forest and wetland areas remaining in the 100 m buffer between any two sites, and (2) the number of road crossings between any two consecutive sites. The number of road crossings was normalized by the distance between the consecutive sites.

Analytical Methods

The physical conditions of the study streams were explored and compared using descriptive statistics, parametric tests, and nonparametric tests. Descriptive statistics such as means and proportions were used to analyze gradient, morphology, planform, bar features, and pool abundance. For ordinal variables the median was used to measure the center of the distribution instead of the mean (Afifi *et al.,* 2004). Analysis of variance (ANOVA) was used to test for differences in LWD abundance among the four study streams (Zar, 1984). The Kruskal-Wallis test, a nonparametric ANOVA, was used to test for differences in the ordinal data, including bank stability, structural complexity, embeddedness, and cementation (Zar, 1984). Dunn's nonparametric multiple comparison test was used following the Kruskal-Wallis test to investigate pairwise differences between the streams (Zar, 1984).

A multimetric index was created to compile the measurements of the physical attributes into a single, lumped score of physical stream condition. Six attributes were chosen to be components of the physical stream conditions index (PSCI). Table 3 lists the attributes, their descriptions, and their scoring criteria. These attributes were selected because they are widely observed to vary systematically through a gradient of human influence and because they include many of the responses to urbanization commonly reported in the literature. Channel size and LWD abundance, the two metrics collected as continuous data, were ranked to match the ordinal metrics in four categories. Channel size enlargement values followed a normal distribution, and therefore the ranks were chosen using the mean and standard deviation

TABLE 3. A List of Metrics of the Physical Stream Conditions Index (PSCI) and Their Scoring Criteria.

Parameter	Description	Scoring 1	Scoring 2	Scoring 3	Scoring 4	Correlation With PSCI[1]
Channel Size	Rank based on enlargement above an expected channel size given the watershed size[2]	> 90 percent larger	50 to 90 percent larger	15 to 50 percent larger	15 percent larger	0.26
LWD Abundance	Rank based on quantity of LWD pieces in the 100 m reach[3]	< 5	5 to 9	10 to 14	> 14	0.73
Bank Stability	Qualitative rank of bank conditions in the 100 m reach[4]	Unstable	Moderately Unstable	Slightly Unstable	Stable	0.70
Structural Complexity	Qualitative rank of stream's structural complexity[5]	Poor	Fair	Good	Excellent	0.80
Embeddedness	Qualitative rank of percentage of embedded substrate[6]	75 to 100 percent	50 to 75 percent	25 to 50 percent	< 25 percent	0.59
Cementation	Qualitative rank of compactness of riffle substrate[7]	Poor	Fair	Good	Excellent	0.68

[1]Spearman's correlation coefficient.
[2]Expected channel sizes calculated using regional regression of nonurban streams (Figure 3; Booth, 1990).
[3]May *et al.,* 1997.
[4]Henshaw and Booth, 2000.
[5]Barbour *et al.,* 1999.
[6]Scholz and Booth, 2001.
[7]McBride, 2001.

values. LWD abundance data did not follow a recognizable distribution. Large woody debris abundance was ranked using equal intervals with the highest rank (> 14) based on the average LWD count for the reference stream, Thorndyke Creek. Lacking any conceptual basis to favor one attribute over another, all attributes were ranked with equal weighting, using a numerical scale of 1 to 4, and their individual scores totaled for the index score. Higher scores indicate better physical quality of the stream.

The PSCI was analyzed via simple and multiple regressions with landscape metrics using an acceptable error rate of 5 percent. The PSCI and all predictor variables were checked for normality via the inspection of normal probability plots. No transformations of the PSCI data or the predictor variables were needed. Correlations between the PSCI and its metrics were identified using Spearman's correlation coefficients, and correlations between the landscape metrics were identified using Pearson's correlation coefficients (Zar, 1984). Longitudinal trends in the PSCI were also explored, particularly in comparison to the intactness of the riparian buffer between two adjacent sites. The change in the PSCI score (Δ PSCI) was calculated as the difference in PSCI score between consecutive sites along the stream longitude. Positive values of Δ PSCI indicate downstream improvement, and negative values of Δ PSCI indicate downstream decline. Changes in PSCI score between consecutive sites can be used to test for local effects because the watershed characteristics are virtually identical for consecutive sites. All statistical tests and analyses were performed using SPSS software for Windows (SPSS Inc., 1999).

RESULTS

Physical Stream Conditions

Geomorphic characteristics at all sites were similar in many respects, including gradient, morphologic classification, planform, bar features, pool abundance, and substrate size (Table 4). Channel gradients ranged from 0.3 percent to 2.5 percent. All sites had pool-riffle or plane bed morphology. Channel planform was either meandering or straight; none of the sampled sites were braided. Most reaches had storage features in the form of point or alternate bars. Most of the reaches had an average of four pools per 100 m. Substrate size distributions were very similar among reaches, and the median grain size (d_{50}) ranged from 16 to 45 mm.

Other conditions varied substantially, including bankfull channel dimensions, LWD abundance, bank stability, structural complexity, embeddedness, and cementation (Table 5). Channel dimensions reflected a characteristic relationship with watershed size – as watershed size increased, the channel's cross-sectional area at bankfull increased. The cross-sectional areas of the sampled sites were plotted against watershed area (Figure 3). Thorndyke Creek's channel sizes were larger than expected given the regional regression of non-urban streams (Booth, 1990), which may be a result of current or former logging activity. Large woody debris abundance was significantly different among the study streams ($p = 0.003$, ANOVA). Ranks of bank stability were significantly different among the study streams ($p < 0.0005$, Kruskal-Wallis), but pairwise comparisons showed that several streams had similar rankings (e.g., Juanita and Swamp Creeks; Table 5). Ranks of structural complexity were

TABLE 4. Geomorphic Characteristics of the Four Study Watersheds From Surveys of Multiple Sites.

Stream	n	Mean Channel Gradient (percent)	Range of Channel Gradients (percent)	Proportion of Sites With Pool-Riffle Morphology (percent)	Proportion of Sites With Bar Features (percent)	Mean Pool Count (No./100 m)	Range of Pool Counts (No./100 m)	Substrate d_{50} (mm)*
Juanita	7	1.1	0.8 to 2.0	100	78	4	3 to 6	22.6
Swamp	28	1.1	0.3 to 2.0	75	84	3	1 to 8	45
Little Bear	22	1.2	0.5 to 2.5	73	58	4	1 to 10	32
Thorndyke	13	1.3	1.0 to 2.0	70	100	4	2 to 6	16

*Substrate size at farthest downstream site.

TABLE 5. Variable Physical Characteristics of Study Streams.

Stream	n	Cross-Sectional Area (m²)[1]	Expected Cross-Sectional Area (m²)[2]	Mean LWD Count (No./100 m)	Range of LWD Counts (No./100 m)	Median Ranks[3] Bank Stability	Structural Complexity	Embeddedness	Cementation	Mean PSCI Scores (std.)[4]	Range of PSCI Scores	Maximum ΔPSCI Score[5]
Juanita	7	3.6	1.8	4	1 to 13	2^{A}	2^{D}	3^{EF}	2^{HJ}	12.3 (2.5)	9 to 15.5	3.5
Swamp	28	6.1	3.8	6	0 to 25	2.5^{AB}	2^{D}	3^{E}	2^{H}	14.4 (2.4)	10.5 to 19.5	7.5
Little Bear	22	5.6	3.0	9	1 to 24	3^{BC}	3^{D}	4^{FG}	3^{J}	16.7 (3.5)	12 to 22.5	6.5
Thorndyke	13	4.6	2.5	14	0 to 26	3^{C}	3.5	4^{G}	3	19.4 (1.3)	18 to 22.5	2.5

[1]Cross-sectional area of farthest downstream site.
[2]Expected cross-sectional areas calculated using regional regression of nonurban streams (Figure 3; Booth, 1990).
[3]Capital letters (e.g., A) denote which median ranks are not significantly different by Dunn's nonparametric multiple comparison test ($\alpha = 0.05$; Zar, 1984).
[4]Standard deviation values in parentheses.
[5]Δ PSCI is calculated as the PSCI score of one site minus the PSCI score of its upstream neighbor.

significantly different among the study streams ($p < 0.0005$, Kruskal-Wallis), but the three urban streams (Juanita, Swamp, and Little Bear Creeks) were indistinguishable from each other in pairwise comparisons. Ranks of embeddedness were significantly different among the study streams ($p < 0.0005$, Kruskal-Wallis), but some stream pairs had similar rankings (e.g., Juanita and Little Bear Creeks). Ranks of cementation were significantly different among the study streams ($p < 0.0005$, Kruskal-Wallis), but two stream pairs (Juanita and Swamp Creeks, Juanita and Little Bear Creeks) were indistinguishable from each other.

Correlations Among Landscape Metrics at Different Scales

The quantity of urban land cover in the subwatershed showed very different relationships with the quantity of the urban land in the buffer and local zones. Even though the 100 m buffer zone occupies only 16 percent of the subwatershed zone on average, its land cover was nearly indistinguishable from that of the subwatershed. This strong correlation was demonstrated by a correlation of total urban land in the 100 m buffer zone to total urban land in the subwatershed ($r = 0.99$, $p < 0.0005$, Table 6). Because the quantity of urban land in the 100 m and 200 m buffer zones was so closely correlated with that in the subwatershed zone, the buffer zone metrics were abandoned in the subsequent analysis. In contrast, the percentage of urban land was often considerably different between the local zones and the subwatershed zones. Correlations between the subwatershed zones and the local zones were not significant for the intense urban land metric and the intense and grassy urban land metric, but the total urban land in the subwatershed and local zones were correlated ($r = 0.69$ for 500 m local zone, $r = 0.73$ for 1,000 m local zone).

Connectivity metrics were highly correlated with many of the magnitude metrics (Table 6). Generally, watersheds had no "disconnected" urban land, at least in the way connectivity was quantified in this study; none of the study sites had high quantities of urban land and low measures of connectivity. Road density was strongly correlated with the amount of total urban land in the subwatershed by regression analysis ($r = 0.97$, $p < 0.0005$), and the differences in median flow path lengths between the urban streams was slight, ranging from approximately 300 m to 400 m. In contrast, the third connectivity metric (UPRD) varied considerably, ranging from about 100 m to 1,800 m. The UPRD metric was not significantly correlated with any other landscape metrics (Table 6).

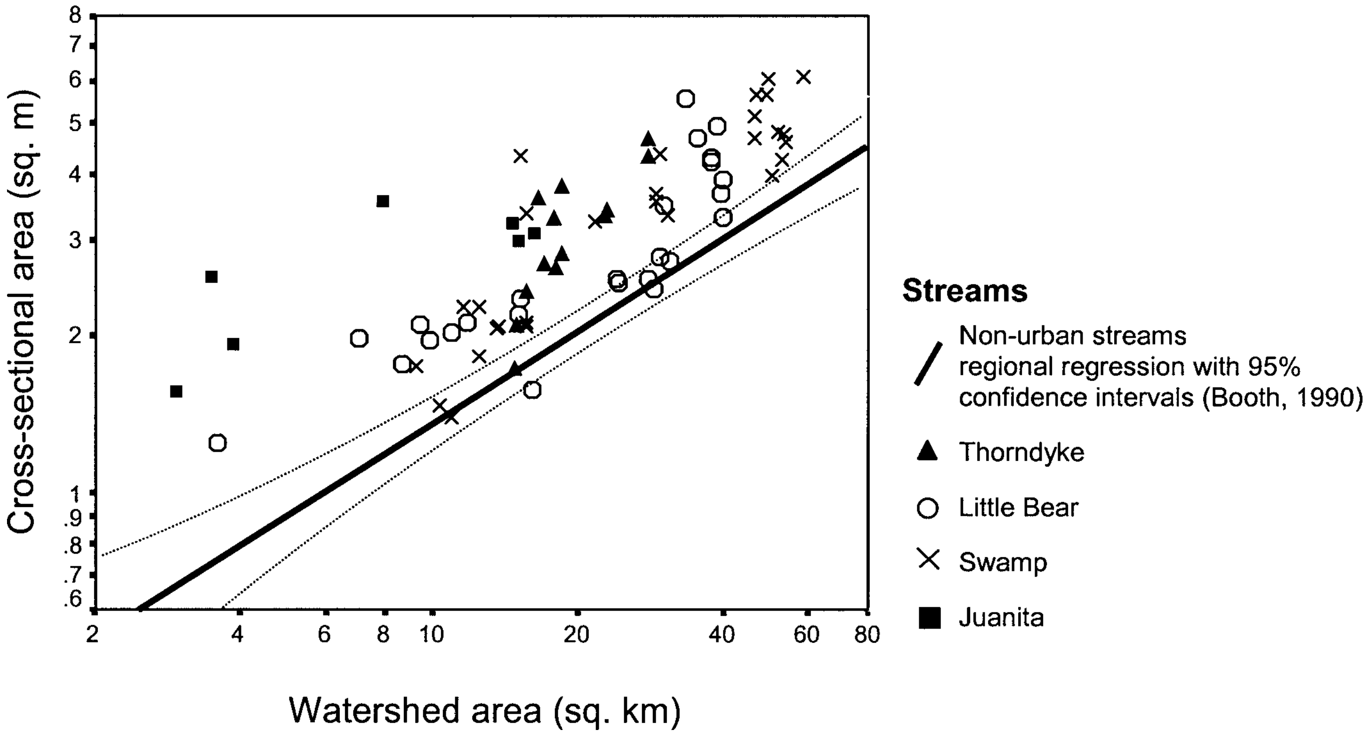

Figure 3. Plot of Channel Cross-Sectional Area Versus Watershed Area for the Study Sites With a Regional Regression Line for Nonurban Streams (Booth, 1990).

PSCI and Urbanization

The mean PSCI scores responded predictably to differences in urbanization. Measured PSCI values ranged from 9 to 22.5 out of a total possible range of 6 to 24. Correlations between PSCI and its metrics indicate that all metrics contributed almost equally to PSCI scores, except for channel size which had a lower correlation coefficient (r = 0.26, Table 3). In general, PSCI scores were greater for watersheds with less urbanization (Table 5). The PSCI showed a significant decline with increasing percent total urban land in the subwatershed zone, though the regression relationship is not compelling (Figure 4a; $R^2 = 0.42$, $p < 0.0005$). When PSCI was regressed with the total urban land within the local zones, the resulting relationships provide some explanation of the variability (Figure 4b and 4c).

Better relationships between the PSCI and the landscape metrics were found using multiple regression techniques instead of single regression models. A better explanation of the variability in the PSCI scores is given by a multiple regression of percent intense and grassy urban land in the subwatershed zone (IGU_{SUB}) and in the 500 m local zone (IGU_{L1}; $R^2 = 0.52$, $p < 0.0005$). Other pairings of urban land magnitude metrics in the subwatershed and local zones provide comparable, statistically significant models. In an attempt to further explain the PSCI, a connectivity metric was added to the regression model. Of all connectivity metrics, only one, upstream distance to a road crossing (UPRD), produced a significant regression model ($R^2 = 0.41$, $p < 0.0005$):

$$PSCI = 20.1 - 11.8\ IGU_{SUB} - 9.4\ IGU_{L1} + 1.7\ UPRD \quad (1)$$

where IGU_{SUB} and IGU_{L1} are in percent and UPRD is in meters.

The sites from Thorndyke Creek were excluded from this regression model because the connectivity metrics (as defined) were not valid in a watershed lacking true urban land cover. For the three urban streams, the regression model in Equation (1) outperforms the regression model with the two magnitude metrics ($R^2 = 0.38$, $p < 0.0005$).

Longitudinal Trends

The PSCI scores were analyzed for longitudinal trends in the three urban watersheds. The variability in PSCI scores among sites in the same urban watershed was high, as compared to the variability in the reference watershed (see measures of standard deviation in Table 5). Swamp and Little Bear Creeks had

TABLE 6. Pearson's Correlation Coefficients Between Landscape Metrics (- not significant, p > 0.05).

Landscape Metric	Abbreviation	IU_{SUB}	IU_{B1}	IU_{B2}	IU_{L1}	IU_{L2}	IGU_{SUB}	IGU_{B1}	IGU_{B2}	IGU_{L1}	IGU_{L2}	TU_{SUB}	TU_{B1}	TU_{B2}	TU_{L1}	TU_{L2}	RDD	MFPL	UPRD
Intense Urban Land (percent)																			
Subwatershed	IU_{SUB}	1																	
100 m buffer	IU_{B1}	0.92	1																
200 m buffer	IU_{B2}	0.95	0.99	1															
500 m local zone	IU_{L1}	-	-	-	1														
1 km local zone	IU_{L2}	-	-	-	0.87	1													
Intense and Grassy Urban Land (percent)																			
Subwatershed	IGU_{SUB}	0.89	0.87	0.87	-	-	1												
100 m buffer	IGU_{B1}	0.83	0.87	0.86	-	-	0.97	1											
200 m buffer	IGU_{B2}	0.84	0.87	0.86	-	-	0.98	1	1										
500 m local zone	IGU_{L1}	-	-	-	0.82	0.73	-	-	-	1									
1 km local zone	IGU_{L2}	-	-	-	0.7	0.8	-	-	-	0.84	1								
Total Urban Land (percent)																			
Subwatershed	TU_{SUB}	0.62	0.65	0.64	-	-	0.87	0.89	0.91	0.37	0.38	1							
100 m buffer	TU_{B1}	0.64	0.66	0.64	-	-	0.88	0.91	0.91	0.36	0.37	0.99	1						
200 m buffer	TU_{B2}	0.6	0.64	0.63	-	-	0.85	0.89	0.9	0.39	0.39	1	0.99	1					
500 m local zone	TU_{L1}	0.21	0.26	0.25	0.47	0.44	0.43	0.44	0.47	0.79	0.68	0.69	0.67	0.7	1				
1 km local zone	TU_{L2}	0.23	0.29	0.27	0.41	0.48	0.46	0.49	0.51	0.71	0.79	0.73	0.72	0.74	0.91	1			
Connectivity Metrics*																			
Road density	RDD	0.4	0.37	0.36	-0.26	-0.32	0.72	0.73	0.76	-	-	0.97	0.93	0.95	0.44	0.54	1		
Median flow path length	MFPL	-0.29	-0.26	-0.28	0.23	-	-	-	-	0.39	0.47	-	-	-	0.34	0.49	0.36	1	
Upstream distance to road	UPRD	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	1

*Correlations of connectivity metrics included data from the three urban watersheds only.

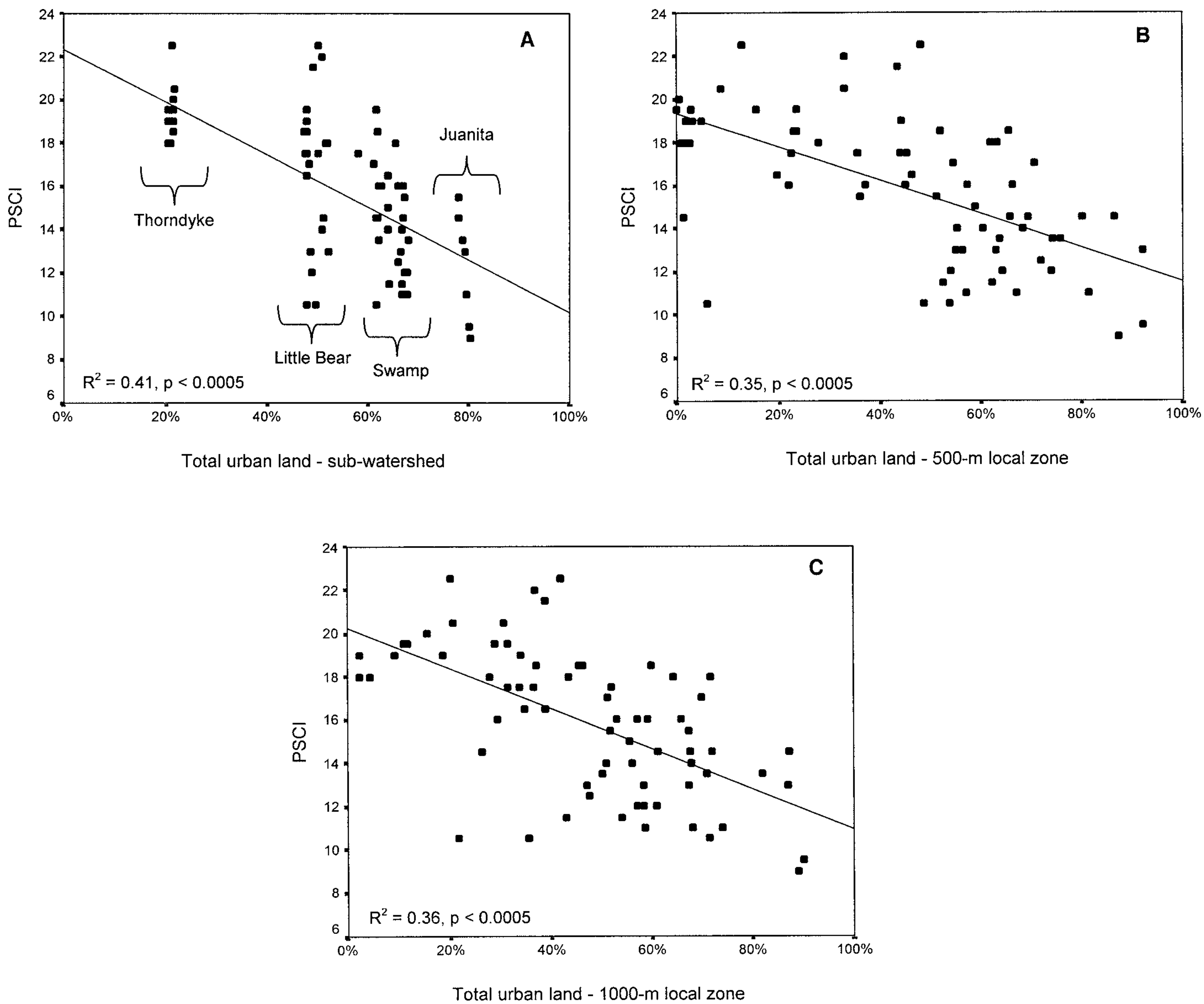

Figure 4. Plots of the Relationships Between PSCI Scores and Urbanization in the (A) Subwatershed, (B) 500 m Local Zone, and (C) 1,000 m Local Zone With Linear Regression Lines.

the greatest overall range in PSCI score (Table 5). Plots of PSCI scores as a function of channel distance demonstrate that conditions changed rapidly between consecutive sites and that continuous downstream trends were not apparent (Figure 5). The change in PSCI scores of consecutive sites were found to range from no change (Δ PSCI = 0) to substantial change (Δ PSCI = 7.5). The change in PSCI scores between consecutive sites was occasionally as great as the total range in PSCI scores within an entire watershed.

The intactness of the riparian buffer explained some of the longitudinal changes in the PSCI score. The PSCI scores were found to significantly improve in the downstream direction (Δ PSCI > 0) when the 100 m buffer between sites was at least 35 percent forested (p = 0.05; two-sample t-test with unequal variance) (Zar, 1984). The differences in Δ PSCI were highly significant when sites were grouped using the median value of forest buffer (50 percent), which facilitated a two-sample t-test (unequal variance) with equal sample sizes (n = 27, p = 0.002, Figure 6a). The presence of road crossings between consecutive sites likely promoted downstream decline in PSCI scores (Δ PSCI < 0; Figure 6b). For consecutive sites with many road crossings between them, the Δ PSCI was often negative. These two riparian factors were not significantly correlated (r = -0.19, p = 0.16) but appeared to act in concert (Figure 6c). When the buffer between consecutive sites was either not fragmented by a road crossing or fragmented by less than three road crossings per km, the downstream change in PSCI was significantly higher for sites with at least a 50 percent forested buffer (p = 0.08 and p = 0.03, two-sample t-test with unequal variance). When more than three road crossings per km were present, a forested buffer was apparently less effective, resulting in a smaller and less significant relative improvement in PSCI scores (p = 0.10, two-sample t-test with unequal variance).

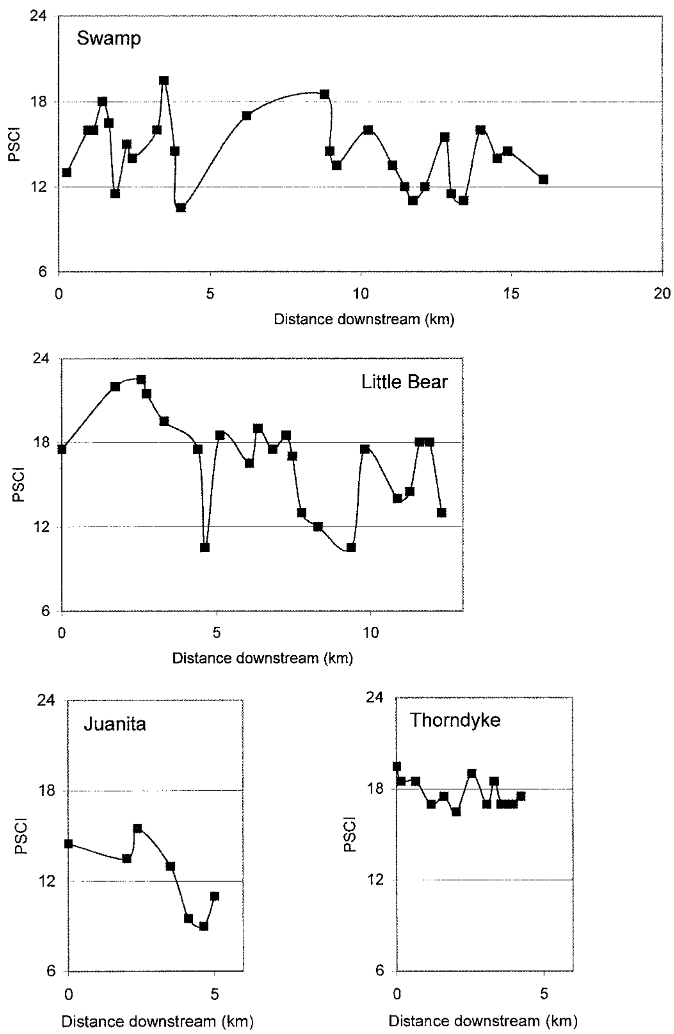

Figure 5. Longitudinal Profiles of PSCI Scores for the Study Streams.

DISCUSSION

Heterogeneity in Physical Stream Conditions

Local instream physical conditions are heterogeneous and are a function of the geomorphic context, the urbanization of the watershed, and the landscape conditions at the local scale. The range of physical stream conditions was greatest for Little Bear Creek and Swamp Creek (Figure 4a, Figure 5, Table 5), suggesting that moderately urbanized watersheds may be more heterogeneous than highly urbanized watersheds or forested, nonurban watersheds. The heterogeneity of moderately urbanized streams is partially explained by the amount of urbanization in the local zone and the intactness of the local riparian buffer. The effects of local urbanization, road crossings, and deforested riparian buffers may be more pronounced in stream systems that have not been overwhelmed by the effects of extensive watershed scale urbanization. Watershed scale urbanization likely sets a maximum attainable best condition, while local and riparian urbanization can further degrade physical conditions. Road crossings appear to be a key point of disruption in urban streams, interrupting the riparian zone and providing a point source for storm water discharges. Other studies have pinpointed roads as key stressors in urban landscapes (May *et al.,* 1997; Marina Alberti, University of Washington, personal communication, December 2003).

Physical Stream Conditions Index

The PSCI effectively integrates a variety of qualitative attributes that are strongly influenced by urbanization into a meaningful, quantitative score. The PSCI functions well as a general measure of the physical integrity in streams, responding in an intuitively reasonable and statistically significant manner to gradients of urbanization. The PSCI correlates well with the proportion of urban land in the subwatershed and local zones (Figure 4). To further evaluate the utility and robustness of the PSCI, however, it needs further validation with other sampling efforts.

The applicability of the PSCI may be limited by the sampling and geographic scope of this study. This index could be used in other Puget Sound Lowland small order (first-order to third-order) streams without hesitation. Applying the PSCI beyond this region or in larger-order streams, however, would not be recommended without first testing its applicability. With that said, most of the PSCI's individual metrics are measures of common symptoms of urban streams in other parts of this country and the world, such as bank instability (Neller, 1988; Trimble, 1997), increased channel size (Pizzuto *et al.,* 2000; Hession *et al.,* 2003), and the loss of LWD (Booth *et al.,* 1997; May *et al.,* 1997).

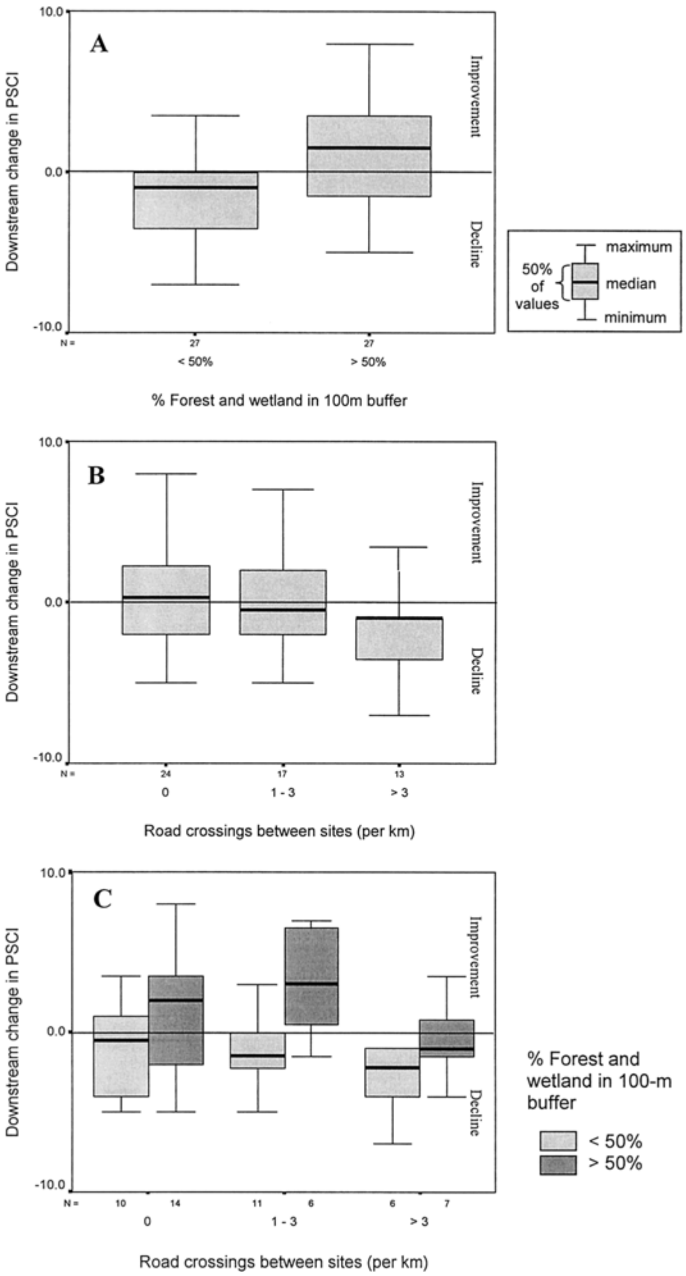

Figure 6. Boxplots of Relationships Between the Change in PSCI Scores (Δ PSCI) and (A) the Amount of Forested or Wetland Buffer Between Consecutive Sites, (B) the Number of Road Crossings Between Consecutive Sites, and (C) the Combined Effect of Buffer Conditions and Road Crossings.

Measuring Urbanization

The quantity, location, and distribution of urbanization can be successfully quantified with relatively simple, GIS based landscape metrics. In some instances, the variety of landscape metrics explored in this study provided a more robust characterization of the urbanized landscape than more commonly used lumped measures of urbanization, such as percent total impervious area. The urbanization of the local zone and the proximity to road crossings provided further explanation of the physical stream conditions of each site; however, some landscape metrics are so closely related that they cannot help decipher stream conditions (i.e., urban land in the buffer zone with urban land in the subwatershed and road density with urban land). Other studies have uncovered similar correlations between land cover in buffers and watersheds (Fitzpatrick *et al.,* 2001; Morley and Karr, 2002; Wang and Kanehl, 2003). Although not useful for better understanding stream conditions, these relationships between landscape metrics provide insight to the nature of the urban landscape.

The pattern of urbanization in the Puget Sound lowlands appears to be fairly homogeneous, as is demonstrated by two key results. First, urban land is evenly distributed throughout the study watersheds in relation to the stream network. The nearly equivalent median flow path lengths found in this study indicate that urban land is not clustered near or far from any particular stream channel, which is consistent with the finding that the urbanization of riparian buffers mirrors the urbanization of the entire watershed. Second, urban areas appear to be equivalently connected to the stream network, as measured by the connectivity metrics in this study. An increase in urban land leads to an increase in the number of roads connecting urban areas to stream channels. The minimal variation in median flow path lengths among the urban streams also demonstrates that urban areas have uniform connectivity.

In contrast, other studies have found variations in connectivity to be an important and influential factor (Bledsoe and Watson, 2000; Wang *et al.,* 2001; Walsh, 2004). Bledsoe and Watson (2000) have studied the change in stream power associated with increased impervious areas and have found it to be sensitive to the connectedness of those impervious areas. A study of Wisconsin urban streams found that the amount of connected impervious area was the best measure of urban impact to several biotic and physical indicators (Wang *et al.,* 2001). A recent study in the Puget Sound region has determined that the number of road crossings per stream kilometer best predicts biological integrity in streams of 42 drainage basins (Marina Alberti, University of Washington, personal communication, December 2003). The importance of connectivity in predicting urban stream conditions may be a function of how connectivity is measured. Road density, as a metric of connectivity and as a coarse estimate of the extent of hydraulic connections to the channel network, did not provide any additional explanatory power in this study. If connectivity can be measured using more detailed information on storm water drainage, as in Wang *et al.* (2001), it may be an important predictor of stream health.

Important Zones of Influence

Results suggest that physical stream conditions are impacted by urbanization in the subwatershed and local zones to nearly equivalent degrees. The regression of PSCI against subwatershed and local zone intense and grassy urban land revealed that these landscape metrics were equally important predictor variables. The combination of intense and grassy urban land (IGU) had a better regression relationship with PSCI than the total urban land (TU) that includes forested urban land. Forested urban lands with low total impervious areas likely do not impact urban streams as severely as the other urban land areas. These results mirror those of other studies. Although watershed conditions are undeniably influential, many studies have identified a disproportionate influence of the local or riparian zone (Steedman, 1988; Wang *et al.,* 2001; Morley and Karr, 2002; Wang and Kanehl, 2003). A similar study of several Puget Sound streams found that biological integrity was equally well predicted by urbanization in the watershed and by urbanization in the local area (Morley and Karr, 2002). Wang *et al.* (2001) found that connected impervious area immediately adjacent to a stream, within either a local zone or a buffer zone, had the strongest influence on an index of biotic integrity and base flow.

In this study, the R^2 values of the various regression models tested suggest that approximately half the variability in physical stream conditions, as measured by PSCI, can be explained by various landscape metrics. Therefore, landscape metrics should not be expected to adequately predict stream conditions, and they cannot be used as a surrogate to instream assessments. Both GIS based analysis and instream assessments of physical or biological conditions are required to evaluate any particular stream system.

Downstream Recovery

Longitudinal trends in the PSCI scores show that partial recovery of physical conditions is possible where a degraded stream flows through an intact forested 100 m riparian buffer. Stream segments with road crossings and without substantial forested riparian buffers tended to have PSCI scores that declined in the downstream direction. The results showed improved physical conditions where the 100 m riparian buffer was at least 35 percent forested. The greatest downstream improvements in physical stream conditions were realized in areas that had few road crossings and substantial forest or wetland riparian buffers within a 100 m corridor of the stream channel.

There are several possible processes acting along a stream channel that could improve physical conditions. Undeveloped riparian zones in the Puget Sound Lowlands typically have active floodplains and riparian wetlands. The roughness of a forested riparian zone and wetland areas can attenuate peak storm flows and reduce specific stream power (Bledsoe and Watson, 2000). If the erosive force of peak flows can be diminished, stream reaches will likely experience less disturbance in their channels, resulting in more stable streambeds and banks. If forested riparian zones and wetlands can significantly slow peak flows and temporarily store storm water, fine sediment suspended or carried in the water column has the potential to filter out and remain deposited in wetlands or on floodplains or within the channel in bars. An intact forested riparian zone also allows the recruitment of LWD and, by definition, precludes many direct anthropogenic impacts, such as channel straightening or streambank armoring.

Management Implications

The results of this study have specific management implications. The amount of development in a watershed is extremely influential on the physical and biological conditions in streams, which necessitates watershed wide land use planning for successful protection of streams. Watershed land use is not the sole determinant of stream conditions, however, and a strategy that imposes only a watershed wide limit on development will be inadequate. Local land cover is extremely important to physical stream conditions, and therefore this zone of the watershed should have high priority in planning and regulations. If urban development can proceed while maintaining intact, undeveloped riparian buffers, the impact of urbanization should be less than from traditional development patterns (Wang *et al.,* 2001). The results also suggest restoration potential for degraded urban streams. If riparian buffers can be reforested and road crossings eliminated or avoided in certain reaches of streams in watersheds with moderate urbanization, partial recovery of a stream's physical integrity is possible.

CONCLUSIONS

This study demonstrates that the effects of urbanization on physical stream conditions are influenced by spatial scale and landscape patterns. Urbanization of both the entire contributing watershed and the part of the watershed closest to the stream appear to have approximately equal weight in influencing a stream's physical conditions, analogous to a prior study of biological conditions in the same region (Morley and Karr, 2002). Urbanization in the watershed is highly influential to streams and likely sets a maximum attainable best condition, yet conditions are strongly modified by the local landscape conditions. Physical conditions can improve downstream from degraded stream reaches if the riparian zone is substantially forested and devoid of road crossings.

Results also highlight the utility of several methodologies used in this study. The PSCI effectively integrates a set of physical attributes, responding in an intuitively reasonable and statistically significant manner to gradients of urbanization in the Puget Sound lowlands. The GIS based analysis generated several landscape metrics that described the quantity, location, and distribution of urban land in the study watersheds and explained much of the variability in physical stream conditions. This study integrated these methodologies to interpret the effects of spatial scale, connectivity, and longitudinal trends in urban streams.

In sum, with better information on the interaction of urbanization and stream ecosystems, policies and management strategies for protecting stream integrity in developing areas can be improved. With more robust knowledge the landscapes can be modified to preserve those streams or stream segments that still function while targeting rehabilitation efforts to those degraded portions of streams that have realistic chances for improvement.

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