Spatial effects of urbanization on physical conditions in Puget Sound Lowland streams

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Abstract

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Urban development threatens local and global ecosystems. In the Puget Sound region, urbanization has dramatically altered stream ecosystems by changing their flow regimes and their physical attributes. This study of urbanization effects on streams had three objectives: 1) to assess physical stream conditions within and among four watersheds spanning a range of urbanization, 2) to use a geographic information system (GIS) to comprehensively characterize the urban landscape within these watersheds, and 3) to relate in-stream physical conditions to the landscape conditions of each watershed. To address the first objective, I used a rapid stream assessment technique to document the condition of several physical attributes along the mainstem channels of the four watersheds. The assessed streams had considerable heterogeneity in physical condition. In order to rate the overall physical condition, six attributes were used as components of a multi-metric index, termed the physical stream conditions index (PSCI). The PSCI helped quantify relationships between stream and landscape conditions. Landscape conditions of each watershed were measured using several GIS-derived landscape metrics (the second objective). The final objective was to consider how the location and distribution of urban land might affect the degree of impact to a stream's physical attributes. Physical conditions (as measured by the PSCI) were best explained by three of the landscape metrics: the quantity of urban land in that part of the watershed draining to the sampled site, the quantity of urban land within 500 m upslope of the sampled site, and the proximity of the sampled site to the closest upstream road crossing. A stream's physical condition improved downstream from degraded reaches when the stream flowed through portions of intact forested riparian buffers devoid of road crossings. In sum, the results of this study suggest that if urban development can

be built such that riparian areas are untouched, functioning stream reaches may be better preserved. Further, similar studies using GIS-based landscape analysis may quickly target rehabilitation efforts to stream reaches that have realistic opportunities for improvement.

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1. Introduction

Land cover change is one of the most significant and substantial of all anthropogenic changes. Humans have transformed the land cover of one-third to one-half of Earth's ice-free surfaces (Vitousek, 1994). A particularly permanent and dramatic transformation is urbanization. Urban development, coupled with human population growth, threatens local and global ecosystems and biodiversity. In the Pacific Northwest, stream and river ecosystems have been impacted to such an extent that wild salmon have disappeared from about 40% of their historical breeding grounds and remaining populations are greatly reduced in number (National Research Council, 1996). Although the decline of this key species is attributed to numerous impacts, urbanization is a prime culprit, especially in the Puget Sound region.

The urbanization of the Puget Sound region has dramatically altered the natural stream-flow regime and the physical and geomorphic conditions within stream systems. Prior to anthropogenic influences, this region was blanketed with conifer forests growing atop thick glacially derived soils. As a result of development, forested land has been replaced with buildings, roads, and lawns. These impervious surfaces, as well as the extensive changes to the soil profile and the native vegetation community, have changed conditions and processes in lowland streams, which results in impaired stream health.

Urban development will undoubtedly continue in this region and elsewhere; managers and policymakers may only be able to influence the location and distribution of the development. We must find less detrimental ways of developing our landscapes and more effective stream rehabilitation efforts so that we can preserve functioning and healthy stream systems in an ever-more populated area. There is a need for studies that identify which patterns of urbanization exert the least harm on stream systems. Successful watershed management in the urban environment also requires a full understanding of how a stream's ecosystem is affected by various impacts that accompany urbanization. The conceptual model that follows offers a means to dissect and organize the complex, multi-faceted subject of urban streams.

Conceptual model of stream degradation

Strong connections tie the conditions of a stream to the state of its contributing watershed. Simply stated, a watershed dictates the health of its stream (Riley, 1998); however, the relationship is a complicated one. The conceptual model outlined by Karr and Chu (1999) provides a concise framework for considering the effects of urbanization on several aspects of streams (Figure 1.1). A myriad of human influences can alter processes in stream systems, manifesting themselves in changes to what can be grouped into five “factors”: flow regime, physical habitat structure, water quality, energy source, and biological interactions. These factors are established merely to aid our understanding of stream systems; they can be regarded separately, but not independently, for interaction among them is inevitable. Changes to these five factors alter the biological condition in streams. Frequently, an urban stream experiences changes to all five factors.

The first factor, flow regime, is markedly different in an urban system than it would be in a natural, forested watershed. Commonly, flows in urban streams are “flashy,” referring to their drastically altered disturbance regime. These “flashy” characteristics (increased peak storm flows, shortened falling limbs of the storm flows, and lowered base flows) are illustrated in two hydrographs, one from an urban stream (Miller Creek) and a comparable but non-urban stream (Bear Creek), both located in the Puget Sound Lowland region (Figure 1.2; Konrad, 2000). In the natural, non-urban watershed, the stream receives water primarily through subsurface flow. In comparison to an urban stream, the natural stream has a longer lag time to the peak flow, a lower absolute peak, and a higher base flow. The urban stream’s flashiness is the result of less water storage in the subsurface and a more efficient drainage system. In urban watersheds, runoff is quickly and effectively delivered to the stream channel via stormwater pipes or road ditches.

The second factor, physical habitat structure, generally includes all physical and geomorphic attributes of a stream, which may be altered directly or indirectly by urbanization. Until recently, urban developers would often replace natural streams with pipes or straightened channels, completely obliterating the existing physical habitat. Physical habitat may also degrade indirectly, in response to an altered flow regime and/or sediment regime. For example, the larger urban storm flows may force a stream to become smoother or larger to accommodate increased discharge, in turn changing the physical habitat structure.

The final three factors (water quality, energy source, and biological interaction) are beyond the scope of this study but warrant explanation because they are influenced by urbanization as well. Water quality can be altered by many sources in the urban environment. Streams can be impaired by oils and metals from road runoff, by pesticides and herbicides in lawn runoff, and by sewage from leaking wastewater pipes or septic tanks. In an urban stream, changes to the energy source, which is mainly organic material (e.g. leaf litter), are particularly pronounced when the riparian zone is disturbed. Development within a once-forested riparian zone of low-order streams can alter the aquatic system by changing the dominant energy supply from organic material to sunlight, which has ramifications for the entire food web. These types of ramifications for the biological community are captured by the fifth factor, biological interaction. In an urban stream, biological interactions may be indirectly altered by changes to all of the four factors described above. An urban landscape also promotes the introduction of exotic species, which may directly affect the interactions of the native biological community.

In sum, the biology of aquatic systems is altered by human activities (e.g. land cover changes, effluent discharges, water withdrawals, fish harvesting, introduction of exotic species) which influence these five factors (Karr and Chu, 1999). Ultimately, we are most concerned with the biological condition of the stream, whether the aim is to preserve a declining species such as salmon or, more generally, to protect and rehabilitate healthy or once-healthy aquatic ecosystems. In the Puget Sound region, biological condition is frequently assessed using the benthic index of biological integrity (B-IBI). Biological monitoring using this technique of a multi-metric index is an integrative approach for measuring conditions which can indicate the level of human influence.

B-IBI has a definite value as a stream assessment tool, but it may not provide a clear diagnosis. B-IBI responds to all five of the factors described above, but the index does not distinguish unequivocally which of the five factors is (or are) the source(s) of the biological impairment. This shortfall leads to a management quandary: what elements of the watershed or stream does one target to rehabilitate a degraded stream? In order to answer this question, studies must tease out the effects of urbanization on distinct elements of stream systems. This study focuses on conditions that express the exclusively physical and geomorphic factors, flow regime and physical habitat structure. The following section explores past research on changes to these factors.

Physical and geomorphic conditions of urban streams

Past research – flow regime

Many studies have documented changes to the flow regime in urban streams (Leopold, 1973; Hollis, 1975; Booth, 1991; Konrad, 2000). One of the first of such studies (Leopold, 1973) documented a development-induced increase in the magnitude and frequency of storm flows. This 20-year study of an urbanized tributary to the Potomac River, Maryland, found that the number of floods exceeding channel capacity increased from an average of two per year to more than ten per year. Another study, published soon thereafter, linked the amount of change to the peak storm flows with the intensity of urbanization (Hollis, 1975). A greater increase in peak discharges resulted in those watersheds with greater amounts of impervious surfaces. Even watersheds with modest urban development (10% to 20% effective impervious area) were later found to experience a two- to three-fold increase in peak flows (Booth, 1991).

Past research – physical habitat

Physical habitat is primarily structured by three driving forces: transport capacity, sediment supply, and vegetation (Figure 1.3; Montgomery and Buffington, 1998). These driving forces all act in concert to construct the types of streams we observe. The transport capacity of a stream is dependent upon the flow regime and valley gradient (Montgomery and Buffington, 1998). The transport capacity may change significantly in an urban stream due to the altered flow regime. Yet the other driving forces, sediment supply and vegetation, also do not escape from impacts of urbanization.

Urbanization can change the frequency, the volume, and the size of the sediment delivered to stream channels. With the initial development in a watershed, a stream will typically receive a first flush of sediment from construction activity, followed by a decline in total sediment supply as the area becomes fully built out (Wolman and Schick, 1967). Older urban streams may become sediment-deprived if natural sediment sources (e.g. colluvium erosion, mass wasting, tree-throw) are blocked while transport capacity increases due to greater flows.

Changes to vegetation can be just as severe in the urban landscape. Native riparian vegetation is oftentimes removed during development and replaced with structures or non-native vegetation, such as lawns. When forested riparian zones are lost, the recruitment of large woody debris (LWD), a key element in Pacific Northwest streams, is often diminished. Even in undeveloped riparian zones, exotic species can infiltrate, changing the species composition of the riparian community, which in turn influences the physical conditions within the stream. The type and extent of vegetation present in the riparian zone can influence channel dimensions (Davies-Colley, 1997), stream bank stability due to variable root strength, and reach morphology due to the effect of LWD on the routing of water and sediment (Naiman et al., 1998).

When these three driving forces are altered, the channel responds accordingly by adjusting its dimensions, morphology, and sediment size (Montgomery and Buffington, 1998). Past research has documented changes to these elements of the physical habitat in urban streams. Cross-sectional dimensions often enlarge to accommodate the increased peak discharges (Hammer, 1971). A study of urban streams in Philadelphia found their median width 26% greater than the median width of comparable rural channels (Pizzuto et al., 2000). Channel enlargement can occur in proportion to the discharge increase or, in the case of channel incision, enlargement can outpace the discharge increases that originally initiated the change (Booth, 1990). With channel enlargement comes an additional influx of sediment, which can potentially be quite voluminous (see below; Trimble, 1997; Nelson, 1999).

Channel dimensions may also change in distinct phases and at accelerated rates. Graf's work (1975) in the Denver area revealed that suburban development first caused an expansion of floodplains, which was followed by channel incision. When a channel changes its dimensions, physical habitat is also disrupted by the instability of the system. Neller's study (1988) of channel bed and bank erosion in a pair of urban and rural watersheds found significant differences in erosion rates. The urban stream's banks were eroding 3-6 times faster than its rural counterpart, and upstream knickpoint migration was 2-4 times greater (Neller, 1988).

Channel morphology is often altered in urban streams as well. A recent study found that urban streams were straighter and smoother than comparable streams in rural watersheds (Pizzuto et al., 2000). Urban streams tend to lose their roughness elements (e.g. sinuosity, bars, pools) in order to convey the larger peak storm flows. Another important roughness element and morphologic feature is large woody debris (LWD), which also declines with increasing urbanization (Figure 1.4; May et al., 1997).

Sediment size may be finer or coarser in urban streams. The grain-size distribution commonly shifts to include much smaller sizes in urban streams (Booth and Jackson, 1997). The higher proportion of fine sediment originates from stormwater runoff laden with small particles and stream channel erosion. For example, channel erosion in San Diego Creek, California was found to contribute two-thirds of the total sediment yield of the basin, which is considerably larger than a historical estimate of one-fourth of the total yield in the time period of the 1930s to the early 1980s (Trimble, 1997). However, sediment size may not respond in the same manner in all urban watersheds. Pizzuto et al. (2000) did not find a significantly greater proportion of fine sediment (less than 2 mm) in urban streams compared to similar rural streams. Furthermore, their study found that sediment in the size range of 2 to 64 mm was selectively removed from urban streams (Pizzuto et al., 2000).

Great progress has been made in the study of urban streams, but these systems are still not completely understood. Past research has thus shown that streams can react and respond to urbanization in a multitude of ways. Most of the physical changes are not independent; they interact to form a complex urban stream system. Many of the studies mentioned have been designed to observe the most dramatic comparisons, paring or lumping strictly non-urbanized watersheds with highly urbanized watersheds. Moderately urbanized streams, with their inherent variability in physical stream conditions and landscape configuration, have not been the focus of most studies. In addition, past research on the physical and biological conditions of urban streams have often utilized gross, aggregate measures of urbanization which suffice for most comparative studies.

Measuring urbanization

Often, the degree to which a watershed is urbanized is used as a predictor of a stream's physical or biological condition. "Urbanization" is commonly quantified using simple, aggregated measures such as the percentage of impervious surfaces, population density, or road density. The watershed is often the area evaluated because it is the total portion of the landscape that contributes water and sediment to the stream. Unfortunately, relationships found between gross measures of urbanization in a watershed and the conditions of urban streams can be plagued with great variability. An example of one such relationship is shown in Figure 1.5, a plot of stream health (as measured by the B-IBI) versus urbanization (represented as the percentage of total impervious area in the watershed). It shows a general, undeniable decline in biological integrity with increasing watershed imperviousness, but anomalies and outliers exists. In other words, the amount of impervious surface in a watershed cannot be used solely to predict the physical or biological conditions of a stream.

Percent impervious area is an incomplete and imprecise indicator of urbanization, incapable of capturing the heterogeneity and complexity of the urban landscape. As a result, basing watershed evaluation and protection solely on total impervious surfaces is not an appropriate management strategy**.** In general, to resolve various applied environmental problems including urban stream degradation, techniques are needed that go beyond simple, summary statistics of a transformed landscape.

Quantitative methods that link landscape patterns and ecological processes are now considered critical to basic ecological research (Turner and Gardner, 1991). Because all ecological processes occur in a spatial context, research efforts must take a spatial perspective. In an urban ecosystem, understanding patterns of development and their implications for any type of urban impact to the aquatic or terrestrial environment will allow planning and regulatory efforts to focus on what is critical in determining environmental quality.

In the context of urban streams, the amount, the location, and the distribution of urban land in a watershed are the key spatial variables that should affect the extent and severity of the urban influence on a stream. As seen in the example above, the amount of impervious surfaces is influential to stream conditions; however, these impervious surfaces do not equivalently contribute to stream degradation. Some are more influential than others, perhaps depending on their location and distribution.

The influence of urban land on the five factors of a stream ecosystem is partially, but not entirely, determined by the location of urban lands within a watershed. Because the five factors function at different scales (Figure 1.6), they respond according to where the urban land is located. Energy source and physical habitat structure are influenced most strongly by the local conditions at a particular reach of a stream (Allan et al., 1997). When urban development occurs adjacent to a stream, the stream may no longer be shaded (a change in energy source) and its physical habitat may be altered from channel modifications (channel straightening, rip-rapped banks). Conversely, the flow regime and sediment supply are determined primarily by watershed conditions, or the larger geomorphic context (Allan et al., 1997). For example, impervious surfaces in any part of the watershed will limit the infiltration of rainwater and diminish subsurface and groundwater recharge. Yet some impervious may be significantly more influential than others based on their proximity to the stream channel or their connection to the stream channel (termed *effective impervious areas*; Booth and Jackson, 1997) because they deliver runoff directly to the stream.

The distribution of urban land may also influence the impacts that urbanization has on the surrounding ecosystem. The distribution of urban land can be more precisely described by different landscape variables such as urban form, land use heterogeneity, and land use connectivity (Alberti et al., in prep). These variables define the structure and pattern of urban development and may be influential to the effects of urbanization on terrestrial and aquatic ecosystems.

Land use connectivity may be especially important in determining how effective urban lands are in impacting stream systems. Connectivity is defined as “how spatially or functionally continuous a patch, corridor, network or matrix of concern is” (Zipperer et al., 2000). In an urban area, high connectivity of forest land and patches in an otherwise fragmented landscape may be beneficial, or even essential, for maintaining metapopulations of a variety of animal and plant species (Zipperer et al., 2000). Conversely, highly connected urban land with a large fraction of impervious surfaces may be detrimental to stream ecosystems. Urban land that is more connected to the stream network creates a watershed that is more efficient in shedding stormwater from its surfaces, creating a more unnatural state. This connectivity of urban land can occur in various ways. A higher density of roads provides more conduits for stormwater via pipes or ditches. Where more roads cross streams, additional stormwater outfalls are created, allowing for more connection points with the stream. Urban land may also be more connected to the stream simply by being closer to the stream channel as opposed to the upland areas of a watershed.

There is a significant need for dependable, statistically sound tools to evaluate the amount, location, and distribution of urban land in watersheds. Measures of urbanization that go beyond single, watershed-scale numbers will help us to understand and predict the severity and extent of urban effects on stream systems. Better methods of characterizing urban watersheds will also aid watershed management, identifying key areas to focus remedial or protective efforts. The relationships between the physical integrity of urban streams and the status of the surrounding landscape are pivotal in shaping our understanding of urban stream ecosystems. With better information on the interaction of land cover change and stream ecosystems, we should be able to improve policies and management strategies for protecting stream integrity in developing areas (Wear et al., 1998).

Study objectives

This study has three main objectives. The first objective is to assess the physical and geomorphic features within and among watersheds spanning a range of urbanization. There is a common belief that urban streams are degraded throughout. Are urban streams truly homogenous? If not, what determines their physical and geomorphic heterogeneity?

The second objective is to determine better methods to measure urbanization. The standard measure of urban land cover change is in units of percent total impervious area in the watershed. How can we increase the comprehensiveness and sophistication of our characterization of the urban landscape? How can we quantify concepts such as connectivity? Work on this objective of the study proceeded with the collaboration of an interdisciplinary research group at the University of Washington including Marina Alberti (Urban Planning), Derek Booth (Civil & Environmental Engineering), Kristina Hill (Landscape Architecture), and Daniele Spirandelli (Landscape Architecture). This group conceived and evaluated several measures of urbanization.

The third objective is to identify relationships between the physical and geomorphic stream conditions and these more comprehensive measures of urbanization. Can measures that incorporate the amount, the location, and the distribution of urban land provide further explanation for the physical and geomorphic conditions of urban streams?

HUMAN ACTIVITIES

Land use (urban, farms, logging, grazing)
Effluent discharge
Water withdrawal
Discharge from reservoirs
Sport and commercial fisheries

change processes to influence one or more of

FIVE FACTORS

Flow regime: *discharge, timing of stream flow*
Physical habitat: *channel structure, substrate, morphology*
Water quality: *temperature, dissolved oxygen, contaminants*
Energy source: *allochthonous or autochthonous*
Biological interactions: *competition, predation, disease*

thereby altering

BIOLOGICAL CONDITION

Figure 1.1 Conceptual model of the effect of human activities on stream ecosystems. Adapted from Karr and Chu, 1999.

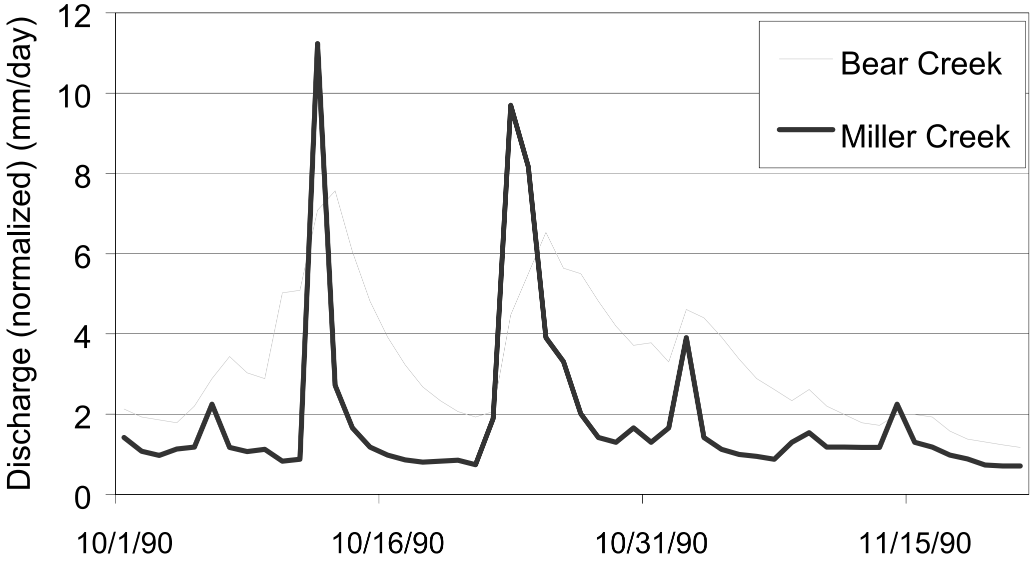

Figure 1.2 Hydrographs compared from urban Miller Creek and non-urban Bear Creek. Adapted from Konrad, 2000.

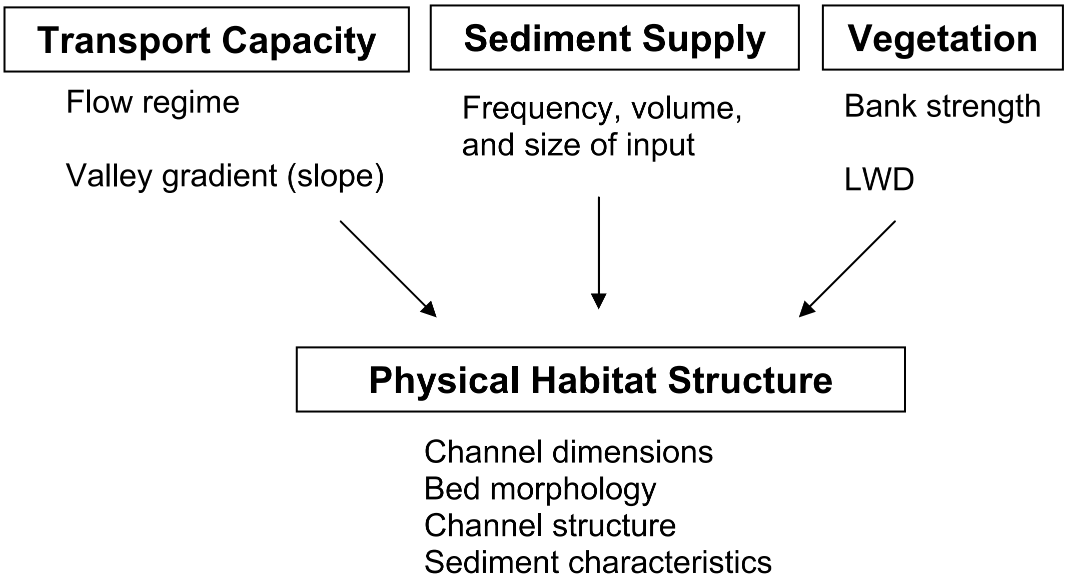

Figure 1.3 Driving forces structuring physical habitat in stream systems. Adapted from Montgomery and Buffington, 1998.

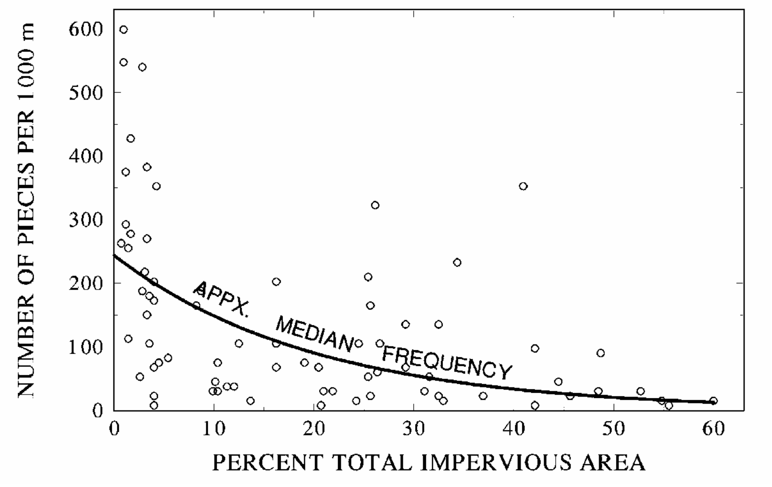

Figure 1.4 Large woody debris (LWD) frequency in Puget Sound lowland streams. Adapted from May et al., 1997.

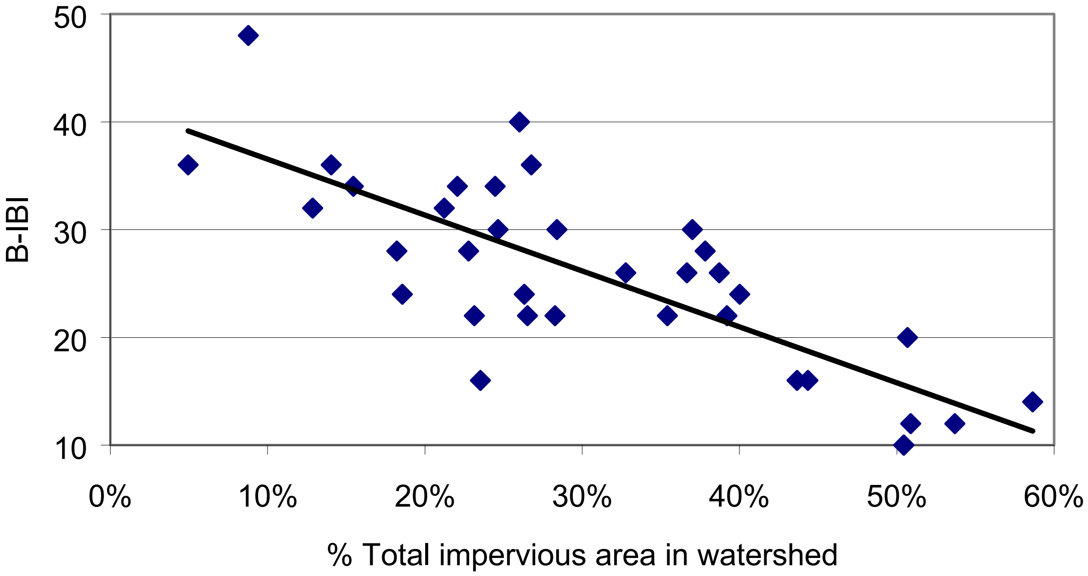

Figure 1.5 Biological condition (B-IBI) versus percent total impervious area in watershed. Data from Booth et al., 2001.

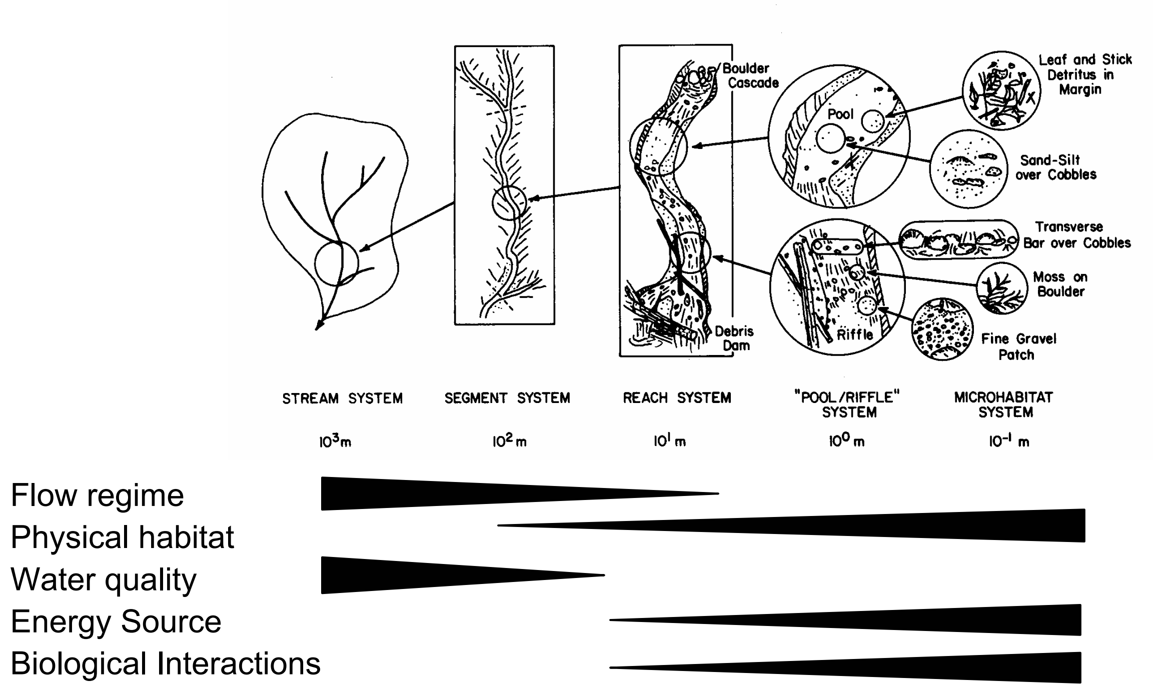

Figure 1.6 The effect of spatial scale on the functioning of five factors. Top: hierarchical relationships among habitat and landscape features of streams. From Frissell et al., 1986. Bottom: A speculative account of the influence exerted by sub-watershed to local landscape on the five factors. Adapted from Allan et al., 1997.

2. Methods

Field Methods[1]

Study streams

I conducted this study on four streams in the Puget Sound Lowland region (Figure 2.1). The Puget Sound region shows a pronounced gradient from dense urban areas to sparsely populated rural areas and so serves as a good region to evaluate the effects of the magnitude and spatial distribution of urbanization.

The four stream systems were chosen based on similarities in watershed size, surface geology, and relief ratio (Table 2.1). The watersheds fall within a size range of 15 to 60 km^2, and they are predominantly underlain by glacial till. 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 measured roughly parallel to the major drainage (Dunne and Leopold, 1978), range from 11 to 23 m/km among the study watersheds.

The study watersheds were also selected to explore differences in land cover and in-stream biological condition. Thorndyke Creek, on the western side of the Olympic Peninsula, served as a reference stream. Its watershed has very little development and is predominantly forested. Juanita Creek, which flows into the northwest side of Lake Washington, was chosen because its watershed is highly urbanized. Little Bear Creek and Swamp Creek, nearly adjacent watersheds that both flow into the Sammamish River just upstream from Lake Washington, have intermediate levels of urbanization. These two systems were of particular interest due to their biological conditions, as previously measured by the B-IBI. Little Bear Creek has significant spatial variability in its B-IBI scores, whereas Swamp Creek is one of the most uniformly healthy streams in the region for its level of urbanization (Morley, 2000).

Methodology

My intent was to assess many sites along each of the study streams to capture longitudinal variation in physical stream conditions. The study streams were sampled

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[1] This portion of the study was a sole effort of the author. Data was collected with the help of several field assistants.

using a rapid assessment (see below) during the summer of 2000. The assessments were based on average conditions within 100-m reaches; they were completed every 300 to 500 m along the mainstem channel, except where access was prohibited, in wetlands, or in non-alluvial reaches (e.g. reaches constrained by bank armoring). Each site was located using a Garmin 12XL global positioning system (GPS) unit.

There are several stream-assessment techniques available, but for this study they were inadequate for two reasons. First, several methods have been developed either in other distinctly different regions or for monitoring of impacts other than urbanization, such as forestry. As with any region, the Puget Sound Lowland has a unique combination of climate, geology and urban development, and requires customized treatment. Secondly, some methods combine physical, biological, and chemical aspects of stream degradation (Platts et al., 1983; MacDonald et al., 1991; Galli, 1996; Barbour et al., 1999). Because my emphasis was to capture the in-stream physical and geomorphic condition of the study streams, adhering to a broader sampling regime was beyond my scope. Instead, I chose to create a custom stream assessment to focus on physical stream changes typically found in urban streams. I measured a range of physical attributes, or parameters, borrowing methods from various stream assessment techniques most suitable to this region.

Both quantitative and qualitative measures were taken to describe channel morphology, estimate channel dimensions, describe channel structure, characterize the substrate, and classify riparian conditions. Channel morphology was described by the following features: bed morphology, bed sediment storage features, channel planform, floodplain classification, and gradient. It was necessary to determine the morphology of each reach, because reaches of different morphologies respond differently to changes in transport capacity and sediment supply (Montgomery and Buffington, 1998). Bed morphology was classified using Montgomery and Buffington’s (1998) alluvial channel reach types: cascade, step-pool, plane bed, pool-riffle, and dune-ripple. The presence of sediment-storage features was recorded as well as their type (alternate bars, mid-channel bars, point bars; Knighton, 1998). The channel planform was classified into three basic groups: straight, meandering, or braided (Leopold and Wolman, 1957). A reach’s floodplain was described as active, partially active, inactive (i.e. terraces but no active floodplain), anthropogenic fill, or none for colluvial and bedrock reaches (J.

Pizzuto, personal communication, 1998). Gradient was measured at each reach using a clinometer and stadia rod.

Channel dimensions were recorded with bankfull width and depth measurements, because urban stream channels often enlarge to accommodate larger and more frequent peak flows. Bankfull elevation was determined considering a combination of the presence or absence of perennial vegetation, topographic breaks in the bank, and any change in sediment size or texture (Dunne and Leopold, 1978). A width and average depth were measured at a representative riffle and pool feature for each reach, using a tape and stadia rod, and bankfull cross-sectional area was derived from these dimensions.

Channel structure was evaluated based on stream bank stability, pool frequency, large woody debris (LWD) abundance, and stream complexity. The first structural element, stream bank stability, was visually evaluated along each 100-m reach. Reaches were ranked as stable, slightly unstable, moderately unstable, or unstable (Table 2.2; Figure 2.2; Henshaw and Booth, 2000). Banks will appear eroded and unstable if a channel is actively enlarging; therefore, bank stability is an appropriate attribute to monitor in an urban stream.

Pool frequency was measured with a simple pool tally along each 100-m reach. A pool was counted if it spanned the width of the channel and had a residual depth greater than ¼ of the bankfull depth (Montgomery et al., 1995). Pools tend to diminish in both frequency and depth in urban streams (Pizzuto et al., 2000). A pool count provided a quick method to evaluate pools.

LWD abundance was also measured by a simple count. I tallied LWD within the active bankfull channel using a minimum diameter criterion of 25 cm and a minimum length criterion of 3 m (Scholz and Booth, in press). Because LWD declines in streams with more urbanized watersheds and is critical to the physical and biological health of stream ecosystems, it was another appropriate attribute to include in the assessment.

The final measurement of channel structure was a visual assessment of stream complexity. I qualitatively rated a reach's complexity, or diversity, in four classes from excellent/complex to poor/simple. The visual assessment was based on the reach's diversity in channel geometry, planform, types of pool and riffle features, and overall structure (Figures 2.3, 2.4; Table 2.3). This parameter is subjective and thus requires a single observer to keep the measurements consistent. This parameter can be considered a rank of overall roughness in the reach. Because urban streams tend to be smoother and commonly appear simplified, generally corresponding to degraded habitat, this parameter was developed to identify such a change.

Substrate measurements were taken at bar/riffle features in the reaches and included a measure of the substrate size composition, an evaluation of riffle embeddedness and cementation, and a measurement of the abundance of fine sediment. Substrate size was measured at several reaches per stream using a variation on the Wolman pebble count method (1954). I randomly sampled 100 pebbles at the upstream end of one bar/riffle feature, or in uniform channel-spanning riffles in reaches where no bars were present (Reid and Dunne, 1996; Kondolf, 1997). The intermediate axes were measured for particles greater than 2 mm in size and then tallied using the Wentworth classification scale. Substrate size has been found to both coarsen or become finer in urban stream systems, and so these measurements were taken to investigate any size changes within the individual streams and among different streams.

Substrate embeddedness in riffle features was measured using three different methods. Embeddedness rates the degree to which large substrate particles are surrounded or covered by fine sediment (Platts et al., 1983). For the first method, I randomly selected approximately 10 cobbles, estimated the extent of each particle’s embeddedness (the portion of the cobble surrounded by fine sediment), and then rated the overall embeddedness of the reach using four categories: 0-25%, 25-50%, 50-75% and 75-100% (Barbour et al., 1999). The second method was a visual estimation of the percent fines in the riffle, as a percentage of the riffle surface area (Platts et al., 1983; Galli, 1996). The third method accompanied the pebble count; I tallied the number of sampled pebbles that were embedded and calculated a percentage based on the total count of sampled pebbles. Embeddedness is a commonly evaluated attribute in both urban streams and in logged watersheds, although the techniques used for its measurement are not consistent.

Riffle condition was also evaluated using a measure of cementation. Cementation is best described as the compactness and hardness of the riffle substrate. This condition is largely a result of silt and clay intrusion into the interstices of a gravel bed, and as such it should be related to the degree of embeddedness. I used four classes (poor, fair, good and excellent) to describe the range of riffle compaction, from concrete-like to loose and easily mobilized. Table 2.4 provides an expanded description of the classes. A similar cementation method has been used for monitoring the impacts of an urban development project in King County (Comings et al., 2000).

The final substrate measurement evaluated the abundance of fine sediment. I estimated a percentage of the entire bed surface (i.e. riffles, pools, bars) covered with fine sediment within the 100 m reach. Typically, fine sediment is more prevalent in urban streams because of channel erosion and suspended sediment in stormwater runoff.

The riparian zone was evaluated using two attributes, the width/integrity and the forest quality (May 1996; Table 2.5). The width and integrity of the forest buffer was rated as one of the following: wide/intact, moderate/few breaks, narrow/broken, or little/none. Likewise, the quality of the forested buffer was characterized by four classes: old growth/mature forest, mature/young forest, young forest, and no forest. These riparian assessments were based on the average riparian zone condition along the 100-m reach.

Spatial Methods[2]

This section details the types of data used in the spatial analysis and the specifics of the analysis. Several spatial data sources were needed to characterize the study watersheds and to allow for spatial analyses of the watersheds. The intent of the spatial analyses was to characterize the landscape contributing to each sampled site via quantitative metrics. This characterization took on two aspects. First, I partitioned the landscape into different zones. Second, I calculated a variety of landscape metrics within these zones. These metrics are quantitative descriptions of the landscape, which focus on the magnitude and connectivity of urban land cover. All processing of spatial data was completed within a GIS using Arc/INFO 8.0.1 and ArcView 3.2 software (ESRI, Redlands, CA). All data are projected in UTM Zone 10 (NAD 27). Although GIS data serve as models of features of the true landscape, accuracy is always limited by spatial

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[2] The compilation of data and the execution of the spatial analyses were completed solely by the author. The concepts for some of the spatial analyses were developed jointly with an interdisciplinary research group including Marina Alberti (Urban Planning), Derek Booth (Civil & Environmental Engineering), Kristina Hill (Landscape Architecture), and Daniele Spirandelli (Landscape Architecture).

errors, data quality, map scale and other factors. A brief description of each data type follows.

Data sources

Reach locations. Each sampled site was located using a Garmin 12XL GPS unit. The coordinates of each site's location point were entered manually and a point shapefile was created (Figure 2.5). The error of these GPS points is approximately +/- 10 m.

Elevation. I used the 10-m, 1:24,000 digital elevation model (DEM) because it is the most resolute topographic data available that completely covers all four study watersheds (Figure 2.6). The DEM and its metadata are available online at the Washington State Geospatial Data Archive (http://wagda.lib.washington.edu/ data/washdata.html, 1999).

Hydrology. The hydrology data originates from the Department of Natural Resources hydrography data layer, as compiled for the Puget Sound Regional Synthesis Model (PRISM) project (Figure 2.5). The streams and water body boundaries are derived from 7.5 minute U.S. Geological Survey's (USGS) topographic maps and aerial photos (http://wa-node.gis.washington.edu/nsdi/metaserver/metadata/prism.harveys_ hydro.html, 1998).

Land cover. I used a land cover classification of the Landsat 1998 image specifically derived for assessing watershed conditions in urban, and urbanizing, areas of western Washington (http://depts.washington.edu/cuwrm). The 30-m grid has seven categories, three of which are types of urban land: forest urban, grass urban, and paved urban (Figure 2.7). Table 2.6 lists all of the categories and compares the classification with actual land cover determined from orthophotos. This accuracy assessment reveals expected trends for the different classes and good discrimination between the developed and undeveloped areas. The true land cover for individual, same-class pixels can vary greatly as demonstrated by the standard deviation values. Therefore, uncertainty in the classification is great when considering an individual pixel or a small number of pixels (Hill et al., 2000).

Wetlands. Wetland boundaries were obtained from the National Wetlands Inventory (NWI) of the U.S. Fish and Wildlife Service (Figure 2.7). The NWI is based on aerial photointerpretation and aims to provide better geospatial information on wetlands than found in the USGS topographic maps. Full metadata on the NWI can be found online (http://www.nwi.fws.gov/download.htm). I superimposed the NWI wetland data layer on the Landsat land cover grid. The merged land cover grid was then resampled to a 10-m size to facilitate grid calculations with the 10-m DEM-derived grids. NWI wetlands were included because the land cover classification for western Washington identifies some portions of wetlands improperly (K. Hill, personal communication, 2000).

Roads. The composite roads data layer from the Puget Sound Regional Council, as compiled for the PRISM project (1997), was used in the analyses (Figure 2.5). The extent of the data set does not include the Thorndyke Creek watershed. The few roads in Thorndyke Creek were screen digitized from 7.5 minute, 1:24,000 USGS topographic maps. Unimproved dirt roads were not included.

Landscape zones

The first portion of the spatial analysis involved the creation of multiple landscape zones for each sampled site. Often, the primary zone of interest is the watershed, the total contributing area of the landscape. Watersheds are the basic, fundamental units for the physical study of hydrologic and geomorphic processes and for the management of land and water resources (Newson, 1992). Sub-watersheds were delineated for each sampled site using the hydrologic functions in Arc/INFO's GRID extension.

The required steps to create sub-watersheds are described. First, the 10-m DEM (Figure 2.6) was adjusted using a filling process. This command alters the elevation values so that the DEM grid will no longer contain any closed depressions. This is a necessary step for the hydrologic commands to function. The second step is to create a flow-direction grid from the depressionless DEM. This grid indicates the direction of surface flow for each 10-m grid cell, or pixel. From the flow-direction grid, a flow-accumulation grid is created. The accumulated flow represents the number of up-slope cells that drain into each cell. Cells with high flow-accumulation values can be considered areas of concentrated surface runoff. An approximated stream grid was generated from the flow-accumulation grid. Any cell with a flow accumulation of 2000 or greater was considered part of the stream network. This is equivalent to setting the minimum contributing area to 0.2 km^2. This derived stream network compared well with the DNR vector hydrology data and with results from a local study of the minimum watershed size of perennial streams (M. Liquori, personal communication, 2001). Site location points were adjusted, where necessary, to fall directly on this stream network grid. Sub-watersheds for each site then could be automatically delineated with the Arc GRID watershed function.

I was interested in deriving other spatial zones in addition to that of the sub-watershed, in order to evaluate their relative influence on physical stream conditions. One such zone was the “buffer.” The buffer zone for any one site is the total riparian area upstream from the site location (Figure 2.8). This methodology was adapted from Morley (2000) and is similar to other riparian buffer spatial analyses (Lammert, 1995; Roth et al., 1996; Allan et al., 1997; Davis, 1998; Schuft et al., 1999). These methodologies all use a straight-line distance from the stream to delineate the buffer boundary. I took a slightly different approach and determined the buffer via distances along topographic flow paths. A flow-path length grid was derived for this purpose. A value on this grid is equivalent to the downstream distance along the topographic surface flow path. I created two buffer zones of different widths, 100 m and 200 m.

The third zone of interest was the “local.” This zone was also adapted from Morley (2000) and other similar methods (Lammert, 1995; Roth et al., 1996; Allan et al., 1997). In these methods, the local zone is that portion of the riparian buffer within some distance from a point of interest. I choose to define a local zone slightly differently; it is that portion of the total watershed closest to the site (Figure 2.9). In other words, it is the area uphill from the site location and within a specified distance along the topographic flow paths. This zone was determined as such to delineate the most proximal, hydrologically-significant area to each site. I created two local zones of different sizes. One zone encompasses the uphill area within 500 m from the downstream-most point of the reach. The other includes the area within 1000 m from the downstream-most point of reach.

Landscape metrics

The purpose of creating these three types of zones (sub-watershed, buffer, and local) was to calculate various landscape metrics within each zone. Landscape metrics provide quantitative measures of the condition of the landscape. In this study, landscape metrics were derived to measure two aspects of urbanization, its magnitude and the connectivity of urban land.

I was able to measure the magnitude, or quantity, of urbanization in three ways due to the level of detail on urban areas provided by the land cover classification. The classification distinguishes a paved urban land category, the most intense urban land cover category. Because about 90% of the surface is impervious in this category (Table 2.6), I used it as the basis for the first metric for the magnitude of urbanization. For this metric, I calculated the percent of paved urban land within each of the three zones for each site. The second magnitude metric is calculated as the percent of paved urban land and grass urban land combined, within each zone. The grass urban land category is the second-most intense class of urban land because it has the next highest proportion of impervious surfaces, about 70% on average (Table 2.6). The third magnitude metric was the percent of all urban land categories (paved, grass, and forest) within each zone.

The connectivity of urban land was measured with three types of metrics: road density, path length distances, and distance from sites to road crossings. Road density is an important connectivity metric because roads commonly act as conduits for stormwater flow, either through pipes or ditches, and conceptually as connectors of urban land to stream channels. In an area with greater road density, one would expect greater efficiency in the drainage. Road density was calculated for each of the three spatial zones as the total length of roads (km) within a particular zone divided by the total area of the zone (km^2). Road density has also been used successfully as a surrogate index of urban development (May et al., 1997; Konrad, 2000).

Another metric conceived to measure connectivity was the median flow path length from urban land to the stream network. This metric represents how close the urban land is to the stream channel. In theory, this metric would distinguish between a watershed with urban land concentrated near the stream network and a watershed with urban land located only in upland areas. The metric was calculated using GIS functions, where distances were measured from each urban land cover cell (paved, grass, or forest urban) to the closest stream along the downhill flow path. The median value of these measured path lengths was used as the value for the metric. This metric was only determined within each site’s sub-watershed zone. It is redundant at the local and buffer scales, because these zones are delineated from a certain path length distance to begin with.

The final metric devised to quantify connectivity was a measure of the distance to the nearest road crossing. Using ArcView's measuring tool, I computed the distance from each site to the closest upstream road crossing. The road crossing had to be a significant one (i.e. a possible conduit of ample stormwater); driveways and dead-end roads were not considered significant. This metric represents how impacted by a road crossing a particular site is likely to be.

Analytical Methods[3]

Analysis was conducted in five phases: 1) the analysis of the physical stream data, 2) the analysis of the land cover data as quantified with landscape metrics, 3) the assessment of relationships between individual physical stream attributes and landscape metrics, 4) the creation of a multi-metric index based on physical stream condition, and 5) the analysis of the index.

First, I evaluated the data collected during the rapid stream assessment. I explored the similarities and differences in the physical stream conditions among the reaches. Some of the observed differences in the measured physical attributes were hypothesized to be a result of the geomorphic setting. For example, an attribute like bankfull cross-sectional area is a function of the size of the contributing watershed. I explored other relationships between physical attributes and intrinsic geomorphic factors (watershed size, location of the reach on the longitudinal profile, and channel gradient). Finally, I identified significant relationships between some of the measured attributes. The statistical tests employed depended on the nature of the data. For continuous, normal data I used regression analysis. Spearman's rank correlation test was used for ordinal, non-normal data when comparing methodologies. T tests were also used for comparing continuous data with nominal, categorical attributes.

Secondly, I explored the results from the spatial analysis by assessing the landscape metrics and determining interrelationships among them. I compared the land cover distribution in each of the study watersheds. I used the land cover distribution within each of the landscape zones as a way to compare the zones and to determine if

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[3] This portion of the study was a sole effort by the author.

the zones were independent of each other. I also assessed the variation found in the landscape metrics created to measure connectivity. The connectivity metrics were compared to the magnitude metrics of urban land. The landscape metrics were all continuous data, and, therefore, regression analysis provided the best means to test for relationships between metrics.

The next step was to test the response of individual physical attributes to increasing urbanization. The measurements of each physical attribute were first grouped by watershed. Because the study watersheds were so different in the amount of total urban land, this grouping provided a way to see the response of each attribute to different levels of urbanization in the watershed zone. The measurements of each attribute were also segregated into four groups according to the percent of total urban land in the 500-m local zone. In this way, attributes could be visually inspected for their response to increasing urbanization within the local zone and it facilitated the use of a non-parametric analysis of variance, the Kruskal-Wallis Test (Zar, 1984). The qualitative data were analyzed for differences between the study watersheds and between the four levels of local urbanization by using an analysis of variance by ranks (Kruskal-Wallis) and by performing non-parametric multiple comparisons (Dunn's test) to determine any significant differences between the groups (Zar, 1984). This effort was performed in order to select components for a multi-metric index.

A multi-metric index was created in order to compile the measurements of the physical attributes into a single, general score of physical stream condition. By definition, a multi-metric index is a number that integrates several components to indicate an overall condition (Ball, 1982; Plafkin et al., 1989; Rankin, 1995; Raven et al., 1998; ANS, 1999; Karr and Chu, 1999). This integrative approach to measuring condition can help diagnose causes of degradation in complex ecological systems (Karr and Chu, 1999). Another benefit of a multi-metric index is its statistical versatility. Given that a multi-metric index is continuous and normally distributed, familiar tests can be applied to identify significant differences in index values (Karr and Chu, 1999).

Six attributes were chosen to be components of the physical stream conditions index (PSCI). Table 2.7 lists the attributes, their descriptions, and their scoring criteria. These attributes were selected because they varied systematically through a gradient of human influence and because they account for the diversity of responses to urbanization commonly reported in the literature. Lacking any conceptual basis to favor one attribute over another, all attributes are ranked with equal weighting, using a numerical scale of 1 to 4. The ranks are then totaled for the index score, which can range from a minimum of 6 to a maximum of 24. Scores increase as the physical quality of the stream increases. The physical conditions observed in the best reaches of the reference stream, Thorndyke Creek, established the criteria for assigning the highest ranks. Bank stability, complexity, embeddedness, and cementation were all ranked into four qualitative classes in the field. Non-integer scores were only used in cases where no single category adequately described conditions. To facilitate equal weighting, the continuous measures of channel size and LWD abundance were also grouped into 4 classes.

The channel size rank is based on how enlarged the actual bankfull cross-sectional area is as compared to the "expected" cross-sectional area. The expected channel size is a function of watershed size and is derived from a regional data set on bankfull cross-sectional areas of watersheds with less than 6% effective impervious area (Booth 1990; Figure 2.10). An expected channel size for each reach was calculated using the regression equation,

$$A_e = 0.577\ W^{0.36} \qquad (1)$$

where A_e is expected cross-sectional area (m^2) and W is watershed area (km^2). The grouping for this rank was based on the mean (-0.17) and standard deviation (0.11) of the residuals (R), where,

$$R = \log(A_e) - \log(A_a) \qquad (2)$$

and A_a is the actual cross-sectional area measured at each reach. A histogram of the residuals shows a nearly normal distribution (Figure 2.11). The ranks were assigned as follows: for R less than –0.28, 1; for R greater than –0.28 and less than –0.17, 2; for R greater than –0.17 and less than –0.06, 3; and for R greater than -0.06, 4. The residuals were generally negative because the actual channel sizes were usually larger than expected. Table 2.7 includes the equivalent percent enlargement for each of these ranges of residuals.

The LWD rank was assigned based on the results of the data collected. The abundance of LWD at reaches varied considerably from zero to 26 pieces per 100 m. LWD counts were grouped based on the attribute's distribution (see Results, Figure 3.9). Additionally, the average LWD count at the reference reaches was approximately 14, which helped establish the high score for this component. The quantity of LWD required for each rank of 1 to 4 is listed in Table 2.7.

After determining each of the six physical stream attributes, they were combined into the PSCI. The PSCI was regressed with metrics representing the magnitude and connectivity of urban land. Several combinations of these landscape metrics were tested using simple and multiple regression to determine those that had the best relationship with PSCI score.

Longitudinal trends in the PSCI were also explored. The change in the PSCI score (Δ PSCI) was calculated as the difference in PSCI score between consecutive sites along the stream's longitude. Δ PSCI was compared to the intactness of the riparian buffer between the two sites. "Intactness" was quantified with two items, the number of road crossings between sites normalized by the distance between the sites, and the proportion of forested land and wetland remaining in the 100-m buffer between sites. These two items were grouped into categories to facilitate testing with simple 2-sample t tests.

Finally, the PSCI scores were compared to B-IBI scores using regression techniques. Because B-IBI scores were only available for 14 sites in Little Bear and Swamp creeks, this comparison had limited robustness.

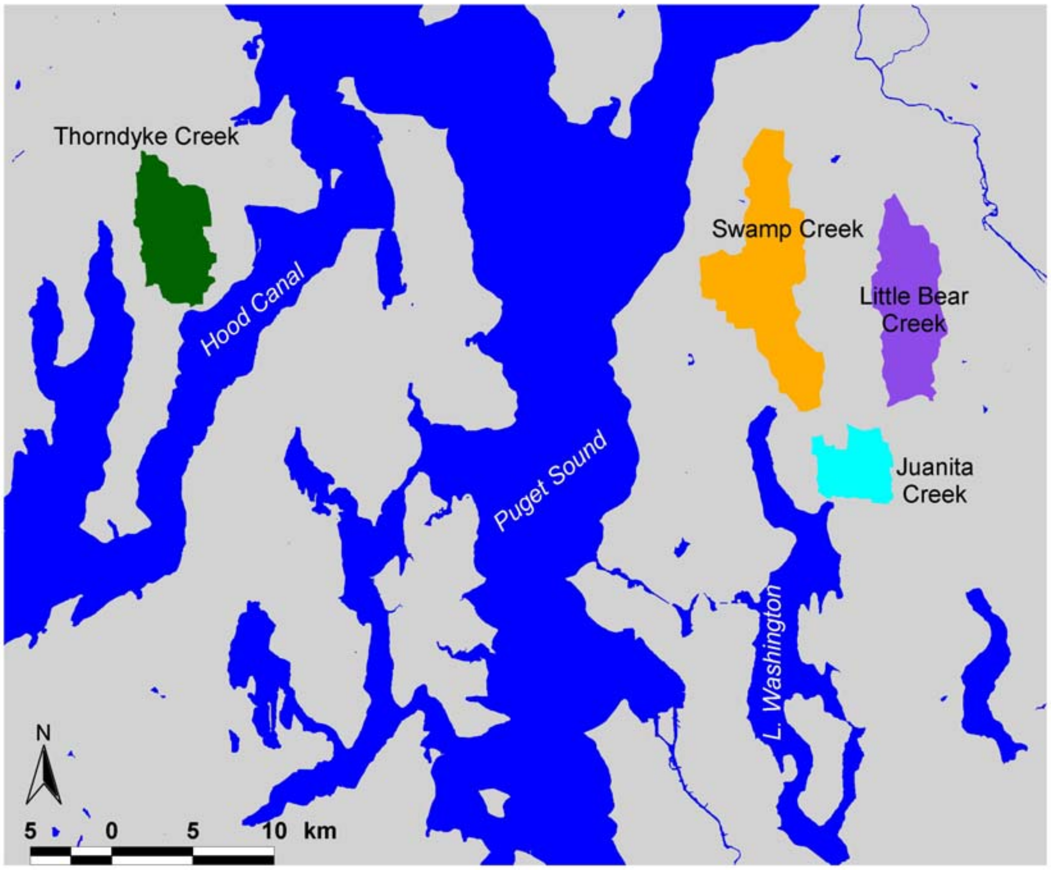

Figure 2.1 Regional map with study watersheds.

Figure 2.2a Example of stable bank (score = 4).

Figure 2.2b Example of unstable bank (score = 1).

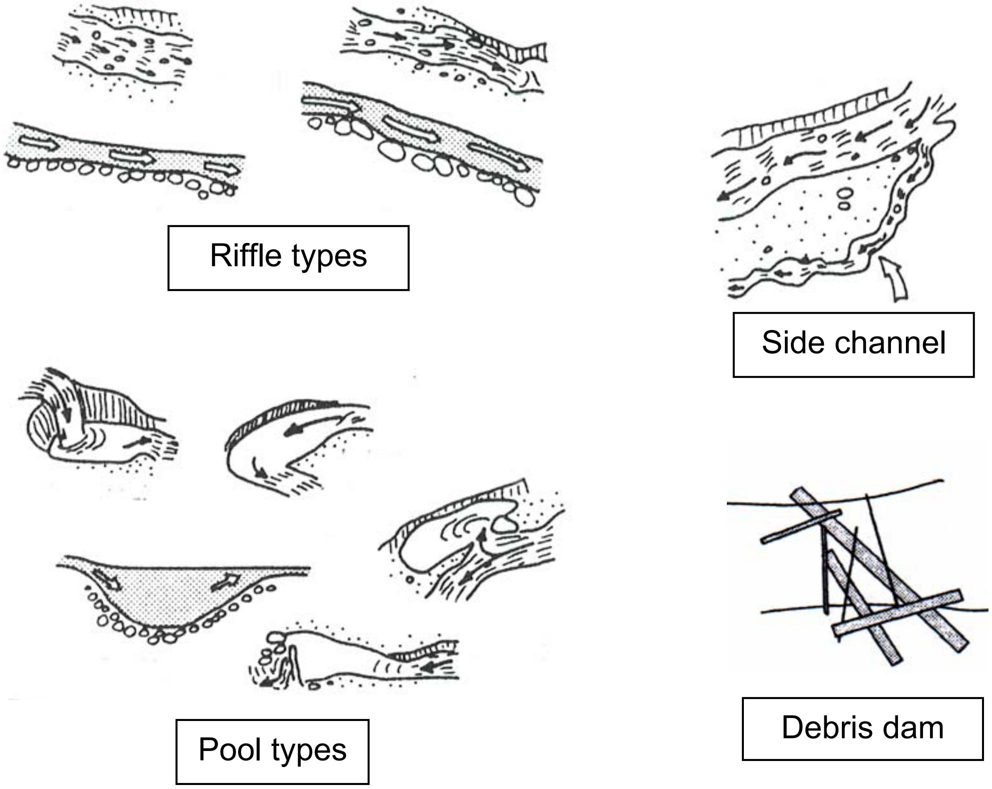

Figure 2.3 Components of stream complexity. Adapted from Frissell et al., 1996.

Figure 2.4a Example of excellent complexity (score = 4)

Figure 2.4b Example of poor complexity (score = 1)

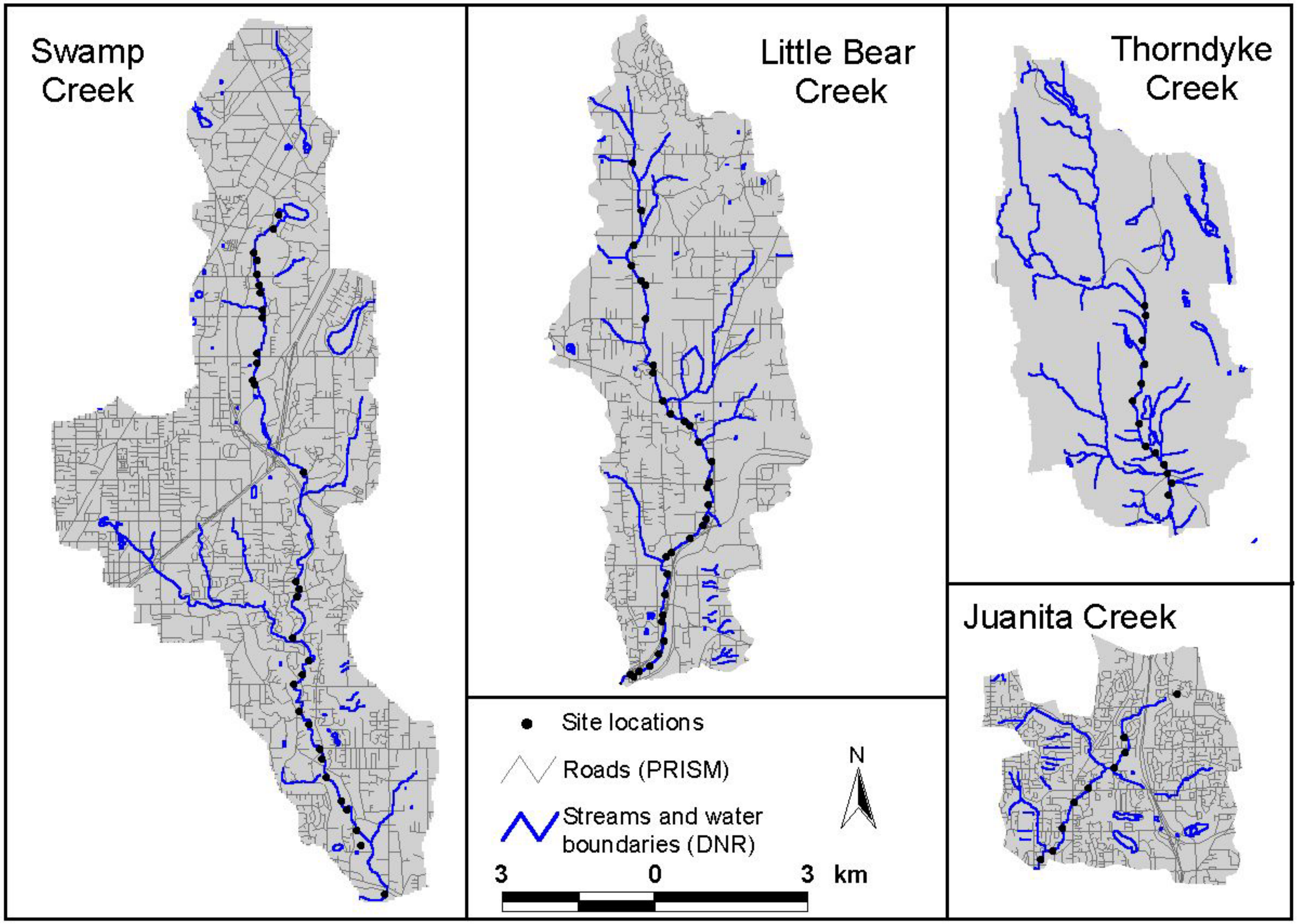

Figure 2.5 Map of study watersheds with site locations, roads, and streams.

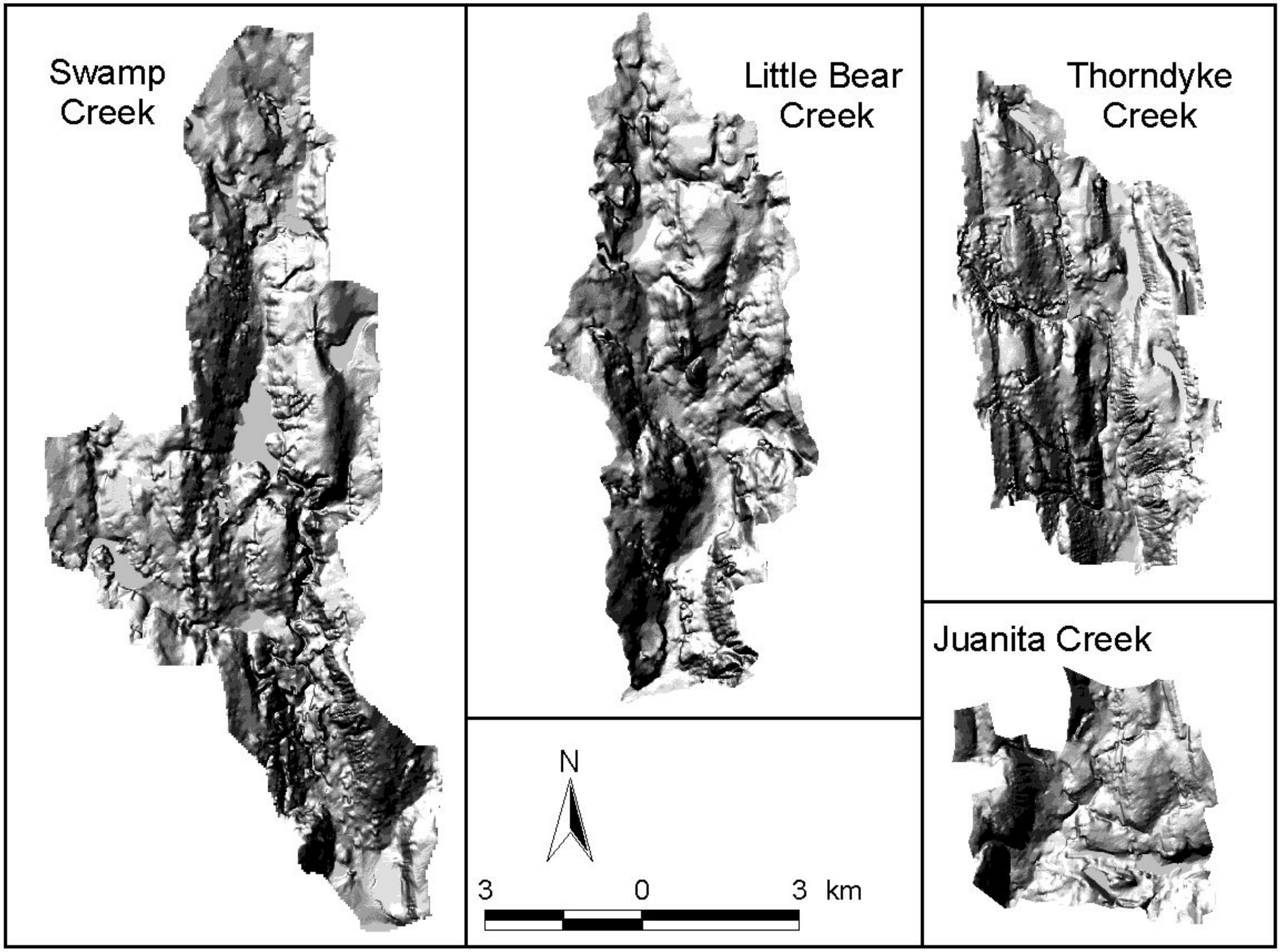

Figure 2.6 Map of study watersheds showing shaded relief from 10-m DEM.

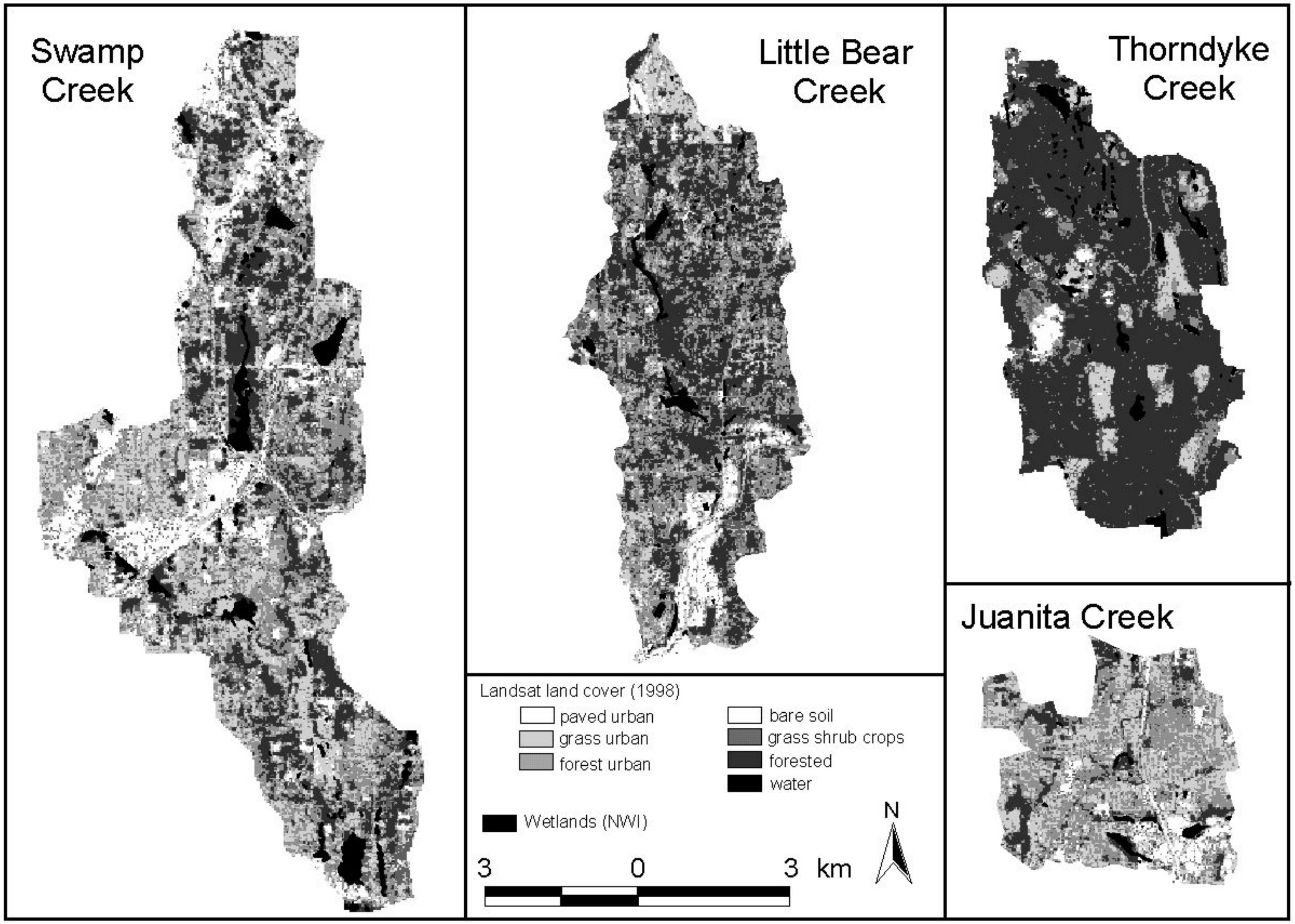

Figure 2.7 Map of study watersheds with Landsat land cover classification and NWI wetlands.

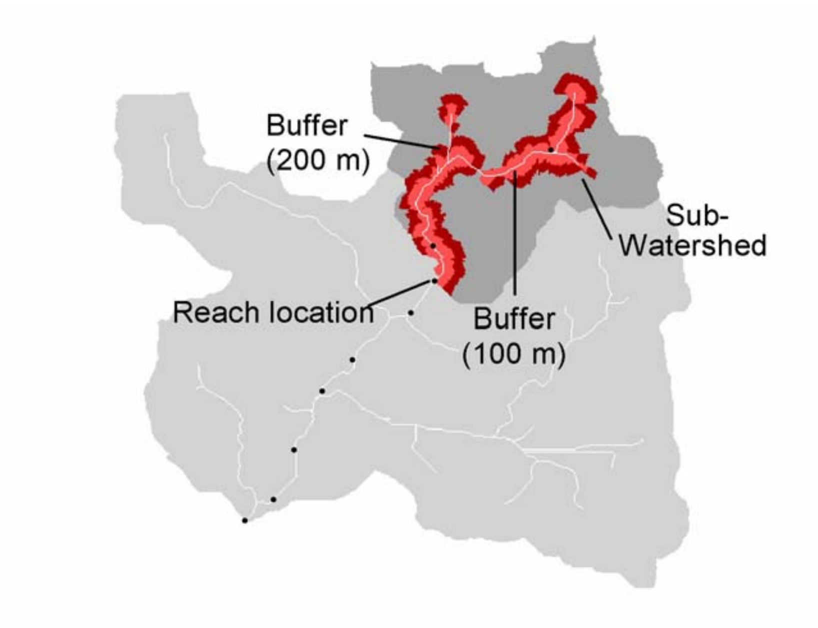

Figure 2.8 Map of Juanita Creek illustrating two sizes of buffer zones and the sub-watershed zone for one site.

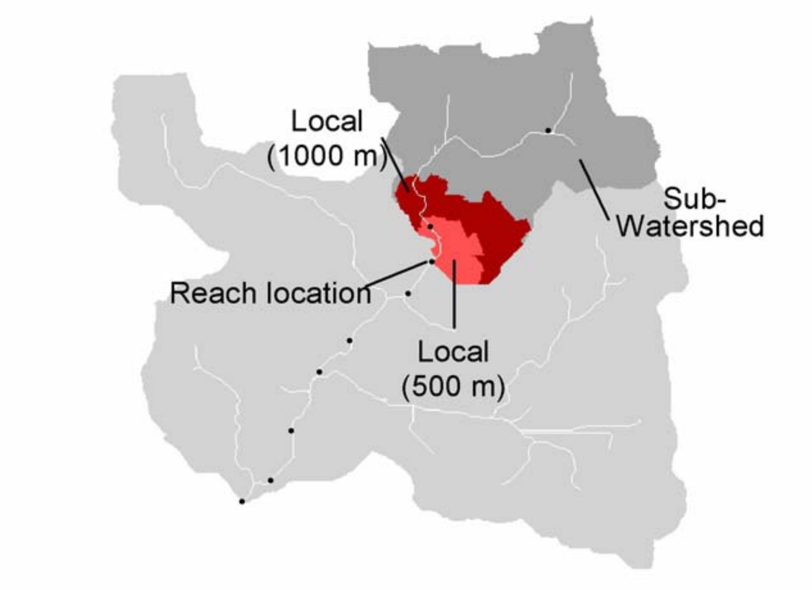

Figure 2.9 Map of Juanita Creek illustrating two sizes of local zones and the sub-watershed zone for one site.

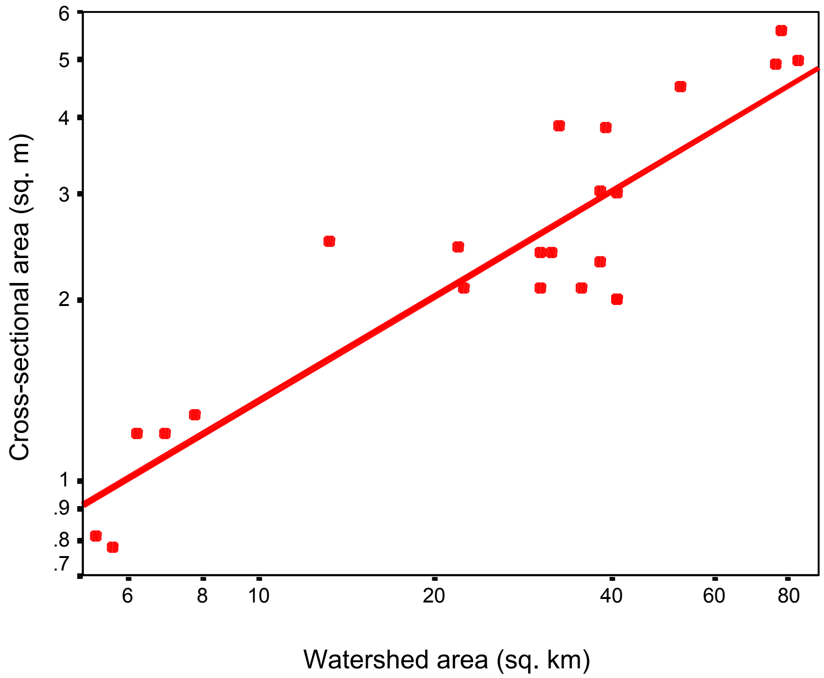

Figure 2.10 Channel size versus watershed area for non-urban Puget Sound streams. Data from Booth, 1990.

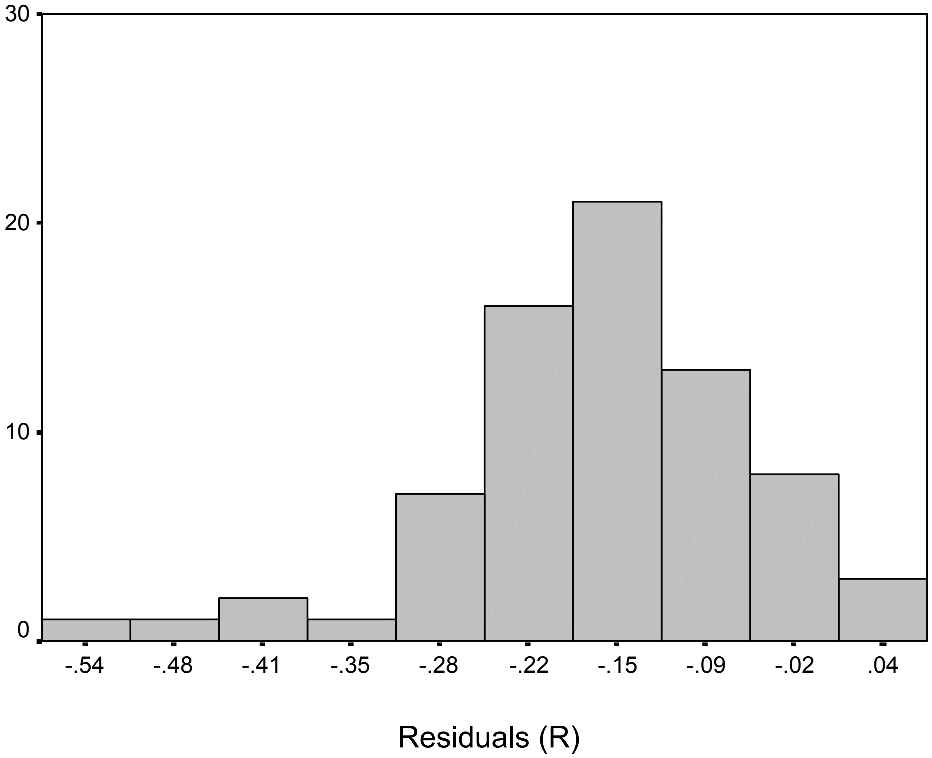

Figure 2.11 Distribution of residuals (R) from expected channel size.

Table 2.1 Watershed Characteristics.

Watershed	Watershed size (km^2)	Relief ratio (m/km)	Surface geology (%)			
			Glacial till	Glacial outwash	Alluvium	Other
Swamp Creek	58.5	10.8	79%	16%	4%	1%
Little Bear Creek	40.0	12.8	68%	29%	3%	1%
Thorndyke Creek	28.1	18.4	77%	20%	2%	0%
Juanita Creek	16.2	23.4	45%	46%	0%	9%

Table 2.2 Bank stability classification criteria. From Henshaw and Booth, 2000.

Classification category	Description
Stable	Perennial vegetation to waterline
	No raw or undercut banks (except for some erosion on outside of meander bends)
	No recently exposed roots
	No recent tree falls
Slightly unstable	Perennial vegetation to waterline in most places
	Some scalloping of banks
	Minor erosion and/or bank cutting
	Recently exposed tree roots rare but present
Moderately unstable	Perennial vegetation to waterline sparse (mainly scoured or stripped by lateral erosion)
	Bank held by hard points (trees, boulders) and eroded back elsewhere
	Extensive erosion and bank undercutting
	Recently exposed tree roots and fine root hairs common
Unstable	No perennial vegetation at waterline
	Banks held only by hard points
	Severe erosion of both banks
	Recently exposed tree roots common
	Tree falls and/or severely undercut trees common

Table 2.3 Stream complexity classification criteria.

Classification category	Description
Excellent	Diverse and complex structure
	Variety in channel units (pools, riffles, glides)
	Side channels and/or debris dams present
	Diverse microtopography
	Variable channel geometry
Good	Less diverse and complex structure
	Some variety in channel units
	Side channels and/or debris dams less frequent
	Some heterogeneity in microtopography and channel geometry
Fair	Little diversity or complexity in structure
	Little variety in channel units
	Very few side channels and/or debris dams
	Little heterogeneity in microtopography and channel geometry
Poor	Simple structure
	No variety in channel units
	No side channels or debris dams present
	Homogenous microtopography
	Very little variety in channel geometry

Table 2.4 Riffle cementation classification criteria

Classification category	Description
Excellent	Gravel and cobbles are loose throughout the riffle
	Very easy to penetrate riffle surface with heel pressure
	Very little fine material released with heel pressure
Good	Gravel and cobbles are tighter, but still loose at the downstream end of the riffle
	Some effort needed to penetrate riffle surface
	Some fine material released with heel pressure
Fair	Gravel and cobbles are compacted and tight (perhaps loose only at the downstream end of the riffle)
	Considerable effort needed to penetrate riffle surface
	Substantial fine material released with heel pressure
Poor	Gravel and cobbles are cemented throughout riffle (concrete-like)
	Very difficult to penetrate riffle surface
	Lots of fine material released downstream with heel pressure (rich plume)

Table 2.5 Riparian zone classification criteria. Adapted from May, 1996.

Category	Width/integrity	Forest quality (estimated stand age)
Optimal	Wide/intact riparian buffer	Old growth/mature forest
	Buffer is continuous along entire reach on both sides of the stream	
	Closest development is at least 30 meters away from the stream	
Sub-optimal	Moderate width/few breaks to riparian buffer	Mature/young forest
	Buffer is not continous along entire reach	
	Development may occur within 30 meters of the stream	
Marginal	Narrow width/many breaks to riparian buffer	Young forest
	Only patches of buffer remain along reach	
	Development within 30 meters of the stream	
Poor	Little to no riparian buffer	No forest
	Development within the immediate riparian zone on both sides of the stream	

Table 2.6 Comparison of classified Landsat image and land cover observed from orthophotos.

Classified Categories		Actual land cover (% averaged for 56 pixels, [] - standard deviation)						
		Water	Trees	Shrubs/ grass	Pavement	Bare earth	Pavement or bare earth	Shadow
Undeveloped	Water	100 [0]	0 [0]	0 [0]	0 [0]	0 [0]	0 [0]	0 [0]
	Forest	0 [1]	96 [15]	1 [6]	1 [2]	2 [14]	0 [0]	0 [0]
	Grass/shrub/crop	0 [0]	1 [5]	94 [16]	3 [14]	2 [8]	0 [0]	1 [5]
Developed	Bare soil	1 [4]	2 [4]	0 [1]	7 [17]	91 [20]	0 [2]	0 [0]
	Forested urban	0 [0]	39 [27]	23 [34]	34 [25]	0 [0]	5 [9]	3 [7]
	Grass/shrub urban	1 [6]	4 [4]	21 [25]	70 [28]	1 [6]	3 [7]	0 [1]
	Paved urban	1 [5]	5 [19]	2 [12]	92 [23]	0 [0]	0 [0]	0 [1]

Table 2.7 Components of the physical stream conditions index (PSCI).

Parameter	Description	Scoring 1	2	3	4
Channel size	Rank based on enlargement above an expected channel size given the watershed size	> 90% larger	50 - 90% larger	15 - 50% larger	< 15% larger
Bank stability	Qualitative rank (see Table 2.2)	Unstable	Moderately unstable	Slightly unstable	Stable
LWD abundance	Rank based on quantity of LWD pieces in the 100-m reach	< 5	5 - 9	10 - 14	> 14
Complexity	Qualitative rank (see Table 2.3)	Poor	Fair	Good	Excellent
Embeddedness	Qualitative rank	75 - 100%	50 - 75%	25 - 50%	< 25%
Cementation	Qualitative rank (see Table 2.4)	Poor	Fair	Good	Excellent

3. Results

This section is divided into four main parts: 1) physical stream conditions, 2) landscape metrics, 3) individual physical attributes and landscape metrics, and 4) the physical stream conditions index (PSCI). In the first part, I present the results from the rapid stream assessment, specifically the conditions and relationships between the physical stream characteristics measured at the sampled sites. In total, 87 sites were sampled: nine in Juanita Creek, 31 in Swamp Creek, 34 in Little Bear Creek, and 13 in Thorndyke Creek. In the second part, I detail results from the spatial analysis completed for the contributing area to each of the 87 sites. Third, I show how particular landscape metrics (or metrics in combination) explain some but not all of the variability in the measurements of individual physical attributes. Finally, I describe the results of the multi-metric PSCI, its relation to various landscape metrics, and its correlation with the B-IBI.

Physical stream conditions

Channel morphology at all sites was similar in many, but not all, respects. Channel gradient ranged from 0.3% to 2.5%. All sites had plane bed or pool-riffle bed morphology (Montgomery and Buffington, 1998). Of the total sites, 20% were plane bed, 68% were pool-riffle, and 12% were indeterminate, having characteristics of both morphologies. Channel planform was either meandering or straight; none of the sampled sites were braided. Likewise, bar features were either point bars or alternate bars; mid-channel bars were not found in any of the sites. Finally, 31% of the sites had active floodplains, 54% had inactive floodplains (i.e. terraces but no active floodplains), and 15% were partially active.

The four study streams also have similar longitudinal profiles. These profiles are plotted with stream bed elevation versus downstream distance and with tick marks indicating the location of sample sites (Figures 3.1, 3.2, 3.3, 3.4). The longitudinal profiles of these streams display a fairly uniform gradient; in addition, the urban stream profiles are interrupted with several flat and convex segments. Thorndyke Creek's profile is smoother throughout and more concave in the lower half.

Channel dimensions show a characteristic relationship with watershed size; as watershed size increases, the channel's cross-sectional area at bankfull increases. The cross-sectional areas of the sampled sites are plotted against watershed area (Figure 3.5). This graph also includes regression lines for a set of urban and non-urban streams in the Puget Sound region (Booth, 1990). The regression equation for the urban streams in this study (Juanita, Swamp, and Little Bear creeks) is

$$A = 0.78\ W^{0.44} \tag{3}$$

where A is cross-sectional area (m^2) and W is watershed area (km^2). A comparison of this study's regression line and the regression line from the set of non-urban streams indicates that Juanita, Swamp, and Little Bear creeks are, on the whole, larger than the non-urban streams. Thorndyke Creek is somewhat anomalous in that its channel size more rapidly increases with increasing watershed area than either the regional streams or the other streams in this study.

Channel structure, as measured by pool abundance, bank stability, complexity, and LWD abundance, showed variable results. Pool counts showed the least amount of variability among all of these measures of channel structure. The distribution of the counts is very non-uniform, and few sites have extreme values (Figure 3.6). Pool frequency simply did not vary much from site to site, and more than half of the sampled sites had an average of four pools per 100 m. The other three channel structure attributes displayed considerably more variability among the sampled sites. Bank stability scores are almost uniformly distributed (Figure 3.7) with a modal rank of 3 (i.e. slightly unstable banks). The results from the qualitative complexity measurement were relatively uniformly distributed as well (Figure 3.8); most sites had a score of 2 or 3. LWD abundance also showed wide variation (Figure 3.9), ranging from zero to 26 pieces per 100 m with a mean of about 8 pieces per 100 m.

Results from different measurements of the substrate are described in three parts: substrate size distribution, riffle condition, and the prevalence of fine sediment. Pebble counts revealed similar substrate size distributions at many of the sampled sites (Figures 3.10, 3.11, 3.12, 3.13), with d_{50} in the range of 20 to 40 mm. Swamp Creek has slightly larger substrate overall, which can be seen in the box and whisker plots of the d_{50} sizes for each stream (Figure 3.14). Although substrate size commonly decreases with downstream distance in large river systems (Knighton, 1998), only Thorndyke Creek of the four streams here showed even minor downstream fining of the substrate.

There were a few exceptions to the uniformity of the substrate size distributions. Site 21 in Swamp Creek and sites 24, 15, and 13 in Little Bear Creek had considerably higher proportions of fine sediment (i.e. substrate smaller than 2 mm). Site 26 in Little Bear Creek and sites 5 and 9 in Swamp Creek were also outliers with coarser substrate than the other sites. All of these outliers seem to be best explained by the site's location on the longitudinal profile. Those sites with finer substrate are located on flat portions or just upstream of flat portions on the profile, whereas the sites with coarser substrate are located on the steeper, convex segments of the profile.

Riffles were evaluated for embeddedness and cementation of the substrate. The results from the embeddedness rank method were compared to the results of two other embeddedness methods, an estimate of percent fines in the riffle and the percentage of embedded particles sampled in the pebble count. The Spearman rank correlation test determined that the embeddedness rank correlated significantly with the other 2 methods (Table 3.1; Zar, 1984). Nearly all of the sampled riffles were less than 50% embedded, and, additionally, an almost equal portion were grouped in the zero to 25% and 25% to 50% embedded classes (Figure 3.15). Scores for the cementation of the riffles of each site vary more than the embeddedness scores (Figure 3.16); however, the majority of sites were classified as fair (2) or good (3) (i.e. gravel and cobbles are tight, but not entirely compacted).

The prevalence of fine sediment, as measured by the percent of the channel bottom covered in fine sediment, had variable results. Percent fines ranged from 20% to 100% among the sampled sites. Percent fines was not related to channel slope (Figure 3.17). Percent fines was correlated with the presence or absence of storage features (point or alternate bars). The mean percent fines in sites with bars was 39%, significantly lower than the mean percent fines in sites without bars, 53% ($p = 0.005$; Zar, 1984).

Landscape metrics

The results of the spatial analysis can be grouped into two parts. First, I present the results of those metrics associated with the magnitude of urbanization, as measured by the quantity of urban land cover. Second, I show the results from the metrics that quantify the concept of connectivity. Results also revealed some correlations and redundancy in the landscape metrics, which rendered some metrics useless.

Magnitude of urbanization

The land cover of the four watersheds spans a broad range from largely urbanized to overwhelmingly forested (Figure 3.18). As classified, total urban land represents approximately 80%, 65%, 50% and 20% of the watersheds of Juanita, Swamp, Little Bear, and Thorndyke Creeks, respectively. Although the land cover analysis indicates that Thorndyke Creek has 20% total urban land, its watershed in fact has no urban development, with the exception of a few paved roads. Portions of the watershed are actively logged; clearcuts were locally misclassified as urban land cover.

The land cover distribution was nearly equivalent between the two buffer-zone sizes and the two local-zone sizes. A stacked bar chart which pairs the land cover distribution of the two buffer-zone sizes (100 m and 200 m) for the most downstream site of each stream shows that the two widths of buffer zone have little variation in land cover distribution (Figure 3.19). A regression of the total urban land within the larger versus the smaller buffer zone showed a nearly congruent proportion of urban land within each zone (Figure 3.20, $R^2 = 0.98$). Similar graphs were drawn to compare the two local-zone sizes (500 m and 1 km). In this case, the bar chart and scatterplot reveal that the two dimensions of the local zones are correlated, especially in the heavily forested Thorndyke Creek; however, these zones are not correlated to the same extent as the two dimensions of the buffer zones (Figures 3.21, 3.22; $R^2 = 0.83$). In addition, Swamp and Little Bear creeks are more heterogeneous in land cover, and, therefore, their local zones are most different.

Land cover in the sub-watershed shows very different relationships with that of the smaller zones. Even though the 100-m buffer zone occupies only 16% of the sub-watershed zone on average, its land cover is nearly indistinguishable from that of the sub-watershed (Figures 3.23, 3.24; $R^2 = 0.98$). Because the quantity of urban land in the buffer zones was so closely correlated with that in the sub-watershed zone, the buffer-zone metrics were abandoned in the subsequent analysis. In contrast, the percentage of total urban land is often considerably different between the 500-m local zone and the sub-watershed zone (Figures 3.25, 3.26; $R^2 = 0.48$).

Connectivity of urban land

Connectivity was quantified with various landscape metrics including road density, median flow path length, and distance to road crossings. In sum, these metrics showed that urban land becomes more connected with the stream network as it becomes more prevalent. Generally, watersheds with “disconnected” urban land did not exist, at least in the way I quantified connectivity.

The first connectivity metric evaluated was road density. Road density has been used as a surrogate measure for watershed urbanization, but I have used it here as a metric for connectivity because stormwater is typically routed to streams via pipes and ditches along roads. A scatterplot shows a strong relationship between road density and total urban land within the sub-watershed zone ($R^2 = 0.98$; Figure 3.27). In contrast, road density is much more variable in the local zone and shows no relationship to the quantity of urban land in the sub-watershed (Figure 3.28).

The second connectivity metric was the median flow path length from urban land pixels to the stream network. Figure 3.29 shows the distribution of the median flow path lengths, as determined for all sub-watershed zones within each study watershed. The overall range in median flow path lengths (160 m to 410 m) is not large, and the medians of the median flow path lengths are nearly identical (350 m) for the three urban streams. Thorndyke Creek has the shortest median flow path lengths because the only true urban lands in the watershed (three paved roads) are predominantly located adjacent to tributaries.

A similar connectivity metric based on median flow path lengths, but by an alternative method, showed different results. This method measured flow path lengths from urban land pixels to the closest stream *or* road (D. Spirandelli, written communication, 2001). This metric was calculated for nine of my sub-watersheds, which made a comparison of the two metrics possible. The two are not related and give different results, in that the alternative method produces considerably shorter distances (Figure 3.30). The median flow path lengths from the alternative method are also strongly correlated with road density in the sub-watershed zone (Figure 3.31). Because of this strong correlation, the median flow path length by the alternative method was not used in subsequent analyses.

The final connectivity metric is the upstream distance to a road crossing (Figure 3.32). The total range in this metric is from about 100 m to 1800 m for the urban streams, although the median values for all three urban streams are rather similar. This metric varies more in Swamp Creek and Little Bear creeks, as compared to the more urbanized Juanita Creek. The upstream distance values for Thorndyke Creek are considerably larger, because it has only two road crossings.

Physical attributes and landscape metrics

The individual physical stream attributes selected for this study were anticipated to show the effects of urbanization within both the sub-watershed and local zones. These physical attributes include bankfull cross-sectional area, bank stability, complexity, LWD counts, riffle embeddedness, and riffle cementation; they are also the physical attributes that make up the components of the multi-metric index, PSCI. Several other attributes including pool counts, sediment size, and channel slope were fairly uniform throughout many of the sampled sites, and, therefore, they are excluded from this section and did not become components in the multi-metric index. Percent fines were excluded from further analysis and the PSCI because this attribute was neither significantly different in Juanita, Swamp, or Little Bear creeks nor significantly different in sites with different levels of local urban land (95% confidence). Although these attributes (especially pools) are important components of stream habitat, they did not add any benefit to the index.

Cross-sectional area was regressed in several iterations with two independent variables, watershed size and various metrics representing the proportion of urban land in the sub-watershed and local zones (Appendix A). The combination of watershed size and the percent paved and grass urban in the 1-km local zone offered the best prediction of cross-sectional area ($R^2 = 0.66$, $F = 72$, $p < 0.0005$). The standardized coefficient of the watershed area is much larger in this model, indicating that channel size is primarily influenced by the size of the contributing watershed. The regression of cross-sectional area with watershed size and urban land in the sub-watershed revealed that none of the three magnitude metrics in that zone were significant parameters in the model (Appendix A).

Bank stability declines with increasing watershed urbanization and also with increasing urban land in the local zone. Bank stability is significantly different among the study watersheds, as seen in the box-plot (Figure 3.33; $\chi^2 = 20.4$, $p < 0.0005$). The most stable banks were found in Thorndyke Creek, while the most unstable banks were found in Juanita Creek. A second box-plot shows how bank stability significantly improves when the local zone has less urban land (Figure 3.34; $\chi^2 = 31.1$, $p < 0.0005$).

The qualitative measure of stream complexity has a similar relationship to urban land in the sub-watershed and local zones. The same two box-plots were constructed for this attribute (Figures 3.35, 3.36). Complexity was significantly different among the four watersheds and among different levels of local urban land ($\chi^2 = 18.1$, $p < 0.0005$ and $\chi^2 = 23.6$, $p < 0.0005$, respectively). Most of the sites assessed in Juanita Creek had more simplified channel structure than sites in Thorndyke Creek. Complexity scores at sites in Swamp and Little Bear creeks spanned the entire range of possible scores, but these streams had different median scores, 2 and 3, respectively.

LWD abundance is similarly affected by urbanization in the sub-watershed and local zones (Figures 3.37, 3.38; $F = 5.05$, $p = 0.003$ and $F = 5.27$, $p = 0.002$, respectively). However, some sites did not have any LWD regardless of the amount of urban land in the sub-watershed or local zone. This may be due to natural variability or, more likely, other influences on LWD in an urban watershed such as selective removal. The variation in LWD was also related to the adjacent riparian zone condition. More LWD was found in sites with wide and intact riparian zones with mature forested vegetation. The median LWD count in these sites was about 12 pieces per 100 m, whereas the median count in sites with little to no forested riparian zone was about 2 pieces per 100 m (Figure 3.39).

The two riffle attributes, embeddedness and cementation, did not have as much variability as some of the other physical attributes; however, they still show a significant response to different levels of urbanization. The median embeddedness score was 3 (25 –50% embedded) for sites in Swamp and Juanita Creeks, whereas the median score was 4 (0-25% embedded) for sites in Little Bear and Thorndyke creeks (Figure 3.40). Significant differences in embeddedness scores were seen between some watersheds and some levels of local urban land ($\chi^2 = 26.3$, $p < 0.0005$ and $\chi^2 = 12.6$, $p = 0.01$; Figure 3.41). The results on riffle cementation illustrated significant differences in the same manner ($\chi^2 = 26.8$, $p < 0.0005$ and $\chi^2 = 20.0$, $p < 0.0005$, respectively; Figures 3.42, 3.43). Riffles were less cemented in Thorndyke and Little Bear Creeks and in sites with less than 25 percent urban land in the local zone.

Physical stream conditions index (PSCI)

The PSCI values, a sum of 6 key component scores (see Table 2.7) range from 9 to 22.5 out of a total possible range of 6 to 24. Figure 3.44 shows sites with various index scores. A comparison of the box-plots of the PSCI for each study stream reveals that the median value significantly increases in a step-wise fashion from the most urban watershed to the least urban watershed ($F = 15.6$, $p < 0.0005$, Figure 3.45). Little Bear Creek has the most variability in the PSCI score, whereas Thorndyke Creek, the reference stream, has the least variability. The range in PSCI score for Thorndyke Creek is four, and excluding one outlier point it is just over two.

Simple and multiple regression analysis techniques were used to find the best relationships between the PSCI and landscape metrics that quantify the magnitude and connectivity of urban land (Appendix B). The PSCI shows a decline with increasing percent total urban land in the sub-watershed zone, though the regression relationship is not compelling (Figure 3.46; $R^2 = 0.42$). When PSCI is regressed with the total urban land within the 500-m local zone, the relationship provides slightly less explanation of the variability (Figure 3.47; $R^2 = 0.36$). A better explanation of the variability in the PSCI is given by a multiple regression of percent paved and grass urban land in the sub-watershed zone and in the 500 m local zone ($R^2 = 0.52$, $F = 38.38$, $p < 0.0005$); Other pairings provide comparable models (Appendix B).

In an attempt to further explain the PSCI, the connectivity metrics were added to the regression model. The sites from Thorndyke Creek were excluded from this set of regressions, because the connectivity metrics (as defined) were not applicable in a watershed without urban land. Of all connectivity metrics, only one, upstream distance to a road crossing, added further explanatory power to the regression model (Appendix B). With this metric included, about 10 percent more of the variability was explained by the model. The regression model is:

$$\mathrm{PSCI} = 20.1 - 11.8\,U_S - 9.4\,U_L + 1.7\,D \qquad (4)$$

where U_S is percent paved and grass urban land in the sub-watershed, U_L is percent paved and grass urban land in the 500-m local zone, and D is the upstream distance (km) to the closest road crossing (Table 3.2). This model illustrates that urbanization at the sub-watershed and local zones has an additive effect in degrading urban streams and that the influence of urbanization at the sub-watershed and local zones is nearly equivalent (see standardized coefficients in Appendix B). This significance of D as a predictor variable is consistent with the physical stream conditions associated with road crossings, which are key points of disruption in urban streams. Road crossings interrupt the riparian zone and can alter a stream's fluvial processes. Furthermore, they are commonly locations of stormwater discharge to the channel in urban watersheds.

The PSCI was also analyzed for longitudinal trends. The sites sampled in Thorndyke Creek were again excluded from this portion of the analysis, because this analysis was not applicable to a non-urban watershed. The sites sampled in Juanita Creek had the least change in PSCI but did show a general decline in the PSCI score in the downstream direction (Figure 3.48). The sites in Swamp Creek showed no longitudinal trend (Figure 3.49). Little Bear Creek had the best conditions in the most upstream sites and variable conditions in the sites farther downstream (Figure 3.50). Variability between even consecutive sites, however, could be nearly as great as that along the channel as a whole.

To further explore the longitudinal change in the PSCI score, I considered the riparian conditions and the number of road crossings between consecutive assessed sites. The presence of an intact forested riparian buffer promotes downstream improvement in physical stream conditions, as measured by the PSCI. More significant improvements in the PSCI score resulted when the riparian buffer was more than 50% forested ($p = 0.002$; Figure 3.51). The sites were grouped using the median value (50% forested buffer) in order to facilitate a simple 2-sample t-test with equal sample sizes. Similar t tests were performed by separating sites by other proportions of forested buffer (20%, 35%, 65%, and 80%). Only the groups separated by the 35% and 50% thresholds were significantly different from each other (Table 3.3). The sites were similarly segregated into three groups according to the number of road crossings between consecutive sites. The grouping of the sites resulted from natural breaks in the data. In cases where the riparian buffer between consecutive sites was fragmented by more than 3 roads per km, more significant declines in the PSCI score resulted when compared to those sites without road crossings between them ($p = 0.09$; Figure 3.52).

Finally, considering these two factors together, they appear to act in concert. When the buffer between sites was fragmented by less than 3 road crossings per km, the downstream change in PSCI was significantly higher for sites with at least a 50% forested buffer ($p = 0.08$ and $p = 0.03$; Figure 3.53). When more than 3 road crossings per km were present, a forested buffer was less effective, resulting in a smaller and less significant relative improvement in PSCI scores ($p = 0.10$).

The PSCI was significantly correlated with the B-IBI. B-IBI scores were only available for 14 of the 87 sites and were only from sites in Swamp and Little Bear creeks. A regression analysis of the two indices illustrates that B-IBI scores are fairly well predicted by PSCI scores ($R^2 = 0.63$,$F = 20.7$, $p = 0.001$; Figure 3.54). The site with PSCI = 14.5 and B-IBI = 32 is an outlier due to its anomalous lack of LWD (only 2 pieces in the reach).

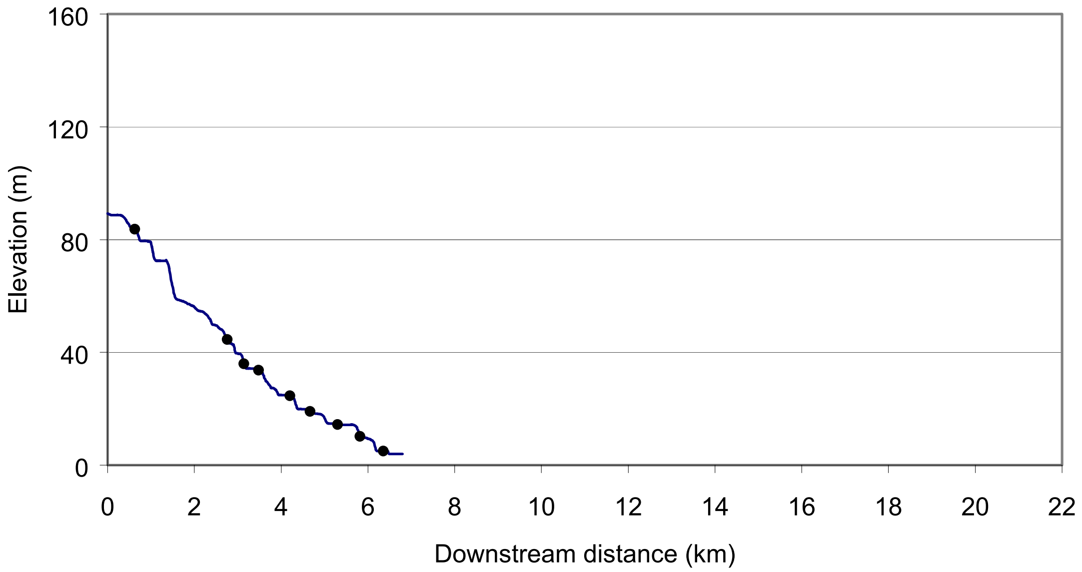

Figure 3.1 Longitudinal profile of Juanita Creek. Dots indicate sampled sites.

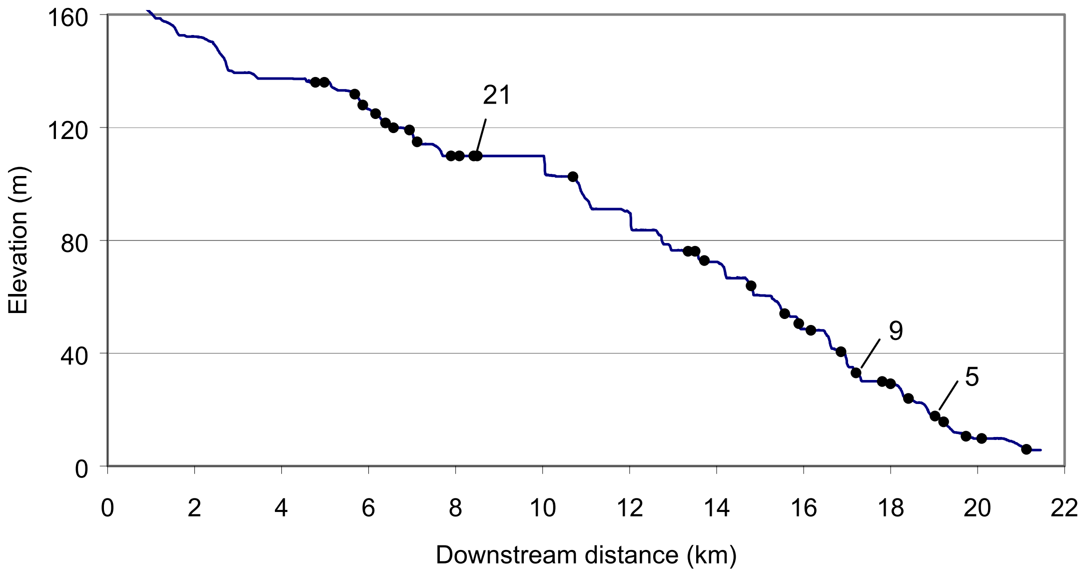

Figure 3.2 Longitudinal profile of Swamp Creek. Dots indicate sampled sites. Numbers identify sites with substrate larger or smaller than average.

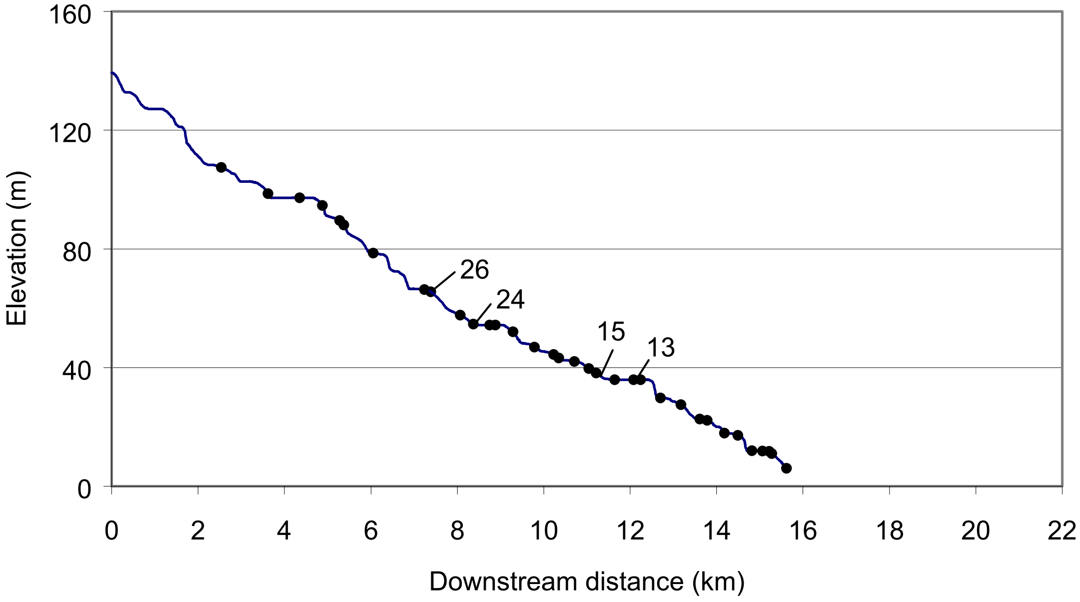

Figure 3.3 Longitudinal profile of Little Bear Creek. Dots indicate sampled sites. Numbers identify sites with substrate larger or smaller than average.

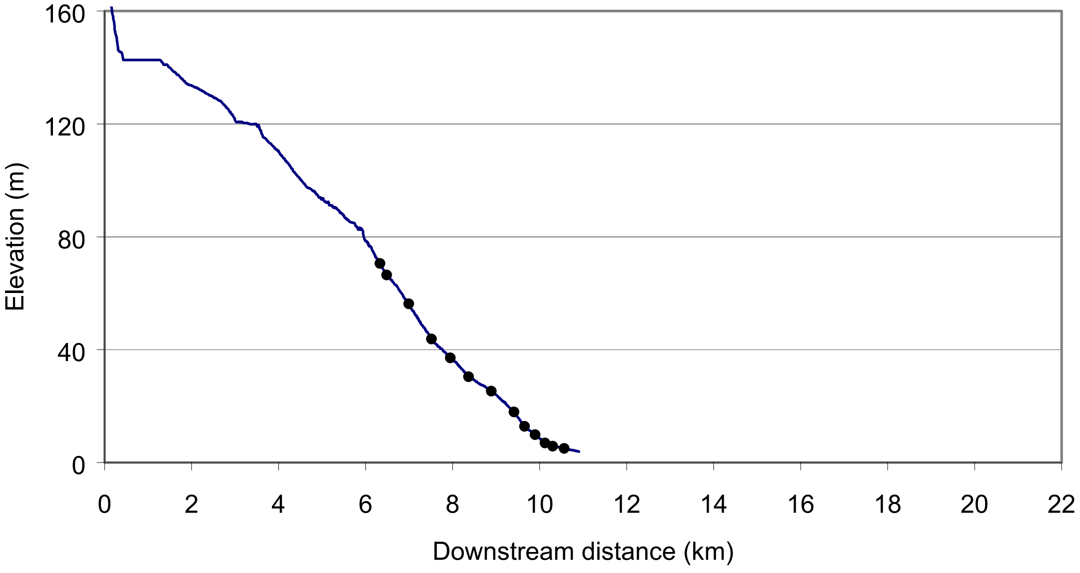

Figure 3.4 Longitudinal profile of Thorndyke Creek. Dots indicate sampled sites.

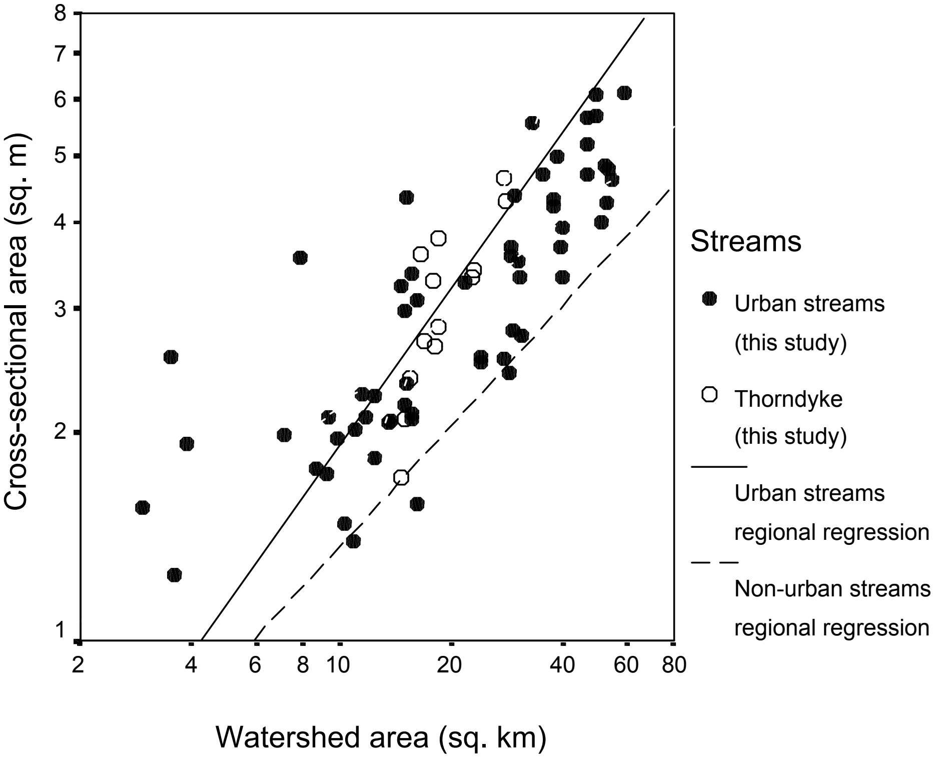

Figure 3.5 Channel size versus watershed area.

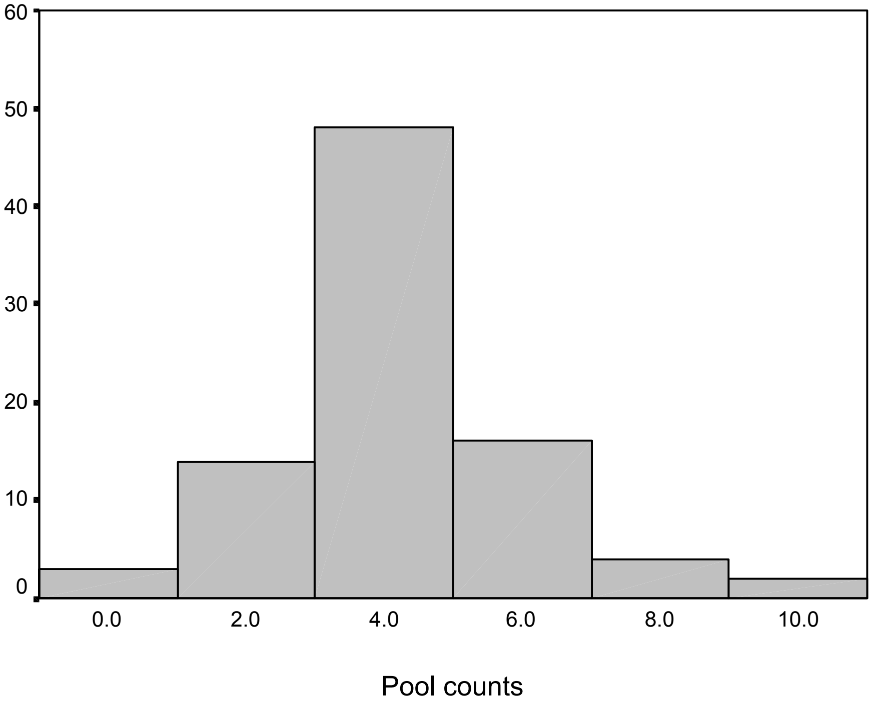

Figure 3.6 Distribution of pool counts.

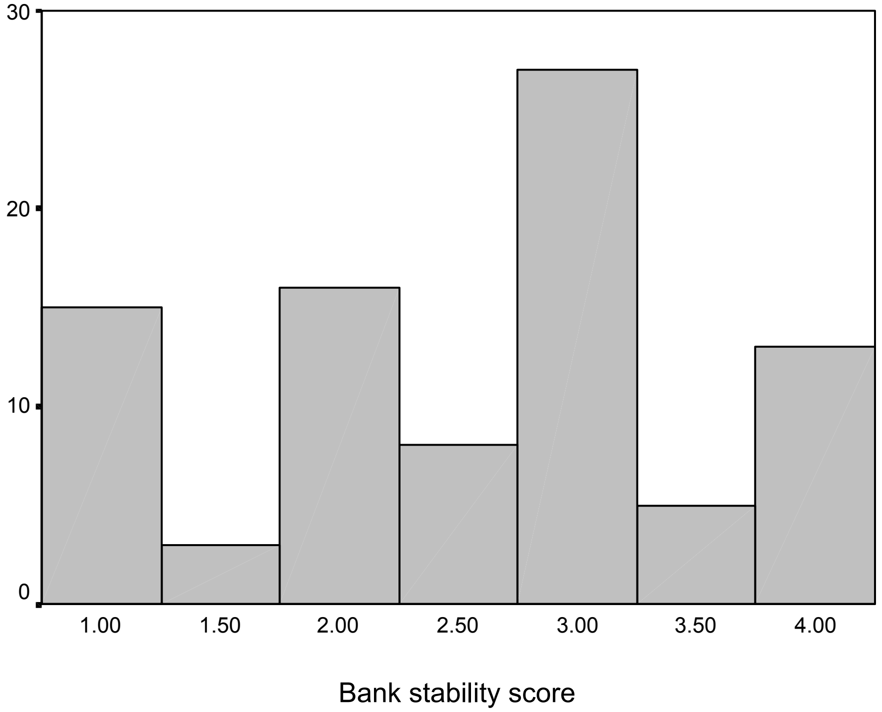

Figure 3.7 Distribution of bank stability scores.

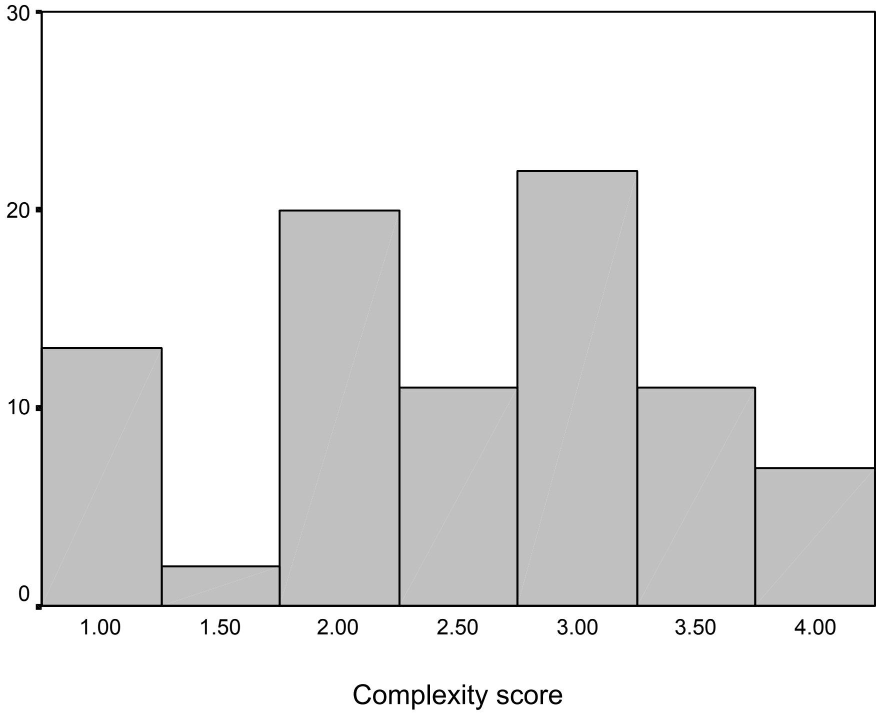

Figure 3.8 Distribution of complexity scores.

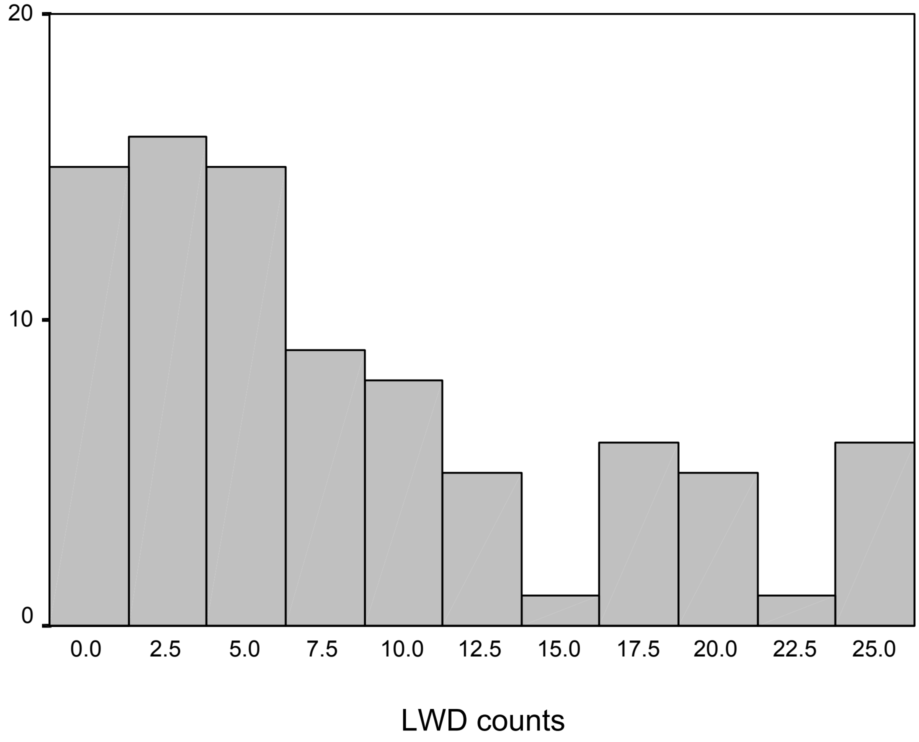

Figure 3.9 Distribution of LWD counts.

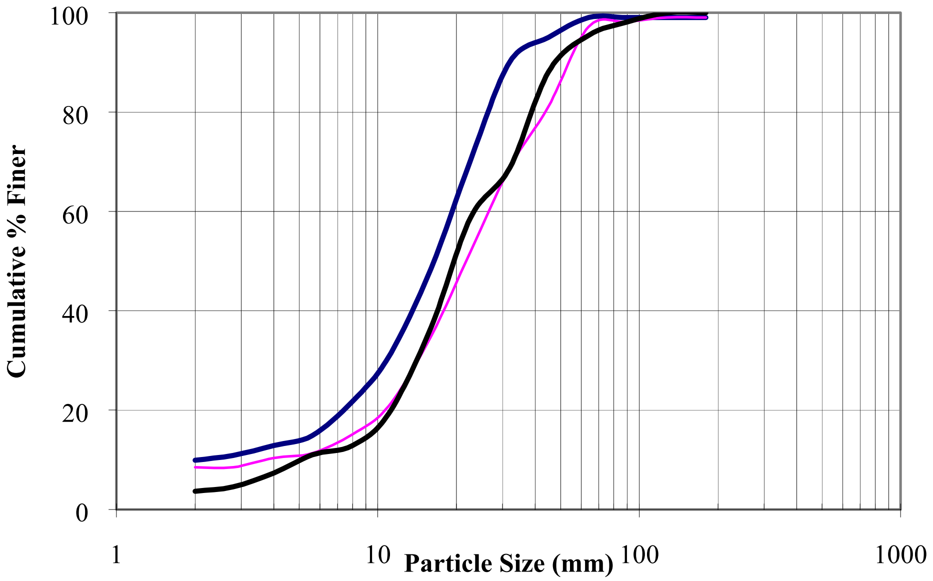

Figure 3.10 Substrate size distributions of Juanita Creek.

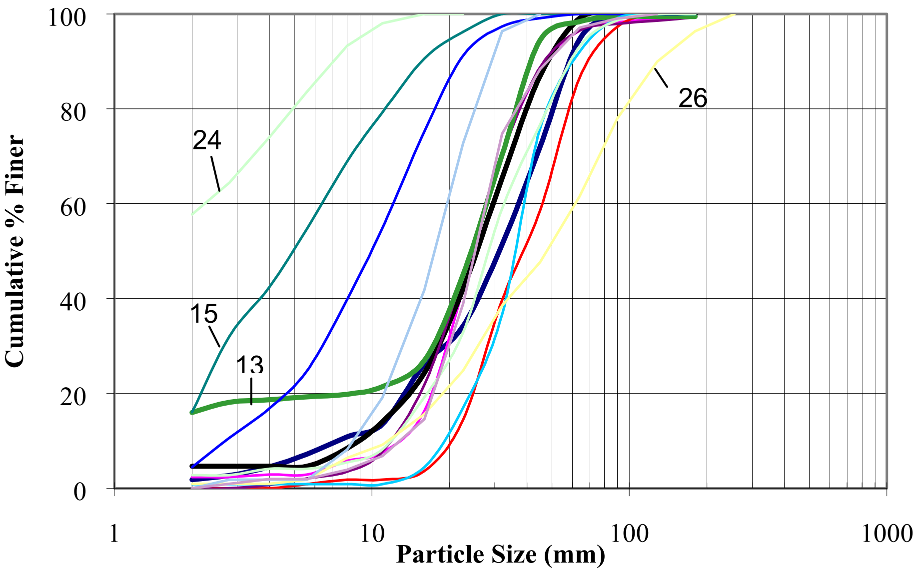

Figure 3.11 Substrate size distributions of Swamp Creek.

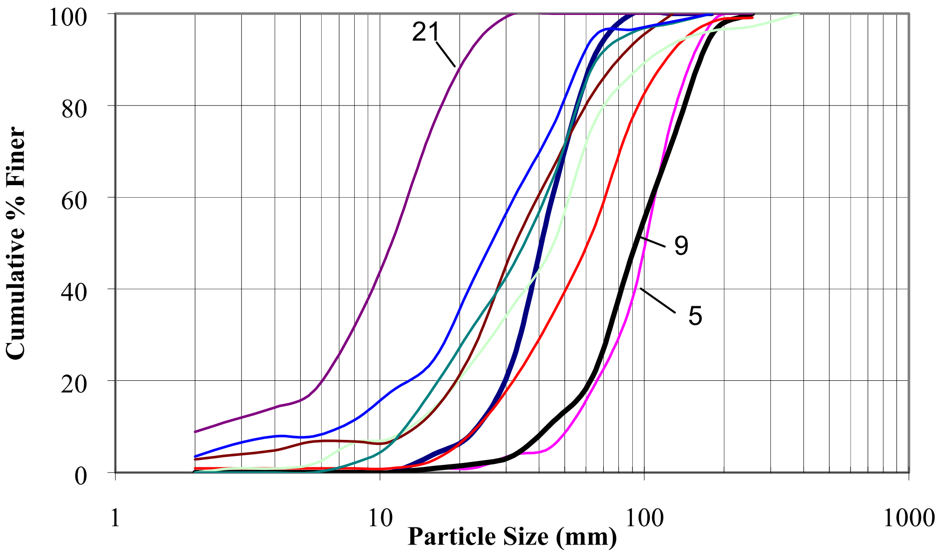

Figure 3.12 Substrate size distributions of Little Bear Creek.

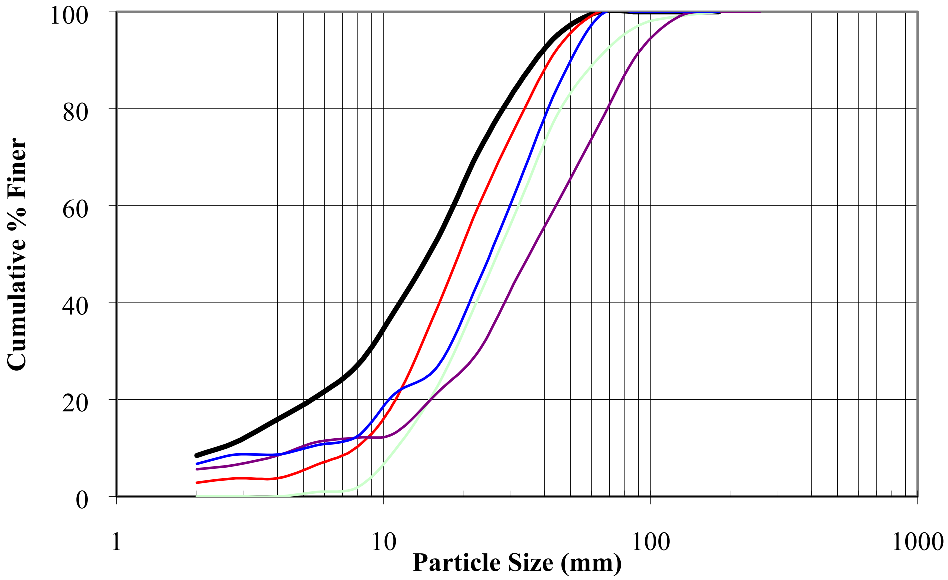

Figure 3.13 Substrate size distributions of Thorndyke Creek.

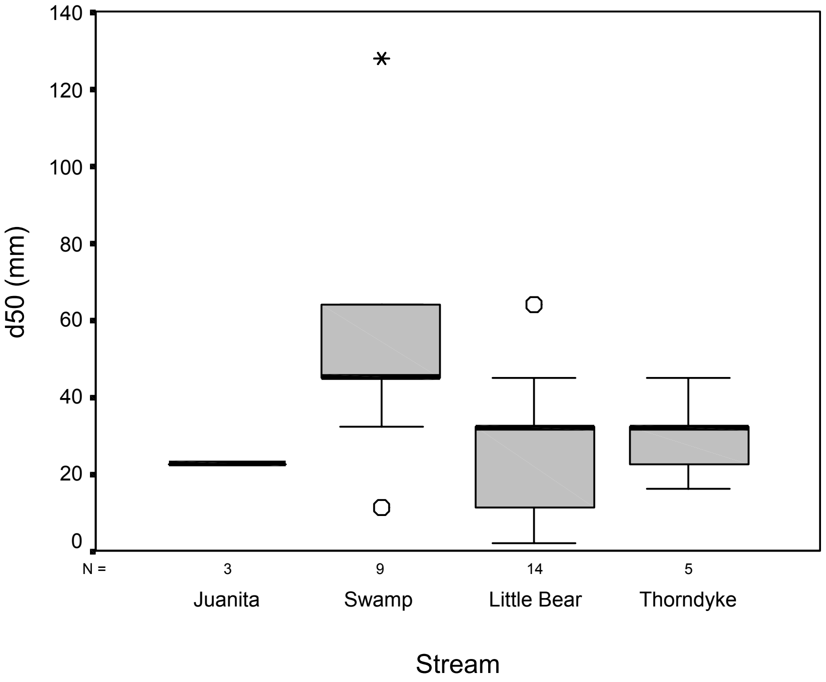

Figure 3.14 Comparison of d_{50} by study stream. Box plot description: Solid line – median, box – 50% of values, whiskers - highest and lowest values excluding outliers, open circles – outliers with values 1.5 to 3 box lengths beyond the upper or lower edge of the box, asterisks – outliers with values more than 3 box lengths beyond the upper or lower edge of the box.

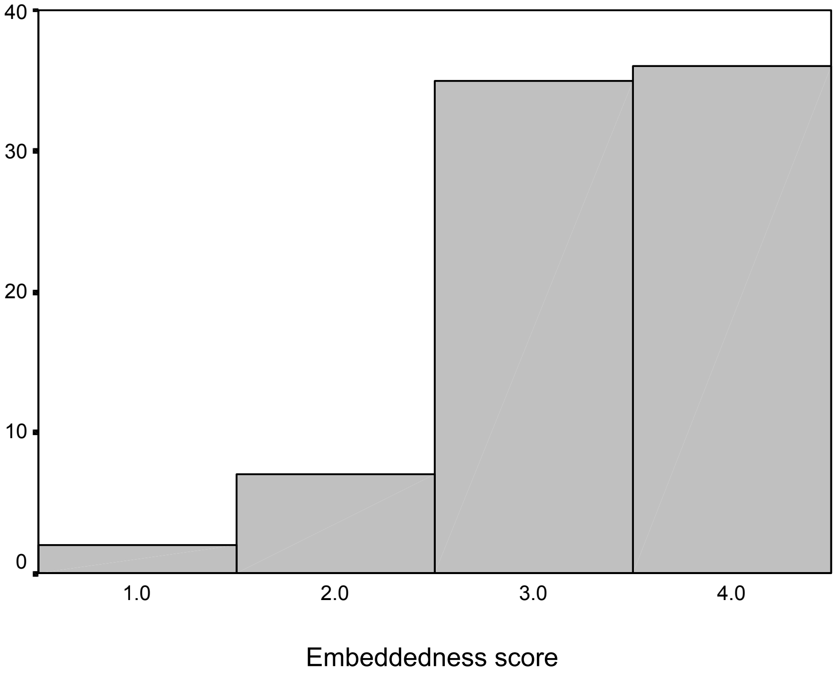

Figure 3.15 Distribution of embeddedness scores.

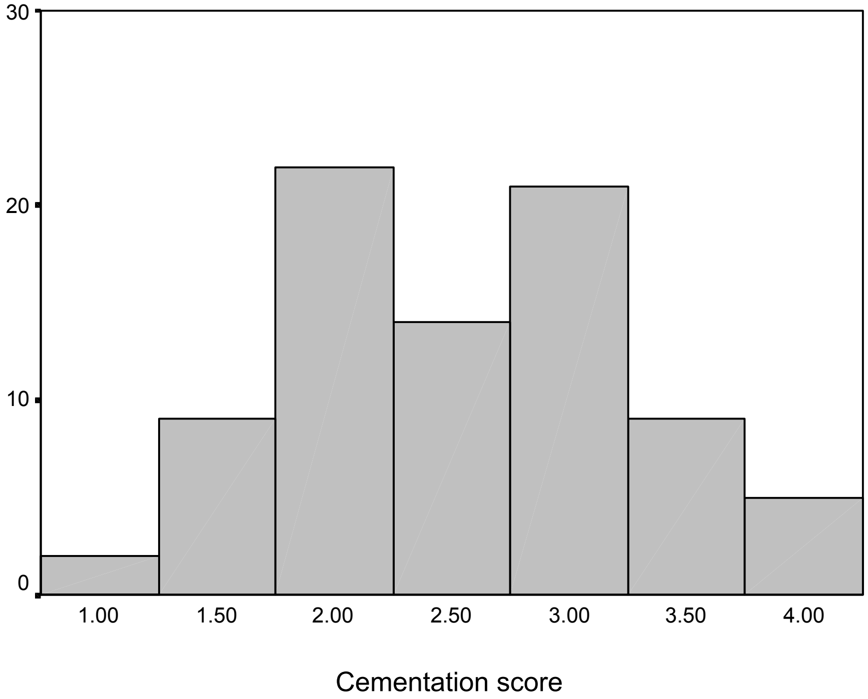

Figure 3.16 Distribution of cementation scores.

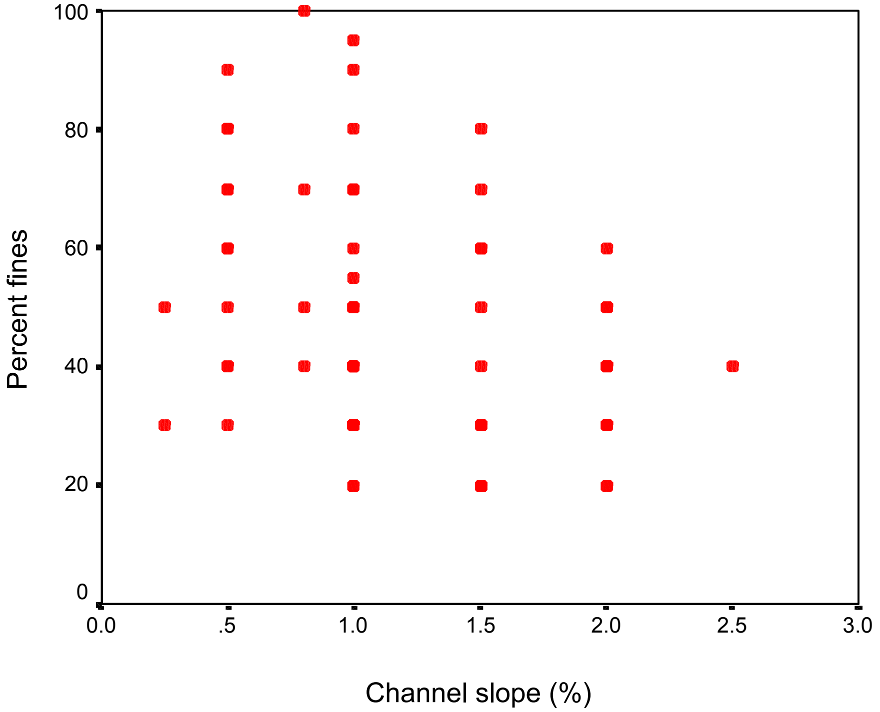

Figure 3.17 Percent fines versus channel slope of the reach.

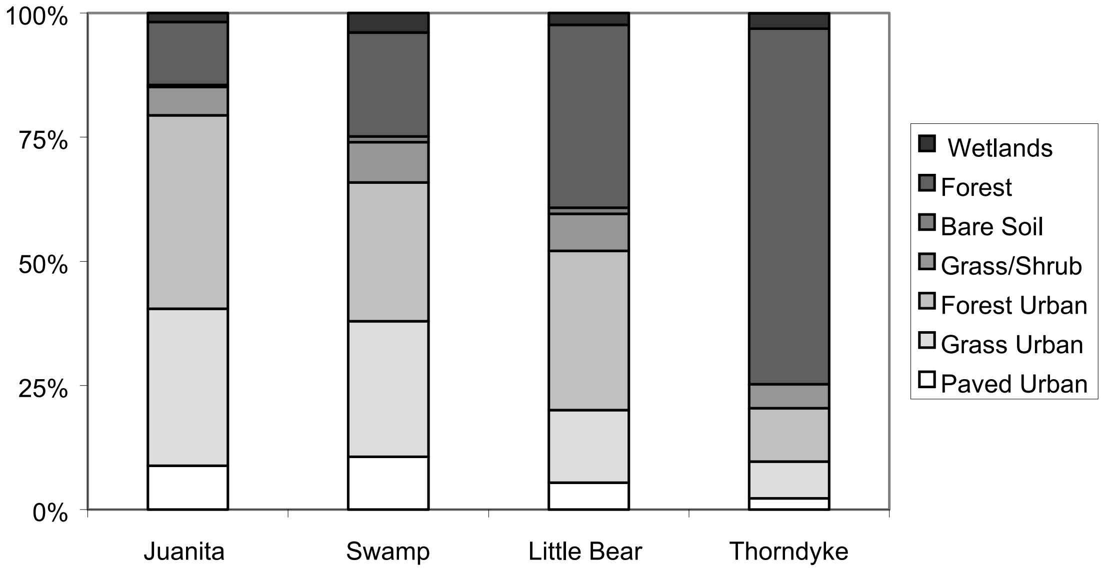

Figure 3.18 Land cover distribution of each study watershed.

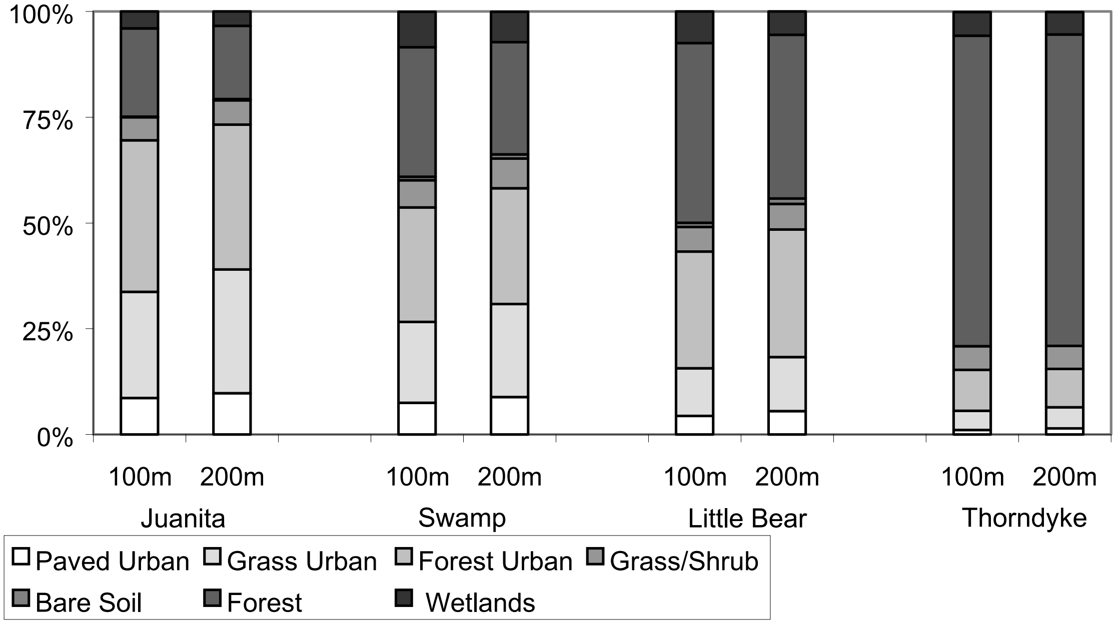

Figure 3.19 Land cover distribution within 100-m and 200-m buffer zones.

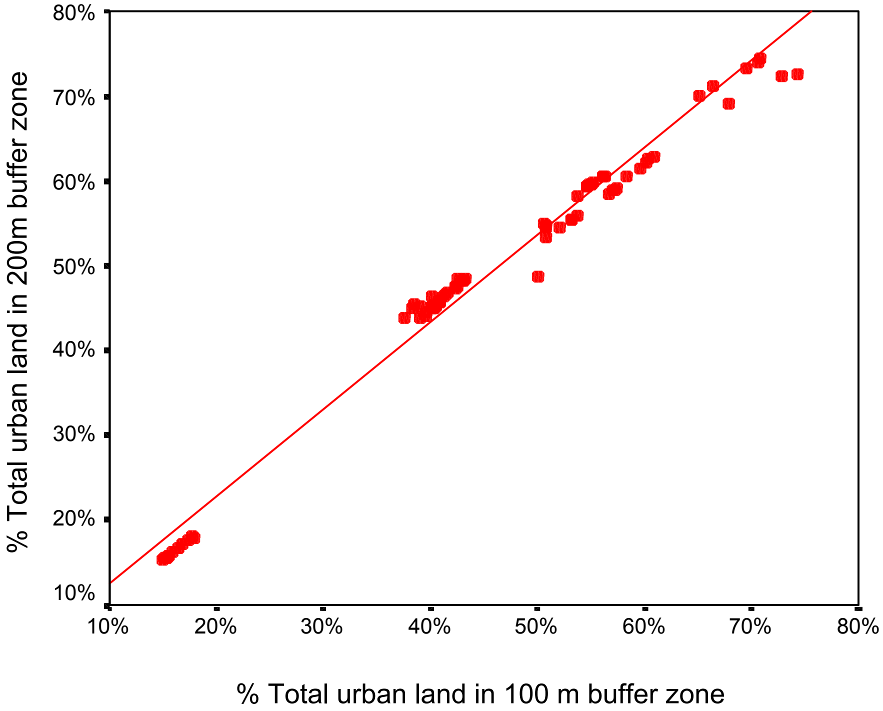

Figure 3.20 Comparison of urban land within 100-m and 200-m buffer zones.

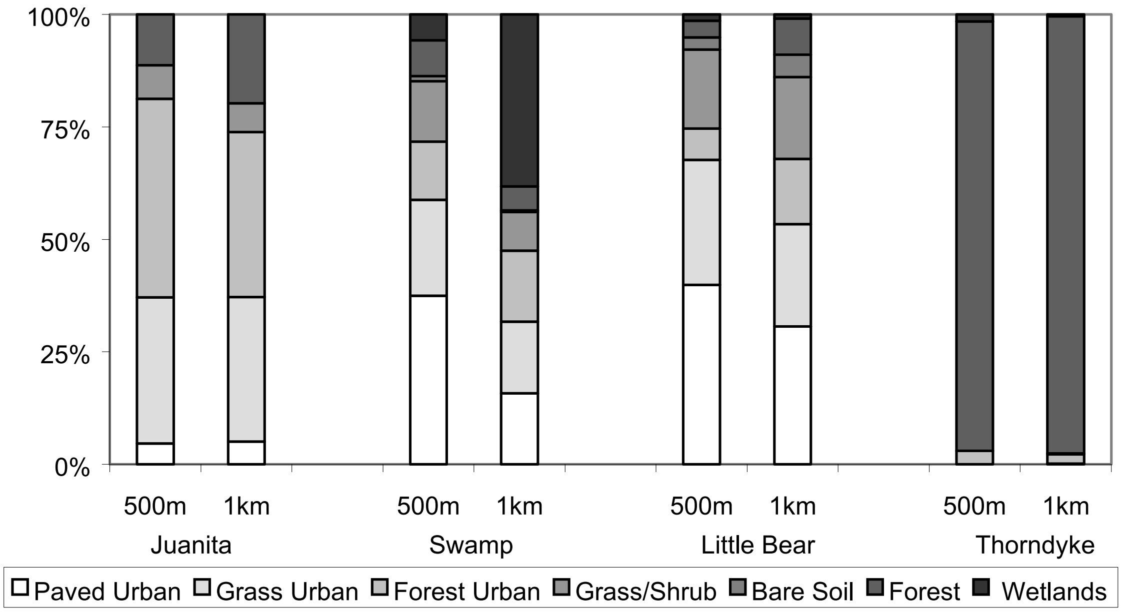

Figure 3.21 Land cover distribution of the 500-m and 1-km local zones.

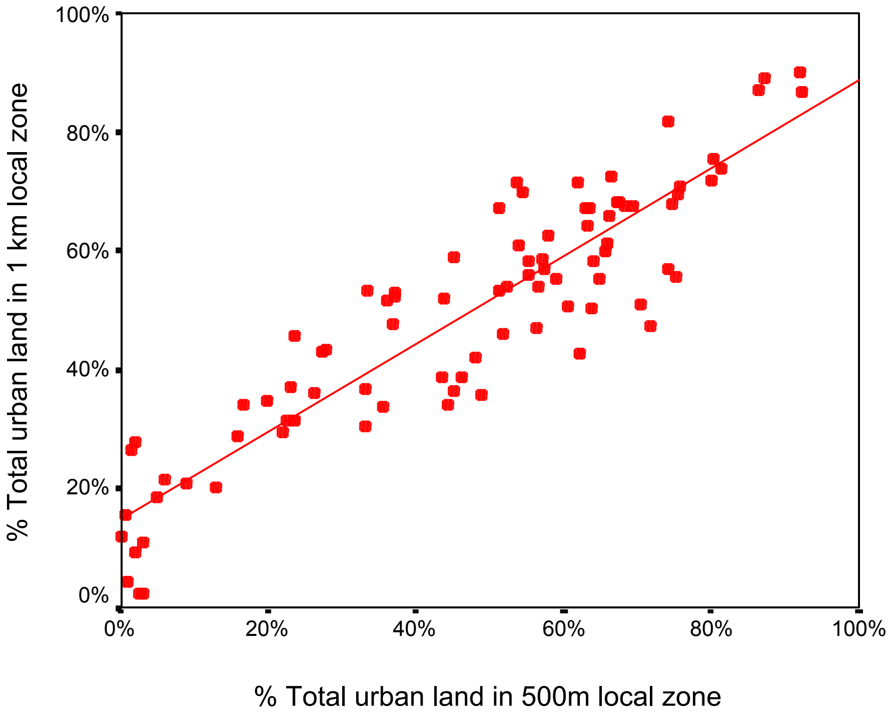

Figure 3.22 Comparison of urban land within 500-m and 1-km local zones.

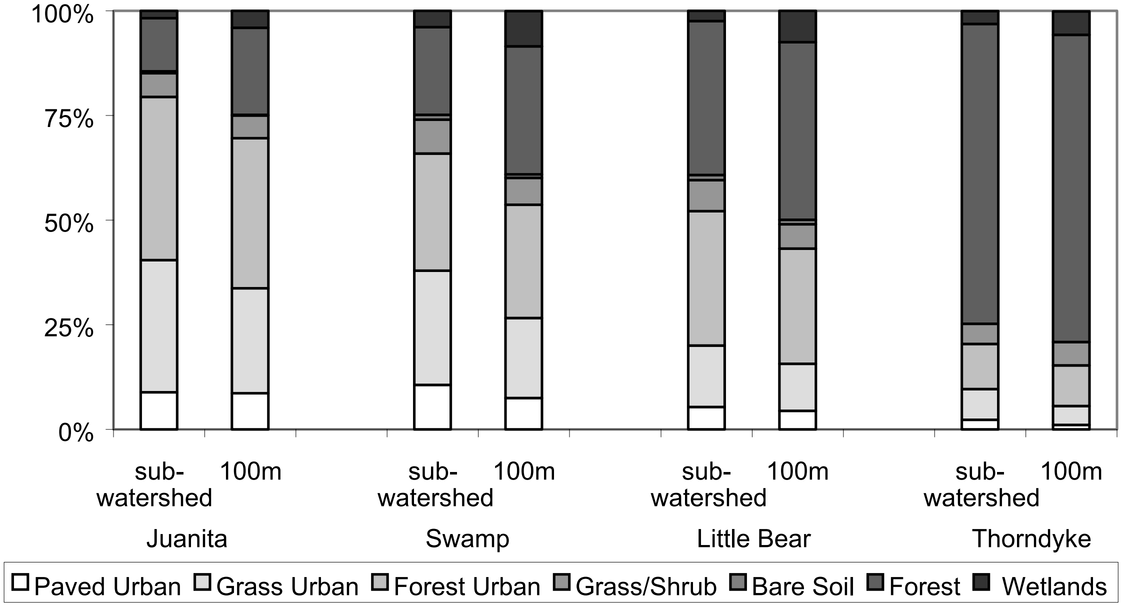

Figure 3.23 Land cover distribution of the sub-watershed and 100-m buffer zones.

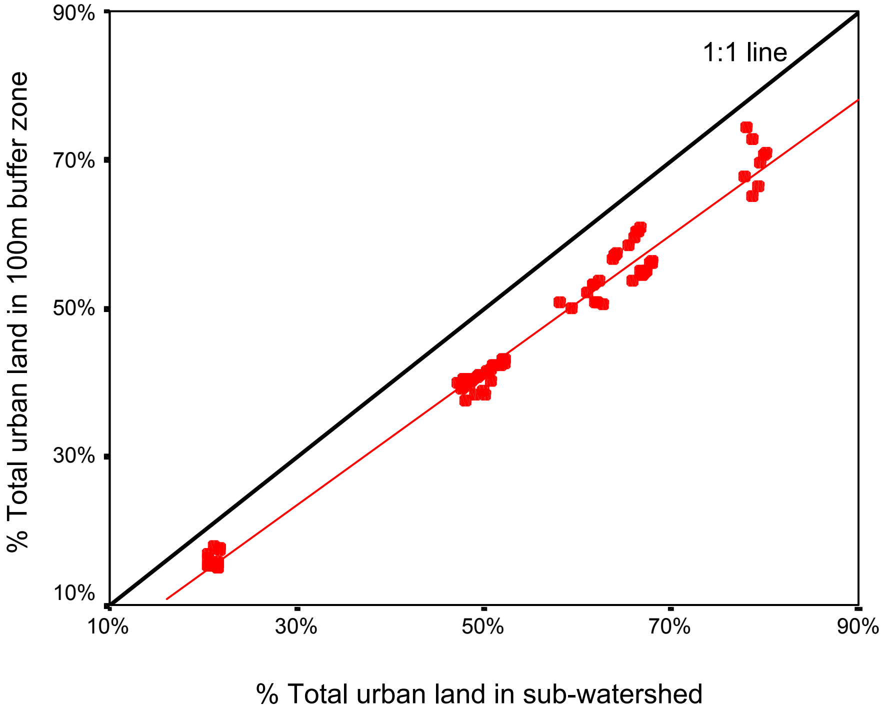

Figure 3.24 Comparison of urban land within the sub-watershed and 100-m buffer zones.

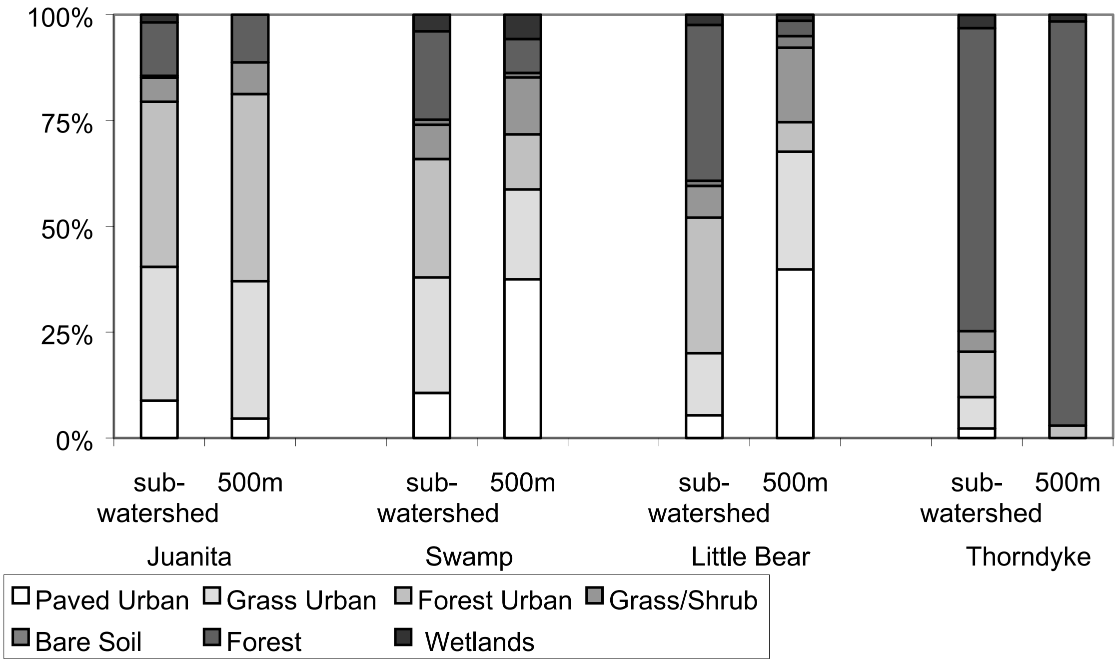

Figure 3.25 Land cover distribution of the sub-watershed and 500-m local zones.

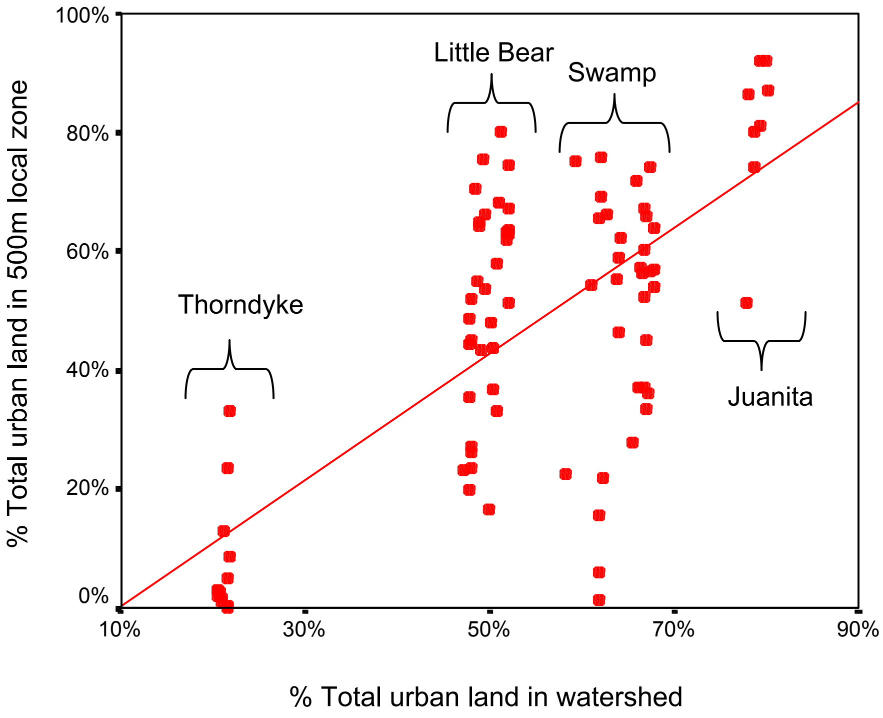

Figure 3.26 Comparison of urban land within the sub-watershed and 500-m local zones.

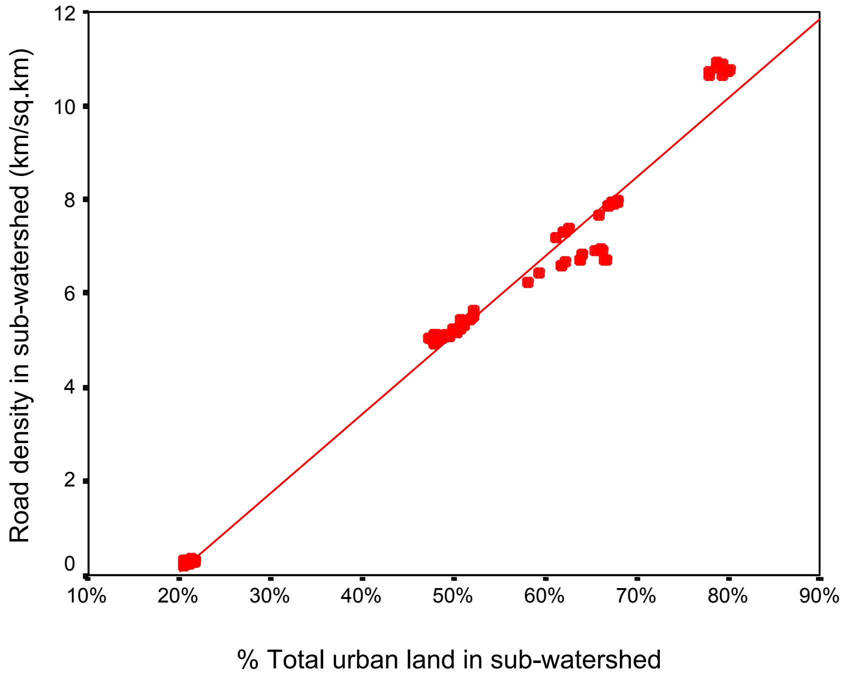

Figure 3.27 Comparison of road density and percent total urban land in the sub-watershed.

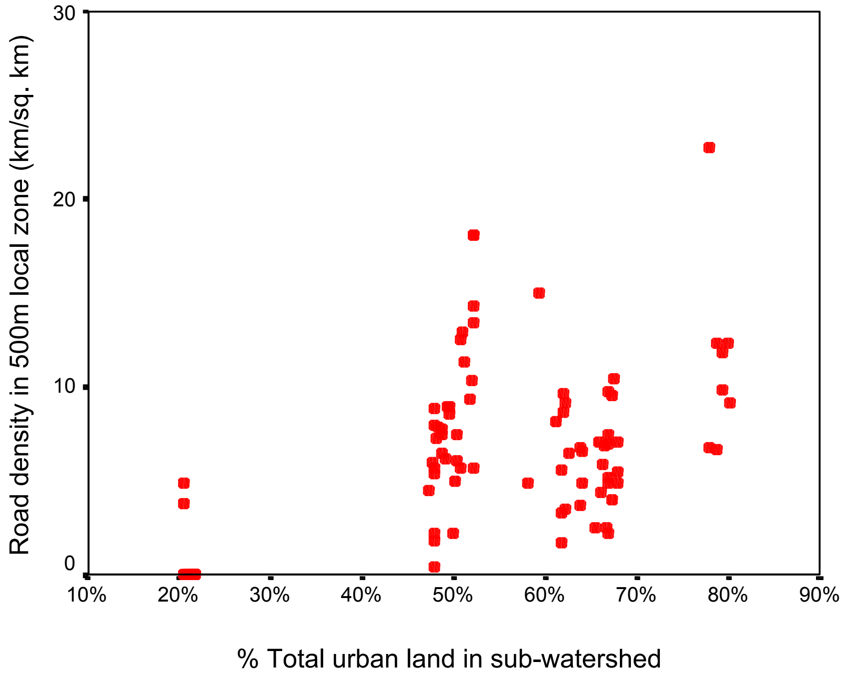

Figure 3.28 Comparison of local road density and percent total urban land in the sub-watershed.

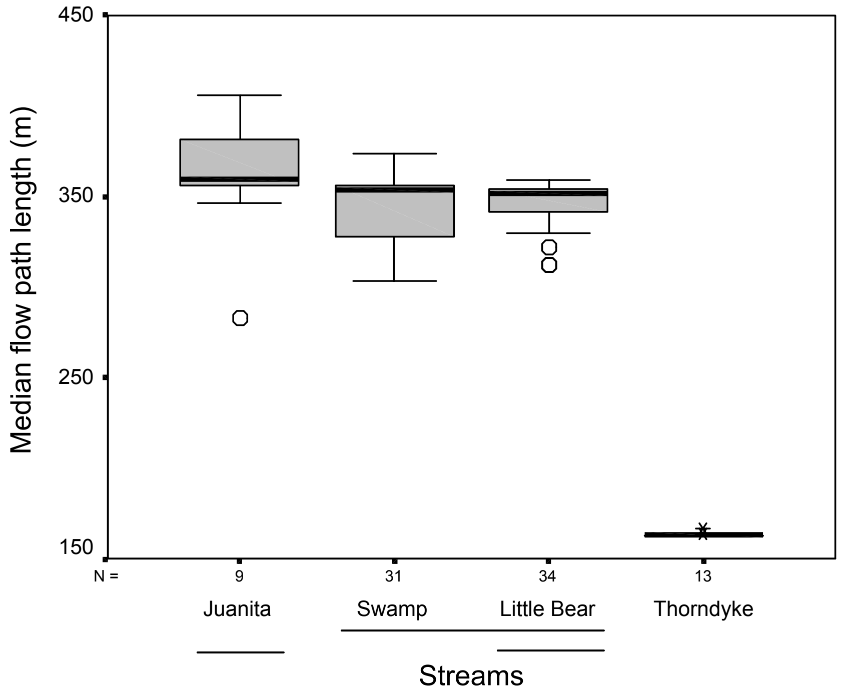

Figure 3.29 Comparison of median flow path lengths by study stream (N is number of sub-watersheds, lines show stream pairs not significantly different by Tukey's test, $\alpha = 0.05$, see Figure 3.14 for box plot description).

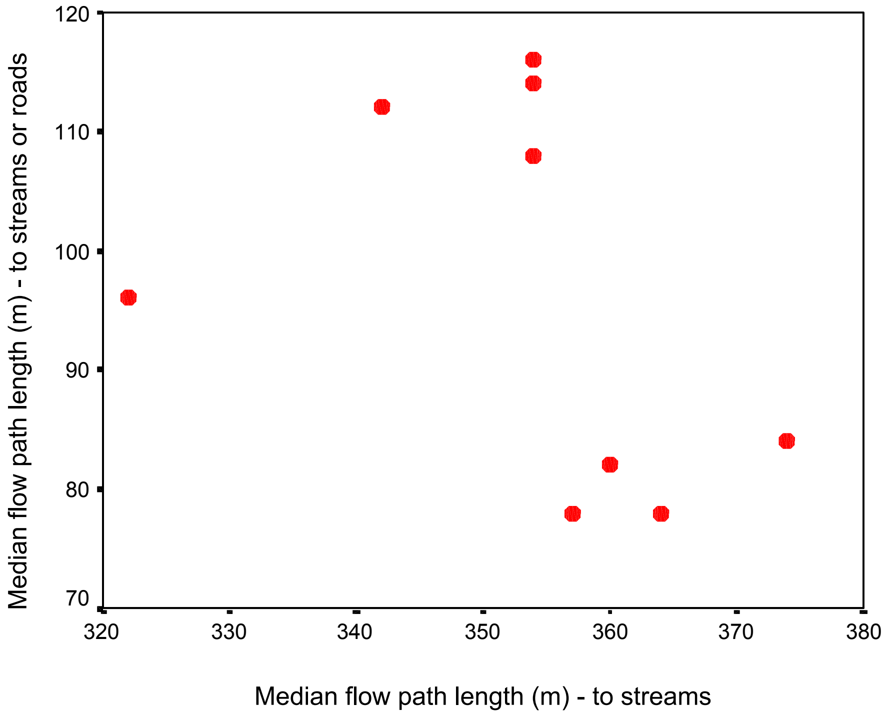

Figure 3.30 Comparison of median flow path lengths from different methods.

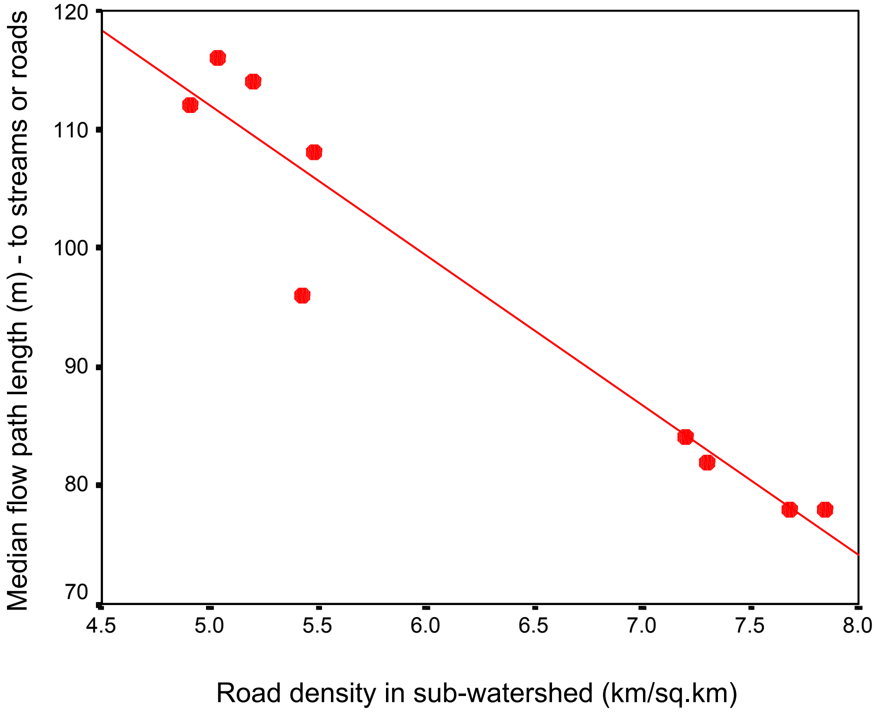

Figure 3.31 Comparison of median flow path length and road density.

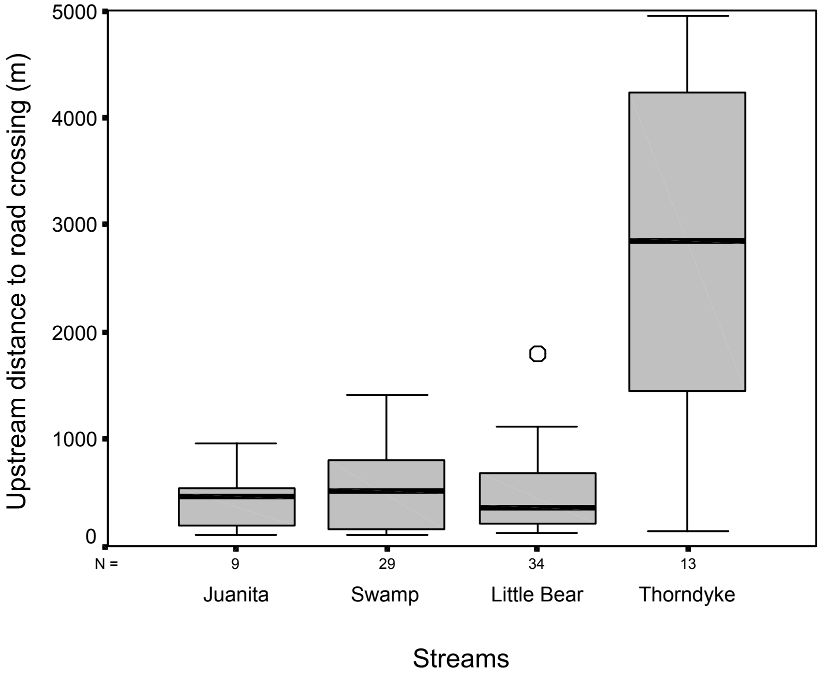

Figure 3.32 Comparison of the upstream distance connectivity metric by study stream (N is the number of sites, see Figure 3.14 for box plot description).

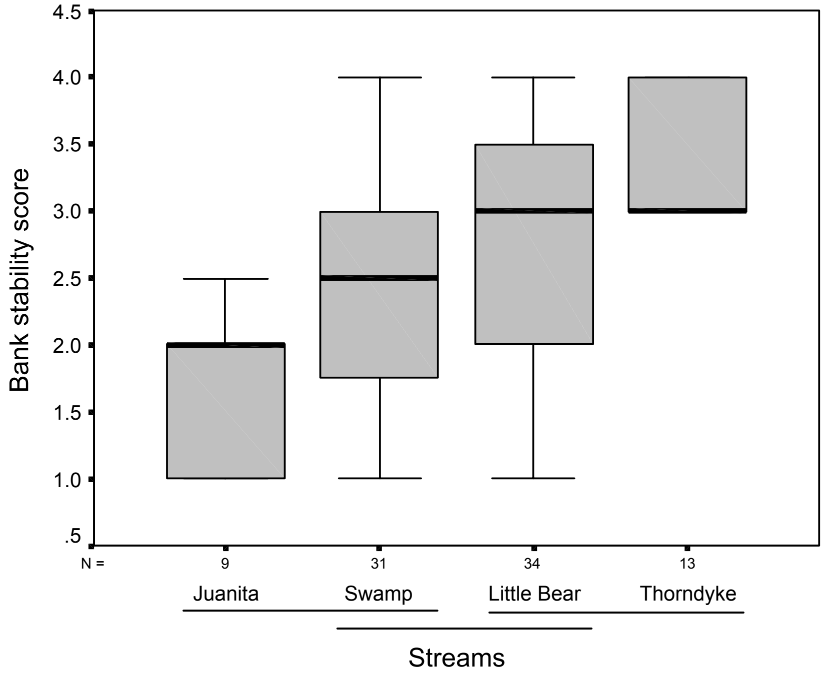

Figure 3.33 Comparison of bank stability scores by study stream (N is number of sites, lines show stream pairs not significantly different by Dunn's test, $\alpha = 0.05$, see Figure 3.14 for box plot description).

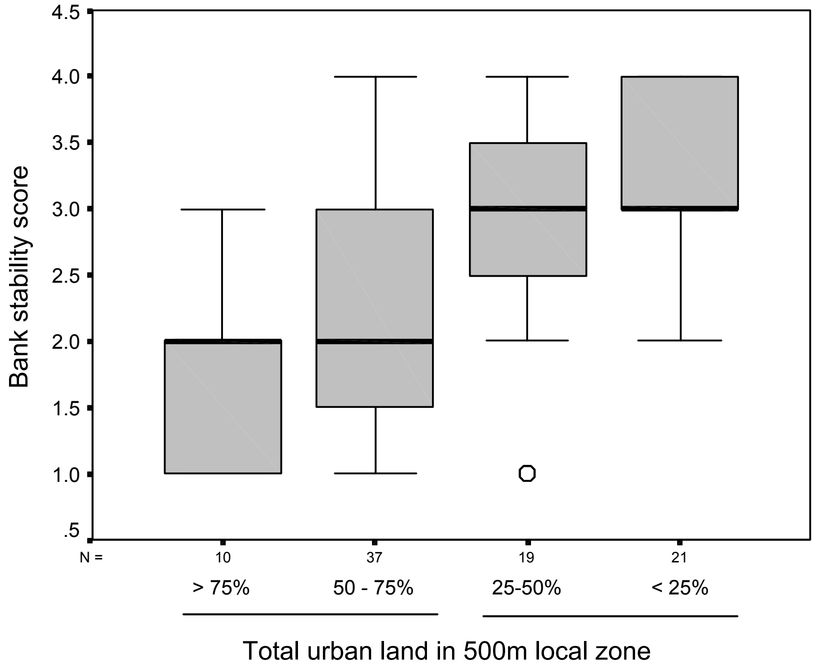

Figure 3.34 Comparison of bank stability scores by local percent urban land (N is number of sites, lines show groups not significantly different by Dunn's test, $\alpha = 0.05$).

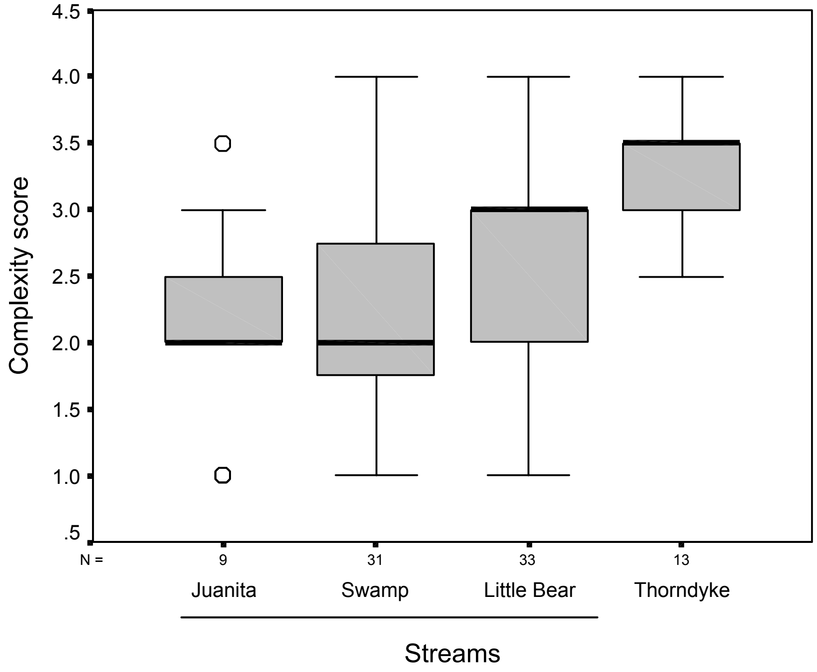

Figure 3.35 Comparison of stream complexity scores by study stream (N is number of sites, line shows streams not significantly different by Dunn's test, $\alpha = 0.05$, see Figure 3.14 for box plot description).

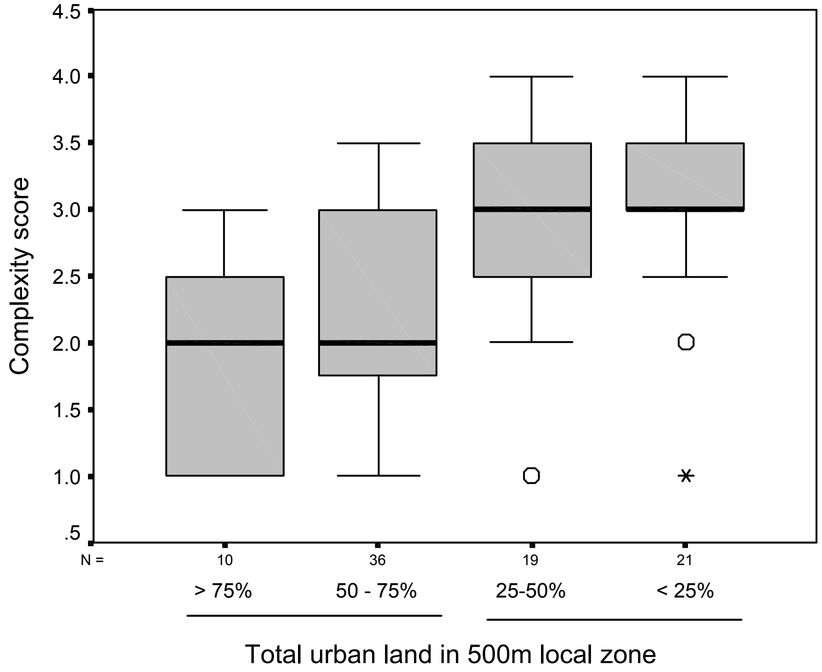

Figure 3.36 Comparison of stream complexity scores by local percent urban land (N is number of sites, lines show groups not significantly different by Dunn's test, $\alpha = 0.05$, see Figure 3.14 for box plot description).

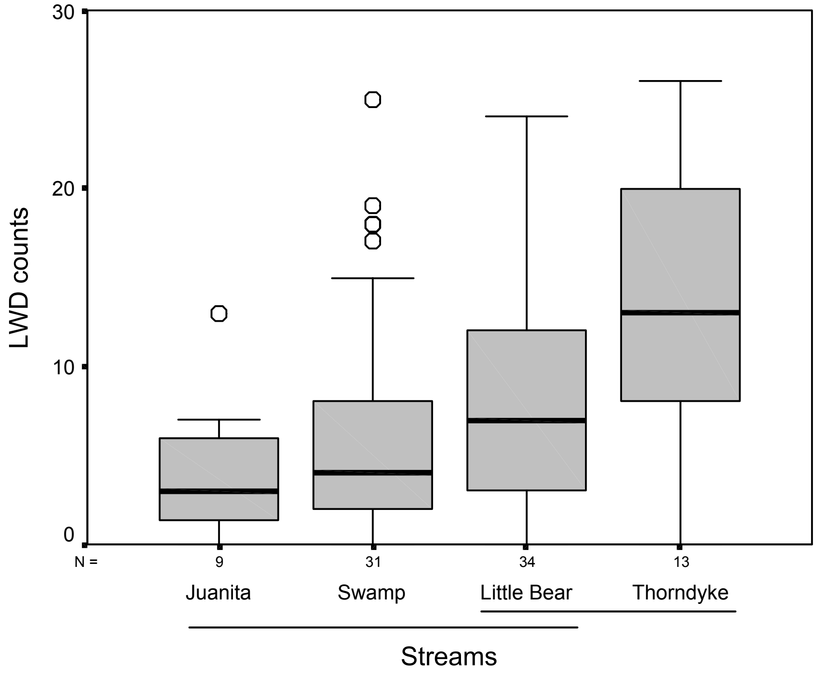

Figure 3.37 Comparison of LWD counts by study stream (N is number of sites, lines show streams not significantly different by Tukey's test, $\alpha = 0.05$, see Figure 3.14 for box plot description).

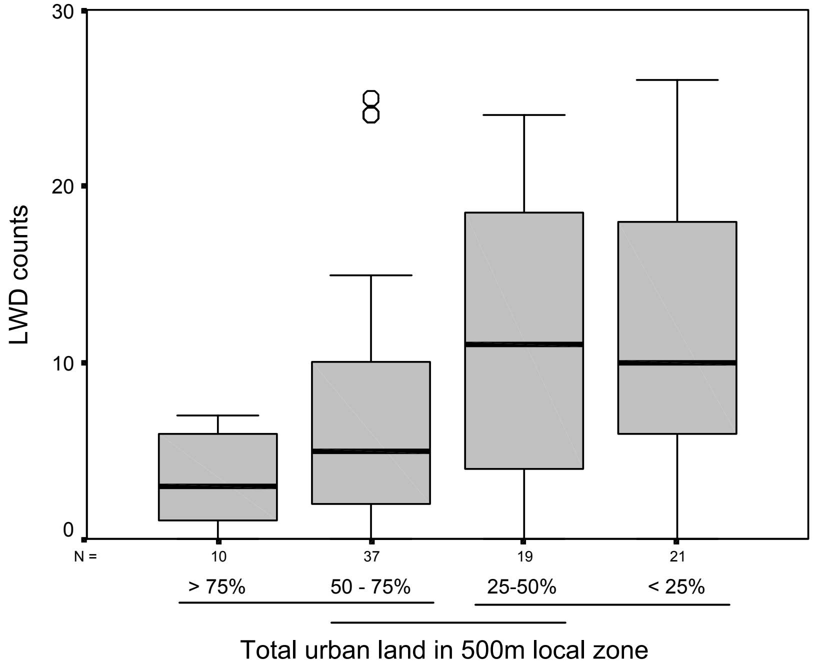

Figure 3.38 Comparison of LWD counts by local percent urban land (N is number of sites, lines show groups not significantly different by Tukey's test, $\alpha = 0.05$, see Figure 3.14 for box plot description).

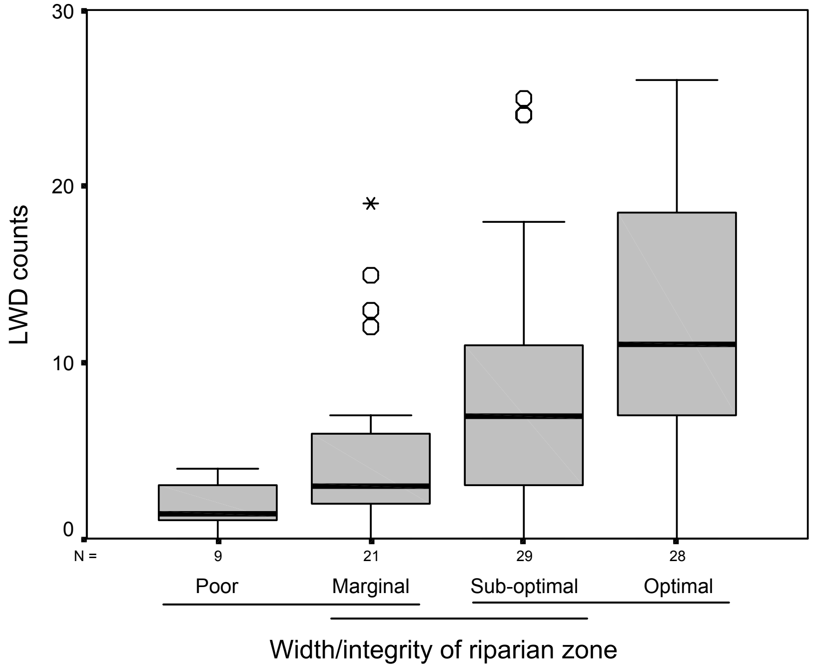

Figure 3.39 Comparison of LWD counts at sites as grouped by riparian zone conditions (N is number of sites, lines show groups not significantly different by Tukey's test, α = 0.05, see Figure 3.14 for box plot description).

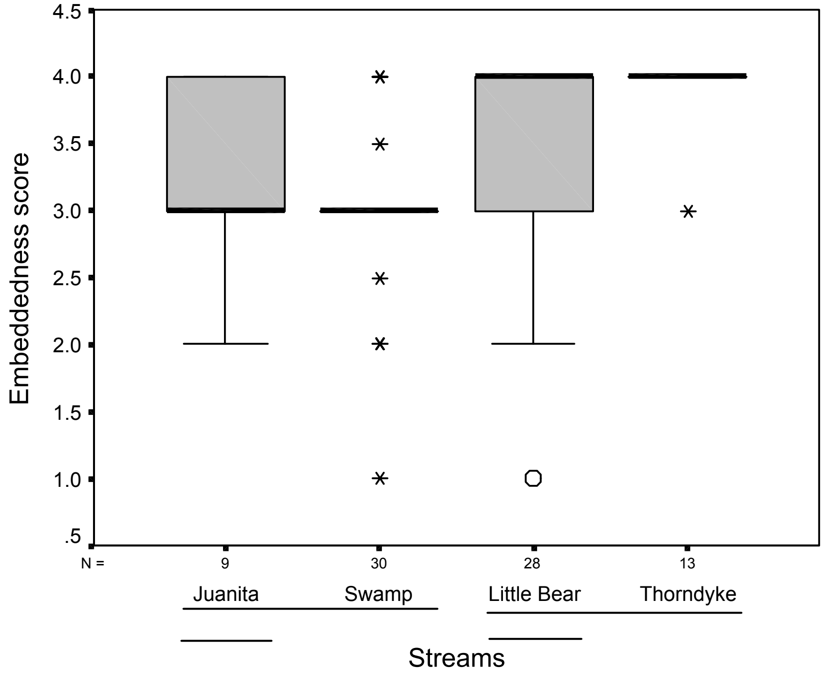

Figure 3.40 Comparison of embeddedness scores by study stream (N is number of sites, lines show streams not significantly different by Dunn's test, α = 0.05, see Figure 3.14 for box plot description).

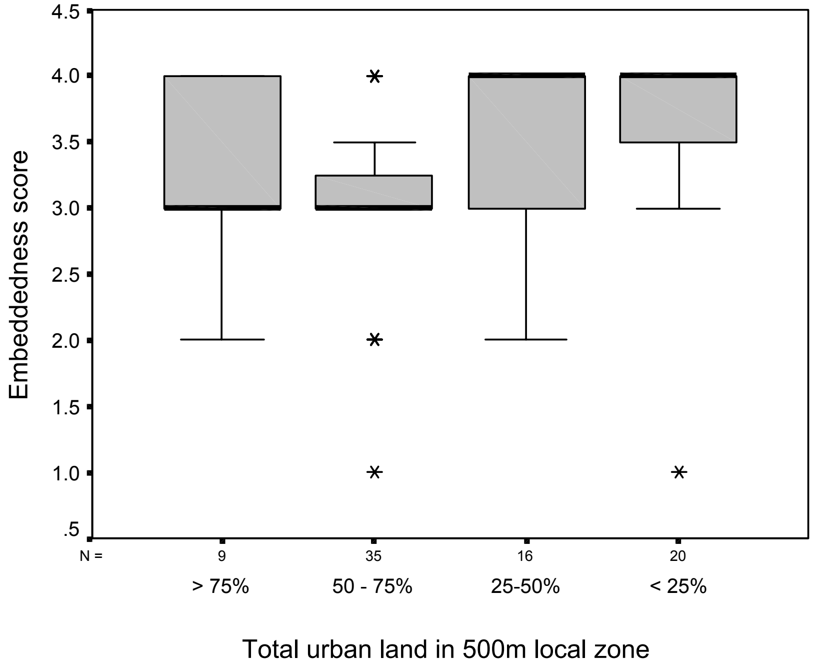

Figure 3.41 Comparison of embeddedness scores by local percent urban land (N is number of sites, only the categories 50-75% and <25% are significantly different by Dunn's test, α = 0.05, see Figure 3.14 for box plot description).

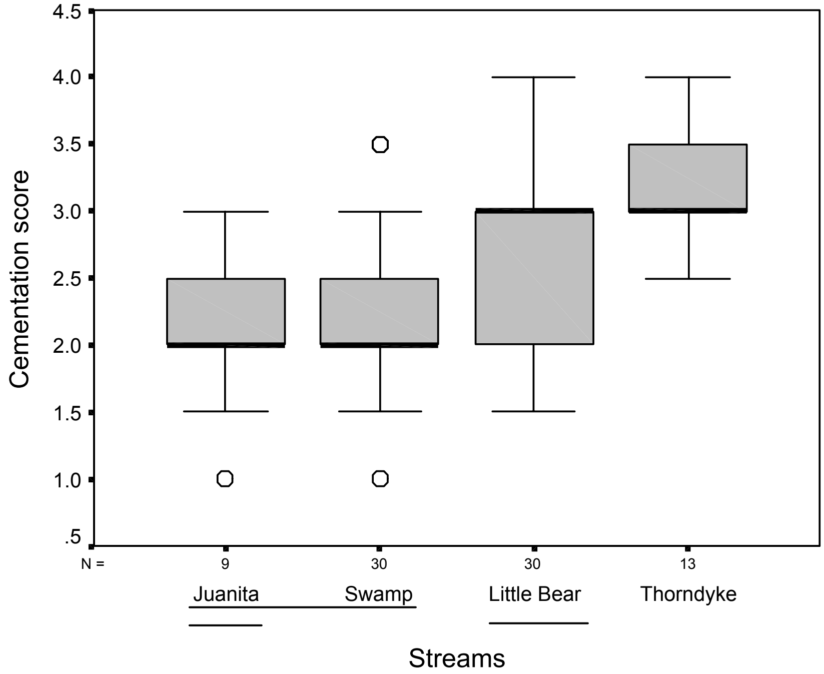

Figure 3.42 Comparison of cementation scores by study stream (N is number of sites, lines show streams not significantly different by Dunn's test, α = 0.05, see Figure 3.14 for box plot description).

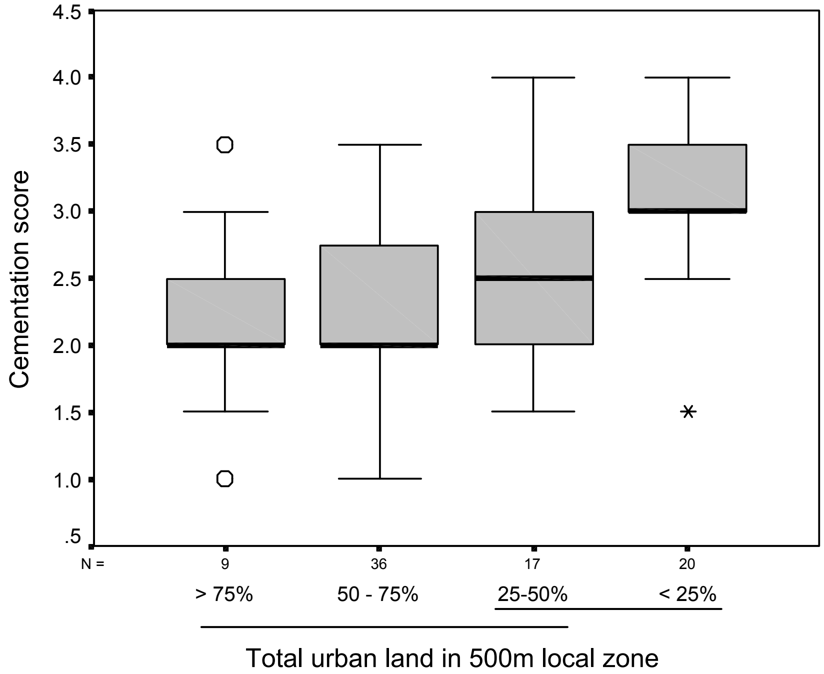

Figure 3.43 Comparison of cementation scores by local percent urban land (N is number of sites, lines show groups not significantly different by Dunn's test, $\alpha = 0.05$, see Figure 3.14 for box plot description).

Figure 3.44a Juanita Creek reach. PSCI = 9.

Figure 3.44b Juanita Creek reach. PSCI = 15.5.

Figure 3.44c Thorndyke Creek reach. PSCI = 20.5.

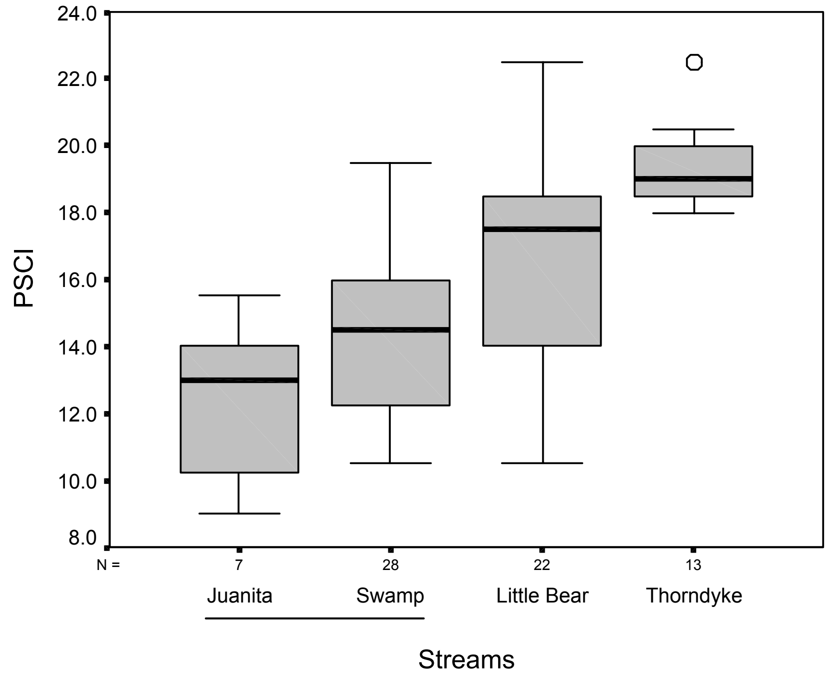

Figure 3.45 Comparison of PSCI scores by study stream (N is number of sites, line shows streams not significantly different by Tukey's test, α = 0.05, see Figure 3.14 for box plot description).

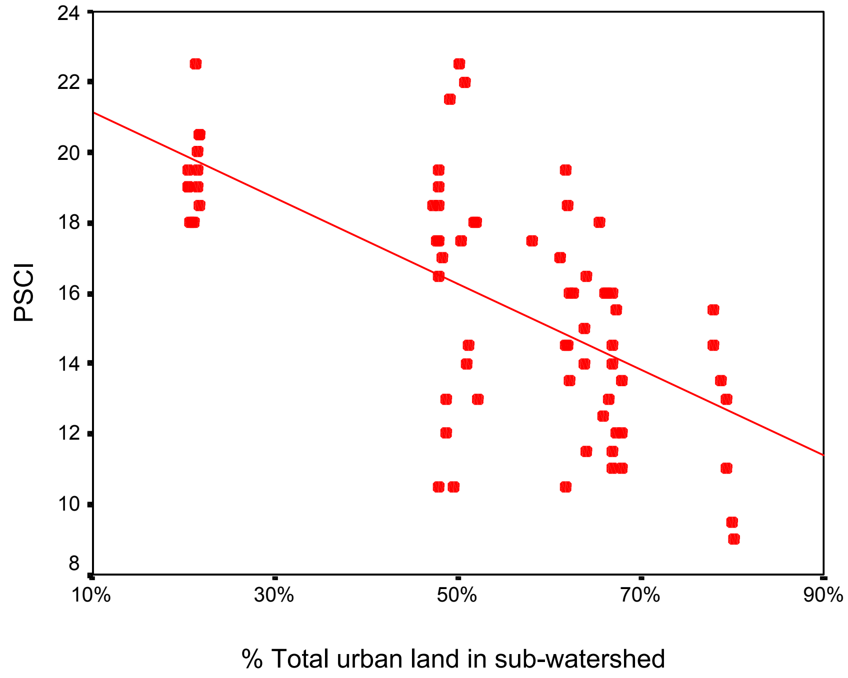

Figure 3.46 Regression of PSCI against percent total urban land in the sub-watershed zone.

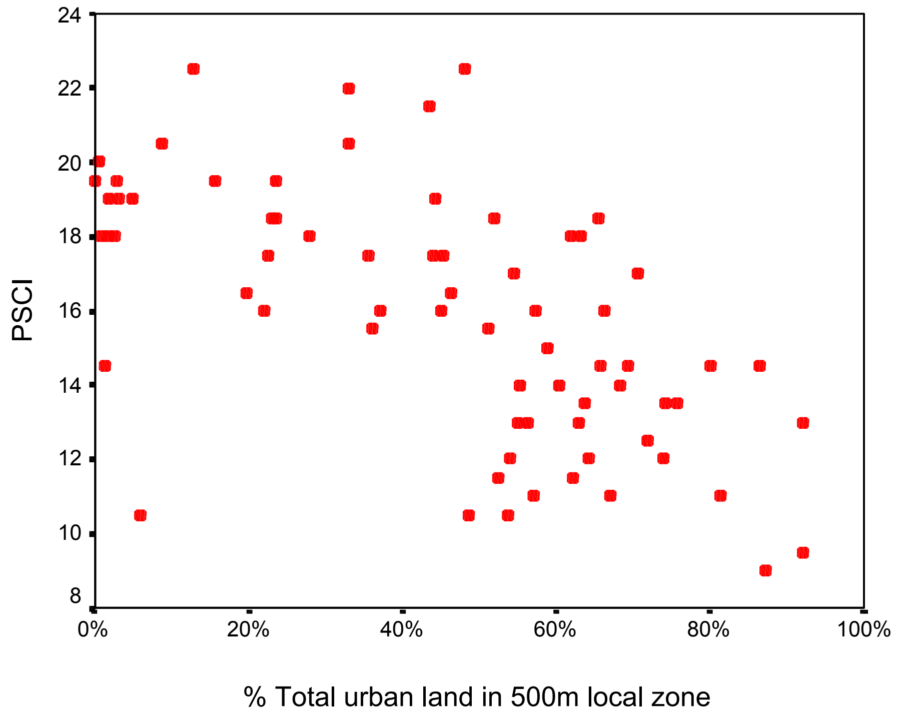

Figure 3.47 Regression of PSCI against percent total urban land in the 500-m local zone.

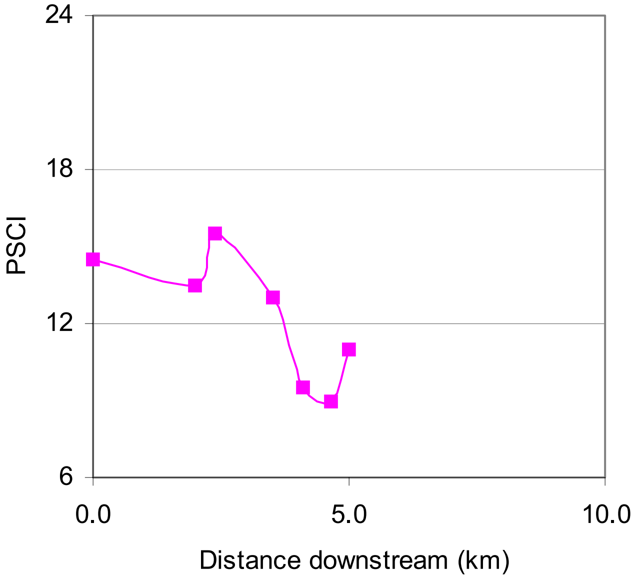

Figure 3.48 PSCI scores along the length of Juanita Creek.

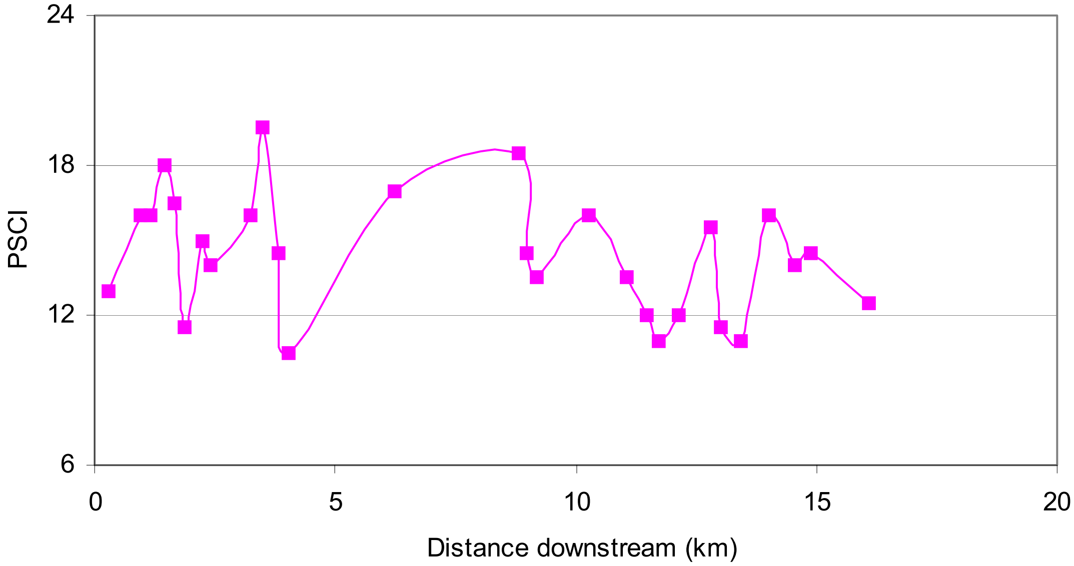

Figure 3.49 PSCI scores along the length of Swamp Creek.

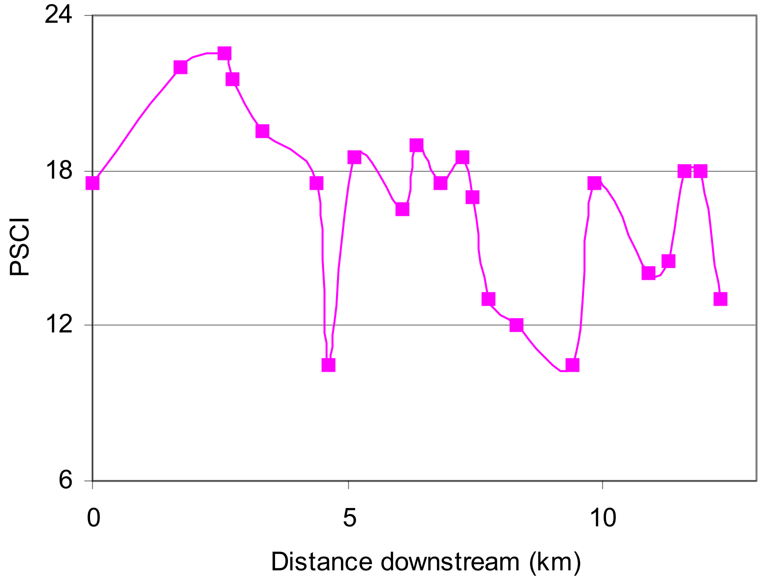

Figure 3.50 PSCI scores along the length of Little Bear Creek.

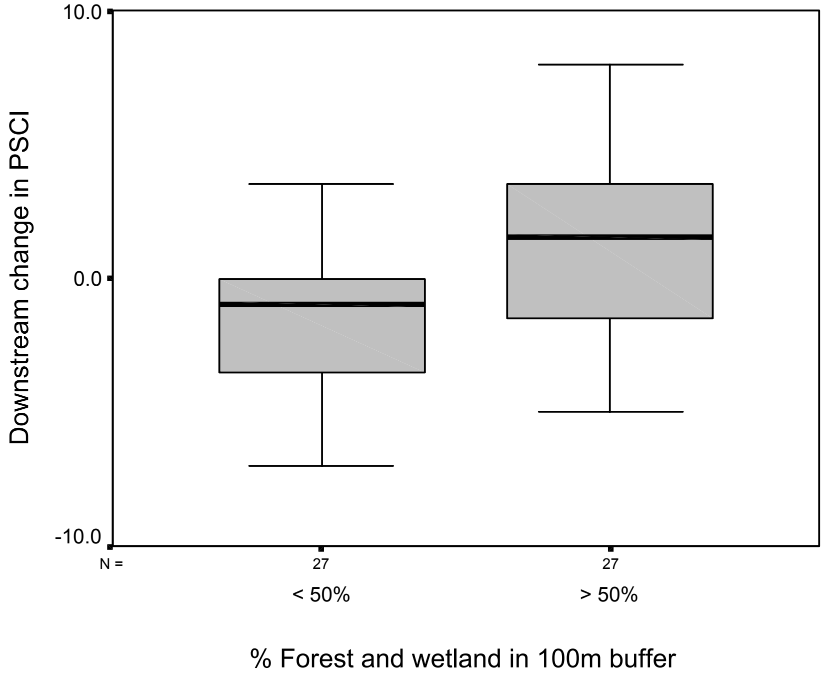

Figure 3.51 Comparison of Δ PSCI and percent forested buffer between consecutive sites (Significantly different by t test, unequal variance, p = 0.002, see Figure 3.14 for box plot description).

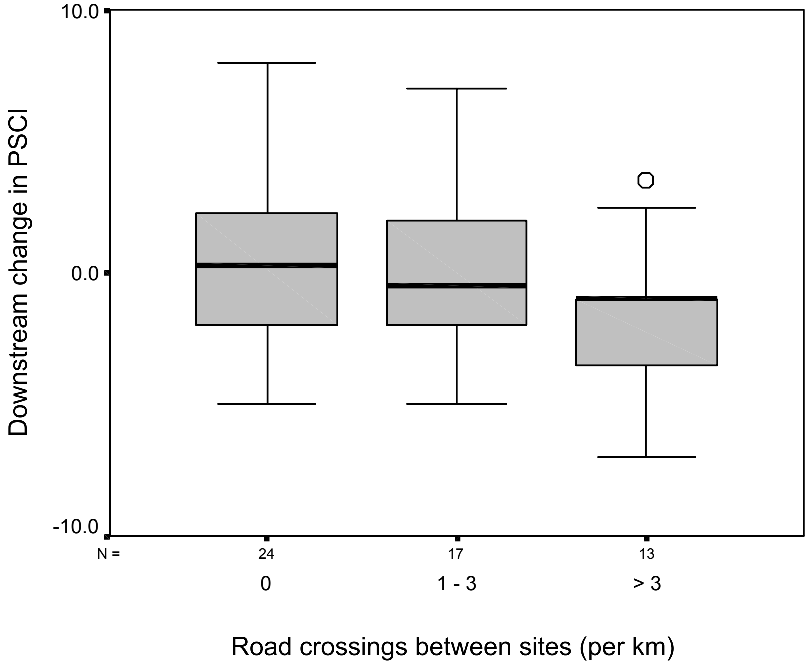

Figure 3.52 Comparison of Δ PSCI and number of road crossings between consecutive sites (The two extreme groups are significantly different by t test, unequal variances, p = 0.09, see Figure 3.14 for box plot description).

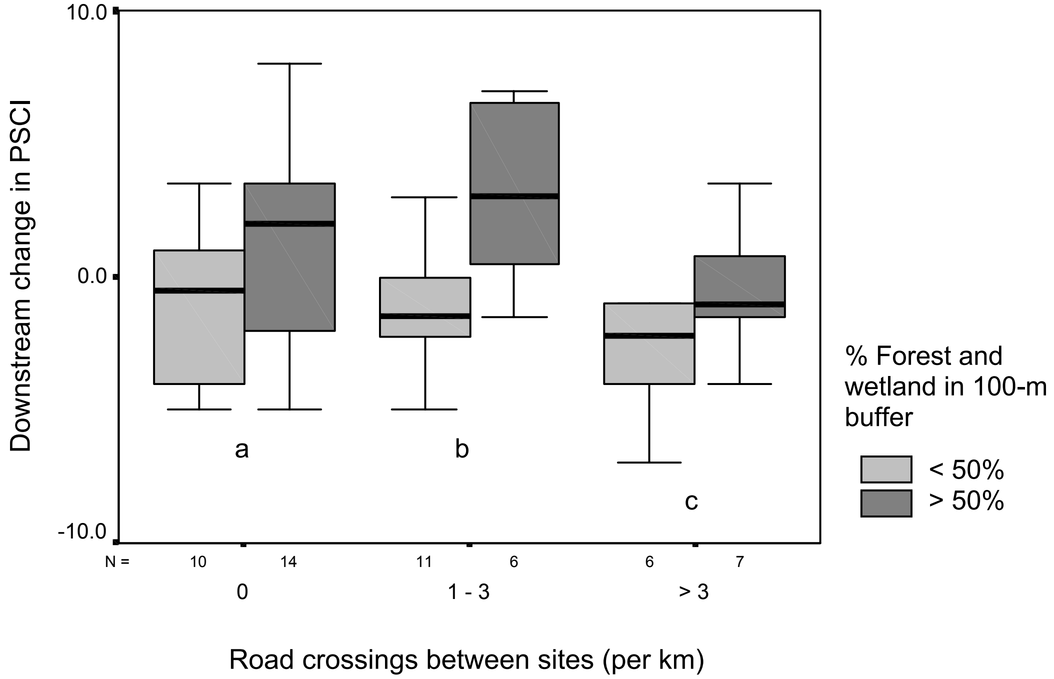

Figure 3.53 Multiple comparison of Δ PSCI with number of road crossings and percent forested buffer (t tests, unequal variance, a: p = 0.08, b: p = 0.03, c: p = 0.10, see Figure 3.14 for box plot description).

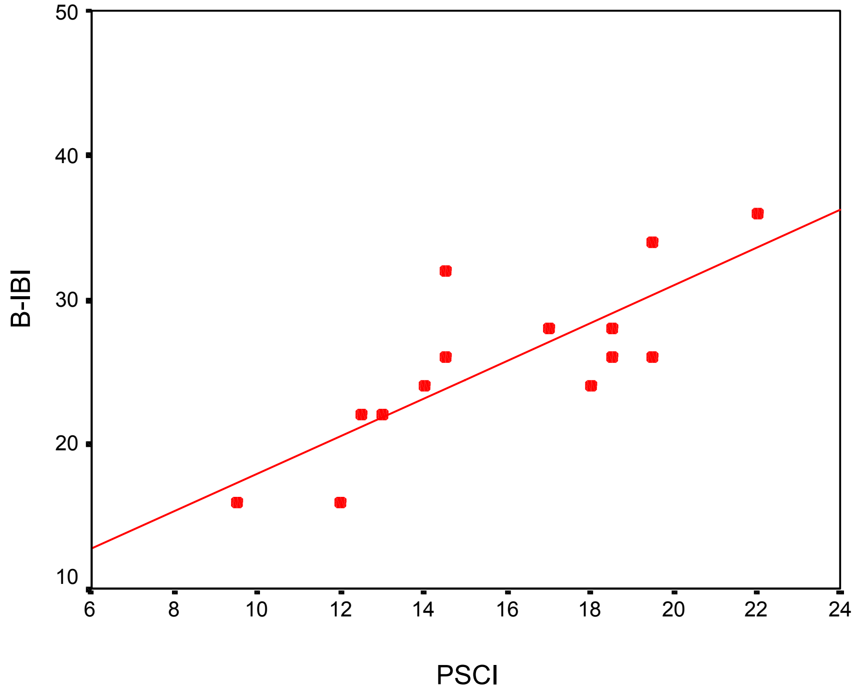

Figure 3.54 Regression of B-IBI against PSCI.

Table 3.1 Correlations of embeddedness measures.

Method 1	Method 2	r_s	p	n
Embeddedness rank	% fines in riffle	0.413	< 0.001	78
Embeddedness rank	% of particles embedded	0.606	< 0.01	20

r_S: Spearman's rank correlation coefficient

Table 3.2 Range of data for each predictor variable of the regression model (4).

Variable	Description	Minimum	Median	Maximum
U_S (%)	Paved and grass urban land in sub-watershed	9%	22%	44%
U_L (%)	Paved and grass urban land in 500-m local zone	0%	18%	69%
D (km)	Upstream distance to closest road crossing	0.1	0.5	5.0

Table 3.3 Comparison of Δ PSCI using various thresholds of percent forest land in the buffer.

% Forest and wetland land in buffer[1]	< 20%	> 20%	< 35%	> 35%	< 50%	> 50%	< 65%	> 65%	< 80%	> 80%
n	5	49	17	37	27	27	37	17	44	10
Mean Δ PSCI	-0.2	-0.2	-1.7	0.5	-1.5	1.2	-0.5	0.7	-0.3	0.6
p value[2]	0.973		0.015		0.002		0.224		0.510	

[1] Buffer zone is 100-m wide and the portion between consecutive sites

[2] t test results, unequal variance

4. Discussion

The results can be summarized into six key points:

- The assessed urban streams do not have uniform physical and geomorphic conditions throughout their mainstem channels. Local in-stream physical attributes are heterogeneous and are a function of the geomorphic context, the urbanization of the watershed, and the landscape conditions at the local scale.
- The physical stream conditions index (PSCI) functions well as a general measure of the physical and geomorphic integrity in streams, responding in an intuitively reasonable and statistically significant manner to gradients of urbanization.
- The quantity, location, and distribution of urbanization can be successfully quantified with relatively simple, GIS-based landscape metrics.
- Landscape metrics provide explanatory power to both individual physical in-stream attributes and the PSCI.
- Longitudinal trends in the PSCI scores show that partial recovery of physical conditions is possible when a degraded stream flows through an intact forested riparian buffer without road crossings.
- The implications of this study for the management of urban streams are that both watershed land use planning and the preservation of uninterrupted forested riparian zones are crucial to maintain functioning stream ecosystems.

Heterogeneity in physical stream conditions

Several of the evaluated physical attributes varied considerably between and within each study stream. Variability in physical stream conditions was greatest for Little Bear Creek and Swamp Creek, whereas conditions in Thorndyke and Juanita creeks were more homogenous. The modest longitudinal variation seen in Thorndyke Creek is most likely an expression of the natural variability in stream systems, because the geomorphic setting was uniform and there was little apparent human activity that might otherwise cause differences between sites. In contrast, the larger variations in conditions measured in the two watersheds with moderate levels of urbanization suggest that factors functioning primarily at a local scale can influence the ecosystem of an urban stream.

The minimal variability that was seen in Juanita Creek could be explained by two scenarios: 1) even favorable local factors (i.e. riparian forests) may be overwhelmed by the overall urbanization of the watershed, or 2) detrimental local factors (i.e. road crossings) may become so abundant as to impose uniformly degraded conditions. Only one site on Juanita Creek had a wide intact forested buffer (Edith Moulton Park), which precluded rigorous testing of the first scenario with this data set. This particular site did have better physical conditions than its closest upstream and downstream neighbors; however, the improvement was modest (∆ PSCI = 2). Results from this watershed are consistent with the second scenario, in that this highly urbanized watershed does have highly urbanized local zones (Figure 3.26). With the exception of the site in Edith Moulton Park, which is 80% urban in the sub-watershed and only 50% urban in the local zone, all of the Juanita sites have between 75% to 90% urban land in their local zones. This range in amount of urban land in the local zones is much narrower than that in the moderately urbanized watersheds.

The geomorphic context strongly influenced some of the physical attributes of these four streams. Their similar bed morphology, local channel gradient, median sediment size, and longitudinal profile shape were partly a consequence of the initial criteria used for the selection of watersheds, and also due in part to the shared geologic history of the Puget Sound Lowland region. Interestingly, Thorndyke Creek's longitudinal profile was considerably smoother and more concave than the urban streams, which were interrupted by flat and convex segments. These irregularities may be a result of urbanization via an impact yet unexplored, or, perhaps, may be evidence of a series of migrating knickpoints responding to the lowering of Lake Washington in 1917 (Willingham, 1992). The change in lake elevation would have affected the three urban streams but not Thorndyke Creek.

Physical stream conditions index

The PSCI effectively integrates a variety of qualitative attributes that *are* strongly influenced by urbanization into a meaningful, quantitative score. It correlates well with the B-IBI, an index that has been proven to respond to a gradient of urbanization, indicating levels of degradation to aquatic biota (Figure 3.54; Karr and Chu, 1999; Morley, 2000). Perfect correlation between these two indices should not be expected because the B-IBI responds to changes in multiple factors that affect aquatic systems, whereas the PSCI provides direct and indirect measurement of only two: the physical habitat structure and flow regime. The PSCI also correlates well with the proportion of urban land in the sub-watershed and local zones (Figures 3.46, 3.47). The PSCI appears to be a useful index, responsive to the effects of urbanization; to further evaluate the utility and robustness of the PSCI, it should be validated with another sampling effort.

The utility of the PSCI in assessing the physical condition of streams is also suggested by its relatively good precision. The error in the PSCI due to natural variability and observer imprecision is most likely on the order of +/- 2 score points. All but one of the reaches from the reference stream had PSCI scores within a 3-point range, and 50% of the reaches had scores within a 2-point range. Thorndyke Creek is not a pristine reference stream, and it probably has some variability in conditions due to logging activity in its watershed; however, it provides the best available estimate of the inherent error in the PSCI to solely measure the stream's response to urbanization. The intrinsic variability (i.e. variability not attributable to urbanization) is partially a function of natural heterogeneity, especially in stream channel size (Knighton, 1998) and in LWD abundance (Naiman et al., 1998). The 2-point error bracket also includes the error associated with inaccurate or inconsistent assignment of ranks for the qualitative parameters.

The applicability of the PSCI may be limited, however, by the geographic and stream sampling scope of this study. This index could be used in most other Puget Sound Lowland small-order (1st – 3rd order) streams without much hesitation. Applying the PSCI beyond this region or in larger order streams would not be recommended without first testing its applicability. That said, most of the PSCI's components are physical attributes that show a common response to urbanization in other parts of this country and the world (Neller, 1988; Galli,1996; Roth et al., 1996; Trimble, 1997; Pizzuto et al., 2000).

Measuring urbanization

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 gross measures of urbanization, such as percent total impervious area in the contributing watershed. The urbanization of the local zone (another “magnitude” metric) and the proximity to road crossings (a “connectivity” metric) 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. Although not useful for better understanding of stream conditions, these relationships between landscape metrics do provide insight to the nature of the urban landscape.

Two land-cover metrics, those of the sub-watershed and of the buffer zones, are strongly positively correlated (Figure 3.24): with a more urbanized watershed, less forested land is likely to remain in the riparian buffer. Yet the correlation between sub-watershed and buffer-zone urban land is not one-to-one. The proportion of urban land is consistently less in the buffer zones than in the sub-watershed zones (by about 10%), indicating that a smaller proportion of land has been developed in the riparian buffers of these three urban streams than in the watershed as a whole.

“Connectivity,” as measured by two of the three metrics presented here, is clearly not an independent variable in the urban landscape. One of the metrics, road density, closely parallels the quantity of urban land in a sub-watershed (Figure 3.27); increasing urbanization leads to an increasing number of pathways connecting stormwater to urban streams. Median flow path length, the second measure of connectivity evaluated, was also not particularly informative. This metric had little variability, implying that urban land is fairly evenly spread throughout the sub-watersheds. None of the sub-watersheds have urban land that was clustered considerably farther away from the stream channel, a situation that might have lessened the impact of urban development on a stream’s ecosystem. The sub-watersheds of Juanita Creek have slightly longer median path lengths, but this probably is a result of the watershed’s more equant shape, tending to yield longer median flow path lengths.

Other studies have found connectivity to be a more important and influential factor than found in this study. 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 spatial configuration, connectedness, and conveyance of those impervious areas. These researchers have also demonstrated the importance of connectivity in a modeling effort of the Goodwin Creek watershed in Mississippi (Bledsoe and Watson, 2001). Two watershed scenarios were simulated, one with connected impervious areas and one with disconnected impervious areas. The results showed that connected impervious areas clearly increased peak flow magnitude in the range of 32% to 109%, depending on spatial configuration and model parameters (Bledsoe and Watson, 2001). The land cover distribution was imposed in this study, however, and not based on actual land cover images from urban areas.

Conceptually, the connectivity of urban land is an important variable in urban streams. There are two possible reasons why the connectivity metrics used here failed to provide further explanation of stream conditions. One reason is that connectivity is positively correlated with the proportion of urban land. Highly urbanized watersheds with low connectivity may not exist, and, therefore, we cannot test for connectivity effects independently unless we simulate watersheds (as in Bledsoe and Watson, 2001). However, such simulated watersheds may have no counterparts in reality, undermining the utility of this type of modeling effort.

Another plausible reason is a lack of adequate data. Estimating connectivity with road density or with median flow path length based on 30-m Landsat land cover data may be too coarse of a representation. If spatial data of stormwater infrastructure were readily available with consistent coverage throughout the study watersheds, connectivity might be more accurately and precisely measured.

In contrast, one connectivity metric, the distance upstream from the sampling site to the nearest road crossing, did prove useful. The PSCI was higher for sites that were farther from an upstream road crossing. This connectivity metric is different from the other two in that it measures how “connected” a particular segment of stream is to the closest urban land, whereas the other connectivity metrics try to estimate the overall connectivity of urban land in the sub-watershed as a whole. This connectivity metric may be more relevant and useful because it is a single, specific measure, not a lumped measure attempting to describe an attribute of the entire sub-watershed.

Landscape metrics as predictor variables

The results suggest that physical stream conditions are impacted by urbanization in both the sub-watershed and in the local zone to equivalent degrees. Most of the individual physical attributes degraded with increasing urbanization in the local zone, and they also tended to be more degraded in the more urbanized watersheds, specifically Juanita and Swamp creeks. The regression of PSCI against sub-watershed and local zone urban land revealed that these independent landscape metrics also contributed equally to the prediction of the PSCI score (see Appendix B).

Many studies have tried to determine what portion of the landscape is most influential to stream integrity. Identifying the most influential zone is important, so that managers can strategize and prioritize efforts that aim to rehabilitate or protect stream systems. Although watershed conditions are undeniably influential, many studies have identified a disproportionate influence of the local or riparian zone (Steedman, 1988; Lammert, 1995; Davis, 1998; Naiman et al., 1998). Similar to my findings, the B-IBI scores of several Puget Sound streams were found to be equally well predicted by urbanization in the watershed and by urbanization in the local area (Morley, 2000). In a study of stream health in larger urbanized watersheds (~1000 km^2), the 10-100 km^2 of drainage watershed immediately above a sampling station was most important in predicting stream quality (Steedman, 1988). In contrast to my findings, however, another study using indices of habitat quality and biological integrity attributed significantly greater importance to watershed land use than the local or riparian land use (Allan et al., 1997).

Determining which landscape zone is of greatest influence to a stream is problematic. One major problem is the fact that study design can greatly influence which scale is deemed the most important. Studies that sample several independent watersheds with one or two sites per watershed are best-suited to detect watershed-wide effects, whereas studies that sample several sites per watershed are more likely to identify local effects (Allen et al., 1997). A study of 23 sites in seven tributaries of the Raisin River basin in Michigan determined that a habitat index and an index of biological integrity (IBI) correlated best with land use in the sub-watershed (Roth et al., 1996). Additionally, their correlations became progressively weaker as the spatial scale was reduced to more local scales. In complete contrast, another study in the same region observed that only local riparian conditions were significant predictors of a habitat index and an IBI (Lammert, 1995). Although my study sampled about 10 to 30 reaches per stream in four watersheds, the local and sub-watershed zones were found to be equally important. Because the four watersheds span such a large range in urban land cover, the effect of sub-watershed land cover on the measured attributes is reinforced.

The overarching result of this study is the equivalent importance of the sub-watershed and local zones in determining physical stream condition. Given no urbanization in the local zone, physical condition is primarily dictated by urbanization of the sub-watershed. With an increasingly greater proportion of urban land in the local zone for a set level of sub-watershed urbanization, physical conditions progressively degrade. This is an expected result because several of the components of the PSCI (cross-sectional area, bank stability, embeddedness, and cementation) are greatly influenced by transport capacity and sediment supply, driving forces primarily determined at the watershed scale, while LWD abundance and stream complexity are components more influenced by the local riparian zone. The effect of sub-watershed urbanization at setting an upper bound to the physical integrity of streams is similar to the upper bound seen in the relationship with biological integrity (Figure 1.5; Booth et al., 2001). The proportion of paved urban and grass urban land in the sub-watershed and local zones were the most significant metric, which is understandable because these two urban land cover categories have the greatest proportions of impervious surfaces (Table 2.6). Additionally, those surfaces are more likely to be effective impervious surfaces because areas classified as paved or grass urban tend to be intensely developed and so likely have the most efficient stormwater drainage. These areas also have the least potential for stormwater infiltration, simply due to their high proportion of impervious surfaces.

In sum, GIS-based analysis of urban watersheds provides some but not all of the explanation of the physical and biological conditions in streams. The R^2 values of the various regression models tested suggest that approximately half of the variability in conditions 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 in-stream assessments. Both GIS-based analysis and in-stream assessments of physical or biological conditions are required to best understand any particular stream system.

Downstream recovery

Results substantiate the important role of the local zone, including its ability to promote downstream recovery of physical stream conditions. One variable in the regression model suggests that degradation to the in-stream physical conditions is most severe in close proximity to a road crossing and becomes less severe with increasing downstream distance from a road. The portion of the analysis that explored the change in PSCI between consecutive sites (Δ PSCI) helped clarify where downstream recovery was possible. Where the segment of stream between consecutively sampled sites had an uninterrupted forested buffer, a larger improvement in PSCI score occurred than for those without such a buffer. Sites with roads and developed land between them tended to decrease in PSCI score. The results from the series of t tests of the effect various proportions of forested land in the riparian buffer on Δ PSCI suggest that the buffer must be at least 35% to 50% forested to be beneficial to physical conditions.

There are several possible recovery processes acting along a stream channel that have effects on a stream's physical components. Undeveloped riparian zones in the Puget Sound Lowlands typically have active floodplains and stream-side 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 successfully diminished, stream reaches will experience less enlargement of their channels, resulting in more stable stream beds and banks. If forested riparian zones and wetlands can significantly slow peak flows and temporarily store stormwater, 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. This process would definitely improve two components of the PSCI, the embeddedness and cementation of riffles. An intact forested riparian zone also allows the recruitment of LWD and inhibits direct anthropogenic impacts, such as channel straightening or stream bank armoring, efforts often used in developed areas to protect stream-side land or structures.

Management implications

The results of this study have specific management implications. The amount of development in a watershed is extremely influential to 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 would be inadequate. Local land cover is extremely important to physical stream conditions, with either advantageous or disadvantageous effects depending on its makeup, and therefore this zone of the watershed should also have high priority and considerable attention in matters of planning and the establishment of regulations. Finally, the results suggest hope for degraded urban streams. If riparian buffers can be reforested and road crossings eliminated in certain reaches of streams, partial but still substantive recovery of a stream's physical integrity is possible.

5. Conclusion

Urbanization of both the entire contributing watershed and the part of the watershed closest to the stream appear to have equal weight in influencing a stream's physical conditions. This result has important management implications. Urbanization in the watershed is highly influential to streams and likely sets a maximum attainable best condition; local urbanization can considerably exacerbate the effect. If management strategies can restrict development in areas adjacent to streams and limit road crossings (and any other point sources of stormwater discharge), a stream's physical attributes can achieve the best condition for a given level of watershed urbanization. Otherwise, even greater degradation is possible.

The design of this study allowed for the assessment of longitudinal trends in physical stream conditions. Physical conditions can improve downstream from degraded stream reaches if the riparian zone is substantially forested and devoid of road crossings. Stream rehabilitation efforts that reforest the riparian buffer, even along short reaches, and/or remove the physical and hydraulic connections to urban disturbance via road crossings, have the potential to significantly improve physical conditions in moderately urbanized streams. With greater amounts of urbanization in a watershed, the beneficial influence of the local riparian zone apparently diminishes. For example, when highly urbanized Juanita Creek flows through a predominantly forested local zone the improvement in physical stream conditions index (PSCI) score is modest at best.

The results also highlight the usefulness of several methodologies utilized 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. The GIS-based analysis generated several landscape metrics that better described the quantity, location, and distribution of urban land in the study watersheds. These metrics provided insight into the nature of local urban landscapes and explained much of the variability in individual physical stream attributes and in the PSCI scores.

The findings of this study invite further questions. How much urban land in the watershed will overwhelm the beneficial effects of near-stream land use to the point where rehabilitation of the riparian zone or local channel site would produce no discernable effects? What length of intact riparian buffer is necessary to permit downstream recovery? How “intact” does the riparian buffer have to be to produce beneficial effects? What width of buffer or size of the local zone envelopes the area most influential to reach-scale physical conditions? Answering these questions would necessitate a study to explore multiple spatial scales in a larger set of watersheds, spanning a range of urbanization.

In sum, with better information on the interaction of urbanization and stream ecosystems, we should be able to improve policies and management strategies for protecting stream integrity in developing areas. Hopefully with more robust knowledge, like that provided by this study, we can mold our landscapes to preserve those streams or stream segments that still function, and we can target rehabilitation to those degraded portions of streams that have realistic chances for improvement.

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Appendix A. Regression results of cross-sectional area with various landscape metrics.

Independent variables		Adjusted R^2	F	p	Standardized coefficients	p	VIF*
Zone	Metric						
Sub-watershed	Area (km^2)	N/A	N/A	N/A			
Sub-watershed	Paved urban land (%)					0.90	
Sub-watershed	Area (km^2)	N/A	N/A	N/A			
Sub-watershed	Paved & grass urban land (%)					0.27	
Sub-watershed	Area (km^2)	N/A	N/A	N/A			
Sub-watershed	Total urban land (%)					0.14	
Sub-watershed	Area (km^2)	N/A	N/A	N/A			
Local (500 m)	Paved urban land (%)					0.43	
Sub-watershed	Area (km^2)	0.65	67.82	< .0005	0.759	< 0.0005	1.05
Local (500 m)	Paved & grass urban land (%)				0.167	0.02	1.05
Sub-watershed	Area (km^2)	N/A	N/A	N/A			
Local (500 m)	Total urban land (%)					0.15	
Sub-watershed	Area (km^2)	N/A	N/A	N/A			
Local (1 km)	Paved urban land (%)					0.56	
Sub-watershed	Area (km^2)	0.66	72.00	< .0005	0.755	< 0.0005	1.04
Local (1 km)	Paved & grass urban land (%)				0.203	0.01	1.04
Sub-watershed	Area (km^2)	0.64	66.19	< .0005	0.786	< 0.0005	1.00
Local (1 km)	Total urban land (%)				0.145	0.04	1.00

* Variance inflation factor indicates severity of multicollinearity between predictor variables.
When VIF is greater than 10, multicollinearity unduly influences the regression model (Neter et al., 1996).

Appendix B. Regression results of PSCI with various landscape metrics.

	Independent variable(s)		Adjusted R^2	F	p	Standardized coefficients	p	VIF*
	Zone	Metric						
Simple regressions	Sub-watershed	Paved urban land (%)	0.19	17.03	<0.0005	N/A	N/A	N/A
		Paved & grass urban land (%)	0.32	33.37	<0.0005	N/A	N/A	N/A
		Total urban land (%)	0.41	49.45	<0.0005	N/A	N/A	N/A
	Local (500 m)	Paved urban land (%)	0.08	6.75	0.011	N/A	N/A	N/A
		Paved & grass urban land (%)	0.36	39.06	<0.0005	N/A	N/A	N/A
		Total urban land(%)	0.36	39.78	<0.0005	N/A	N/A	N/A
	Local (1 km)	Paved urban land (%)	0.07	6.48	0.013	N/A	N/A	N/A
		Paved & grass urban land (%)	0.31	32.24	<0.0005	N/A	N/A	N/A
		Total urban land (%)	0.35	38.60	< 0.0005	N/A	N/A	N/A
Multiple regressions (2 predictor variables)	Sub-watershed	Paved urban land (%)	0.30	15.95	< 0.0005	-0.485	< 0.0005	1.01
	Local (500 m)	Paved urban land (%)				-0.352	0.001	1.01
	Sub-watershed	Paved urban land (%)	0.49	34.21	< 0.0005	-0.378	< 0.0005	1.02
	Local (500 m)	Paved & grass urban land (%)				-0.557	< 0.0005	1.02
	Sub-watershed	Paved urban land (%)	0.44	27.64	< 0.0005	-0.300	0.002	1.09
	Local (500 m)	Total urban land (%)				-0.523	< 0.0005	1.09
	Sub-watershed	Paved & grass urban land (%)	0.42	26.36	< 0.0005	-0.593	< 0.0005	1.00
	Local (500 m)	Paved urban land (%)				-0.334	0.001	1.00
	Sub-watershed	Paved & grass urban land (%)	0.52	38.38	< 0.0005	-0.431	< 0.0005	1.10
	Local (500 m)	Paved & grass urban land (%)				-0.474	< 0.0005	1.10
	Sub-watershed	Paved & grass urban land (%)	0.44	28.59	< 0.0005	-0.354	0.001	1.37
	Local (500 m)	Total urban land (%)				-0.424	< 0.0005	1.37
	Sub-watershed	Total urban land (%)	0.45	29.24	< 0.0005	-0.619	< 0.0005	1.02
	Local (500 m)	Paved urban land (%)				-0.214	0.02	1.02
	Sub-watershed	Total urban land(%)	0.50	36.05	< 0.0005	-0.459	< 0.0005	1.37
	Local (500 m)	Paved & grass urban land (%)				-0.365	< 0.0005	1.37

Appendix B. Regression results of PSCI with various landscape metrics.

	Independent variable(s)		Adjusted R^2	F	p	Standardized coefficients	p	VIF*
	Zone	Metric						
Multiple regressions (2 predictor variables)	Sub-watershed	Total urban land(%)	0.44	28.09	< 0.0005	-0.441	0.002	2.23
	Local (500 m)	Total urban land(%)				-0.280	0.04	2.23
	Sub-watershed	Paved urban land (%)	0.28	14.32	< 0.0005	-0.461	< 0.0005	1.00
	Local (1 km)	Paved urban land (%)				-0.315	0.003	1.00
	Sub-watershed	Paved urban land (%)	0.43	26.66	< 0.0005	-0.355	< 0.0005	1.04
	Local (1 km)	Paved & grass urban land (%)				-0.501	< 0.0005	1.04
	Sub-watershed	Paved urban land (%)	0.43	26.47	< 0.0005	-0.295	0.003	1.10
	Local (1 km)	Total urban land (%)				-0.514	< 0.0005	1.10
	Sub-watershed	Paved & grass urban land (%)	0.42	25.83	< 0.0005	-0.591	< 0.0005	1.00
	Local (1 km)	Paved urban land (%)				-0.326	0.001	1.00
	Sub-watershed	Paved & grass urban land (%)	0.48	32.58	< 0.0005	-0.437	< 0.0005	1.11
	Local (1 km)	Paved & grass urban land (%)				-0.427	< 0.0005	1.11
	Sub-watershed	Paved & grass urban land (%)	0.43	27.33	< 0.0005	-0.351	0.002	1.41
	Local (1 km)	Total urban land (%)				-0.412	< 0.0005	1.41
	Sub-watershed	Total urban land (%)	0.45	29.55	< 0.0005	-0.622	< 0.0005	1.02
	Local (1 km)	Paved urban land (%)				-0.220	0.017	1.02
	Sub-watershed	Total urban land (%)	0.49	33.69	< 0.0005	-0.488	< 0.0005	1.32
	Local (1 km)	Paved & grass urban land (%)				-0.326	0.002	1.32
	Sub-watershed	Total urban land(%)	0.43	27.10	< 0.0005	-0.455	0.002	2.44
	Local (1 km)	Total urban land(%)				-0.252	0.08	2.44
	Sub-watershed	Paved & grass urban land (%)	0.38	18.08	< 0.0005	-0.396	< 0.0005	1.00
	Local (1 km)	Paved & grass urban land (%)				-0.508	< 0.0005	1.00

Appendix B. Regression results of PSCI with various landscape metrics.

Independent variable(s)			Adjusted R^2	F	p	Standardized coefficients	p	VIF*
	Zone	Metric						
Multiple regressions (3 predictor variables)	Sub-watershed	Paved & grass urban land (%)	N/A	N/A	N/A			
	Local (500 m)	Paved & grass urban land (%)						
	Sub-watershed	Road density					0.40	
	Sub-watershed	Paved & grass urban land (%)	N/A	N/A	N/A			
	Local (500 m)	Paved & grass urban land (%)						
	Local (500 m)	Road density					0.99	
	Sub-watershed	Paved & grass urban land (%)	N/A	N/A	N/A			
	Local (500 m)	Paved & grass urban land (%)						
	Local (1 km)	Road density					0.90	
	Sub-watershed	Paved & grass urban land (%)	N/A	N/A	N/A			
	Local (500 m)	Paved & grass urban land (%)						
	Sub-watershed	Median path length (total urban)					0.43	
	Sub-watershed	Paved & grass urban land (%)	0.41	13.78	< 0.0005	-0.383	0.001	1.00
	Local (500 m)	Paved & grass urban land (%)				-0.474	< 0.0005	1.03
	Sub-watershed	Upstream distance to road				0.210	0.05	1.03

* Variance inflation factor indicates severity of multicollinearity between predictor variables.

When VIF is greater than 10, multicollinearity unduly influences the regression model (Neter et al., 1996).

🟦 These regression models do not include data from Thorndyke Creek.