Urban Stream Rehabilitation in the Pacific Northwest

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ABSTRACT

Our goal in this project has been to develop a robust approach to urban stream rehabilitation, using examples from the Puget Lowland region of western Washington, that blends knowledge from the physical, biological, and social sciences by:

- documenting the consequences of urban development on urban streams;
- understanding the causes of the resulting ecological degradation; and
- using that understanding to evaluate rehabilitation strategies and techniques.

Although stream conditions are not unambiguously correlated with urbanization, the multiple effects of urban development on stream systems make rehabilitation progressively more difficult at progressively greater levels of development. Rehabilitation success is *most* likely in those watersheds with relatively low levels of development that display paradoxically poor biological and/or physical conditions. However, two critical elements in the urban environment are commonly omitted in the pursuit of successful stream rehabilitation:

Hydrologic changes, which are often ignored in both new development and in postdevelopment stream "rehabilitation." Even where drainage regulations apply to new development, they do not achieve genuine mitigation of urban-induced increases in runoff, because the mitigation is focused on hydrologic measures with little or no biological significance. In contrast, annual and inter-annual flow patterns are closely related to in-channel disturbance frequency and biological health and are largely unaffected by traditional hydrologic mitigation.

The actions of people, which affect stream health at multiple scales, particularly via the *local* stream conditions that are overwhelmingly determined by the behavior of streamside neighbors. Their effects are so influential because of their proximity and because they commonly abut most of the length of an urban channel network.

A consequence of our findings is an overall strategy for pursuing effective rehabilitation:

- Recognize and preserve high-quality, low-development watershed areas.
- Aggressively (and completely) rehabilitate streams where recovery of ecosystem elements and processes is possible, likely only in low-development areas with relatively low to moderate levels of ecological health.
- Rehabilitate selected elements of mid-range urban watersheds, where complete recovery is not feasible but where well-selected efforts may yield direct improvement. In general, however, there is little evidence that in-stream projects can reverse even the local expressions of watershed degradation in urban channels.
- Improve the most degraded streams by first analyzing the acute cause(s) of degradation, but recognize that the restoration potential for populations of original instream biota is minimal.
- In the most highly developed watersheds, education and/or community outreach is not just appropriate but crucial.

1 INTRODUCTION

Urban streams of the Pacific Northwest have been altered, and generally degraded, from their natural, pre-urban state. Although the consequences of urbanization are readily visible, easily accessible, and relatively permanent, remarkably little systematic research has been done on the changes in physical, chemical, and biological processes (and their consequences) in these systems during the course of urbanization (Naiman et al. 1995). Even less effort has been made to understand the role of people as unintentional, and often unseen, individual agents of channel and watershed changes. As a result, most efforts at restoring or rehabilitating urban watercourses have little foundation from which to choose promising candidate streams, to determine specific restoration approaches, or to define attainable physical and biological objectives for the completed project. Although *restoration* to a pre-development state is commonly acknowledged as infeasible in the urban landscape, some degree of *rehabilitation* should be possible and, in light of recent Endangered Species Act listings of anadromous salmon and Clean Water Act goals, mandatory.

Our goal is to develop a robust approach to rehabilitation that blends knowledge from the physical, biological, and social sciences by:

- documenting the consequences of urban development on urban streams;
- understanding the causes of the resulting ecological degradation; and
- using that understanding to evaluate rehabilitation strategies and techniques.

We focus on urban systems because people have become the major agent of physical and biological change on the earth's surface and because urbanization is a progressively greater influence on aquatic systems in both spatial extent and intensity. We take a multidisciplinary approach because each element—physical, biological, and social—is a critical factor in stream degradation as well as a source of insight about how to accomplish meaningful protection and restoration goals.

We focus on streams of the Puget Lowland region of western Washington, with the City of Seattle as its geographic and demographic center (Figure 1). Climate is mild and maritime, with three-quarters of the annual rainfall (ca. 1000 mm) falling in the autumn and winter months (October through March). Rainfall intensities are low relative to other temperate regions but days of measurable precipitation are numerous. Freezing temperatures are not common during storms, and well over 90 percent of the precipitation falls as rain or rapidly melting snow.

The topography and geology of the Puget Lowland show only modest variability. The predominant soil, covering about two-thirds of the land surface, derives from weathering of a silty-sandy glacial till, which in undisturbed watersheds produces a strong permeability contrast between the overlying soil and the underlying till. Much of the till underlies the upland plateau of the Lowland, widely expressed at altitudes of about 120-150 m. That plateau is dissected by major river valleys and the arms of Puget Sound, which impose both steep-gradient and low-gradient reaches on the lowland stream channels as they flow off the plateaus, down the incised escarpments, and across the riverine valleys and floodplains. This topography is largely inherited from the last continental glaciation about 15,000 years ago in this area; postglacial

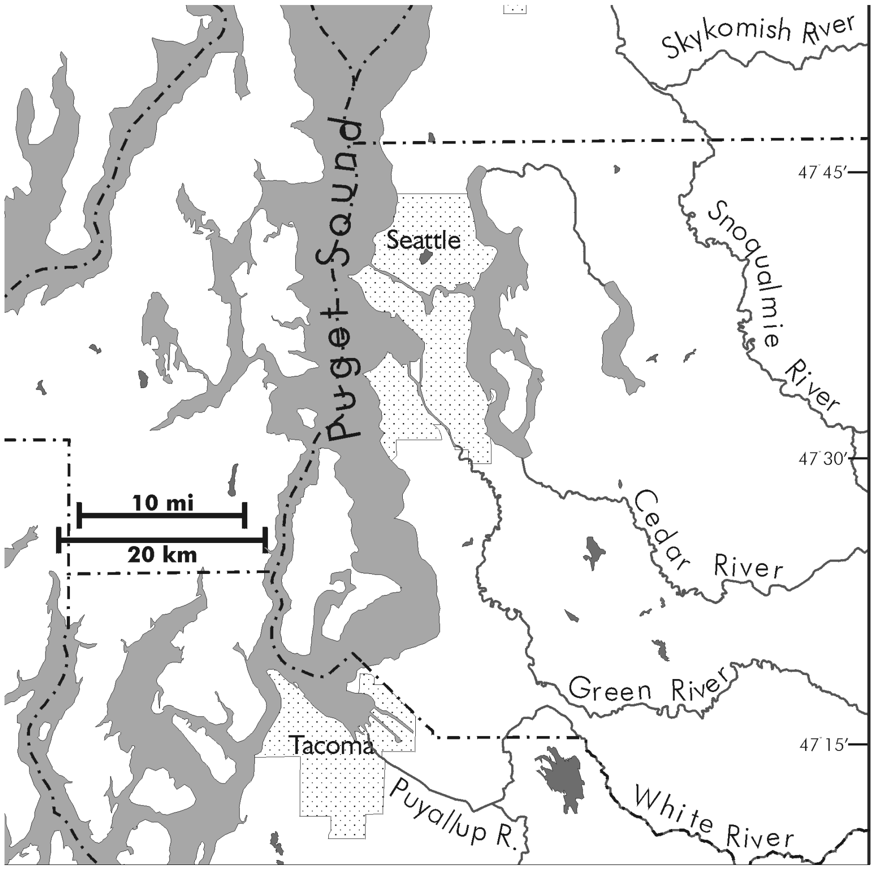


Figure 1. Area of the central Puget Lowland.

modification has not yet greatly altered this topography. Locally, bedrock uplands jut through the plateaus and form the steep headwaters of lowland streams; farther east, the Cascade Range gives rise to the major rivers that traverse the Lowland on their way to Puget Sound.

Urban development in this region began in the 1800's with population centers on Puget Sound and nearby large inland lakes, spread along transportation corridors up the major river valleys through the 20th century, and is now expanding onto the adjacent upland plateaus. Previously undeveloped land on the plateaus is being urbanized at the rate of several thousand hectares per year (King County 1999).

Several factors make the Puget Sound region an ideal region for this study. First, streams within our study region share relatively uniform soil, climate, and topographic characteristics. Second, we can investigate a wide range of watershed development intensities and ages within a circumscribed area. Third, all study watersheds have (or once had) high biological significance, including presence of anadromous salmonids. Fourth, undeveloped areas remain that have been protected from the most egregious forms of development. Fifth, moderately degraded watersheds still support regionally valuable biological resources that can be protected and even restored with improved understanding of the effect of specific urbanization activities on streams. Finally, careful application of knowledge derived from this study can be instrumental in targeting the massive expenditures expected in the region in the next decade to activities most likely to preserve endangered species, protect water quality, and thereby maintain cherished components of regional quality of life.

In addition to the studies conducted specifically for this investigation, we have used the guidance and conclusions drawn by other recent assessments, particularly those that have identified some of the clear determinants (and non-determinants) of aquatic-system health in this region (see May 1996; summarized in May et al. 1997, and Horner et al. 1997; also Karr 1998, Karr and Chu 1999 2000). As a result, our work for the present study did not assess all potential effects of urban development with equal detail. For example, we did not evaluate chemical water quality because recognized criteria for toxic effects were found rarely to be violated in this region, except in the most urbanized watersheds (Bryant 1995). We did not characterize the variability in substrate cementation and embeddedness, because high levels of fine-sediment intrusion into stream beds are already known to degrade instream biota and affect salmonid behavior (Newcombe 1996), and because a progressive increase in fine sediment with increasing watershed urbanization has already been documented (Wydzga 1997). Instead, we focused here on better understanding the *sources* of fine sediment.

Earlier work showed that a wide range of biological conditions in different watersheds can occur at relatively low levels of human disturbance (Karr and Chu 2000). We concentrated our attention on lightly urbanized watersheds, because the influence of one or another environmental stressor might be easiest to isolate and discern. The prior success in using biological indicators, particularly the benthic index of biotic integrity (B-IBI; Karr and Chu 1999) to characterize the initial loss of aquatic-system health, made this approach a cornerstone of our work.

1.1 CONCEPTUAL FRAMEWORK

Stream biotas evolve over millennia as a result of the complex interactions of chemical, physical, and biological processes. A catalog of all the elements (or parts) of those systems and the processes through which they interact would encompass virtually everything we know about Earth's biogeochemical systems. A landscape's regional topography, climate, geological substrate, soil, vegetation types, and biogeography define in large part the biota of the region.

Human activity alters chemical, physical, and biological processes and thereby changes the character of the river biota. Under the Clean Water Act, States are charged with the responsibility of restoring and maintaining the "integrity" of the Nation's waters. The word integrity as used was "intended to convey a concept that refers to a condition in which the natural structure and function of ecosystems is maintained" (GPO 1973, page 76).

Use of integrity in this context has several important dimensions. First, it establishes a goal based on *natural* condition. Natural systems are "capable of preserving themselves at levels believed to have existed before irreversible perturbations caused by man's activities" (GPO 1973, page 77). Second, it provides a scientific foundation and framework (ecosystem structure and function) to the definition and therefore measurement of that condition. Finally, it establishes a normative concept, the suggestion about how things should (or should not) be. It specifically notes that "any change induced by man which overtaxes the ability of nature to restore conditions to "natural" or "original" is an unacceptable perturbation." (GPO 1973, page 77). In short, the first broad goal of the 1972 Act—protect and restore the biological integrity of receiving waters—was unambiguous.

The challenge of the past 30 years has been to accomplish this goal. Although incremental steps have been made, the grand vision of the Congress in 1972 remains elusive. Success depends on a concerted effort to understand in the broadest sense possible the effects of human actions on the character of rivers and streams. That effort requires an unprecedented integration of knowledge from diverse disciplines, a central goal of this project.

Some human actions have direct effects on a river and its biota; these include, for example, construction of dams, channelization, introduction of alien taxa, and overharvest of fishes. Other actions have more indirect effects: clearing of natural vegetation in uplands, for example, alters rates of delivery of water and sediment to stream channels. The release of toxins that bioaccumulate may influence the abundance and distribution of top carnivores.

Anyone attempting to catalog human activities that influence river condition is quickly overwhelmed. The list is long, complex and, one soon recognizes, it contains a huge combination of those activities. Moreover, those activities interact with topographic, geological, climatological, and biological differences among watersheds. One can list simple actions, such as discharge of point-source effluent or straightening of the river channel for example. Alternatively, one can list more complex activities, such as urbanization, that represent the integration of many actions, each of which influences aquatic condition in its own unique way.

A diversity of research and synthesis activities in the last 20 years suggests that this long list of factors and interactions can be grouped into five major classes of environmental "features" (Table 1). Although simplistic in a number of ways, these "features" provide a tractable organizing structure for those thinking about the condition of water bodies (Karr et al. 1986, Karr 1991, NRC 1992, Yoder and Rankin 1998). When one or more of these features, or sets of variables, is affected by human activities the result is ecosystem degradation, degradation that is most conveniently and sensitively measured as a change in the river biota.

Using the biota as a guiding framework can aid our efforts to understand, prevent, or reverse the effects of human actions that might degrade aquatic systems. Environmental decision-makers can and should use the condition of living systems as a benchmark, guide, and goal for their work (Karr 2000). Biological measures provide better information about actual environmental quality than chemical and physical measures (Keeler and McLemore 1996) because those biological measures are one step closer to the factors that constitute environmental quality for living things. Finally, biological measures are important because they provide a robust scientific framework to inform the largely cultural process of deciding how humans treat rivers, and thus the benefits they will derive from those rivers (Karr and Rossano in press).

Human actions that alter critical features of a stream system have the potential to degrade stream conditions. Unhealthy streams can become unhealthy in many different ways, a fact often lost on water-resource managers focusing narrowly on chemical pollutant concentrations, the number of NPDES permits issued, stormwater runoff, or fish habitat. The broad-based approach implicit in the five features is more likely to solve water resource problems because a more integrative diagnosis of the cause of degradation is required. Furthermore, the results are more likely to prove cost-effective because solutions may capitalize on natural cleaning processes analogous to how secondary treatment purifies sewage (Karr et al. 1986). The effects of soluble nutrients, which often produce blooms of nuisance algae in streams, can, for example, be reduced by ensuring that streams have overhanging cover. Shading restricts light and thus limits the

Table 1. Five features of water resources altered by the cumulative effects of human activity with examples of degradation associated with urbanization (modified from Karr 1995).

Features	Human actions	Components altered	Urban stream degradation
Flow regime	Altered land cover that affects upland soil structure and reduces soil-moisture content Dams and levees Water withdrawal	Temporal distribution of floods and low flows, magnitude of uncommon and extreme events	Channel erosion, altered channel morphology, washout of biota, unseasonable drying of stream and streambed; disconnection from and loss of floodplains
Physical habitat structure	Channelization, Remove organic material, sedimentation, debris flows	Substrate type, water depth and speed, spatial and temporal complexity of physical habitat	Sedimentation and loss of spawning gravel, impediments to migratory movements, lack of woody debris, destruction of riparian vegetation and overhanging banks, lack of deep pools
Water quality	Industrial effluent CSO contaminants Domestic effluent Atmospheric deposition, road deicing measures	Temperature, turbidity, dissolved oxygen, acidity, alkalinity, organic and inorganic chemicals, heavy metals, toxic substances	Increased water temperature, turbidity, oxygen sags, nutrient enrichment, chemical contaminants
Energy sources	Altering riparian cover, removing organic material	Type, amount, and size or organic particles in stream, seasonal pattern of energy availability, allochthonous vs. autochthonous production	Altered supply and kind of organic material for food web, reduced availability of fish carcasses
Biotic interactions	Overharvest Alien introductions Riparian vegetation management Human intrusions	Competition, parasitism, disease, predation	Increased predation on young-of-year fish; genetic swamping from hatchery fish; alien plants, fish, invertebrates, diseases, and parasites, altered riparian vegetation

growth of algae. Lowered production of algae, in turn, affects the aquatic invertebrate community and the processing of organic matter.

Invoking this approach, however, requires that ambient stream condition be assessed, especially in biological terms, and that information be integrated with surveys designed to identify site-specific stressors. Our goal is to show that we can recognize certain recurring conditions that can be used to guide not only efficient evaluation of these systems but also decisions about restoration and development activities to minimize future damage. We want to reside in the middle ground between the approach that suggests that all streams and watersheds are unique, and so require detailed assessment before *any* constructive actions can be taken; and the alternative approach that all streams are limited by, for example, chemical pollutants or stormwater runoff, and so require no specific assessment before applying a solution "known" *a priori*. The significant stressors within individual watersheds must be identified and evaluated before general treatments are initiated.

In this paper, we use the terms "urban" and "urbanizing" in a broad sense because we are concerned with the effects of human activity of any kind within the process of urbanization. Our data have been collected along a gradient of increasing human activity where each new increment provides additional housing, transportation, shopping, and jobs for the growing population of the Puget Sound region, and where the endpoint of this development activity is already represented by the neighborhoods and industrial areas of Seattle and the other urban centers of the region.

This development not only converts forested landscapes to urbanized ones but also produces innumerable individual actions by individual streamside and watershed residents. Yet we know little about people's actions in these landscapes. Importantly, almost no research has been done to establish a connection between public participation or education and the success of aquatic habitat rehabilitation. Scant research is available on human perceptions of riparian landscapes (Herzog 1985, House and Sangster 1991, Gregory and Davis 1993), less on attitudes toward restoration (Tunstall et al. 2000), and even less on human behavior in the riparian context (Kaplan and Kaplan 1989). Most of the money spent on public education has been focussed on teaching citizens about the biological needs of a species in hope this education will translate into caring behavior. Little or no research shows that translation occurring. We also do not know what motivates individuals to care for nearby nature, only that when community involvement becomes broad, well organized and vocal, this activity shapes political processes to continue rehabilitation without regard to either the physical or biological potential of an urban stream or with rigorous process to define how best to attain that goal.

1.2 STUDY SITES

For this study, 45 sites were selected from 16 second and third-order streams in King and Snohomish counties (Table 2) that shared the following characteristics:

- Watershed area between 10 and 40 km^2
- Local channel gradients between 0.5 and 2.0 percent
- Watershed soils, watershed elevation, and climate typical of the central Puget Lowland
- Dominant source of human disturbance is urban development.

At every site benthic invertebrates were sampled between 1997 and 1999 (Morley, 2000); substrate data were collected at 19 of the sites, and hydrologic analysis occurred at the 11 sites located in close proximity to gauging stations without intervening tributary input (Konrad 2000). Restoration efforts at six King County streams were included in this effort to evaluate the response of invertebrates to LWD placement, a common restoration technique in Pacific Northwest streams (Larson 1999).

Table 2. Study sites.

Stream [1]	Site ID	Address (closest cross-streets)	Closest city	Site coordinates [2]	
				Lat.	**Long.**
Big Bear	BB971	Woodinville-Duvall Rd. & 210th Ave. NE	Woodinville	47.7579	122.0569
Big Bear	BB972	NE 164th St. & Mink Rd.	Redmond	47.7469	122.0596
Big Bear	BB973/981	NE 148th St. & Mink Rd.	Redmond	47.7364	122.0652
Big Bear	BB974	NE 148th St. & Mink Rd.	Redmond	47.7359	122.0657
Big Bear	BB975	NE 133rd St. & Bear Creek Rd.	Redmond	47.7183	122.0755
Big Soos	BS971	SE 290th St. & Kent - Black Diamond Rd.	Auburn	47.3407	122.1345
Forbes	FO98US	NE 106th Dr. & Forbes Creek Dr.	Kirkland	47.6967	122.1893
Forbes	FO98DS	108th Ave. NE & Forbes Creek Dr.	Kirkland	47.6961	122.1954
Jenkins	JE971	164th Pl SE & Covington-Sawyer Rd.	Covington	47.3462	122.1210
L.Jacobs	LJ99US	Sammamish Pkwy. SE & SE 43rd Wy.	Sammamish	NA	NA
L.Jacobs	LJ98US	Sammamish Pkwy. SE & SE 43rd Wy.	Sammamish	47.5649	122.0460
L.Jacobs	LJ99DS	Sammamish Pkwy. SE & SE 43rd Wy.	Sammamish	NA	NA
L.Jacobs	LJ98DS	Sammamish Pkwy. SE & SE 43rd Wy.	Sammamish	47.5654	122.0491
Little Bear	LB971	180th St. SE & 51st Ave. SE	Mill Creek	47.8336	122.1631
Little Bear	LB981	189th St. SE & 51st Ave. SE	Mill Creek	47.8264	122.1618
Little Bear	LB982	196th St. SE & 51st Ave. SE	Bothell	47.8197	122.1608
Little Bear	LB983 [3]	216th St. SE & 63rd Ave. SE	Bothell	47.8010	122.1497
Little Bear	LB972	228th St. SE & Hwy. 9	Woodinville	47.7909	122.1444
Little Bear	LB973/984	233rd Pl. SE & Hwy.9	Woodinville	47.7858	122.1449
Little Bear	LB974	233rd Pl. SE & 63rd Ave. SE	Woodinville	47.7819	122.1477
Little Bear	LB985	NE 195th St. & 136th Ave. NE	Woodinville	47.7728	122.1552
Little Bear	LB986	NE 177th Pl. & 134th Ave. NE	Woodinville	47.7587	122.1589
Little Bear	LB987	NE 178th St. & 130th Ave. NE	Woodinville	47.7560	122.1669
May	MA971	NE31st & Jones Ave.	Renton	47.5191	122.1937
Miller	MI971	168th Pl. SW & 8th Ave. SW	Normandy Park	47.4471	122.3475
North	NO981 [3]	183rd St. SE & John Bailey Rd.	Mill Creek	47.8344	122.2219
North	NO982	236th St. NE & Fitzgerald Rd.	Bothell	47.7804	122.1871
Rock	RO981 [3]	SE 262nd St. & Summit Landsburg Rd.	Maple Valley	47.3650	122.0136
Rock	RO971/982	SE 248th St. & Cedar River Pipeline Rd.	Maple Valley	47.3794	122.0197
Seidel	SE981	NE 133rd St. & 198th Ave. NE	Redmond	47.7185	122.0725
Soosette	SO99US	SE 304th St. & Hwy. 18	Auburn	NA	NA
Soosette	SO98DS	SE 304th St. & Hwy. 18	Auburn	NA	NA
Struve	ST981	NE 150th St. & 206th Ave. NE	Redmond	47.7336	122.0593
Swamp	SW981	164th St. SW & 28th Ave. W	Lynnwood	47.8509	122.2659
Swamp	SW982	181st Pl. SW & Butternut Rd.	Lynnwood	47.8321	122.2594
Swamp	SW983	Magnolia Rd. & Filbert Rd.	Lynnwood	47.8257	122.2553
Swamp	SW971	Larch Wy. SW & Locust Wy.	Brier	47.8109	122.2560
Swamp	SW972	Larch Wy. SW & Locust Wy.	Brier	47.8097	122.2566
Swamp	SW973/984	Larch Wy. SW & Locust Wy.	Brier	47.8090	122.2561
Swamp	SW985 [3]	Locust Wy. & Cypress Wy.	Brier	47.7995	122.2572
Swamp	SW986 [3]	Locust Wy. & Cypress Wy.	Brier	47.7993	122.2566
Swamp	SW987	Locust Wy. & Cypress Wy.	Brier	47.7991	122.2581
Swamp	SW988 [3]	Lockwood Rd. NE & Carter Rd.	Kenmore	47.7778	122.2496
Swamp	SW98US	NE 185th St. & 173rd Ave. NE	Kenmore	47.7661	122.2414
Swamp	SW99MS	NE 185th St. & 173rd Ave. NE	Kenmore	NA	NA
Swamp	SW98DS	NE 185th St. & 173rd Ave. NE	Kenmore	47.7635	122.2404
Swamp	SW989	NE 175th St. & 80th Ave. NE	Kenmore	47.7547	122.2343
Thornton	TH971	NE 107th St. & 15th Ave. NE	Seattle	47.7065	122.3136
Thornton	TH98US	NE 105th St. & 35th Ave. NE	Seattle	47.7066	122.2889
Thornton	TH98MS	NE 105th St. & 36th Ave. NE	Seattle	47.7056	122.2876
Thornton	TH98DS	NE 105th St. & 39th Ave. NE	Seattle	47.7053	122.2860

[1] basins are listed alphabetically and sites ordered from upstream to downstream

[2] units: degrees, datum: WGS84; [3] invertebrates collected but not processed at this site

2 METHODS

Our methods were chosen to explore the nature, and the causes, of change to aquatic-system health along a gradient of human activity. To characterize that gradient of "human activity" we used a traditional measure of land cover, total impervious area, but explored in detail its limitations. For "aquatic-system health" we used a measure of in-stream biology appropriate to regulatory mandates and stream-rehabilitation goals. In determining the causes of change, we focused on the factors judged to be most broadly influential in the urbanizing environment: changes in watershed hydrology, the actions of streamside residents, loss and replacement of habitat structure, and sources of fine sediment.

2.1 LAND-COVER CLASSIFICATION

Characterizing land-cover changes, the most general and pervasive effect of urbanization, is crucial to project success. Historically, 1:12,000-scale airphotos have been manually discriminated by a technician into eight or so different "classes." Discrimination is at the judgement of the operator, following established guidelines; typical minimum unit areas are one to five acres (about 100 m minimum dimensions). The validity of these evaluations are rarely evaluated by ground-truthing. Typical analyses require about 1 person-week for a 30-km^2 area, and even a trained operator cannot improve the speed of land-use evaluations.

We developed an alternative approach using Landsat satellite imagery to produce the same general type of land-cover characterization as is widely used across the region. Our methodology focuses on the need to assess watershed conditions in the urban, and urbanizing, parts of western Washington. We chose classes of land cover to reflect categories that can be readily distinguished from satellite data and are likely to influence runoff and watershed characteristics.

Our classification scheme follows a five-step process designed to be intuitive while yielding accurate results.

STEP 1: Image Manipulation

Seven-band Landsat satellite images from 1998 with a resolution of 30 meters (each pixel represents 900 m^2) were obtained for northwestern Washington State. Raw Landsat images was imported into the ERDAS Imagine software package and geocorrected to the UTM projection (zone 10N, spheroid [Clarke, 1866], datum NAD27) using digital orthophotos (DOQQ's) as the reference projection source. This allowed the raw Landsat and classified images to be compared directly to the DOQQ's using the geographic linking function in the Imagine viewer. Bands 2, 3 and 4 of the raw Landsat image, corresponding to reflectances received by the satellite sensors in various wavelength ranges, were used singly and in combination to produce a 4-layer image that formed the basis of the classification.

STEP 2: Training Sites

The next step in the process was the identification of and delineation of training sites used to define the characteristic pattern, or "signature," of the 4-layer image for each land-cover category. "Training sites" are areas of known land cover, usually no more than 1000 m^2 in size, determined from ground truthing in the field or from inspection of digital orthophoto quarter quadrangles (DOQQ's). We used a combination of both methods to obtain a series of suitable training sites for each desired class. Separate training sites were created for a total of 9 classes, using a two-tier scheme. The first tier consisted of 4 broad land cover classes: "intense urban" (land nearly completely paved or built upon), "water," "vegetation," and "broad urban" (everything remaining). The second tier consisted of 5 finer classes that subdivided the "vegetation" and "broad urban" classes into "deciduous vegetation," "coniferous vegetation," "grassy/shrubby vegetation," "forested urban" (developed land with significant canopy coverage), and "grassy urban" (developed land with few trees but significant grass coverage).

STEP 3: Signature Extraction

Once selected, the outlines of the training sites were overlaid on the 4-layer image. Using the Signature Editor module in Imagine, spectral signatures were simultaneously extracted from each of the 4 layers, yielding "signatures" for each training site within each class. Signatures correspond to a cluster of reflectance values within each band. Signatures within each class were then combined to obtain a single spectral signature range in 4-dimensional space for each class. The output of this step thus consisted of 9 distinct sets of signatures.

STEP 4: Supervised Classification

The first supervised classification was conducted on the 4-layer image using just the first-tier signatures (*i.e.* intense urban, water, vegetation, and broad urban). The classification used rules that calculate the statistical probability of a pixel belonging to a particular class, based on the variance and covariance of the spectral signatures. A second supervised classification was then conducted on the 4-layer image using the second-tier signatures (deciduous vegetation, coniferous vegetation, grass/shrub, forested urban, and grassy urban). This new five-class image took all pixels in the study area and assigned them to one of the second-tier categories. The final step was to combine each of these images into a final composite seven-class image with the following descriptive labels: forested, grass/shrub, open water, bare earth, intense urban, grassy urban, and forested urban.

STEP 5: Accuracy Assessment

The final step involved an accuracy assessment of the classed image. We took two approaches, both using digital and printed overlays of the classified images and the DOQQ's. Fifty pixels from each of the seven categories were randomly selected; they were chosen from clusters of 25 (5-by-5) uniformly classified pixels to ensure that minor mis-registration of the orthophotos did not skew the analysis. The orthophoto corresponding to the center pixel in each 5-by-5 group was displayed on the computer monitor and divided into a 10-by-10 grid. Each of the one hundred grid cells of the orthophoto was visually identified into one of seven categories (open water, trees, shrubs/ grass, pavement, bare earth, pavement or bare earth, and shadows) and compared to the category of the classified pixel. The percentage of "correctly" classified pixels could then be evaluated, as could the average percentage of a particular land cover (such as "pavement") for each of the seven classes.

2.2 BIOLOGICAL CONDITION AT MULTIPLE LAND-COVER SCALES

Biological conditions were used as the primary indicator of aquatic-system health in this study. The measure chosen was the benthic index of biological integrity (B-IBI; Karr 1998, Karr and Chu 1999) because it has proven to be a robust method of characterizing in-stream biological condition. A multimetric index such as the B-IBI provides more comprehensive and robust assessments than narrowly focused chemical standards. Biological assessments do more than indicate river health; those based on multimetric indexes can also diagnose causes of degradation, suggest treatments to halt or reverse damage, and evaluate the effectiveness of management actions (see Karr 1991, Davis and Simon 1995, Karr and Chu 1999, Simon 1999, Jungwirth et al. 2000 for more detailed discussion and examples).

For this study, we collected invertebrates from each site in September when flows are typically stable, taxa richness is high, and field crews have easy access to sites (Fore et al. 1996; Morley and Karr, *in review*). At each stream site, we used a Surber sampler (500-µm mesh, 0.1 m^2 frame) to collect three samples along the mid-line of a single riffle. We preserved invertebrates in the field in a solution of 70% ethanol and returned samples to the lab for identification under microscopy—typically to the level of genus (Morley 2000). We analyzed these data (Karr 1998) according to the 10-metric B-IBI, an index which includes measures of taxa richness, disturbance tolerance, and feeding ecology (Table 3). Following procedures first outlined for fish (Karr 1981, Karr et al. 1986), and later for invertebrates (Ohio EPA 1988; Fore et al. 1996), we assigned metric scores of five (values at or near what is expected at sites with little or no human influence), three (moderately divergent from condition at such sites), and one (severely divergent) to each of the ten raw metric values. These scores were then summed to obtain a site and time specific B-IBI that ranged from 10 (very poor) to 50 (excellent).

We calculated extent of urbanization in each study basin over three spatial scales: subbasin, riparian, and local (Figure 2; Morley and Karr, *in review*). We used the 1998 classified Landsat image to evaluate land cover categories among the 16 study basins, which reflect the dominant development trends across the Puget Sound lowlands: conversion of forested lands to urban and suburban centers (Figure 3). We tested four combinations of these land cover categories for association with biological and physical stream condition: (1) % Coniferous (native land cover for the region), (2) % Forested (coniferous + deciduous), (3) % Urban (urban forested + urban grassy + intense urban), and (4) % Intense Urban (nearly fully paved, or bare soil). Within the GIS-programs ArcInfo and ArcView we performed subbasin delineation, stream buffering, and map overlays.

Table 3. The ten metrics of the B-IBI and their predicted response to urbanization. Urbanization is measured here as the % total impervious area over the sub-basin. (Modified from Karr 1998.)

Metric	Description	Response
Taxa richness & composition		
Total taxa	Richness[1]	Decrease
Mayfly taxa	Richness[1]	Decrease
Stonefly taxa	Richness[1]	Decrease
Caddisfly taxa	Richness[1]	Decrease
Population attributes		
Dominance[3]	Relative abundance[1]	Increase
"Long-lived" taxa	Richness[2]	Decrease
Tolerance & intolerance		
Intolerant taxa	Richness[2]	Decrease
Tolerant taxa	Relative abundance[1]	Increase
Feeding & other habits		
"Clinger" taxa	Richness[1]	Decrease
Predators	Relative abundance[1]	Decrease

[1] Mean of three replicates, [2] cumulative of three replicates, [3] of three most abundant taxa

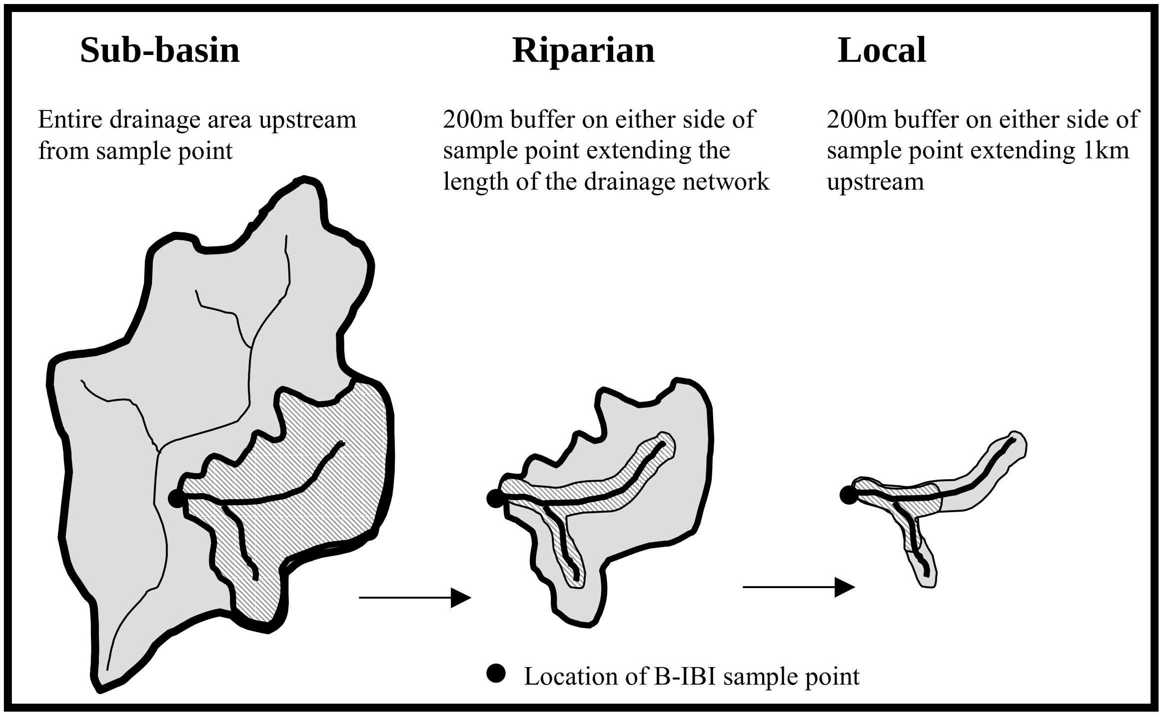


Figure 2. Diagram of GIS-based landscape analysis. Buffer width dimensions were broad enough to include those functions commonly cited in association with riparian corridors.

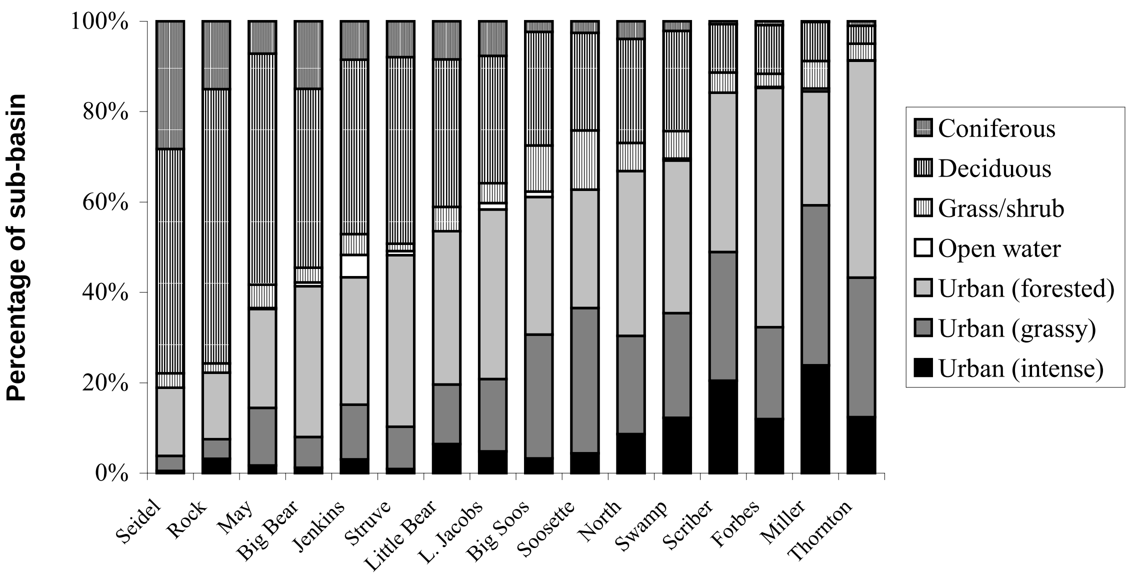


Figure 3. Distribution of land cover categories within the study basins, which are ordered from least to most urban.

2.3 HYDROLOGIC CHANGES

We judged that the temporal patterns of stream flow would be a critical element of our stream ecosystems (Shelford and Eddy 1929; Odum 1956; Horwitz 1978; Poff and Allan 1995; Poff et al. 1997) and would display significant changes in response to urban development (Carter 1961; Sawyer 1963; Harris and Rantz 1964; Leopold 1968; and Hollis 1975; Dinicola 1990; Burges et al. 1998). From a consideration of the interdependencies of the five features of aquatic systems (Table 1) and our appreciation of the nature of urbanization, our focus was on how hydrologic changes resulting from urban development may influence stream ecology. Two aspects of stream flow patterns were addressed: (1) their relationship to in-stream biological conditions and (2) the patterns of flood disturbance in urban and non-urban streams throughout the Puget Lowlands. We postulate that biological conditions and flood disturbance patterns are related to stream flow patterns rather than urban development *per se*; that is, we expect changes in biological conditions and flood disturbance patterns result from the inevitable hydrologic consequences of urban development.

2.3.1 Stream Flow Patterns and Biological Conditions

While the hydrologic consequences of urban development are well-documented at the scale of an individual storm, much less attention has been given to annual and inter-annual scales over which they will have a persistent biological influence. We analyzed the relationship between these longer term stream-flow patterns and biological conditions at 13 Puget Lowland streams gaged by USGS, King County, or Snohomish County during WY (“Water Year,” running from October 1 to September 30) 1989 to 1998 and where benthic macroinvertebrates have been monitored between 1994 and 2000 (Kleindl 1995; Karr and Chu 2000, Morley 2000, Morley and Karr in review). The streams are Big Bear, Big Beef, Covington, Des Moines, Hylebos, Miller, North, Jenkins, Juanita, May, Mercer (Kelsey), Rock, and Swamp Creeks (Figure 4). Table 4 identifies the streams, the basin area at each gage, and road density in the basin (the ratio of road length to basin area). Where macroinvertebrates have been monitored at multiple sites on a stream, the site closest to the stream gage is used.

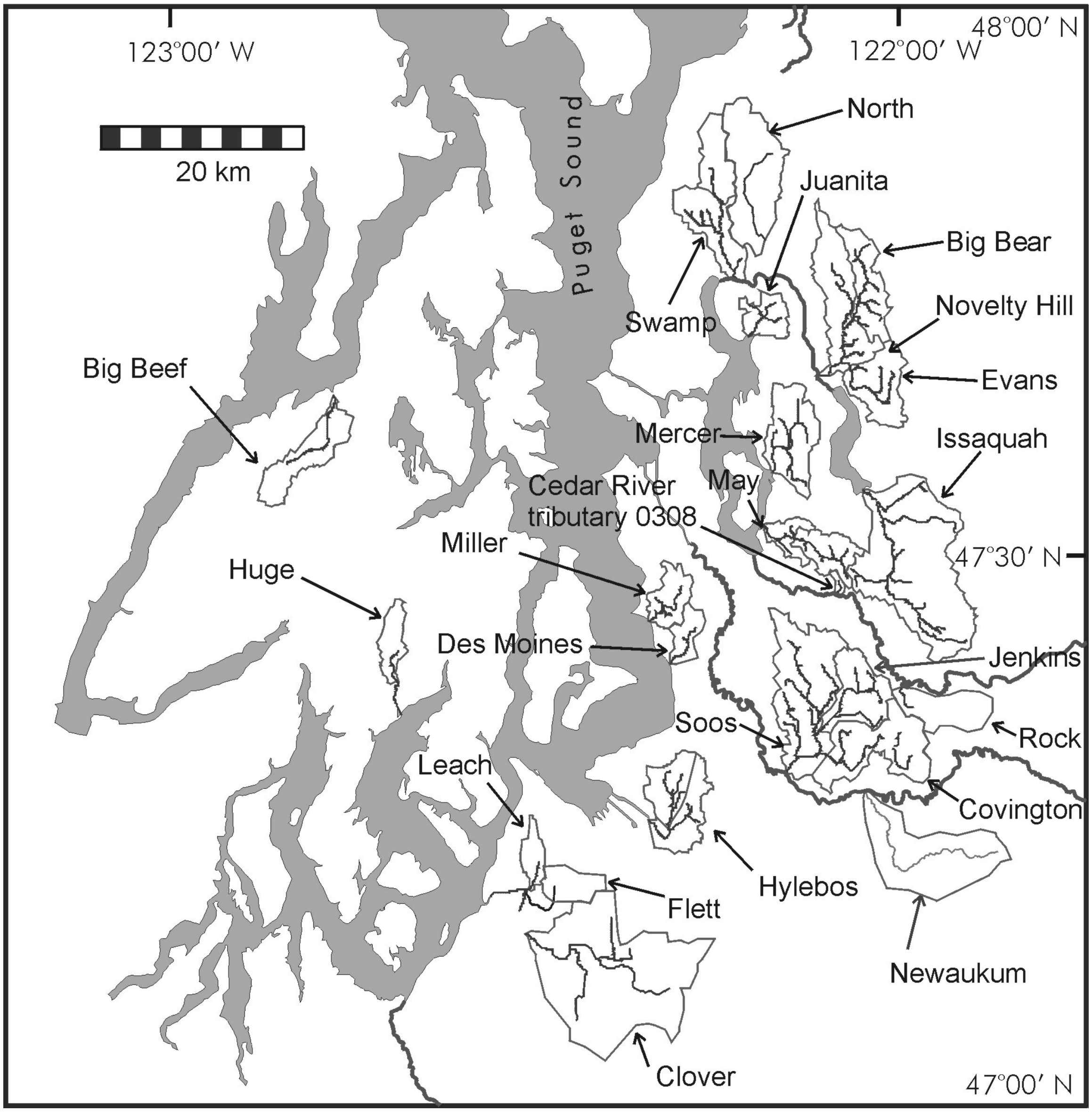


Figure 4: Map of streams in the Puget Lowland used in the hydrologic analysis.

Table 4: Drainage area, road density, and operators of stream gages used in hydrologic analysis.

Suburban streams	Drainage area (km^2)	Road density (km/km^2)	Stream gage operators
Huge Creek	17	2.5	USGS
May Creek @ Coal Cr. Pkwy.	24	4.0	King Co.
Rock Creek	32	2.7	USGS/King Co.
May Creek near mouth	32	5.0	USGS/King Co.
Big Beef Creek	35	2.1	USGS
Bear Creek @ 133rd Ave. N.E.	36	4.4	USGS/King Co.
Jenkins Creek	37	5.4	King Co.
Covington Creek	55	4.0	King Co.
Newaukum Creek	70	2.6	USGS
Soos Creek	171	4.7	USGS
Urban streams			
West Fork Hylebos Creek	8	7.6	King Co.
Leach Creek	12	9.9	USGS
Des Moines Creek near mouth	14	7.9	King Co.
Miller Creek near mouth	21	10.6	King Co.
Swamp Creek near Filbert Rd.	25	7.4	Snohomish Co.
Mercer Creek	37	9.1	USGS
Swamp Creek near mouth	59	7.9	USGS
North Creek	67	7.5	Snohomish Co.

This group of streams allows us to assess the effects of both natural (physiographic) factors (e.g., surficial geology, topography) and land use on stream biological condition. Streams may have different biologic conditions, in spite of similar levels of urban development, if they have different stream flow patterns. Conversely, biological conditions may be similar in streams with different levels of urban development if the streams have similar flow patterns.

Initially, we reviewed a number of stream flow statistics as indicators of the hydrologic effects of urban development, using three criteria. First, the value of any hydrologic indicator must change over time during periods of urban development in a stream's basin. Second, hydrologic indicators should distinguish between streams with distinct stream flow patterns that are likely to have biological influences, regardless of whether the cause of the difference is primarily land use or natural physiographic differences. Finally, a robust hydrologic indicator will not differentiate between stream flow patterns during different periods simply due to climatic variability.

The hydrologic effects of urban development has been documented with stream flow measures such as annual flood magnitude and base flow rates (Carter, 1961; Sawyer, 1963). Konrad (2000) found that mean annual flood increases over time in response to urban development in Puget Lowland streams but does not provide a basis for distinguishing the hydrologic effects of urban development among a group of streams. Likewise, low-flow statistics (e.g., area-normalized mean discharge for August) did not vary with urban development. The inability of these hydrologic measures to represent differences between streams with different levels of urban development is likely due to regional physiographic heterogenity in the Puget Lowland and to localized weather patterns. Since traditional measures of hydrologic regime did not meet our criteria, particularly for comparisons between streams, we needed to develop measures that identify both hydrologic changes in stream and differences between streams that result from urban development and are likely to have ecological effects.

We calculated three hydrologic statistics to represent the storm and base flow patterns over annual and inter-annual time scales that are likely to have a persistent influence on the biological conditions of streams: (1) the fraction of a year that the daily mean discharge rate exceeds the annual mean discharge rate (T_{Qmean}); (2) the fraction of a multiple year period that the discharge rate of a specified flood quantile is exceeded ($T_{0.5\ yr}$ is the cumulative duration that stream flow exceeds the discharge of a flood occurring on average twice per year); and (3) the coefficient of variation of the annual maximum flood (CV_{AMF}).

The three hydrologic measures characterize stream flow patterns of progressively shorter duration and higher magnitude variability. Mean annual discharge is exceeded approximately 30% of the time in Puget Lowland streams. The discharge rate of a flood occurring, on average, twice a year is exceeded less than 10% of the time. The discharge rate of an annual maximum flood is exceeded less than 2% of the time.

All three statistics, T_{Qmean}, $T_{0.5\ yr}$, and CV_{AMF}, are inversely related to the level of urban development in a stream basin (Konrad 2000) and so express the hydrologic mechanisms by which urbanization ultimately can influence biological health. Inverse relationships are expected for T_{Qmean} and $T_{0.5\ yr}$ because of re-distribution of water from base flow to storm flow and the rapid rise and recession of storm flow in urban streams. Likewise, CV_{AMF} is expected to be lower in streams with higher levels of urban development given the results of rainfall-runoff modeling by James (1965) and the observations of Hollis (1975), which both showed a greater relative increase in the magnitude of small, frequent floods than the relative increase of large, infrequent floods in response to urban development.

T_{Qmean} was calculated for each of the 13 streams. The fraction of the year that the daily mean discharge rate (Q_{daily}) exceeded the annual mean discharge rate (Q_{mean}) was determined for each year of record for each stream. T_{Qmean} was calculated as the average annual fraction of a year that Q_{daily} exceeds Q_{mean}.

$T_{0.5\ yr}$ was calculated for each of 8 Puget Lowland streams (Covington, Des Moines, Miller, North, Jenkins, May, Mercer, and Swamp Creeks) using the quantile (i.e., duration) from flow duration curves associated with the discharge rate of a flood occurring on average twice a year, or a "0.5 yr flood". Both flow duration and flood frequency were based on 15-minute stream flow data, with the exception of Mercer Creek where only daily mean discharge data were available to construct a flow duration curve. The period of record varies among the streams from 4 to 10 years. The annual flood frequency for each stream was calculated from a partial duration series (Langbein 1949). The partial duration series used here comprises stream flow peaks (i.e., local maxima in a hydrograph) that exceeded a stream-specific threshold discharge rate and were separated by at least 10 days. Where multiple peaks occurred within 10 days of each other, the highest value was used. The threshold discharge rate for each stream was selected so that each series had 30 to 50 floods.

CV_{AMF} was calculated for each of the 11 Puget Lowland streams (all except Big Beef and Des Moines) using the series of annual maximum discharge rates. The CV_{AMF} was calculated assuming that annual maximum flood peaks follow a two-parameter log-normal distribution:

$$CV_{AMF} = \sqrt{\exp(\sigma_Y{}^2) - 1} \qquad (1)$$

where $\sigma_Y{}^2$ is the variance of the natural logarithms of the annual maximum flood discharge rates (Stedinger et al. 1993). The two-parameter log-normal distribution is an appropriate assumption, given that the generalized skew coefficient for logarithms of the annual maximum floods in the Puget Lowland region is 0.02 (Interagency Advisory Committee on Water Data 1982).

2.3.2 Patterns of Flood Disturbance in Puget Lowland Streams

We investigate patterns of flood disturbance in 13 Puget Lowland streams in the context of varying urban development and hydrologic regime. Our hypothesis is that the spatial extent of stream-bed disturbance during a flood of a given frequency, in our case the median annual or “2-year” flood, increases with the level of urban development in a stream basin. While this may seem like an obvious consequence of increased peak discharge rates in streams, the particle-size distribution of gravel bed streams is not fixed. Thus, we expect that the substrate in urban gravel-bed streams will become coarser and the channel will become wider in response to increased storm flow. At issue is whether these adjustments compensate for the increased peak discharge rates such that the disturbance regime of the stream recovers.

The extent of bed disturbance during the median annual flood was estimated at 19 gravel bars in 13 Puget Lowland streams (Figure 4 and Table 4). A stream gage is located no more than 1 km away from each site. The stream basins span the range of urban development in the Puget Lowland region, as indicated by road density from less than 3 km/km^2 (Big Beef, Huge, and Rock Creeks) to over 7 km/km^2 (Des Moines, Leach, Miller, and Swamp Creeks) with many streams having intermediate levels of urban development (Big Bear, Covington, Jenkins, May, Newaukum, and Soos Creeks).

The stream basins in the analysis display the range of physiographic features found in the Puget Lowland including glacial till-mantled plateaus (e.g., Big Bear and Big Beef Creeks), glacial outwash plains and valleys (e.g., Rock, Jenkins, and Miller Creeks), lakes and wetlands (e.g., Jenkins, Covington, and Big Bear Creeks), ravines (e.g., Miller, May, and Des Moines Creeks, and Cedar River Tributary 0308), broad floodplains (e.g., Swamp Creek) and shallow groundwater (e.g., Jenkins Creek). Additionally, Big Beef, Newaukum, and May Creeks have high-elevation headwaters in bedrock uplands. The diversity of physiographic features represented in these stream basins produce a wide range of hydrologic patterns, particularly at lower levels of urban development. The results of the analysis therefore should be applicable to gravel bed streams throughout the Puget Lowland region and other temperate, maritime regions.

For each stream, a straight reach with a transverse or mid-channel bar (Church and Jones 1982) was identified. Flow is well distributed across the channel and unencumbered by large obstructions or vegetation in the channel with no large zones of flow separation or other severe cross-channel velocity gradients. The bars form a riffle in the stream at most sites, which are pool-riffle channels, except in Swamp Creek where the bed is relatively planar and the amplitude of the bar is low. Multiple reaches in some streams were analyzed to provide replicate sites within a stream (Miller, May, and Jenkins Creeks) or because there are two gages in the stream (May and Swamp Creeks).

Each reach was surveyed to construct a longitudinal profile of the reach and cross-section of the channel across the foreset (downstream) slope of the bar. The particle-size distribution of the surface material on the bar was determined using a Wolman (1954) pebble count, in which 100 particles were selected at random from the stream bed within 5 m of the surveyed cross-section, and their intermediate axis length was measured to the nearest mm. Sand grains (< 2 mm) were noted and included in the count but represented less than 10% of the particles in all samples. Table 5 lists the water surface slope and D_{50} of the particle-size distribution of surface material for each bar.

The analysis of stream disturbance regime relies on a series of hydraulic calculations. The median annual flood ($Q_{2\ yr}$) was estimated from discharge records for WY 1989 to WY 1998, though data were not available for every stream gage in all of these years. $Q_{2\ yr}$ represents either an "instantaneous" peak or the maximum discharge rate for a 15-minute interval.

The hydraulic radius for $Q_{2\ yr}$ was calculated using the laws of mass conservation and Manning's equation for the mean velocity of uniform flow:

$$Q = uA = \frac{S^{0.5} R^{0.67}}{n} RP \qquad (2)$$

where u is mean velocity through a channel cross-section, A is the flow cross-sectional area, S is the local energy gradient of the stream flow, P is the wetted channel perimeter, n is a roughness coefficient, and R is the hydraulic radius.

The Manning roughness coefficient (n) must be specified in (2) before calculating the hydraulic radius. Flow resistance in streams depends on the size, pattern, and concentration of surface roughness elements, vegetation and organic debris, channel form, obstructions in the channel, flow depth, and the stability of the free surface (Keulegan 1938; Chow 1959; Rouse 1965; Ikeda and Isumi 1990). The roughness coefficients for cross-sections in May, Swamp, and Jenkins creeks were calculated using Manning's equation and mean current velocity from measurements made during periods of storm flow ($Q \approx 1$ to 2 m^3/s).

Table 5: Slope and particle-size distribution statistics at 19 gravel bars in the disturbance analysis.

		Slope	**D_{50}** m	**D_{84}** m
Big Beef Creek near mouth		0.011	0.045	0.090
Huge Creek near mouth		0.012	0.030	0.046
Rock Creek @ pipeline crossing	A	0.024	0.071	0.143
	B	0.018	0.043	0.089
Covington Creek near mouth		0.011	0.046	0.089
Big Bear Creek @ NE 133rd St.		0.007	0.037	0.081
Newaukum Creek near mouth		0.014	0.065	0.175
May Creek @ Coal Creek Parkway		0.012	0.045	0.110
May Creek near mouth	A	0.009	0.040	0.083
	B	0.012	0.031	0.070
Jenkins Creek near mouth	A	0.005	0.031	0.059
	B	0.007	0.048	0.090
Soos Creek near mouth		0.003	0.033	0.054
Swamp Creek at Filbert Road		0.010	0.040	0.083
Swamp Creek near Kenmore		0.005	0.021	0.042
Des Moines Creek near mouth		0.017	0.037	0.059
Leach Creek		0.013	0.030	0.068
Miller Creek near mouth	A	0.010	0.029	0.056
	B	0.006	0.022	0.060

For all other streams, the roughness coefficient had to be estimated. Several approaches have been developed to account for the many sources of flow resistance (e.g., Einstein and Barbarossa 1952; Leopold and Wolman 1957; Chow 1959; Barnes 1967; Hey 1979). Two empirical equations, developed by Jarrett (1984) and Bathurst (1985) for gravel-bed streams with slopes of 0.002 to 0.04, were used here to estimate the roughness coefficients in those streams where stage and discharge were not measured (Miller, Leach, Huge, Soos, Newaukum, Covington, Des Moines, Big Bear, Rock, and Big Beef Creeks).

Jarrett (1984) developed an equation for Manning's roughness coefficient based on velocity measurements in 21 high gradient (water surface slopes greater than 0.002) gravel bed streams in Colorado. He approximated n as:

$$n = 0.32 S^{0.38} R^{-0.16} \tag{3}$$

with a root mean square percentage error of estimates of 28%.

Bathurst (1985) developed an empirical flow resistance equation for 15 gravel-bed streams in Britain with high relative roughness (i.e., low flow depths when compared to the protrusion of coarse particles from the stream bed):

$$\sqrt{\frac{8}{ff}} = 5.62 \log\left(\frac{d}{D_{84}}\right) + 4 \tag{4}$$

where ff is the Darcy-Weisbach friction factor, d is the mean water depth (i.e., cross-sectional area divided by wetted channel width) and D_{84} is the length that is greater than the intermediate axis of 84% of the particles on the stream bed. The root mean square percentage error of estimates of ff was 34% of the calculated values. The Darcy-Weisbach friction factor is related to Manning's roughness coefficient by:

$$n = \sqrt{\frac{ff}{8gR^{1/3}}} \tag{5}$$

The average value of n derived from (3) and (5) was used as a first estimate of Manning's roughness coefficient (n_1) in the hydraulic calculations for all of the streams except Jenkins, May, and Swamp Creeks, where n was estimated from water velocity and stage measurements. A second estimate of the Manning roughness coefficient was made to assess the sensitivity of shear stress calculations to n. The data used to develop (3) and (5) were collected during large, infrequent floods, when the total flow resistance is largely a result of grain roughness. In smaller floods, such as those considered in this analysis, form drag may contribute considerably to total flow resistance (Parker and Peterson 1980; Prestegaard 1983). Thus, (3) and (5) may underestimate total flow resistance for the sites in this analysis. For the second estimate of Manning's roughness coefficient, n_2, the first estimate of n_1 is increased by 50%, which is greater than the root mean square percentage error of either (3) or (5).

The hydraulic radius (R) was calculated at a surveyed cross-section by solving (2) iteratively for a series of flow depths until the calculated discharge rate (Q) was equal to the $Q_{2\ yr}$. Two calculations were made, first, using n_1 and, then, using n_2. Table 6 provides the value of the parameters for the hydraulic calculations at each gravel bar.

Table 6: Hydraulic conditions for the median annual flood.

		Q	R	Manning's n	
Median annual maximum flood		m^3/s	m	low	high
Big Beef Creek near mouth		18.1	0.61	0.044	0.065
Huge Creek near mouth		4.9	0.45	0.040	0.060
Rock Creek @ pipeline crossing	A	3.8	0.27	0.058	0.087
	B	3.8	0.25	0.046	0.069
Covington Creek near mouth		4.2	0.36	0.043	0.065
Big Bear Creek @ NE 133rd St.		4.2	0.50	0.039	0.059
Newaukum Creek near mouth		16.5	0.70	0.050	0.075
May Creek @ Coal Creek Parkway		6.1	0.47	0.045	[a]
May Creek near mouth	A	6.9	0.71	0.041	[a]
	B	6.9	0.37	0.028	[a]
Jenkins Creek near mouth	A	4.7	0.48	0.035	[a]
	B	4.7	0.61	0.040	[a]
Soos Creek near mouth		18.6	1.03	0.032	0.048
Swamp Creek at Filbert Road		6.5	0.60	0.042	[a]
Swamp Creek near Kenmore		11.4	0.69	0.033	[a]
Des Moines Creek near mouth		4.9	0.41	0.044	0.066
Leach Creek		2.4	0.28	0.043	0.065
Miller Creek near mouth	A	6.2	0.47	0.039	0.059
	B	6.2	0.65	0.036	0.054
[a] Manning's n calculated from velocity measurements					

The extent of bed disturbance during the median annual flood is estimated using the results of bed tag experiments described in Konrad (2000). Figure 5 is a plot of the peak τ_0^* at seven gravel bars in Jenkins, May, and Swamp Creeks during floods in WY 1998 and 1999 and the fraction of bed tags moved from each bar. The experiments demonstrated a direct relationship between the spatial extent of bed disturbance entrained during a flood to the peak τ_0^* for that flood. The dimensionless shear stress (τ_0^*) was calculated for each bar using

$$\tau_0^* = \frac{\tau_0}{(\gamma_s - \gamma_w)D_{50}} \qquad (6)$$

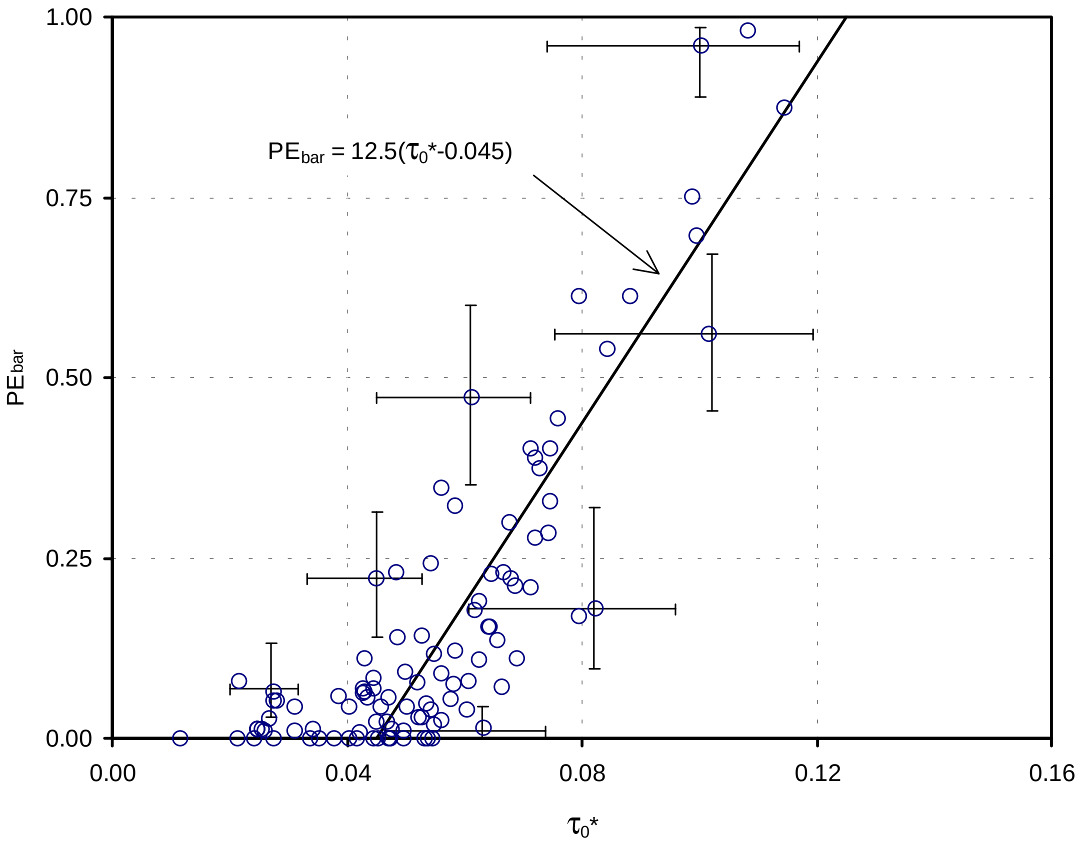


Figure 5: The extent of bed disturbance during floods illustrated by the increasing level of partial entrainment of a gravel (PE_{bar}) as a function of dimensionless shear stress (τ_0*).

where γ_s = bed material specific weight (26500 N/m^3), γ_w = specific weight of water (10000 N/m^3), and D_{50} is the median of the particle-size distribution of the surface material on each gravel bar.

The extent of bed disturbance during a flood is expressed as partial entrainment, PE, which represents the fraction of a gravel bar's surface entrained. PE is approximately related to the peak dimensionless shear stress during a flood by a linear function:

$$PE = \begin{Bmatrix} 0 & \tau_0{}^* \leq 0.045 \\ 12.5\left(\tau_0{}^* - 0.045\right) & 0.045 < \tau_0{}^* < 0.125 \\ 1 & \tau_0{}^* \geq 0.125 \end{Bmatrix} \qquad (7)$$

Estimates based on Equation 7 have a root mean square error of 0.099 and are ±0.31 of the observed values of PE.

A first-order uncertainty analysis was used to assess the error in the estimated values of PE. The standard deviation (σ) of a variable (y) that is a linear function of multiple, uncorrelated variables (x_i) is estimated as:

$$\sigma_y = \sqrt{\sum_i \sigma_{x_i}^2 \left(\frac{\partial y}{\partial x_i}\right)^2} \qquad (8)$$

where the partial differential terms are evaluated at the estimated average values of x_i (Benjamin and Cornell 1970, p. 184).

For the uncertainty analysis, (8) was applied twice. First, (8) was used to calculate the standard deviation of estimates of τ_0* as function of the standard deviation of τ_0 and D_{50}. The standard deviation of τ_0* was calculated assuming τ_0 had a uniform probability of falling between the low estimate of τ_0 based on n_1 and the high estimate of τ_0 based on n_2: $(\tau_{high} - \tau_{low})/\sqrt{12}$. The standard deviation of D_{50} was estimated as half of the difference between the 45th and 55th percentiles of the particle-size distribution, which provide nonparametric estimates of one standard deviation below and above, respectively, of the D_{50} for a sample size of 100 (Helsel and Hirsch 1993, p. 70).

After the standard deviation of τ_0* was calculated, (8) was used to calculate the standard deviation of estimated values of PE where the estimated value of PE is a function of τ_0* and the distribution of PE at a given value τ_0*. The standard deviation of PE at a given τ_0* was calculated using assuming PE has a uniform probability of occurring within 0.31 of the values of PE calculated from (7) (i.e., the standard deviation of PE was $0.62/\sqrt{12}$). The interval of ±0.31 around (7) contains all observed values of PE_{bar}.

We compare values of PE_{bar} for the median annual flood to the level of urban development and hydrologic regime for each stream. We use road density as a measure of urban development using the same calculations described above. We characterize the hydrologic regime of the stream in terms of the ratio of $Q_{2\ yr}$ to the discharge rate exceeded 5% of the time ($Q_{0.05}$). $Q_{0.05}$ was calculated from daily mean discharge rates for the period from WY 1989 to 1998. $Q_{0.05}$ serves as a reference discharge rate at which bed load transport rates are likely to be low (Konrad 2000). In this sense, gravel bars are at equilibrium with $Q_{0.05}$ at each of the streams we investigated.

The ratio $Q_{2\ yr}/Q_{0.05}$ provides an index of the magnitude of the median annual flood relative to a high flow for which the stream bed is relatively stable. We expect little disturbance during the median annual flood when the value of this ratio is close to 1 and increasing levels of disturbance as the ratio increases.

2.4 INDIVIDUAL BEHAVIORS OF STREAMSIDE RESIDENTS

We sought to recognize and to understand recurring individual behaviors involving urban streams, particularly those that directly affected riparian systems. Our biological assessment was designed to discriminate the relative importance of watershed-scale and local-scale disturbances to aquatic systems; here, we looked to the determinants of those local conditions, insofar as the lowland streams in western Washington pass predominantly through private property, under private ownership. We focused primarily on individual *behavior* rather than on attitudes or opinions, because people will not necessarily do as they profess (Anderson 1996). We assume that behavior is the last phase of a complex, iterative, seamless and ongoing cognitive and subjective process whereby humans perceive the landscape, form attitudes toward it, evolve values for it, and finally act in it. Another premise is that streamside residents consider their backyards as private places where they make landscape decisions without regard to community norms (Nassauer 1993).

The assessment strategy had three parts—a survey of stream professionals, an in-depth evaluation of the behavior of streamside residents, and an evaluation of the values held by residents having different relationships with a nearby stream. The "expert" group of the first assessment comprised professionals with day-to-day responsibilities for streams. We selected 18 from a list of 98 to represent geographic and professional diversity. The question posed to them in face-to-face interviews was, "From your personal knowledge what types of individual behavior takes place in the riparian corridor?" We then mailed questionnaires to 60 additional experts. The mailed questionnaire listed the actions cited by the first interviewees, and asked these respondents to locate where they had seen these behaviors occur and if they knew of additional actions. Thirty-two percent responded to our mailed survey. Later we shared the survey data with the experts and asked them to offer explanations as to why they thought these behaviors occurred, and to suggest solutions to the damaging behavior that they saw.

To understand individual behavior, we next turned to the residents themselves. Eighteen residents who lived along 2 streams were interviewed (Parker 1998) and asked to use cognitive mapping (Golledge and Stimson 1997) to describe the changes they would make to their backyards if "time and money were not constraints." The interviewers use landscape design vocabulary and specially did not use any terms common to riparian features, salmon habitat, or aquatic conditions (Appendix 1). Nor did they ask the subjects about landscaping along the stream, although the base map did show the stream since it was usually one of the property lines. Using the interview results, we designed a questionnaire (Appendix 2) that asked streamside residents to rate the likelihood of them acting to achieve three landscaping objectives "***without regard to time and money***." These three goals for backyard landscaping were: 1) control for privacy, 2) special designs for their family, and 3) ecological care. The survey requested some demographic information such as length of time living in this home and the gender of the person responsible for the backyard design. We also asked a general question: "What are the three most important considerations in landscaping or gardening in your backyard?"

Two of these variables are well known in landscape design theory—*control for privacy* (Chermayeff and Alexander 1963) and the creation of *unique home landscapes* to represent a family's tastes (Stahl 2000). We included the third category, *ecological care*, because it was mentioned by two cognitive map interviewees and has been very widely mentioned in the local press. We hypothesized that *ecological care* would be the most favored choice because it represented a regional mindset regarding a quality-of-life issue revolving around salmon. This survey was mailed to 520 stream side homes along three riparian corridors in suburban Seattle. Seven percent were returned as "undeliverable," and 96 (18%) completed surveys were returned. No follow-up letters were sent or calls made to increase the return rate. We compiled these data using an analysis of means.

To compare what the residents said were their goals with what actually happened in their backyards, we conducted a photo survey of 40 backyards. We also recorded the state of ten adjacent backyards of streamside residents who did *not* respond to the survey, and where the conditions differed prominently from those responding to the survey. The photo surveys and field data were content analyzed using a visual data base.

The final study (Bouma 2000) was an attempt to determine how, if in any way, people's concepts and values of a stream differed among three groups: 1) those who lived along the stream and were involved in stream restoration, 2) those who lived along the stream and were not involved, and 3) those who did not live along a stream and but were involved. Residents living in the Thornton Creek Watershed were selected to be interviewed because it is the most developed landscape in the study area, yet it still has 68% single family homes and has more than 70% open water flow (not in pipes). Thornton Creek citizen groups are active in clean-up, restoration, and education activities for many years and have been featured prominently in Seattle newspapers. Thus, one might expect to find broad understanding of creek concepts and values in this watershed because of wide public involvement and education.

Ten residents in each of the three groups were interviewed face-to-face using the Conceptual-Content Cognitive Map (3CM) developed by Kearney and Kaplan (1997). The subjects were asked questions such as "Imagine you are talking to a close friend who doesn't live in the area and has never seen Thornton Creek. What would you tell them about the creek's importance to you?" The respondents' words were recorded on a card. Later, the residents were asked to sort the cards into groups that seemed similar. The individual groups were content analyzed as to components, categories, and main themes.

2.5 STREAM RESPONSE TO REPLACING LARGE WOODY DEBRIS

Urban stream rehabilitation projects using large woody debris (LWD) are common, particularly in the Pacific Northwest, where LWD is recognized as an important element in physical habitat for salmonids. Six in-stream rehabilitation projects were chosen for this study based on their location in urban watersheds, their use of in-stream log placement as a primary strategy for achieving local rehabilitation goals, and their inclusion of fish habitat enhancement as an objective. The six evaluated projects lay in physically similar watersheds but with widely different levels of human disturbance. Most projects had been built within 4 years of this study (one was 10 years old) and most project lengths ranged from 200-400 m (one was over 1400 m). None included additional measures to reduce urban-induced degradation at the watershed scale.

To determine if projects were successful in improving physical and biological conditions, monitoring was conducted in, and upstream from, reaches where LWD was added. At the projects where pre-project physical data existed, pre- and post-project stream conditions were compared. For projects without pre-project data, post-project conditions were compared to data reported in the literature for Puget Lowland streams and/or to reaches upstream of each project.

Residual pool depths (RPDs), the difference between depth of water in the pool and at the top of the downstream riffle, were measured in the field and calculated from longitudinal thalweg surveys. Pre-project pool numbers were available at three of the projects. Pool counts were converted to average pool spacing, expressed as the distance between pools in units of bankfull channel widths. Two categories of pools were identified: pools formed by wood, and pools formed by other mechanisms. The number of pieces of wood associated with a given pool was also counted.

All pieces of wood in the bankfull channel greater than 10 cm diameter and longer than 1 m were counted. Where pre-project data were available, the movement of LWD in the project reaches was estimated. Any influence of LWD on in-channel sediment storage was identified; where LWD was trapping sediment, the depth of the stored sediment was estimated. The overall volume of sediment in the reach was estimated by measuring the total volume of all alluvial bars in the channel.

The influence of LWD in controlling grade in a given reach was estimated using a longitudinal profile of the channel thalweg. The change in the water surface elevation at LWD steps were summed and divided by the total drop in elevation over the reach to yield the percent of the elevation change controlled by LWD.

Benthic invertebrate samples were collected at five of the six rehabilitation projects and analyzed according to the B-IBI. Monitoring sites were located immediately upstream and downstream of each restoration project. These paired sites were selected to be as similar as possible in all regards except for the presence of added LWD. All but one site was sampled in 1998 and two of the more recently completed projects were re-sampled in 1999. B-IBI scores above and below projects were compared with a paired t-test (Zar 1996).

2.6 SOURCES OF IN-STREAM SEDIMENT

In-stream sediment, particularly fine (i.e. sand and silt-sized) sediment, degrades aquatic resources in a variety of contexts. For salmonids, the flow of oxygenated water through the substrate is a key factor in egg-to-fry survival; the fraction of bed sediment below a threshold size of 0.85 mm (medium-coarse sand; Young 1991) provides a satisfactory index of potentially lethal reductions in permeability. Fine sediment also affects the habitat of benthic invertebrates (Quinn et al. 1992); its degrading influence on B-IBI scores in Puget Lowland streams was shown by Wydzga (1997).

A watershed-scale sediment budget was developed on a developing, mixed-land-use watershed (Issaquah Creek) to determine the relative effects of land-use practices, including urbanization, on sediment supply and delivery into the channel network, and to guide management responses towards the most effective source-reduction strategies (Nelson 1999). Sediment-production processes and rates were stratified by land-use categories and analyzed to emphasize the relative sources of sediment, and in particular the manner(s) in which the influence of urban development is manifest in watershed processes. Fine and coarse sediment production rates were quantified separately, because of their differing expression in the downstream system, and because of differences in the problems and management solutions associated with each. Published yield coefficients for total suspended solids (TSS), nearly all from the Pacific Northwest, were used for many of the urban land uses, including residential and commercial development, construction areas, quarry, and road-surface erosion. Sediment production from agricultural property was estimated using the Universal Soil Loss Equation (USLE) (Wischmeier and Smith 1978). In forested areas, the dominant sediment-generating process was landslides, which, in this watershed, are associated almost exclusively with stream channels. An inventory of slides was made by evaluating conditions along several representative tributary streams where sediment delivery is nearly equivalent to sediment production. Landslide volumes were estimated from length, depth, and width measurements of observed landslide scars adjacent to the channels. The slides were classified into age categories, estimated from vegetative growth, to determine average delivery rates.

The sediment contribution of channel expansion in response to urban-increased discharges was calculated by comparing predevelopment bankfull channel areas (from regional values and modeled forested discharges; King County 1990) and modern measured channel dimensions (Wharton et al. 1989; Booth 1990). The contribution of roads was determined by dividing them into three categories: "paved," "gravel residential," and "gravel forested." Roads in residential areas that are connected to storm sewer systems were not included in the road-surface erosion calculations, because sediment from these roads would have been included in the sediment yield coefficient for urban residential areas. Gravel roads were assigned published unit-length yield coefficients appropriate to their level of use (Reid and Dunne 1984, 1996).

Predictions of the sediment budget were tested with downstream calculations of bedload sediment transport on two reaches on lower Issaquah Creek (King County 1991) and on one reach of Middle Issaquah Creek, using field measurements and flow-duration data (King County 1991) as inputs into a sediment transport equation. Based on the evaluation of Gomez and Church (1989), we have used the Bagnold (1980) equation in this setting. The calculated transport capacity was compared to the estimated upland sediment production in the mainstem of Issaquah Creek. Channel surveys from bridges, spanning as much as 30-50 years between measurements, were also reviewed to determine general sedimentation trends within the mainstem channel of Issaquah Creek. The delta growth rate of the Issaquah Creek delta, the repository for much of the fine sediment transported down Issaquah Creek that has been expanding into Lake Sammamish for at least 50 years, was evaluated using multiple historical aerial photographs from 1944 through 1995. The visible portion of the delta was measured and adjusted for slope to estimate the volume of annual growth of the delta.

2.7 SUMMERTIME STREAM TEMPERATURES

Because high summertime stream water temperature is an assumed consequence of human development with potentially severe biological consequences, we evaluated the likely magnitude of this factor on aquatic health. Yet this evaluation requires both assessment of the specific study sites and a regional context for the specific measurements. A model could nominally accomplish this goal, but the uncertainty in the results led us to collect a sufficient number of spatially separated measurements under uniform climatic conditions to define the pattern of high temperatures across the region. We therefore coordinated simultaneous temperature measurements, using identical protocols, at broadly distributed locations that spanned a variety of topographic, geologic, and human influences (Booth and Wall 1998). More than 100 individuals, representing approximately 20 different agencies and community groups, collected more than 600 temperature measurements across the south-central Puget Lowland from

3:00 to 5:00 PM PDT (2200 to 2400 UTC), on August 19th, 1998, August 3rd, 1999, and August 4th, 2000. Sites were arrayed to provide coverage of drainage areas ranging from 100 km^2 down to about 1 km^2, approximately the typical lower limit of perennial flow (Konrad 2000). Both temperature data (air and water) and site data (flow conditions and riparian canopy) were recorded. For flow conditions the site-data categories were *free-flowing stream*, *sluggish flow*, *stagnant pool(s)*, and *no water*; for riparian canopy, *full sun*, *partial (shrubs dominant)*, *partial (trees dominant)*, and *full shade*.

The data were analyzed through both regression relationships (particularly between water temperature, land cover, and riparian canopy conditions), and spatial analysis. Land-cover data derived from the 1998 Landsat image were used along with geologic and soils data compiled from those published maps currently available in digital format (Ralph Haugerud, USGS, pers. comm. 2000). Several dozen sites were independently visited by two (or more) field surveyors to evaluate data accuracy.

2.8 RESTABILIZATION OF URBAN CHANNELS

The final component of this study evaluated one important aspect of the effects of *time*—can stream channels, which are well known to change their form as a result of watershed urbanization, restabilize under subsequent conditions of constant urban land use without direct intervention through rehabilitation? Streams in seven developed and developing watersheds were evaluated for their channel stability and degree of urbanization, using field and historical data. Field sites were located in straight, plane-bed reaches (as defined by Montgomery and Buffington 1998) to limit the effects of local geomorphic influences on observed channel stability. Cross sections and bankfull channel boundaries were measured; sites were also grouped into four stability categories by visual observation of indicators such as bank erosion and vegetation extent, determined independently by two field observers to assess reproducibility. The bank stability ratings for sites on three streams were compared with multiple cross sections previously surveyed over the past decade (Booth and Henshaw 2001) to test the observational technique as an indicator of long-term channel instability. The "relative bed stability index" of Olsen et al. (1997), was evaluated at all sites from pebble-count data (Wolman 1954) and channel geometry. This metric compares the critical bed shear stress required to mobilize the D_{84}-size particle (τ_{c84}), a common measure of the material that maintains the framework of the bed sediment, to bed shear stress at bankfull flow (τ_{bf}),

Historical channel information was collected to help establish patterns of change over time and to assess long-term channel stability; the most useful were previously measured cross sections, USGS rating curves, and bridge inspection records. Changes in land cover in each watershed were coarsely characterized from aerial photographs (1970, 1971, 1980, and 1988) and previously classified 25-meter resolution Landsat Thematic Mapper images (1991 and 1995) for each watershed (see Hill et al. 2000). Land cover was discriminated only as to "undeveloped" and "developed" areas, of which the latter consisted of residential, commercial, and industrial land uses and included grassy areas with likely high runoff potential (Wigmosta and Burges 1997).

3 RESULTS

The results of this work lead from a robust characterization of land cover, through our primary indicator of aquatic-system condition, into an examination of some of the critical determinants of that condition. Because we did not explore each of the five environmental features of aquatic systems (Table 1) in equal detail (and some not at all), this study is not a comprehensive diagnosis of the causes of degradation in urban streams. Instead, we focused on those features that are affected most ubiquitously in the urbanizing landscape; through their analysis, we provide not a cookbook solution to every degraded stream but instead a guide for where to look first for some of the most severe problems, and for the types of rehabilitation strategies that have the greatest chance of success.

3.1 LAND-COVER CLASSIFICATION

The result of the Landsat image classification was full GIS coverage of the Puget Lowland at 30-m resolution into seven classes of land cover— forested, grass/shrub, open water, bare earth, intense urban, grassy urban, and forested urban. Because the training sites were exclusively in lowland areas and focused on urban-related land covers, the classification should be most useful in these areas and progressively less accurate in more distant, high-relief areas or those with significantly different vegetation communities. To test the accuracy of the classification, we also made two related checks based on the comparison of GIS-classified pixels with their corresponding observer-classified orthophotos.

The first accuracy assessment was a classic error check, wherein classified pixels are judged to be "correctly" or "incorrectly" identified. The criteria of each class, determined from the results of the signature extraction for the 1998 image, are listed in Table 7. The analysis for the 1998 image (Table 8) shows an overall accuracy of 77 percent, with the worst performance for the two classes with the greatest mixture of land covers: *grassy urban* (most pixels were "more urban" than anticipated) and *forested urban* (the misclassified pixels were both more and less urban than expected).

For our intended application, however, these "misclassifications" were not important, because we were concerned not with a correspondence with preestablished categories but with a robust characterization of land cover. We therefore took a second approach to accuracy assessment—accepting the pixel classification as a given, and simply characterizing *a priori* the land cover associated with each of the seven categories (open water, coniferous vegetation, deciduous vegetation, grass/shrub, intense urban, grassy urban, and forested urban). From this approach, values for each of the 56 pixels in each category were combined to yield averages and standard deviations for the different *land covers*, visible in an orthophoto, for each of the seven *classes*. Of greatest applicability to this study, impervious-area percentages (combining pavement and bare earth) for the seven classes are listed in Table 9.

Table 7: Criteria for "correct" land-cover classification.

	Water	**Trees**	**Grass**	**Bare earth**	**Paved**
Forested Urban		≥25%			≥20% & <60%
Grassy Urban		<25%	≥25%		<60%
Paved Urban					≥60%
Grass/Shrub/ Crops			≥50%		<20%
Water	≥80%				<20%
Bare Soil			<20%	≥75%	
Forested		≥70%			<20%

Table 8. Error matrix for the 1998 classification.

		OBSERVED (from orthophotos)								
EXPECTED (i.e. pixels as classified)		forested urban	grassy urban	paved urban	Grass/ shrub/ crops	water	bare soil	forested	**Row Total**	Consumer's accuracy*:
	Forested urban	27	5	4	9	0	0	5	**50**	54%
	Grassy urban	0	9	35	6	0	0	0	**50**	18%
	Paved urban	0	0	47	1	0	0	2	**50**	94%
	grass/shrub/ crops	0	0	0	49	0	0	1	**50**	98%
	Water	0	0	0	0	50	0	0	**50**	100%
	bare soil	0	1	7	3	0	39	0	**50**	78%
	Forested	0	0	0	1	0	0	49	**50**	98%
	Column Total	**27**	**15**	**93**	**69**	**50**	**39**	**57**	**350**	
Producer's accuracy**:		100%	60%	51%	71%	100%	100%	86%		**77% = overall accuracy rate**

* "Consumer's accuracy" is the percentage of pixels of a given class that *actually* meet that class's criteria.

** "Producer's accuracy" is the percentage of a given land-cover type that is correctly classified.

These average values follow the expected trends for the different classes; however, actual land covers for individual pixels of the same class can vary widely. The standard deviations for each cover type in each class are generally of the same magnitude of the average values themselves; estimates of land cover for a single (or a small number) of pixels have a high probability of diverging significantly from the average values. Statistical analysis (Hill et al. 2000) indicate that a minimum area of about 2-3 square kilometers is necessary to reduce the likely error in impervious-area percentage to a percent or two. In all watersheds evaluated in this study this minimum threshold is exceeded, and in most cases by at least an order of magnitude.

3.2 BIOLOGICAL CONDITION AT MULTIPLE LAND-COVER SCALES

Across all study sites, urban land cover correlated approximately equally well with B-IBI at each of the three spatial scales (Figure 6): ***subbasin*** (i.e. the entire watershed area contributing to the sample point; $r^2 = .54$, $p < 0.001$), ***riparian*** (a 200-m-wide buffer on each side of the stream extending the full length of the upstream drainage network; $r^2 = .56$, $p < 0.001$), and ***local*** (a 200-m-wide buffer on each side of the stream extending 1 km upstream; $r^2 = .50$, $p < 0.001$; Morley and Karr, *in review*). Because riparian and subbasin land cover so closely correlated with each other ($R^2 = .95$, $p < 0.001$), we focus primarily on contrasting subbasin and local scale effects for the remainder of this paper. Of the ten metrics that comprise B-IBI, seven were better predicted by subbasin rather than local land cover. Stonefly taxa richness, relative abundance of tolerant taxa, and relative abundance of predator taxa were the three exceptions where the relationship with local land cover was stronger.

Multiple sample sites on Little Bear and Swamp Creek provided further opportunity to examine the role of spatial scale in land cover urbanization—but with a basin rather than regional focus (Morley and Karr, *in review*). Within these two basins, the spatial pattern of development differed in several important ways. At the subbasin scale, Swamp Creek was *more* urbanized than Little Bear, with 70% vs. 54% urban land cover, respectively. But at the local scale, the reverse pattern held: Swamp Creek had a more forested riparian corridor immediately upstream of sample sites than did Little Bear. In Little Bear, B-IBI variability was strongly related to local land-cover urbanization (Figure 7a). The maximum score (B-IBI = 40) on this stream occurred at the site with the least amount of local urban land cover (32%), in comparison to the low (B-IBI = 16) with 71% local urban land cover. Extent of subbasin urban land cover varied less (49 to 54%) across the nine study sites on Little Bear Creek, and was not correlated with B-IBI. In Swamp Creek, neither subbasin nor local urban land cover varied substantially (Figure 7b), an observation that is concordant with limited variability in B-IBI (22–32 [25% of the range] vs. 16–40 [60%] in Little Bear).

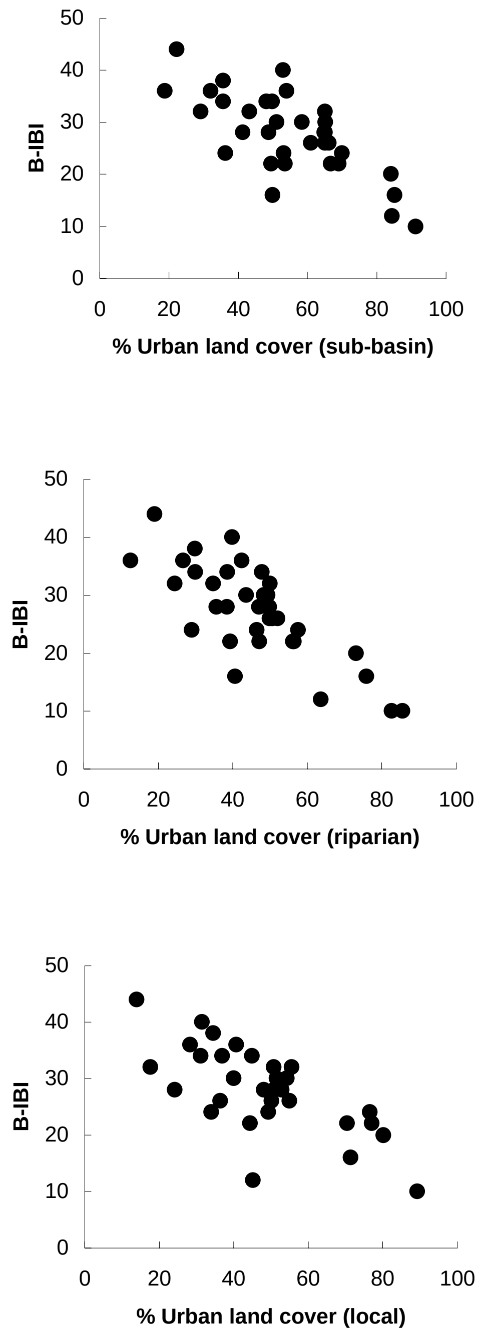


Figure 6. Relationship of urban land cover to B-IBI at each of the three spatial scales investigated.

Table 9. Average values of impervious-area percentages, determined from orthophotos for each of the seven classes.

Categories from the classified Landsat image:	**Observed impervious-area percentages:**
"UNDEVELOPED"	
Open water	0
Forested	3
"DEVELOPED"	
Grassy/shrubby vegetation	5
Bare earth	98
Forested urban	38
Grassy urban	74
Intense urban	92

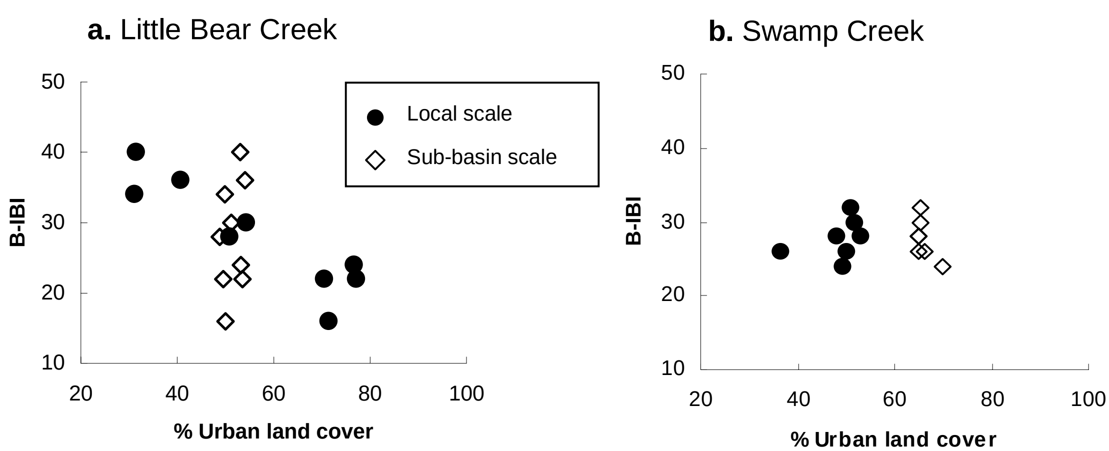


Figure 7. Variability in B-IBI scores as functions of percent urban land cover in (a) Little Bear Creek and (b) Swamp Creek. In Little Bear Creek, scores were strongly influenced by the *local* land cover; in Swamp Creek, neither of the spatial scales (nor the B-IBI scores) showed much variability.

3.3 HYDROLOGIC CHANGES

The hydrologic analyses for this study emphasized the conditions that respond to changes in watershed urbanization and that have a strong, plausible influence on biological health. These conditions include the pattern of stream flow over one or more years, as expressed by three alternative new hydrologic metrics, and the probability and extent of streambed disturbance during a relatively common flood event, the median annual flood.

3.3.1 Annual and Inter-Annual Stream Flow Patterns

Three hydrologic measures that were evaluated capture the storm- and base-flow patterns over these longer time scales. We recommend them as new metrics with which to characterize the magnitude of urban influence on stream flow. The metrics are (1) the fraction of a year that the daily mean discharge rate exceeds the annual mean discharge rate (T_{Qmean}); (2) the fraction of a multiple-year period that the discharge rate of a specified flood quantile is exceeded ($T_{X\ yr}$ is the cumulative duration that stream flow exceeds the discharge of a flood occurring on average 1/X times per year); and (3) the coefficient of variation of the annual maximum flood (CV_{AMF}). Differences in both T_{Qmean} and $T_{X\ yr}$ between urban and suburban streams are expected because differences in peak discharge and recession rates, and the lack of differences in annual discharge, are readily observed in gage records for these two groups of streams.

1. Fraction of Time That Mean Daily Discharge Rate is Exceeded

The hydrologic effects of urban development are evident in flow-duration curves normalized by mean discharge, even amidst the variability generated by physiographic differences among the basins in the Puget Lowland. In urban streams, the fraction of time that the mean discharge rate is exceeded, T_{Qmean}, (i.e., $Q_{daily}/Q_{mean} > 1$) generally is less than 30%, while in suburban streams T_{Qmean} is generally greater than 30%. The lower values of T_{Qmean} in urban streams result from more rapid storm flow recession and lower wet-season base flow. The difference in T_{Qmean} between urban and suburban streams corresponds to the observation of lower discharge in urban streams for the 20 to 40% quantiles of area-normalized flow-duration curves.

T_{Qmean} generally varies inversely with urban development among Puget Lowland streams (Figure 8). For WY 1989 to 1998, the mean value of T_{Qmean} for 11 urban streams was smaller (0.29) than for 12 suburban streams (0.34). The difference is statistically significant ($p < 0.01$ using Student's t-test of samples with equal variance). All but one suburban stream (Huge Creek) had values of T_{Qmean} greater than or equal to 0.32; all but one urban stream (Clover Creek) had a value of T_{Qmean} less than or equal to 0.31.

Independent of urban development, larger streams typically have more attenuated stream flow patterns than smaller streams and, as a consequence, higher values of T_{Qmean} (Figure 9). The mean value of T_{Qmean} for the larger streams (drainage greater than 30 km^2) is 0.35 and significantly greater than the mean value for the smaller streams (drainage area < 30 km^2) which was 0.28. An analysis of the mean values of T_{Qmean} between urban and suburban streams with drainage areas greater than 20 km^2 indicates significantly lower values in urban streams ($p < 0.01$ based on Student's t-test of samples with unequal variance). Thus, T_{Qmean} may be a reliable indicator of urban development only for comparison between stream basins with similar drainage area and, potentially, other physiographic factors.

In a stream with stable land use, T_{Qmean} varies little from year to year. The coefficient of variation for annual values of T_{Qmean} during the period of 1989 to 1998 was less than 17% for all of the streams except a small tributary to Miller Creek. Since T_{Qmean} does not vary much between years, it can be estimated reliably from a relatively short (e.g., ~ 10 years) stream flow record. In contrast, T_{Qmean} changes during periods of urbanization. Annual values of T_{Qmean} for Mercer Creek illustrate a systematic decline during a period of urban development from 1960 to 1998 (Figure 10).

2. Fraction of Time That Stream Flow Exceeds the Magnitude of a Frequent Flood

The fraction of time that stream flow exceeds the magnitude of a flood with an average frequency of 1/X times per year, $T_{X\ yr}$, compares the frequency of a discharge to its cumulative duration. $T_{X\ yr}$ is influenced by the frequency of storms, the duration of storm flow, and streamflow recession rates after storms. Streams with short-duration storm flow and rapid storm flow recession have low values of $T_{X\ yr}$.

Values of $T_{X\ yr}$ were estimated for 11 Puget Lowland streams from flow-duration curves for a series of frequent floods. Both flow duration and flood frequency were based on 15-minute stream flow data, with the exception of Mercer Creek where only daily mean discharge data were available to construct a flow-duration curve. The period of record varies among the streams from 4 to 10 years.

The cumulative duration of time that stream flow exceeds the magnitude of a flood of a given frequency is systematically shorter in urban streams than suburban streams. Although almost any flood magnitude could be used to demonstrate these results, we chose a flood occurring twice a year on average (i.e., 0.5 yr flood), because it has plausible geomorphic and biological significance—it occurs relatively frequently and is sufficiently large to transport streambed sediment. The cumulative duration of time that the stream discharge exceeds the magnitude of $T_{0.5\ yr}$ is less than 0.01 for all of the urban streams and more than 0.01 for all of the suburban streams. $T_{0.5\ yr}$ distinguishes between streams with moderate levels of urban development (Cedar tributary 0308; Swamp, North, and May Creeks) from those with lower levels (Rock, Jenkins, and Covington Creeks). Moreover, $T_{0.5\ yr}$ varies with road density within these groups. The relationship does not appear to vary with drainage area, as demonstrated by the relatively small variation between the curves for North Creek (100 km^2) and Cedar Tributary 0308 (2.7 km^2) which have similar, moderate levels of urban development in their basins.

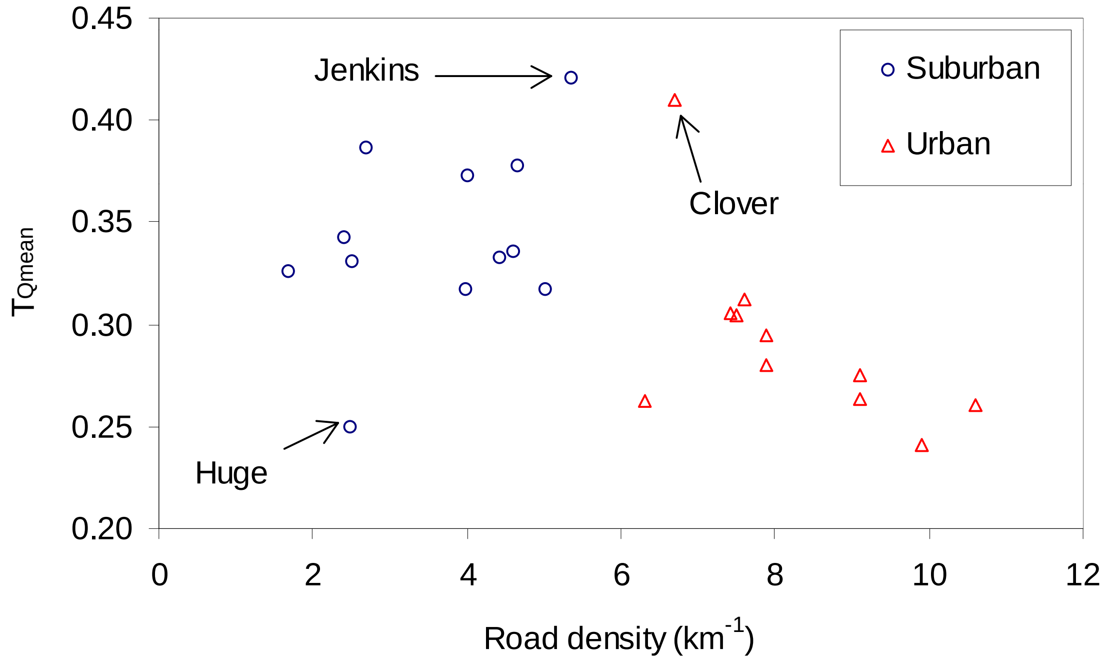


Figure 8: Fraction of year that mean discharge rate is exceeded (T_{Qmean}) as a function of road density.

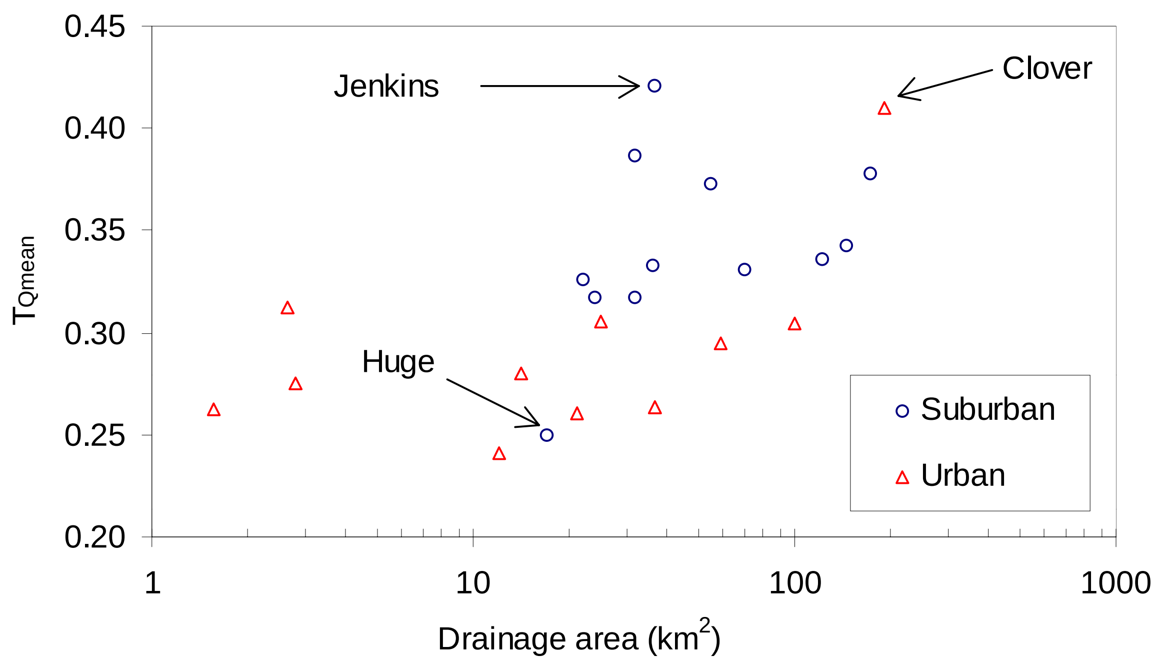


Figure 9: Fraction of year that mean discharge rate (T_{Qmean}) is exceeded as a function of drainage area for 18 streams during WY1989-1998

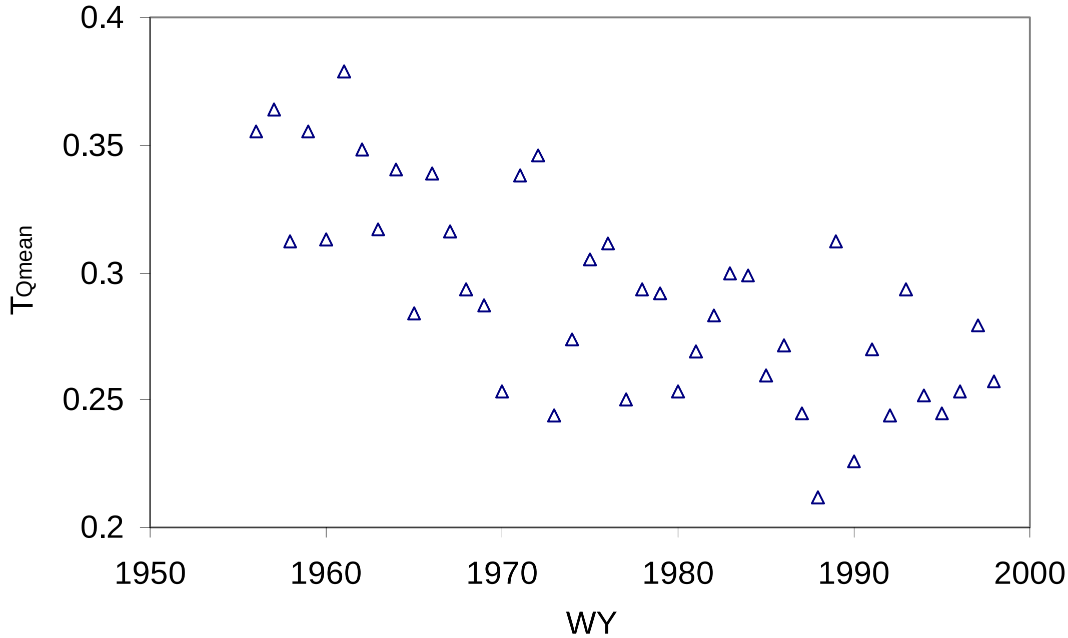


Figure 10: Fraction of the year that daily mean discharge exceeded annual mean discharge rate (T_{Qmean}) for Mercer Creek for WY 1954 to 1998

3. Coefficient of Variation of the Annual Maximum Flood Distribution

Increased flood magnitude is a characteristic effect of urban development on stream flow. Differences in flood patterns between urban and suburban streams were evaluated by comparing the annual maximum flood distributions for 25 Puget Lowland streams spanning the range of urban development in the region. The maximum instantaneous (or 15-minute mean) discharge rate for each water year was selected for the period WY 1989 to 1998. The geometric mean annual maximum peak rate and the area-normalized value of the mean were calculated for each stream. Flood distributions for an earlier period (WY 1960 to 1969) were constructed for 12 of the streams to assess changes over time in the flood distributions of individual streams.

Simulated and observed effects of urban development show a differential increase in the magnitude of smaller, frequent floods relative to larger floods. As a result, the coefficient of variation of annual maximum floods (CV_{AMF}) in a stream should decrease in response to urban development.

The area-normalized peak discharge rates of mean annual floods are higher in urban streams than suburban streams, and the variation in the flood distribution for urban streams is lower than the variation in the flood distribution for suburban streams (Figure 11). The urban streams had a mean CV_{AMF} of 0.5 while the suburban streams had a mean CV_{AMF} of 1.0. However, the lower values of CV_{AMF} in urban streams may be due in part to the effects of different basin sizes (Smith 1992). Because of the long gage record required and temporal variability in this metric, CV_{AMF} may not be useful for characterizing hydrologic change due to land use in a single stream basin, but it may discriminate between urban and suburban streams for a common period of time.

These three hydrologic measures characterize annual and multiple-year stream flow patterns over a range of temporal scales reflecting progressively less common hydrologic conditions. Each of these metrics has particular strengths and limitations (Table 10). The fraction of a year that stream flow is greater than the annual mean discharge rate (T_{Qmean}) is a reliable indicator of hydrologic change over time in a stream basin, but it varies with drainage area and other physiographic conditions and so should only be used to compare similar stream basins. In contrast, the cumulative duration that the discharge rate exceeds the magnitude of a frequent flood ($T_{0.5\ yr}$) is a robust indicator of urban development in the Puget Lowland showing little sensitivity to drainage area. $T_{X\ yr}$, however, must be estimated using discharge data of high temporal resolution (e.g., 15-minute or hourly) from a period of multiple years. The last metric investigated, the coefficient of variation of annual maximum floods (CV_{AMF}), can serve as a basis for comparing the high flow regime of a group of streams during a common time period, but it is highly variable over time and so it is not a reliable indicator of the hydrologic consequences of land use changes in a stream basin.

The biological conditions of streams vary directly with each of these stream flow metrics. The relationship between B-IBI and stream flow patterns is less variable for T_{Qmean} (Figure 12) than for CV_{AMF} (Figure 13). B-IBI ranges by 10 points in the neighborhood of any given value of T_{Qmean} but by over 20 points for any value of CV_{AMF}. The relationship between B-IBI and $T_{0.5\ yr}$ is the least variable (Figure 14), but only 8 streams were analyzed.

The character of macroinvertebrate assemblages as reflected by B-IBI are more closely related to annual stream flow patterns, as represented by T_{Qmean} and $T_{2/yr}$, than to interannual variation in the distribution of large floods, as represented by CV_{AMF}. B-IBI generally increases increasing T_{Qmean}, indicating higher taxonomic diversity, more complex trophic structure, and less dominance (relative abundance of the most abundant organisms) of the most common taxa in the macroinvertebrate assemblages.

The relationship between T_{Qmean} and B-IBI indicates the important influence of the seasonal distribution of stream flow on the biological condition of streams. In streams with relatively high base flow, T_{Qmean} will be large, indicating fewer days in a year when the discharge rate is less than the annual mean flow rate. In this case, we expect any process or condition dependent on stream flow (e.g., the area or depth of aquatic habitat available in a stream, the downstream transport of nutrient through a reach, temperature) would be less variable during the year with fewer days of extreme values.

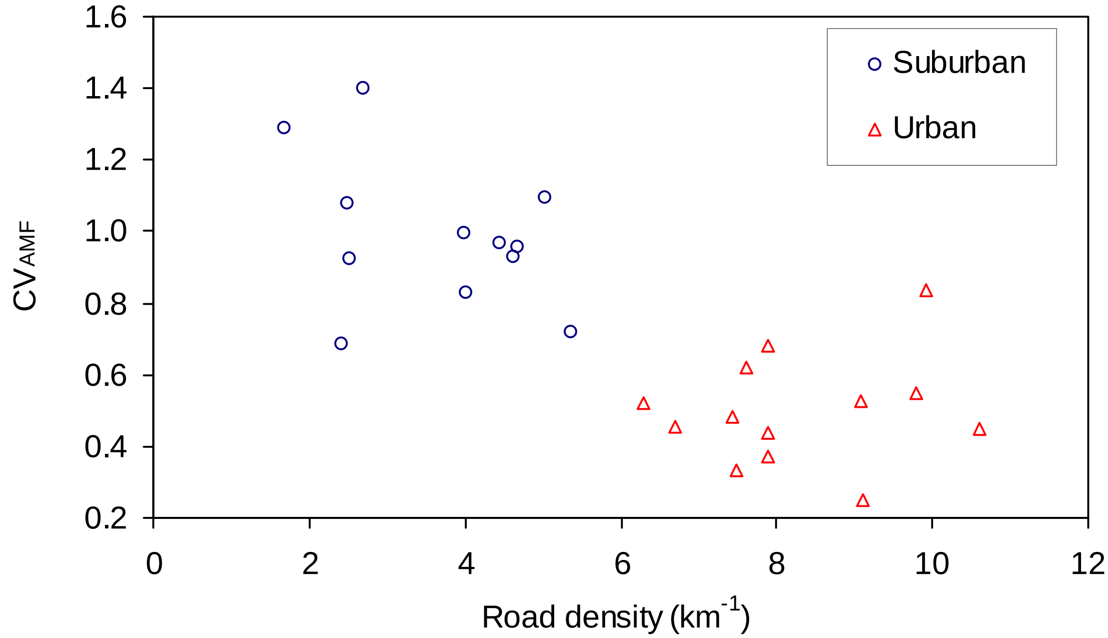


Figure 11: Coefficient of variation of annual maximum flood as a function of road density during WY 1989 to 1998.

Table 10: Metrics indicating the hydrologic effects of urban development

Metric	Useful to Identify Changes Over Time?	Sensitive to Basin Size?	Data needs	Hydrologic Focus	Applicability
T_{Qmean}	Yes	Yes	Daily flows for ca. 10 years	Wet-season base flows relative to peak discharges.	Comparison of change in urban effects in one basin over time, or between basins of similar size
$T_{0.5\ yr}$	Not tested	No	15-minute or 1-hour flows; multiple-year record	Common wet-season storm flows relative to peak discharges.	Comparison of urban effects between basins having high-resolution gage data
CV_{AMF}	No	Yes, for basins <20 km^2 and > 200 km^2.	Annual peak discharge	Large storm peaks.	Comparison of hydrologic influence between basins over same period of time

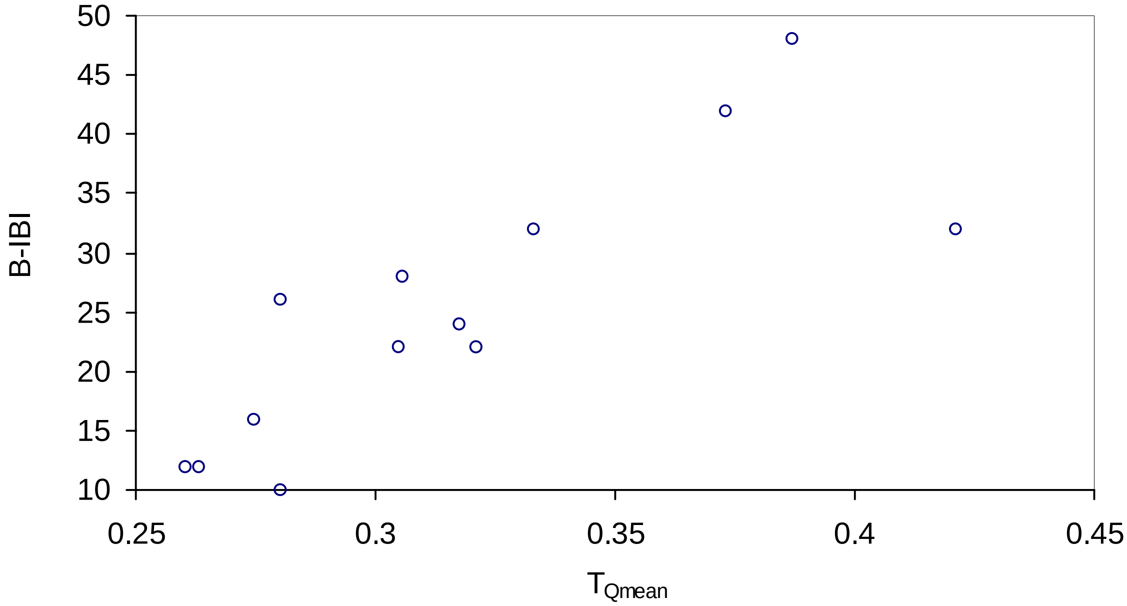


Figure 12: Benthic index of biological integrity (B-IBI) plotted against fraction of time that daily mean discharge rate exceeds annual mean discharge rate (T_{Qmean}) for 13 Puget Lowland streams.

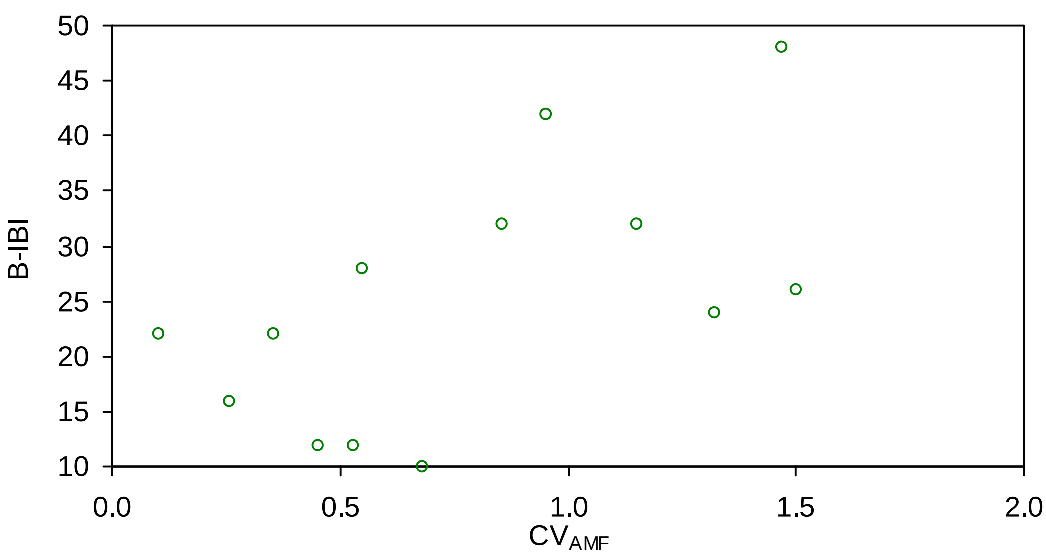


Figure 13: Benthic index of biological integrity (B-IBI) plotted against the coefficient of variation of the annual maximum flood (CV_{AMF}) for 13 Puget Lowland streams.

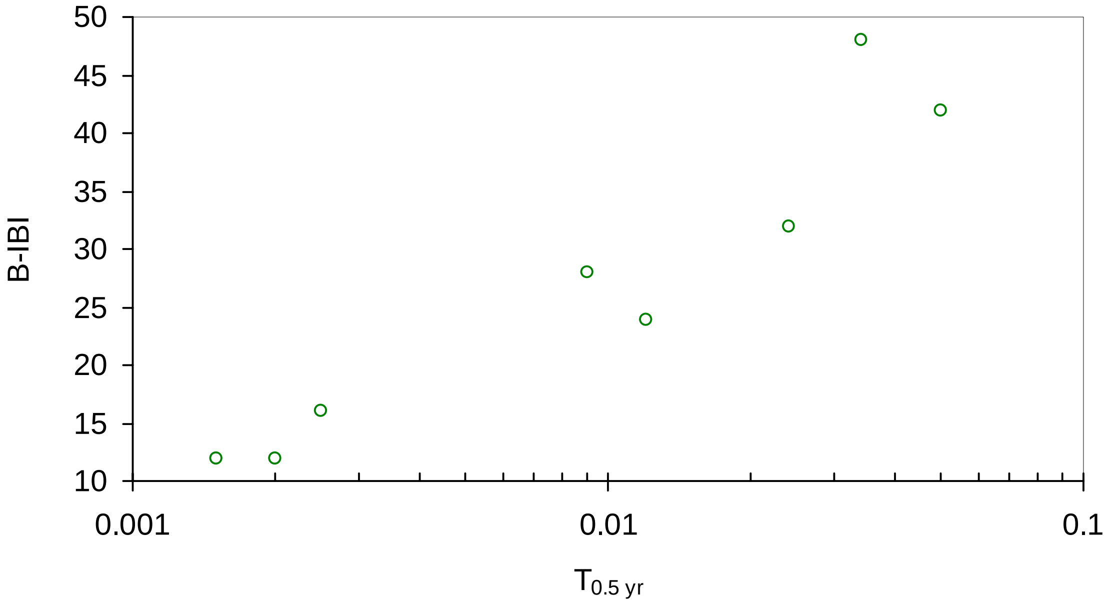


Figure 14: Benthic index of biological integrity (B-IBI) plotted against the fraction of the period of record that discharge exceeded the magnitude of a "1/2 yr" flood ($T_{0.5.yr}$) for 8 Puget Lowland streams.

3.3.2 Disturbance During the Median Annual Flood

The estimates of partial entrainment (PE) for the median annual flood (Q_{2yr}) show a strong relationship with land use. The values range from 0.17 for Jenkins and Soos creeks to 0.96 for Des Moines Creek, with an average value of 0.55 for all sites. None of the highly urban streams are likely to have low levels of disturbance during the median annual flood. PE is less than 0.30 only in streams where road densities are less than 6 km/km^2 (Rock, Covington, Big Bear, Soos, and Jenkins Creeks) (Figure 15). Low levels of development do not assure low levels of disturbance, however: Big Beef, Newaukum, and Huge creeks have road densities less than 3 km/km^2, but PE is greater than 0.50 during the median annual flood at these sites.

The extent of disturbance during the median annual flood in streams with intermediate levels of urban development ranges widely. At the downstream sites on May Creek, where the road density is 5.0 km/km^2, the values of PE were 0.50 and 0.62. In contrast, the sites on Jenkins Creek, where the road density is 5.4 km/km^2, had PE values of 0.01 and 0.09. Indeed, floods approximately equal to the median annual maximum flood were observed to entrain most of the surface material at the May Creek sites but little of the surface material at the Jenkins Creek sites.

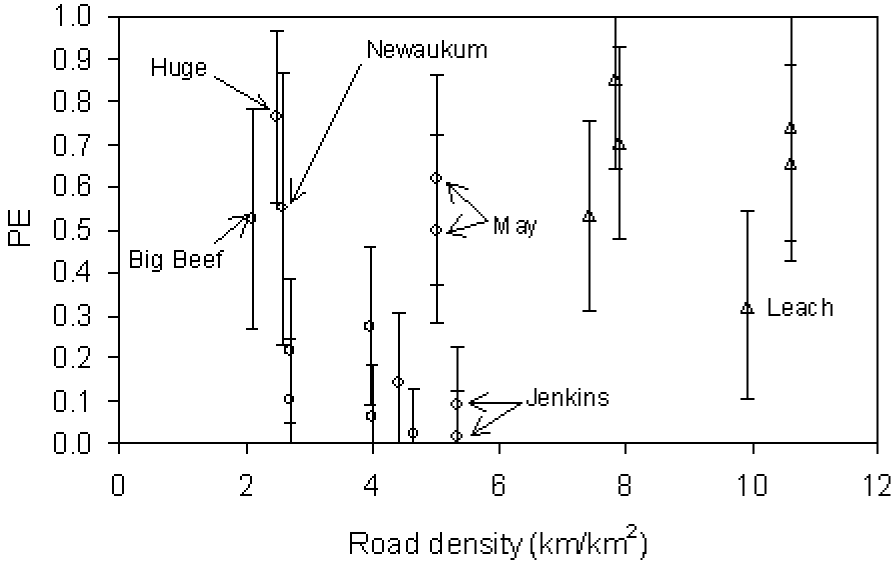


Figure 15: Partial entrainment (PE) during the median annual maximum flood, with error bars ± 1 standard deviation, plotted against road density

The extent of stream-bed disturbance during the median annual maximum flood does not vary consistently with urban development in a stream basin; stream flow *patterns* provide a better explanation for the predicted differences in the extent of disturbance between the sites. Under the hypothesis of hydrologic control, the extent of bed disturbance during the median annual flood (PE) should be a function of the ratio of the peak magnitude of the median annual flood to the magnitude of the reference discharge, for which we use $Q_{0.05}$. Since τ_0* is relatively constant among streams for $Q_{0.05}$ (Figure 16) and τ_0 increases with Q among the sites, PE will necessarily vary with Q_{2yr}/Q_{ref}.

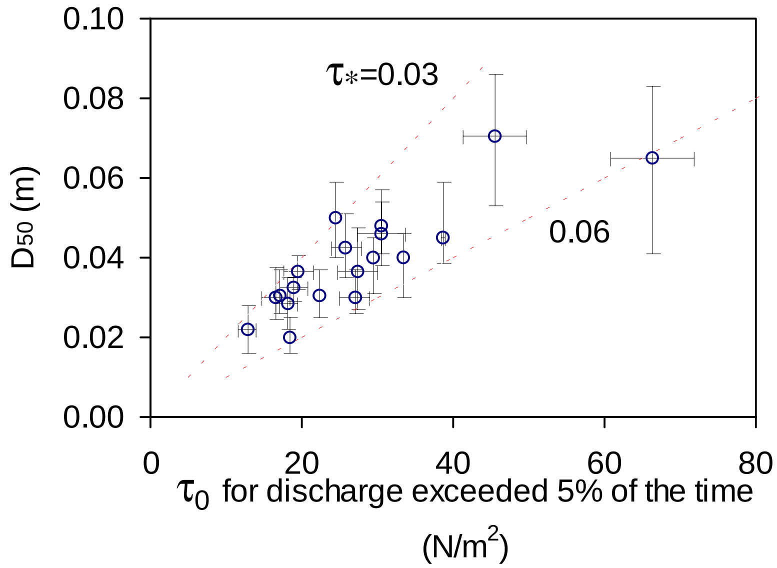


Figure 16: Median of the particle-size distribution for the gravel bar surfaces as a function of shear stress for discharge exceeded 5% of the time with 95% confidence intervals.

Among the reference discharges, $Q_{0.05}$ had values of τ_0* with the lowest variability and a mean value closer to the center of the hydraulic criteria for size-selective bed load transport than the other hydrologic statistics. PE at the sites varies directly with $Q_{2\ yr}/Q_{0.05}$ (Figure 17) illustrating a general trend of increasing extent of bed disturbance as the Q_{2yr} is larger relative to $Q_{0.05}$. The concordance of the sites with the general trend in Figure 17, versus the scatter in Figure 15, supports a hypothesis of hydrologic control over stream bed disturbance patterns regardless of the level of development in a stream basin, though the extent of disturbance during the median annual flood varies widely for streams where the $Q_{2\ yr}$ is 2 to 5 times the magnitude of $Q_{0.1}$.

3.4 INDIVIDUAL BEHAVIORS OF STREAMSIDE RESIDENTS

Seattle streamside experts believe behavior by individuals that leads to stream degradation is the norm. The experts listed 46 different behaviors; 85% were negative actions, while only 15% were positive. When these data were analyzed spatially some activities, such as buffer clearing, seemed to occur in all areas, while other activities such as clearing for firewood occurred mainly in the far suburbs. Also dumping occurred everywhere, but was cited less frequently where housing prices were higher.

When asked to verify findings, the experts unanimously agreed they believed the negative results were accurate and believed the major causes of the public's negative behavior were ignorance of biology and connections between stream health, human health, and cumulative impacts. One respondent echoed the rest--"people think first of their personal, financial or aesthetic concerns and what the stream needs secondarily. Even ardent conservationists mostly fall into this group."

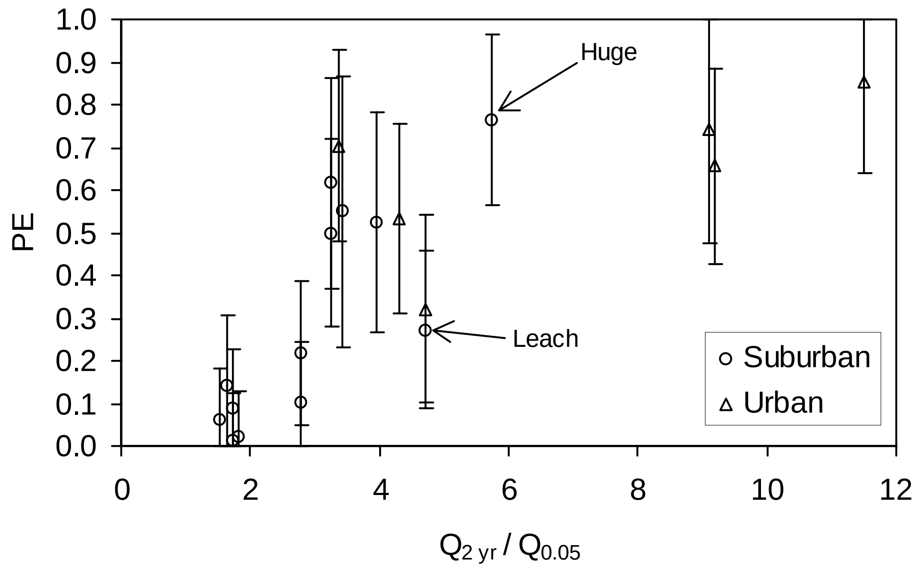


Figure 17: Partial entrainment (PE) during the median annual maximum flood, with error bars ± 1 standard deviation, plotted against the ratio of the flood's discharge (Q_{2yr}) to the discharge exceeded 5% of the time ($Q_{0.05}$).

Few experts believed regulations were a solution. The most mentioned solutions were to: 1) encourage individual stewardship, 2) increase knowledge on how an individual can make a difference, and 3) increase biological education for the public.

The analysis of means of the mailed survey results shows *ecological care* rated higher than *privacy* or *unique home landscapes*. This is true for each stream corridor studied and all the responses taken together. However, the differences between the mean values for the three categories were not statistically significant. In response to the general question on the mailed survey--what are the three "most important considerations in the landscaping or gardening," less than 10% indicated that any ecological considerations were important. These minority responses included "planting native species, helping salmon habitat, creating song bird habitat, and composting." The overwhelming response (>75%) to this "important consideration" question, was "low maintenance." Many respondents repeated this three times on their survey.

The content analysis of photo surveys of the homes where "ecological care" rated as the highest goal did show some ecological care behaviors such as composting, but no behaviors that could be described as stream-side rehabilitation or restoration. The most prominent "ecological care" behavior was compliance with corridor buffer regulations in the newer subdivisions on lots with a steep grade separation between the backyard and the stream. On the other hand, no one had planted buffers in older subdivisions where the trees had previously been cleared.

In four adjacent backyards (10% of the 40 photo surveyed) highly degrading activities were recorded. These included clearing of all vegetation down to the stream edge with resulting erosion, spraying of herbicides to kill vegetation in the buffer, regrading steep banks into paved terraces for sport courts, and using the corridor as a trash dumping area.

In four photo-surveyed backyards (10%) elaborate and special landscape designs had been created using dug ponds, in two cases, a series of ponds, accessing the high ground water adjacent to the stream. In one case we recorded a grassed stream edge of more than 200 feet with two concrete burial vaults set into the bank (salmon rearing boxes as described by the resident). On this site they had a series of hoses leading from upstream into the boxes. They were proud to tell us that each year they obtained hatchery fry and raised "silver" salmon and always had neighborhood gatherings and parties to watch the "sockeye" salmon spawning. Clearly, some residents place value on their direct experience with fish.

In "older" suburban sites (>10 years old), we photo-recorded many backyards with benches located in grass areas along the stream edge. In the newer subdivisions where the buffer was mostly intact, we also recorded stream side benches at the end of a path leading through the buffer from the family's part of the backyard. These were often simple settings where one person might sit and contemplate nature. Clearly, people desire the direct connection with the water.

The results of the 3CM interviews (the Conceptual-Content Cognitive Map of Kearney and Kaplan 1997) in the Thornton Creek watershed demonstrated that there are differences among the three groups. The "creekside involved" residents most often listed personal connections, aesthetics, flow of the water and their connection to the community as the more important creek factors, whereas "creekside-non-involved" residents listed property issues and erosions as more important creek factors. The "non-creekside but involved" residents listed education and wildlife habitat as the more important creek components.

No overall themes emerged from the 3CM results for the "creek-side uninvolved" group, while difference in the general theme between the other two groups became one of scale due to proximity to the creek. A personal descriptive scale was the dominant theme for those involved who lived on the creek, while a community scale and ecological theme dominated the response for those involved not living on the creek. Seventy percent of the 3CM responses indicated an emotional health connection to the creek, mainly a positive response. But no respondent indicated an actual physical connection between the health and conditions of the creek and one's personal physical health.

3.5 STREAM RESPONSE TO REPLACING LARGE WOODY DEBRIS

Results of the evaluation of instream projects using large woody debris displayed several consistent themes. LWD loadings were highest—in the range of least degraded urban streams—in unanchored projects (Figure 18). Only one of the streams, however, had LWD frequency considered ideal for a natural stream (Bisson et al. 1987; WAFPB 1997). At the projects where the wood was anchored, LWD loadings were lower and typical of moderate to highly degraded urban streams and clear-cuts. At all projects, typically less than one-third of the added LWD came in contact with the low-flow channel or obstructed at least one-third of the channel width. Where LWD was anchored or large, a higher fraction of the LWD was in the low-flow channel and obstructed flow. Where LWD was the most mobile, less than one-fifth of the pieces obstructed more than 30% of the flow.

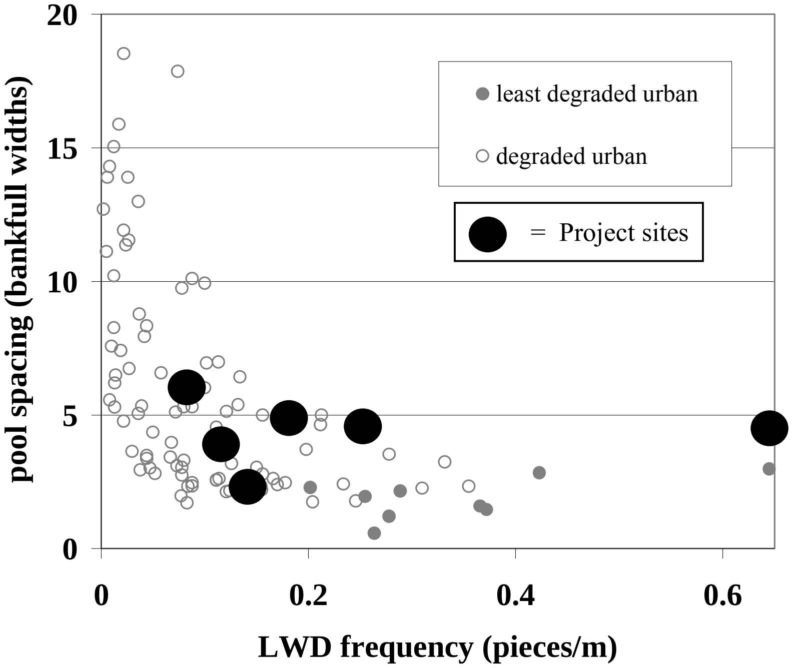


Figure 18. Large woody debris loading and pool spacing at the six project sites in comparison to other urban channels in the region.

Since the projects were installed, all had experienced discharges greater than the 2-year flood peak flow rates, and three sites experienced approximately 10-year flows. No anchored LWD moved at any of the project reaches, and where over 50% of the unanchored LWD were key pieces there was also no significant LWD movement. In the projects with unanchored LWD and few or no key pieces, however, LWD movement was documented.

Post-project pool spacing was not correlated to LWD loading (Figure 18). At three sites, pool spacing was wide compared to the least degraded urban streams with the same amount of LWD. Where the LWD was anchored, pool spacing was most similar to the forested and least-degraded urban streams despite low LWD frequencies. In the three project reaches where pre-project data existed, pool spacing shortened after LWD was added.

Where there was no pre-project information on pools, the influence of added LWD on pools was evidenced by the high proportion of pools formed by added LWD. In each of the project reaches, 50-80% of the pools were formed by added LWD, a proportion comparable to forested streams (Montgomery et al. 1995; Beechie and Sibley 1997; Nelson 1999). More of the added LWD was associated with pools where the LWD was anchored (30-70%) than projects where LWD was unanchored (15- 18%). In forested streams, 20-40% of LWD was associated with pools, suggesting that unanchored LWD in urban channels does not have a similar geomorphic effect as in undisturbed watersheds. Both types of LWD addition raised pool numbers, at least slightly, towards those of less disturbed streams.

About one-third of the estimated in-channel sediment storage was associated with LWD at most sites, although LWD generally did not retain sediment in the form of a discrete wedge. In all but one stream, sediment storage associated with LWD increased by 50-100% where LWD frequency increased. Added LWD contributed most to grade control (11-23%) on the steepest streams where wood spanned the full width of the channel, but it contributed little to grade control on the low-gradient streams. Although several projects sought to reduce downstream sedimentation by retaining sediment in the reach, only limited success was observed. LWD can retain some sediment in certain configurations, but this storage was exceeded by high sediment loads.

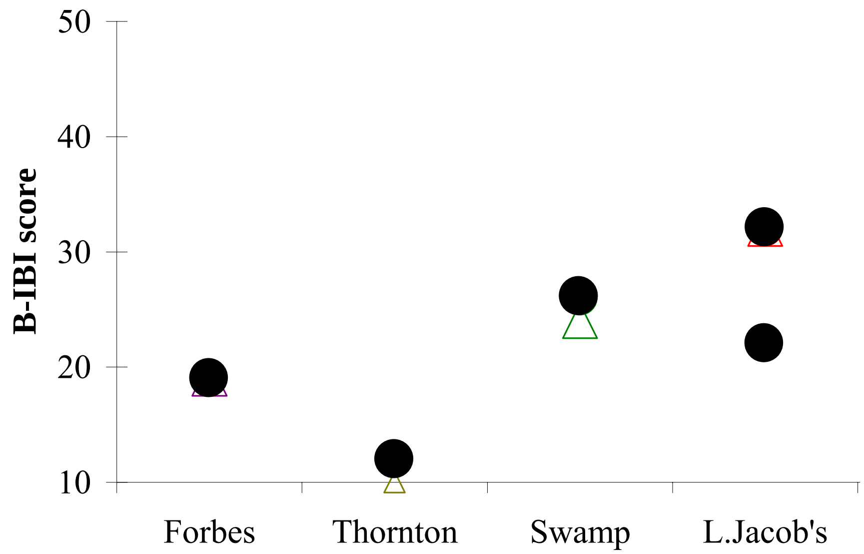
Addition of LWD had little demonstrable effect on biological condition (see Figure 19a) as measured by B-IBI. Two projects had been in place only one year when this study was conducted, and although invertebrates rapidly re-colonize the benthos following disturbance, this process may take longer if sources of colonizers are more distant (Gore 1985) or if the channel is still re-equilibrating (Booth et al. 1997). Additional sampling in 1999, however, still showed no improvement in biological condition. Neither did B-IBI increase when sampling sites were located within, rather than downstream of, project boundaries.

Local physical channel characteristics, particularly LWD frequency but also pool spacing and stored sediment upstream of the benthic invertebrate sampling sites, generally were not correlated with B-IBI. There was only a very weak positive relationship between B-IBI and extent of bank erosion, median grain size, or bed stability (indicated by a ratio of critical shear stress to boundary shear stress: see Olsen et al. 1997). In contrast, B-IBI was much better correlated with the level of urban development in the local riparian zone and with overall watershed urbanization (Figure 19b). In total, these scores indicate that although projects several hundreds of meters long may improve some measures of physical habitat (i.e. pool spacing) in a stream reach over the evaluated time scales of 2-10 years, they have little influence on the benthic invertebrate assemblage.

3.6 SOURCES OF IN-STREAM SEDIMENT

The current annual sediment production rate in the mixed-land-use watershed chosen for this investigation, the Issaquah Creek basin, showed an estimated 33-percent increase (44 tonnes km^{-2} yr^{-1} currently, relative to a pre-development estimate of 33 tonnes km^{-2} yr^{-1}). The main sources of sediment in the basin are landslides (50%), channel-bank erosion (20%), and road surface erosion (15%). Less significant sources of sediment included agriculture, construction, and landfill and gravel quarry operations. Although the Issaquah Creek basin is developing, forest lands still occupy over 70 percent of the basin area and produce the majority of sediment, where steep slopes contribute to a high landslide rate and efficient sediment delivery to the channel network. Urban land uses account for only 18 percent of the basin area and contribute very little sediment directly to the overall budget, because developed areas have only modest yields and a relatively small fraction of the basin is under construction at any given time. For example, Wolman and Schick (1967) measured very high discharges of suspended sediment from construction sites in Maryland from areas of up to a few km^2, but mostly no more than a few hectares. On a watershed scale, their measured sediment yields were several orders of magnitude lower.

a.



b.

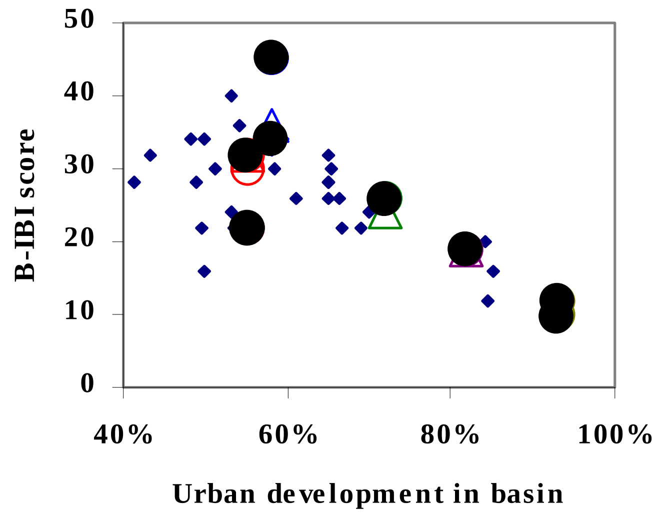


Figure 19. Factors influencing B-IBI scores at LWD project sites. Figure 19a shows the lack of influence of LWD at project sites (heavy dots) when compared to their corresponding upstream (i.e. untreated) localities (open triangles). In contrast, upstream watershed development shows a strong influence (Figure 19b).

Here, fine sediment accounted for approximately 60 percent of the total sediment production, primarily from landslides in undeveloped areas, forest-land gravel roads, and channel bank erosion. Landslides and channel bank erosion also contribute significant amounts of coarse sediment to the overall budget. Relative to the total sediment budget, the urban land surface accounted for a disproportionately high percentage of fine sediment, indicating there are opportunities for better management of urban stormwater runoff and construction-site erosion. The *primary* source of sediment from urban areas, however, was an indirect one—channel expansion in response to increased discharges (see also Trimble 1997). Urbanization and channel expansion are functionally related through changes in hydrology, which in turn depend on the area and intensity of development, the efficiency with which stormwater runoff is channeled into streams, and the underlying soils and topography.

3.7 SUMMERTIME STREAM TEMPERATURES

Summertime stream temperatures are only modestly influenced by watershed urbanization. They are most directly influenced by changes to the riparian canopy, long recognized as a significant factor in stream temperature. With each increasing observer-described local canopy classification, the median and the range of measured temperatures climb upward (Figure 20). The thermal consequences of riparian conditions in combination with flow conditions are particularly marked (Figure 21). The warmest condition (full sun on stagnant water) may not be the most biologically significant, however, because even though it reduces the length of suitable summertime habitat for cold-water fish it does not represent a major thermal input of hot water into potentially cooler reaches farther downstream. We see no relationship between watershed land cover and measured temperature (Figure 22), reflecting the groundwater source of summertime baseflow and the apparent lack of significant influence of the surrounding urbanization (an outcome that may depend on the region's low summertime rainfall). These data also do not display a clear relationship between measured temperature at our project sites and their corresponding B-IBI scores, probably because elevated temperature is but a symptom of underlying causes that do not necessarily affect biological health equivalently at all locations.

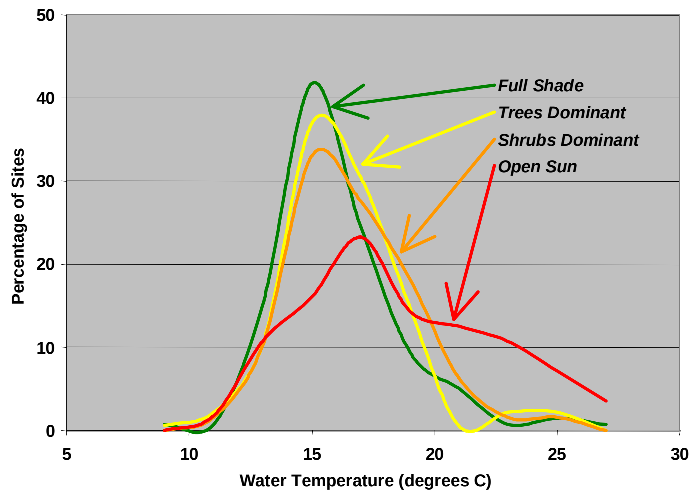


Figure 20. Pattern of observer-described riparian canopy conditions ("full sun," "trees dominant," "shrubs dominant," and "open sun") on the distribution of reported water temperatures. Data are from the year-2000 survey.

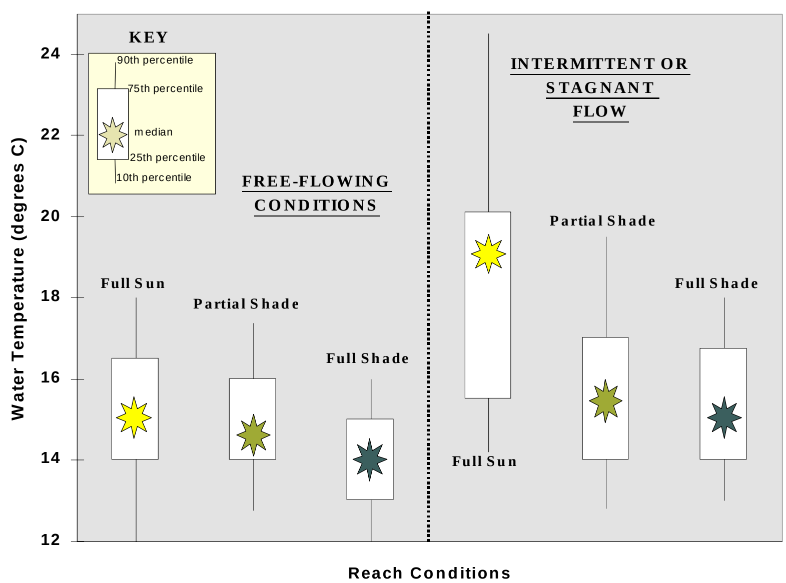


Figure 21. Distribution of reported temperatures for different combinations of flow and riparian conditions. "Partial shade" is a combination of the "trees dominant" and "shrubs dominant" categories of Figure 20.

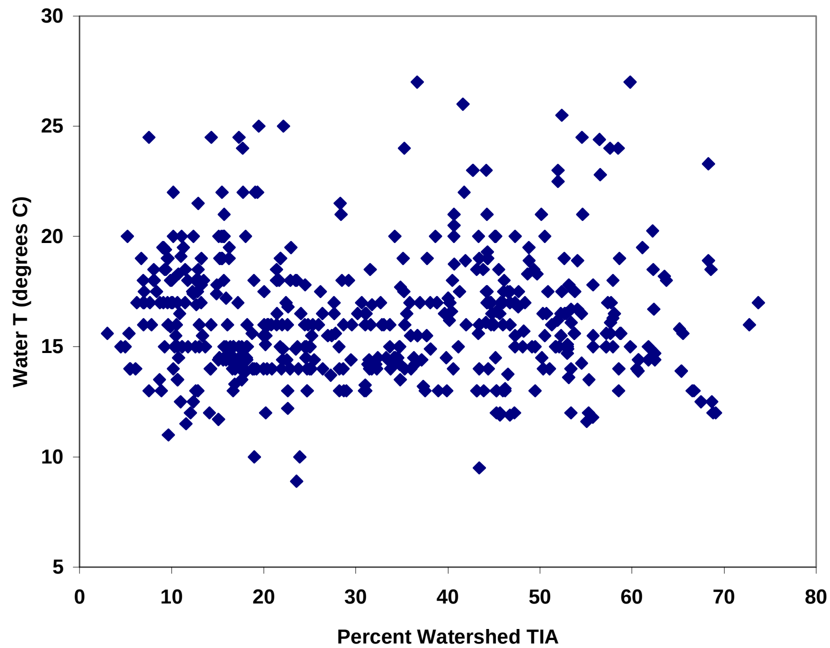


Figure 22. Contributing total impervious area in the upstream watersheds, determined from the classified 1998 Landsat image, vs. the measured stream temperature during the 1999 survey. No pattern is apparent.

3.8 RESTABILIZATION OF URBAN CHANNELS

The level of urbanization in a watershed exerts at most a coarse effect on the likelihood that the stream channel will be stable, and the rate at which urban development is occurring shows no systematic influence at all (Figure 23). In this study, channels in the less developed watersheds were stable or only slightly unstable, and pronounced instability was observed only in the most developed watersheds. Yet watersheds at even very low levels of development can display major channel adjustments (Booth 1990, Booth and Henshaw 2001). Conversely, stable (presumably restabilized) channels were observed in this study in highly urbanized settings. These examples show that the level of channel response is more likely controlled by conditions in the channel and watershed other than general levels of contributing urban land cover. In particular, it appears that restabilization potential depends on how changes in the watershed affect the channel's flow and sediment regimes, and the responsiveness of the channel and watershed to these changes.

Both the qualitative stability assessments and the calculated bed stability index of Olsen et al. (1997) consistently produced similar levels of *relative* stability. Moreover, the stability levels indicated by these short-term observations were quite consistent with long-term stability results based on repeated cross-section surveys for three of the four sites where long-term data were available; the disparity at the fourth site is attributable to the effects of a discrete event in the long-term record. This suggests that the stability assessment techniques used in this study may have some utility where long-term geomorphic assessment is infeasible.

Study results indicate that restabilization of lowland urban stream channels can, and commonly does, occur even in highly urbanized watersheds. However, the degree of stability is not well predicted by either the magnitude of developed area or the rate of recent development. When, and if, an individual channel will restabilize depends on a combination of hydrologic and geomorphic characteristics of the channel and its watershed, beyond simply the magnitude or rate of urban development. The hydrologic regime and geologic setting appear to be important controlling factors; extent of grade control and condition of the riparian corridor likely play noteworthy, but less influential, roles. It should be noted, however, that restabilization alone is not sufficient to benefit aquatic biology, because a restabilized cross section will typically be less geomorphically complex than the pre-urbanization channel form.

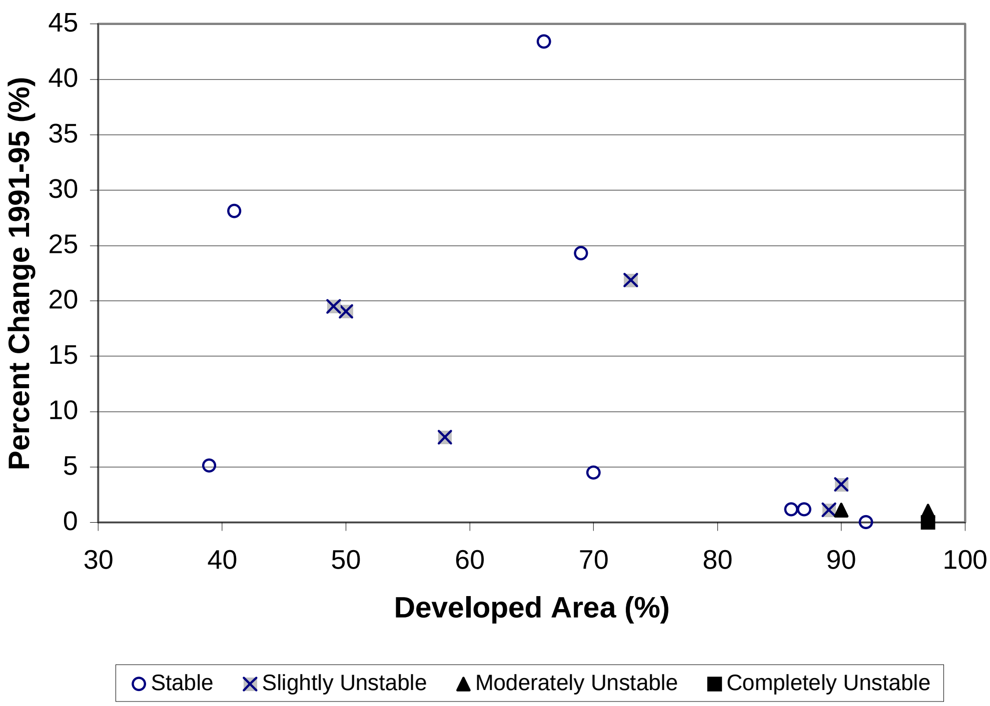


Figure 23. Observed channel stability as a function of developed area and recent change in development. At most a coarse relationship is present between the degree of instability and the intensity of upstream urban land uses.

4 DISCUSSION

4.1 CHARACTERIZING THE EFFECTS OF URBANIZATION ON STREAMS

The relationship between urban development and aquatic-system condition has been investigated for decades (Larimore and Smith 1963, Hynes 1970 1974, Tramer and Rogers 1973, Trautman and Gartman 1974, Karr et al. 1985). One study showed a rapid decline in biotic diversity where watershed imperviousness much exceeded 10 percent (Klein 1979). The importance of both riparian condition and watershed urbanization as a determinant of stream fish assemblages was shown for Lake Ontario streams by Steedman (1988). A selective review of urbanization studies was compiled by Schueler (1994); additional work on this subject has been made by a variety of Pacific Northwest researchers (*e.g.*, Kleindl 1995, May 1996, Fore et al. 1996, Booth and Jackson 1997, Karr 1998, Horner and May 1999, Karr and Chu 1999 2000). Many of these studies use "percent watershed imperviousness" (either *total* or *effective*) to characterize human development, an approach that we have maintained here as well.

Many of the effects of human disturbance, however, do not require the creation of new impervious surface—for example, clearing of riparian vegetation, application of pesticides, physical alteration of stream channels, or introduction of invasive species (Karr and Chu 2000). The wide range of biological condition illustrated by B-IBI, particularly at relatively low levels of imperviousness, demonstrate the inadequacy of impervious area as an integrative measure of human influence. This metric does not reflect the cumulative consequences of human activities on the health of a river, and it is not a substitute for direct evaluation of that health.

Nevertheless, imperviousness is clearly associated with stream-system decline in the urban (and urbanizing) environment, and we can recognize clear, if complex, physical processes that link imperviousness to many (though not all) processes of stream degradation, particularly the change in hydrologic properties of the land surface and the underlying soil resulting from a loss of watershed permeability through soil removal, compaction, and/or paving. Imperviousness is an *index* of human activity in a watershed; many of the other changes that *also* degrade streams are progressively more likely ashuman activity increases. Indeed, the upper limit of attainable stream conditions shows good correlation to this overall measure of urban development, displaying a "factor ceiling distribution" (Thomson et al. 1996) that defines the best biological condition one can expect for a given impervious percentage. That relationship does not preclude other effects from being present, however, that will not be recognized if the "index" is mistaken for the full suite of ecological consequences.

4.2 HYDROLOGIC EFFECTS OF URBANIZATION

Hydrologic alteration of urban watersheds is a particular focus of this work, even though "flow regime" is only one of the elements by which a stream can be degraded by development. The flow regime is influenced from the first expression of human activity in a watershed, be it vegetation clearing, channelization, soil compaction, or road construction (Poff et al. 1997). It also directly affects biological conditions in streams, through changes in flow patterns that in turn influence the frequency and spatial extent of physical disturbances in stream ecosystems. Although every other element of these ecosystems can be affected by human disturbance, their changes are more variable in any given watershed and their influence less easy to recognize at low intensities. Many *also* are influenced by watershed hydrology.

The hydrologic consequences of urban development are so profound that they are likely to influence many stream flow patterns and, thus, can be measured by many different hydrologic statistics. Simple hydrologic parameters such as flood recurrences and flow durations, the measures traditionally used to evaluate flood hazard, incompletely characterize urban influences. The challenge of this study was to identify *which* measures best reflect the hydrologic effects of urban development on the biology of streams. Lotic communities are resilient to and recover rapidly from individual storms and periods of seasonal low flow. Storm and low flow patterns over multiple-year periods, however, are likely to have persistent biological influences. Thus, hydrologic changes that make a difference for ecological processes and conditions over relatively long periods are likely to have the most important role in urban stream degradation.

Stream discharge, measured in terms of a volume or rate, is unlikely to provide much of an indication of the ecological condition of a stream with the exception of low flows. In this context, annual peak discharge, which is one of the principal statistics used to characterize the hydrologic effects of urban development, does not provide an ecologically-relevant stream flow measure. There is no *a priori* reason that an increase in flood discharge should degrade stream ecosystems, given that healthy streams may be of any size.

The increase in storm flow relative to base flow in urban streams is more likely to have ecological consequences. Potential consequences include lower flow depths during base flow, particularly in channels widened by increased storm flow, a shift in transport of organic material and nutrients from low flow periods to storms, and an increase in the frequency and extent of bed disturbance as storm flow is higher relative to lower flows that stabilize the stream bed. While the relative shift in storm and base flows are evident as an increase in the "flashiness" of storm hydrographs, the ecological significance of the change is realized over periods of years spanning many storms. Biological conditions in our gaged urban streams vary consistently with the hydrologic parameters T_{Qmean} and $T_{0.5\ yr}$, which provide measures of the flashiness of stream flow over annual and multiple-year periods.

4.3 THE ACTIONS OF INDIVIDUALS

From our questionnaires and our records of backyard stream corridors, we can begin to answer some of the key questions about the behavior, the consequences, and the opportunities provided by streamside neighbors. This discussion is based only on the conditions surveyed in this study and so cannot yet be generalized to other landscape situations.

1. Do individual residents degrade or protect riparian corridors in their backyards?

The regional experts we consulted believe that individuals mostly degrade riparian corridors. This does not seem to be the common situation in the backyards we studied. A few individuals have done massive damage on some sites (and whom we might call "ecopaths"), even within watersheds where public environmental education is ongoing, stream stewards are involved, and buffer regulations exist. In other words, a few can do a lot of degradation regardless of existing regulations and education. The general backyard situation, however, is more one of benign neglect. The common condition we recorded is that individuals may not do anything to degrade but neither do they take positive actions to rehabilitate stream corridors.

2. Is individual behavior in riparian corridors broadly predictable?

From the field surveys, we have been able to attribute all backyard conditions to one or a combination of the three categories—ecological care, privacy, and unique home landscape. By adding ecopathy recorded in the field surveys, we believe that these four categories could be used to predict individual behavior in suburban backyards in the Seattle area. The ecological care category remains the one with the least measurable evidence. This may be true because caring behavior such as using organic fertilizers and not using pesticides were not accurately recorded using the photo survey techniques.

3. Does an individual's behavior agree with his/her stated attitudes toward landscape design objectives?

Yes, to a limited degree. The mean rated values of all the categories did not differ significantly and the field survey substantiated that backyard design choices were evenly displayed with the exception of the four elaborate dug pond designs and the salmon box landscape. While each backyard was visually different, most of them had the same components: a sitting area, lawn, a few trees, an occasional vegetable garden, and flowering shrubs. This visual homogeneity is likely because backyard landscape designs mostly reflect the composite needs similar among many families.

The unpredicted ecopathic conditions we recorded were, with one exception, in backyards of people who did not respond to our initial survey. Furthermore residents of three degraded backyards did not respond to a second request to complete the written survey. The one exception was a response from a home owner who returned the form and wrote he was not completing the survey because he believed the University was working with a “government that had gone too far already impinging on his property rights.”

4. What measures can be taken to protect corridors?

The experts agree more regulations are not needed. More may not be needed, but stricter enforcement of existing regulations may prevent repeat ecopathic behavior. Protection now seems to be more attributable to site conditions rather than individual behavior. For example, protection occurs more often by residents who respect subdivision covenants regarding the buffer area when their backyards are vertically separated from the stream. In other words, it is more difficult for the resident to get close to the stream.

The experts believe corridor protection may come from encouraging individual stewardship, showing how an individual can make a difference, and increasing biological education. The first two have potential, but sometimes people see themselves “making a difference” as good stewards even as they are continuing forms of destructive behavior (e.g., “loving the stream to death”). In the case of backyard ponds and fish boxes, those residents were proud of their stewardship, seemed to know about the biology of salmon, and told us how they believed their actions were “salmon friendly.” They had little understanding as to how their actions did not exhibit the best ecological care.

5. How can good individual behavior be encouraged?

Good ecological care is mostly described as a list of actions an individual must refrain from doing, such as not using inorganic fertilizers or letting pesticides run off into salmon streams. Little guidance is given on how an individual can design backyards ecologically. The results of the first cognitive mapping interviews indicate that when asked about “landscaping your backyard without regard for time and money," people do not think about ecological designs. They think first and foremost about decorative changes yet they overwhelmingly desire landscapes with "low maintenance," perhaps because little information on restoration or ecological landscape design is available to homeowners.

Planting a buffer where none exists was not a landscaping option chosen by any resident, is not shown in many horticultural guides, and has not been explored fully by local professional landscape designers. It may be that buffers are only thought of as a uniform width of vegetation because regulations describe them as such. The lack of a buffer is not described as a creative opportunity to have more trees and wildlife habitat in one's backyard configured in various designs to fit a family's backyard needs.

6. How can positive individual behavior toward suburban/urban streams be engendered among residents?

This is a complex issue, but people who are involved in Thornton Creek and live along the creek place their highest value on the personal rewards of that connection. Given the many simple streamside benches we found, we believe others also value that personal connection. Those who lived adjacent to Thornton Creek and were not involved could not describe why the creek was valuable to them personally; they could only cite negative issues such as a property concerns. Why do they lack a personal emotional connection to the creek?

A search for the answer to that question is compelling. It likely will not come from teaching these people more about the biology of the stream. It could come from a spiritual source as many religions are now advocating ecological stewardship. It could come from an educational program that specifically was aimed toward the "doubters" along the stream. Such an educational program might point out the clear connection between stream health and personal well being. In all cases, one recommendation is to aim more education toward the individual and what positive steps s/he might take toward ecological backyard designs and personal stewardship.

5 MANAGEMENT IMPLICATIONS

Urbanization is a particularly challenging stressor for streams, because it can damage many parts of an aquatic ecosystem. It also can simultaneously eliminate opportunities for future rehabilitation by permanent alteration of topography and soils, and by the local (or absolute) extinction of native biota. That is why successful urban stream rehabilitation is hard to accomplish in practice—so many environmental features, both physical and biological, have been changed permanently. As such there are limits imposed on the ultimate condition of urban streams, even with comprehensive rehabilitation. This results of this study can improve the effectiveness of any such rehabilitation, however, because they point more clearly to some of the most common and critical causes of that degradation, the reasons why rehabilitation efforts most commonly fail, and an overall strategy for a more successful approach.

5.1 CAUSES AND ASSESSMENT OF DEGRADATION

Any human action that alters critical components of a stream system, either its parts or its processes, has the potential to degrade stream conditions. Streams can become unhealthy in many different ways. A consequence of this truth, however, is that ambient stream condition must always be assessed, especially in biological terms, and that the resulting information must then be integrated with surveys designed to identify site-specific stressors. We can recognize here the investigations most likely to yield useful information, but the significant stressors within any individual watershed must still be identified and evaluated before general treatments are initiated.

Our detailed focus on one feature, *flow regime*, demonstrates the importance of this particular aspect of the aquatic system but does not contradict the need for broad, comprehensive assessment. Urban development is not the sole determinant of flow regime, although it is a significant influence—watershed geology, climate and weather, and channel-network hydraulics will also be influential. Nor is flow regime the sole determinant of biological health, although it is a very significant factor and is ubiquitous, to some degree or another, in virtually all urban watersheds. As a result:

- Any given level of urbanization will have different influences on the flow regime of different streams because of intrinsic watershed characteristics (geology, soil permeability and depth, topography, channel network) and because of the interactions of flow with other stream feature.
- No single assessment (e.g., amount of impervious areas in the watershed) can adequately predict flow regime, or the consequences of its change on stream conditions.
- Rehabilitation, even with optimal analysis and execution, will not produce the same biological results in every stream, because even a "rehabilitated" flow regime will not be the same in every watershed or interact with other environmental factors in the same way. Every stream cannot be made equally "good."

5.2 LIMITATIONS TO SUCCESSFUL REHABILITATION

In general, rehabilitation efforts fail because one or more of the five critical features of stream systems (Table 1) are not addressed, or are addressed only inadequately. We have studied only a few in detail, focusing on those that appear most broadly important; we have recognized the relative significance of others from the existing literature; and we can note others, particularly the consequences of human-disturbed biotic interactions, that are almost certainly influential but remain largely unexplored in this and prior studies of urban stream rehabilitation. From this work, we can identify two critical elements in the urban environment that are commonly omitted, yet crucial, in the pursuit of stream rehabilitation:

1. Hydrologic Changes

Hydrologic changes are commonly ignored when they result from infill or low-density development, which are normally presumed to be unimportant, or when they are a predictable byproduct of inadequate mitigation of high-density development. This has severe consequences for the rehabilitation potential of urban streams, because hydrologic changes have been demonstrated through this (and previous) work to be particularly damaging to stream ecosystems. The first condition, infill and low-density development (*e.g.*, one dwelling unit per five acres), can result in the degradation of aquatic resources even where drainage regulations are nominally in place (Booth and Jackson 1997).

Even where drainage regulations are in place and apply to the new development in a watershed, they generally do not achieve genuine mitigation of urban-induced increases in runoff. In large measure this is because the standards of mitigation are applied to hydrologic measures with little or no biological significance. Regulatory standards normally apply to peak flows or to flow durations, metrics evaluated over a multi-decade record. In contrast, measures of annual and inter-annual flow patterns are unrecognized and so unevaluated. Our study results show that these flow patterns are closely related to in-channel disturbance frequency and biological health; they are largely unaffected by traditional hydrologic mitigation (Booth et al. 2000).

2. The Effects of People

The actions of people influence stream health at multiple scales. In aggregate, human populations alter the hydrologic regime of a watershed through widespread changes to the landscape. Our work has also demonstrated, however, the equally important influence of *local* stream conditions, which in the urbanizing Puget Lowland is overwhelmingly determined by the behavior of streamside neighbors. Their effects are so influential because of their proximity and because they commonly abut most of the length of an urban channel network. Their actions may be benignly neglectful but are rarely restorative, and they are influenced by factors rarely addressed in a rehabilitation plan:

1) the efficacy of existing riparian corridor regulations and the vigor in enforcing them,
2) the level of care (or lack thereof) by individual residents along the stream,
3) the quality and number of neighborhood groups who are providing ad hoc corridor protection,
4) the success of educational efforts, both that which targets those individuals who live along the stream but at present place no personal value on it and that which relates human health to the health of the stream.

5.3 A STRATEGY FOR SUCCESSFUL REHABILITATION

Although stream conditions are not unambiguously correlated with urbanization, the multiple effects of urban development on stream systems make rehabilitation progressively more difficult at progressively greater levels of development. Rehabilitation success is *most* likely in those watersheds with relatively low levels of development that display paradoxically poor biological and/or physical conditions. This assertion is empirically based on examples where low watershed development and good in-stream conditions coexist. Rehabilitation, as classically defined, is *least* likely to produce improvements in highly developed watersheds, because the inverse state (high levels of development with very good biological and/or physical conditions) are simply not observed in this (or any previous) study, in the Pacific Northwest or elsewhere in the country.

A consequence of these observations is an overall strategy for pursuing effective rehabilitation:

- Recognize and preserve high-quality, low-development watershed areas.
- Aggressively (and completely) rehabilitate streams where recovery of ecosystem elements and processes is possible. This condition is likely to be met only in low-development areas with relatively low to moderate levels of ecological health, because the agents of degradation are probably easier to identify and more amenable to correction.
- Rehabilitate selected elements of mid-range urban watersheds, where complete recovery is not feasible but where well-selected efforts may yield direct improvement, particularly in areas of public ownership.
- Improve the most degraded streams by first analyzing the acute cause(s) of degradation, but recognize that the restoration potential for populations of original instream biota is minimal.
- In the most highly developed watersheds, education and/or community outreach is not just appropriate but crucial. Here, the level of public interest is likely to be highest, streamside residents have greater direct individual influence over whether healthy stream conditions are maintained, and most of the riparian corridor is not under public ownership or control.

We offer specific recommendations for rehabilitation efforts:

1. Make direct, systematic, and comprehensive evaluation of stream conditions in areas of low to moderate development. Numerous assessment schemes already exist, some with an intentional focus on urban systems (*e.g.*, Scholz and Booth 2001). The underlying assessment (and subsequent rehabilitation) objectives, however, are more important than the specific assessment methodology chosen.
2. The hydrologic consequences of urban development cannot be reversed without extensive re-development of urban areas, which is infeasible in the near future. Likewise, the recovery of physical and biological conditions of streams is infeasible without hydrologic restoration over a large fraction of the watershed land area. This conflict can be resolved only if there are particular, ecologically relevant characteristics of stream flow patterns that can be managed in urban areas. Effective hydrologic mitigation will require approaches that 1) can delay the timing of stormflow discharges in relatively small storms and 2) can store significant volumes of rain for at least days or weeks. In the long run the goal should be to mimic the hydrologic responses across the hydrograph and not just truncate the high or low flow components. The rate of rise and decline of the hydrograph is just as important as the existence of peaks and lows. This almost certainly requires greater reliance on hillslope ("on-site") storage to better emulate the hydrologic regime of undisturbed watersheds, either through dispersed infiltration, on-site detention, or forestland preservation (*e.g.,* Konrad and Burges 2001).
3. Our results indicate that the effectiveness of localized patches of riparian corridor in maintaining biological integrity varies as a function of basin-wide urbanization (Morley and Karr, *in review*). Where overall basin development is low to moderate, natural riparian

corridors have significant potential to maintain or improve biological condition. Protecting high-quality wetland and riparian areas that persist in less-developed basins may also serve as a source of colonists (be they plants, invertebrates, fish, etc.) to other local streams that are subject to informed restoration efforts. At the same time, even small patches of urban land conversion in riparian areas can severely degrade local stream biology. As both a conservation and restoration strategy, protection and re-vegetation of riparian areas is critical for preventing severe stream degradation (Osborne et al. 1993), but these measures alone are not adequate to maintain biological integrity in streams draining highly urban basins (Roth et al. 1996; Morley and Karr, *in review*).

4. Approaches must be developed to address the unanticipated, and unappreciated, consequences on channel conditions of human actions in the name of backyard improvements. Regional and national efforts now fall particularly short in this regard.
5. There is little evidence that these in-stream projects can reverse even the local expressions of watershed degradation in urban channels. Addition of LWD to the urban streams we examined produced more physical channel characteristics typical of undisturbed streams, such as pools and sediment storage sites formed by LWD. Any increase in sediment storage and grade control in these moderate-slope alluvial channels was less assured. The steepest project reaches examined did not store more sediment, although LWD provided more grade control in the steepest reaches. Stabilizing or retaining sediment to reduce downstream sedimentation and associated flooding was not accomplished by adding LWD to the channel. No positive effect on biological condition from the restoration activities was detected over the time scales sampled; the physical characteristics in the reach that did change displayed no clear relationship to biological condition.
6. Aggressive efforts at channel stabilization during the period of active watershed urbanization will probably achieve only limited rehabilitation gains at high and perhaps unnecessary cost, even though bank armoring projects are often constructed in the name of stream-habitat "improvement." Most lowland channels achieve a stable physical form some years or decades following urbanization, with or without human intervention. Yet the restabilization of urban channels, either by natural processes or by direct intervention, is generally incompatible with true "rehabilitation," because the resulting channel is rarely biologically hospitable and often is socially unwelcome as well.

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APPENDIX 1: PROTOCOL FOR INTERVIEWS

This survey has 2 parts.

Part 1 Backyard landscaping exercise.

Instructions to the interviewers

1. Thank them for volunteering and remind them that this interview can be stopped at any time. Give them a copy of the consent to interview form that they signed. Tell the homeowner that you need to be able to look out onto their backyard so you can determine distances and help them place things

2. Ask them to think about how they would landscape their backyard if they had all the time and money to do anything they wanted to do. Say, "**we want to know what they would do if money and time were not constraints.**" Tell them that you will help them "make this plan" while your partner makes notes of the process

3. Find a comfortable spot where the clip board can be placed on a table or horizontal surface. Show the homeowner the drawing of his/er home and name each of the mylar pull-up plants and landscaping features that s/he has to use. Do not explain each plant but describe it generally if the subject asks what does it look like. Don't give any horticultural advice. Say the study, "The study doesn't allow me to give advice."

4. First ask what plants or features they would keep in their back yard and then sketch these features in using an erasable flow tip. Tell them that the drawing you did is erasable and you can change at any time if they so desire.

5. Get them start by asking them to place trees, shrubs and features on the base map. Resist doing this for them. Ask them to tell you what they are attempting to accomplish or what design functions they want to achieve as they place these items. The second interviewer should be making careful notes. (*placed trees along creek--said he "wanted a place for his grandchildren's swing")*

6. If they slow down, ask if you can help they achieve any design that they are having a hard time achieving. Then help them place things in the landscape but DO NOT SELECT THE ITEM, ASK THEM. **NEVER LEAD THEM INTO AN ANSWER.**

7. Try and converse with them as they go along without distracting them too much. Afterwards, if you think you don't have enough information as to why they did something ask specifically.

Part 2: Written survey (same as Mailed survey)

8. ASK THEM TO TAKE ONE MORE SHORT SURVEY. AFTER THEY HAVE COMPLETED PART 2-- **Thank them by saying, "We really appreciate your help in this study to learn how people who live along creeks in this region landscape their backyards."** be sure they answer the photo permission question and complete the "Consent Form." Make sure they have a copy of the consent to photograph form.

9. In the end, thank them profusely for helping the University. Ask them if they want a copy of the results when the study is over--it will be a year or more before any of this is published.

APPENDIX 2: BACKYARD LANDSCAPES SURVEY

Please rate how important each of the following would be as design goals for your backyard landscape if time and money were not constraints.

IMPORTANCE: 5 = VERY
4 = USUALLY
3 = SOMEWHAT
2 = ALMOST NEVER
1 = NEVER

1. Having visual privacy in the backyard.	5 4 3 2 1
2. Providing a place to entertain outdoors or to have a family play or game area.	5 4 3 2 1
3. Marking the edges of my property.	5 4 3 2 1
4. Having a place to compost	5 4 3 2 1
5. Having the best looking lawn in the neighborhood	5 4 3 2 1
6. Planting trees and shrubs to overhang the creek.	5 4 3 2 1
7. Landscaping with a minimum amount of commercial fertilizer.	5 4 3 2 1
8. Making sure the neighbor's tree and shrubs do not overhang into our yard.	5 4 3 2 1
9. Having the best flowers in the neighborhood.	5 4 3 2 1
10. Landscaping so that the backyard is an extension of our home.	5 4 3 2 1
11. Keeping a "natural" area of native trees and plants.	5 4 3 2 1
12. Placing rocks or timbers along the creek edge to hold the bank.	5 4 3 2 1

13. List the 3 most important considerations your family takes into account when you make decisions concerning the landscaping, gardening or features in your backyard:

A.____

B.____

C.____

14. How many people live home?_________

How many males?_______How many females?___________.

15. The landscape decisions in our backyard are made by (circle one choice):

mostly by a woman----mostly by a man----are shared family decision

16. The size of your property is?__________________

17. How long has your family has lived in the Pacific Northwest?__________________

18. How long has you family lived in this house?___________________

APPENDIX 3: PUBLICATIONS LIST

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Physical, Biological, and Social Considerations
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