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Message from the Director

This issue of the Newsletter highlights the results of our recently completed three-year project, "Urban Stream Rehabilitation in the Pacific Northwest," funded by the U. S. Environmental Protection Agency as part of their joint EPA-NSF "Waters and Watersheds" program. That work has already resulted in a number of reports, publications, and theses, of which several have already been summarized in previous issues of the Newsletter. This article, however, provides a broader synthesis of the multiple parts of that effort.

In last quarter's Newlsetter, I mentioned two upcoming events that now require updates. The first, the proposed merger of our center with the Center for Streamside Studies, is in the "review" stage. It has been recommended by the advisory boards and associated academic participants of both centers, and we now await administrative decision. The second, the scheduling of the annual regional stream temperature survey on August 11th, has been met with some applause and some dismay (it's on a Saturday). Although we can do nothing about the timing of a satellite overflight with which we are coordinating this year, we are looking to define a *second* day, somewhat earlier in the same week, to allow those agencies with interest and (weekday-only) staff resources to collect data on their streams and to set those data in a regional context. We will be making contact via our email lists from last year's effort; if you did not receive them last year but want to be included this year, please get in touch soon (cuwrm@u.washington.edu).

❖ *Derek Booth*

Urban Stream Rehabilitation in the Pacific Northwest

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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. Even

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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 in this project has been 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 most specifically on urban streams of the Puget Lowland region of western Washington, with the City of Seattle as its geographic and demographic center. 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.

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 might 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.

Earlier work showed that a wide range of biological conditions in different watersheds can occur at relatively low levels of human disturbance (May, 1996; 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: CONDITIONS AND STREAM CONDITIONS

Stream biota 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

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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.

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. 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.

Human actions that alter multiple, critical features of a stream system are likely to degrade stream conditions. Unhealthy streams thus 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 or amount of 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.

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.

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

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).

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).

2 METHODS

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Stream	Site ID	Address (closest cross-streets)
Big Bear	BB971	Woodinville-Duvall Rd. & 210th Ave. NE
Big Bear	BB972	NE 164th St. & Mink Rd.
Big Bear	BB973/981	NE 148th St. & Mink Rd.
Big Bear	BB974	NE 148th St. & Mink Rd.
Big Bear	BB975	NE 133rd St. & Bear Creek Rd.
Big Soos	BS971	SE 290th St. & Kent - Black Diamond Rd.
Forbes	FO98US	NE 106th Dr. & Forbes Creek Dr.
Forbes	FO98DS	108th Ave. NE & Forbes Creek Dr.
Jenkins	JE971	164th Pl SE & Covington-Sawyer Rd.
L.Jacobs	LJ99US	Sammamish Pkwy. SE & SE 43rd Wy.
L.Jacobs	LJ98US	Sammamish Pkwy. SE & SE 43rd Wy.
L.Jacobs	LJ99DS	Sammamish Pkwy. SE & SE 43rd Wy.
L.Jacobs	LJ98DS	Sammamish Pkwy. SE & SE 43rd Wy.
Little Bear	LB971	180th St. SE & 51st Ave. SE
Little Bear	LB981	189th St. SE & 51st Ave. SE
Little Bear	LB982	196th St. SE & 51st Ave. SE
Little Bear	LB983 3	216th St. SE & 63rd Ave. SE
Little Bear	LB972	228th St. SE & Hwy. 9
Little Bear	LB973/984	233rd Pl. SE & Hwy.9
Little Bear	LB974	233rd Pl. SE & 63rd Ave. SE
Little Bear	LB985	NE 195th St. & 136th Ave. NE
Little Bear	LB986	NE 177th Pl. & 134th Ave. NE
Little Bear	LB987	NE 178th St. & 130th Ave. NE
May	MA971	NE31st & Jones Ave.
Miller	MI971	168th Pl. SW & 8th Ave. SW
North	NO981 3	183rd St. SE & John Bailey Rd.
North	NO982	236th St. NE & Fitzgerald Rd.
Rock	RO981 3	SE 262nd St. & Summit Landsburg Rd.
Rock	RO971/982	SE 248th St. & Cedar River Pipeline Rd.
Seidel	SE981	NE 133rd St. & 198th Ave. NE
Soosette	SO99US	SE 304th St. & Hwy. 18
Soosette	SO98DS	SE 304th St. & Hwy. 18
Struve	ST981	NE 150th St. & 206th Ave. NE
Swamp	SW981	164th St. SW & 28th Ave. W
Swamp	SW982	181st Pl. SW & Butternut Rd.
Swamp	SW983	Magnolia Rd. & Filbert Rd.
Swamp	SW971	Larch Wy. SW & Locust Wy.
Swamp	SW972	Larch Wy. SW & Locust Wy.
Swamp	SW973/984	Larch Wy. SW & Locust Wy.
Swamp	SW985 3	Locust Wy. & Cypress Wy.
Swamp	SW986 3	Locust Wy. & Cypress Wy.
Swamp	SW987	Locust Wy. & Cypress Wy.
Swamp	SW988 3	Lockwood Rd. NE & Carter Rd.
Swamp	SW98US	NE 185th St. & 173rd Ave. NE
Swamp	SW99MS	NE 185th St. & 173rd Ave. NE

Table 2.
Study sites.

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 we initially 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 (Hill et al. 2000). 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 (see the Fall 2000 issue of the Newsletter).

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. 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). At each stream site, we used a Surber sampler (500-mm 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; see also the Spring 2000 issue of the Newsletter). We analyzed these data according to the 10-metric B-IBI, an index which includes measures of taxa richness, disturbance tolerance, and feeding ecology. 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).

2.3 HYDROLOGIC CHANGES

We judged that the temporal patterns of stream flow would be a critical element of our stream ecosystems (Poff et al. 1997) and would display significant changes in response to urban development. 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

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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. The hydrologic metrics developed for this project were described in the Fall 2000 issue of the Newsletter.

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).

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 (see the Summer 2000 issue of the Newsletter).

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 is 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. The full coverage is available for downloading on the Center's web site *(depts.washington.edu/cuwrm)*.

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 1): ***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*). Riparian and subbasin land cover closely correlated with each other ($r^2 = .95$, $p < 0.001$); little is gained by assessing *both* of these land cover scales. Here, we have focused primarily on evaluating the influences of the subbasin- and local-scale effects. Using the 1998 classified Landsat land cover image and representative impervious-area percentages (Hill et al. 2000), we can also display the overall pattern of BIBI and total impervious area at our study sites (Figure 2).

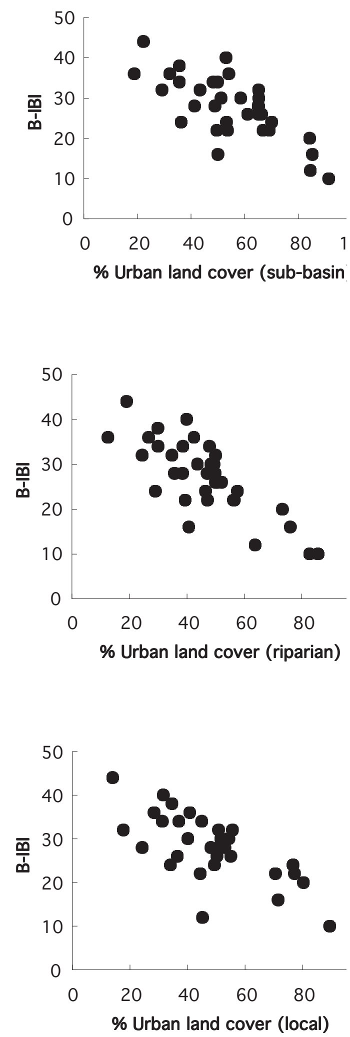

Figure 1. Relationship of urban land cover to B-IBI at each of the three spatial scales investigated.

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

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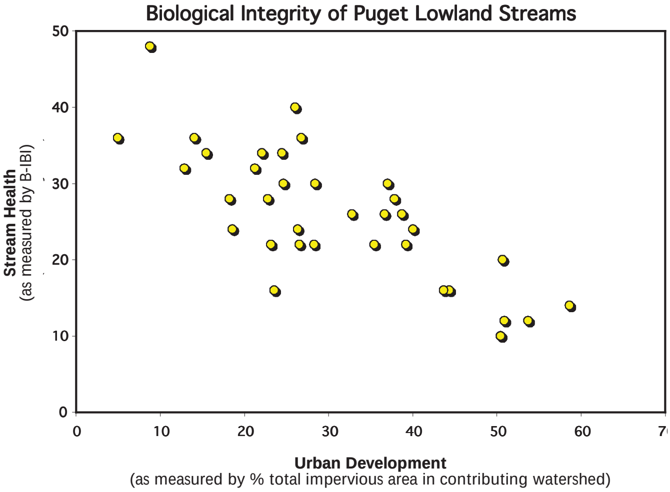

Figure 2.
Relationship between total impervious area and BIBI scores.

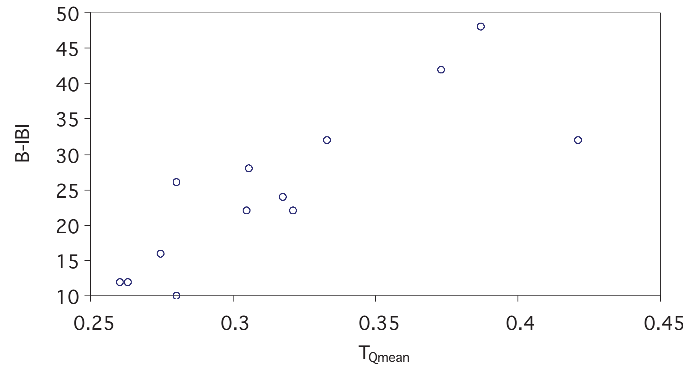

Figure 3a:
Benthic index of biological integrity (B-IBI) plotted against fraction of time that daily mean discharge rate exceeds annual mean discharge rate (T_{Qmean}) for 13 Puget Lowland streams.

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. These metrics show good, and in some instances very good, correlation with biological health (Figure 3).

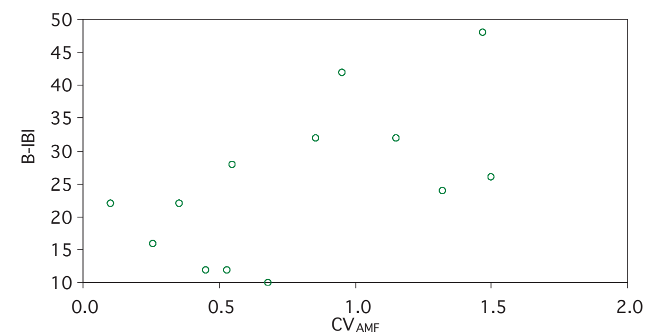

Figure 3b:
Benthic index of biological integrity (B-IBI) plotted against the coefficient of variation of the annual maximum flood (CV_{AMF}) for 13 Puget Lowland streams.

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."

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.

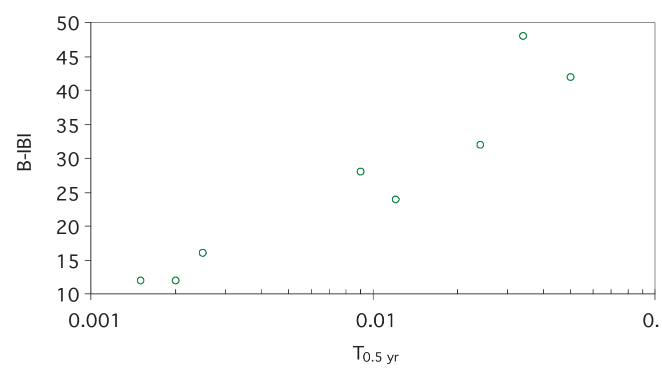

Figure 3c:
Benthic index of biological integrity (B-IBI) plotted against the fraction of the period of record that discharge exceeded the magnitude of a "1/2 yr" flood ($T_{0.5.yr}$) for 8 Puget Lowland streams.

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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.

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 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.

4 DISCUSSION

4.1 CHARACTERIZING THE EFFECTS OF URBANIZATION ON STREAMS

Many of the effects of human disturbance 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. The 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. 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," imperviousness, 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 (Table 1). 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.

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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.

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.

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 shift some energies, now being expended to educate and influence *groups*, toward the *individual* and to show 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

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such there are limits imposed on the ultimate condition of urban streams, even with comprehensive rehabilitation. The 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. Yet 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 (Booth and Jackson 1997). Yet even where drainage regulations are in place and have been applied to new development, 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

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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.
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. Where overall basin development is low to moderate, natural riparian corridors have significant potential to maintain or improve biological condition. 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 (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.

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Hydrologic Monitoring of the Seattle Ultra-Urban Stormwater Management Projects

By Adrienne Miller, Graduate Research Assistant, Department of Civil and Environmental Engineering, University of Washington

Increased urbanization has led to significant hydrological and ecological changes throughout the Puget Sound Lowland region. Direct physical alteration of the subsurface soil water storage capacity, natural drainage network, and land use patterns have permanently modified the hydrologic regime. The results are increased stormwater peak flow rates and volumes, increased frequency of floods, and decreased water quality in the receiving bodies of water. In an attempt to mitigate urbanization impacts, creative approaches are necessary to manage urban stormwater.

This thesis documents the monitoring of two Seattle Public Utilities "ultra-urban" stormwater management projects. In this context, "ultra-urban" is defined as any built environment within the City of Seattle, including a variety of industrial, commercial, residential, and mixed land use types. The two ultra-urban stormwater projects monitored are the Viewlands Demonstration Swale and the Street Edge Alternative (SEA) Streets Millennium Project, located in the Pipers Creek Watershed in North Seattle. The projects are designed to benefit runoff-receiving waters in both reducing stormwater quantities and improving runoff quality.

This thesis examines the hydrologic and hydraulic performance of the Viewlands Swale during post-construction monitoring and compares it to theoretical pre-construction performance. The Viewland Demonstration Swale is limited in its ability to mitigate large amounts of stormwater (above volumes produced by a 6-month, 24-hr storm) before discharges reach the natural drainage network. The main constraint on swale effectiveness is its limited soil water storage capacity and available land area. Once storage capacity is reached during the course of a storm, the swale has little impact in attenuating peak flow rates or reducing inflow volumes.

At the SEA Street site, baseline performance is monitored and compared to the theoretical performance of both conventional and post-construction street designs. The dominant characteristic of the residential block is runoff-response that is precipitation-driven and flashy. As a result, the runoff hydrograph closely follows the start, rise, and fall of the precipitation hyetograph. The post-construction performance of the SEA Streets project has yet to be made, but the project attempts to control stormwater production at the source and in the upper watershed. Hence it focuses on the root of the problem and recognizes that the impacts of the developed upper-watershed ultimately dictate the health of the stream. ❖

Using Air Conductivity and Soil Texture as Indicators of Infiltration Rates for Stormwater Infiltration Ponds

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Infiltration facilities are commonly used to reduce the hydrologic impacts of residential and commercial development. The purpose of infiltration ponds is to capture and retain stormwater runoff and allow it to infiltrate into the ground. The Washington State Department of Transportation sponsored a project to develop rapid lab-based methods to estimate infiltration rates when designing stormwater infiltration ponds. Field-scale infiltration rates of 15 ponds were compared with lab-based estimates of saturated hydraulic conductivity (K_s). Estimates of K_s were obtained from air conductivity laboratory measurements and from regression equations based on the grain-size distribution of soil samples (including one regression equation already in common use, the Hazen equation).

The air conductivity of synthetic and natural soil samples was measured using an air permeameter and K_s values were calculated from these measurements. Regression equations to predict K_s used the grain size parameters d_{10}, d_{60}, and d_{90} (i.e. 10th, 60th, and 90th percentiles of the grain diameters). The closest conservative fit regression equation is $0.87d_{10}^2$. This equation is similar to the Hazen equation Cd_{10}^2, where C is a constant ranging from 0.4 to 1.50. K_s values measured using the air permeameter over-predicted the field scale infiltration rates by factors of 5 to 618. The regression equation and Hazen equation were off by factors of 0.01 to 197, and so the Hazen equation provides a "better" estimate of K_s than the other regression equations. Although grain size analyses can be used as an indicator of the potential infiltration rate, this component alone cannot effectively predict infiltration rates for site-specific ponds. ❖

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