The Washington Water RESOURCE

The quarterly report of the Center for Urban Water Resources Management

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CONTENTS

Message from the Director

This issue of the *Newsletter* is being prepared on the eve of the upcoming American Geophysical Union's annual meeting in Washington DC, with sessions focusing on "Urban Rivers" and "The Scientific Basis for Stream Restoration." Interestingly, the public affairs staff of this organization identified these topics as worthy of a formal press conference for which our work here will be the primary topic of the presentation.

Following the lead of the last issue, this edition of the Newsletter highlights another of the research results from our three-year project on urban stream rehabilitation: that of Sarah Morley's use of biological indicators to evaluate causes of stream degradation. That article begins on the next page. We are also seeing continued progress on a related effort, our classification of the 1998 Landsat image of the Puget Sound lowland. Previously, Erik Botsford and Kristina Hill of the Landscape Architecture Department had classified a 1991 image with the particular goal of simplifying land-cover analyses for hydrologic calculations and impervious-area determinations in the urban and suburban parts of the lowland (this analysis, and the classified image, are available on the Center's web site). Making a similar analysis of the 1998 image has proven a challenge, because of image availability, undocumented resampling of the original data, atmospheric corrections, and our decision to release the data only *after* a full validation of the classification had been completed. However, Erik and Kristina, along with Michelle Kondo in the Department of Urban Design and Planning, have now finished the classification and also a first round of accuracy assessment. In this round, they evaluated 50 clusters for each of the eight land cover classes in the classified image. The results are very encouraging, with very good accuracy overall that ranges from a maximum of 100% "correct" for water to a minimum of 75% correct for the "grassy urban" land cover category. The next round will expand the number of clusters checked for several of the land cover types, which will allow greater rigor in characterizing the classification accuracy but is very unlikely to affect the conclusions.

In the last issue I made reference to the Center's web site, located at http://depts.washington.edu/cuwrm/. In it you will find, among many other things, a link on the RESEARCH page to a long-running and rapidly expanding project that is investigating geologic conditions, and geologic hazards, across the Puget Lowland. Although the connection between geology and "urban water resource management" may not be immediately obvious, the connections between water moving over and through the ground surface, and the geologic materials that underlie that surface, are multiple and profound. I encourage you to take a look at the project's web site at http://www.geology.washington.edu/sea-geo, and consider a 3-day course on this subject that will be offered through the PEPL program at Engineering Professional Programs in early September.

Continued on page 2

The Washington Water Resource is the quarterly publication of the Center for Urban Water Resources Management at the Department of Civil and Environmental Engineering, University of Washington, Box 352700, Seattle, WA 98195.

Web address:
http://depts.washington.edu/cuwrm/

MESSAGE (from page 1)

Finally, a reminder of the date of our annual review of the Center's research—the morning of Friday, October 20, at the Center for Urban Horticulture. We will spend one-half day presenting our work of the last year; however, we also recognize that there are other investigators, located elsewhere in the University community, who are also making great progress on related issues. As a result, the Center's advisory board and I have had discussions with our affiliated center in Forestry, the Center for Streamside Studies, and we are optimistic that our respective annual reviews may be combined into a single event with a broadened watershed focus in 2001.

❖ *Derek Booth*

Effects of Urbanization on the Biological Integrity of Puget Sound Lowland Streams: Restoration With a Biological Focus.

By Sarah A. Morley, Graduate Research Assistant, School of Fisheries, University of Washington

INTRODUCTION

With millions of dollars in federal funds recently allocated for salmon recovery and a public increasingly active in river conservation, hundreds of urban stream restoration projects are being installed around the Puget Sound Lowlands. What is worrisome is a deficiency of consistent pre- and post-project monitoring to guide project placement and design, and to evaluate what techniques are working where. The mission underlying the majority of these projects is salmon recovery, yet very rarely are salmon or any other element of stream biota directly monitored to assess restoration success.

Because declining biological conditions in running waters have many potential causes, a broad perspective is needed for their protection. The overall objective of this study is to apply tools of biological monitoring to urban stream management and restoration. The specific method of biological assessment utilized is the benthic index of biological integrity (B-IBI), a multimetric index based on attributes of stream benthic invertebrates (Karr and Chu 1999). This study has three components: 1) analysis of B-IBI variability relative to land cover change at multiple spatial scales, 2) evaluation of the diagnostic properties of B-IBI (e.g., how do metrics of this index respond to different channel impact types?), and 3) assessment of biological response associated with in-stream restoration projects.

METHODS

Study site selection

Between 1997 and 1999, benthic invertebrates were collected from 16 second and third-order streams in King and Snohomish counties (Table 1). In total, 45 study sites were selected that reflected a gradient of urban development. Two basins (Little Bear and Swamp Creek) were sampled at nine and ten sites respectively to examine within-basin variation in biological condition. Substrate data were provided by a concurrent study at 18 invertebrate monitoring sites (Konrad 2000). Hydrologic analysis was limited to 11 monitoring sites located in close proximity to gauging stations without intervening tributary input. Restoration efforts at five King County streams were selected to evaluate the response of invertebrates to LWD placement, a common restoration technique in Pacific Northwest streams (Larson 1999).

Benthic macroinvertebrates

Invertebrates sampling at each site was performed in September, using a Surber sampler to collect three samples along the mid-line of a single riffle. Invertebrates were preserved in the field in a solution of 70% ethanol and returned to the lab for iden-

Continued on page 3

EFFECTS OF URBANIZATION (from page 2)

Basins	area (km^2) [1]	% urban [1]	No. of sites
Lk. Washington / Cedar River			
Thornton Creek	25	91	4
Scriber Creek	15	84	1
Swamp Creek	58	70	10
North Creek	57	67	1
Little Bear Creek	40	54	9
Big Bear Creek	61	41	5
Struve Creek	4	48	1
Seidel Creek	7	19	1
Forbes Creek	5	85	2
Laughing Jacobs Creek	16	59	4
May Creek	30	36	1
Rock Creek	43	22	1
Green River			
Jenkins Creek	69	43	1
Big Soos Creek	42	61	1
Soosette Creek	14	63	2
Puget Sound			
Miller Creek	22	85	1

[1] values correspond to sample site farthest downstream

Table 1. Study basin area, land cover, and sampling intensity.

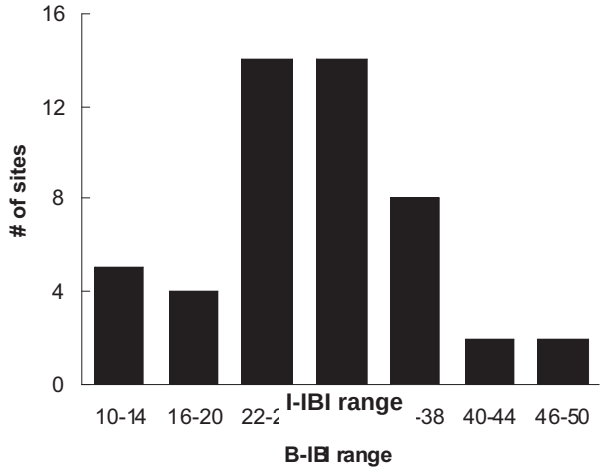

Figure 2. Distribution and range of B-IBI across all study sites (median = 28, mean = 27.4, standard deviation = 8.9).

tification under microscopy. Following procedures first outlined for fish (Karr et al. 1986), and later for invertebrates (Fore et al. 1996), metric scores of one, three, or five were assigned to each of ten raw metric values. These scores were then summed to provide a site and time specific B-IBI that ranged from 10 (very poor) to 50 (excellent).

Land cover analysis

Extent of urbanization in each study basin was calculated over three spatial scales: sub-basin, riparian, and local (Figure 1). The GIS land cover layer used in this analysis was a 1998 satellite classification with a mapping resolution of 30m (Botsford et al. 1998). Sub-basin delineation, stream buffering, and map overlays were performed in ArcInfo and ArcView to determine land cover distribution for each sample site. Graphical analysis and simple linear regression were used to evaluate land cover urbanization relative to B-IBI.

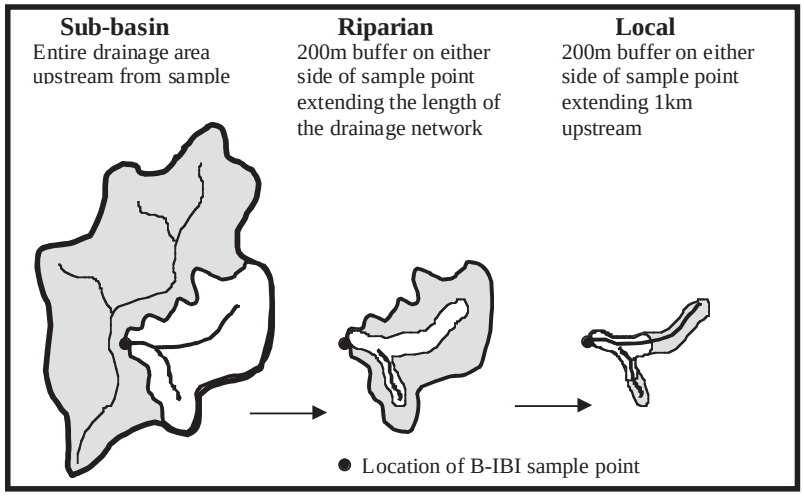

Figure 1. Diagram of GIS-based landscape analysis. Buffer widths dimensions were selected so as to be broad enough to include those functions commonly cited in association with riparian corridors, but not unrealistically narrow given the relative accuracy of geographical datasets used in basin delineation and buffer analysis.

Substrate and flow evaluation

Seven parameters that characterized the stream substrate and hydrology were evaluated in relation to biological condition. Size distribution of surface substrate was characterized by a Wolman pebble-count (Konrad 2000). Hydrologic data were downloaded from continuous recording hydrologic gauging stations, and provided by King County Hydrologic Information Center and Snohomish County Surface Water Management. Graphical analysis and simple linear regression were used to analyze the relationships between B-IBI and selected metrics to substrate and flow.

Restoration project assessment

B-IBI assessment was conducted in collaboration with concurrent evaluation of physical project condition (Larson 1999). Pre-construction invertebrate data were available for only one project (Soosette Creek; Greenberg 1995). In order to determine if restoration efforts were successful in improving biological condition, monitoring sites were located immediately upstream (control) and downstream (treatment) of projects. At three of these paired sites, an additional mid-stream site was sampled to test for localized effects. A paired t-test was used to compare control and treatment B-IBI.

RESULTS

B-IBI

Invertebrate biota of nearly all sites sampled in this study indicated mild to severe stream degradation. Although B-IBI varied from 10 (Thornton Creek) all the way up to 48 (Rock Creek; Figure 2), only 10% of sites sampled across the study were comparable or only slightly divergent from reference condition for

Continued on page 4

EFFECTS OF URBANIZATION (from page 3)

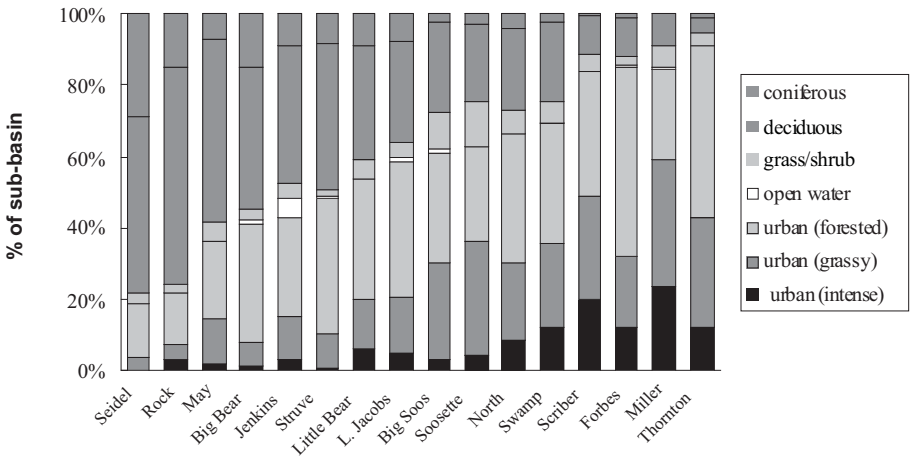

Figure 3. Distribution of land cover categories within study basins. Basins are ordered from least to most urban. With the exception of open water, all seven land cover categories are present in each of the 16 study basins. Combined forested categories range from 5-78% of the total area of the basin, and combined urban categories from 19-91%.

the region. On Little Bear, biological condition was good in the headwaters with a B-IBI of 40, but this score rapidly dropped down to 16 over a distance of approximately 10 km. In contrast, B-IBI varied relatively little between a high of 32 and a low of 22 along a 14 km length of Swamp Creek. Overall, highest B-IBI's (>38) were concentrated in less developed headwaters and unincorporated areas of King and Snohomish counties, while scores of 16 or less were located in areas of high residential and/or commercial development.

Land cover

The distribution of land cover among the 16 basins of this study reflects current development trends around the Puget Sound lowlands conversion of forested lands to urban and suburban centers (Figure 3). Of the various groupings of land cover measures tested, a combination of all urban land cover categories was best correlated with B-IBI ($r^2 > .49$, $p < 0.001$), and is used throughout this study in relation to biological and physical stream response. Because riparian and sub-basin land cover were so closely correlated ($r^2 = .95$, $p < 0.001$), the remainder of this study focuses on B-IBI response at the sub-basin and local scales.

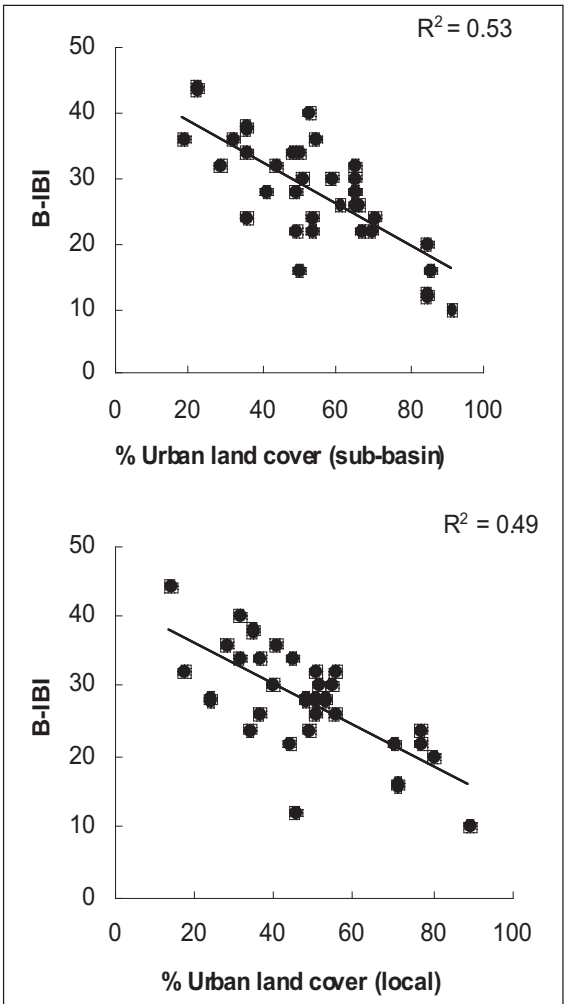

Figure 4. B-IBI *v* urban land cover across all sites.

B-IBI v land cover

Across study sites in all 16 basins, both sub-basin and local land cover were strongly correlated with B-IBI (Figure 4). When these two scales are combined in a multiple regression model, urban land cover explains 59% of variability in B-IBI ($p < 0.001$). B-IBI variability within the intensely sampled Swamp and Little Bear Creek basins tells a slightly different story. At the sub-basin 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 was observed: all sample sites on Swamp Creek were *less* urbanized than the six sites on lower Little Bear. In Little Bear Creek, B-IBI variability was strongly related to local land cover change (Figure 5a). In Swamp Creek, neither sub-basin nor local urban land cover varied substantially (Figure 5b), an observation that is concordant with limited variability in B-IBI.

B-IBI v substrate and flow

The pattern in B-IBI and metrics across sites was also explained to some degree by local channel features. Of the channel parameters tested, three were statistically related to biological response and/or to the extent of upstream urbanization: relative roughness (84^{th}-percentile pebble diameter divided by bankfull depth) and two measures of discharge flashiness. Two measures of particle size distribution (D_{16} and D_{50}) were better predicted by sub-basin area than urban land cover, suggesting that variation in particle size was more a factor of natural basin differences than anthropogenic impacts. Neither measure of peak flow explained any degree of variability in B-IBI or metrics; invertebrates seem to respond more to the degree of flow *fluctuation* than to the sheer magnitude of peak events.

Continued on page 5

EFFECTS OF URBANIZATION (from page 4)

Restoration project evaluation

Addition of LWD had little demonstrable effect on biological condition as measured by B-IBI (Larson, 1999; see the Winter 2000 issue of the *Newsletter*). Additional sampling in 1999 still showed no improvement in biological condition nor was there an improvement when samples were collected within project boundaries. Overall, B-IBI was much better correlated with the level of local urban land cover than with the presence or absence of a LWD project. Only post-treatment B-IBI on Soosette Creek scored significantly higher than either the upstream control site or pre-project collection. But here, the "control" site on this creek was considerably more urbanized than the treatment (53% vs. 13%), and thus serves as a poor comparison by which to judge the effects of LWD addition. Biological improvement observed on Soosette Creek may also be due to natural downstream recovery over the last decade.

DISCUSSION

Biological condition of Puget Sound lowland streams

Extensive and diverse activity throughout the Puget Sound basin has altered the region's landscapes with especially devastating effects on stream biota. Half of the stream sites sampled in this study were in poor biological condition; almost all sites lacked even a single "intolerant" taxon and at the most urbanized sites no stoneflies were found. Although the sites from this study were not randomly selected, such degraded conditions are typical of many streams in and around major metropolitan areas in the region (Kleindl 1995). The survival of wild salmon in the Pacific Northwest depends on many factors, crucial among them being high quality streams for spawning and rearing of young.

Measuring urbanization—the importance of spatial scale

Because humans modify watersheds in many ways, a broad definition of anthropogenic disturbance is appropriate for use in conjunction with biological assessment. None of the measures of land cover tested in this study were perfect fits with B-IBI, but overall, a grouping of equally weighted urban land cover categories explained a high degree of variability in B-IBI. This simple yet broad definition of urbanization is more inclusive of a variety of potential impact types than what is captured by impervious area models. Taking a broader definition of disturbance refers also to examining how urban development influences stream condition over multiple spatial scales. B-IBI in the urban streams of this study responded strongly to land cover change over both the entire sub-basin and local scale. Rarely is land cover homogenous across urbanizing basins and as a consequence biological condition may also vary substantially along a length of stream.

Diagnostic properties of B-IBI

B-IBI responded predictably across a gradient of urbanization, but it was also sensitive to changes in substrate and flow conditions. In particular, channel roughness and hydrologic flashiness were both correlated with B-IBI. High values of relative roughness, as observed on Rock Creek, may indicate a greater diversity of flow conditions (e.g., availability of slow-water refugia) during high flow events. In terms of flow regime, Rock Creek was also one of the least flashy sites. Stream invertebrates are adapted for life in strong currents, but few are able to exist under conditions of extreme and unpredictable flow fluctuation. The two most urban basins in this analysis were also the flashiest; biological condition at sites on these creeks was severely degraded.

Are current models of restoration working?

Overall, B-IBI did not detect any substantial positive effect on biological condition from the restoration activities at the time scales sampled. Biologically, placing logs devoid of bark, roots, branches, or leaves into urban streams is not equivalent to natural recruitment, where wood is but one benefit of a forested riparian corridor and comes in a variety of forms, sizes, and configurations. In order to achieve meaningful long-term biological recovery, restoration efforts must take a broad focus to address why wood is lacking from urban streams in the first place, and what else is amiss. This entails looking beyond local scale in-stream habitat manipulation to address factors operating across the entire basin.

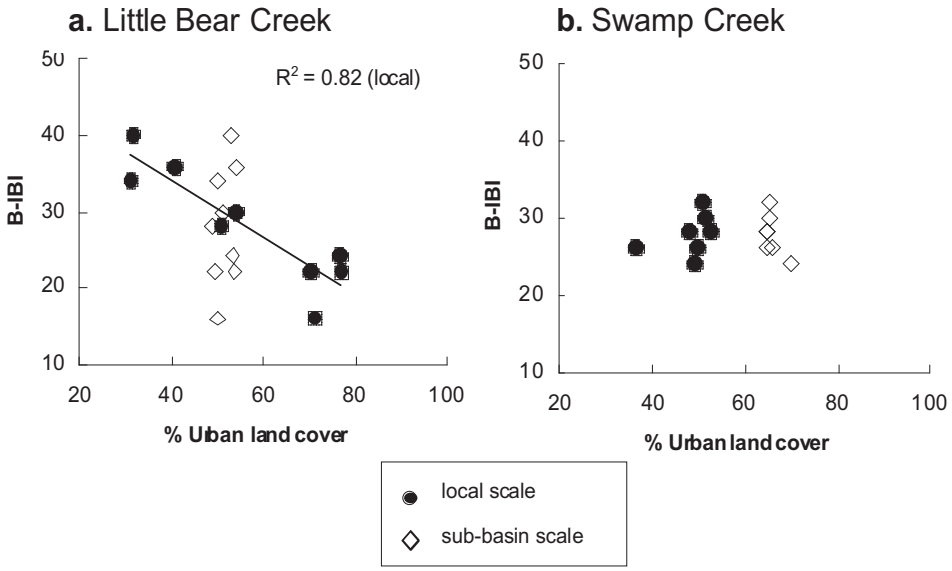

Figure 5. B-IBI *v* urban land cover in Little Bear and Swamp Creek. Note that for Swamp Creek, the most downstream site is excluded; local land cover could not be accurately determined here due to discrepancies between geographical datasets.

Continued on page 6

EFFECTS OF URBANIZATION (from page 5)

Riparian corridor conservation

As both a conservation and restoration strategy, protection and reforestation of riparian areas is critical for preventing severe stream degradation, but alone these measures are not adequate to maintain biological integrity in streams draining highly urban basins.

In Little Bear Creek, high B-IBI was associated with sites located in headwater reaches of intact riparian corridor. Further downstream, B-IBI decreased dramatically as local riparian vegetation was replaced by development. Neighboring Swamp Creek was more urbanized at a sub-basin scale but less so along the stream margin. Although B-IBI throughout this stream never indicated the severe degradation observed on lower Little Bear, sites on Swamp creek also never scored particularly high. In some of the most urban basins of this study (e.g., Forbes and Miller Creek), B-IBI was still very poor even in reaches with some degree of forested corridor.

Conclusions

The underlying goal of many urban stream management and restoration practices in the Pacific Northwest is biological. Instead of defining "critical thresholds" of basin development to generate formulas for stream protection, the biological condition of the streams that drain those basins should be examined directly. Routine biological assessment is also critical for deciding how most effectively to spend limited restoration dollars. This study looked at a small sub-set of one type of restoration project: placement of large woody debris in small lowland streams. The results presented here can by no means be generalized across all types of restoration projects in the Pacific Northwest. But that is precisely the problem; at present, we don't know what's working and what is not so as to learn by example. By ignoring the biology of those urban streams we seek to restore, we make the same mistake that has contributed to the current state of Puget Sound Lowland streams and rivers.

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On-site Residential Stormwater Detention

By Christopher P. Konrad and Stephen J. Burges, Department of Civil and Environmental Engineering

On-site stormwater detention

Stormwater can be managed in residential areas using dispersed, small-scale systems upslope of the channel network much in the way forested hillslopes stored and infiltrated stormwater. On-site systems include roof downspout detention and infiltration systems, permeable pavements, alternative landscaping, and soil amendments. We distinguish between single-purpose detention systems, which simply hold stormwater and retard its release, and multiple-purpose systems, which divert stormwater from surface drainage networks to subsurface drainage, domestic uses, or dry-season irrigation.

On-site storage systems can provide a reliable water supply during much of the year without employing large storage reservoirs in regions with frequent, long-duration, low-intensity storms. Many civilizations over millennia and across the earth have used small, multiple-purpose detention systems in urban and residential areas to gain the dual benefits of water supply and improved drainage (Hofkes and Huisman, 1983; Crouch, 1993).

Simulation of On-Site Stormwater Management System

On-site detention systems are simulated with a discrete-time, mass-balance model which represents runoff from an impermeable surface (typically roofs, sidewalks and driveways in a residential area) as the product of the surface area and rain depth falling during a time step. The simulated surface provides no depression storage, evaporative losses, or time delay between rainfall and runoff (Hollis and Ovenden 1988).

Two types of detention systems are simulated: single-purpose systems which would only provide storm flow control, and multiple-purpose systems from which releases are extracted for residential use. Releases from actual systems depend on design of storage tanks and control devices which are not considered here.

Continued on page 7

STORMWATER DETENTION (from page 6)

Description of hydrologic tIme-series

A continuous time series record of rainfall is used as input to the detention simulation model and two stream flow records are used to assess the performance of the simulated systems. Time-series records of discharge from Evans Creek, a largely forested, 37-km^2 stream basin, and runoff from Novelty Hill, a forested 0.37-km^2 subbasin within the Evans Creek basin, are used as standards for evaluating the discharge from an on-site system.

Outflow recorded at the Novelty Hill gage illustrates the pre-development runoff response of a forested zero-order catchment in the Puget Sound lowlands to storms over a broad range of antecedent conditions. Subsurface storm flow is the dominant runoff mechanism. There is no surface or shallow subsurface flow from Novelty Hill for half of the year during the summer and autumn; stream flow lags the onset of winter rains as the soil pores fill with water. Even after the onset of flow (20 November 1990 during the gaged period), runoff from Novelty Hill during early season storms is strongly attenuated.

Sizing on-site detention systems

We consider two objectives for preliminary sizing of on-site detention systems: limiting the maximum release rate to that observed at Novelty Hill, which was approximately 20 mm/day, and preventing spills while maintaining a consistent, low release rate. A detention system releasing water continuously at 20 mm/day would require a storage capacity equal to a 40 mm depth over the catchment area to prevent spills during the period of analysis. For longer time intervals of 5 to 100 days, an on-site detention system with 150 mm of storage and releasing water at a constant rate of 6 mm/day would effectively prevent any spills during the period of analysis.

Another approach for sizing on-site detention systems is to match storm flow recession from Novelty Hill. During the winter of 1991, which includes a variety of low- to high-intensity rainfall and a range of antecedent conditions, the recession coefficient K_R for Novelty Hill varied from 0.6 to 0.7, equivalent to a storage coefficient K_S of approximately 0.4.

A single linear reservoir cannot, however, match peak discharge and recession rates from a forested hillslope. Thus, in consideration of the natural hydrologic behavior of Novelty Hill and practical concerns regarding the size of reservoirs, we chose to simulate single-purpose detention systems with maximum release rates of 5 mm/day and 10 mm/day and storage volumes of 20 mm and 100 mm which give K_S values of 0.05 to 0.5 (K_R of 0.6 to 0.95). For a 100-m^2 roof, which represents a roof area for single residences in the region (Wigmosta et al. 1994), the simulated detention systems would require reservoirs of 2,000 and 10,000 liters, respectively. The reservoirs could be located beneath the residence as part of the structure or as stand-alone tanks or pools.

For multiple-purpose systems, we also tested storage volumes of 20 mm and 100 mm to facilitate comparison with single-purpose on-site detention systems. Release rates for simulated multiple-purpose systems approximate plausible rates of extraction for residential water use, which is approximately 400 l/day per capita in the region (Tacoma Public Utilities, 1995). This extraction rate for a two-person household, normalized for a 100-m^2 catchment, is 8 mm/day. We used a constant extraction rate of 5 mm/day.

Results

Results of seven simulations are reported. Multiple-purpose systems (M) are represented by three simulations: M1 (20 mm of storage, 5 mm/day extraction rate), M2 (100 mm of storage, 5 mm/day extraction rate), and M3 (100 mm of storage, 5 mm/day extraction rate during summer months). Single-purpose systems (S) are represented by four simulations: S1 (100 mm of storage, 5 mm/day maximum release rate); S2 (100 mm of storage, 10 mm/day maximum release rate), S3 (20 mm of storage, 5 mm/day release rate), and S4 (20 mm of storage, 10 mm/day release rate). Simulation results are described in terms of the area normalized volume (i.e., depth) and duration of flows exceeding 5 and 10 mm/day, the median discharge, and the duration of flow exceeding 0.3 mm/day (Table 1). Statistics from hydrologic records for Novelty Hill and Evans Creek provide standards for comparison of on-site system performance.

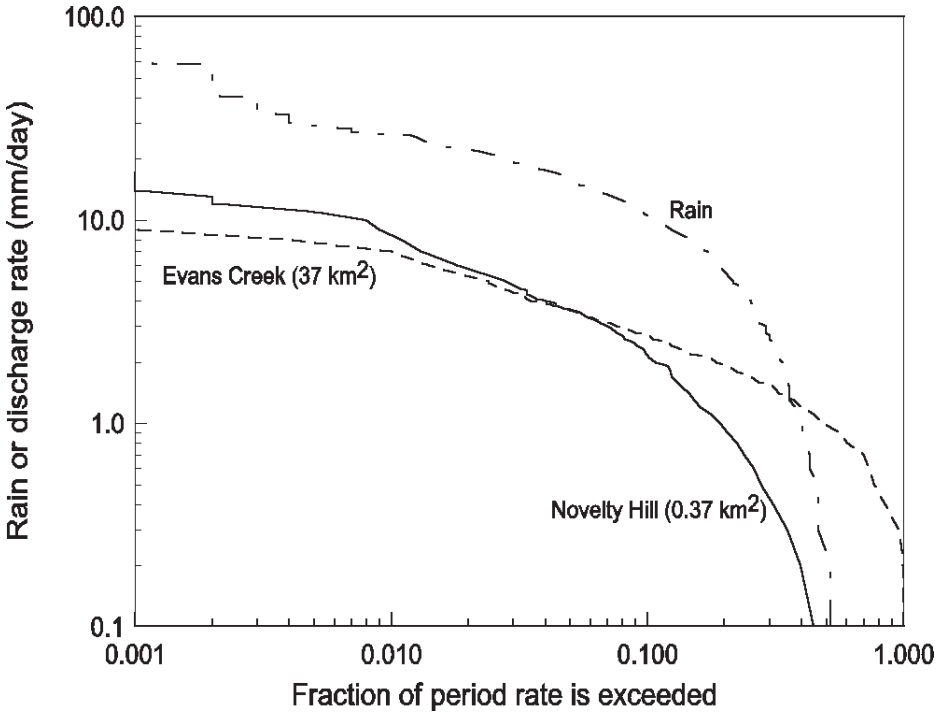

Figure 1: Daily duration curves for rain rate and flow rates at Novelty Hill, and Evans Creek.

Continued on page 8

Professional Engineering Practice Liaison (PEPL) Program

The PEPL (Professional Engineering Practice Liaison) Program, in cooperation with the Center for Urban Water Resources Management, offers a continuing education program in urban water resources management.

As part of the benefits extended to supporters of the Center for Urban Water Resources Management, member organizations are eligible for a discount if sending groups of three or more to the same course. For further information, please contact:

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STORMWATER DETENTION (from page 7)

Hydrologic records

The rain depth for the period of analysis (1 October 1990 to 30 June 1993) was 3243 mm with 52% of the days having measurable rain. Median daily rainfall was 0.25 mm. Daily rainfall exceeded 5 mm/day for 22% of the period and totaled 2700 mm. Daily rainfall exceeded 10 mm/day for 11% of the period and totaled 1889 mm. Durations curves for rainfall, Novelty Hill, and Evans Creek are provided in Figure 1.

Multiple-purpose systems

Figure 2 shows the daily flow-duration curves for "spills" (*i.e.* uncontrolled outflow) from the three simulated multiple-purpose systems. The multiple-purpose system M1, which has the larger storage capacity (100 mm), spilled at total of 52 mm which is equal to 7% of runoff from Novelty Hill. Spills at rates greater than 10 mm/day amounted to 34 mm or 35% that of Novelty Hill. In terms of low flow, M1 spilled water only 8% of time as compared to 52% of the time for Novelty Hill.

Cumulative spills from M2 were slightly less (617 mm) than Novelty Hill for the period of record. Spills from M2 at rates greater than 10 mm/day totaled 327 mm, or 3 times the amount of runoff exceeding a rate of 10 mm/day from Novelty Hill. Spills from M2 at rates greater than 10 mm/day occurred 2% of the time. While a small storage capacity reduces the performance of on-site systems during high flows, M2 still extracts 90% of the rain for the period of analysis compared to 98% for M1.

The multiple-purpose detention system M3, which limits extraction of stormwater to the summer months (and also at a rate of 5 mm/day) provides little attenuation of storm flow except during the first storms in autumn. The total amount of stormwater discharged at rates greater than 5 mm/day was 1998 mm, which occurred 16% of the time (Figure 2). Given that the majority of rain falls in autumn, winter, and spring, a reservoir would need a storage capacity equal to the annual volume of runoff from a catchment, in this region about 1 m, to maximize the water available for summer watering.

Single-purpose systems

Flow duration curves for outflow (controlled release plus uncontrolled spill) from single-purpose systems are shown in Figure 3. S1, which has a 100 mm reservoir and 20 mm/day maximum release rate, limited the amount of stormwater discharged above 10 mm/day to 382 mm. This is 4 times the total runoff from Novelty Hill that exceeds 10 mm/day but is only slightly greater than spills from the smallest multiple-purpose system (M2) exceeding 10 mm/day. S1 was the only system we considered here that had a sustained outflow of at least 0.2 mm/day throughout the period of analysis. This rate is approximately equal to the lowest recorded discharge for Evans Creek, normalized for drainage area.

Increasing the maximum controlled release rate of a 100-mm reservoir to 10 mm/day (S2) reduced the amount of stormwater discharged at rates greater than 10 mm/day to 47 mm, which is less than observed at Novelty Hill. S2 discharged a larger volume of stormwater (1352 mm) at rates greater than 5 mm/day, however, than either Novelty Hill (228 mm) or S1 (547 mm). The median daily discharge from both S1 and S2 was approximately 2.8 mm.

A single-purpose linear reservoir with 20 mm of storage and a maximum release rate of 5 mm (S3) discharged 1847 mm at rates greater than 5 mm/day. This is comparable to the amount released by S1, which has a larger reservoir and the same maximum controlled release rate. Because of its smaller storage capacity, however, S3 is not as effective as S1 at controlling higher discharges: total discharge from S3 at rates exceeding 10 mm/day was 1098 mm and lasted for 6% of the period (Figure 7). S3 had a median discharge of 2.2 mm and exceeded 0.2 mm/day for 90% of the time, which is comparable to the median and low flow discharge from S1.

Continued on page 9

STORMWATER DETENTION (from page 8)

DISCUSSION

Whereas small, single-purpose, on-site detention systems cannot replicate the runoff-response of a forest hillslope, they can attenuate the peak responses generated from impermeable surfaces. The smallest system considered here, S3, discharged a total of only 1098 mm at rates greater than 10 mm/day, compared to 1889 mm of total rainfall. The capacity of a reservoir providing this volume of storage, 20 mm over a 100-m^2 roof, is 2000 liters and could be integrated into many residential sites without limiting other uses of the land.

Single-purpose systems with larger storage capacities, represented by simulations S1 and S2, reduce the volume and duration of discharge during large storms, but they have little effect on the pattern of discharge at rates less than 5 mm/day. The additional cost of larger reservoirs may be justified, but only by evaluation of the deleterious ecological effects of storm flow with high magnitude but low frequency.

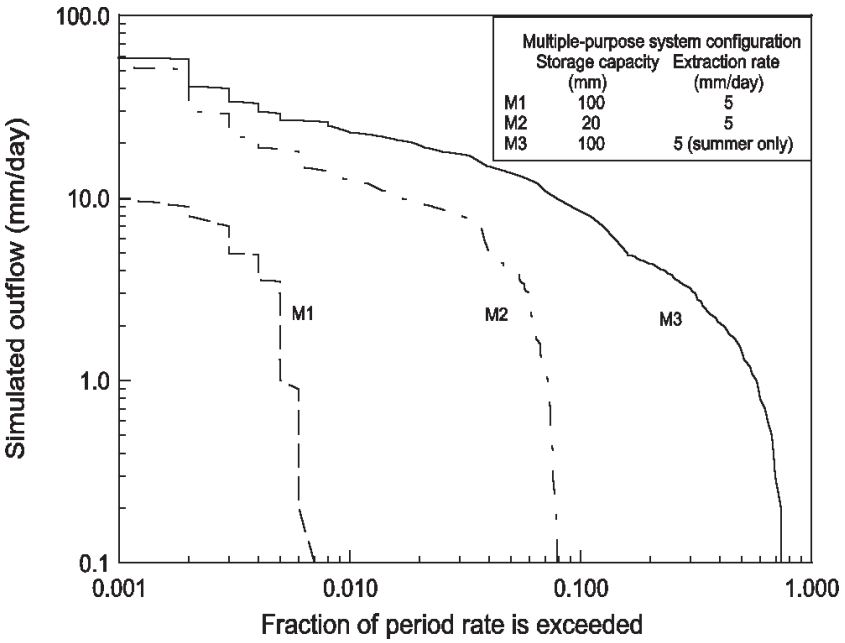

Figure 2: Flow duration curves for simulated uncontrolled spill, not including extracted water from three multiple-purpose systems.

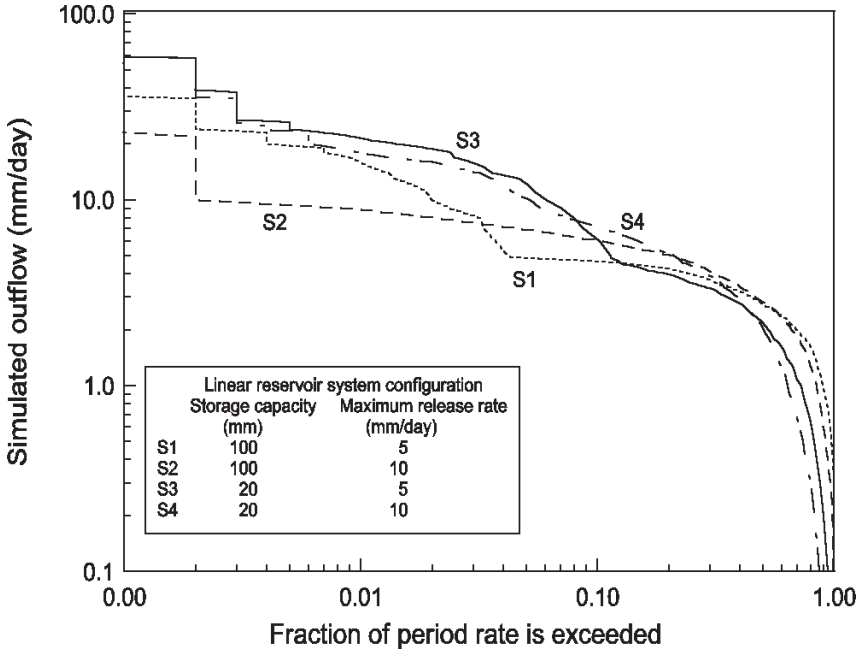

Figure 3: Flow duration curves for simulated controlled release and uncontrolled spill from four single-purpose, linear reservoirs.

Stormwater control during the largest storms can be improved if maximum release rates are increased, which will provide greater active storage capacity (*i.e.* an emptier pond) at the start of the next storm. This leads to an apparent paradox: the single-purpose system with 10 mm/day maximum release rate (S2 and S4) discharged *less* storm flow at rates greater than 10 mm/day than the system with the same storage capacity but lower (controlled) release rates (S1 and S3 respectively). There is a tradeoff, however, for increasing maximum release rates of a linear reservoir: the systems with the lower maximum release rate (S1 and S3) discharged less water at rates greater than 5 mm/day than the systems with equivalent storages but higher release rates (S2 and S4). Since 5 mm/day represents the 3% flow duration for Novelty Hill and 2% for Evans Creek, it is probably not an ecologically benign flow rate; any increase in duration would be cause for concern.

While stormwater management systems are traditionally designed to limit *peak* rates, they may be able to restore low-flow patterns as well. The single-purpose systems sustain discharge at rates comparable to minimum flow conditions in Evans Creek over long periods (83 to 100% of the period of analysis), particularly when designed with low release rates. In contrast, all of the multiple-purpose systems (M1, M2, and M3) discharge water for less than 10% of the period of analysis, compared to approximately 50% for Novelty Hill and 100% for Evans Creek. This illustrates another tradeoff: single-purpose systems are better suited for maintaining or augmenting low-flow discharge, while multiple-purpose systems best attenuate high flows.

CONCLUSIONS

We have demonstrated the potential to meliorate some hydrologic effects of residential development using on-site stormwater management. There are many practical details that

Continued on page 10

STORMWATER DETENTION (from page 9)

were not addressed, however, which will be necessary concerns for any demonstration and implementation of on-site stormwater management.

Runoff production from a zero-order hillslope catchment and second-order stream basin provide standards for evaluating the performance of on-site detention systems. The differences between surface runoff produced at the hillslope scale (0.37 km^2) and stream flow from a larger catchment (37 km^2) emphasize the importance of monitoring hydrologic processes over a range of spatial and temporal scales when assessing land-use effects and developing mitigation schemes.

Relatively small on-site detention systems can be used to manage much of the stormwater generated from impermeable surfaces during frequent, low-intensity storms in the Puget Sound Lowland. Small, single-purpose systems can be effective for hydrologic mitigation, particularly for the range of intermediate-magnitude discharges exceeded 10 to 30% of the time, and for providing sustained base flow. To match the peak discharges and intervening recessional flows of a forested catchment, however, a single-purpose on-site detention system requires a much larger storage capacity, approaching 150 mm. Even smaller storage capacities can be employed when stormwater is extracted for use, though these multiple-purpose systems can diminish base flow if some of the extracted water is not eventually returned to the local surface-water or groundwater system.

On-site detention augments channel-based stormwater management by taking advantage of spatially diffuse storage and release, without dedicating the area solely to stormwater management. On-site systems can manage stormwater before it is concentrated in drainage systems, providing opportunities for emulating natural hillslope processes after land has been developed. The benefits of different system configurations (*i.e.* storage capacities and release rates) cannot be represented by a single measure. The tradeoffs among systems must be evaluated in terms of the value of restoring different aspects of the hydrologic cycle in residential areas.

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New Resource for Alternative Stormwater Management Strategies

The Low-Impact Development Center is a non-profit organization formed in 1998 to serve as a technical clearinghouse for information and issues related to Low Impact Development (LID), and to facilitate research, education, and strategies for the implementation of LID technology. This technology is based on site specific approaches to maintain watershed viability by maintaining each site's hydrologic regime. The Center's mission includes research, development of models, stormwater management regulations and ordinances, ecosystem monitoring plans, and development of public outreach and environmental protection strategies. This is done with an interdisciplinary approach that includes researchers, public officials, citizen groups, and practitioners so that practical solutions can be achieved. Members of the Center have been instrumental in the development of LID technology in the Mid-Atlantic Region (Prince George's County, MD, LID Design Manual) and are currently working on the development of the National Manual for LID technology which is being prepared for the US Environmental Protection Agency. Other current and future activities include the development of manuals for other regions of the country and international applications, monitoring of LID case studies, and application of LID technologies to solving CSO and SSO problems.

Starting this fall, the Center will offer one and two day training and certification programs on Bioretention, which is one of the foundations of LID technology. These workshops will include information for designers, reviewers, inspectors, program administrators, and developers. Members and staff at the Center have been involved in the research and implementing of bioretention since its inception.

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Publication update of current projects at the Center (with dates of Newsletter articles and available Center publications, if available)

Project	Newsletter Issue	Center Publication
Urban stream rehabilitation:	Su 98	
Riparian buffers in urban watersheds	W 97	
Landsat land cover interpretation	Sp 99, W 00	E16 (on CUWRM web)
Regional, synchronous stream temperature survey	Su 98, F 98	CUWRM web data
Effectiveness of LWD in rehabilitation projects	W 00	K25
Sediment budget of mixed-use watershed	F 99	K23
Rates of stream channel restabilization	Su 99	K24
Biological evaluation of urban streams	Sp 00	
Urban Planned Development monitoring:	F 99	
Relationship of turbidity to total suspended solids		
Monitoring of ephemeral streams		
Infiltrative parking lot surfaces	W 96, F 96	K19
Stream habitat assessment protocols	W 99	E17 (on CUWRM web)
Puget Lowland geology and geologic hazards	Sp 97, Su 98	linked web site
Water-quality effects of road ditches and swales	F 99	
Ultra-urban stormwater management evaluation	F 99	
Urban Issues Library	F 99	On CUWRM web site
Highway stormwater treatment testing	W 00	
Remote sensing of stream temperature	W 00	
Review of water reuse case studies		
The impact of urban patterns on ecosystem dynamics		

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