The Washington Water RESOURCE

The quarterly report of the Center for Urban Water Resources Management

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Message from the Director

Two of our longest running efforts are featured in this issue of the *Newsletter*—but whether their longevity reflects the difficulty of the tasks or merely the inefficiencies of our operation I am hard-pressed to decide! Nonetheless, the results should be well worth the wait. The first article, on new hydrologic metrics for identifying and quantifying the influence of urban development on stream flows, addresses a critical need in our understanding, monitoring, and mitigating of stormwater impacts on stream-channel geomorphology and biology. It is but one chapter of Christopher Konrad's Ph.D. dissertation, which itself is but one component of the Center's three-year project on urban stream rehabilitation; other parts of those efforts will continue to appear in subsequent newsletters as they reach conclusion.

The second article also arises from the rehabilitation project, with added resources from two projects at the University, PRISM (Puget Sound Regional Synthesis Model) and an NSF-funded project in the College of Architecture and Urban Planning that is investigating the ecological effects of urban patterns across the landscape. With this second article we announce the release of the Center's land-cover classification of the 1998 Landsat image of the Puget Lowland, using a simplified set of categories that should be particularly useful for those trying to characterize levels of urban development across watersheds rapidly and systematically, and for those constructing hydrologic models of those areas.

The Center's largest Annual Review to date was held on October 20th; as an encore, we have joined forces with our sister center in Forestry and Fisheries, the Center for Streamside Studies, and will co-host the next presentation of research results from the two centers on Thursday, February 1, 2001 in the HUB Ballroom on the University of Washington campus. This is a full-day affair; watch our web site or that of CSS, http://depts.washington.edu/cssuw/, for upcoming information.

For those readers of this newsletter who are interested in further broadening their access to information, I also commend to you the Center for Watershed Protection (http://www.cwp.org/), who has an impressive set of printed resources and a widely distributed print and electronic newsletter. Our own web site (http://depts.washington.edu/cuwrm/) has undergone some recent reorganization, reflecting the increased number of project reports and our desire to make more information available by direct electronic access. All on-line reports are available from the RESEARCH page, past years' newsletters from the SUBSCRIPTIONS page, and the order form for non-electronic documents from the PUBLICATIONS page.

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MESSAGE (from page 1)

Once again the end-of-year season is upon us, and so Center subscription renewals for 2001 will be sent out in January. Subscriptions cover the cost of the newsletter and help support many of the ongoing, cooperative functions of the Center as well. Support from the colleges of Engineering and Forest Resources continue to allow us to maintain the same subscription rates that have been in effect since the Center began in 1990. I also remind you that all are welcome to add additional recipients of the newsletter to your subscription without charge, because our interests are all best served through the broadest distribution of information.

Derek Booth ❖

New Metrics to Characterize the Influence of Urban Development on Stream Flow Patterns

By Christopher Konrad, Center for Urban Water Resources Management

INTRODUCTION

Urban development greatly modifies hillslope hydrologic processes, particularly the production of runoff. These changes produce characteristic stream flow patterns at a storm scale, such as increased peak discharge rate for a given amount of rainfall. Yet the "classic" metrics of urban-induced hydrologic change, such as the fractional increase in the 2-year discharge, are poorly suited to characterize the magnitude of such changes, because they do not facilitate comparisons between basins and they do not have any demonstrable (or even plausible) linkage with other important instream conditions, particularly biological health.

Although biological degradation is ubiquitous in urban streams, the effects of storm-scale hydrologic changes on the biological conditions of urban streams are difficult to deduce because biological conditions in streams re-establish quickly, often within months, after hydrologic disturbances such as floods and droughts (Boulton et al., 1992; Bayley and Osborne, 1993; Jones et al., 1995). Over annual or multiple-year time scales, however, changes in stream flow patterns may have a persistent influence on the biological conditions of urban streams (Poff et al., 1997).

Three hydrologic measures are presented here that capture the storm- and base-flow patterns over these longer time scales, and that are recommended as new metrics with which to characterize the magnitude of urban influence on stream flow: (1) the fraction of a year that the daily mean discharge rate exceeds the annual mean discharge rate (T_{Qmean}); (2) the fraction of a multiple-year period that the discharge rate of a specified flood quantile is exceeded ($T_{X\ yr}$ is the cumulative duration that stream flow exceeds the discharge of a flood occurring on average 1/X times per year); and (3) the coefficient of variation of the annual maximum flood (CV_{AMF}). These metrics are analyzed in light of natural physiographic variability and urban development, using discharge records from stream gages in the Puget Lowland region.

ANALYSIS OF PUGET LOWLAND STREAM FLOW PATTERNS

The hydrologic effects of urban development in the Puget Lowland are characterized in terms of differences in flow patterns between selected urban and suburban streams (Table 1), and changes in flow patterns in those streams, during the latter half of the 20th century. Differences between urban and suburban streams were analyzed for the period of record from Water Years (WY) 1989 to 1998 (i.e., 1 October 1988 to 30 September 1998). Changes over time in individual streams were analyzed by

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comparing hydrologic measures for the period from WY 1960 through WY 1969 to the period from WY 1989 through WY 1998

The stream basins span the range of urban development found in the Puget Lowland, as indicated by road densities (i.e., the total length of road in a stream basin divided by its drainage area). The road data do not include logging and service roads or private driveways. Where an analysis or discussion is facilitated by simplifying this range, "urban" streams are defined as having road densities > 6 km/km^2 and "suburban" streams have road densities < 6 km/km^2. Within each category, however, stream basins vary with respect to their level of urban development.

Although this analysis focuses on the hydrologic conditions resulting from urbanization, it is not clear if the hydrologic differences between streams resulting from differences in basin area or other physiographic conditions also have ecological effects comparable to urban development. For example, the lower diversity of macroinvertebrate and fish assemblages in small streams (Giller and Malmqvist, 1998) may reflect the hydrologic effects of basin scale described above. Furthermore, natural physiographic conditions are likely to influence the hydrologic sensitivity of a basin to land use (e.g., the extent to which stream flow patterns change in response to incremental urban development). The analysis therefore includes a broad range of stream basins to evaluate whether urban development has characteristic hydrologic effects unlike those of natural physiographic conditions.

Suburban streams	Drainage area (km^2)	Road density (km/km^2)	Stream gage operators
Novelty Hill	0.37	0.0	King Co.
Canyon Creek	7.0	1.3	King Co.
Huge Creek	17	2.5	USGS
East Fork Issaquah Creek	22	1.7	King Co.
May Creek @ Coal Cr. Pkwy.	24	4.0	King Co.
Rock Creek	32	2.7	USGS/King Co.
May Creek near mouth	32	5.0	USGS/King Co.
Big Beef Creek	35	2.1	USGS
Bear Creek @ 133rd Ave. N.E.	36	4.4	USGS/King Co.
Evans Creek	37	3.6	King Co.
Jenkins Creek	37	5.4	King Co.
Covington Creek	55	4.0	King Co.
Newaukum Creek	70	2.6	USGS
Bear Creek @ Union Hill Rd.	123	4.6	King Co.
Issaquah Creek	145	2.4	USGS
Soos Creek	171	4.7	USGS
Urban streams			
Miller tributary 031A	1.6	6.3	King Co.
Cedar River tributary 0308	2.7	7.6	King Co.
Des Moines Creek above Tyee pond	2.8	9.1	King Co.
Leach Creek	12	9.9	USGS
Des Moines Creek near mouth	14	7.9	King Co.
Juanita Creek	17	11.3	USGS
Flett Creek	20	9.8	USGS
Miller Creek near mouth	21	10.6	King Co.
Swamp Creek near Filbert Rd.	25	7.4	Snohomish Co.
Mercer Creek	37	9.1	USGS
Swamp Creek near mouth	59	7.9	USGS
North Creek	67	7.5	Snohomish Co.
Clover Creek	189	6.7	USGS

Table 1:
Drainage area, road density, and operators of stream gages used in hydrologic analysis.

MEASURES OF ANNUAL AND INTER-ANNUAL STREAM FLOW PATTERNS

The differences between urban and suburban stream flow patterns over annual and multiple-year periods are examined here using three measures: (1) the fraction of a year that the daily mean discharge rate exceeds the annual mean discharge rate (T_{Qmean}); (2) the cumulative fraction of a multiple-year period that the discharge rate of a specified flood quantile is exceeded ($T_{X\ yr}$); and (3) the coefficient of variation of the annual maximum flood (CV_{AMF}). The analysis of changes in stream flow patterns over time includes six urban streams (Juanita, Leach, Mercer, Swamp, and Clover Creeks) and six suburban streams (Huge, May, Rock, Newaukum, Soos, and Issaquah Creeks)

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. Likewise, differences in the CV_{AMF} between urban and suburban streams are expected given the results of rainfall-runoff modeling by James (1965) and the observations of Hollis (1975), which both showed a greater relative increase in the magnitude of small, frequent floods than the relative increase of large, infrequent floods in response to urban development.

Fraction of Time That Mean Daily Discharge Rate is Exceeded

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

The patterns in T_{Qmean} observed for the nine streams above was analyzed using stream flow records for 23 Puget Lowland streams for the period from WY 1989 to 1998. The fraction of

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

T_{Qmean} generally varies inversely with urban development among Puget Lowland streams (Figure 1). The mean value of T_{Qmean} during WY 1989 to 1998 for 11 urban streams was 0.29 while it was 0.34 for 12 suburban streams. The difference is statistically significant ($p < 0.01$ using Student's t-test of samples with equal variance). Suburban streams had values of T_{Qmean} greater than or equal to 0.32 with the exception of Huge Creek. Urban streams had values of T_{Qmean} less than or equal to 0.31 with the exception of Clover Creek.

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

Huge and Clover Creeks stand out from the other data points in Figure 1. Huge Creek has a relatively low value of T_{Qmean} (26%) among suburban streams. Two factors may account for the low value of T_{Qmean} in Huge Creek: it has a smaller drainage area (17 km^2), and it receives greater rainfall during storms. As noted in the earlier analysis of stream hydrographs, these characteristics promote a "flashy" storm flow pattern in Huge Creek with high peak discharge rates and rapid recession rates. In contrast, Clover Creek has a high value of T_{Qmean} (41%) in spite of a moderate level of urban development (road density 6.7 km/km^2). The high value of T_{Qmean} for Clover Creek likely results from the influence of lakes and permeable glacial outwash soils in its basin, which attenuate higher flows and sustain discharge during dry periods. Clover Creek is also the largest urban streams analyzed here.

In a stream with stable land use, T_{Qmean} varies little from year to year. The coefficient of variation for annual values of T_{Qmean} during the period of 1989 to 1998 was less than 17% for all of the streams except a small tributary to Miller Creek. Since T_{Qmean} does not display high inter-annual variability, it can be estimated reliably from a relatively short (e.g., ~ 10 years) stream flow record. In contrast, T_{Qmean} for a stream changes over a period of urban development. Annual values of T_{Qmean} for Mercer Creek illustrate a systematic decline during a period of urban development from 1960 to 1998 (Figure 3).

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

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

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

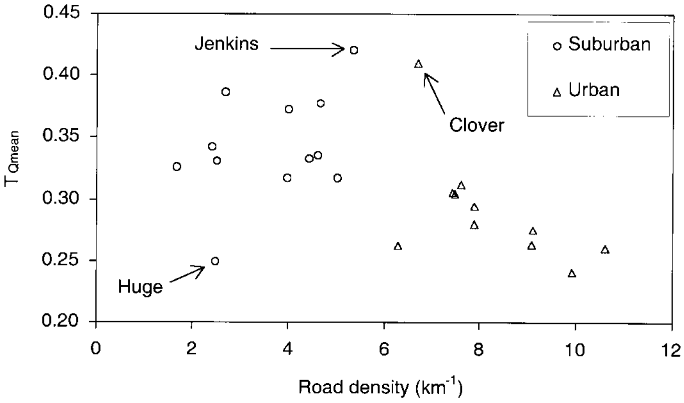

Figure 1:
Fraction of year that daily mean discharge rate exceeded annual mean discharge rate (T_{Qmean}) as a function of road density.

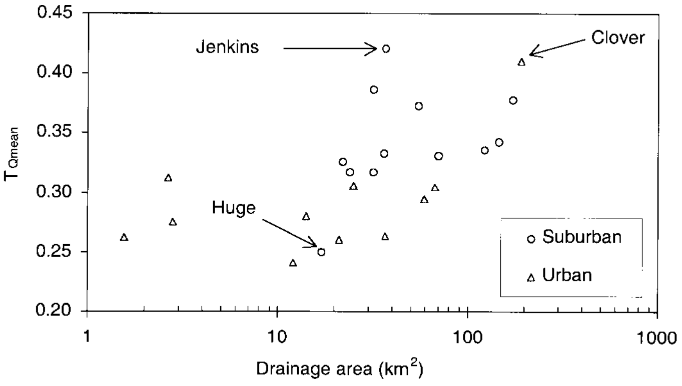

Figure 2:
Fraction of year that daily mean discharge rate exceeded annual mean discharge rate (T_{Qmean}) as a function of drainage area for 18 streams during WY1989-1998.

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stream was calculated from a partial-duration series. The partial-duration series used here comprises stream flow peaks (i.e., local maxima in a hydrograph) that were separated by at least 10 days. The threshold discharge rate for each stream was selected so that each series had 30 to 50 floods.

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

Coefficient of Variation of the Annual Maximum Flood Distribution

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

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

The area-normalized peak discharge rates of mean annual floods are higher in urban streams than suburban streams, and the variation in the flood distribution for urban streams is lower than the variation in the flood distribution for suburban streams (Figure 4). The urban streams had a mean CV_{AMF} of 0.5 while the suburban stream had a mean CV_{AMF} of 1.0. However, the lower values of CV_{AMF} in urban streams may be due in part to the effects of different basin sizes. Because of the long gage record required and temporal variability in this metric, CV_{AMF} may not be useful for characterizing hydrologic change due to land use in a single stream basin, but it may discriminate between urban and suburban streams for a common period of time.

APPLICABILITY

The three hydrologic measures characterize annual and multiple-year stream flow patterns over a range of temporal scales reflecting progressively less common hydrologic conditions. Mean annual discharge is exceeded about 30% of the time in Puget Lowland streams. The discharge rate of a 0.5 yr flood is exceeded less than 10% of the time in all streams (and less than 1% of the time in urban streams). The discharge rate

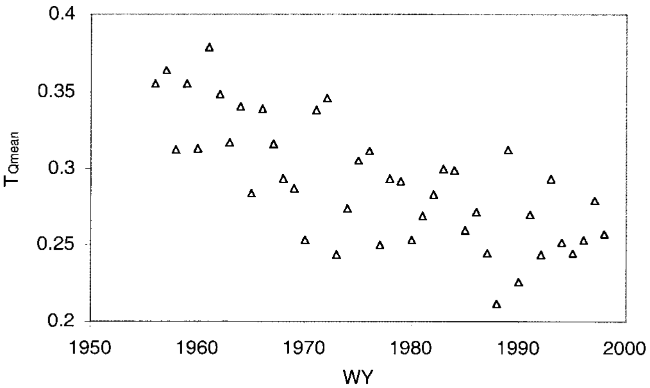

Figure 3:
Fraction of the year that daily mean discharge exceeded annual mean discharge rate (T_{Qmean}) for Mercer Creek for WY 1954 to 1998.

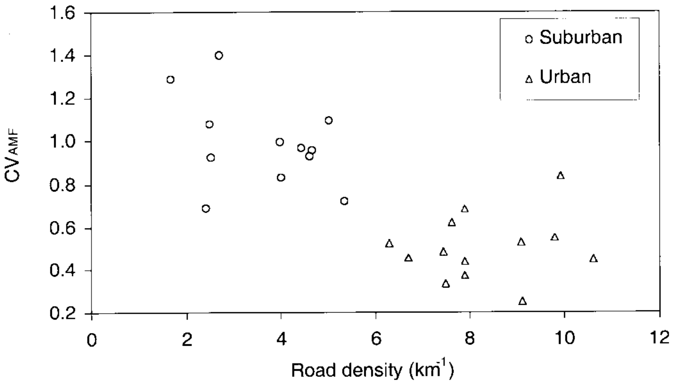

Figure 4:
Coefficient of variation of annual maximum flood (CV_{AMF}) as a function of road density during WY 1989 to 1998.

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of an annual maximum flood is exceeded less than 2% of the time. The applicability of a particular metric depends, in part, on the flow condition of interest. For example, T_{Qmean} would be relevant where winter base flow levels are of concern while CV_{AMF} would be more appropriate where infrequent floods are of interest.

For Puget Lowland streams, the mean annual discharge rate (Q_{mean}) is representative of recessional flow after storms and wet-season (winter and spring) base flow. Urban development increases storm flow recession rates and decreases wet-season base flow in streams, so that there are more days when stream flow is less than Q_{mean}. T_{Qmean} has low inter-annual variability, so it can be used to analyze the hydrologic effects of urban development over time for a stream and to compare flow patterns in urban and suburban streams even when those streams have different periods of recorded discharge. However, physiographic factors, such as lakes, surficial geology, topography, and basin area, influence the value of $T_{Qmean.}$. For basins less than 20 km^2, the value of T_{Qmean} may be relatively low (<30%) even in suburban basins. As a result, T_{Qmean} may have limited application for assessing stream flow patterns in such small basins. For basins larger than 20 km^2, T_{Qmean} was systematically greater than 30% in suburban streams and less than 30% in urban streams

$T_{0.5\ yr}$ indicates the duration over a multiple-year period that discharge exceeds the level of a common flood (e.g., one occurring on average twice a year). $T_{0.5\ yr}$ varies inversely with road density such that urban streams have low values (i.e., short durations) and suburban streams have higher values. Although assessing streams using $T_{X\ yr}$ requires a continuous time-series of high resolution (e.g., 15-minute) discharge data, the metric does not appear to be sensitive to basin size.

CV_{AMF} is an indicator over a multiple-year period of the variation of the largest annual flood in a stream. Urban streams flow patterns can be distinguished from suburban stream flow patterns, even for smaller streams, using CV_{AMF}. CV_{AMF} is generally lower for urban streams than suburban streams but it varies considerably over periods of decades even when land use is fairly stable. Consequently, CV_{AMF} is not useful for assessing land use change over time or differences between streams with gages covering different periods of record. While CV_{AMF} appears less sensitive to basin area than does T_{Qmean}, a larger sample, particularly of small (< 20 km^2) suburban streams and large (>20 km^2) urban streams, is necessary to confirm this preliminary observation.

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

Table 2:
Metrics indicating the hydrologic effects of urban development

SUMMARY

Each of the three metrics of urban hydrologic influence has particular strengths and limitations (Table 2). The fraction of a year that stream flow is greater than the annual mean discharge rate (T_{Qmean}) is a reliable indicator of hydrologic change over time in a stream basin, but it varies with drainage area and other physiographic conditions and so should only be used to compare similar stream basins. In contrast, the cumulative duration that the discharge rate exceeds the magnitude of a frequent flood ($T_{0.5\ yr}$) is a robust indicator of urban development in the Puget Lowland showing little sensitivity to drainage area. $T_{X\ yr}$, however, must be estimated using discharge data of high temporal resolution (e.g., 15-minute or hourly) from a period of multiple years. The last metric investigated, the coefficient of variation of annual maximum floods (CV_{AMF}), can serve as a basis for comparing the high flow regime of a group of streams during a common time period, but it is highly variable over time and so it is not a reliable indicator of the hydrologic consequences of land use changes in a stream basin.

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A Rapid Land Cover Classification Method for Use in Urban Watershed Analysis

By Kristina Hill, Erik Botsford, and Derek Booth, Departments of Landscape Architecture and Urban Design & Planning, and the Center for Urban Water Resources Management

Because of the profound effect of urban development on aquatic systems, characterizing the land cover of a region is critical for a variety of resource-management applications. In the Pacific Northwest, this characterization has been used most commonly to correlate the intensity of human activity with observed stream or wetland conditions, in order to predict the health of the stream system or to guide the allocation of mitigation efforts. For example, measured biological conditions in lowland streams are regularly presented in terms of "impervious area percentage" of the contributing watershed. Land cover is a primary input parameter for numerical hydrologic models (such as the Hydrologic Simulation Program Fortran [HSPF], widely used by the surface-water management agencies of King County, Snohomish County, the cities of Seattle and Bellevue, and the consultants of these and smaller jurisdictions throughout western Washington).

Unfortunately, there is little consistency or quality control in how land-cover data are collected and analyzed. Some of this variety is entirely appropriate—the methods and the products for assessing wilderness-area potential in the Cascade Range have little overlap with those used to plan optimal siting of commuter-rail stations, for example. Yet certain applications constantly reemerge, and so typical procedures have been developed but only on an *ad hoc* basis.

Remotely sensed data from satellites provide an alternative source of information on land cover over very large areas. The traditional approach to classifying remotely sensed data from satellites into discrete classes of land cover involves a lengthy process of automated classification, clustering of spectral signatures, much fine-tuning, and an eventual supervised classification. This process can be both time and resource-intensive. It is also continually being refined, and so the methodologies are not consistent.

The current project was initiated with a grant from PRISM (Puget Sound Regional Synthesis Model) at the University of Washington, and continued with additional funds from the Center for Urban Water Resources Management and several grant-funded projects. Through it, we have developed an alternative approach using Landsat satellite imagery to produce the same general type of land-cover characterization as has currently found widespread acceptance and use across the region. The full classified images for both the 1991 and 1998 Landsat data are now freely available for downloading, in ArcInfo- and ArcView-compatible format, in the RESEARCH section of the Center's web site.

The classification was designed to achieve maximum utility and consistency for a *particular* group of users—individuals and agencies needing to assess watershed conditions in the urban, and urbanizing, parts of western Washington. The classes of land cover produced have been chosen to reflect the categories that can be readily distinguished in the satellite data and to have important differences in their associated runoff and watershed characteristics.

Our classification scheme followed a multi-step process, consisting of:

1. Combination and manipulation of the raw satellite images;
2. Selection of training sites, where different land-cover categories could be defined;
3. Extraction of the "typical" Landsat signatures for each coverage;
4. Classification of the entire image, following the characteristics defined for each class; and
5. Assessment of the classification's accuracy by checking actual field conditions at selected locations.

This summary focuses on the final step of this process, the accuracy assessment of the classed images. We took two approaches, both using digital and printed overlays of the classified images and digital orthophotos. One hundred (1991 image) or 50 (1998 image) pixels from each of the seven categories were randomly selected; they were chosen from clusters of 25 (5-by-5) uniformly classified pixels to ensure that minor mis-registration of the orthophotos did not skew the analysis. The orthophoto corresponding to the center pixel in each 5-by-5 group was displayed on the computer monitor and divided into a 10-by-10 grid. Each of the one hundred grid cells of the orthophoto was visually identified into one of four (1991) or seven (1998) categories (1991: open water, trees, shrubs/ grass, and pavement or bare earth; 1998: open water, trees, shrubs/ grass, pavement, bare earth, pavement or bare earth, and shadows).

The first accuracy assessment was a classic error check, wherein classified pixels are judged to be "correctly" or "incorrectly" identified. The criteria, determined from the results of the signature extraction for the 1998 image, are listed in Table 1. The analysis for the 1998 image (Table 2) shows an overall accuracy of 77 percent, with the worst performance for the two classes with the greatest mixture of land covers: *grassy urban* (most pixels were "more urban" than anticipated) and *forested urban* (the misclassified pixels were both more and less urban than expected).

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URBAN WATERSHED ANALYSIS *(from page 7)*

However, we were less concerned with a correspondence with preestablished categories than with having a robust characterization of land cover. We therefore took a second approach to accuracy assessment—accepting the pixel classification as a given, and simply characterizing *a priori* the land cover associated with each of the seven categories (open water, coniferous vegetation, deciduous vegetation, grass/shrub, intense urban, grassy urban, and forested urban). From this approach, values for each of the 100 (1991) or 56 (1998) pixels in each category were combined to yield averages and standard deviations for the different *land covers*, visible in an orthophoto, for each of the seven *classes*. Values are tabulated in the Appendix. In particular, impervious-area percentages (combining pavement and bare earth) for the seven classes are listed in Table 3.

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

Table 1:
Criteria for "correct" land-cover classification.

These average values follow the expected trends for the different classes, and in general the 1998 classification does a better job of discriminating developed from undeveloped land uses. However, actual land covers for individual pixels of the same class can vary widely. The standard deviations for each cover type in each class are generally of the same magnitude of the average values themselves, and so estimates of land cover for a single (or a small number) of pixels have a high probability of diverging significantly from the average values.

The magnitude of this uncertainty, and the number of pixels needed to reduce it to a predetermined level, can be estimated using the expectation of normally distributed variability in the range of measured values (an expression of the central limit theorem in statistical analysis). If we explicitly define a maximum acceptable range for the 95-percent confidence interval for specific land-cover types (trees, impervious area, etc.), the minimum number of aggregated pixels (N_{min}) needed to achieve that range can be calculated. As a general rule, low-development watersheds of just a few hundred acres should have estimates of total imperviousness within a few percent; more urban areas will require areas of one-half to one square mile for equally reliable results. The most urban areas should be evaluated over areas of one to two square miles (or more).

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

Table 2:
Error matrix for the 1998 classification.

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URBAN WATERSHED ANALYSIS *(from page 8)*

Other Landsat Land-Cover Classifications

Our effort is not the *only* Landsat land-cover classification available for the Puget Sound region, and it is surely not the most suitable for a number of potential applications. Its particular strengths are (1) a focus on land-cover categories with particular hydrologic attributes, and (2) statistical validation of the classification, so that ranges of uncertainty are known and quantifiable.

Other classifications include:

1. That coordinated by PRISM, which hosted a "Regional Classified Landcover Workshop" on January 22nd 1999. At that meeting, regional remote sensing professionals discussed the various advantage and disadvantage to classification protocols. The results of this workshop (1) confirmed the utility of taking a hybrid unsupervised/supervised approach to the classification process, and (2) initiated five important regional partnerships for the use and continued collaboration of this process (King County's Water and Land Resources Division, NOAA Coastal Change Analysis Program, Western Washington University, Olympic Natural Research Center, and the Center for Urban Water Resource Management). From this initiative, PRISM has subsequently analyzed and classified the 1998 Landsat image for the Puget Lowland area to describe sixty-nine unique spectral signatures (classes) for which long descriptive names were attached. One example of that approach was to use ground truth information to form thirty seven more general and targeted classes that emphasized the various types of vegetation which combine to form recognizable land covers. Finally, a very general land-cover classification was created by combining these targeted classes into twelve general land-cover classes. A more complete description of this process, and the resulting image, is available at *http://courses.washington.edu/urbdp467/intro.html*

2. Spectral Mixture Analysis, being developed by Eugene Martin at The Community and Environment Spatial Analysis Center (http://www.commenspace.org). Spectral Mixing Analysis (SMA) is a physically based image analysis process that supports repeatable and accurate extraction of quantitative sub-pixel information. Unlike supervised and unsupervised image classification, SMA does not rely on the detection or identification of pixel clusters with similar reflectance spectra; rather, it considers each pixel individually and assesses the presence and proportion of select end members. SMA produces fraction images that are pixel by pixel measures of the percent composition for each end member in the spectral mixing model. Available through their web site is a CD of the land cover analysis with data on forest canopy and impervious surfaces in the Cedar River Watershed. ❖

Categories from the classified Landsat image:	Observed impervious-area percentages: 1991	1998
"UNDEVELOPED"		
Open water	0	0
Coniferous vegetation	1	—
Deciduous vegetation	4	—
Forested	—	3
"DEVELOPED"		
Grassy/shrubby vegetation	29	5
Bare earth	—	98
Forested urban	23	38
Grassy urban	31	74
Intense urban	62	92

Table 3:
Average values of impervious-area percentages, determined from orthophotos for each of the seven classes.

1998 IMAGE	**Actual Land Cover from Orthophotos (percentages, averaged for 50 pixels; standard deviation shown in brackets)**						
Categories from the classified Landsat image:	Open Water	Trees	Shrubs/ grass	Pavement	Bare earth	Pavement or bare earth	Shadows
"UNDEVELOPED"							
Open water	100 [0]	0 [0]	0 [0]	0 [0]	0 [0]	0 [0]	0 [0]
Forested	0 [1]	96 [15]	1 [6]	1 [2]	2 [14]	0 [0]	0 [0]
Grassy/ shrubby vegetation	0 [0]	1 [5]	94 [16]	3 [14]	2 [8]	0 [0]	1 [5]
"DEVELOPED"							
Bare earth	1 [4]	2 [4]	0 [1]	7 [17]	91 [20]	0 [2]	0 [0]
Forested urban	0 [0]	39 [27]	23 [34]	34 [25]	0 [0]	5 [9]	3 [7]
Grassy urban	1 [6]	4 [4]	21 [25]	70 [28]	1 [6]	3 [7]	0 [1]
Intense urban	1 [5]	5 [19]	2 [12]	92 [23]	0 [0]	0 [0]	0 [1]

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

Project	Newsletter Issue	Center Publication
Urban stream rehabilitation:	Su 98	
Riparian buffers in urban watersheds	W 97	
Landsat land cover interpretation	Sp 99, F 00	CUWRM web report
Regional, synchronous stream temperature survey	Su 98, F 98	CUWRM web report & 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
Urbanization effects on stream biology	Sp 00	K26
Metrics of hydrologic change from urbanization	F 00	
Urban Planned Development monitoring:	F 99	CUWRM web report
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, F 00	G15 (on CUWRM web)
Urban stormwater management evaluation	F 99	
Urban Issues Library	F 99	On CUWRM web site
Highway stormwater treatment testing	W 00, F 00	G14 (on CUWRM web)
Remote sensing of stream temperature	W 00	
Review of water reuse case studies		
The impact of urban patterns on ecosystem dynamics		

Sampling Benthic Macroinvertebrates in Small Headwater Streams

Diversity and abundance of benthic macroinvertebrates have commonly been used as indicators of biological integrity in streams. Because certain taxa are more tolerant to disturbance than others, species type, diversity, and abundance are very effective and reliable indicators of biological stream conditions. However, biological sampling in headwater streams poses some unique problems, because modest and entirely natural year-to-year variability in seasonal precipitation can produce profound differences in biological habitat (i.e., water vs. no water) without any corresponding human influence.

As part of the Center's ongoing monitoring of two Urban Planned Developments (UPD's) in north-central King County (see the Fall 1999 issue of the Newsletter), Heidi Wachter has been exploring the unique problems of evaluating the biological condition of headwater streams to evaluate any consequences of human activity farther upstream. In the watersheds of these two UPD's, baseline sampling for benthic macroinvertebrates was first conducted in May and June 1991 by outside consultants. Of the twelve sites originally sampled, seven were in locations that are currently defined as wetlands, another site no longer has water, and one site's dominant substrate type is silt/mud. Six of these twelve sites had high percentages of diptera (flies, midges) and oligochaeta (earthworms), taxa that generally indicate poor habitat quality because they are tolerant to acidic and low dissolved oxygen. Despite minimal human disturbance as of 1991, much of the baseline data showed "poor habitat" simply due to the location selected for the sampling: in wetlands, in low flow or standing water, and/or in silt-dominant substrate.

When the Center initiated stream monitoring efforts in 1997, benthic macroinvertebrate sampling sites were relocated to free-flowing reaches of these streams. We endeavored to find well-oxygenated riffles, where stream conditions suggest macroinvertebrates would likely be found and where such samples are normally collected. Although samples were collected in five streams in September 1997, flows were inadequate in 1998 (and at some sites non-existent) for sampling. In 1999, two sampling efforts were made, in both spring and autumn, to determine the interval when benthic macroinvertebrate sampling would be feasible and reproducible from year-to-year. The spring 1999 sampling effort consisted of multiple sampling events, with samples collected in designated streams at two-week intervals. Seven sites were successfully sampled in late May 1999 and a second time 2 weeks later. By the third two-week period, sampling in most riffles was not possible due to reduced flows so sampling was discontinued. Sampling in autumn 1999 was also largely unsuccessful due to inadequate flows, with only two sites sampled.

Spring and autumn results were compared to evaluate which time is more appropriate for sampling benthic macroinvertebrates. Due to low flows, autumn sampling results lacked data for several of the streams, supporting a decision to sample in the spring. A family-level comparison of the spring 1999 and autumn 1997 results indicated a consistently lower taxa richness metrics for autumn samples, indicating species diversity was decreased in the autumn with respect to spring. Two streams, however, had autumn richness metrics that were similar or slightly increased relative to spring results, displaying some of the differences in autumn flow regimes between the UPD streams. For example, one of these streams maintains a minimal flow level during the late summer months providing year-round hyporheic flow, which could reduce seasonal differences in the macroinvertebrate community structure.

Sampling efforts from 1997-1999 indicate that autumn flow regimes in the UPD streams are not adequate from year-to-year to support systematic biological assessment using benthic macroinvertebrates. Additionally, seasonal declines in taxa richness were observed for four metrics, indicating benthic macroinvertebrate diversity is greater generally in spring months than autumn. Therefore, annual sampling to evaluate overall biological conditions in headwater streams should occur during the middle to late spring, after successive winter storm events have ended but before flows decrease to levels that prohibit sampling and stress biological communities without any corresponding human influence. ❖

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