Effects of urban development in the Puget Lowland, Washington, on interannual streamflow patterns: Consequences for channel form and streambed disturbance

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[1] Recovery and protection of streams in urban areas depend on a comprehensive understanding of how human activities affect stream ecosystems. The hydrologic effects of urban development and the consequences for stream channel form and streambed stability were examined in 16 streams in the Puget Lowland, Washington, using three streamflow metrics that integrate storm-scale effects of urban development over annual to decadal timescales: the fraction of time that streamflow exceeds the mean streamflow (T_{Qmean}), the coefficient of variation of annual maximum streamflow (CV_{AMF}), and the fraction of time that streamflow exceeds the 0.5-year flood ($T_{0.5}$). Urban streams had low interannual variability in annual maximum streamflow and brief duration of frequent high flows, as indicated by significant correlations between road density and both CV_{AMF} and $T_{0.5}$. The broader distribution of streamflow indicated by T_{Qmean} may be affected by urban development, but differences in T_{Qmean} between streams are also likely a result of other physiographic factors. The increase in the magnitude of frequent high flows due to urban development but not their cumulative duration has important consequences for channel form and bed stability in gravel bed streams because geomorphic equilibrium depends on moderate duration streamflow (e.g., exceeded 10% of the time). Streams with low values of T_{Qmean} and $T_{0.5}$ are narrower than expected from hydraulic geometry. Dimensionless boundary shear stress (τ^*) for the 0.5-year flood was inversely related to $T_{0.5}$ among the streams, indicating frequent and extensive bed disturbance in streams with low values of $T_{0.5}$. Although stream channels expand and the size of bed material increases in response to urban streamflow patterns, these adjustments may be insufficient to reestablish the disturbance regime in urban streams because of the differential increase in the magnitude of frequent high flows causing disturbance relative to any changes in longer duration, moderate flows that establish a stable channel.

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1. Introduction

[2] Human populations occupy or otherwise are appropriating an increasing portion of the Earth's land surface in many regions with urban developments of buildings, roads, and cultured landscaping such as lawns. Urban developments have direct effects on the terrestrial ecosystems they occupy but also indirect effects on aquatic ecosystems resulting from changes in the processes that link streams, lakes, estuaries, and other wetlands to the surrounding landscape. In urban streams, sediment transport and streambed disturbance provide a potential nexus between hydrologic changes and biological responses [*Orser and Shure*, 1972; *Booth et al.*, 2004].

[3] The hydrologic effects of urban development have been described primarily in terms of streamflow statistics for a single event (e.g., changes in the peak streamflow with a given return period, lag to peak/time of concentration, recession rate, and storm volume) that have social, but not necessarily geomorphic or ecological significance. Biological conditions in streams reestablish quickly often within months after high flows [*Shelford and Eddy*, 1929; *Stehr and Branson*, 1938; *Fisher et al.*, 1982; *Power and Stewart*, 1987; *DeBrey and Lockwood*, 1990; *Boulton et al.*, 1992; *Bayley and Osborne*, 1993; *Jones et al.*, 1995] demonstrating the resiliency (in the sense of *Denslow* [1985]) of lotic communities. Where disturbances are frequent and extensive, however, lotic communities have low diversity, relatively simple trophic structure, and are dominated by a few taxa [*Gorman and Karr*, 1978; *Schlosser*, 1985; *White and Pickett*, 1985; *Robinson and*

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Table 1. Estimated Percentage of Increase as a Consequence of Urban Development in Magnitude of Floods With Various Return Intervals[a]

Return Interval, years	Increase in Flood Magnitude due to Urban Development, %
2	100–600
10	20–300
100	10–250

[a]Compiled from *Carter* [1961], *James* [1965], *Anderson* [1968], *Leopold* [1968], *Hollis* [1975], *Sauer et al.* [1983], and *Bailey et al.* [1989].

Minshall, 1986; *Power et al.*, 1988; *Death and Winterbourn*, 1995].

[4] A disturbance-based link between hydrologic changes and biological responses in urban streams depends on changes in streamflow patterns at a timescale of years that modify the frequency and extent, or regime, of stream disturbance. We introduce three streamflow metrics to integrate storm-scale hydrologic effects of urban development over multiple-year periods and provide a preliminary assessment of how interannual streamflow patterns influence channel form, bed stability, and the disturbance regime of alluvial streams in the Puget Lowland, Washington.

2. Effects of Urban Development on Streamflow

[5] Urban development modifies hydrologic processes when vegetation and soil are cleared from the land surface, the surface is graded, depressions (e.g., wetlands) are filled, remaining soils are compacted, and buildings, roads, and drainage systems are constructed. These actions reduce the water storage capacity of hillslopes and the vegetation covering them. With less storage capacity and thinner, less permeable soils, soils saturate faster during storms, shallow subsurface flow is reduced, and overland flow increases. Hillslope flow paths are truncated by artificial drainage networks formed by roads, ditches, and storm sewers. Runoff travels more rapidly by shortened, overland paths, open channels, and pipes to streams. The combined effects of these changes are a faster rise and recession of streamflow, higher peak rates, and increased storm flow (i.e., quick response runoff) volume from a given amount of precipitation. The hydrologic effects of urban development are particularly evident in the Pacific Northwest's temperate forests, where hillslope storage and subsurface flow are dominant components of the hydrologic cycle and are particularly vulnerable to land use changes [*Burges et al.*, 1998].

[6] Early efforts to model runoff production in cities incorporated the effects of urban development [*Horner and Flynt*, 1936], but it was not until the 1960s that the storm-scale effects were characterized in terms of increased storm flow volume, peak streamflow, recession rate, and decreased time to peak streamflow [*Carter*, 1961; *Savini and Kammerer*, 1961; *Sawyer*, 1963; *Harris and Rantz*, 1964; *Leopold*, 1968]. Further investigations showed the increase in peak streamflow is most pronounced for small, frequent floods (Table 1) [*James*, 1965; *Hollis*, 1975; *Sauer et al.*, 1983; *Bailey et al.*, 1989], particularly under dry antecedent conditions (e.g., dry season and early wet season storms).

[7] Cumulative streamflow volume, which can be represented by the mean streamflow rate (Q_{mean}), does not typically change in response to urban development [*ASCE Task Committee on the Effects of Urbanization on Low Flow, Total Runoff, Infiltration, and Groundwater Recharge*, 1975; *Rose and Peters*, 2001; *Konrad and Booth*, 2002] except in cases where water is imported to or exported from a basin. At the hillslope scale, however, *Burges et al.* [1998] showed that annual runoff as a percentage of precipitation ranged from 12 to 30% in a forested, zero-order catchment but ranged from 44 to 48% in a suburban catchment where much of the forest cover had been cleared. The contrasting responses to urban development of zero-order basins and those of larger basins is likely because some groundwater bypasses the outlet of a zero-order basin, but then seeps into the channel network downstream. Thus the redistribution of water from groundwater recharge to runoff at the hillslope scale affects the water balance in a zero-order basins (less groundwater flow out of the basin) but manifests only as a change in the timing and not the amount of streamflow in higher-order basins.

[8] Base flow may either increase in response to irrigation during a dry season [*Harris and Rantz*, 1964] or decrease because of the reduction in groundwater recharge [*Sawyer*, 1963; *Simmons and Reynolds*, 1982]. *Ku et al.* [1992] showed that the effect of urban development on groundwater recharge on Long Island depended on whether storm water was routed to infiltration basins or to streams and tidewater. In western Washington, the effects of urban development on base flow vary with season: wet season base flow normalized for drainage area was inversely related to road density in 21 streams, but dry season base flow was not (Figure 1). Likewise, changes in runoff due to urban development did not result in lower annual 7-day low flow in three urban streams in western Washington [*Konrad and Booth*, 2002]. Three streams where local ground and

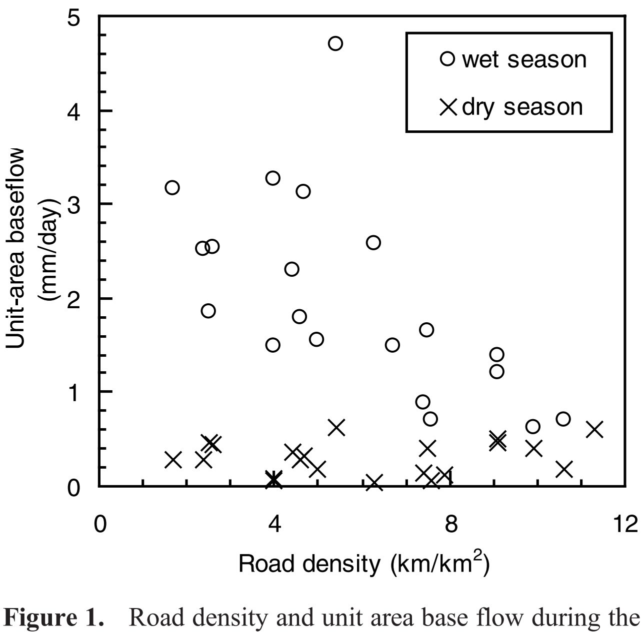

Figure 1. Road density and unit area base flow during the wet season (15–25 April 1991) and the dry season (August 1994) for 21 streams in western Washington [after *Konrad and Booth*, 2005].

surface water resources provide commercial and domestic water supplies (Soos, Newaukum, and Issaquah Creeks), however, did have significantly decreasing trends in annual 7-day low flow during the last decades of the 20th century [*Konrad and Booth*, 2002].

3. Effects of Urban Development on Stream Channels

[9] *Bledsoe and Watson* [2001] concluded that increased high flows have the potential to destablize urban streams under the assumptions of fixed channel dimensions and size of bed material, but morphologic adjustments to increased high flows may be expected in alluvial channels. Urban channels typically expand though incision and widening in response to increased storm flows [*Hammer*, 1972; *Morisawa and Laflure*, 1979; *Whitlow and Gregory*, 1989; *Booth*, 1990; *Trimble*, 1997] unless actions are taken to harden or otherwise stabilize the channel. Streambed material may become coarser in response to increased high-flow magnitude [*Thoms*, 1987; *Finkenbine et al.*, 2000] where sediment loads have not increased commensurately with high flows. In these cases, the differential transport of fine particles leaves a coarse armor layer or lag deposit of gravel on the streambed.

[10] Some morphologic changes in urban streams such as increased fine sediments covering stream beds [*Wolman and Schick*, 1967], stream bed aggradation [*Ebisemiju*, 1989], and increased drainage density [*Graf*, 1977] are not strictly responses to altered streamflow patterns. Some changes may confound the morphologic responses of channel to urban streamflow patterns. For example, channels may be narrower where banks have been deforested [*Hession et al.*, 2003] or artificially stabilized to protect infrastructure or property. As a result, stream channels do not necessarily expand in response to urban development or the expansion lags after development [*Leopold*, 1973; *Hollis and Luckett*, 1976].

[11] Adjustments in channel width and streambed material in response to increased storm flow in alluvial reaches where riparian vegetation is intact can be anticipated qualitatively from geomorphic equilibrium theory [*Leopold and Maddock*, 1953; *Lane*, 1955], but a quantitative prediction about whether channel response will reestablish streambed stability (i.e., frequency and extent of streambed material entrainment) is elusive because of the complexity of hydrologic changes in an urban stream. The form of an alluvial channel and the size of its bed material reflect the range of streamflows that erode and deposit sediment, the supply of sediment to the channel, the sediment forming the bed and the banks, bank vegetation, and elements of channel roughness including large woody debris [*Schumm*, 1960; *Harvey*, 1969; *Buffington and Montgomery*, 1999a, 1999b].

[12] Even without the complication of nonhydrologic factors, geomorphic equilibrium theory does not provide a clear basis for the choice of a reference streamflow to represent the complex hydrologic changes resulting from urban development. *Richards and Wood* [1977] used mean annual maximum streamflow (Q_{AMF}) as a reference flow to predict morphologic responses to urban streamflow patterns, in which case, the channel width could be predicted from a power function of Q_{AMF}. Predictions of channel responses, however, are sensitive to the choice of a reference flow in light of the complex hydrologic effects of urban development, which vary from no expected change in Q_{mean} to a doubling or more of Q_{AMF} and include second-order effects such as changes in the rate of streamflow rise and recession.

[13] An alluvial channel will stabilize under any streamflow that persists for a long duration provided there is a sufficient fraction of immobile particles to cover the bed [*Lane*, 1955] and a limited upstream supply of mobile particles [*Gessler*, 1970; *Little and Mayer*, 1976; *Chin et al.*, 1992]. During high flows with a sustained duration, small and unconstrained particles are moved to more stable positions between larger particles and under eddies along the channel margins, exhausting the in-channel supply of sediment readily available for transport at this flow. The streambed will be covered by a coarse surface layer with particles in structural arrangements that strengthen the bed surface [*Laronne and Carson*, 1976; *Gomez*, 1983; *Parker and Sutherland*, 1990]. As a result, the bed becomes stable for that flow. In contrast, streamflow that previously had been exceeded for only brief periods will be able to entrain much of a bed surface and produce a high sediment transport rate because there has not been sufficient time to exhaust the in-channel sediment supply available for transport [*Reid and Laronne*, 1995].

[14] The focus of this investigation is gravel bed streams in western Washington, which were formed primarily by fluvial erosion of glacial sediments. These streams generally lack an abundant supply of sand and finer sediments, relative to their transport capacity during small floods, to build lateral bars, floodplains, and stream banks. Nonetheless, poorly sorted glacial deposits forming hillslopes and valley bottoms provide a range of sediment sizes to streams allowing streambed material to adjust freely to changes in the transport capacity of the stream.

[15] Over time, streams are exposed to a range of streamflows with varying durations. *Wolman and Miller* [1960] proposed that the geomorphic effect of a flood is determined by the cumulative flow duration of similar flows but also by variability in the distribution of the magnitudes of all prior events. As a result, a channel's width may be determined by either moderate, long-duration flows where the total variability in channel-forming flows is low, or by higher, infrequent, and short-duration flows where the total variability of channel-forming flows is high. The persistence of a flood's effect depends on channel type: a channel with a short "memory" of floods and highly variable flows will often be narrow, because small floods are more common than large floods, and will be wide only after recent large floods [*Yu and Wolman*, 1987]. Gravel bed streams, however, are likely to have long memories of high-flow events because their limited supply of fine-grained sediments does not allow banks to be built during small floods. Thus their widths are expected to vary directly with high flow variability.

[16] Two important issues regarding the geomorphic equilibrium of urban streams have not been resolved by either theoretical or empirical approaches. First, what is an appropriate reference flow for evaluating the geomorphic responses of alluvial streams to urban streamflow patterns?

Second, are channel adjustments (widening and coarsening of the bed) sufficient to reestablish the frequency and extent of bed material entrainment in urban streams? We examine these issues first by introducing three streamflow metrics that resolve some hydrologic effects of urban development over periods of years and can be expected on theoretical grounds to have geomorphic significance. We then evaluate the variation of these metrics with respect to urban development and their geomorphic consequences for streams in the Puget Lowland, Washington.

4. Streamflow Metrics Linking the Hydrologic Effects of Urban Development to Fluvial Geomorphology

[17] We considered a variety of streamflow metrics that integrate storm-scale effects of urban development over multiple-year periods. We selected three to represent the range of streamflows that influence on channel morphology and to distinguish the comparative influences of broad-based flow duration, high-flow duration, and variability in annual maximum floods.

4.1. T_{Qmean}

[18] The fraction of time that streamflow exceeds the mean streamflow, T_{Qmean} is likely to vary inversely with urban development among stream basins as a result of the redistribution of runoff, primarily from hillslope storage and subsurface runoff before development to overland and open-channel flow after development. The mean annual value of T_{Qmean} was calculated for a period of Y years as

$$T_{Qmean} = \frac{1}{Y}\sum_{y=1}^{Y} F_y[Q_{mean}(y)], \qquad (1)$$

where y is the ordinal year number from 1 to Y and $F_y[Q_{mean}(y)]$ is the inverse of the cumulative distribution function of streamflow for year y evaluated at the annual mean streamflow, $Q_{mean}(y)$, for year y (i.e., the annual value of T_{Qmean}). T_{Qmean} provides a measure of the asymmetry of the frequency distribution of daily streamflow but with less sensitivity than the skew coefficient to occasional high flows, which we address via the other two streamflow metrics.

[19] We hypothesize that the adjustments of stream channels to Qmean will depend on the cumulative duration that Qmean is exceeded. Thus we expect streams with low values of T_{Qmean} will be narrower than expected from hydraulic geometry based on Q_{mean} because Q_{mean} references flows with a shorter cumulative duration and thus potentially less capacity to transport sediment, than in streams with higher values of T_{Qmean}. Likewise, we expect streams with low values of T_{Qmean} will be less stable at Q_{mean} than those with high values of T_{Qmean}.

4.2. CV_{AMF}

[20] The coefficient of variation of annual maximum streamflow (CV_{AMF}) is likely to vary inversely with the level of urban development among streams, because the peak streamflow of small, frequent floods increases by a larger percentage of their predevelopment value than the peak streamflow of large, infrequent floods (Table 1). CV_{AMF} is calculated, assuming that the annual maximum streamflow at a particular gage location follows a two-parameter lognormal distribution, using:

$$CV_{AMF} = \sqrt{\exp\left(\sigma_q^2\right) - 1}, \qquad (2)$$

where σ_q^2 is the variance of the natural logarithms of the annual maximum streamflow [*Stedinger et al.*, 1993]. The annual maximum flow series for streams in the Puget Lowland region are well approximated by two-parameter lognormal distributions because the regional skew coefficient in logarithmic space for annual maximum streamflow is only 0.02 [*Lettenmaier and Burges*, 1980; *U.S. Interagency Advisory Committee on Water Data*, 1982].

[21] We hypothesize that streams with high flood variability will adjust to larger floods. Thus we expect streams with high values of CV_{AMF} will have relatively wide channels compared to the widths expected from hydraulic geometry based on Q_{AMF} while streams with low values of CV_{AMF} will be narrower than expected. Likewise, we expect streams with low values of CV_{AMF} will be less stable at Q_{AMF} than streams with high values of CV_{AMF}.

4.3. $T_{0.5}$

[22] The frequency of high flows in an urban stream is likely to increase more than the cumulative duration of those flows through the combination of increased peak streamflow and more rapid storm flow recession. The relationship between the frequency and cumulative duration of frequent high flows was defined using the annual return period of streamflow calculated from a partial duration series of peaks above a threshold for each stream [*Langbein*, 1949]. Local maxima in the 15-min time series of streamflow that exceeded a specified threshold were identified for each stream. If there were local maxima that occurred within 20 days of each other, only the largest was retained as a peak. The criterion of 20 days was selected because there is little hydrologic memory of preceding events after 20 days for even the largest catchment, with an area of 171 km^2, in the analysis. The threshold streamflow was adjusted and the procedure was repeated until the partial duration series had between 30 and 50 streamflow peaks for the period of analysis. The return interval (R_Q) for a given streamflow (Q) was calculated as the number of years of analysis, Y, divided by the number of peaks (P_Q) equal to or greater than Q:

$$R_Q = \frac{Y}{P_Q}. \qquad (3)$$

[23] The duration of time that Q was exceeded (i.e., the flow duration quantile for Q) was obtained from the cumulative distribution function of (15-min) streamflow for each stream. The flow duration quantile (T_R) for streamflow with return period of R ranges from about 0.2 to 4 years. The flow duration quantiles and return periods (T_R, R_Q) form a series for each stream representing the relation between the exceedence duration and return

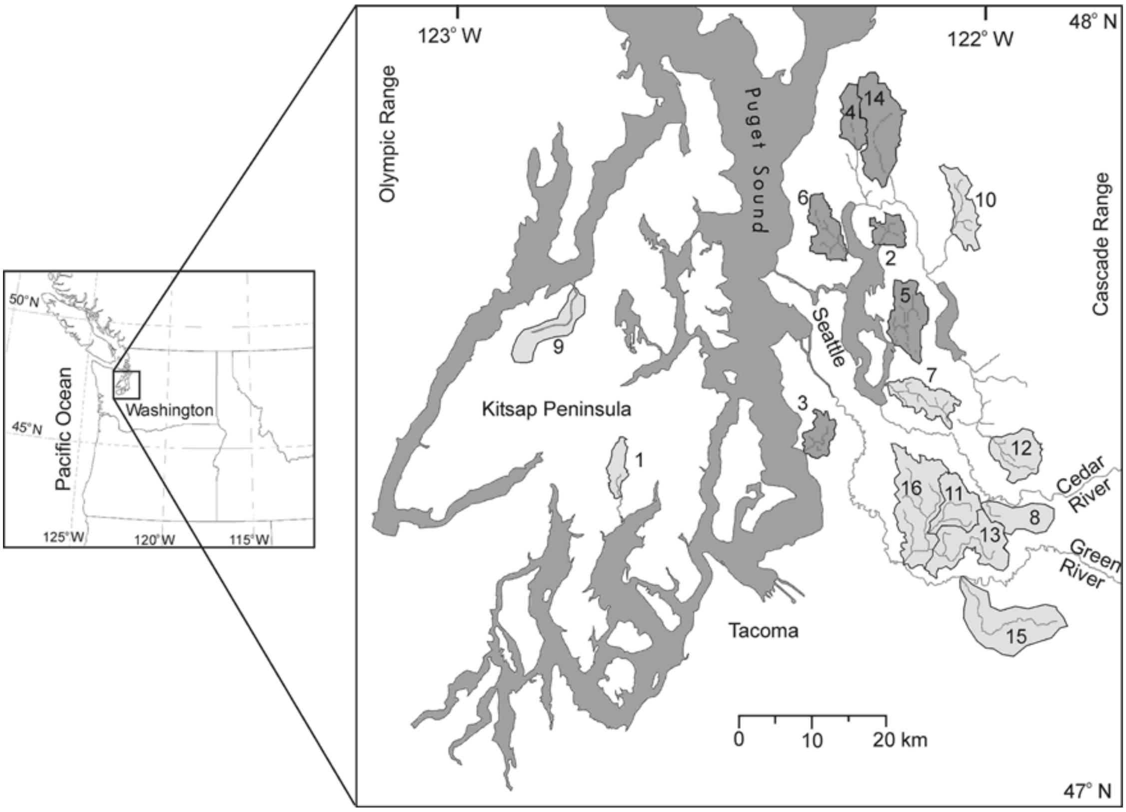

Figure 2. Drainage basins for 16 streams in the Puget Lowland, Washington. See Table 2 for key to streams. Basins with road density greater than 6 km/km^2 are darker shading.

period of streamflow. The fraction of time ($T_{0.5}$) that streamflow exceeds the 0.5-year flood ($Q_{0.5}$ or streamflow exceeded on average twice a year) was selected for the analysis as an indicator of peak flows likely to occur during the wet season in western Washington.

[24] We hypothesize that gravel bed streams are not fully adjusted to short-duration, high flows and the extent of adjustment to a given flow depends on the cumulative duration of that flow. Under this hypothesis, streams with low values of $T_{0.5}$ would be narrower than expected from hydraulic geometry based on $Q_{0.5}$ and will be less stable during a 0.5-year flood than streams with high values of $T_{0.5}$.

5. Analysis of Streamflow Patterns in the Puget Lowland

[25] Streamflow patterns were analyzed for 16 streams in the Puget Lowland, Washington (Figure 2 and Table 2). The Puget Lowland is a trough located between the Cascade and

Table 2. Basin Characteristics, Streamflow Record, and Analysis Groups for Puget Lowland Streams[a]

Number in Figure 2	Streams	Drainage Area, km^2	Valley Slope	Stream Density, km/km^2	Road Density, km/km^2	Channel Width, m	Period of Analysis, water years	Group
1	Huge Creek	17	0.012	0.25	2.5	6.5	1990–2001	A, B
2	Juanita Creek	17	0.013	0.55	11.3	–	1980–1989	A
3	Miller Creek	21	0.014	0.49	10.6	6.2	1989–1998	A
4	Swamp Creek	25	0.007	0.21	7.4	8.2	1989–1998	A
5	Mercer Creek	31	0.007	0.47	9.1	9.0	1988–2001	A
6	Thornton Creek	31	0.010	0.54	13.0	9.4	1996–2001	A
7	May Creek	32	0.009	0.64	5.0	11	1989–1998	A, B
8	Rock Creek	32	0.010	0.09	2.7	12	1995–1998	A, B
9	Big Beef	35	0.010	0.32	2.1	13	1996–2001	B
10	Bear Creek	36	0.006	0.51	4.4	11	1989–1991, 1993–1998	A, B
11	Jenkins Creek	37	0.003	0.55	5.4	13	1988–1998	A, B
12	Issaquah Creek	40	0.059	0.53	2.5	14	1989–2001	B
13	Covington Creek	55	0.006	0.57	4.0	13	1988–1994	B
14	North Creek	67	0.006	0.46	7.5	15	1989–1998	A
15	Newaukum Creek	70	0.035	0.43	2.5	16	1990–2001	B
16	Big Soos Creek	171	0.005	0.39	4.7	21	1990–2001	B

[a]Streamflow metrics for group A were analyzed with respect to road density; streamflow metrics in group B were analyzed with respect to drainage area and mean streamflow.

Olympic Ranges that was carved by repeated glaciations leaving broad, north-south trending valleys with intervening plateaus and plains at elevations generally less than 300 m above sea level. Puget Sound, an inlet of the northeastern Pacific Ocean, is in the largest of these valleys. Poorly sorted and cemented glacial till typically forms the tops of plateaus. Highly permeable, weakly consolidated sand and gravel outwash forms broad plains and valley bottoms, and also is exposed beneath till in the sidewalls of incised ravines and valleys. Fine-grained lacustrine deposits (interbedded sand, silt, and clay) are found beneath the glacial sediments, commonly close to sea level. Bedrock is exposed in the foothills of the Cascade and Olympic Ranges at the outer margins of the Puget Lowland.

[26] The region has a humid maritime Mediterranean climate with wet winters and dry summers. The region receives approximately 1 m of precipitation per year, mostly from frequent, low-intensity rainfall during winter storms. Precipitation varies locally, with the highest amounts at upper elevations along the perimeter of the Puget Lowland, on the Kitsap Peninsula to the west, and in the northern part of the Puget Lowland where moisture-laden air masses from the northwest and southwest frequently converge.

[27] The stream basins range in area from 17 to 171 km^2 and have a variety of topographic features, including mountain headwaters, plateaus with lakes and wetlands, ravines, and broad valleys. The streams have gravel and cobble beds with lesser amounts of sand and boulders and gradients from 0.005 to 0.02. Streamflow records with a 15-min interval were available for 4 to 14-year periods from water year 1988 to 2001 for all streams except Juanita Creek near Kirkland, where daily mean streamflow from water year 1980 to 1989 was used (Table 2). Older data for other streams were excluded generally to limit the effect of variable climatic condition on the results of the analysis, but also to maintain the integrity of the assumption that changes in land use in a basin during the period of analysis were less than the variation between basins in land use during the period of analysis. Nonetheless, some variation in streamflow metrics between streams may be a consequence of the variation in the periods of analysis.

[28] The level of urban development in each stream basin was expressed in terms of road density, the total length of roads [km] in a stream basin, divided by its drainage area [km^2]. Road lengths within each drainage basin were calculated from vector representations of roads that include interstate and state highways and county roads (circa 1990) in a geographic information system. Logging and service roads or private driveways were not included in the road data or the road density calculations. Calculated road densities in 8 of the basins were compared to estimates of percent total impervious area (%TIA) based on a 1998 LANDSAT image [*Booth et al.*, 2004] to check the assumption that the relative level of urban development among basins had not changed during the period of analysis. Road densities calculated from circa 1990 GIS data were highly correlated with %TIA from 1998 (Pearson product moment correlation coefficient, $\rho = 0.96$, $p = 0.0001$). Road density is hydrologically significant because it indexes the dissection of a landscape by artificial drainage networks (ditches and road surfaces) and the reduction in hillslope flow path lengths. In contrast to %TIA [e.g., *Elvidge et al.*, 2004], road density is calculated from roads in the whole basin (not a sample fraction) and does not require interpretation of remotely sensed images. Regardless, the results from a nonparametric analysis do not differ if either road density or %TIA is used as the index of urban development given the strong correlation between these two measures.

[29] Road density represents the differences in land use from dense urban to rural in the Puget Lowland. The highest road densities (>9.0 km/km^2) are in the drainage basins of Juanita, Mercer, Miller, and Thornton Creeks (Table 2), which drain parts of Seattle and surrounding highly developed suburbs. Forest cover in these basins is limited to steep slopes and narrow riparian corridors. The drainage basins of North and Swamp Creeks have intermediate road densities (7.4 to 7.5 km/km^2) with a mix of commercial and dense residential developments but also lower-density residential areas with pastures and forests. The drainage basins of May, Bear, Jenkins, and Big Soos Creeks have road densities ranging from greater than 4.0 to 5.0 km/km^2, representing mostly low-density residential developments with pastures, forests, and a few large residential and commercial developments. The lowest road densities (2.1 to 4.0 km/km^2) are in the drainage basins of Big Beef, Covington, Huge, Issaquah, Newaukum, and Rock Creeks, which are mostly rural with extensive forests and pastures with limited (new) residential developments.

[30] The locations of streamflow gages in the Puget Lowland are biased toward more gages in smaller urban streams and larger rural streams and fewer gages in large urban streams or small rural streams. This bias introduces catchment size as a potential confounding factor in the assessment of the hydrologic effects of urban development. Streamflow patterns vary with drainage area in ways that are similar to the variation with land use: streamflow in small urban streams rises rapidly during storms, attains high peak streamflow on a unit area basis, and recesses rapidly [*Dunne and Leopold*, 1978, p. 284] much like in urban streams. Other patterns may also depend on catchment size. For example, *Smith* [1992] demonstrated that intermediate-size stream basins (drainage areas between 26 and 260 km^2) in the central Appalachian region of Maryland and Virginia had the greatest variability in and magnitude of CV_{AMF}.

[31] We controlled for the potential influence of catchment size by limiting the analysis of streamflow metrics and urban development to a subset of 11 streams (group A) with narrow ranges of drainage areas (17 to 67 km^2) and mean streamflow (0.21 to 1.6 m^3/s) (Table 3). Road density is not significantly correlated to drainage area for these 11 basins (Kendall's rank correlation coefficient, $\tau = -0.11$, $p = 0.64$) or mean streamflow ($\tau = -0.20$, $p = 0.44$). We also analyzed variation in streamflow metrics with drainage area and mean streamflow for a second subset of streams (group B) with low levels of urban development (Figure 3). This analysis provides additional evidence for or against any confounding influence from catchment size but does not represent a robust test of the influence of catchment size the streamflow metrics, which is beyond the scope of this investigation and would require analyzing a wider size range. Group B had 10 streams with drainage areas from 17 to 171 km^2, mean streamflow of 0.32 to 3.6 m^3/s, and road densities less than 6 km/km^2. Road density was not

Table 3. Values of Five Reference Streamflows for Puget Lowland Streams[a]

Streams	Q_{mean}, m^3/s	Q_{10}, m^3/s	Q_1, m^3/s	$Q_{0.5yr}$, m^3/s	Q_{AMF}, m^3/s
Huge Creek	0.32	0.61	2.4	1.5	3.8
Juanita Creek	0.35	0.74	2.0	–	6.3
Miller Creek	0.21	0.42	2.2	4.8	7.5
Swamp Creek	0.43	1.03	3.6	3.7	6.0
Mercer Creek	0.64	1.36	4.9	7.3	10.3
Thornton Creek	0.30	0.59	1.3	1.9	3.2
May Creek	0.68	1.50	5.1	4.1	7.7
Rock Creek	0.47	1.10	2.3	1.4	3.0
Big Beef	1.44	2.72	11.2	9.8	13.3
Bear Creek	0.91	1.81	6.5	5.3	5.0
Jenkins Creek	1.08	2.07	4.3	3.3	5.0
Issaquah Creek	1.31	3.00	8.1	8.3	15.1
Covington Creek	0.82	3.10	4.9	2.4	4.9
North Creek	1.55	3.99	10.9	13.2	17.5
Newaukum Creek	1.63	3.20	10.2	6.4	17.4
Big Soos Creek	3.57	8.28	17.8	11.7	20.9

[a] Q_{mean} is mean streamflow for the period of analysis, Q_{10} is the streamflow exceeded 10% of the time, Q_1 is the streamflow exceeded 1% of the time, $Q_{0.5yr}$ is the peak streamflow exceeded on average during two events per year (the 0.5-year flood), and Q_{AMF} is the geometric mean annual maximum streamflow.

significantly correlated to drainage area (τ = 0.159, p = 0.52) or mean streamflow (τ = 0.05, p = 0.86) for these 10 streams. Five streams were common to both groups.

[32] The significance of the correlation between each streamflow metric and road density was evaluated with a one-sided test of the null hypothesis that Kendall's rank correlation coefficient, τ, was equal to or greater than 0. Likewise, the hypothesis that streamflow patterns were directly related to catchment size (either through drainage area or mean streamflow) was evaluated using a one-sided test of the null hypothesis that τ for each streamflow metric and each stream size metric was equal to or less than 0.

[33] The geomorphic consequences of various streamflow patterns were assessed in terms of empirical models for channel width (hydraulic geometry) and streambed stability for 15 streams (all except Juanita Creek) where geomorphic data were collected in WY 1998–1999, toward the end of the period of the streamflow record. Channel cross sections and long profiles, approximately 10 channel widths long, were surveyed in the field with an autolevel and stadia rod. The selected reaches were relatively straight with alluvial bed and banks and no obvious downstream constrictions (e.g., bridges) that would produce backwater at high flows. Channel widths were measured at the banks, which were identified by vegetation or a break in the slope between the (steeper) side of the channel and the (flatter) floodplain or bar top surfaces.

[34] Channel width models based on power functions of reference streamflows were developed from five reference flows. The reference flows include the three flows (Q_{mean}, Q_{AMF}, $Q_{0.5yr}$) that are the basis for the streamflow metrics, and flows corresponding to streamflow exceeded 10% of the time (Q_{10}) and the 1% of the time (Q_1). We tested the relative hypothesis that the reference flows vary in their ability to represent the range of flows influencing channel width by calculating the probability that the variances of model errors were equal using an *F* test. The flow with the lowest model error was used as the best single indicator of the range of streamflows influencing channel width. No difference between two models indicated that either reference flow provides equivalent representation of the effect of streamflow on channel width.

[35] Many investigations have demonstrated the importance of flow duration in cumulative sediment transport and channel form [*Wolman and Miller*, 1960; *Pickup and Warner*, 1976; *Andrews*, 1984; *Andrews and Nankervis*, 1995; *Costa and O'Connor*, 1995]. We anticipated that width models based on either Q_{10} or Q_1 would produce the lowest errors because they reference flow duration and thus have a mechanistic basis for influencing channel width. Furthermore, we hypothesized that the errors of the models based on Q_{mean} and $Q_{0.5\ yr}$ would have a bias

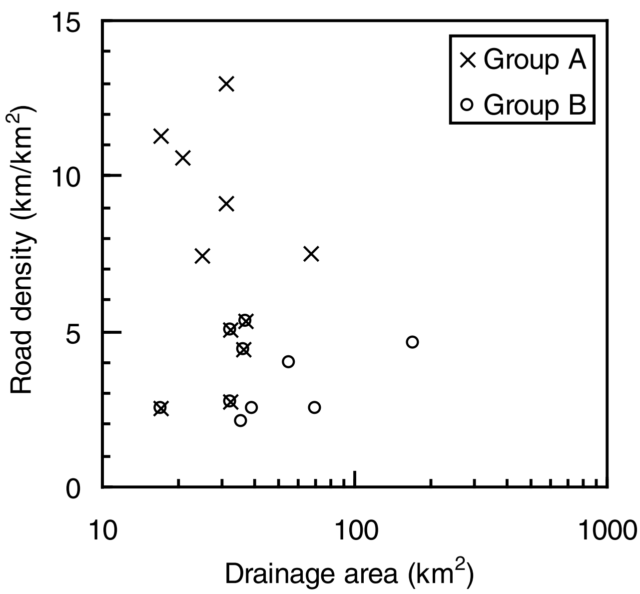

Figure 3. Relation between drainage area and urban development, represented by road density, for two groups of streams in the analysis. Group A streams have drainage area of 17–67 km^2 and road density of 2.1–13 km/km^2. Group B streams have drainage area of 17–171 km^2 and road density of 2.1–6 km/km^2.

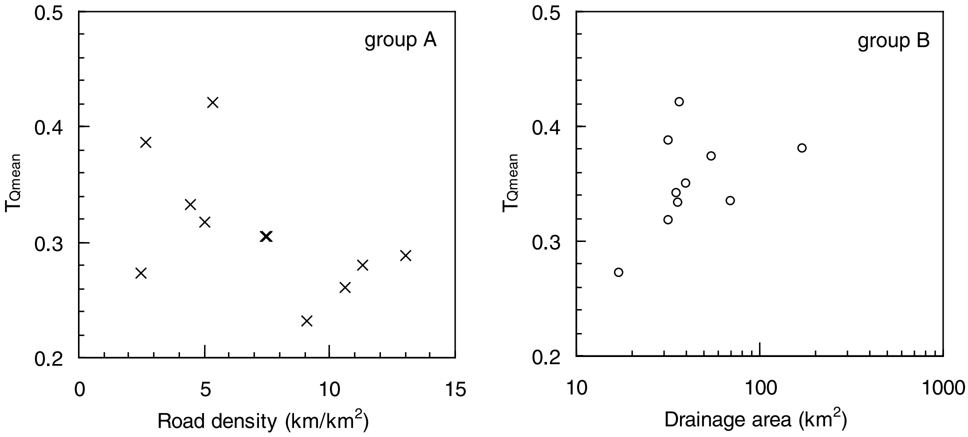

Figure 4. Relations between T_{Qmean} and road density (group A streams) and drainage area (group B streams).

related to the cumulative duration of these reference flows and that the errors would be lower for a two-parameter model that incorporated T_{Qmean} and $T_{0.5yr}$ respectively. Finally, we hypothesized that the error of the model based on Q_{AMF} would have a bias because the total variability of annual floods is not represented and that the error would be lower for a two-parameter model that incorporated CV_{AMF}. The ultimate purpose of these various hypotheses is to identify reference flows that can be used in hydraulic geometry to quantify the geomorphic response of alluvial channels to the complex hydrologic effects of urban development.

[36] The analysis of streambed stability was similar to that of channel width. Channel stability for the five reference streamflows was assessed in terms of dimensionless total boundary shear stress, τ^*, which provides an index of the probability and spatial extent of bed material entrainment [*Gessler*, 1970; *Konrad et al.*, 2002]:

$$\tau^* = \frac{\gamma RS}{(\gamma_s - \gamma)D_{50}}, \tag{4}$$

where γ is the specific weight of water, γ_s is the specific weight of sediment, R is the hydraulic radius of the stream, S is the 1-D energy slope (approximated by the high water surface slope) and D_{50} is the median length of the intermediate axis of surface bed material. The particle size distribution of the streambed material was estimated from Wolman pebble counts of between 100 and 300 particles on the bed surface. The hydraulic radius was calculated for Q_{mean}, Q_{AMF}, and $Q_{0.5yr}$ assuming uniform flow conditions in the reach using Manning's equation scaled by cross-sectional area, A, of the channel:

$$Q = A\left(\frac{R^{0.67}S^{0.5}}{n}\right), \tag{5}$$

where n was either calibrated from observations of stage and streamflow at the cross section of interest or as the average value of n calculated from an empirical relation based on R and S developed by *Jarrett* [1984] and a relation based on R and D_{84} (the 84th percentile of the particle size distribution of the streambed material) developed by *Bathurst* [1985].

[37] The median and variation in τ^* among the streams at each of the five reference flows were evaluated to assess whether any of these streamflow statistics reference a state at the limit of bed stability (low probability of bed material entrainment) in all of the streams. Additionally, the variation in τ^* for Q_{mean}, Q_{AMF}, and $Q_{0.5yr}$ was compared to variation in the respective streamflow metric (T_{Qmean}, CV_{AMF}, and $T_{0.5yr}$). Correlation between τ^* and any of the metrics would indicate that cumulative duration of Q_{mean} or $Q_{0.5yr}$ or the variability of Q_{AMF} influences streambed stability at these flows.

6. Relations Between Streamflow and Urban Development

[38] The relations between the five reference streamflows normalized for drainage area and road density provide an initial perspective on the hydrologic effects of urban development. Road density was positively and significantly ($p < 0.05$, one-tailed Kendall's rank correlation test) correlated only with $Q_{0.5\ yr}$ and Q_{AMF}, which represent reference flows based on the frequency of events. The reference flows based on the cumulative volume of runoff (Q_{mean}) or the duration a flow is exceeded (Q_{10} and Q_1) were not significantly correlated with road density. Thus urban development differentially increases the frequency of high flows but not their cumulative duration.

[39] The complex hydrologic effects of urban development, which can be illustrated at the storm scale with hydrographs or at longer scales by considering the differential changes in reference streamflows, can be quantified over interannual periods using the three streamflow metrics: T_{Qmean}, CV_{AMF}, and $T_{0.5yr}$. Streamflow exceeds the annual mean streamflow for a shorter fraction of the year in urban streams, generally less than 0.3, than in rural streams, generally more than 0.3 (Figure 4 and Table 4); however, the rank correlation between road density and T_{Qmean} was not definitive ($\tau = -0.38$, $p = 0.06$; Table 5) in group A. The variation in T_{Qmean} for the urban gradient streams is comparable to the decreasing trends in T_{Qmean} from more than 0.3 to less than 0.3 shown for three western Washington streams including Mercer and Juanita creeks [*Konrad and Booth*, 2002]. The weaker rank correlation ($\tau = -0.36$, $p = 0.09$) between T_{Qmean} and drainage area

Table 4. Values of Three Streamflow Metrics for Puget Lowland Streams[a]

Streams	T_{Qmean}	CV_{AMF}	$T_{0.5}$
Huge Creek	0.27	1.24	0.025
Juanita Creek	0.28	0.66	–
Miller Creek near mouth	0.26	0.45	0.003
Swamp Creek @ Filbert Rd.	0.31	0.48	0.010
Mercer Creek	0.23	0.39	0.004
Thornton Creek	0.29	0.79	0.004
May Creek near mouth	0.32	1.09	0.014
Rock Creek	0.39	1.40	0.042
Big Beef	0.34	1.71	0.013
Bear Creek @ 133rd Ave. N.E.	0.33	0.97	0.013
Jenkins Creek	0.42	0.72	0.024
Issaquah Creek near Hobart	0.35	0.75	0.009
Covington Creek	0.37	0.83	0.064
North Creek	0.30	0.31	0.006
Newaukum Creek	0.33	0.89	0.029
Big Soos Creek	0.38	0.89	0.039

[a]T_{Qmean} is the fraction of a year that daily streamflow exceeds mean annual streamflow, CV_{AMF} is the coefficient of variation of the log-transformed peak annual streamflows, and $T_{0.5}$ is the cumulative fraction of time that streamflow exceeds the peak of a 0.5-year flood.

(Figure 4 and Table 5) for group B suggests that catchment size may influence T_{Qmean}, but was unlikely to have been a confounding factor in the relationship between T_{Qmean} and road density in group A.

[40] T_{Qmean} is relatively stationary over time in streams where land use is stable [*Konrad and Booth*, 2002, 2005]. For example, T_{Qmean} for water years 1995 to 1998, which was the period of analysis for Rock Creek and the shortest period of analysis of any stream, was 0.26 in Huge Creek compared to 0.27 for water years 1989 to 2001 and was 0.22 in Mercer Creek compared to 0.23 for water years 1988 to 2001. Thus variation in storm patterns either due to geographic location or different periods of analysis was unlikely to have influenced the results.

[41] Although there is only a weak relationship between road density and T_{Qmean} among these 16 streams, T_{Qmean} declined in Mercer (Figure 5) and Juanita Creeks during the second half of the 20th century when there was extensive urban development in the basin, but not in Big Soos, Big Beef, Huge, Newaukum, or Issaquah Creeks, which had much lower rates of development [*Konrad and Booth*, 2002]. Likewise, *Konrad and Booth* [2005] identified significant decreases over time in annual values of T_{Qmean} in some urbanizing streams around the United States but not others that had initially low values of T_{Qmean}. T_{Qmean} appears to integrate a range of physiographic and climatic conditions other than land use that produce the broad temporal distribution of streamflow relative to the mean.

[42] The variation in annual peak flows was lower in urban streams than in rural streams (Figure 6 and Table 4). CV_{AMF} was inversely related to road density ($\tau = -0.45$, $p = 0.03$) for group A (Table 5). CV_{AMF} was not a simple monotonic function of road density: the minimum variation in annual floods occurred at intermediate levels of urban development (about 8 km/km^2). In contrast to T_{Qmean}, CV_{AMF} is sensitive to the period of analysis because the mean and variance of annual flood distributions vary at the short timescales (a decade at most) required in this analysis to satisfy the assumption of stable land use in a basin. For example, CV_{AMF} for water year 1995 to 1998 was 0.75 in Huge Creek, compared to 1.25 for the period from water year 1989 to 2001 and was 0.37 in Mercer Creek compared to 0.40 for the period from water year 1988 to 2001. Thus the values of CV_{AMF} for streams with short periods of analysis (e.g., Big Beef, Covington, Rock Creek, and Thornton) or different periods of analysis (Juanita Creek) may not be reliable for comparison and may have contributed to the increasing values of CV_{AMF} at the highest levels of urban development. The correlation between CV_{AMF} and catchment size was not statistically significant in group B (Figure 6 and Table 5).

[43] The cumulative duration that streamflow exceeded the magnitude of a 0.5-year flood was shorter in urban streams than in rural streams (Figure 7). For the urban gradient, $T_{0.5}$ was inversely related to road density ($\tau = -0.63$, $p = 0.006$) with rural stream generally having values of $T_{0.5}$ greater than 0.01 and urban streams having value of $T_{0.5}$ less than 0.01 (Table 4). For streams with low levels of urban development, however, $T_{0.5}$ does not show a strong relationship to road densities. The rank correlation between $T_{0.5}$ and either drainage area or mean streamflow was not significant (Table 5). Different periods of analysis between streams should not affect the results as the values of $T_{0.5}$ did not vary in Huge Creek or in Mercer Creek for the subset period from 1995 to 1998.

[44] The complete set of duration and return interval pairs (T_Q, R_Q) shows that the relation between urban development and T is not unique for R = 0.5 year; it holds for nearly any streamflow with a frequency greater than 1 peak per year ($R < 1$) or exceeded more than 0.4% of the time (Figure 8). The converse relationship between the frequency of a peak event and the cumulative duration that the flow had been exceeded over the previous years is also evident: the frequency of a flow exceeded for a given duration is generally higher in urban streams than in rural ones.

[45] Physiographic differences between basins may account for the variation in $T_{0.5}$ in some cases. Streams that are large (Big Soos Creek), drain glacial outwash plains (Jenkins Creek), or have lakes (e.g., Covington Creek) are likely to have sustained runoff during storms and, consequently, relatively high values of $T_{0.5}$. Streams with headwaters at higher elevations (e.g., Big Beef, Newaukum, and Issaquah Creeks) have more intense rainfall, rapidly receding streamflow, and, consequently, relatively low values of $T_{0.5}$.

7. Geomorphic Consequences of Urban Streamflow Patterns

[46] Streamflow patterns influenced by urban development have important consequences for channel form and

Table 5. Kendall Rank Correlation (τ) and Probability (p) That $\tau = 0$ for Relations Between Three Streamflow Metrics and Road Density (Group A) and Catchment Size (Group B)

	T_{Qmean}	CV_{AMF}	$T_{0.5}$
Group A streams			
Road density	−0.38 (0.06)	−0.45 (0.03)	−0.72 (0.002)
Group B streams			
Drainage area	0.34 (0.09)	−0.22 (0.19)	0.11 (0.32)
Mean streamflow	0.18 (0.23)	−0.11 (0.36)	−0.09 (0.36)

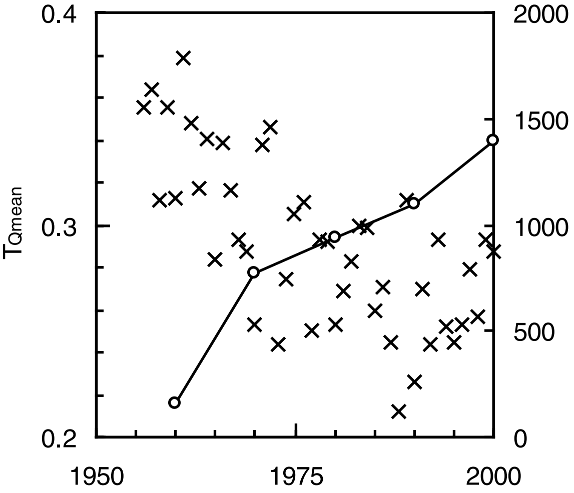

Figure 5. Annual values of T_{Qmean} (crosses) for Mercer Creek and decadal population density (line) in Bellevue, Washington, which includes the Mercer Creek basin.

stability. These consequences are evident in relations between channel widths and reference streamflows. Channel width models based on Q_{mean} and Q_{10} had the lowest standard error (1.3 m) of any of the models ($p < 0.05$ based on an F test that variances of the other model errors was equal to the variance of the model based on Q_{10}, Table 6). Incorporating streamflow metrics did not significantly improve the width models (Table 6). For example, although the bias in widths calculated from $Q_{0.5yr}$ was correlated with the cumulative duration of that flow ($T_{0.5yr}$) ($\tau = 0.54$, p = 0.005 based on a two-tailed Kendall rank correlation test; Figure 9), the reduction in the standard error of channel width from 3.3 m for the univariate equation based on $Q_{0.5yr}$ to 2.2 m for the bivariate equation based on $Q_{0.5yr}$ and $T_{0.5yr}$ was not significant (p = 0.12 that the variances of one- and two-variable models were equal based on an F test, Table 6). Although stream channel width is better referenced by flows of moderate duration (Q_{10}) than those of moderate frequency ($Q_{0.5yr}$) (Figure 10), we can only tentatively link the variability of channel width predicted from $Q_{0.5yr}$ to the cumulative duration that that flow is exceeded.

[47] Channel stability, as indicated by τ^*, varies among the five reference streamflows. Median τ^* for the 15 streams ranged from 0.025 for Q_{mean} to 0.071 to Q_{AMF} (Table 7). These values span conditions from a low probability and small spatial extent of bed material entrainment to a high probability and large extent of bed material entrainment [*Gessler*, 1970; *Konrad et al.*, 2002]. Of all five reference flows, τ^* at Q_{10} had the lowest variability among the 15 streams (0.026 to 0.046). These values generally represent the lower range of incipient motion for gravel bed streams [*Buffington and Montgomery*, 1997], which is consistent with Q_{10} referencing equilibrium conditions between streamflow and channel morphology. The variability of τ^* for all other reference flows, except Q_{mean}, was significantly greater than for Q_{10} (Table 7). The median (0.024) and range (0.018–0.037) of τ^* at Q_{mean} generally represented more stable bed conditions than those associated with Q10. The variation of τ^* at Q_{mean} was not correlated with T_{Qmean}.

[48] Variation of τ^* for $Q_{0.5\ yr}$ was correlated with $T_{0.5}$ ($\tau = -0.57$, p = 0.002 based on a two-tailed Kendall rank correlation test, Figure 11) and spanned values from 0.033 to 0.078. The range of values indicates that streambed disturbance for a 0.5-year flood varies among the streams. Moreover, the spatial extent of disturbance is likely to be greatest in streams where the flood peak was exceeded only briefly on a cumulative basis in previous years (low value of $T_{0.5\ yr}$). Variation in τ^* for Q_{AMF} was not correlated with CV_{AMF} suggesting that stability of a stream channel under flows equal to the mean annual flood does not depend on the variability of annual maximum floods.

[49] The hydrologic changes resulting from urban development could affect either "top-down" control of channel equilibrium where large floods set the channel width and size of bed material or "bottom-up" control where longer duration but lower streamflows determine channel width and bed material size. In top-down control, streambed disturbance would be a function of the peak streamflow in a flood relative to the peak streamflow of the largest floods and thus the frequency and extent of streambed disturbance would be inversely related to CV_{AMF}. Frequent, small floods would be expected to entrain sediment from a larger portion of the streambed in a stream with a low value of CV_{AMF}

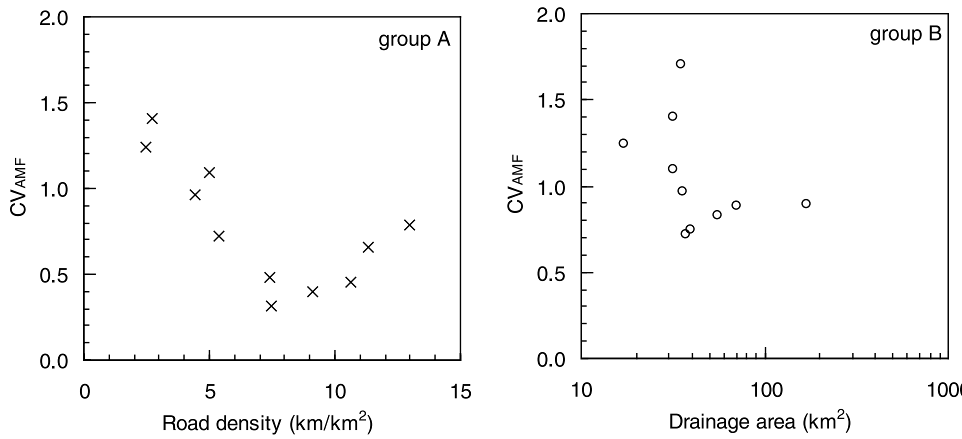

Figure 6. Relations between CV_{AMF} and road density (group A streams) and drainage area (group B streams).

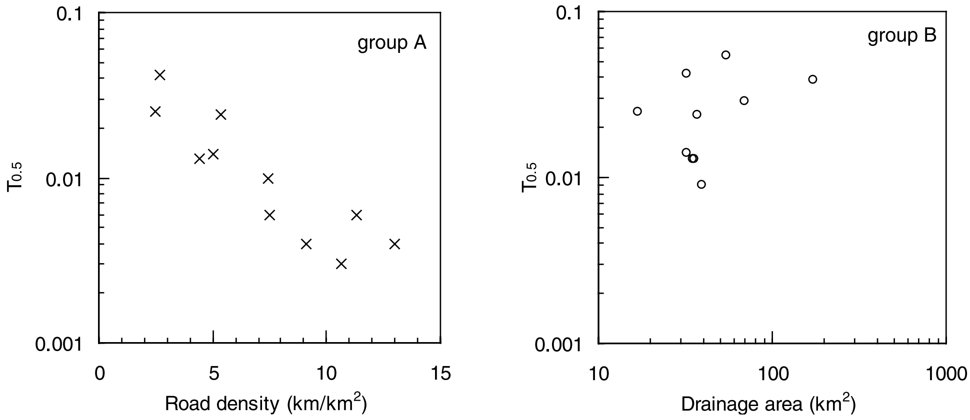

Figure 7. Relations between $T_{0.5}$ and road density (group A streams) and drainage area (group B streams).

than in a stream with a high value of CV_{AMF}. For bottom-up control, streamflow must transport sediment for some time longer than a single storm to set the channel width and size of bed material, for example, through the development of an armor layer.

[50] Three lines of evidence support the notion of bottom-up hydrologic control of geomorphic equilibrium in these streams. First, the power relations for channel width based on Q_{mean} and Q_{10} have smaller errors compared to Q_1, $Q_{0.5yr}$, or Q_{AMF}. Second, estimates of τ^* for Q_{10} generally represent a state at or approaching incipient motion of streambed material among the streams. This result supports bottom-up control by moderate flows having prolonged duration. Third, the state of streams during a 0.5-year flood varied from one of relative stability to one where extensive bed material entrainment was

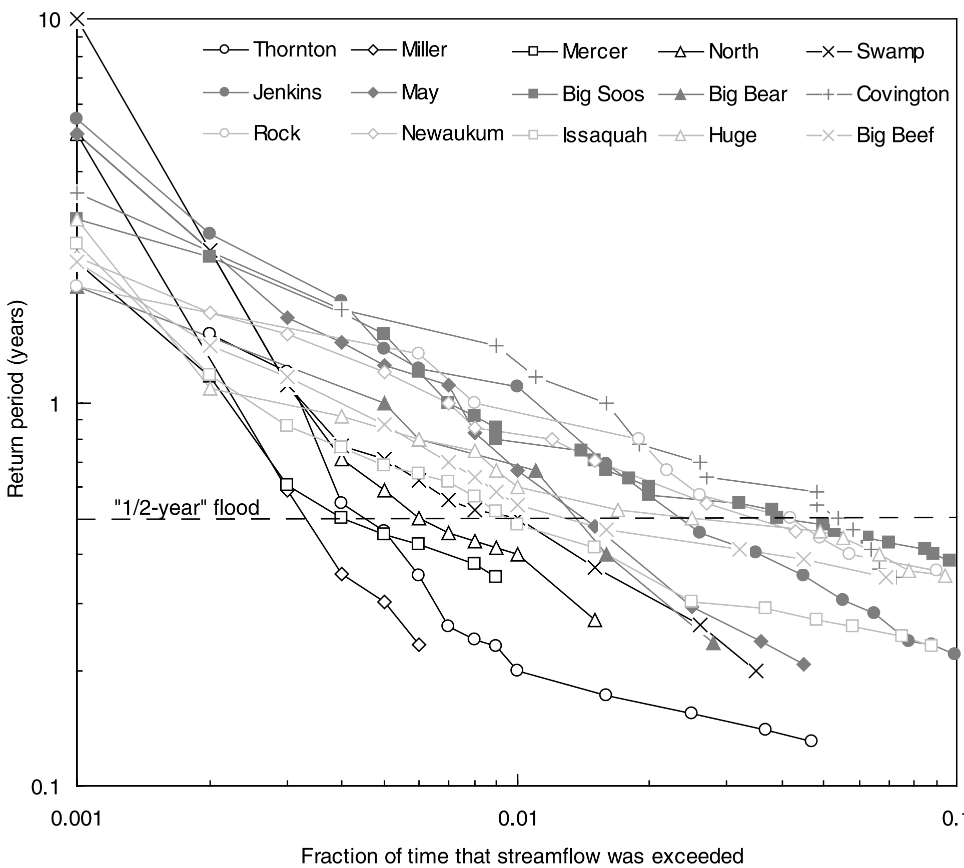

Figure 8. Exceedence duration and average return period of high flows in Puget Lowland streams. $T_{0.5}$ for a given stream corresponds to the ordinal value at the intersection of the dashed line and the respective duration-frequency curve for that stream. Streams are listed in descending order of road density. $T_{0.5}$ is less than or equal to 0.01 for all streams with road densities greater than 6 km/km^2 (solid lines) and is greater than or equal to 0.009 for all streams with road densities less than 6 km/km^2 (shaded lines).

Table 6. Empirical Models for Channel Width Based on Power Functions of Five Reference Streamflows

Width Model	Standard Error,[a] m
Streamflow exceeded 10% of the time (Q_{10})	
$9.2\ Q_{10}^{0.39}$	1.3
Mean streamflow (Q_{mean})	
$12.6\ Q_{mean}^{0.4}$	1.3
$12.6\ (Q_{mean}^{0.4} + T_{Qmean} - 0.32)$	1.1[b]
Mean annual maximum streamflow (Q_{AMF})	
$5.5\ Q_{AMF}^{0.36}$	3.0[c]
$5.5\ Q_{AMF}^{0.36} + 1.8\ (CV_{AMF} - 1.0)$	2.8[b,c]
0.5-year flood ($Q_{0.5yr}$)	
$7.5\ Q_{0.5yr}^{0.3}$	3.3[c]
$7.5\ Q_{0.5yr}^{0.3} + 140\ (T_{0.5} - 0.02)$	2.2[b,c]
Streamflow exceeded 1% of the time (Q_1)	
$6.4\ Q_1^{0.37}$	2.0[c]

[a]Standard error between calculated and observed widths for 15 streams (mean observed width for all streams was 12 m).
[b]None of the errors for the two-variable models are significantly lower than the errors for the one-variable models.
[c]Errors for the models based on Q_{mean} and Q_1 are significantly higher than the errors for the model based on Q_{10}.

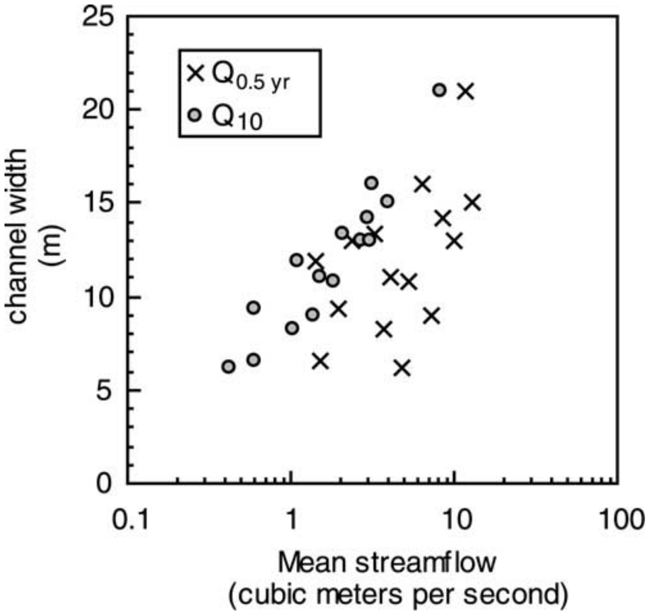

Figure 10. Channel width plotted against streamflow exceeded 10% of the time (Q_{10}) and the 0.5-year flood ($Q_{0.5yr}$).

likely. The level of stability was related to $T_{0.5}$. In this case, the incremental disturbance by a 0.5-year flood would be less in streams with a high value of $T_{0.5}$, because previous flows equal to and greater than the 0.5-year flood peak would have had time to transport sediment, widening the channel and exhausting the supply of mobile particles on the streambed. The lack of a relation between τ^* and either Q_1 or CV_{AMF} contradicts top-down control of streambed stability based on short-duration high flows or the variability of the peak flows.

[51] The exceedence duration of streamflow represents neither, the stochastic sequencing of floods, whereby high flows can destroy an armor layer such that subsequent lower flows may transport sediment until an armor layer has been reestablished, nor the episodic supply of sediment to a stream, which can alter the stability of the bed independently of streamflow rate. Nonetheless, flow duration provides a physical basis for an equilibrium between streamflow and channels where, over time, streamflow can transport a fraction (but not all) of the available sediment.

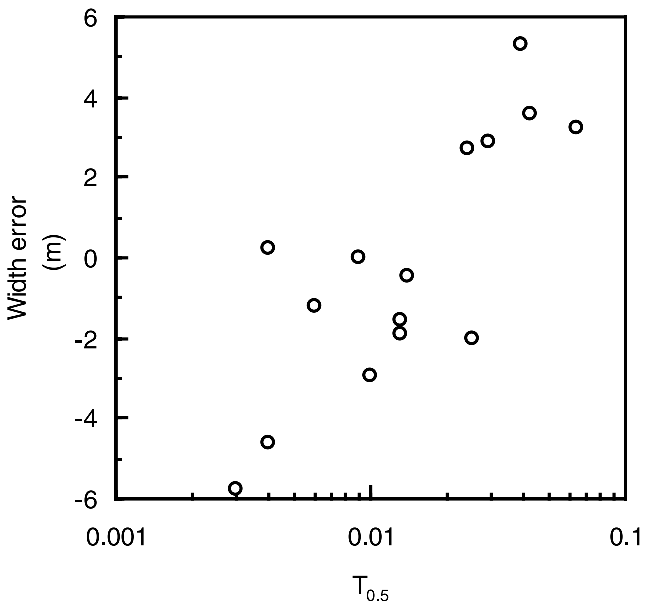

Figure 9. Error in width calculated from a power function (Table 6) of the 0.5-year flood plotted against the fraction of time streamflow exceeds the 0.5-year flood ($T_{0.5}$).

[52] Although we cannot rule out Q_{mean} as a reference flow for geomorphic equilibrium based on this analysis, Q_{mean} references the total volume of streamflow over a year – much of which is likely to have little geomorphic effect in gravel bed streams. *Leopold and Maddock* [1953, p. 3] introduced mean streamflow as an index of geomorphically effective flows for hydraulic geometry because “as a rough generalization, it may be stated that the mean annual rates of discharge at all points on a large number of rivers are equaled or exceeded about the same percent of time.” While Q_{mean} may represent a constant flow duration quantile for the large western rivers examined by *Leopold and Maddock* [1953], *Morgan* [1936, p. 425] identified a number of influences on the distribution of daily flows relative to the mean, including: “... topography, arrangement of tributaries with regard to time of concentration of surface flow, geologic structure, soil, vegetation, weather, and human

Table 7. Comparison of Dimensionless Shear Stress for Five Reference Streamflows

	τ^*		
Reference Streamflow	Median	Minimum	Maximum
Q_{mean}	0.024	0.018	0.037
Q_{10}	0.037	0.026	0.046
$Q_{0.5yr}$[a]	0.060	0.033	0.078
Q_1[a]	0.063	0.041	0.078
Q_{AMF}[a]	0.069	0.044	0.097

[a]Variance of τ^* at these reference streamflows is significantly greater than the variance of τ^* at Q^{10}.

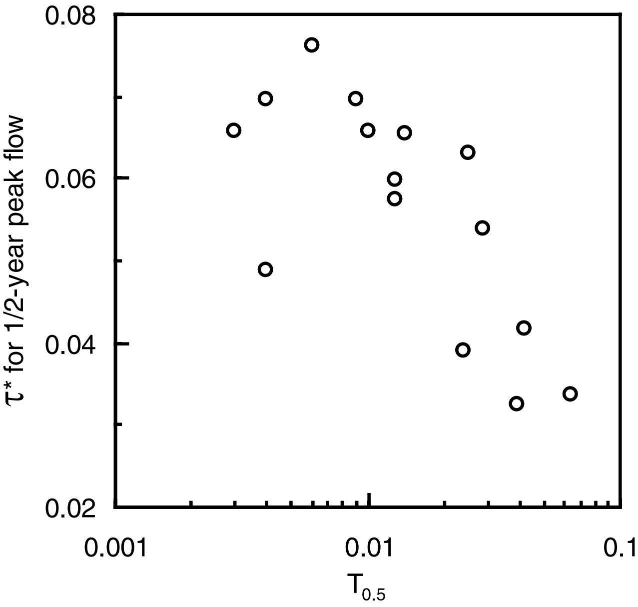

Figure 11. Dimensionless shear stress for the 0.5-year flood plotted against the fraction of time streamflow exceeds the 0.5-year flood ($T_{0.5}$).

developments related to flow of water.'' In the case of urban development, the temporal distribution of streamflow is expected to shift with brief periods of flow greater than Q_{mean} and long periods of flow less than Q_{mean} but no change in Q_{mean}. In this case, no channel response would be predicted from hydraulic geometry based on Q_{mean} though some channel expansion is expected in urban streams.

[53] *Wolman and Miller* [1960] proposed that the geomorphic effectiveness of a given streamflow is related to its duration and its magnitude relative to the cumulative distribution of streamflow. They concluded that ''frequent'' floods transported most of the sediment through a stream basin based on the cumulative duration of those floods rather than on their frequency. Given the variable relation between flow duration and flood frequency among streams with different levels of urban development (as shown in Figure 8), it is important for hydrologists to maintain a distinction between the frequency and the duration that streamflow is exceeded. Flow duration may serve as a better index of geomorphically effective flows than flow frequency in gravel bed streams because sediment transport acting over time, not instantaneously, is expected to exhaust the supply of mobile sediment from the channel bed and banks.

[54] By combining flow duration a basis for geomorphic equilibrium and evidence that urban development disproportionately increases the frequency but not the cumulative duration of high flows, we arrive at the tentative result that gravel bedded, alluvial channels with moderately limited sediment supplies are likely to experience more frequent and extensive bed disturbance not just during a transient period of adjustment to urban development but even at a new equilibrium state with a flashy streamflow regime. Streams in arid environments [e.g., *Reid and Laronne*, 1995] may provide a natural analog of these urban streams because high flows that occur frequently do not persist long enough to exhaust the supply of mobile particles on the streambed, and thus streambed material is frequently entrained during rapid runoff producing storms.

8. Conclusions

[55] Variation in interannual streamflow patterns, represented by three metrics (T_{Qmean}, CV_{AMF}, and $T_{0.5}$) was associated with urban developments for 11 streams in the Puget Lowland, Washington. T_{Qmean} is the fraction of a year that daily streamflow exceed mean annual streamflow, Q_{mean}. Streamflow exceeds Q_{mean} on fewer days and is less than Q_{mean} on more days in urban streams than in rural streams, as indicated by the correlation between T_{Qmean} and road density. Variation in T_{Qmean} with urban development quantifies the redistribution of runoff from wet season base flow periods to high-flow periods over multiple-year periods. Q_{mean} provided a reliable reference streamflow for an empirical relation between streamflow and channel width and stream channels generally appear to be stable at Q_{mean} with no dependence on T_{Qmean}.

[56] CV_{AMF} is the coefficient of variation of the log-transformed peak annual streamflows. Annual maximum streamflow had lower variation in urban streams as indicated by the correlation between CV_{AMF} and road density. Mean annual maximum streamflow was not a reliable reference flow for predicting channel width or bed stability and neither geomorphic condition was related to the variability of annual floods.

[57] $T_{0.5}$ is the cumulative fraction of time that streamflow exceeds the peak of a ''0.5-year flood,'' the peak streamflow exceeded on average during two events per year. $T_{0.5yr}$ varied among streams from 0.002–0.004 at the highest levels of urban development to around 0.03 at the lowest levels of urban development, indicating the brief duration of frequent high flow events in urban streams. Streambed stability during a 0.5-year flood was inversely related to $T_{0.5yr}$, which indicates increased streambed disturbance in urban streams.

[58] Streamflow duration may provide a better basis for referencing geomorphically effective flows and an equilibrium between streamflow and channel form in gravel bed streams than frequency or a central measure of all flows. The streamflow exceeded 10% of the time, Q_{10}, provided a reliable basis for an empirical channel width model and was generally associated with a state around the threshold of motion for a streambed in both urban and rural streams. If gravel bed streams are generally at equilibrium with flows of moderate duration (exceeded on the order of 10% of the time), urban streamflow patterns are likely to lead to increased frequency and extent of streambed disturbance even after any transient adjustments of the channel because the magnitudes of all geomorphically effective flows do not increase commensurately with the magnitudes of frequent high flows in urban streams.

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