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EFFECTS OF URBANIZATION ON FLOW DURATION AND STREAM FLASHINESS: A CASE STUDY OF PUGET SOUND STREAMS, WESTERN WASHINGTON, USA[1]

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ABSTRACT: The overall influence of urbanization on how flows of different frequency might change over time, while important in hydrologic design, remains imprecisely known. In this study, we investigate the effects of urbanization on flow duration curves (FDCs) and flow variability through a case study of eight watersheds that underwent different amounts of growth, in the Puget Sound region in Western Washington State, United States. We computed annual FDCs from flow records spanning 1960-2010 and, after accounting for the effects of precipitation, we conducted statistical trend analyses on flow metrics to quantify how key FDC percentiles changed with time in response to urbanization. In the urban watersheds, the entire FDC tended to increase in magnitude of flow, especially the 95th-99th percentile of the daily mean flow series, which increased by an average of 43%. Stream flashiness in urban watersheds was found to increase by an average of 70%. The increases in FDC magnitude and flashiness in urbanizing watersheds are most likely a result of increasing watershed imperviousness and altered hydrologic routing. Rural watersheds were found to have decreasing FDC magnitude over the same time period, which is possibly due to anthropogenic extractions of groundwater, and increasing stream flashiness, which is likely a result of reductions in base flow and increasing precipitation intensity and variability.

(KEY TERMS: urbanization; streamflow; flow duration curve; flashiness.)

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INTRODUCTION

The world's population is becoming increasingly urbanized. In 1950, 30% of people worldwide lived in urban areas, but by 2014, this number had increased to 54% (United Nations, 2015). In the United States (U.S.), it is projected that 84% of the population will live in urban areas by the year 2030 (United Nations, 2015). Physiographic changes associated with urbanization can dramatically alter the hydrologic response in a watershed undergoing urban development, which in turn can have cascading effects on aquatic habitat, flood risk, and stream channel morphology (*e.g.*, Booth and Jackson, 1997; Booth and Bledsoe, 2009).

When naturally vegetated areas are replaced with impervious surfaces such as rooftops and pavement, rainfall flows more rapidly into adjacent streams. This results in larger flood peaks and a decreased lag

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time between the center of mass of rainfall and the peak flow rate for a given storm (*e.g.*, Leopold, 1968; Hollis, 1975; Boyd *et al.*, 1993; Smith *et al.*, 2002; Hopkins *et al.*, 2015). Vogel *et al.* (2011) found that current design floods in heavily urbanized locations could be 2-5 times larger than they were at a time prior to urbanization. Storm sewers and artificial drainage networks also contribute to reduced lag time and increased flood peaks (*e.g.*, Leopold, 1968; Smith *et al.*, 2005).

The effects of urbanization on base flows have also received considerable attention, although the overall response is less clear. It is generally assumed that urbanization causes reduced infiltration and therefore decreased base flows (*e.g.*, NRC, 2009), and this is borne out in some circumstances (*e.g.*, Simmons and Reynolds, 1982; Price, 2011). However, leaks from sewer lines and water mains combined with other nuisance and point source discharges can contribute significantly to watershed outflows and potentially cause base flows to increase with urbanization (*e.g.*, Lerner, 2002; Bhaskar and Welty, 2012). Declining base flows can also result from shallow groundwater extractions (Sophocleous, 2002). In Western Washington, urbanization contributes to a reduction in base flow during the wet season. The same effect is not seen in the dry season. This occurs because urbanization prevents the shallow subsurface flow that supports wet-season base flow but urbanization does little to impact deep subsurface flow that supports summertime base flow (Konrad and Booth, 2005).

Despite a number of studies focused on quantifying how urbanization affects high- and low-magnitude discharges, the effects of urbanization on the full spectrum of flows remains imprecisely known. This is a hindrance for those desiring to estimate such a spectrum of discharges in an urbanizing area. The full spectrum of flows is often represented by a flow-duration curve (FDC), which provides a simple graphical view of the frequency and magnitude of all flows of a particular temporal density for a given period of time. The distribution of flows provided by an FDC is a critical component of geomorphic magnitude-frequency analysis (Wolman and Miller, 1960). When the flow frequency distribution is multiplied by a rating curve describing sediment transport as a function of water discharge, the resulting sediment yield curve can be used to compute metrics that are important for stable channel design. These metrics may include the effective discharge, *i.e.*, the discharge corresponding to the peak of the sediment yield curve (*e.g.*, Andrews, 1980; Doyle *et al.*, 2007); the half-load discharge, *i.e.*, the flow corresponding to the 50th percentile of the cumulative sediment yield curve (Sholtes and Bledsoe, 2016); and the sediment capacity-supply ratio, *i.e.*, the ratio of the total sediment capacity to sediment supply from upstream (Biedenharn *et al.*, 2000; Soar and Thorne, 2001).

Here we present a case study on the effect of urbanization on FDCs for a group of watersheds in the Puget Sound region of Western Washington, U.S., that underwent different amounts of urbanization in the second half of the 20th Century. These are relatively well studied watersheds. Konrad and Booth (2002) found that in this region, the fraction of the year over which the mean annual discharge was exceeded decreased in urbanized catchments, while the maximum annual discharge increased. The fraction of the year over which the mean annual discharge is exceeded is low in flashy streams with high peak discharge and rapid recession rates. Conversely, this fraction is higher in streams with relatively large, consistent groundwater inflows. This suggests that the streams Konrad and Booth (2002) studied were increasing in flashiness.

Konrad *et al.* (2005) found that after development, the frequency of a flow exceeded for a given duration is generally higher in urban streams than in rural ones. In this article, we expand on this work to investigate long-term temporal trends in the full spectrum of streamflows in urban and rural catchments. Using daily streamflow and precipitation records collected from 1960 to 2010, we compute annual FDCs and perform trend analyses on flow metrics computed from the FDCs to investigate how the full spectrum of flows is affected by urbanization, and the potential implications that shifts in the FDC may have on stream channel morphology and stable channel design.

METHODS

Study Area

The Puget Sound region has seen tremendous population growth in recent decades. The population of the four-county region of King, Kitsap, Pierce, and Snohomish Counties has grown from approximately 1.5 million people in 1960 to 3.7 million in 2010 (Washington State, 2012). In 2010, the Puget Sound basin composed 70% of the state's population (Cuo *et al.*, 2009). The hydrologic effects of urbanization are particularly evident in the Pacific Northwest, because the region's temperate forests are dominated by hillslope storage and subsurface flow. Impervious surfaces associated with urbanization disrupt these processes by reducing infiltration and shifting flow from the subsurface to the surface (Burges *et al.*, 1998; Konrad *et al.*, 2005).

The Puget Sound basin receives approximately 1,000 mm of precipitation annually, with higher elevations receiving greater amounts. The majority of precipitation occurs as rain in the fall and winter months, with over 75% of precipitation occurring between October and the end of March (Kruckeberg, 1991).

We selected eight watersheds in the Puget Sound basin for analysis, which are shown in Figure 1 and summarized in Table 1. We limited our analysis to watersheds with drainage areas <200 km^2 to promote uniformity in size amongst rural and urban basins. We also limited our analysis to watersheds with mean elevations <300 m above sea level to select rainfall as the dominant form of precipitation over snowfall. The study watersheds were required to have at least 25 years of daily discharge data collected at a U.S. Geological Survey gaging station between 1960 and 2010. We disregarded any years for which there was only a partial flow record.

The hydrologic effects of urbanization are generally tied to watershed imperviousness, but widespread satellite-derived data on land use and land cover in the region only go back to the year 2001 (Homer *et al.*, 2004). Historical population density data, however, are available through decadal census data, and strong relationships between watershed imperviousness and population density have been shown in the literature (Stankowski, 1972; Sheng and Wilson, 2009). We therefore used historic U.S. Census tract data to quantify population and population density in the watersheds over time. Geographic maps of census tract boundaries and associated population tables were obtained for censuses conducted in 1960, 1970, 1980, 1990, 2000, and 2010 (Minnesota Population Center, 2011). Watershed populations for each decade were estimated from census tract data following the method of Sheng and Wilson (2009). Census tracts for each decade were re-mapped to the watershed boundaries in ArcGIS. For census tracts located only

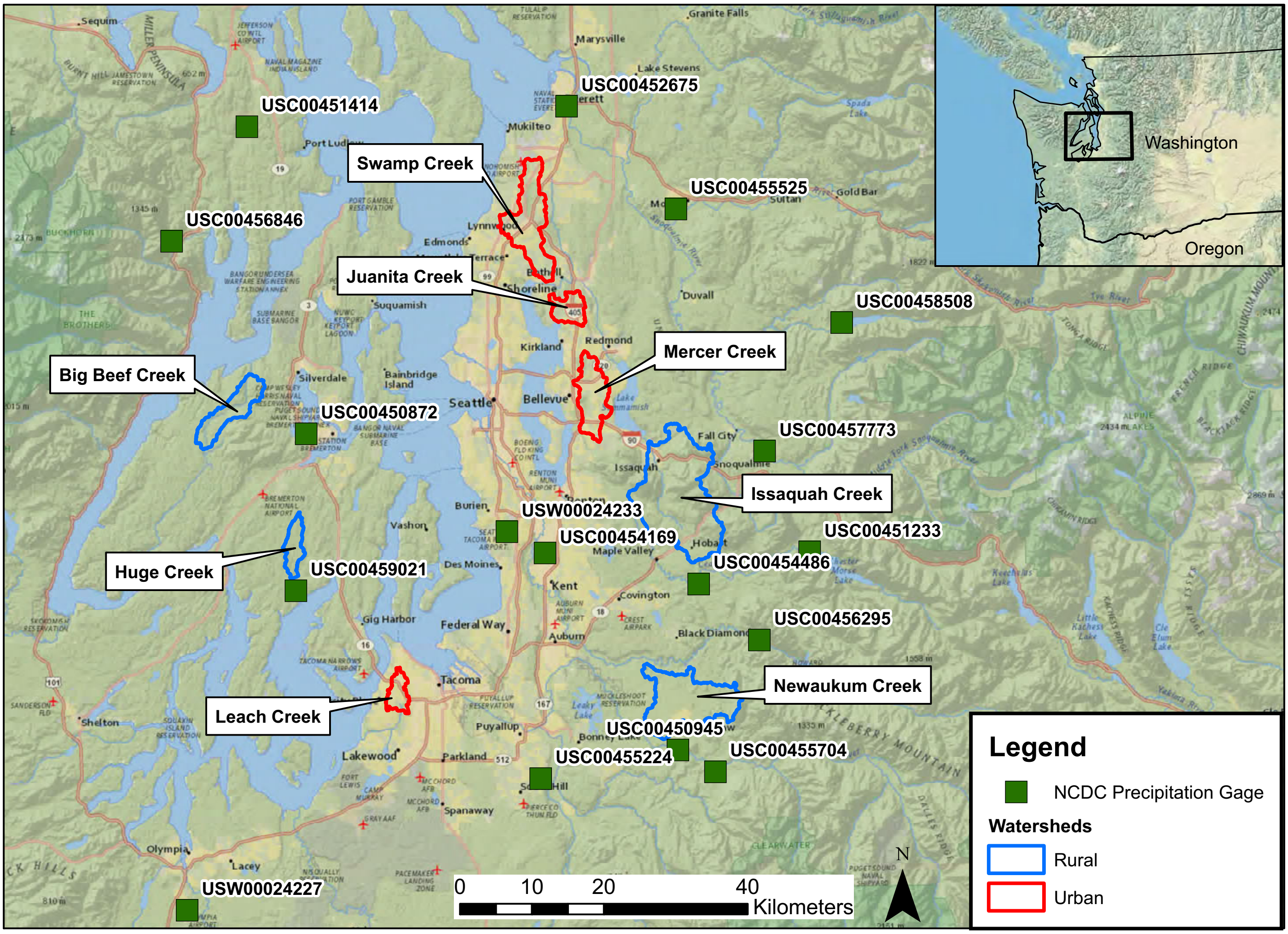

FIGURE 1. Map of Watersheds and Precipitation Gages Used in the Analysis. NCDC, National Climatic Data Center.

TABLE 1. Characteristics of Watersheds Included in the Case Study.

Station Name	USGS Gage No.	Drainage Area (km^2)	Streamflow Analysis Period	Estimated Population Density in 2010 (people/km^2)	Average Population Growth 1960-2010 (people/km^2/yr)	2011 Percent Impervious Surfaces	Class
Juanita Creek near Kirkland, Washington	12120500	17	1964-1990	1,908	35.1	40.9	Urban
Mercer Creek near Bellevue, Washington	12120000	31	1960-2010	1,526	24.9	39.4	Urban
Swamp Creek at Kenmore, Washington	12127100	25	1964-1990	1,680	29.1	38.6	Urban
Leach Creek near Fircrest, Washington	12091200	12.2	1960-2010	1,533	13.5	48.9	Urban
Newaukum Creek near Black Diamond, Washington	12108500	70	1964-2010	120	1.3	7	Rural
Issaquah Creek Mouth near Issaquah, Washington	12121600	145	1964-2010	174	2.9	6.4	Rural
Big Beef Creek near Seabeck, Washington	12069550	35	1970-2010	79	1.6	2.7	Rural
Huge Creek near Wauna, Washington	12073500	17	1960-2010	87	1.3	3.4	Rural

Note: USGS, U.S. Geological Survey.

partially within the watershed, the population was split in proportion to the census tract area within the watershed. Because urban census tracts are relatively small in area (often <10 km^2), this method should provide a reasonable estimate of watershed population on decadal time intervals.

In order to examine the current relationship between impervious surfaces and population density in Washington State, and to provide support for the use of population density as a surrogate for impervious cover, we compared population density in the year 2010 (Minnesota Population Center, 2011) against average impervious percentage in 2011 (Homer *et al.*, 2015) of each census tract in the state of Washington.

Population growth in the eight study watersheds is shown in Figure 2. The sites readily fall into two groups: we classify those with a population density >1,000 people/km^2 in 2010 as "urban" watersheds, and those with a population density of <100 people/km^2 in 2010 were categorized as "rural" watersheds.

Flow Metrics

Generation of FDCs. Annual FDCs were generated for each year of daily discharge data. A FDC is a plot of Q_p, the pth quantile of daily streamflow *versus* the exceedance probability p that streamflow Q is larger than some value q:

$$p = 1 - P\{Q \leq q\}. \tag{1}$$

For large streamflow datasets ($n \geq 100$), the Weibull plotting position provides an unbiased estimate for the exceedance probability of each observed streamflow. For smaller annual datasets, however, the Weibull plotting position is an inefficient estimator, and smoother estimates of the quantile function can be developed using a more complex estimator. We therefore construct annual FDCs, using the so-called $Q_{p,3}$ method described in Vogel and Fennessey (1994).

Once the annual FDCs were generated for each watershed, we estimated from them a set of flow percentiles that were used in trend analyses. We express flow percentiles as Q_x, where x is the percent of flows smaller than Q_x; *i.e.*, the Q_{99} for a given year has an exceedance probability $p = 0.01$ and is larger than 99% of the rest of the flows in that year. In our analysis, we calculated annual estimates of Q_{99}, Q_{98}, Q_{95}, Q_{90}, Q_{75}, Q_{50}, Q_{25}, and Q_{10} for each gage.

Base Flow, Runoff, and Base-Flow Index. Base flow is the component of total streamflow that enters a stream from a persistent and slowly varying source (Sophocleous, 2002). We used the Web-based Hydrograph Analysis Tool (WHAT) (Lim *et al.*, 2005) to separate daily flows into runoff and base-flow components. WHAT uses a recursive digital filter with parameters representative of "perennial streams with porous aquifers" to separate high-frequency signals associated with runoff from low-frequency signals associated with base flow. Although the base-flow component of the hydrograph identified by this technique may not directly reflect groundwater contributions to streamflow, this methodology removes the subjective aspects from manual

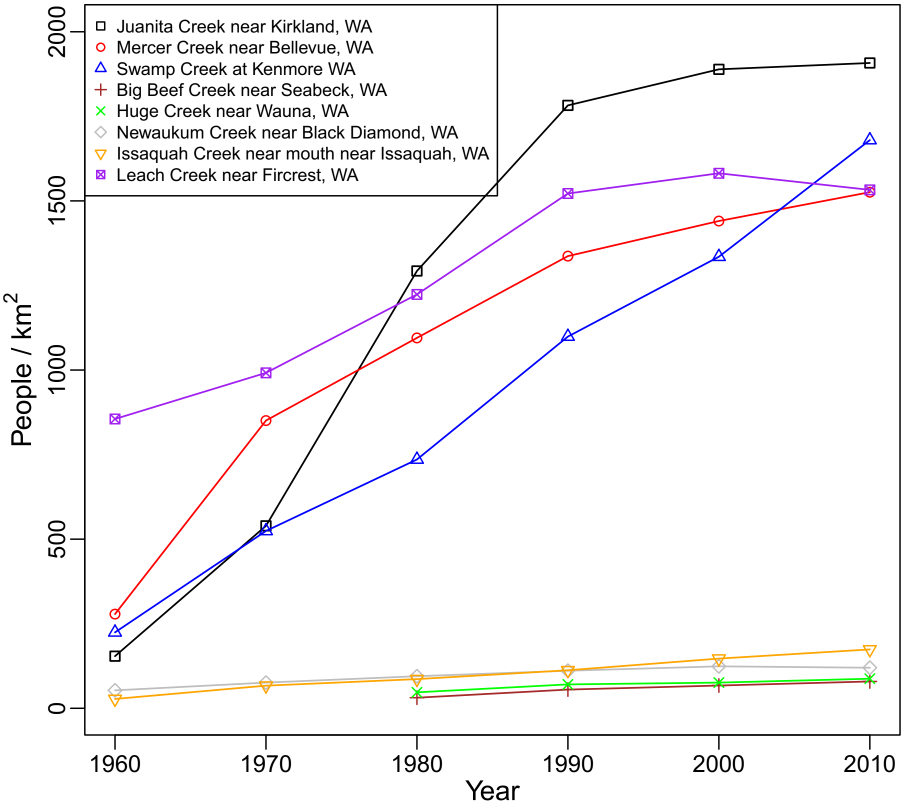

FIGURE 2. Estimates of Watershed Population Density from 1960 to 2010 in the Study Watersheds.

hydrograph separation and provides a fast and reproducible means to separating hydrographs over long periods of time (Lim *et al.*, 2005).

Upon separation of the hydrograph into base-flow and runoff components, the average daily base flow and runoff were computed for each year of record during the analysis period. Additionally, the base-flow index (BFI) was calculated for each year of the analysis. The BFI, which is the ratio of base flow to total streamflow (Bloomfield *et al.*, 2009), is useful for parameterizing streamflow by its origin.

Flashiness. Streams and rivers that experience rapid variations in streamflow over time are often termed "flashy." Watershed urbanization has been linked to flashy streamflow behavior in previous studies (*e.g.*, Graf, 1977; Walsh *et al.*, 2005). Here, we use the Richards-Baker (RB) flashiness index (Baker *et al.*, 2004) to characterize this behavior:

$$\mathrm{RB} = \frac{\sum_{i=1}^{n} |q_i - q_{i-1}|}{\sum_{i=1}^{n} q_i}. \tag{2}$$

In Equation (2), i denotes the day and n is the number of days of flow record analyzed. The RB index is high for flashy hydrographs and low when hydrographs rise and fall gradually. Although subdaily data may provide a more accurate description of flashiness in urban watersheds, they were not available over the full study period, so daily flow data were used to compute annual values of RB. The RB flashiness index was originally intended to be calculated with daily flow data, and as such, the RB index still provides a reliable measure of stream flashiness (Baker *et al.*, 2004).

Precipitation Metrics

An objective of our analysis was to investigate trends in the streamflow metrics described above and relate these trends to watershed urbanization. Trends in precipitation, however, may confound that analysis. We therefore used historical rainfall observations to compute several metrics describing precipitation events over the period of record, and used these to separate out the influence of precipitation on trends in the flow metrics.

Daily precipitation series for each watershed from 1960 to 2010 were spatially interpolated from nearby National Climatic Data Center daily precipitation gages (Figure 1). We used an inverse distance weighting procedure (Lu and Wong, 2008; Li and

Heap, 2011; Chen and Liu, 2012) to interpolate data from the rain gages over the watersheds. The interpolated rainfall at the watershed of interest, R_p, was calculated as

$$R_p = \sum\nolimits_{i=1}^{N} w_i R_i \tag{3a}$$

$$w_i = d_i^{-1} / \sum\nolimits_{i=1}^{N} d_i^{-1}, \tag{3b}$$

where w_i is the weighting of rainfall station i; R_i is the rainfall at station i; d_i is the distance from rainfall station i to the centroid of the watershed of interest, and N is the number of rainfall stations used in the calculation. In our analysis, we used the five nearest precipitation gages ($N = 5$).

These daily rainfall series were used to calculate a number of metrics aimed at quantifying different precipitation characteristics. To quantify the total magnitude of precipitation, the precipitation was summed on an annual basis. To capture the intensity of single and multiple day precipitation events, we calculated the maximum annual 1, 2, 3, and 7-day precipitation totals. Lastly, to quantify variability in precipitation, we calculated the coefficient of variation in each year of daily precipitation records.

Trend Analysis

For each watershed, the correlation coefficient (r) and coefficient of determination (r^2) between the annual time series of each flow metric and each precipitation metric were computed. Over all of the watersheds, nearly all flow metrics were most strongly correlated with the total annual precipitation (Table 2). To account for the effects of precipitation on trend analyses, for each watershed we performed a linear regression of all of the flow metrics on the total annual precipitation, and performed a trend analysis on the residuals (*e.g.*, Hirsch *et al.*, 1991; Helsel and Hirsch, 1992; Nelson *et al.*, 2006).

We used the nonparametric Mann-Kendall test (Mann, 1945; Kendall, 1975) to identify statistically significant trends in the precipitation-adjusted FDC percentiles, annual daily-average base flow, annual daily-average runoff, BFI, and RB flashiness index. The test is particularly useful as missing values are allowed and the data do not need to conform to any particular distribution (Gilbert, 1987). We accounted for serial correlation of the residuals by prewhitening the data following the Yue *et al.* (2002) method. The Mann-Kendall rank correlation coefficient τ was computed for each watershed from the time series of each precipitation-adjusted flow metric residual. Here, we identify significant trends by comparing the p-values from each Mann-Kendall test for each site to the critical values that control the false discovery rate, q^*, at 0.05 (Benjamini and Hochberg, 1995). In some instances, this means that a Mann-Kendall test with $p < 0.05$ may not be significant because multiple inferences are being made for the data from a given site.

We also characterized the magnitude of the trends in these flow metrics with the nonparametric Theil-Sen estimator (Theil, 1950; Sen, 1968), which is a robust estimate of the slope of the trend of the prewhitened flow metric residuals. The overall percent change in each flow metric over the period of record was then estimated from this line.

RESULTS

Population Density and Imperviousness

The relationship between population density and impervious cover was analyzed for more than 1,200

TABLE 2. Average Coefficient of Determination (r^2) between Flow Metrics and Precipitation (P) Metrics.

	Annual P	Max 1 Day P	Max 2 Day P	Max 3 Day P	Max 7 Day P	Max 10 Day P	CV
Runoff	0.57	0.14	0.17	0.20	0.20	0.19	0.18
Base flow	0.53	0.07	0.08	0.09	0.09	0.09	0.09
BFI	0.20	0.11	0.15	0.17	0.21	0.18	0.15
Q_{99}	0.31	0.22	0.28	0.32	0.33	0.30	0.32
Q_{98}	0.43	0.14	0.20	0.24	0.27	0.27	0.25
Q_{95}	0.52	0.12	0.16	0.20	0.21	0.23	0.21
Q_{90}	0.54	0.10	0.13	0.16	0.16	0.17	0.15
Q_{75}	0.54	0.08	0.08	0.10	0.07	0.07	0.09
Q_{50}	0.35	0.05	0.07	0.08	0.06	0.05	0.05
Q_{25}	0.16	0.04	0.05	0.05	0.06	0.05	0.05
Q_{10}	0.10	0.04	0.05	0.05	0.07	0.05	0.06
RB	0.14	0.13	0.17	0.17	0.16	0.14	0.16

Note: BFI, base-flow index; CV, coefficient of variation; RB, Richards-Baker index.

Washington State census tracts. For census tracts with <50% impervious surface, as is the case with our eight study watersheds (Table 1), population density was found to explain 74% of the variance in percent imperviousness (Figure 3), suggesting that population density is a reasonable surrogate for impervious surfaces for watersheds that are <50% impervious.

Trends in Flow Metrics

Accounting for the influence of total annual precipitation, and prewhitening the data to account for serial correlation, tended to improve the identification of significant trends. For example, Figure 4 shows annual Q_{95} values computed at Mercer Creek, one of the urbanizing watersheds, prior to and after accounting for the effect of precipitation. Prior to accounting for precipitation, there is no trend in the original Q_{95} values ($p = 0.16$) and the Theil-Sen slope is 0.006 $m^3/s/yr$. In contrast, the residuals following regression of the Q_{95} on total annual precipitation in Mercer Creek and prewhitening to remove serial correlation (red circles; note that for plotting purposes the residuals have been added to the median of the original Q_{95} values) show less scatter, and a significant trend ($p = 0.011$, with a Theil-Sen slope of 0.0083 $m^3/s/yr$).

Figure 5 shows FDCs averaged over the periods 1960-1969, 1970-1979, 1980-1989, 1990-1999, and 2000-2009 for each of our study watersheds. While the temporal evolution of FDCs varies by location, qualitative differences between urban and rural watersheds can be discerned. In Leach Creek, an urbanizing basin, it is evident that the high flows increased in the 1970s and 1980s and have remained high since then, while the low flows in Leach Creek increased slightly in the 1980s and increased again in the 2000s (Figure 5d). The FDC of rural Newaukum Creek, on the other hand, has not shown much change during the period of record, with only a slight decrease in the lowest flows (Figure 5e).

The results of the Mann-Kendall tests are summarized for all of the prewhitened, precipitation-corrected flow metrics in all watersheds in Table 3. FDCs in the urban watersheds were generally characterized by increasing high flows and low flows, although increases in low flows (Q_{10} and Q_{25}) were only statistically significant for Leach Creek. The high flows (Q_{99}, Q_{98}, and Q_{95}) showed statistically

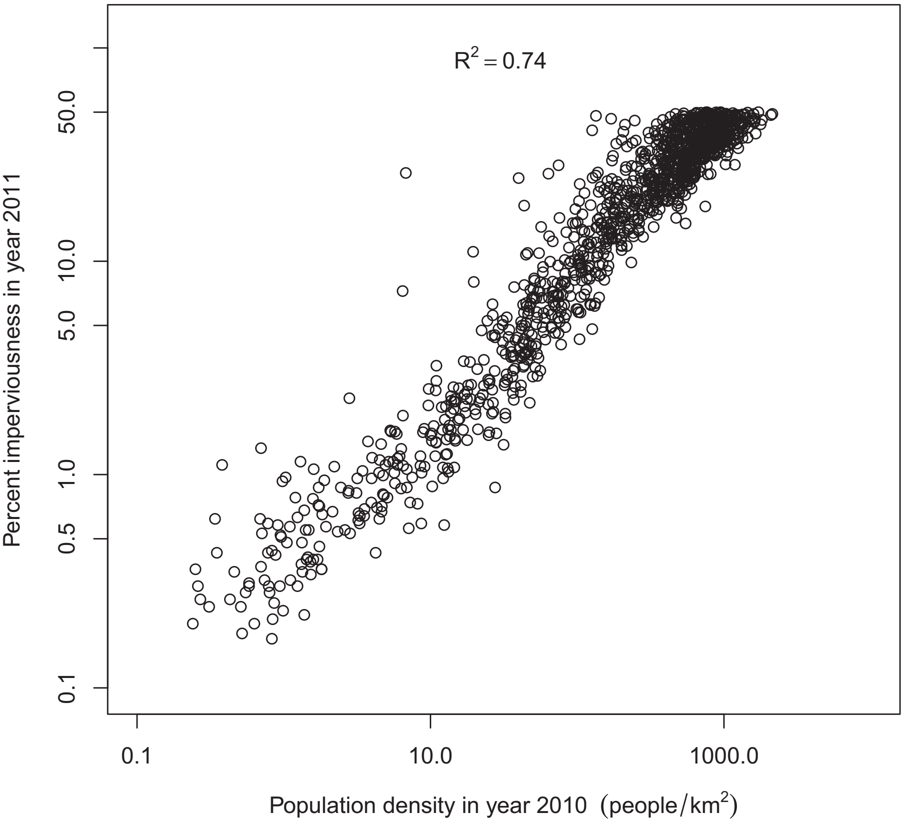

FIGURE 3. Relationship between Impervious Surfaces (computed from the 2011 National Land-Cover Database, Homer *et al.*, 2015) and Population Density for Census Tracts in the State of Washington That Are <50% Impervious.

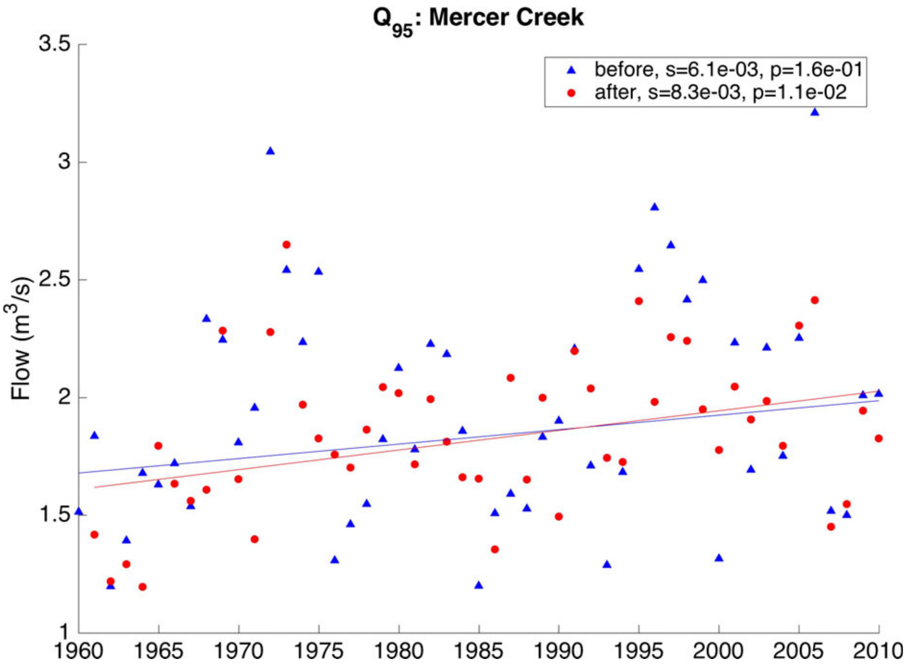

FIGURE 4. Trend in Q_{95} in Mercer Creek. Blue triangles show the trend in Q_{95} without accounting for the effects of total annual precipitation or prewhitening to remove serial correlation (Theil-Sen estimator = 0.0061 m^3/s/yr; p = 0.16); red circles show the prewhitened residuals from the regression of Q_{95} on total annual precipitation (Theil-Sen estimator = 0.0083 m^3/s/yr; p = 0.011).

significant increasing trends in Mercer Creek and Leach Creek. The RB flashiness index showed a statistically significant increasing trend in all four urban watersheds. Three of the four urban watersheds showed a statistically significant decreasing trend in BFI, largely driven by strongly increasing trends in runoff.

For the rural watersheds, nearly all of the Mann-Kendall τ coefficients for the FDC percentiles are negative, indicating a decreasing trend, but the only statistically significant trend is for the Q_{10} in Issaquah Creek. In these watersheds, both base flow and runoff generally show decreasing trends, but the magnitude of the decrease in base flow tends to be larger than that for runoff, leading to decreases in BFI. Despite the decreasing trends in flow percentiles, base flow, and runoff, all four rural watersheds show an increasing trend in RB flashiness, although the trend is only statistically significant in Issaquah Creek.

Figure 6 presents the percentage change in each of the FDC quantiles over the period of record estimated from the Theil-Sen slope of the trend in the prewhitened, precipitation-adjusted flow data for all watersheds, as well as averages from the four urban and four rural watersheds. On average, the entire FDC shifted upward in urbanizing watersheds, particularly the high flows, while the entire FDC tended to shift downward in rural watersheds, particularly for the low flows.

The rate of change in each of the flow metrics, *i.e.*, the Theil-Sen slope of each of the prewhitened, precipitation-adjusted flow metric time series, is plotted against population growth rate for each watershed in Figure 7. The clearest relationship appears in the RB flashiness index (Figure 7i), which increases more rapidly in more rapidly urbanizing watersheds (R^2 = 0.88; p = 0.00056). With the exception of Swamp Creek, the highest flows (Q_{98} and Q_{99}) increase more rapidly with more rapidly urbanizing watersheds (Figures 7d and 7e), and the BFI decreases more rapidly in more rapidly urbanizing watersheds (Figure 7c). Relationships between changes in moderate to low flows (Q_{75} to Q_{10}, Figures 7h-7k) and the rate of urbanization are not readily apparent, and may reflect site-specific water importation or exportation and flow augmentation, as discussed in the following section.

DISCUSSION

Impact of Urbanization on the FDC

Our results indicate that urbanization has the potential to significantly increase the magnitude of the entire FDC (Table 3, Figures 6 and 7). This is in agreement with other work showing that urbanization can cause significant increases in flood magnitude (Konrad, 2003; Hejazi and Markus, 2009). Increases in watershed imperviousness are known to

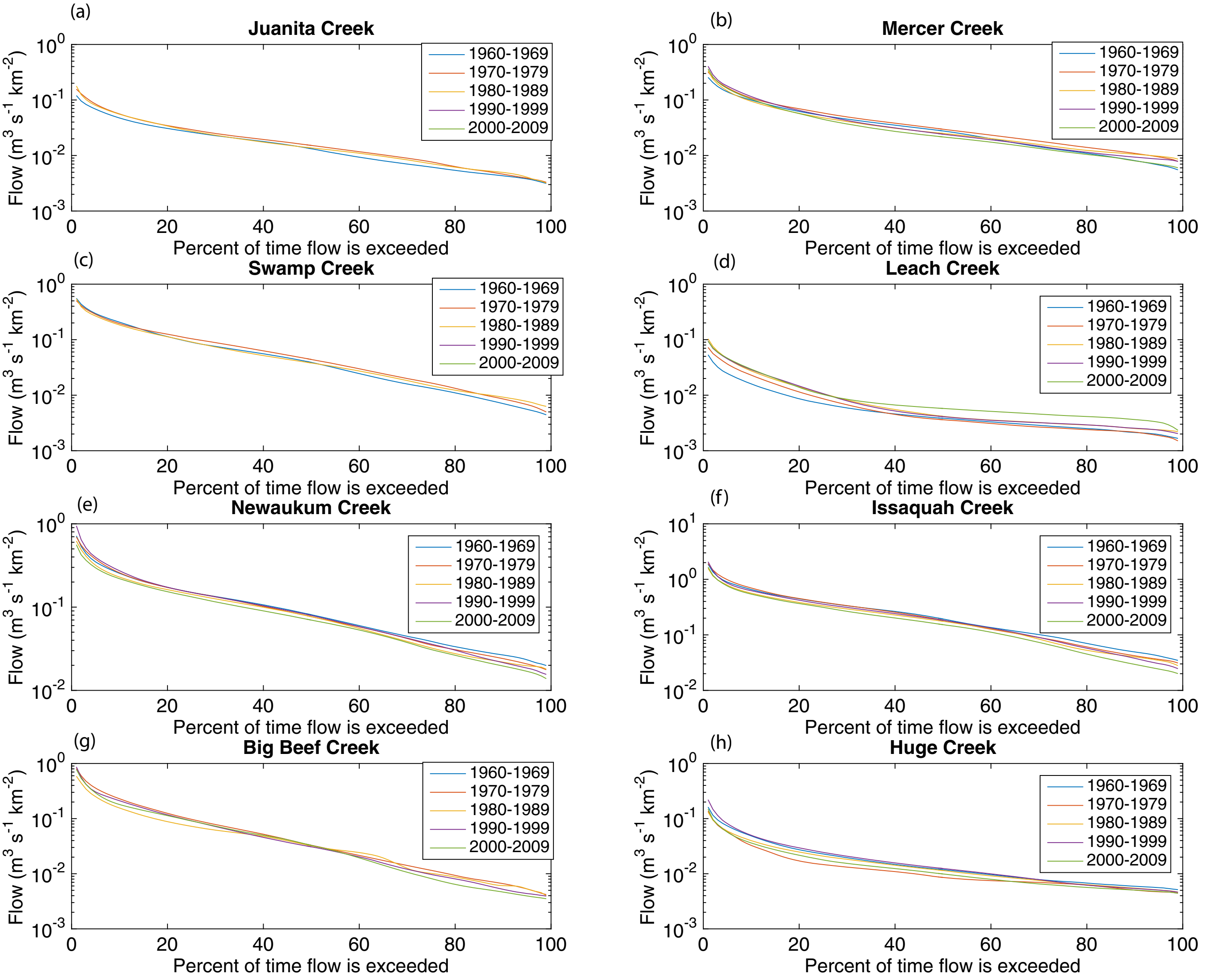

FIGURE 5. Decade-Averaged Flow Duration Curves for All Sites.

cause increased streamflow rates and runoff volumes (*e.g.*, Boyd *et al.*, 1993; Booth and Jackson, 1997; Smith *et al.*, 2002; Hawley and Bledsoe, 2011), a result that is mirrored in this analysis. Smaller watersheds such as Juanita Creek had a greater relative increase in streamflow magnitude than larger watersheds such as Mercer Creek. This is due in part to the fact the larger watersheds generally have a greater average streamflow than small watersheds and are thus more resistant to hydrologic alterations. This fact should also be considered when comparing the results of the smaller urban watersheds to the larger rural watersheds.

While many studies have found that urbanization generally decreases the magnitude of low flows due to decreased contributions from groundwater storage (Simmons and Reynolds, 1982; Rose and Peters, 2001; Price, 2011), here we find that on average, the magnitude of low discharges (10th-25th percentile) increased in urban watersheds. This is probably due in part to flow augmentation in one of the four urban watersheds. Since 1993, Leach Creek has had low flows augmented by a groundwater well (Kimbrough *et al.*, 2001). It is not known if similar programs have been adopted at the other urban watersheds analyzed in this study. Others have suggested that increases in base flow in urban watersheds can also be the result of leakages in storm sewer and water distribution systems, or lawn watering in certain regions (Lerner, 2002; Meyer, 2002).

Results of the flow analysis for rural watersheds indicated that the magnitude of the extremely high

TABLE 3. Mann-Kendall τ Rank Correlation Coefficient from Trend Tests of the Prewhitened, Precipitation-Adjusted Flow Metrics.

Site No.	Site Name	Urban/ Rural	Runoff	Base Flow	BFI	Q_{99}	Q_{98}	Q_{95}	Q_{90}	Q_{75}	Q_{50}	Q_{25}	Q_{10}	RB
12120500	Juanita Creek	Urban	**−0.18** *1.1E-03*	−0.24 *7.4E-01*	**−0.13** *3.1E-04*	0.02 *1.8E-02*	−0.09 *9.7E-02*	−0.21 *7.8E-01*	−0.18 *5.4E-01*	−0.20 *9.8E-01*	−0.14 *7.8E-01*	−0.14 *4.4E-01*	−0.30 *1.4E-01*	**0.29** *1.8E-05*
12120000	Mercer Creek	Urban	**0.51** *1.0E-06*	**−0.06** *1.2E-03*	**−0.56** *1.7E-10*	**0.35** *7.3E-04*	**0.25** *8.2E-03*	**0.04** *1.1E-02*	0.09 *4.1E-02*	0.00 *8.5E-02*	**0.04** *1.9E-04*	0.12 *1.4E-01*	0.22 *9.8E-02*	**0.63** *3.5E-11*
12127100	Swamp Creek	Urban	−0.04 *7.9E-01*	−0.18 *2.5E-01*	−0.19 *2.2E-01*	−0.16 *2.7E-01*	−0.19 *1.8E-01*	−0.23 *1.1E-01*	−0.29 *4.2E-02*	−0.01 *9.8E-01*	−0.03 *8.7E-01*	0.03 *8.3E-01*	0.21 *1.4E-01*	**0.67** *3.4E-06*
12091200	Leach Creek	Urban	**0.61** *2.7E-09*	**0.56** *4.4E-08*	**−0.27** *9.0E-03*	**0.42** *2.4E-05*	**0.46** *4.3E-06*	**0.54** *5.6E-08*	**0.51** *3.5E-07*	**0.41** *3.6E-05*	**0.36** *3.4E-04*	**0.45** *5.6E-06*	**0.52** *1.5E-07*	**0.37** *1.8E-04*
12108500	Newaukum Creek	Rural	0.11 *3.0E-01*	−0.07 *5.2E-01*	−0.24 *1.8E-02*	−0.03 *7.6E-01*	−0.10 *3.3E-01*	−0.02 *8.3E-01*	0.10 *3.4E-01*	0.10 *3.5E-01*	0.11 *2.7E-01*	−0.01 *8.9E-01*	−0.18 *7.2E-02*	0.02 *8.8E-01*
12121600	Issaquah Creek	Rural	−0.18 *7.2E-02*	−0.24 *1.9E-02*	−0.13 *1.9E-01*	0.02 *8.8E-01*	−0.09 *3.6E-01*	−0.21 *3.7E-02*	−0.18 *7.5E-02*	−0.20 *4.7E-02*	−0.14 *1.7E-01*	−0.14 *1.8E-01*	**−0.30** *3.1E-03*	**0.29** *5.4E-03*
12069550	Big Beef Creek	Rural	−0.08 6.1E-01	−0.06 6.9E-01	0.13 4.0E-01	0.00 9.8E-01	0.00 9.8E-01	−0.03 8.3E-01	−0.04 7.9E-01	0.00 9.8E-01	0.02 8.9E-01	−0.26 7.1E-02	−0.32 2.2E-02	0.05 7.6E-01
12073500	Huge Creek	Rural	−0.02 *8.6E-01*	−0.14 *2.0E-01*	−0.09 *4.0E-01*	0.05 *6.5E-01*	−0.04 *7.5E-01*	−0.17 *1.1E-01*	−0.19 *8.3E-02*	−0.11 *3.0E-01*	−0.11 *2.9E-01*	−0.19 *8.3E-02*	−0.21 *5.1E-02*	0.20 *6.5E-02*

Note: Positive values indicate an increasing trend; negative values indicate a decreasing trend. Bold values indicate the trend is significant when controlling the false discovery rate at $q^* < 0.05$. The *p*-value for each Mann-Kendall test is shown in italics below the τ value.

discharges (98th-99th percentile) exhibited only a very slight decrease over time. Conversely, the magnitude of low discharges (10th-25th percentile) generally exhibited a decreasing trend, although insignificant, with the exception of Issaquah Creek and the 10th percentile discharge (Figure 6). It is possible that these trends are the result of shifting precipitation patterns related to climate change. While precipitation magnitude and intensity were monitored over time, precipitation seasonality was not, and could play a role in these results. We suspect however, that the decreases in the 10th percentile discharge are to some degree the result of groundwater extraction.

The 10th percentile discharge tends to correlate with base-flow periods in the months of July or August for these watersheds (see Figure S1), overlapping periods in which irrigation demands are the highest for many crops. Groundwater is used in many of these watersheds for agricultural and municipal purposes, and demand on groundwater is such that nearly all of the groundwater in Washington State is already legally allocated (Washington State, 2012). Groundwater extractions have been directly linked to reductions in streamflow in many locations (Winter *et al.*, 1998). Additionally, strong evidence shows that groundwater and streamflow are highly interconnected in the Puget Sound basin (Morgan and Jones, 1999). The 25th percentile discharge often corresponds with base flows in the months of October-December. While groundwater extraction for agriculture is decreased during this time period as compared with July-August, municipal usage rates remain high and are a potential cause of this decline.

Flashiness was observed to increase greatly in our urban watersheds over the analysis period. This is likely due to the increase in impervious surfaces, and the advent of stormwater conveyance systems associated with urban development. This has been observed in previous studies across the country (Schoonover *et al.*, 2006; Gregory and Calhoun, 2007) and within the Puget Sound basin (Konrad and Booth, 2002; Konrad *et al.*, 2005). Increasing flashiness in the rural watersheds is likely tied to reductions in base flow, which reduces the sum of the daily mean flows and causes the denominator of the RB flashiness metric to decrease, thereby causing the RB flashiness metric to increase.

Implications for Channel Morphology and Stream Channel Design

Hydrologic changes caused by urbanization have the potential to impact channel morphology (Hammer, 1972; Hawley *et al.*, 2012). Previous studies

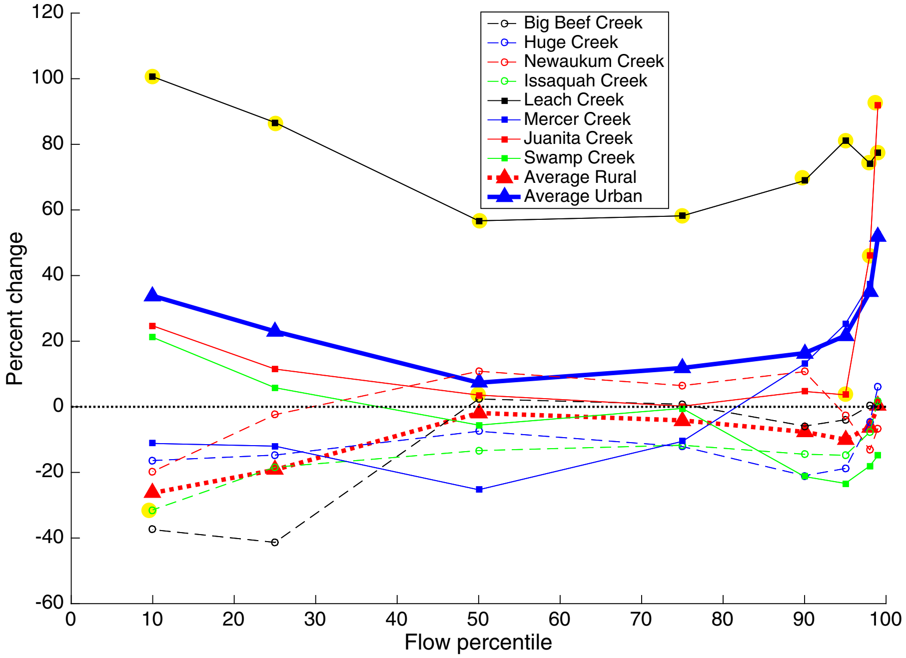

FIGURE 6. Percent Change in the Trend of the Prewhitened, Precipitation-Adjusted Flow Duration Curves Percentiles over the Analysis Period (1960-2010). Rural watersheds have open markers and dashed lines; urban watersheds have filled markers and solid lines. Percentiles with statistically significant trends (see Table 3) are highlighted with yellow circles. The average of the four rural and four urban watersheds is shown in the thicker lines.

have linked urbanization to channel widening and incision (Booth, 1990; Galster *et al.*, 2008; Hawley and Bledsoe, 2013). Additionally, stream flashiness can cause bank instability through rapid wetting and drawdown (Thorne, 1990). While many studies have shown that urbanization increases the peak magnitude of flood events (Konrad, 2003; Hejazi and Markus, 2009), this study demonstrates that in certain regions, urbanization may increase the magnitudes of flows spanning the entire FDC. In these circumstances, the magnitude of high, median, and low flows all increase in response to urbanization.

This result has important implications for stream ecology, flood risk, and public safety. Increases in stream discharge alter wood and sediment recruitment thus changing habitat type and availability (Booth, 1991). Salmon abundance has been shown to decrease with urbanization in this region (Moscrip and Montgomery, 1997). Increased streamflow magnitude and flashiness also pose a significant threat to property and human life (NRC, 2009).

For engineers, shifts in the magnitude of high flows have important implications for sediment transport and channel design calculations such as the calculation of sediment yield and effective discharge, which depend upon the product of the flow frequency curve with a sediment transport rating curve. Shifts in the flow frequency curve, especially in the high flows, may have a large effect on magnitude and shape of the sediment yield curve because sediment transport is generally a highly nonlinear function of streamflow. Additionally, the tendency for RB flashiness to increase more rapidly with more rapid urbanization (Figure 7i) suggests that daily flow data may not capture important sediment transporting flow events in highly urbanized channels, and sub-daily flow data would be needed to accurately compute the effective discharge or half-load discharge (Rosburg *et al.*, 2016).

Channel widening and incision in response to the altered flow and sediment regime in urbanizing basins have the potential to cause large increases in the suspended sediment concentrations of streams. High suspended sediment concentrations stress fish, impair spawning grounds (Newcombe and MacDonald, 1991), reduce light reaching photosynthetic organisms, and disrupt macroinvertebrate life cycles (*e.g.*, Lenat *et al.*, 1981; Waters, 1995; Berry *et al.*, 2003). Channel widening and incision can also damage vital infrastructure such as roads, culverts, and bridges. This reaffirms the relevancy of understanding urbanization's influence on FDCs. Improved understanding of the effects of urbanization on FDCs can inform mitigation strategies for avoiding the detrimental consequences of flow alteration and channel instability on infrastructure and the ecological integrity of streams.

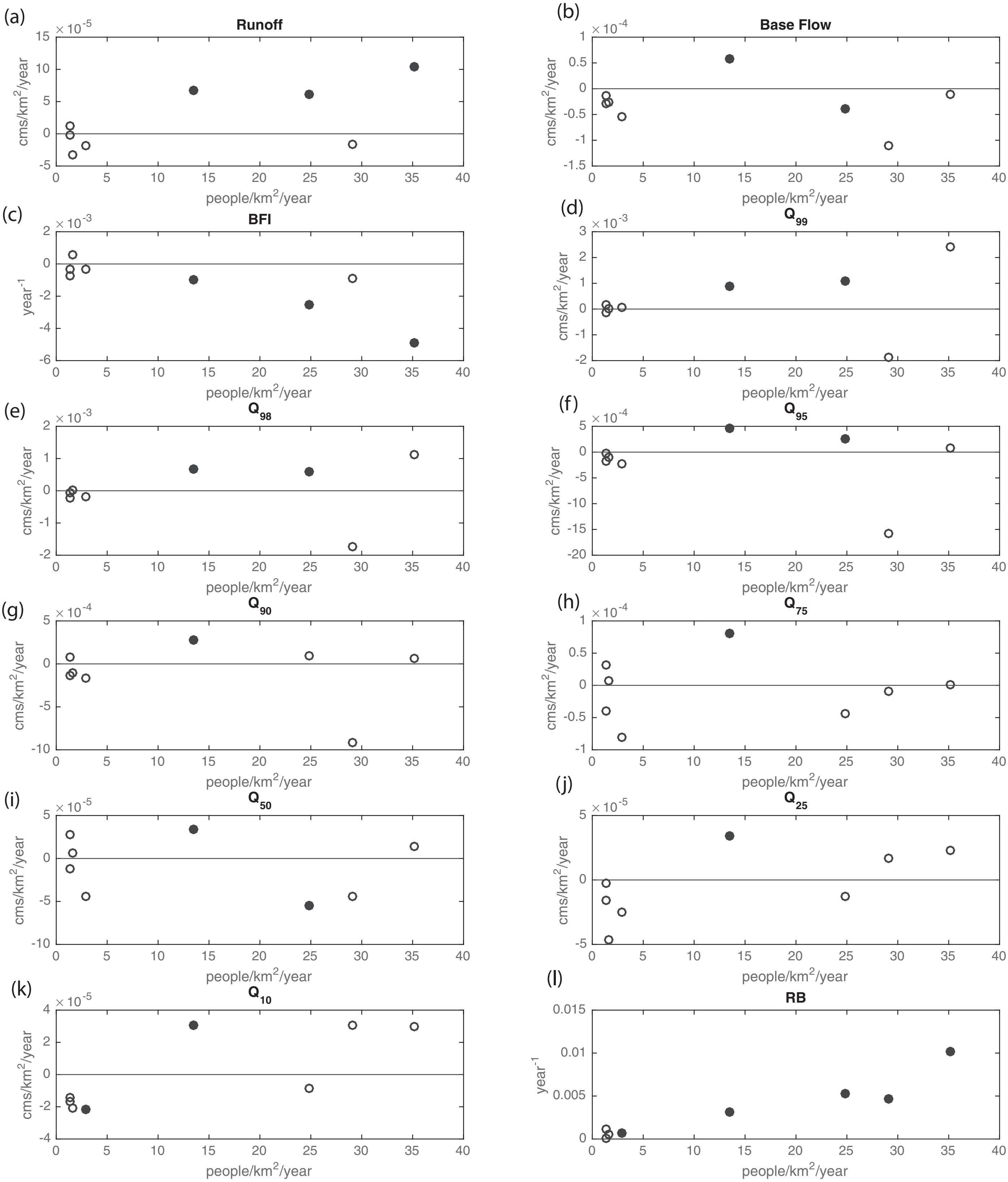

FIGURE 7. Magnitude of the Theil-Sen Nonparametric Slope of the Temporal Trend of the Prewhitened, Precipitation-Adjusted Flow Metrics, Plotted against Population Density Rate of Change. Each circle represents one site. Filled circles indicate the trend is significant when controlling the false discovery rate $q^* < 0.05$.

CONCLUSIONS

In this study, we computed annual FDCs from long-term streamflow records in watersheds that underwent different amounts of development, and used trend analyses to investigate possible linkages between urbanization and temporal shifts in different components of the FDC. The percentiles of the FDC, the runoff and base-flow components of streamflow, and the flashiness of the hydrograph tended to be correlated with total annual precipitation, and accounting for the effects of precipitation reduced the scatter and improved the significance of the temporal trend analyses. Urbanization affected the entire FDC, with both high and low flows increasing with population density. RB flashiness index had a strongly increasing relationship with population density (Figure 7i), suggesting that in highly urbanized basins, sediment transport calculations using daily flow data may underestimate actual values.

This study illustrates the dynamic influence of urbanization on hydrologic processes. This demonstrates the need for robust strategies for forecasting temporal shifts in hydrologic regimes. Because FDCs are often used by scientists and engineers for a wide range of applications including channel design and magnitude frequency analysis, future work that provides locally-calibrated estimates of FDC change with land use would be a valuable contribution to the field, and would advance hydrologic design procedures. Absent an understanding of how FDCs change in response to urbanization, predictions of stream response and analytical channel design procedures such as the analysis of effective discharge will incur a greater degree of uncertainty and risk.

SUPPORTING INFORMATION

Additional supporting information may be found online under the Supporting Information tab for this article: Annual hydrographs for all study sites and years of record.

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LITERATURE CITED

Andrews, E.D., 1980. Effective and Bankfull Discharges of Streams in the Yampa River Basin, Colorado and Wyoming. Journal of Hydrology 46(3):311-330, DOI: 10.1016/0022-1694(80)90084-0.

Baker, D.B., R.P. Richards, T.T. Loftus, and J.W. Kramer, 2004. A New Flashiness Index: Characteristics and Applications to Midwestern Rivers and Streams. Journal of the American Water Resources Association 40(2):503-522.

Benjamini, Y. and Y. Hochberg, 1995. Controlling the False Discovery Rate: A Practical and Powerful Approach to Multiple Testing. Journal of the Royal Statistical Society. Series B (Methodological) 57(1):289-300.

Berry, W., N. Rubinstein, B. Melzian, and B. Hill, 2003. The Biological Effects of Suspended and Bedded Sediment (SABS) in Aquatic Systems: A Review. United States Environmental Protection Agency Internal Report 102.

Bhaskar, A.A. and C. Welty, 2012. Water Balances along an Urban-to-Rural Gradient of Metropolitan Baltimore, 2001-2009. Environmental and Engineering Geoscience 18(1):37-50.

Biedenharn, D.S., R.R. Copeland, C.R. Thorne, P.J. Soar, R.D. Hey, and C.C. Watson, 2000. Effective Discharge Calculation: A Practical Guide. Technical Report No. ERDC/CHL TR-00-15, U.S. Army Corps of Engineers, Washington, D.C.

Bloomfield, J.P., D.J. Allen, and K.J. Griffiths, 2009. Examining Geological Controls on Base Flow Index (BFI) Using Regression Analysis: An Illustration from the Thames Basin, UK. Journal of Hydrology 373(1):164-176, DOI: 10.1016/j.jhydrol.2009.04.025.

Booth, D.B., 1990. Stream Channel Incision Following Drainage-Basin Urbanization. Journal of the American Water Resources Association 26(3):407-417.

Booth, D.B., 1991. Urbanization and the Natural Drainage System — Impacts, Solutions, and Prognoses. Northwest Environmental Journal 7:93-118.

Booth, D.B. and B.P. Bledsoe, 2009. Streams and Urbanization. *In*: The Water Environment of Cities, L.A. Baker (Editor). Springer, New York, New York, pp. 93-123.

Booth, D.B. and C.R. Jackson, 1997. Urbanization of Aquatic Systems: Degradation Thresholds, Stormwater Detection, and the Limits of Mitigation. Journal of the American Water Resources Association 33(5):1077-1090.

Boyd, M.J., M.C. Bufill, and R.M. Knee, 1993. Pervious and Impervious Runoff in Urban Catchments. Hydrological Sciences Journal 38(6):463-478, DOI: 10.1080/02626669309492699.

Burges, S.J., M.S. Wigmosta, and J.M. Meena, 1998. Hydrologic Effects of Land-Use Change in a Zero-Order Catchment. Journal of Hydrologic Engineering 3:86-97.

Chen, F.W. and C.W. Liu, 2012. Estimation of the Spatial Rainfall Distribution Using Inverse Distance Weighting (IDW) in the Middle of Taiwan. Paddy and Water Environment 10(3):209-222, DOI: 10.1007/s10333-012-0319-1.

Cuo, L., D.P. Lettenmaier, M. Alberti, and J.E. Richey, 2009. Effects of a Century of Land Cover and Climate Change on the Hydrology of the Puget Sound Basin. Hydrological Processes 23 (6):907-933, DOI: 10.1002/hyp.7228.

Doyle, M.W., D. Shields, K.F. Boyd, P.B. Skidmore, and D. Dominick, 2007. Channel-Forming Discharge Selection in River Restoration Design. Journal of Hydraulic Engineering 133 (7):831-837.

Galster, J.C., F.J. Pazzaglia, and D. Germanoski, 2008. Measuring the Impact of Urbanization on Channel Widths Using Historic Aerial Photographs and Modern Surveys. Journal of the American Water Resources Association 44(4):948-960, DOI: 10.1111/j.1752-1688.2008.00193.x.

Gilbert, R.O., 1987. Statistical Methods for Environmental Pollution Monitoring. John Wiley & Sons, New York City, New York.

Graf, W.L., 1977. Network Characteristics in Suburbanizing Streams. Water Resources Research 13(2):459-463.

Gregory, M.B. and D.L. Calhoun, 2007. Physical, Chemical, and Biological Responses of Streams to Increasing Watershed Urbanization in the Piedmont Ecoregion of Georgia and Alabama, Chapter B of Effects of Urbanization on Stream

Ecosystems in Six Metropolitan Areas of the United States. U.S. Geological Survey Scientific Investigations Report 2006-5101-B. http://pubs.usgs.gov/sir/2006/5101B.

Hammer, T.R., 1972. Stream Channel Enlargement Due to Urbanization. Water Resources Research 8(6):1530-1540.

Hawley, R.J. and B.P. Bledsoe, 2011. How Do Flow Peaks and Durations Change in Suburbanizing Semi-Arid Watersheds? A Southern California Case Study. Journal of Hydrology 405:69-82, DOI: 10.1016/j.jhydrol.2011.05.011.

Hawley, R.J. and B.P. Bledsoe, 2013. Channel Enlargement in Semiarid Suburbanizing Watersheds: A Southern California Case Study. Journal of Hydrology 496:17-30, DOI: 10.1016/j.jhydrol.2013.05.010.

Hawley, R.J., B.P. Bledsoe, E.D. Stein, and B.E. Haines, 2012. Channel Evolution Model of Semiarid Stream Response to Urban-Induced Hydromodification. Journal of the American Water Resources Association 48(4):722-744, DOI: 10.1111/j.1752-1688.2012.00645.x.

Hejazi, M.I. and M. Markus, 2009. Impacts of Urbanization and Climate Variability on Floods in Northeastern Illinois. Journal of Hydrologic Engineering 14(6):606-616, DOI: 10.1061/(ASCE)HE.1943-5584.0000020.

Helsel, D.R. and R.M. Hirsch, 1992. Statistical Methods in Water Resources. Elsevier, Amsterdam, the Netherlands.

Hirsch, R.M., R.B. Alexander, and R.A. Smith, 1991. Selection of Methods for the Detection and Estimation of Trends in Water Quality. Water Resources Research 27(5):803-813.

Hollis, G.E., 1975. The Effect of Urbanization on Floods of Different Recurrence Interval. Water Resources Research 11(3):431-435, DOI: 10.1029/WR011i003p00431.

Homer, C., C. Huang, L. Yang, B. Wylie, and M. Coan, 2004. Development of a 2001 National Land-Cover Database for the United States. Photogrammetric Engineering & Remote Sensing 70(7):829-840, DOI: 10.14358/PERS.70.7.829.

Homer, C.G., J.A. Dewitz, L. Yang, S. Jin, P. Danielson, G. Xian, J. Coulston, N.D. Herold, J.D. Wickham, and K. Megown, 2015. Completion of the 2011 National Land Cover Database for the Conterminous United States-Representing a Decade of Land Cover Change Information. Photogrammetric Engineering and Remote Sensing 81(5):345-354.

Hopkins, K.G., N.B. Morse, D.J. Bain, N.D. Bettez, N.B. Grimm, J.L. Morse, M.M. Palta, W.D. Shuster, A.R. Bratt, and A.K. Suchy, 2015. Assessment of Regional Variation in Streamflow Responses to Urbanization and the Persistence of Physiography. Environmental Science and Technology 49:2724-2732, DOI: 10.1021/es505389y.

Kendall, M.G., 1975. Rank Correlation Methods (Fourth Edition). Charles Griffin, London, United Kingdom.

Kimbrough, R.A., R.R. Smith, G.P. Rupert, W.D. Wiggins, S.M. Knowles, and V.F. Renslow, 2001. Water Resources Data, Washington, Water Year 2000. U.S. Geological Survey Water-Data Report WA-00-1, 541 pp.

Konrad, C.P., 2003. Effects of Urban Development on Floods. U.S. Geological Survey Fact Sheet 076–03, Tacoma, Washington.

Konrad, C.P. and D.B. Booth, 2002. Hydrologic Trends Associated with Urban Development for Selected Streams in the Puget Sound Basin, Western Washington. U.S. Geological Survey Water-Resources Investigations Report 02–4040, Tacoma, Washington.

Konrad, C.P. and D.B. Booth, 2005. Hydrologic Changes in Urban Streams and Their Ecological Significance. *In*: American Fisheries Society Symposium, Anchorage, Alaska, September 11, 2005, Vol. 47, pp. 157-177.

Konrad, C.P., D.B. Booth, and S.J. Burges, 2005. Effects of Urban Development in the Puget Lowland, Washington, on Interannual Streamflow Patterns: Consequences for Channel Form and Streambed Disturbance. Water Resources Research 41:W07009, DOI: 10.1029/2005WR004097.

Kruckeberg, A.R., 1991. The Natural History of Puget Sound Country. University of Washington Press, Seattle, Washington.

Lenat, D.R., D.L. Penrose, and K.W. Eagleson, 1981. Variable Effects of Sediment Addition on Stream Benthos. Hydrobiologia 79:187-194.

Leopold, L.B., 1968. Hydrology for Urban Land Planning: A Guidebook on the Hydrologic Effects of Urban Land Use. U.S. Geological Survey, Washington, D.C.

Lerner, D.N., 2002. Identifying and Quantifying Urban Recharge: A Review. Hydrogeology Journal 10(1):143-152, DOI: 10.1007/s10040-001-0177-1.

Li, J. and A.D. Heap, 2011. A Review of Comparative Studies of Spatial Interpolation Methods in Environmental Sciences: Performance and Impact Factors. Ecological Informatics 6(3):228-241, DOI: 10.1016/j.ecoinf.2010.12.003.

Lim, K.J., B.A. Engel, Z. Tang, J. Choi, K.S. Kim, S. Muthukrishnan, and D. Tripathy, 2005. Automated Web GIS Based Hydrograph Analysis Tool, WHAT. Journal of the American Water Resources Association 41:1407-1416, DOI: 10.1111/j.1752-1688.2005.tb03808.x.

Lu, G.Y. and D.W. Wong, 2008. An Adaptive Inverse-Distance Weighting Spatial Interpolation Technique. Computers & Geosciences 34(9):1044-1055, DOI: 10.1016/j.cageo.2007.07.010.

Mann, H.B., 1945. Non-Parametric Tests against Trend. Econometricia 13:245-249.

Meyer, S.C., 2002. Investigation of Impacts of Urbanization on Base Flow and Recharge Rates, Northeastern Illinois: Summary of Year 2 Activities. *In*: Proceedings of 12th Annual Research Conference: Research on Agricultural Chemicals and Groundwater Resources in Illinois. http://hdl.handle.net/2142/55237, *accessed* April 2015.

Minnesota Population Center, 2011. National Historical Geographic Information System: Version 2.0. University of Minnesota, Minneapolis, Minnesota.

Morgan, D.S. and J.L. Jones, 1999. Numerical Model Analysis of the Effects of Ground-Water Withdrawals on Discharge to Streams and Springs in Small Basins Typical of the Puget Sound Lowland, Washington. U.S. Geological Survey Water Supply Paper 2492, pp. 1-73.

Moscrip, A.L. and D.R. Montgomery, 1997. Urbanization, Flood Frequency and Salmon Abundance in Puget Lowland Streams. Journal of the American Water Resources Association 33(6):1289-1297, DOI: 10.111/j.1752-1688.1997.tb03553.x.

Nelson, P.A., J.A. Smith, and A.J. Miller, 2006. Evolution of Channel Morphology and Hydrologic Response in an Urbanizing Drainage Basin. Earth Surface Processes and Landforms 31(9):1063-1079, DOI: 10.1002/esp.1308.

Newcombe, C.P. and D.D. MacDonald, 1991. Effects of Suspended Sediments on Aquatic Ecosystems. North American Journal of Fisheries Management 11(1):72-82, DOI: 10.1577/1548-8675(1991)011<0072:EOSSOA>2.3.CO;2.

NRC (National Research Council), 2009. Urban Stormwater Management in the United States. The National Academies Press, Washington, D.C., ISBN: 978-0-309-12539-0.

Price, K., 2011. Effects of Watershed Topography, Soils, Land Use, and Climate on Base Flow Hydrology in Humid Regions: A Review. Progress in Physical Geography 35(4):465-492, DOI: 10.1177/0309133311402714.

Rosburg, T.T., P.A. Nelson, J.S. Sholtes, and B.P. Bledsoe, 2016. The Effect of Flow Data Resolution on Sediment Yield Estimation and Channel Design. Journal of Hydrology 538:429-439, DOI: 10.1016/j.jhydrol.2016.04.040.

Rose, S. and N.E. Peters, 2001. Effects of Urbanization on Streamflow in the Atlanta Area (Georgia, USA): A Comparative

Hydrological Approach. Hydrological Processes 15(8):1441-1457, DOI: 10.1002/hyp.218.

Schoonover, J.E., B.G. Lockaby, and B.S. Helms, 2006. Impacts of Land Cover on Stream Hydrology in the West Georgia Piedmont, USA. Journal of Environmental Quality 35(6):2123-2131, DOI: 10.2134/jeq2006.0113.

Sen, P.K., 1968. Estimates of the Regression Coefficient Based on Kendall's Tau. Journal of the American Statistical Association 63:1379-1389, DOI: 10.2307/2285891.

Sheng, J. and J.P. Wilson, 2009. Watershed Urbanization and Changing Flood Behavior across the Los Angeles Metropolitan Region. Natural Hazards 48(1):41-57, DOI: 10.1007/s11069-008-9241-7.

Sholtes, J.S. and B.P. Bledsoe, 2016. Half-Yield Discharge: Process-Based Predictor of Bankfull Discharge. Journal of Hydraulic Engineering 142(8):04016017, DOI:10.1061/(ASCE)HY.1943-7900.0001137.

Simmons, D.L. and R.J. Reynolds, 1982. Effects of Urbanization on Base Flow of Selected South-Shore Streams, Long Island, New York. Water Resources Bulletin 18:797-805.

Smith, J.A., M.L. Baeck, J.E. Morrison, P. Sturdevant-Rees, D.F. Turner-Gillespie, and P.D. Bates, 2002. The Regional Hydrology of Extreme Floods in an Urbanizing Drainage Basin. Journal of Hydrometeorology 3(3):267-282, DOI: 10.1175/1525-7541(2002)003<0267:TRHOEF>2.0.CO;2.

Smith, J.A., A.J. Miller, M.L. Baeck, P.A. Nelson, G.T. Fisher, and K.L. Meierdiercks, 2005. Extraordinary Flood Response of a Small Urban Watershed to Short-Duration Convective Rainfall. Journal of Hydrometeorology 6(5):599-617.

Soar, P.J. and C.R. Thorne, 2001. Channel Restoration Design for Meandering Rivers. Report No. ERDC/CHL CR-01-1, U.S. Army Engineer Research and Development Center, Vicksburg, Mississippi.

Sophocleous, M., 2002. Interactions between Groundwater and Surface Water: The State of the Science. Hydrogeology Journal 10 (1):52-67, DOI: 10.1007/s10040-001-0170-8.

Stankowski, S.J., 1972. Population Density as an Indirect Indicator of Urban and Suburban Land-Surface Modifications. U.S. Geological Survey Professional Paper 800-B:B219-B224.

Theil, H., 1950. A Rank-Invariant Method of Linear and Polynomial Regression Analysis. I. Nederlandse Akademie van Wetenschappen 53:386-392.

Thorne, C.R., 1990. Effects of Vegetation on Riverbank Erosion and Stability. *In*: Vegetation and Erosion: Processes and Environments, J.B. Thornes (Editor). Wiley and Sons, New York City, New York, pp. 125-144.

United Nations, Department of Economic and Social Affairs, Population Division, 2015. World Urbanization Prospects: The 2014 Revision (ST/ESA/SER.A/366). http://esa.un.org/unpd/wup/FinalReport/WUP2014-Report.pdf, *accessed* April 2015.

Vogel, R.M. and N.M. Fennessey, 1994. Flow-Duration Curves. I: New Interpretation and Confidence Intervals. Journal of Water Resources Planning and Management 120(4):485-504, DOI: 10.1061/(ASCE)0733-9496(1994) 120:4(485).

Vogel, R.M., C. Yaindl, and M. Walter, 2011. Nonstationarity: Flood Magnification and Recurrence Reduction Factors in the United States. Journal of the American Water Resources Association 47:464-474, DOI: 10.1111/j.1752-1688.2011.00541.x.

Walsh, C.J., A.H. Roy, J.W. Feminella, P.D. Cottingham, P.M. Groffman, and R.P. Morgan, 2005. The Urban Stream Syndrome: Current Knowledge and the Search for a Cure. Journal of the North American Benthological Society 24(3):706-723, DOI: 10.1899/04-028.1.

Washington State, 2012. Historical Data Set: Decennial Population Counts for the State, Counties, Cities and Towns. Office of Financial Management. http://www.ofm.wa.gov/pop/april1/hseries/default.asp, *accessed* April 2015.

Waters, T.F., 1995. Sediment in Streams — Sources, Biological Effects, and Control. American Fisheries Society Monograph 7. 251 pp.

Winter, T.C., J.W. Harvey, O.L. Franke, and W.M. Alley, 1998. Ground Water and Surface Water — A Single Resource. United States Geological Survey 1139:79.

Wolman, M.G. and J.P. Miller, 1960. Magnitude and Frequency of Forces in Geomorphic Processes. Journal of Geology 68:54-74.

Yue, S., P. Pilon, B. Phinney, and G. Cavadias, 2002. The Influence of Autocorrelation on the Ability to Detect Trend in Hydrological Series. Hydrological Processes 16:1807-1829, DOI: 10.1002/hyp.1095.