PROJECT TITLE:

PROBABILISTIC CHARACTERIZATION OF STREAMFLOWS IN URBANIZING BASINS

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EXECUTIVE SUMMARY

Given the critical role of the streamflow regime for instream, riparian, and floodplain ecosystem sustainability, modeling the long-term effect of urbanization on streamflow is important to predict possible changes in stream ecosystems. Since flow duration curves are largely used to characterize the streamflow regime and define indices for stream ecosystem health, a stochastic model is presented that links the key physical features of urbanizing basins with rainfall variability to determine the resulting flow duration curves. The model is tested against 11 basins with various degrees of urban development, characterized by the percentage of impervious areas in the basin. Results show that the model is able to reproduce accurately the entire flow duration curve. The analysis performed suggests that the transformation of green (i.e., water used in evapotranspiration) to blue (i.e., streamflow) water in urbanizing basins is an important long-term source of ecohydrological alteration.

1. INTRODUCTION

The implications of anthropogenic perturbations on streamflow regime have been studied in the context of both direct instream perturbations, e.g. dams and diversions [*Botter et al.*, 2010; *Poff et al.*, 2010; *Richter et al.*, 1996], and land-use change, urbanization in particular [*Hamel et al.*, 2013; *Poff et al.*, 2006]. There is growing evidence that the streamflow regime can be very relevant and useful for understanding the implications of urbanization on stream ecology and ecosystems [*Braud et al.*, 2013; *Hamel et al.*, 2013; *Hejazi and Moglen*, 2008; *Smakhtin*, 2001]. Although most of the focus of past research has been on the effect that high flows, enhanced by urbanization, have on stream ecology, low flows might also play an important role. Generally, the observation that instream invertebrate diversity and overall invertebrate abundance decrease with increasing urbanization [*Klein*, 1979; *Paul and Meyer*, 2001] is attributed to the increased frequency of higher flows in urbanizing basins [*Paul and Meyer*, 2001]. On the other hand, modification of low flows can have important impacts, as discussed by *Groffman et al.* [2003], who suggested that lowering water tables can lead to the presence of a greater proportion of upland tree as opposed to wetland species in the riparian zone. Additionally, in urbanizing basins, the streamflow regime can help characterize the interaction between streamflow and water quality [*Nilsson and Renofalt*, 2008; *Shields et al.*, 2008], where streamflow conditions can be associated with stream physicochemical states [*Shields et al.*, 2008]. This has important ecological and societal implications in terms of stream health and the availability of freshwater resources [*Falkenmark*, 2003].

The aim with this project is to employ flow duration curves (FDCs) to describe the streamflow regime of urbanizing basins. *Botter et al.* [2007] presented a stochastic model to derive the statistical properties of streamflow from basins composed by sub-basins with different physical and recession properties. In this study, this model is applied to urbanizing basins by differentiating the contribution to the streamflow from pervious and impervious areas. The model permits the derivation of FDCs as a function of parameters associated with rainfall frequency and depth, and coefficients for the recession from the two different areas of the basin [*Mejía et al.*, 2014]. The aim here is both theoretically and practically relevant. Theoretically, the model can help synthesize information at the basin-scale regarding the interaction between urbanization and hydrologic variability, and thus serve as a unifying framework for understanding change under various macroscopic conditions (climate, geomorphology, terrestrial vegetation, and urbanization). From a practical standpoint, the model permits the quantification of the perturbations induced by the urbanization process on the streamflow regime, and thereby allows a more direct connection between regime perturbation and environmental degradation.

2. METHODOLOGY

2.1 Model description

This methodology is based on the stochastic model described by *Mejía et al.* [2014]. Hereafter this model is referred to as M1. The model assumes that urban basins are comprised of pervious areas that allow effective recharge to groundwater and impervious areas that produce fast urban runoff. The effective recharge is used to account for the filtering effect of the soil moisture dynamics on rainfall, as well as the potential effect of urban sources on recharge. Ultimately, both, slow subsurface runoff, Q_P [L^3/T] (the subscript P denotes effective pervious conditions), and fast urban runoff, Q_I [L^3/T] (the subscript I denotes effective impervious conditions), generate daily streamflow at the outlet of the urban basin such that the total streamflow is $Q = Q_P + Q_I$.

The model assumes that daily rainfall is a marked Poisson process, with events occurring at a constant mean frequency, λ_R [T^{-1}]. Each event carries an amount of water Y [L] drawn from the same exponential probability density function (PDF), $h(y)$, with an average depth γ_R^{-1} [L]. However, other distributional forms can be considered [*Daly and Porporato*, 2010; *Verma et al.*, 2011]. Rainfall events generate effective rainfall only if the depth of the event, *Y*, is larger than d_i [L], whose value is different for pervious and impervious areas. The pervious threshold d_P is used to represent the net contribution of rainfall events to effective recharge, while the impervious threshold d_I indicates that small rainfall events may not contribute to the generation of urban runoff. Since we assume that the effective daily rainfall is equal to the daily rainfall minus the surpassed threshold, the effective rainfall is still a marked Poisson process. Accordingly, with $h(y)$ being exponential, the effective rainfall events occur at a frequency $\lambda_i = \lambda_R \exp(-d_i \gamma_R)$ [T^{-1}] [*Laio*, 2006; *Verma et al.*, 2011], where λ_P and λ_I denote the frequency of effective recharge and urban runoff events, respectively, and their depths remain exponentially distributed with parameter γ_R.

Using the effective rainfall, the following stochastic differential equation is used to represent the dynamics of the contribution to streamflow from both pervious and impervious areas

$$\frac{dQ_i}{dt} = -k_i Q_i + k_i l_i \xi_i(t). \tag{1}$$

Equation (1) says that the time evolution of streamflow follows a deterministic trajectory according to $k_i Q_i$ perturbed by jumps of random amplitudes given by $k_i l_i Y_i$. Thus, rainfall events with magnitude larger than d_i generate spikes of daily streamflow, which then decreases between effective recharge or runoff events at rates k_i [T^{-1}] dependent on basin properties. For the pervious contribution, $1/k_P$ takes the meaning of the mean response time of a linear groundwater reservoir [*Coutu et al.*, 2012a; b; *Hejazi and Moglen*, 2008; *McCuen and Snyder*, 1986]. In the case of the impervious contribution, the parameter k_I reflects the fast response time typical of conventional (connected) stormwater drainage [*Coutu et al.*, 2012a; b; *Hejazi and Moglen*, 2008; *McCuen and Snyder*, 1986]. The land use l_i [L^2] is equal to $(1-U)$ and U for the pervious and impervious contribution, respectively, where U is the fraction of imperviousn area in the basin. The frequency λ_P and λ_I of events occurrence of the marked Poisson processes ξ_P and ξ_I, respectively, are obtained using the threshold d_P and d_I for pervious and impervious areas, respectively.

Equation (1) does not seem to have an analytical solution [*Botter et al.*, 2007; *Mejía et al.*, 2014]. We use instead Monte Carlo simulation to obtain the underlying steady state PDF of the total streamflow Q, $p(Q)$. Using $p(Q)$, the flow duration curve (FDC), $P(Q)$, is given by

$$P(Q) = \int_Q^{\infty} p(x)dx. \tag{2}$$

$P(Q)$ is the exceedance probability associated with streamflow Q. Importantly, note that we use $P(Q)$ here to synthetically represent and quantify the flow regime. Although equation (1) cannot be solved analytically, the statistical moments do have exact solutions. The analytical expressions for the moments are summarized by *Mejía et al.* [2014].

2.2 Statistical moments

Equation (1) does allow exact solutions for the moments of Q. For instance, the mean of Q ($\langle Q \rangle$ [L^3/T]) is given by

$$\langle Q \rangle = \frac{\lambda_P}{\gamma_R} A(1-U) + \frac{\lambda_I}{\gamma_R} AU. \tag{3}$$

Based on the marginal distribution for Q_P and Q_I, equation (3) states that $\langle Q \rangle_1$ is equal to the sum of the mean pervious ($\langle Q_P \rangle_1 = \lambda_P \gamma_R^{-1} A(1-U)$) and impervious ($\langle Q_I \rangle_1 = \lambda_I \gamma_R^{-1} AU$) contributions. Figure 1a illustrates the behavior of equation (3) as a function of the impervious fraction U, which is used to represent changes across an urbanization (human population) gradient. Figure 1a shows that $\langle Q_P \rangle_1 \propto (1-U)$ and $\langle Q_I \rangle_1 \propto U$. Thus, $\langle Q_P \rangle_1$ decreases with increasing loss of storage capacity as implied by $1-U$. Relevantly, it has been suggested that the loss of storage capacity is the primary cause behind the various manifestations of hydrological alteration in urbanizing basins [*Konrad and Booth*, 2005].

The variance of Q ($\mathrm{var}_1(Q)$ [(L^3/T)^2]) is given by

$$\mathrm{var}_1(Q) = \frac{\lambda_P k_P (1-U)^2 A^2}{\gamma_R^2} + \frac{\lambda_I k_I A^2 U^2}{\gamma_R^2} + \frac{2\lambda_P k_I k_P A^2 U(1-U)}{\gamma_R^2} \left[\frac{\gamma_R d_P + 2}{k_I + k_P} \right], \tag{4}$$

where the first term represents the pervious contribution ($\mathrm{var}_1(Q_P)$ [(L^3/T)^2]), the second term the impervious contribution ($\mathrm{var}_1(Q_I)$ [(L^3/T)^2]), and the third term reflects the interaction between the pervious and impervious contributions. Figure 1b illustrates the behavior of (7) using different values of k_I. In this figure, when $k_I \gg k_P$, the variance is dominated by $\mathrm{var}_1(Q_I)$ and as the difference between k_I and k_P diminishes, the dominance of $\mathrm{var}_1(Q_I)$ reduces. Overall, Figure 1b indicates that for growing levels of urbanization, streamflow variability increases due to the variability induced by impervious areas while the pervious contribution tends to become more uniform or less variable. In Figure 1b, the trend of increasing variability with increasing U corresponds qualitatively with the flashiness condition characteristic of many urbanizing basins (see, e.g., *Baker et al.* [2004]).

We also determine the skewness of Q ($s_1(Q)$), which is often used as an indicator of hydrologic alteration when characterizing stream ecological conditions [*Olden and Poff*, 2003]; $s_1(Q)$ is given by

$$s_1(Q) = \frac{\langle Q - \langle Q \rangle \rangle_1^3}{\mathrm{var}_1(Q)^{3/2}}, \tag{5}$$

where the third central moment of Q ($\langle Q - \langle Q \rangle \rangle_1^3$ [(L/T)^3]) can be determined from equation (1) to yield:

$$\langle Q - \langle Q \rangle \rangle_1^3 = \frac{2\lambda_P k_P^2 A^3 (1-U)^3}{\gamma_R^3} + \frac{2\lambda_I k_I^2 A^3 U^3}{\gamma_R^3} + \frac{3\lambda_P k_I k_P A^3 U (1-U)}{\gamma_R^3} \left[\frac{2k_P (1-U)(3 + d_P \gamma_R)}{(k_I + 2k_P)} + \frac{k_I U (6 + 4 d_P \gamma_R + d_P^2 \gamma_R^2)}{(2k_I + k_P)} \right]. \tag{6}$$

The first and second terms in equation (6) are the pervious and impervious contributions, respectively. The two other terms in equation (6) arise from the interaction between the pervious and impervious contributions. The ratio of the first term in equation (6) and $\mathrm{var}_1(Q)^{3/2}$ is treated as the pervious contribution to the skewness ($s_1(Q_P)$). Likewise, the impervious contribution ($s_1(Q_I)$) is defined as the ratio of the second term in equation (6) and $\mathrm{var}_1(Q)^{3/2}$. This way of separating the skewness does not account for the individual effects of $\mathrm{var}_1(Q_I)$ and $\mathrm{var}_1(Q_P)$ on $s_1(Q)$, but it allows comparison of the relative contribution of the different terms in $\langle Q - \langle Q \rangle \rangle_1^3$ on the basis of $\mathrm{var}_1(Q)^{3/2}$. Figure 1c illustrates $s_1(Q)$ as a function of U using different values of k_I. From Figure 1c, when $k_I \gg k_P$, $s_1(Q)$ is controlled by the impervious contribution and as the difference between k_I and k_P diminishes the pervious contribution becomes more relevant. There is also in Figure 1c a tendency for $s_1(Q)$ to remain relatively constant across values of U.

A more complete derivation of equations (3), (4), and (6), can be found in *Mejia et al.* [2014].

3. CASE STUDY

To study the ability of M1 to represent streamflow dynamics in urbanizing basins, we use data from 11 basins situated in the metropolitan areas of the cities of Baltimore and Washington DC. Table 1 summarizes the main characteristics of the selected basins. An advantage of working with this region is that data is available to describe the annual time evolution of the urbanization process. This allows us to match specific time periods in the streamflow record to a given level of urbanization, and to identify time periods where urban growth is relatively mild. The land-use dataset is described in *Beighley and Moglen* [2003].

The selected basins have drainage areas that range from 5.5 to 98.4 km^2, and the fraction of basin impervious area ranges from 5.2 to 36.05% of the total drainage area (Table 1). The pervious land in the basins is predominantly agricultural and urban grassed areas, with riparian corridors being typically forested. The impervious areas are predominantly residential and roads with some commercial areas. Although rainfall tends to be distributed relatively uniformly throughout the year, we employ M1 at the seasonal level because streamflow, and baseflow in particular, tends to exhibit a seasonal dependency [*Moody*, 1986; *Rutledge and Mesko*, 1996].

To illustrate the application of M1, we chose the spring (wet) season (from the beginning of February to the end of April).

The streamflow data was obtained from the US Geological Survey and the rainfall data from NOAA's National Climatic Data Center. The gage numbers are summarized in Table 1. For the wet season, the basins have a mean daily rainfall of 0.885 cm and a mean rainfall frequency of 0.338 days^{-1} (Table 1). The period of analysis for each basin is included in Table 1.

4. RESULTS

This section is divided into two parts. First, M1 is compared against the observed streamflow to assess its performance. Second, the behavior of the moments of the streamflow Q is examined across an urbanization gradient.

4.1 Comparison between M1 and the observed streamflow

Since we are interested in the statistical properties of streamflow, we use FDCs to compare M1 against the observed streamflow [*Smakhtin*, 2001; *Vogel and Fennessey*, 1994]. We thus generated streamflow series via Monte Carlo simulations with M1 and then estimated the empirical FDCs. The application of M1 requires the value of eight parameters (A, U, γ_R, λ_R, λ_I, λ_P, k_I and k_P), most of which can be determined directly from the available datasets. The parameters γ_R and λ_R (Table 1) were obtained from the daily rainfall data in the wet season; λ_I was set equal to λ_R, and λ_P was estimated using equation (3) and the mean observed streamflow. The values of λ_P used are reported in Table 2. The recession parameters, k_I and k_P, are difficult to estimate from the available data. The very few studies that have investigated the effect of anthropogenic perturbations on streamflow recessions indicate that common approaches to recession analysis can misrepresent recessions in human dominated basins [*Wang and Cai*, 2010]. Thus, we tuned up the values of both k_I and k_P to improve the fit between the modeled and observed FDCs using nonlinear optimization [*Byrd et al.*, 1999]. For the optimizations, we used the sum of the absolute distance, in log scale, between the modeled and observed FDC as the objective function (OF). The optimized values for k_I and k_P are reported in Table 2.

Following the parameter estimation approach just described, we determined the FDCs for all the basins in this study. Figures 2a-c compare the modeled and observed FDC for three of the selected basins. From visual inspection, Figures 2a-c show good agreement between M1 and the observed streamflow. We also used the following index of performance to quantify the performance of the FDCs [*Claps et al.*, 2005]:

$$r = 1 - \frac{D^2}{\mathrm{var}(Q)}, \tag{7}$$

where D^2 [(L^3/T)^2] is the mean squared distance between the observed and modeled FDC and $\mathrm{var}(Q)$ [(L^3/T)^2] is the variance of the observed streamflow. A value of $r = 1$ indicates a perfect fit. Table 2 summarizes the values of r and OF. We employ the index in equation (7) because it can be interpreted more easily than OF. The values of r in Table 2 indicate a good performance for all the modeled FDCs. The average r value is 0.96 and the range is from 0.89 to 0.99. Further, we show in Figures 2d-f quantile-to-quantile plots (q-q plots) for the same three basins in Figures 2a-c. The q-q plots confirm that the fits between modeled and observed FDCs are reasonable.

Thus, M1 is able to reproduce the FDCs for streamflow during the wet season in the urbanizing basins of this study. The parameters in M1 can be determined from readily available datasets, with the exception of the two recession parameters that need to be calibrated.

4.2 Moments of the streamflow Q along an urbanization gradient

The behavior of the streamflow moments (i.e. mean, variance, and skewness) along an urbanization gradient is analyzed using M1. The gradient is defined based on the basins used in this study. Figure 3a illustrates the mean streamflow as a function of U. In Figure 3a, $\langle Q_P \rangle_1$ tends to decrease and $\langle Q_I \rangle_1$ to increase with increasing U, while $\langle Q \rangle_1$ exhibits greater variability and a slight tendency to increase across values of U. These trends are further illustrated in Figure 3a (solid lines) using equation (3). The parameters for equation (3) were determined from the average of the parameter values for all the basins in this study. The behavior of $\langle Q_P \rangle_1$ and $\langle Q_I \rangle_1$ in Figure 3a suggests that pervious areas can play a significant role in the long-term behavior of urbanizing basins. To illustrate this point further, we make use of the dimensionless variable

$$\langle \bar{Q} \rangle_1 = \frac{\gamma_R}{\lambda_R A} \langle Q \rangle_1 \ . \tag{8}$$

Using equations (3) and (8) and recalling that we assumed $\lambda_I = \lambda_R$, the sensitivity of $\langle \bar{Q} \rangle_1$ to an instantaneous change in impervious cover is given by

$$\frac{d \langle \bar{Q} \rangle_1}{dU} = 1 - \phi \ , \tag{9}$$

where $\phi = \lambda_P / \lambda_R$ approximately represents the fraction of water not used by vegetation (i.e. blue water) and $1-\phi$ is the fraction used by vegetation (i.e. green water). Hence, the effect of the perturbations induced by U on the streamflow depends on the green water and thereby on the terrestrial vegetation cover in the basin. Interestingly, this also suggests that the perturbations are dependent on the definition of an appropriate baseline condition prior to urbanization.

The results for $\mathrm{var}_1(Q)$ are illustrated in Figure 3b. Figure 3b, which shows a pattern similar to the one implied by equation (4) (solid lines in Figure 3b), indicates that $\mathrm{var}_1(Q_I)$ increases rapidly with U and tends to dominate the value of $\mathrm{var}_1(Q)$, while $\mathrm{var}_1(Q_P)$ decreases with U and contributes little to $\mathrm{var}_1(Q)$. These results support the utility of $\mathrm{var}_1(Q)$ as an indicator of the influence of U on streamflows. Additionally, $\mathrm{var}_1(Q)$ helps identify other factors that control the flashiness of urban streams. For example, the term $\mathrm{var}_1(Q_I)$ in equation (4) indicates that streamflows become more flashy when k_I increases (i.e. the response time of urban areas decreases), the frequency of impervious events (λ_I) increases, and/or the mean rainfall increases.

In Figure 3c, the results for $s_1(Q)$ are also similar to the theoretical results from M1 and in this case to the results implied by equations (5) and (6). Figure 1c indicates that $s_1(Q)$ is controlled by $s_1(Q_I)$ across values of U and that $s_1(Q)$ reaches an approximately constant value after a relatively low level of urbanization. In this regard, $s_1(Q)$ is less effective than $\text{var}_1(Q)$ in quantifying broad changes along an urbanization gradient. $s_1(Q)$ may be most useful for quantifying impacts to sensitive taxa that are strongly affected by low levels of urbanization.

5. CONCLUSIONS

On the basis of the analysis performed, the following conclusions are emphasized:

- The proposed modeling approach is able to capture some of the most common hydrological perturbations associated with increasing urbanization. Ultimately, the modeling approach indicates that the urbanization process can have an influential effect on FDCs, with relevant consequences for stream health.

- The transformation of green to blue water induced by the urbanization process is an important characteristic of the long-term hydrological behavior of urbanizing basins.

- We found a consistent link between the statistical properties characterizing the streamflow regime (i.e. mean, variance, and skewness) and the degree of urban development. This may be useful when assessing the dynamic impacts of urbanization as it takes place in time.

6. ADDITIONAL RESEARCH INDICATED

Further research is necessary to apply the proposed modeling framework to urban basins in Pennsylvania under climate change scenarios. There is little data readily available that reconstructs the urban growth history of basins in Pennsylvania. This severely limits the application of the proposed model. It is recommended that this reconstruction work should be carried out in the future, otherwise long-term studies of the interaction between urbanization and basin hydrology in Pennsylvania will be hampered.

Table 1. Summary of data and parameter values.

Streamflow gage	Rainfall gage	Basin name	Period of analysis	A [km^2]	$\langle Q \rangle / A$ [cm/day]	α_R [cm]	λ_R [1/day]	U [%]
01589100	18-0465	East Branch Herbert Run	1974-1984	6.4	0.159	0.829	0.340	35.75
01589330	18-0470	Dead Run	1964-1974	14.3	0.159	0.909	0.316	30.00
01581700	18-0732	Winters Run	1980-1995	90.1	0.181	0.88	0.352	5.20
01585300	18-8877	Stemmers Run	1977-1989	11.6	0.190	0.898	0.362	30.00
01645200	18-7705	Watts Branch	1968-1979	9.6	0.145	0.841	0.317	25.05
01653500	18-9070	Henson Creek	1955-1966	43.3	0.170	0.917	0.305	28.00
01589300	18-0470	Gwynns Falls	1973-1986	84.2	0.166	0.909	0.316	20.35
01650500	18-7705	Northwest Branch Anacostia River	1972-1982	54.6	0.155	0.841	0.317	8.75
01593500	18-1862	Little Patuxent River	1987-1997	98.4	0.163	0.843	0.347	21.40
01585100	18-8877	Whitemarsh Run	1988-2000	19.7	0.212	0.898	0.362	34.10
01585200	18-0470	West Branch Herring Run	1970-1986	5.5	0.150	0.909	0.316	36.05

Table 2. Summary of additional parameter values, objective function, and index of model performance for M1 and M2.

Streamflow gage	λ_P [1/day]	k_I [1/day]	k_P [1/day]	OF (M1) [log(cm/day)]	r (M1)
01589100	0.106	3.041	0.012	5.65	0.96
01589330	0.109	8.628	0.060	18.02	0.89
01581700	0.216	9.982	0.045	11.54	0.98
01585300	0.167	9.920	0.085	22.90	0.93
01645200	0.132	5.110	0.019	5.46	0.98
01653500	0.129	1.657	0.019	2.10	0.97
01589300	0.140	5.613	0.026	7.65	0.98
01650500	0.173	9.931	0.055	17.53	0.97
01593500	0.170	5.396	0.022	4.18	0.99
01585100	0.154	5.972	0.056	15.20	0.91
01585200	0.099	1.366	0.012	7.52	0.98

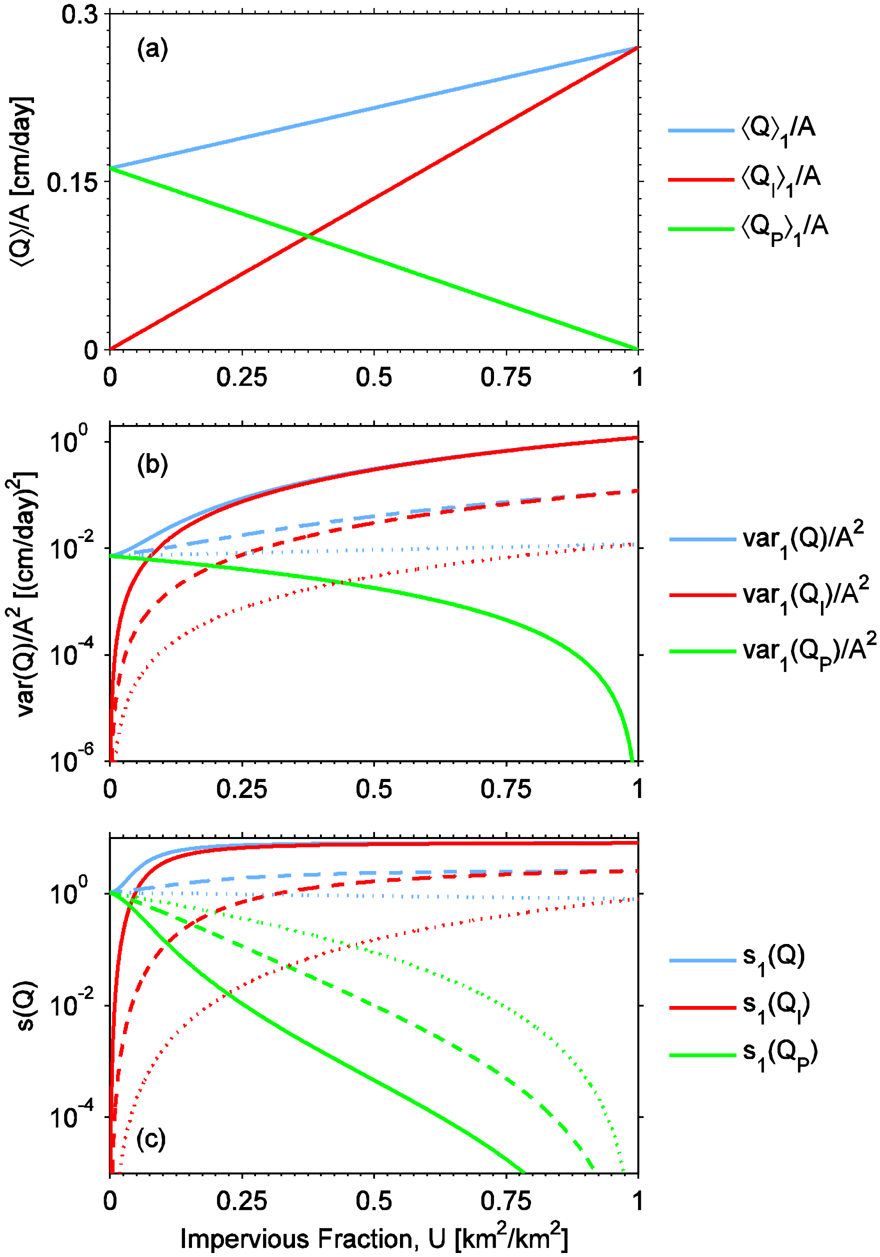

Figure 1. (a) Mean, (b) variance, and (c) skewness for M1 as a function of the imperious fraction in the basin. The solid lines correspond to $k_P / k_I = 0.01$, the dashed lines to $k_P / k_I = 0.1$, and the dotted lines to $k_P / k_I = 1$, where k_P is kept constant at 0.05 days^{-1}. The mean does not depend on k_I or k_P, hence only solid lines are shown in (a). $\mathrm{var}(Q_P)$ in (b) depends only on k_P while $s(Q_P)$ in (c) depends on both k_I and k_P. For the remaining parameters, the following values were used: $\lambda_P = 0.18$ days^{-1}, $\lambda_I = 0.3$ days^{-1}, and $\alpha_R = 0.9$ cm.

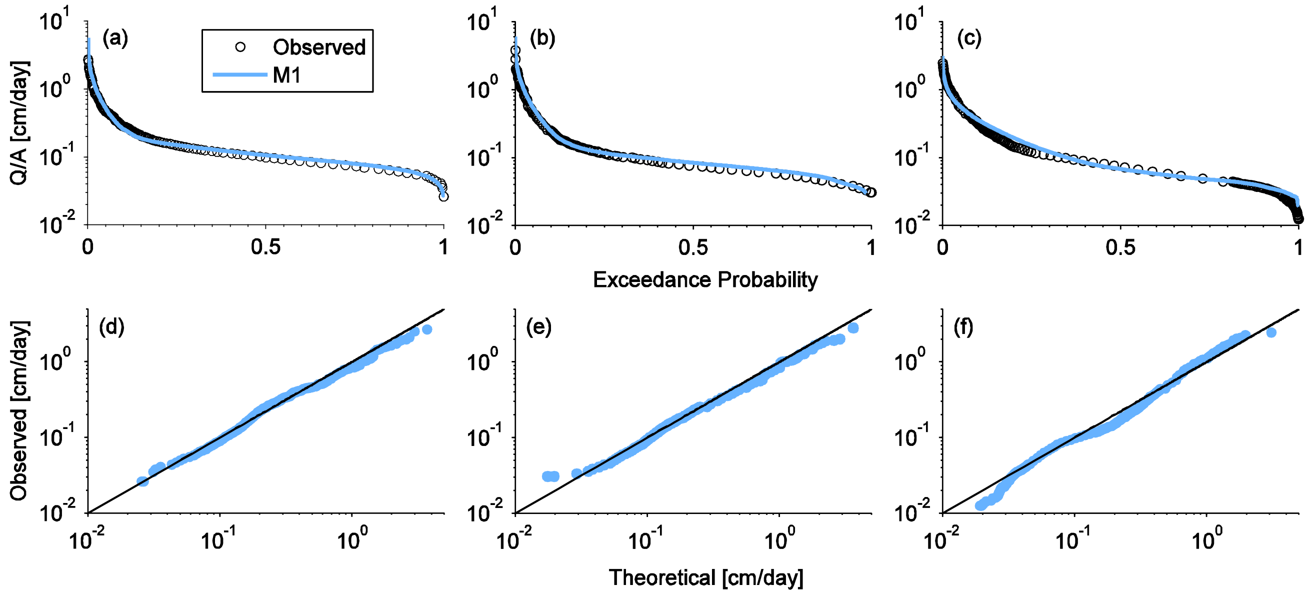

Figure 2. Comparison between the FDC for M1 and the observed streamflow at (a) Gwynns Falls (USGS streamflow gage 01589300), (b) Watts Branch (USGS streamflow gage 01645200), and (c) West Branch Herring Run (USGS streamflow gage 01585200). Quantile-to-quantile plots for M1 at (d) Gwynns Falls, (e) Watts Branch, and (f) West Branch Herring Run. The comparisons are for the wet season (from February to April).

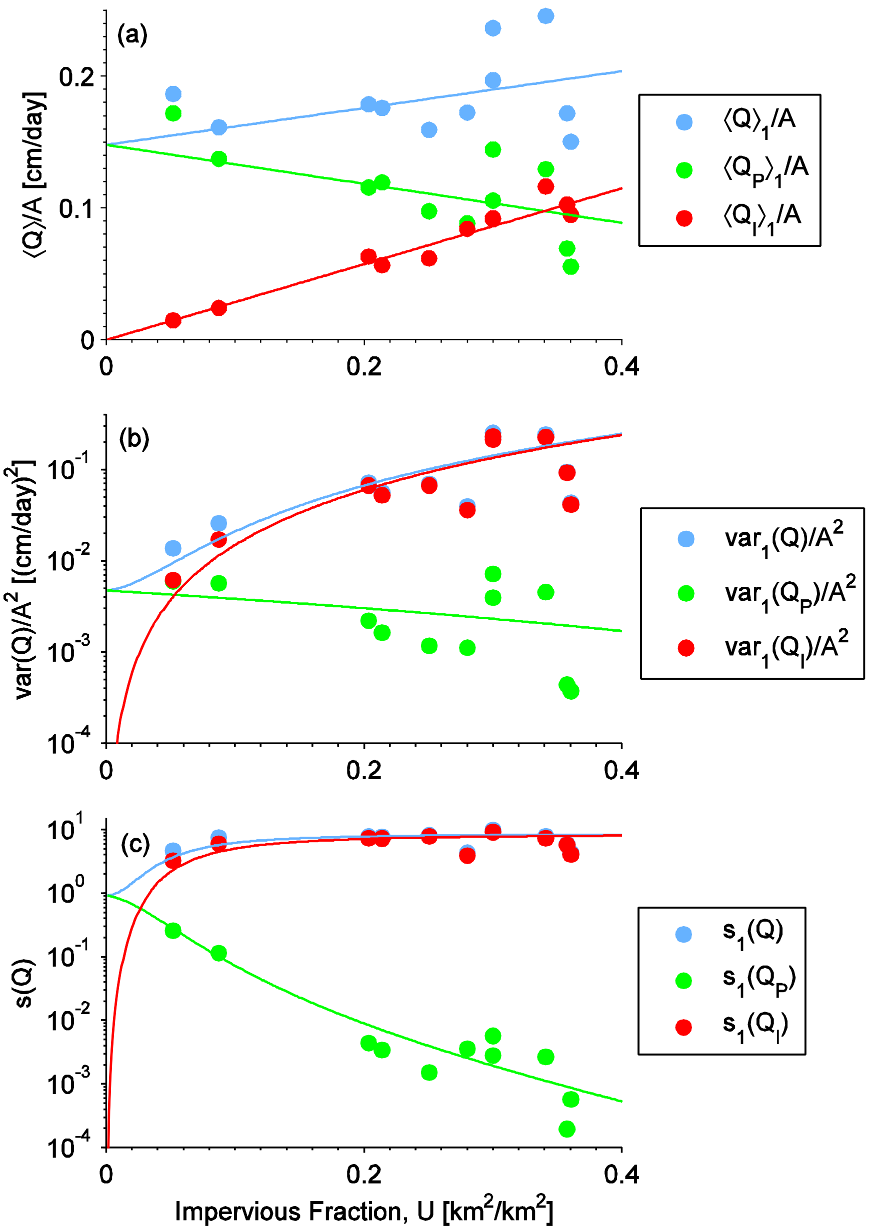

Figure 3. (a) Mean, (b) variance, and (c) skewness for the urbanizing basins in this study using M1 (wet season). The moments are shown as a function of the impervious fraction in the basin to illustrate changes across an urbanization gradient. The solid lines are the analytical moments for M1 (blue), and their associated pervious (green) and impervious (red) contributions, using average parameters values. The average parameters were determined from the parameter values for the 11 basins used in this study.

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Appendix A
Staff: 1 full-time employee was involved.
Students supported: 2 graduate students were partially supported.
Outreach/Extension: Results led directly and indirectly to 2 journal publications and 2 conference presentations.

Appendix B. Impact Statement
TITLE: Probabilistic characterization of streamflow in urbanizing basins
RECAP: A stochastic model of streamflow for urban basins that is directly dependent on climate was proposed and tested.
RELEVANCE: Flow regime alteration due to urbanization is a powerful source of stream degradation that can result in impaired water quality. Quantifying the link between urbanization and flow regime alteration can be used to assess and manage urban watersheds.
RESPONSE: Two graduate students at Penn State worked in developing and testing the model in the summer of 2013 and 2014. The model performance is quite satisfactory. The model could be used to study how the temporal evolution of urbanization drives flow regimes. The novelty and advantage of the model is its ability to link hydrology, climate, urbanization, and stormwater management conditions within a testable framework, applicable to a wide range of conditions.
RESULTS: The proposed modeling approach is able to capture common hydrological perturbations associated with increasing urbanization. Additionally, we found a consistent link between the statistical properties characterizing the streamflow regime (i.e. mean, variance, and skewness) and the degree of urban development. This may be useful when assessing the dynamic impacts of urbanization as it takes place in time.