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Anthropogenic controls from urban growth on flow regimes

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ABSTRACT

Streamflow can be drastically perturbed in urban basins with important implications for stream, floodplain, and riparian ecosystems. Normally, the dynamic influence of urbanization on streamflow is studied via space-for-time substitution. Here we explicitly consider urban growth when determining the flow regime of 14 urban basins. To synthetically represent the flow regime, we employ flow duration curves (FDCs) determined using a stochastic model. The model permits derivation of FDCs that are dependent on few parameters representing climatic, land use, conventional stormwater management, and geomorphological conditions in an urban basin. We use the model, under conditions of urban growth, to assess the influence of urbanization on key model parameters and to determine different indicators of hydrologic alteration. Overall, results indicate consistent changes in the temporal evolution of the perturbed flow regimes, which in this case can largely be explained by the progressive redistribution with urban growth of water from slow subsurface runoff and evapotranspiration to fast urban runoff.

1. Introduction

Environmental flow science deals with the sustainable use of streamflow for meeting both human well-being and ecosystem services [3,53,56]. A keystone of this science is the critical role played by the flow regime as a driver of the diversity and vitality of riverine, riparian, and floodplain ecosystems [41,53,56,57]. In practice, the flow regime is often characterized using indicators of hydrologic alteration or measures of hydrologic perturbation relevant to stream ecology [2,3,33,54]. The utility of the flow regime and hydrologic indicators is widely acknowledged and documented for some streamflow perturbations more than others. For example, perturbations associated with in-stream damming have been widely studied [25,41,42,48,60], while perturbations from urban growth at the basin-scale have been less analyzed [37,52,74], even though there are clear indications that these perturbations can have a strong influence on the flow regime and stream ecological conditions [7,34,37,38,46,66,75].

It is common for studies that quantify the effect of urbanization on abiotic and biotic stream conditions to rely on space-for-time substitution or physical gradients [7,13,21,34,52,76]. For urban basins, space-for-time substitution usually consists of measuring or modeling a hydrologic variable relevant to stream ecology across basins with different levels of urban land-use intensity (i.e., across an urban gradient) [15,52], as well as within time periods where urban growth can be assumed relatively constant. The urban gradient is then used to imply the possible time evolution of the variable [13]. This approach can help overcome challenges related to the lack of temporal urban growth data and, indirectly, nonstationarity. However, there are limitations to the space-for-time substitution approach as discussed, in the context of urban studies, by Carter et al. [15]. In particular, it can obscure the causative link between urban growth and streamflow perturbations.

When quantifying the influence of urbanization on streamflow, the emphasis has been on high flows or flood conditions [6,49,62,70] or, to a relatively lesser extent, low flows or baseflow conditions [27,34,61,63]. In contrast, we emphasize in this study the entire temporal range of streamflow conditions by utilizing the flow regime. Nonetheless, relying on the flow regime alone does not allow explicit consideration of the key drivers, e.g., climatic forcing and land use conditions, of the streamflow dynamics [9,10,58]. To circumvent this, we employ here a previously developed stochastic model of streamflow for urban basins whose parameters account for climatic, urban land use, conventional stormwater management, and geomorphologic conditions [44].

Our main goal with this study is to use the flow regime and related indicators of hydrologic alteration, determined using a stochastic model, as tools to investigate and characterize the perturbations induced by urban growth on streamflow at the basin-scale. In contrast with many of the previous studies, we account here explicitly for urban growth when determining the flow regime of an urban basin.

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2. Methodology

This section is divided into three subsections. First, we describe the stochastic model. Second, we explain the model implementation and how it accounts for urban growth. Third, we define several indicators of hydrologic alteration.

2.1. Modeling approach

To determine the flow regime, we use a stochastic model of daily streamflow for urban basins. The model was initially proposed by Botter et al. [10] for heterogeneous natural basins and adapted by Mejía et al. [44] to account for urban conditions. The model assumes that urban basins are comprised of effective pervious areas that allow effective recharge to groundwater, and effective impervious areas that produce fast urban runoff. The effective recharge is used to account for the filtering effect of the soil moisture dynamics and urban sources on rainfall. The effective imperviousness accounts for the fact that not all the impervious areas may contribute to fast urban runoff. 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 [20,69]. Rainfall events generate effective rainfall only if the depth of the event, Y, is larger than a threshold d_i [L], whose value is different for pervious and impervious areas. Hereafter, the subscript i can be equal to P or I to denote effective pervious or impervious conditions, respectively. The pervious threshold, $d_i = d_P$, is used to represent the net contribution of rainfall events to effective recharge, while the impervious threshold, $d_i = d_I$, indicates that small rainfall events may not contribute to the generation of urban runoff. Since the effective daily rainfall is simply equal to the daily rainfall minus the surpassed threshold, it remains 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}] [39,69], where $\lambda_i = \lambda_P$ and $\lambda_i = \lambda_I$ 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 contributions to streamflow from both pervious and impervious areas

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

Eq. (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 $k_i l_i \xi_i$ ($\xi_i = Y_i$), where i can be P (pervious) or I (impervious). Thus, rainfall events with magnitude larger than d_i generate spikes of daily streamflow that then decrease between effective recharge or runoff events at rates k_i [T^{-1}] that depend on basin properties. For the pervious contribution, k_P^{-1} takes the meaning of the mean response time of a linear groundwater reservoir [18,19,29,43]. In the case of the impervious contribution, the parameter k_I^{-1} reflects the fast response time typical of conventional (connected) stormwater drainage [18,19,29,43]. 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. The land use area l_i [L^2] is equal to $A(1-U^*)$ and $AU*$ for the pervious and impervious contribution, respectively, where A [L^2] is the drainage area and $U*$ is the fraction of effective imperviousness.

The use of the fraction of effective imperviousness U^*, as opposed to the fraction of total imperviousness U, is an added implementation with respect to the model employed by Mejía et al. [44]. We use U^* here to represent the ability of an urban basin to generate fast runoff. It accounts for the fact that not all the impervious areas in an urban basin may be directly connected to the stormwater drainage network, i.e. some impervious areas may drain to pervious areas. This is typically the case with urban stormwater runoff [1,8,40,64].

Further, analytical expressions for the statistical moments of the streamflow pdf can be obtained from Eq. (1). For instance, the mean, $\langle Q \rangle$ [L^3/T], and variance of the streamflow, var(Q) [$(L^3/T)^2$], can be expressed as [10,44]

$$\langle Q \rangle = \langle Q_P \rangle + \langle Q_I \rangle = \frac{\lambda_P}{\gamma_R} A(1-U^*) + \frac{\lambda_I}{\gamma_R} AU^* \quad (2)$$

and

$$\mathrm{var}(Q) = \frac{\lambda_P k_P [(1-U^*)A]^2}{\gamma_R^2} + \frac{\lambda_I k_I (AU^*)^2}{\gamma_R^2} + \frac{2\lambda_P k_I k_P A^2 U^* (1-U^*)}{\gamma_R^2}\left[\frac{\gamma_R d_P + 2}{k_I + k_P}\right], \quad (3)$$

respectively, where $\langle Q_P \rangle$ and $\langle Q_I \rangle$ is the mean pervious and impervious contribution, respectively, to streamflow. All the parameters in Eqs. (2) and (3) were already defined. Eq. (1) does not seem to have an analytical solution for the underlying steady state pdf of the total streamflow Q, $p(Q)$ [10,44]. We use instead Monte Carlo simulation to obtain $p(Q)$. Using $p(Q)$, the flow duration curve (FDC) [71], $P(Q)$, is given by

$$P(Q) = \int_Q^\infty p(x)dx. \quad (4)$$

$P(Q)$ is the exceedance probability associated with streamflow Q. We use $P(Q)$ here to represent the flow regime.

Fig. 1 illustrates the modeling approach. First, a rainfall series is modeled as a marked Poisson process (top horizontal axis in Fig. 1a). This series is then transformed into a streamflow series at the outlet of the urban basin according to Eq. (1) (bottom horizontal axis in Fig. 1a), such that the total streamflow is $Q = Q_P + Q_I$ (i.e., the addition of the green and red curves in Fig. 1a). Note in Fig. 1a that rainfall produces instantaneous jumps on the streamflow series when the threshold levels d_P and d_I are surpassed by the rainfall depth and after the jumps occur the pervious and impervious streamflow each decays exponentially at different rates. Fig. 1b and c shows the streamflow pdf and FDC, respectively, obtained from the modeled streamflow series.

2.2. Model implementation

To explicitly account for the influence of urban growth, as well as hydroclimatic variations, on the FDCs, we divide the entire period of analysis of an urban basin into consecutive, non-overlapping time intervals or windows of equal duration. Within each time interval, we apply the stochastic model to simulate streamflow by treating urbanization as being constant. We use for the size of the time interval a multi-year timescale. This is discussed further in the next section. The application of the model at the multi-year timescale, as opposed to seasonal which was the timescale previously used for this model [44], is supported by previous results for regions with weak to moderate rainfall seasonality [11]. Hydroclimatic variations are incorporated into the proposed framework by allowing the rainfall parameters (i.e., λ_R and γ_R^{-1}) to vary within each time interval [9,55].

The model requires the estimation of eight parameters (A, λ_R, γ_R^{-1}, k_P, k_I, λ_P, λ_I, and U^*), which can be obtained a-priori with the exception of k_P, k_I, and U^*. We obtain the parameters A, λ_R, and γ_R^{-1}, from