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Research Paper

Disentangling the effects of climate and urban growth on streamflow for sustainable urban development: A stochastic approach to flow regime attribution

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ABSTRACT

In urban watersheds, climate variability and change, urban growth, and stormwater management can act concurrently over time to shape and alter the streamflow dynamics. Yet, when assessing the impacts of urbanization on streamflow, these factors are rarely taken simultaneously into consideration. There is thus an emerging need for approaches that allow disentangling the hydrological impacts of land cover change from those due to climate, in the context of long-term, historical changes in urban landscapes. This is here termed flow regime attribution. We demonstrate in this study the ability of a stochastic mechanistic model to perform flow regime attribution. The modeling approach is applied to the Watts Branch watershed, located in metropolitan Washington D.C., United States. To carry out the flow regime attribution, the model is used to compute streamflow indicators of hydrological alteration and perform parameter sensitivity analysis. The application of the model shows that in Watts Branch urban growth drives the long-term temporal trend in streamflow. The mean and variance of streamflow increase at the end of the gauging period by 2 and 7 times, respectively, their value relative to an only climate (no urban growth) scenario. The results show that climate mainly amplifies or dampens the temporal trend according to wet/dry variations in annual rainfall. Further, the model facilitates the attribution process by allowing the derivation of streamflow indicators that directly depend on the model parameters. The proposed modeling approach may be useful for assessing the long-term flow behavior of urban watersheds, and informing sustainable urban development decisions.

1. Introduction

Urban sprawl has resulted in major environmental (Geneletti, La Rosa, Spyra, & Cortinovis, 2017; Johnson, 2001; Su, Gu, Yang, Chen, & Zhen, 2010; Vimal, Geniaux, Pluvinet, Napoleone, & Lepart, 2012; Wilson & Chakraborty, 2013) and human health (Frumkin, 2002) problems. It has brought substantial negative impacts to streams, floodplains, and riparian areas in urban watersheds (Martin-Mikle, de Beurs, Julian, & Mayer, 2015; Miltner, White, & Yoder, 2004; Sharley, Sharp, Marshall, Jeppe, & Pettigrove, 2017; Wu, Bolte, Hulse, & Johnson, 2015a; Wu, Stewart, Thompson, Kolka, and Franz, 2015b). The terms urban watershed and urbanization are used to indicate contemporary suburbanization, i.e., landscapes that have experienced significant urban growth after World War II. In addressing the negative impacts of urban sprawl on hydrological conditions, an emerging challenge is that of distinguishing the impacts associated with urbanization from those due to climate variability and change in a particular watershed and time period (Bindoff et al., 2013; Gallo, Moore, & Wywrot, 2012; Pyke et al., 2011). This is here termed flow regime attribution (Bindoff et al., 2013; National Academies of Sciences, 2016). Separating the impacts of urbanization and climate on streamflow is crucial to inform urban stormwater planning and management decisions about the relative dominance of these two fundamental drivers of hydrological change. Misidentifying their relative dominance could result in stormwater management policy that are, over the long term, ineffective. For example, this could be the case in places where climate is a strong driver of hydrological change but policy may be geared towards mitigating landscape modifications alone.

It is well recognized that urbanization can have a dramatic impact on hydrological conditions (Leopold, 1968); less known is how urbanization interacts with climate variability and stormwater management conditions over time to shape and alter the flow regime. One reason for

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the latter is that impacts are typically studied within the context of recent or current landscape conditions. Indeed, a common approach is to rely on space-for-time substitution (Brown et al., 2009; Carter et al., 2009; Wu et al., 2015b), which consists of using several watersheds with varying levels of urban development, under current conditions, to represent a gradient of urban impacts. Space-for-time substitution necessarily makes assumptions about the temporal trends of urban landscape change (Carter et al., 2009). To avoid making such assumptions (e.g., that historical landscape trends can be captured by current landscape conditions), long-term temporal data and approaches must be used to determine the flow regime.

The flow regime is chosen as the target for attribution as it is a key driver of both abiotic and biotic stream conditions (Poff & Zimmerman, 2010; Postel & Richter, 2003). The flow regime paradigm is normally implemented through the use of streamflow indicators (Poff et al., 2010; Wu et al., 2015a). This can be particularly challenging in urban watersheds for two reasons. First, streamflow dynamics in urban watersheds are inherently nonstationary (Jovanovic, García, Gall, & Mejía, 2016a; Jovanovic, Mejía, Gall, and Gironás, 2016b) because, among other reasons, as watersheds urbanize over time runoff production typically increases. Second, climate variability and change can conflate the impacts of urbanization on streamflow. The latter can be accentuated by a reduction in the filtering capacity of the soil and subsurface watershed components, specifically through directly connected impervious areas (Roy & Shuster, 2009; Shuster, Pappas, & Zhang, 2008). Thus, long-term modeling of urban flow regimes must be able to handle nonstationarity.

It is also highly desirable that such models rely on readily available, long-term data. Long-term hydrometeorological and land cover data are most often available at the daily timescale (Mejía, Rossel, Gironás, & Jovanovic, 2015; Yang & Li, 2011). At the daily timescale the effects on hydrological conditions of urban stormwater features (e.g., stormwater sewer pipes and stormwater control measures such as detention ponds) are not explicitly resolved. The emphasis at this timescale is on the urban water budget and runoff volumes. This limits our ability to configure and verify highly resolved, spatially distributed hydrological models, suggesting the need for macroscopic models (e.g., spatially lumped or semi-distributed) that can capture the essential mechanistic features of urban watersheds (Wu et al., 2015a; Yang & Li, 2011). Further, decision making at the watershed level is often concerned with the overall trends and patterns that emerge over time (Yang & Li, 2011), where a macroscopic approach is suitable.

One approach to the macroscopic modeling of flow regimes is through stochastic mechanistic models (SMMs) (Basso, Schirmer, & Botter, 2015; Botter, Porporato, Daly, Rodriguez-Iturbe, & Rinaldo, 2007a; Botter, Porporato, Rodriguez-Iturbe, & Rinaldo, 2007b; Botter, Porporato, Rodriguez-Iturbe, & Rinaldo, 2009; Ceola et al., 2010). This class of parsimonious streamflow models have been used to study the dynamic interactions between streamflow and various factors, including climate variability (Botter, Basso, Rodriguez-Iturbe, & Rinaldo, 2013), landscape heterogeneity (Doulatyari et al., 2015), dams (Botter, Basso, Porporato, Rodriguez-Iturbe, & Rinaldo, 2010), and floods (Basso, Schirmer, & Botter, 2016). In essence, SMMs represent rainfall as a stochastic process in time and the watershed as a spatial unit capable of infiltrating rainfall and generating surface and/or subsurface runoff, while accounting for key climatic, landscape, and soil parameters. Recently, SMMs were extended to be applicable to urban watersheds (Mejía, Daly, Rossel, Jovanovic, & Gironás, 2014).

Our primary goal with this study is twofold. Firstly, to demonstrate the ability of the SMM to represent nonstationary streamflow dynamics over the long term in an urban watershed. Secondly, to demonstrate its ability to distinguish the influence of climate variability, urbanization, and stormwater management on streamflow. We believe the latter can be relevant and useful to scientists, landscape architects, planners, and engineers facing questions about flow regime attribution in urban watersheds. With ongoing and projected changes in climate, it is becoming increasingly relevant to have quantitative tools that can help explain and explore the potential interactions between climate and urbanization. Such tools are needed to guide urban stormwater mitigation and adaptation actions, and enable tailored solutions to the concurrent stressors of climate and urbanization. The proposed SMM offers an approach to quantify the relative effects of urbanization and climate on flow regimes. The approach may be particularly useful for evaluating preliminary urban planning scenarios by maintaining the number of forcing variables and model parameters required to run the model to a minimum.

2. Modeling approach

2.1. Stochastic mechanistic model (SMM) of streamflow

The SMM simulates daily streamflow in an urban watershed while accounting for factors such as climate, land cover, soils, and stormwater management (Mejía et al., 2014). Note that hereafter we use the term SMM to denote the model by Mejía et al. (2014). Urban watersheds are represented as pervious areas and effective impervious areas that contribute at the watershed outlet baseflow and surface runoff, respectively. Ultimately, the daily streamflow simulated by the SMM consists of the addition of baseflow and surface runoff.

The SMM starts by assuming that the rainfall series, ξ, is a marked Poisson process with exponentially distributed rainfall depths Y (Fig. 1). Rainfall events occur with a frequency λ_R and have a mean magnitude $1/\gamma_R$. For the effective impervious areas in the watershed, excess rainfall ξ_I is generated from the rainfall series when the rainfall depth Y surpasses a threshold d_I ($Y > d_I$) and, for the pervious areas, subsurface recharge ξ_P is generated when $Y > d_P$ (Fig. 1). The subscripts I and P denote impervious and pervious landscape conditions, respectively. Hence, surface runoff is generated from the excess rainfall series ξ_I by rainfall falling on effective impervious areas, while subsurface recharge and baseflow are triggered by rainfall infiltrating into the soil (i.e., $Y > d_P$) in the pervious areas of the watershed. The thresholds d_I and d_P represent the capacity of the landscape to absorb rainfall. In addition, d_I and d_P are related to the mean frequency of effective urban runoff, λ_I, and subsurface recharge, λ_P, respectively, through the equation $\lambda_i = \lambda_R\, exp(-d_i\, \gamma_R)$, where i can be equal to I or P. The derivation of this equation is demonstrated elsewhere (Mejía et al., 2014). Note that the model assumes the soil moisture storage behaves similarly in every event through evaporative losses. This assumption could be relaxed in the future to explicitly account for soil saturation following the approach by Bartlett, Daly, McDonnell,

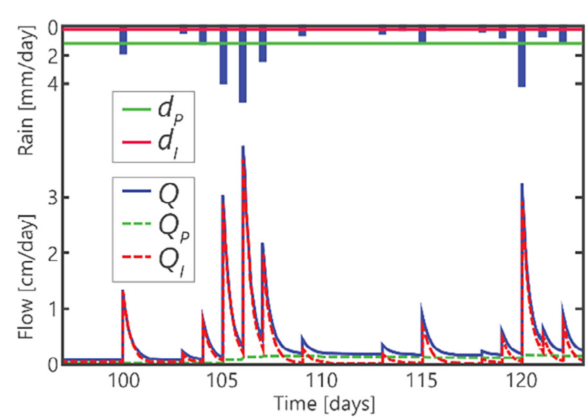

Fig. 1. Illustration of simulated rainfall and streamflow with the SMM. The definition of the variables in the plot is as follows: d_I and d_P are the thresholds above which surface runoff and subsurface recharge occur, respectively; Q_I and Q_P are the surface and subsurface flows, respectively; and $Q_I + Q_P$ is the total streamflow Q at the outlet of the watershed. The subscripts I and P indicate impervious and pervious conditions, respectively.