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The hydromorphology of an urbanizing watershed using multivariate elasticity

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ABSTRACT

A wide range of environmental damages have been linked to the urbanization of watersheds. While much is known about the impacts of urbanization on floods, there remains considerable uncertainty regarding the impact on average and low flows. We introduce a generalized multivariate approach for exploring hydromorphological problems that involves estimation of the multivariate sensitivity (or elasticity) of streamflow to simultaneous changes in climate, land use, and water use. Key advantages of this multivariate sensitivity method are that it does not require model assumptions in the vicinity of the mean, yet it provides confidence intervals and hypothesis tests for the resulting elasticities. A case study highlights the influence of urbanization on the complete range of streamflow. Surprisingly, low streamflows are found to have large positive sensitivity to changes in land use, which departs from the results of several previous studies. Overall, the study demonstrates that changes in climate, land use, and water use must be considered simultaneously to fully understand the hydromorphology of a watershed.

1. Introduction

Hydrologic systems evolve due to a variety of natural and anthropogenic influences such as changes in land use, climate change, and modifications to water infrastructure. The evolution of the watershed system in response to such influences at the scale of years to centuries has been termed its hydromorphological response [20,68]. In this study, we concentrate on the hydromorphological response of watersheds to urbanization.

Over the past few decades, a wide range of environmental damages have been linked to the urbanization of watersheds including, but not limited to: decreased biodiversity, increased flooding, and decreased quality of air, water and soil resources. There have been a variety of efforts to quantify the changes in watershed land use, biodiversity, and other aspects of watershed evolution [25]. There is also increased attention focused on improving our understanding of the impacts of urbanization on stream and watershed ecosystems [47] and this area will receive increased attention in the future [16]. The hydrologic effects of urbanization are primarily a result of both continuous and abrupt land use and infrastructure changes that lead to changes in the land and the atmospheric component of the hydrologic cycle as well as changes in water use. Urbanization leads to increased impervious surfaces as well as the construction of water infrastructure such as municipal distribution systems and structures to accommodate storm water and sewage. Such modifications to the landscape result in changes to the hydrologic cycle and watershed processes.

Most previous evaluations of the hydrologic impact of urbanization have focused on flood hydrology (e.g. [4,6,9,12,43]). It is generally agreed that urbanization will lead to increases in direct runoff and thus increases in flood discharges [5,10,18]. However, it is not clear how urbanization might affect average and low streamflows. Few studies have focused on the impacts of urbanization on average runoff and even fewer on low flows. Several studies have found significant increases in average annual runoff and/or streamflow as a result of urbanization [7,17,29]. Yet, Choi et al. [14] found that average runoff is less affected by urbanization than direct (flood) runoff.

Understanding low flows is particularly important for ensuring adequate water supply for both human use and environmental flows. Urbanization could plausibly lead to either increased or decreased low streamflows. A variety of urban watershed modifications may impact low streamflows including increased impervious surface, soil compaction, vegetation removal, and water transfers into or out of a basin. Early theory reasoned that the increase in impervious surfaces

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often associated with urbanization would reduce infiltration and groundwater recharge, and thus reduce baseflow and low streamflow [43]. However, such theory might not be supported by later empirical studies [24] due in part to the decreases in evapotranspiration which occur when vegetation is removed during the urbanization process.

Overall, it is difficult to generalize the impacts of urbanization on streamflow regimes. Some factors associated with urbanization increase evapotranspiration, recharge and baseflow, while others reduce them. The net impact of these countervailing factors is often unclear. Several studies have argued that urbanization will tend to decrease baseflow [2,21,39,43,50,54,62], and a few studies have provided empirical evidence of this decrease [63,11]. Other studies, though, have documented increases in low flows resulting from urbanization [1,8,34,36,44,46,60,65,10], while others have shown an inconsistent effect [8,40,41,65] or no significant effect [3,24]. Ferguson and Suckling [24] concluded that the insignificant effect in their study was attributable to decreased infiltration being offset by leakage of imported water.

Decreases in baseflow have been attributed to increased impervious surfaces [11,21,43,62,54] and reduced recharge due to vegetation removal [28,48,74,52,73]. Vegetation removal is associated with a variety of countervailing factors including reduced recharge, greater heat advection (e.g. the heat island effect in cities), and reduced evapotranspiration from vegetation. The net effect of such factors can be unclear. For example, Oke [49] found that evapotranspiration rates remained stable despite vegetation removal because of greater heat advection from the land surface.

Other studies argue that baseflow and low flows could increase due to leakage of imported water [10,18,34,36,44,46], reduced evapotranspiration as a result of vegetation removal [1,33,35,38,54,51], and septic effluent [10].

While many previous studies only concentrate on the impact of urbanization on flood hydrology (e.g. [43]), this study seeks to capture a wider hydrologic regime. We hypothesize, as did Claessens et al. [15], that urbanization processes which influence low to average streamflow are complex and can result in simultaneous increases and decreases in low to average streamflow due to the complicated interactions among climate, land use, water use and water infrastructure. This study does not purport to provide a definitive answer to the question of how urbanization impacts low flow. Rather, our primary goal is to inspire others to use the multivariate statistical methodology introduced here to examine various hypotheses relating to the impact of both natural and anthropogenic influences on the hydrologic cycle. Further, our goal is to demonstrate that one can only understand the interactions among land use, climate and water use in an urban watershed if these factors are considered in an integrated fashion using a multivariate approach which properly accounts for their interactions.

There is clearly an increasing interest in the impacts of urbanization on the hydrologic cycle, and it is no longer sufficient to focus solely on the impacts of urbanization on flood events as is so common in the past. A generalized multivariate regression approach is introduced to estimate the sensitivity of streamflow to changes in climate, water use and land use. Our approach provides a framework for developing confidence intervals and hypothesis tests for the resulting elasticities. The proposed method can be used to better understand the impacts of urbanization on streamflow regime, and accounts for simultaneous interactions among land use, climate and water use. The methodology introduced is quite general and should have application to a wide range of problems in hydrology that seek to evaluate the hydromorphological response of a watershed to both natural and anthropogenic influences. After presenting the methodology, a case study is introduced which applies the new methodology and evaluates the generalized hydrologic impacts of urbanization on the full range of streamflow.

2. The generalized elasticity of streamflow to changes in climate, land use and water use

Previous hydrologic investigators introduced the concept of precipitation elasticity to examine the generalized sensitivity of streamflow to changes in precipitation [13,57,53,59]. The precipitation elasticity of streamflow is defined as the proportional change in streamflow Q divided by the proportional change in precipitation P:

$$\varepsilon_p = \frac{dQ/Q}{dP/P} = \frac{dQ}{dP}\frac{P}{Q} \tag{1}$$

Sankarasubramanian et al. [57] define elasticity at the mean value of the climate variable so that

$$\bar{\varepsilon}_p = \frac{dQ}{dP}\frac{\bar{P}}{\bar{Q}} \tag{2}$$

The above definitions of elasticity are quite general, because the variables P and Q may represent instantaneous values, monthly values, annual values, or some other summary statistic of those variables. The interpretation of elasticity is quite simple. For example, if $\varepsilon_p = 2$ for annual streamflows, then a 1% change in precipitation leads to a 2% change in streamflow.

Sankarasubramanian et al. [57] introduced a nonparametric estimator of the precipitation elasticity that was shown to have desirable statistical properties; however, it is only suited to determine the sensitivity of streamflow to changes in a single explanatory variable. A nonparametric approach is important, because elasticity estimates resulting from parametric approaches are highly sensitive to the assumed form of the model used to compute such elasticities, as was shown by Sankarasubramanian et al. [57]. Fu et al. [26] documented the importance of considering a multivariate approach to determination of the sensitivity of streamflow to changes in both temperature and precipitation. Their technique was based on a nonparametric geostatistical smoothing approach which is more challenging to implement and whose application depends on various assumptions concerning the geostatistical smoothing approach. Furthermore, their approach does not yield confidence intervals associated with resulting elasticity estimates, another desirable property. The approach presented by Roderick and Farquhar [53] is also limited and only assesses the sensitivity of streamflow to changes in evapotranspiration (ET), precipitation, and a dimensionless coefficient that indicates the relative magnitudes of ET and precipitation in a given basin. Their model does not explicitly account for human influences (i.e. land use change and groundwater withdrawals).

Saltelli and Annoni [56] argue that the most popular approach to sensitivity analysis in the environmental modeling literature is that of ‘one-factor-at-a-time’ (OAT). They provide a generalized geometric proof that clearly documents the inefficiency of an OAT approach. Instead, we desire a multivariate nonparametric estimator of elasticity to examine the sensitivity of streamflow to changes in climate, land use and water use simultaneously, which also yields minimum variance unbiased estimates of elasticity along with associated confidence intervals. A multivariate approach is important, because it enables us to capture the complex hydrologic interactions among changes in climate, land use, water use and possibly other important factors, and avoids the limitations of an OAT approach. The following section describes two such general approaches to estimation of the multivariate elasticity of streamflow for use in hydromorphological studies, both of which also yield minimum variance, unbiased estimates of elasticities along with associated confidence intervals.

2.1. Multivariate climate, water use, and land use elasticity of streamflow

We wish to determine the generalized sensitivity of streamflow Q, to changes in precipitation P, land use L, and water use W. Our