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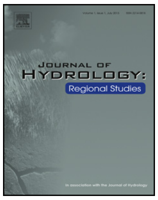

The multivariate climatic and anthropogenic elasticity of streamflow in the Eastern United States

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ABSTRACT

Study region: Eastern United States excluding Florida.
Study focus: We used elasticity to assess the sensitivity of mean and drought flows to changes in climate, land use and land cover (LULC), and water use across a broad region. Three multivariate regression analyses were used for elasticity estimation: nonparametric (NP), double-logarithm (DL), and variable transformation (VT). We demonstrate the importance of using multivariate analysis for elasticity estimation and show that the reliability of elasticity estimates depends critically upon model goodness-of-fit. VT analysis was found to provide more reliable estimates than other analyses across the Eastern U.S., except the Northeast where slight multicollinearity existed in the VT but was absent in the NP models.
New hydrological insights for the region: Changes in climate, LULC, and water use all significantly affected mean and drought flows. The interactions of these factors moderated the effect of precipitation on mean flow for regions where anthropogenic influences cannot be ignored. Human-induced land use changes were found to have a greater influence on drought flow than mean flow. Increased water use significantly reduced mean flow in the Northeast, where urbanization was more prevalent. Although the effect of water use on drought flow was found to be greater than its effect on mean flow, the variations of most water use effect estimates were too large to be concluded as significant.

1. Introduction

In pristine watersheds where natural changes in the land surface occur over a prolong time period given the absence of natural disasters (e.g., earthquakes or forest fires), streamflow variation is predominately affected by climate variation. As we are now in the anthropocene, where few watersheds can be considered pristine and many watersheds have faced drastic changes in land surface due to human activities (Wagener et al., 2010), anthropogenic influences on hydrologic processes can no longer be considered negligible. Moreover, some developed watersheds have also faced increasing water demand and degradation in water quality due to increasing population. Many studies have found that hydrologic impacts due to changes in land use and land cover (LULC) are prevalent in developed watersheds (Andréassian, 2004; Beighley and Moglen, 2003; DeWalle et al., 2000; Oudin et al., 2008; Yildiz and Barros, 2007; Yokoo et al., 2008; Zhang et al., 2001); and that population-driven water demand causes surface and/or groundwater depletion (Canfield et al., 1999; Changnon, 2000; Schot and Van der Wal, 1992; Zarghami et al., 2008; Zarriello and Ries, 2000). Overlooking anthropogenic influences on streamflow (e.g., human-induced land use change and water demand) and its interactions with the natural counterparts (e.g., climate and

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land cover) often misleads the effects of natural factors on streamflow variation. Fragmented assessments focusing only on natural influences on hydrology cannot effectively inform public policies aimed at mitigating damages caused by extreme events and increasing human adaptation capacity. Both natural and human influences on streamflow variation must be systematically accounted for to enable environmental management policies.

Numerous studies have shown that change in climate is the primary factor affecting streamflow variation (Bouwer et al., 2008; Chiew, 2006; Christensen et al., 2004; Fu et al., 2007a,b; Gelfan et al., 2015; Liang et al., 2015; Limbrunner, 1998; Mujumdar and Ghosh, 2008; Revelle and Waggoner, 1983; Risbey and Entekhabi, 1996; Sankarasubramanian et al., 2001; Schaake and Waggoner, 1990; Staudinger et al., 2015; Vogel et al., 1999). Some of these studies have also accounted for the effects of basin characteristics (e.g., Liang et al., 2015; Staudinger et al., 2015; Vogel et al., 1999). An increasing number of studies have considered both the climatic and anthropogenic influences and their interactions on streamflow variation (Allaire et al., 2015; Li et al., 2014; Liang et al., 2015; Ma et al., 2010; Schulze, 2000; Wang and Hejazi, 2011; Xia et al., 2014; Zeng et al., 2014; Zhan et al., 2014a,b; Zhao et al., 2015; Zheng et al., 2009). Most of these studies have either assessed the impacts of integral human activities—i.e., water withdrawal and land use change—on flow (Liang et al., 2015; Xia et al., 2014) or the effects of human-induced changes in land use or basin characteristics on flow (Li et al., 2014; Liang et al., 2015; Schulze, 2000; Wang and Hejazi, 2011; Zeng et al., 2014; Zhan et al., 2014a,b; Zhao et al., 2015; Zheng et al., 2009). Few have been able to partition the effects of human activities on flow into those due to water withdrawals and those due to human-induced land use changes (Allaire et al., 2015; Ma et al., 2010). This study fills this gap by simultaneously assessing the natural and anthropogenic impacts—caused by changes in climate, LULC, and water withdrawals—on streamflow. Although there are numerous studies that have evaluated the sensitivity of mean (Bouwer et al., 2008; Chiew, 2006; DeWalle et al., 2000; Fu et al., 2007b; Liang et al., 2015; Ma et al., 2010; Mujumdar and Ghosh, 2008; Oudin et al., 2008; Risbey and Entekhabi, 1996; Sankarasubramanian et al., 2001; Schaake and Waggoner, 1990; Vogel et al., 1999; Wang and Hejazi, 2011; Yokoo et al., 2008; Zheng et al., 2009) and extreme (Allaire et al., 2015; Beighley and Moglen, 2003; Bouwer et al., 2008; Staudinger et al., 2015) flows to various factors; to our knowledge, this is one of the first studies of its kind to evaluate the integrated impacts of climate, LULC, and water use on drought streamflow conditions across a broad region.

In this paper, we investigate the interactive impacts of seven factors on mean and drought flows across the Eastern U.S.—precipitation, temperature, four types of LULC (forested, urban, agricultural, and grass lands), and water use—by applying three multivariate statistical analyses. We compare the robustness of these statistical models and the variations of the interactive effects estimated by different models. Here we focus on two primary goals. The first goal is to provide a sensible guideline for the estimation of the coupled natural and human effects on mean and drought flows across the Eastern U.S. The second goal is to understand how human activities affect drought and mean flows differentially.

2. Elasticity of streamflow as impact measurement

The impact of a ‘factor’ on streamflow was often assessed by: (1) developing and calibrating a deterministic watershed model and/or a global circulation model (Bouwer et al., 2008; Christensen et al., 2004; Gelfan et al., 2015; Mujumdar and Ghosh, 2008; Schaake and Waggoner, 1990; Schulze, 2000; Staudinger et al., 2015; Wang and Hejazi, 2011), (2) developing a data driven statistical model (Allaire et al., 2015; Chiew, 2006; DeWalle et al., 2000; Fu et al., 2007a,b; Liang et al., 2015; Limbrunner, 1998; Revelle and Waggoner, 1983; Sankarasubramanian et al., 2001; Vogel et al., 1999; Xia et al., 2014; Zheng et al., 2009), or (3) using both aforementioned methods (Ma et al., 2010). In this study, we evaluate the regional ‘factor’ impact on streamflow using multivariate regression analysis, which falls into the second category. Specifically, this regional ‘factor’ impact on streamflow Q is expressed as a dimensionless indicator: the ‘factor’ elasticity of streamflow, denoted as ε_{X_j}, and

$$\varepsilon_{X_j} = \frac{\partial Q/Q}{\partial X_j/X_j}, \tag{1}$$

where X_j represents the j factor affecting streamflow. ε_{X_j} is the ratio of proportional change in streamflow to proportional change in X_j. A larger magnitude of ε_{X_j} indicates a greater X_j effect on streamflow. The dimensionless property of elasticity makes it easy to compare elasticity estimates across different studies. There are two primary advantages of estimating streamflow elasticity using statistical approaches. First, it is straightforward to estimate confidence intervals for an elasticity estimates based on the well-known sampling properties of ordinary least squares regression. This makes it easy to assess uncertainty and stability of an estimate. In contrast, it is more time consuming to conduct uncertainty analysis of an elasticity estimate derived from a deterministic model, which is usually accomplished through sensitivity analysis by perturbing parameters. The second advantage is that a statistically based empirical elasticity estimator generally performs better than the alternative deterministic model-based estimators, especially when the correct functional form in a model is unknown; and when deterministic watershed modeling depends heavily upon the assumed form of the model, model calibration methods, and the input data used (Sankarasubramanian et al., 2001).