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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 approach has some similarities to Tsai and Vogel [67] and Sathyamoorthy et al. [58], yet is novel in its application to streamflow sensitivity. Consider the total differential of streamflow resulting from simultaneous changes in P, L, and W

$$dQ = \frac{\partial Q}{\partial P}dP + \frac{\partial Q}{\partial L}dL + \frac{\partial Q}{\partial W}dW \tag{3}$$

Following the recommendation of Sankarasubramanian et al. [57], estimation of the differentials around the mean values of each variable in Eq. (3) leads to

$$Q - \bar{Q} = \frac{\partial Q}{\partial P}(P - \bar{P}) + \frac{\partial Q}{\partial L}(L - \bar{L}) + \frac{\partial Q}{\partial W}(W - \bar{W}) \tag{4}$$

Dividing each term in Eq. (4) by $\bar{Q}$, and multiplying the three terms on the right hand side by unity in the form of $\bar{P}/\bar{P}$, $\bar{L}/\bar{L}$ and $\bar{W}/\bar{W}$, respectively, results in

$$\left(\frac{Q - \bar{Q}}{Q}\right) = \frac{\partial Q}{\partial P}\frac{\bar{P}}{\bar{Q}}\left(\frac{P - \bar{P}}{\bar{P}}\right) + \frac{\partial Q}{\partial L}\frac{\bar{L}}{\bar{Q}}\left(\frac{L - \bar{L}}{\bar{L}}\right) + \frac{\partial Q}{\partial W}\frac{\bar{W}}{\bar{Q}}\left(\frac{W - \bar{W}}{\bar{W}}\right) \tag{5}$$

Now defining the lower case variables, q, p, l, and w as the four respective terms in parenthesis in Eq. (5) (i.e. the percentage of change from the mean), we obtain

$$q = \bar{\varepsilon}_p \cdot p + \bar{\varepsilon}_L \cdot l + \bar{\varepsilon}_w \cdot w \tag{6}$$

where

$$\bar{\varepsilon}_p = \frac{\partial Q}{\partial P}\frac{\bar{P}}{\bar{Q}}, \quad \bar{\varepsilon}_L = \frac{\partial Q}{\partial L}\frac{\bar{L}}{\bar{Q}} \text{ and } \bar{\varepsilon}_w = \frac{\partial Q}{\partial W}\frac{\bar{W}}{\bar{Q}}$$

are the precipitation, land use and water use elasticity of streamflow, respectively. Note that $\bar{\varepsilon}_p$ in Eq. (6) is identical to the definition of $\bar{\varepsilon}_p$ in Eq. (2). The idea here is to employ ordinary least squares (OLS) regression methods to fit the multivariate linear model in Eq. (6) resulting in minimum variance, unbiased estimates of the three elasticities $\bar{\varepsilon}_p$, $\bar{\varepsilon}_L$ and $\bar{\varepsilon}_W$. The advantages of this approach to elasticity estimation are:

(1) The linear multivariate model in Eq. (6) is derived from the definition of the total differential (Eq. (3)), a basic concept of differential calculus. This approach is nonparametric in the vicinity of the mean, where the differentials are estimated. As the changes in P, L, and W become nonlinear and/or increase in magnitude, the assumption of a linear model could be violated, leading to unreliable results. As shown by Wallis [71], uncertainty regarding the correct model form can lead to multivariate analyses which make little or no sense, thus our approach has the potential to avoid those concerns due to its underlying derivation depending only upon the definition of the total differential, rather than a particular model form.

(2) The estimation method, multivariate ordinary least squares regression, has very attractive properties, as resulting estimators of elasticities are unbiased, and standard errors and confidence intervals for elasticities are available so that hypothesis tests regarding these quantities can be constructed. Corrections for heteroscedasticity [42,66], autocorrelated model errors [19] and other violations of OLS model assumptions [37] are also possible. For example, violations can be addressed through choice of independent variables, model functional form, and robust standard errors.

(3) It is extremely important to include explanatory variables in Eq. (3) which are representative of the dependent variable to make the analysis meaningful. Any number of explanatory variables may be added to the analysis and a *t*-test may be performed to evaluate whether or not a hypothesized elasticity is significantly different from zero. In addition, one can assess which explanatory variables impact streamflow changes the most via an examination of the model sum of squared error contributed by each explanatory variable. When estimating the coefficients in Eq. (6), issues of multicollinearity and heteroscedasticity may become important, as discussed later on.

(4) The explanatory power of the regression in Eq. (6) (i.e. value of R^2) is not preeminent as is often the case in hydrologic analyses. Instead, what matters is that the residuals of the model in Eq. (6) are independent with a constant variance and are normally distributed, in which case, confidence intervals and hypothesis tests regarding the elasticities can easily be constructed. In the case study presented below, we conduct a variety of specification tests related to independence of errors, multicollinearity, and heteroscedasticity.

(5) The meaning of the model parameter estimates in Eq. (6), termed elasticities, are interpretable. For example, if an elasticity is near 0, the variable has no impact on streamflow. If elasticity is near unity, the relation is linear. Values either lower than or in excess of unity imply a nonlinear response. Larger or smaller values indicate greater or lesser streamflow sensitivity to the variable in question.

(6) Eq. (6) can be applied in both time or space. In this study we study the elasticity of a single watershed over time; however, the same type of analysis could be performed by replacing ‘space’ for ‘time’ as is often done in hydrology. Such an analysis would be analogous to the development of regional hydrologic regression models which provide an approach to estimation of regional elasticities (see Vogel et al. 1999, pg 152).

The approach to estimation of elasticity given above leads to an estimate of the multivariate elasticity about the mean values of the various variables as defined in Eqs. (2) and (6). In the following section we describe a parametric approach commonly used in the field of economics which leads to estimates of multivariate elasticity which are not computed about the mean values of the various variables. In other words, one can define elasticity in a number of different ways, as shown for example by the two different definitions in Eqs. (1) and (2), and in this section we show how to estimate elasticities of the form given in Eq. (1).

The concept of elasticity is used widely in the field of economics for determining the sensitivity of demand for a product to its price, termed price elasticity. In economics, a common approach to estimate elasticities which does not depend on mean values such as ε_W in Eq. (1), is to assume the log linear model

$$Q = \theta \cdot P^{\varepsilon_p} \cdot L^{\varepsilon_L} \cdot W^{\varepsilon_w} \cdot \nu \tag{7}$$

Where Q, P, L and W are defined as in Eq. (3)–(6), θ, ε_P, ε_L and ε_W are model coefficients, and ν are log-normally distributed model errors. By taking partial derivatives of Eq. (7) one can easily show that the model coefficients are the elasticities

$$\varepsilon_p = \frac{dQ}{dP}\frac{P}{Q} \quad \varepsilon_w = \frac{dQ}{dW}\frac{W}{Q} \quad \varepsilon_L = \frac{dQ}{dL}\frac{L}{Q}$$

Note here that the elasticity definitions are slightly more general than in Eq. (6) because they are not defined strictly about the mean of the variables. On the other hand, estimation of multivariate elasticities using Eq. (7) requires an assumption regarding the model structure. This is in contrast to Eq. (6), which can be considered a nonparametric approach for values of P, L, and W in the vicinity of the mean.

3. Case study: the hydromorphology of an urbanizing watershed

The following is a case study which illustrates the hydromorphological response of a watershed to changes in climate, land use, and water use. Our case study begins with an exploratory data analyses to frame the problem and is followed by the application of Eqs. (6) and (7) to evaluate the generalized hydromorphological response of an urbanizing watershed. The 24 square mile urbanizing watershed

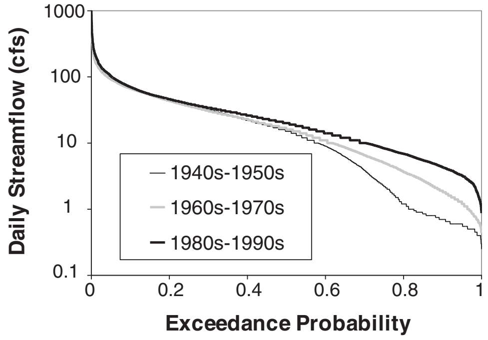

Fig. 1. Daily flow duration curves based on the three different twenty year periods for the Aberjona river watershed, Massachusetts.

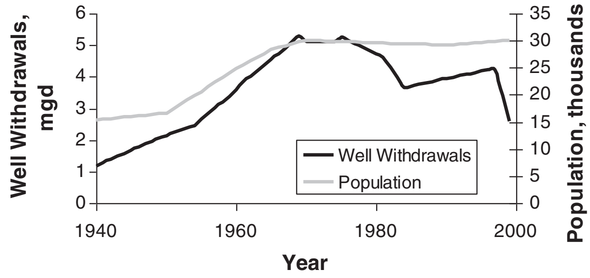

Fig. 2. Well withdrawals and watershed population for the Aberjona River watershed from 1940–1999.

is defined by the U.S. Geological Survey streamflow gage on the Aberjona River at Winchester, Massachusetts (Gage #01102500).

3.1. Exploratory data analysis

Flow duration curves (FDC's) provide a simple, general, graphical overview of the historical variability of streamflow in a watershed and are useful for solving a wide range of water resource engineering problems [69,70]. Fig. 1 illustrates daily flow duration curves (FDC's) for the Aberjona River at Winchester constructed for three non-overlapping 20-year periods: (1) 1940–1959, (2) 1960–1979, and (3) 1980–1999. The FDC's in Fig. 1 are developed using the period-of-record approach described by Vogel and Fennessey [69] and others. What is striking about Fig. 1 is the relatively continuous and nearly uniform increase in streamflows exceeded with a frequency greater than or equal to about 50% from one twenty year period to the next. There are also substantial increases in flood flows, but it is those flows lower than the median daily flow that exhibit the most striking increase over time in Fig. 1. Although the differences between the FDC's in Fig. 1 appear striking, we caution the reader because a log scale is employed, hence the differences between the FDC's depict relative differences, and not absolute differences.

There are at least three hypotheses (or a combination thereof) which could explain the general increase in low flows over time illustrated in Fig. 1: (1) decreased groundwater pumping over time due to concerns over contamination in the 1980s, (2) lower evapotranspiration as a result of the removal of vegetation would lead to a steady increase in low flows, and (3) increases in baseflow resulting from leakage in the water infrastructure (water, sewage and stormwater). Fig. 2 documents that although the watershed population increased steadily until around 1970, it has since leveled off. Similarly, groundwater withdrawals increased until around 1970, leveled off, and then began to decrease after 1980 due to concerns over watershed groundwater contamination. Pumping began to decline as city wells were shut down due to contamination (see [32]) with major well closures in 1979, possibly contributing to the sharp decline from 1979–1981. Most public water supply for the town is obtained by an out of basin transfer from the Massachusetts Water Resources Authority (MWRA) and nearly all of the resulting wastewater is diverted out of the basin to the MWRA treatment facility on Deer Island.

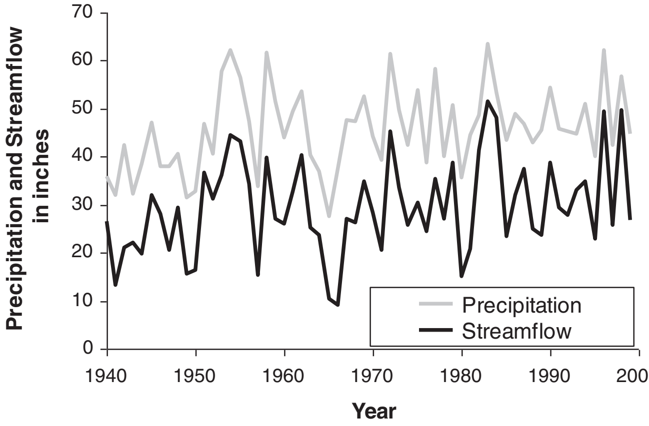

Fig. 3. Annual precipitation and streamflow over the period 1940–1999.

The decrease in well withdrawals after 1980 could explain some of the increase in low flows during the 1980–90 period shown in Fig. 1. However, well water withdrawals increased from 1940–1970 and low flows increased over that period as well; therefore, the impact of water withdrawals is not the only factor influencing low flows.

Coincident with the early increase in groundwater withdrawals and population, there was also a general increase in annual precipitation, *P*, and annual streamflow, *Q*, which occurred over the period 1940–1999 (Fig. 3). The slight linear trends in *P* and *Q* are significant at 1.2% and 2.2% significance levels, respectively, based on a *t*-test of a linear regression model slope coefficient. We conclude from this initial exploratory data analysis that increases in low to medium streamflow resulted from a combination of factors relating to changes in land use, water use and climate. In addition, there are likely other factors that we have not included in the analysis such as leakage from water infrastructure, infiltration from outdoor water use, and a general decrease in evapotranspiration resulting from the removal of vegetation which occurs during the process of urbanization. In the next section we evaluate generalized changes in the hydromorphological regimes of this watershed using the concept of multivariate elasticity. It is exactly these multivariate interactions among land use, climate and water use which form the basis of a hydromorphological investigation.

3.2. Multivariate elasticity results

This section describes the application of the multivariate elasticity approach introduced in Eq. (2)–(6) for determining the impact of climate, land use and water use on the complete range of streamflows on the Aberjona River. Eq. (6) was fit to a time series of annual maximum, Q_{max}, annual average daily streamflow, Q_A, and the daily streamflow which is exceeded 99% of the time in any given year, Q_{99} (a low flow statistic), on the Aberjona river near Winchester, Massachusetts. In all cases the time period considered is 1940–1999. The independent time series for climate, land use and water use in Eq. (6) were annual average basin precipitation (in inches), number of housing units, and annual well withdrawals (in millions of gallons), respectively. Since a time series of the percentage of land use in various categories was not available for this watershed, we use number of housing units as a surrogate for the percentage of land use that is residential and urban. Our land use indicator is the number of housing units within the largest town in the watershed Woburn, which accounts for about half of the total area of the basin.

Table 1
Estimated climate, land use and water use elasticities for flood, average, and low streamflow for the aberjona river watershed near Winchester, MA.

	Flood-Q_{max} Eq. (6)				Average Eq. (6)				Drought-Q_{99} Eq. (6)			
	Coeff. ε	*p*-value	95% CI	Robust std error	Coeff. ε	*p*-value	95% CI	Robust std error	Coeff. ε	*p*-value	95% CI	Robust std error
Elasticity values												
Precipitation, *P*	0.50	**0.000**	(0.345, 0.656)	0.078	1.59	**0.000**	(1.376, 1.796)	0.105	1.22	**0.000**	(0.644, 1.805)	0.290
Housing units, *L*	0.31	0.080	(−0.038, 0.655)	0.173	0.09	0.118	(−0.023, 0.200)	0.055	1.29	**0.000**	(0.743, 1.830)	0.272
Well withdrawals, *W*	0.24	0.222	(−0.149, 0.623)	0.194	−0.16	**0.021**	(−0.292, 0.025)	0.067	−0.14	0.499	(−0.562, 0.277)	0.210
R^2			0.497				0.794				0.523	
Obs			60				60				60	
	Eq. (7)				Eq.(7)				Eq. (7)			
	Coeff. ε	*p*-value	95% CI	Robust std error	Coeff. ε	*p*-value	95% CI	Robust std error	Coeff. ε	*p*-value	95% CI	Robust std error
Elasticity values												
Precipitation, *P*	0.98	**0.005**	(0.312, 1.653)	0.335	1.73	**0.000**	(1.467, 1.985)	0.129	1.59	**0.000**	(1.037, 2.143)	0.276
Housing units, *L*	0.57	**0.021**	(0.090, 1.040)	0.237	0.12	0.096	(−0.021, 0.255)	0.069	1.40	**0.000**	(0.937, 1.858)	0.230
Well withdrawals, *W*	−0.05	0.812	(−0.471, 0.371)	0.210	−0.19	**0.048**	(−0.037, -0.002)	0.093	−0.18	0.358	(−0.558, 0.205)	0.190
Constant	−2.61	0.101	(−5.752, 0.529)	1.568	−2.96	**0.000**	(−4.219, −1.705)	0.627	−17.19	**0.000**	(−19.762, -14.614)	1.285
R^2			0.294				0.767				0.677	
Obs			60				60				60	

Notes: The variables listed: ε, 95% CI, and robust std error, are respectively; the elasticity estimates, their 95% confidence interval, and robust standard error.

Estimates of the elasticities in Eq. (6) were obtained using ordinary least squares regression. Model residuals were tested to ensure that they are uncorrelated, homoscedastic and well approximated by a normal distribution, three requirements which enable us to perform statistical inference on the resulting elasticity estimators. The model specifications generally pass key tests. A remaining issue is heteroscedasticity in the low flow model for Eq. (6).

Independence of errors was tested using Breusch-Godfrey and Durbin-Watson statistics [22,27]. Errors are found to be independent for all fitted models. We also evaluated normality of errors using kernel density plots and Shapiro–Wilk tests [61]. The residuals for most models have an approximately normal distribution. Two models (peak and low flow) based on Eq. (6), appear to have errors that are not normally distributed, based on Shapiro–Wilk tests ($p < 0.05$).

Homoscedasticity (i.e. constant variance of errors) is tested using a White Test [72]. All models appear to be homoscedastic, which the exception of the low flow model specified with Eq. (6). To address this issue of heteroscedasticity, we run all models with robust standard errors. By using robust standard errors, we relax the assumption of identically distributed errors and our test statistics are more trustworthy. When implementing robust standard errors, the *p*-values do not change considerably. This suggests that the extent of heteroscedasticity is not large.

Table 1 summarizes the estimates of climate, land use and water use elasticities for each of the three types of streamflow events: floods, averages and low flows. Shown below each elasticity estimate is the standard error of each elasticity estimator (s_ε) as well as its *p*-value (based on an evaluation of the Student's *t*-distribution). Smaller *p*-values indicate values of elasticity that are more statistically significant than for correspondingly large *p*-values. While we report R^2 values for all models, we emphasize caution in interpreting R^2 values for Eq. (6) specifications, which do not include an intercept term and therefore R^2 values can be misleading.

A number of conclusions may be drawn from the results in Table 1 concerning estimates of elasticity based on our nonparametric multivariate approach given in Eq. (6), as listed below.

(1) *Climate elasticity:* The precipitation elasticity of streamflow, ε_P, is 0.50, 1.6 and 1.2 for flood, average flows and low flows, respectively. A value for ε_P for flood flows (0.50) is consistent with Lins and Cohn [45] who found that precipitation elasticity of floods is usually lower than unity in the United States. A value of ε_P for average annual streamflow (1.6) is consistent with other estimates for undeveloped basins in New England (see Figs. 4 and 5 in [57]). Lins and Cohn [45] found that across broad regions of the U.S., floods are much less sensitive to changes in annual precipitation than are annual average streamflows; our results here are consistent with this finding. We conclude from Table 1 that for this basin, both average annual flows and low flows are more sensitive to changes in annual rainfall than flood discharges. These results imply that for this basin, future changes in annual precipitation will tend to exacerbate average annual streamflows and droughts more than floods. In this initial study we only employ time series of annual precipitation. Future evaluations of the precipitation elasticity of flood flows should consider other statistics of precipitation because changes in storm precipitation intensity and volumes may be more relevant descriptors for flood flows than annual precipitation.

(2) *Land use elasticity*: The housing unit (residential land use) elasticity of streamflow, ε_L, is 0.3 and 1.3 for flood flows and low flows, respectively. The value of ε_P associated with average flows was not significantly different from zero. For this basin, changes in residential land use, as evidenced by increased number of housing units, have had their greatest impact on low flows. It is common knowledge that increases in residential land use tends to exacerbate floods. However, to our knowledge, the extremely large positive sensitivity of low flows to changes in land use shown in Table 1 has never been shown before. While we are unable to say definitively why low flows are so sensitive to urbanization, we are confident that climate and land use played key roles, due to the high statistical significance of both these explanatory variables. Further studies for a much wider class of basins and urbanization levels are needed to support and generalize these findings.

(3) *Water use elasticity*: The water use elasticity of streamflow, ε_W, is −0.16 for average flows. Water use elasticities of flood and low flows were not significantly different from zero. As expected, well withdrawals lead to decreases in average streamflows.

(4) *Variability of elasticity estimates*: The relative variability (or precision) of an elasticity estimate can be measured by its 95% confidence interval. All the models are fit using the same number of observations, in which case smaller *p*-values indicate model coefficients with low variability (i.e. low *p*-values correspond to narrower confidence intervals).

Table 2
Expected direction of bias due to omitted variables.

	Low and average flow			Flood flow		
	Climate $\bar{\varepsilon}_P$	Land use $\bar{\varepsilon}_L$	Water use $\bar{\varepsilon}_W$	Climate $\bar{\varepsilon}_P$	Land use $\bar{\varepsilon}_L$	Water use $\bar{\varepsilon}_W$
Water imported into basin	–	+	–	–	+	–
Stormwater detention	+/–	+/–		+/–	–	
Vegetation removal	+/–	+/–		–	+/–	
Impervious surface		–			+	
Soil compaction	–	–		+	+	
Stormwater conveyance	+/–	–		+/–	+	
Wastewater export from basin	–	–	–		–	–

Notes: Table based on expert judgment of authors.
+indicates upward bias; – indicates downward bias, and +/– indicates that bias in either direction is conceivable.

(5) *Streamflow sensitivity*: The most statistically significant elasticities (smallest *p*-values) and the largest values of elasticity were generally obtained for the low flow statistic Q_{99}. This implies that all three factors (climate, land use and water use) have a significant impact on low flows. For example, an increase in housing units of 1% will lead to a 1.3% increase in low flow. Similarly, a 1% annual increase in precipitation will lead to 1.2% increase in low flow. This is also consistent with the results of recent trend studies which have shown that low flows tend to exhibit the most consistent trends due to changes in climate than any other flow statistic [64].

(6) *Multivariate elasticity*: Perhaps the most important conclusion arising from Table 1 is the fact that streamflow is sensitive to changes in climate, land use and water use, and that all three of these effects must be considered simultaneously to fully understand the hydromorphology of this watershed. Each of these variables is significant in one or more streamflow category (i.e. low, average, flood). We conclude, as did Claessens et al. [15] and Fu et al. [26], that it is necessary to account for the multivariate interactions among land use, climate and water use to fully understand their impacts on streamflow.

All of the above six findings correspond to our multivariate nonparametric estimators of elasticities defined in Eq. (2) and estimated using Eq. (7). Recall we also introduced another definition of elasticity in (1) along with its associated parametric estimator shown in Eq. (7). Table 1 also provides a comparison of estimates of the two different elasticities defined in Eqs. (1) and (2), estimated using Eqs. (7) and (6), respectively. Interestingly, Table 1 indicates that both multivariate approaches yield relatively similar estimates of climate, land use and water use elasticity for low, average and flood flows. In our quest to understand the sensitivity of streamflow to changes in climate, land use and water use; apparently it is much more important to account for the multivariate interactions between streamflow, land use, climate and water use then whether or not a parametric or nonparametric estimator is employed.

4. Discussion

In this section we discuss a few concerns and caveats which should be considered when applying any of the multivariate approaches described here. First, it is important to clarify the unique features of our nonparametric multivariate elasticity approach introduced here in Eqs. (2)–(6). A common approach to generalized sensitivity analysis is to employ 'standardized regression coefficients' (SRC) ([55,56]). The use of SRC is basically a multivariate sensitivity analysis which assumes a linear relationship between the dependent variable and various independent variables of interest, and at first glance looks very similar to our approach. Normally in the use of SRC's, Eq. (4) is standardized by normalizing each deviation in (4) by the standard deviation, rather than the mean (see for example [30,31,55]). Thus, there may be interest in attempting to relate the resulting standardized regression coefficients (SRCs) and the elasticities in (2) and (6). Any such attempt must exercise caution given the fundamental differences between SRC and elasticity based sensitivity analyses. SRC analyses are based on a multivariate regression of a postulated linear model. Assumptions underlying the postulated model can limit the SRC analysis [56]. Another distinction between our approach and SRC is that SRC employs a constant (intercept) term. In contrast, the nonparametric sensitivity analysis, described and employed herein, derives and estimates elasticities using definitions of the total derivative and elasticity. Thus the use of the elasticity analysis (as described in this manuscript) offers three important distinctions from SRC analyses: (i) the application of a linear regression model is derived from first principles and thus does require strong model assumptions within the vicinity of the mean and (ii) resulting elasticity estimators have a very general nondimensional interpretation which is becoming more commonly used in the hydrologic sciences literature [57].

A complex issue surrounding any type of multivariate analysis concerns the issues of multicollinearity and what is termed omitted variable bias (OVB), both topics discussed in most textbooks that address multivariate regression in some detail (see [19]). Farmer et al. [23] provide a detailed discussion of the impact of OVB in regional hydrologic applications. We find no evidence of multicollinearity in any of the models, based on pairwise correlations between independent variables and VIF values. While we cannot test for OVB, we will discuss its implications. OVB is a common concern in econometrics and other applications of multivariate statistics. It arises when independent variables not included in a multiple regression model are correlated with both the independent variables of interest and with the dependent variable OVB results in biased and inconsistent estimates of regression parameters when variables are omitted from the model.

Several variables were omitted from the multivariate analysis due to lack of annual data over the 1940–1999 study period. These variables include water imports and exports, stormwater recharge, detention and conveyance infrastructure, vegetation removal, directly and indirectly connected impervious surfaces, and soil compaction. The direction of OVB will depend on the correlation between the excluded variables and streamflow as well as the explanatory variables considered. A summary of expected direction of bias for key omitted variables is provided in Table 2. For example, percent of land covered by impervious surface is not included in the analysis. Impervious surface and low streamflow are expected to be negatively correlated, while impervious surface and # housing units are positively correlated. Therefore, the estimated elasticity value for land use is likely lower than an unbiased estimate would be for low streamflows.

5. Conclusions

Hydromorphology is defined as the structure and evolution of hydrologic systems [68]. Hydrologic systems tend to evolve in response to anthropogenic and climatic influences which they are subject to, and as a result, nearly all hydrologic processes are nonstationary. Traditionally the field of hydrology has treated nearly all hydrologic processes as stationary. This is certainly not the first hydromorphological study; there have been many previous studies which have dealt with the nonstationary structure and evolution of hydrologic systems. Here we present a simple sensitivity analysis framework to assess climatic and anthropogenic influences on different streamflow regimes.

A generalized nonparametric multivariate regression method was introduced for evaluating the sensitivity of streamflow to changes in climate, land use, water use and other explanatory variables if available. The methodology has a number of important advantages over existing methods of sensitivity analysis including: (1) the method is multivariate and thus has important advantages over one at a time (OAT) sensitivity analysis methods (see [56]); (2) the approach is nonparametric in the sense that it does not require any model assumptions for its derivation and/or use. This is because the derivation of the nonparametric multivariate elasticity approach introduced to assess model output sensitivity is based on the chain rule which results in a multivariate linear model, regardless of the form of the original model which relates streamflow to the various explanatory variables; (3) confidence intervals and hypothesis tests for the significance of the elasticities are easily obtained since the residuals in Eq. (6) are homoscedastic and normally distributed, for most specification; (4) any number of explanatory variables may be included in the analysis and both their relative and absolute impacts on streamflow can be assessed; and (5) perhaps most importantly, the analysis can be applied in both space and time, depending on data availability, so that it provides a useful tool in future studies which seek to evaluate the hydromorphological response of a single watershed (over time) and/or a system of watersheds (in space).

The multivariate elasticity approach introduced here in Eq. (6) was very simple to apply to an urbanizing watershed (the Aberjona River in Massachusetts) and led to a surprisingly rich array of conclusions for this basin:

(1) We found that for this basin, in terms of percent changes in streamflows, both average annual flows and low flows are more sensitive to changes in annual rainfall than are flood discharges. These results imply that future changes in average precipitation for this basin may exacerbate average annual streamflows and droughts more than floods. Our findings regarding the sensitivity (elasticity) of streamflow to changes in precipitation are consistent with the results of Lins and Cohn [45], Sankarasubramanian et al. [57], and other more recent studies.

(2) Our results indicate that low flows for this basin were extremely sensitive to changes in residential land use measured by number of housing units, and that there was a general increase in average to low streamflow over the period 1940–1998 which resulted from the complex interactions among water use, land use and climate. In addition, there was also a general decrease in evapotranspiration over this period (see Fig. 3). Note that we are not claiming from this analysis a particular physical mechanism which led to the general decrease in evapotranspiration, since there are a number of other urban processes, such as leakage from storm water, sewer systems, and water distribution systems, which were not quantified in this study. It is common knowledge that increases in residential land use tends to exacerbate floods; however, the extremely large positive sensitivity of low flows to changes in land use shown in Table 1 conflicts with the results of a number of other studies (see for example [8]). Several previous studies have argued that urbanization can cause reduced recharge and therefore decreased low flows [21,43,54,62]. Further research for a wider class of basins is needed to support and generalize this new result.

(3) Both climate and land use have a significant impact on low flows. This result is consistent with the results of recent trend studies which have shown that low flows tend to exhibit the most consistent trends due to changes in climate than any other flow statistic [64].

(4) This study introduces a methodology which may enable us to improve our understanding of the complex interactions among land use, climate, water use and streamflow. For such analyses to be meaningful, complete reconstructions of records of land use, climate and water use records are needed, either over space or time. In our simple temporal example we did not have access to complete records of all important urbanization processes, thus our conclusions are somewhat tentative. This study highlights the need to develop reconstructions of water use, land-use and other anthropogenic factors for urbanizing watersheds to be able to better assess the impact of future climatic and anthropogenic change on streamflow regimes.

(5) Perhaps the most important conclusion arising from this study is the fact that streamflow is sensitive to changes in climate, land use and water use, and that all three of these effects (and possibly others) should be considered simultaneously to fully understand the hydromorphology of this watershed. It is our hope that future studies will extend our methodology to a much wider and richer cross section of watersheds.

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