The Hydromorphology of an Urbanizing Watershed Using Multivariate Elasticity

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Abstract

The term hydromorphology deals with the structure and evolution of watershed systems over time (e.g. years, decades and centuries). We introduce a generalized multivariate approach for exploring hydromorphological problems that involves estimation of the multivariate sensitivity or elasticity of streamflow to changes in climate, water use and land use. The method does not require a model assumption yet it provides confidence intervals and hypothesis tests for resulting elasticities. A case study highlights the influence of urbanization on the complete range of streamflow and shows that accounting for the simultaneous interactions among land use, climate and water use is a necessary component for understanding the influence of urbanization on streamflow regimes. Although all streamflows are influenced to some extent by changes in climate, land use and water use, in the case study the most striking sensitivities to all three factors are associated with low streamflows.

Introduction

Hydrologic systems evolve due to a variety of both natural and anthropogenic influences: urbanization and changes in climate and water use are examples of such influences. The evolution of the watershed system in response to such influences at the scale of years to centuries, has been termed its hydromorphological response (Dressler et al., 2006). 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 urbanization including, but not limited to: decreases in biodiversity, increased flooding, degradation of human health, decreases in evapotranspiration and decreased
quality of air, water and soil resources. 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 the water use cycle. Urbanization leads to the construction of water distribution systems, as well as an infrastructure to accommodate storm water and sewage. All of these modifications to the landscape result in changes to the hydrologic cycle and watershed processes. There has been a wide range of initiatives relating to watershed management to ameliorate past damages and/or prevent future environmental damages resulting from the urbanization of watersheds. Essentially, watershed systems evolve due to changes in land-use, climate, and an array of other anthropogenic influences.

There have been a variety of efforts to quantify the changes in watershed land-use, biodiversity and other aspects of watershed evolution (Firbank et al., 2003). There is also increased attention focused on improving our understanding of the impacts of urbanization on stream and watershed ecosystems (Nilsson, et al., 2003) and this area will receive increased attention in the future (DeFries and Eshleman, 2004). Most previous evaluations of the hydrologic impact of urbanization have focused on flood hydrology (Leopold, 1968; Brater and Sangal, 1969). For instance, Beighley et al. (2003) found that urbanization increases both peak discharges and flood runoff volumes while decreasing their associated variability. Choi et al. (2003) found that urbanization leads to greater impacts on direct (flood) runoff than total (average) runoff. Similarly, Cheng and Wang (2002) quantified the impact of imperviousness on both the flood peak magnitude and the time of concentration. Beighley and Moglen (2002, 2003) also focus on the impact of urbanization on flood hydrology. They developed methods for adjusting observed time-
series of flood peaks to enable one to estimate the frequency of floods under current land-use conditions.

Fewer studies have focused on the impacts of urbanization on average runoff and even fewer on low flows. Grove et al. (2002) found increases in average annual runoff of more than 60% resulting from urbanization influences during the period 1973 to 1991 for an urbanizing basin near Indianapolis, Indiana. Bhaduri et al. (2001) obtained similar results. In a more comprehensive study for basins across the entire U.S., DeWalle et al. (2000) concluded that urbanization increased mean annual streamflow in rough proportion to average cumulative changes in population density. Dow and DeWalle (2000) review a number of additional studies all of which concluded that the primary response of a watershed to increasing urban land use is an increase in surface runoff. However, Dow and DeWalle (2000) also document significant decreases in watershed evapotranspiration that result from urbanization which is consistent with the results of this study. Claessens et al. (2006) use a monthly water balance model to show that it is necessary to understand the interactions among climate, land use and water use to predict the streamflow regime in an urbanizing watershed.

Schilling and Libra (2003) found that in nearly all watersheds evaluated in Iowa; annual baseflow, annual minimum flow and annual baseflow percentage of flow all increased over time. They suggest that these increases may result from improved land management and conservation practices. Snodgrass et al. (1997) and Brandes et al. (2005) cite numerous studies which obtain conflicting results, some concluding that urbanization increases low streamflows and others concluding that it decreases low streamflows. On the one hand, Leopold (1968), Dunne and Leopold (1978), Klein (1979), Shaw (1994), Barringer et al. (1994), Rose and Peters (2001), Paul et al. (2001)
and many others have argued that urbanization will tend to increase baseflow. On the other hand, Hollis (1977), Snodgrass et al. (1997), Lerner (2002), Meyer (2002, 2005) and Brandes et al. (2005) documented increases in low flows resulting from urbanization. Meyer (2002) found that urbanization increased low flows due to leakage from water, stormwater and sewer systems. Similarly, Lerner (2002) found that leaks from water distribution systems led to increases in groundwater recharge and resulting low flows.

The study by Leopold (1968) is one of the most comprehensive reports on the hydrologic impact of urbanization because it uses cited literature and actual data to arrive at conclusions regarding the generalized impacts of urbanization on flood peaks, flood volumes, sediment discharge, and water quality. However, that study only concentrated on the impact of urbanization on flood hydrology, whereas this study attempts to focus on the entire hydrologic cycle. Interestingly, Leopold (1968), Dunne and Leopold (1978), Shaw (1994), Rose and Peters (2001) and many others have argued that urbanization, or increasing impervious area, causes decreases in groundwater recharge and baseflow. This is counter to the results of Hollis (1977), Snodgrass et al. (1997), Lerner (2002), Meyer (2002, 2005), and Brandes et al. (2005) as well as the results of this study.

**Study Goals:**

There is a general consensus in the literature regarding some of the hydromorphologic impacts of urbanization. It is generally agreed that urbanization will lead to increases in direct runoff and thus increases in floods. It is not clear whether urbanization will cause increases or decreases in baseflow and resulting low streamflows. Increases in baseflow may result from leakage of urban water infrastructure as well as due to decreases in evapotranspiration that result from replacing vegetation with urban infrastructure. In addition, urbanization may produce changes in groundwater recharge
due to changes in the hydraulic routing of water over the landscape. Decreases in baseflows may result from reductions in infiltration due to replacement of vegetation with urban infrastructure and due to exfiltration of soil water into sewer and stormwater systems. Trends in climate, land use and water use within a basin will also lead to associated trends in streamflows. We hypothesize, as did Claessens et al. (2006), that urbanization processes which influence low to average streamflow are extremely 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 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.

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. The methodology introduced in this study 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 evaluates the generalized hydrologic impacts of urbanization focusing on the entire hydrologic cycle of an urbanizing watershed in the suburbs of Boston.
The Generalized Sensitivity or 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
(Schaake, 1990; Sankarasubramanian et al. 2001; Chiew, 2006). The precipitation
elasticity of streamflow is defined as the proportional change in streamflow \( Q \) divided by
the proportional change in precipitation \( P \):

\[
\varepsilon_P = \frac{dQ/Q}{dP/P} = \frac{dQ}{dP} \frac{P}{Q}
\]

Sankarasubramanian et al. (2001) found it useful to define elasticity at the mean value of
the climate variable so that

\[
\varepsilon_P = \frac{dQ}{dP} \frac{\bar{P}}{\bar{Q}}
\]

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. (2001) 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. We desire a multivariate nonparametric estimator of elasticity to
examine the sensitivity of streamflow to changes in climate, land use and water use,
simultaneously. The following section describes a general approach to multivariate
elasticity of streamflow for use in hydromorphological studies.
Multivariate Climate/WaterUse/LandUse Elasticity of Streamflow

We wish to determine the generalized sensitivity of streamflow \( Q \), to changes in precipitation \( P \), land use \( L \), and water use \( W \). Consider the total differential of streamflow resulting from simultaneous changes in \( P \), \( L \), and \( W \)

\[
dQ = \frac{\partial Q}{\partial P} dP + \frac{\partial Q}{\partial L} dL + \frac{\partial Q}{\partial W} dW
\]

Following the recommendation of Sankarasubramanian et al. (2001), estimation of the differentials around the mean values of each variable in (3) leads to

\[
Q - \bar{Q} = \frac{\partial Q}{\partial P} (P - \bar{P}) + \frac{\partial Q}{\partial L} (L - \bar{L}) + \frac{\partial Q}{\partial W} (W - \bar{W})
\]

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

\[
\left( \frac{Q - \bar{Q}}{\bar{Q}} \right) = \frac{\partial Q}{\partial P} \frac{P}{\bar{P}} (P - \bar{P}) + \frac{\partial Q}{\partial L} \frac{L}{\bar{L}} (L - \bar{L}) + \frac{\partial Q}{\partial W} \frac{W}{\bar{W}} (W - \bar{W})
\]

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

\[
q = \varepsilon_p \cdot p + \varepsilon_L \cdot l + \varepsilon_w \cdot w
\]

where

\[
\varepsilon_p = \frac{\partial Q}{\partial P} \frac{P}{\bar{Q}} \quad \varepsilon_L = \frac{\partial Q}{\partial L} \frac{L}{\bar{Q}} \quad \text{and} \quad \varepsilon_w = \frac{\partial Q}{\partial W} \frac{W}{\bar{Q}}
\]

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

1. The linear multivariate model in (6) is based on the definition of the total differential (eq. 1) which is one of the most basic concepts of differential calculus, therefore, there is no question whether or not the model is correct.

2. The estimation method, multivariate ordinary least squares regression, has very attractive properties, because resulting estimates of elasticity’s are unbiased, and standard errors and confidence intervals for elasticities are available so that hypothesis tests can be constructed. Corrections for heteroscedasticity (Stedinger and Tasker, 1985; Kroll and Stedinger, 1998), autocorrelated model errors (Draper and Smith, 1981) and other violations of OLS model assumptions (Johnston, 1984) are also possible.

3. Any number of additional 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, or not. 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.

4. The explanatory power of the regression in (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 (6) are independent with a constant variance and are normally distributed, in which case, confidence intervals and hypothesis tests regarding the elasticities have meaning.

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

(6) Equation (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 Hydromorphology of an Urbanizing Watershed

The following is a case study which dramatizes 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 equation (6) to evaluate the generalized hydromorphological response of an urbanizing watershed. The 24 square mile urbanizing watershed is defined by the U.S. Geological Survey streamflow gage on the Aberjona River at Winchester, Massachusetts (Gage #001102500).

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 (Vogel and Fennessey, 1994, 1995). Figure 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 Figure 1 are developed
using the period-of-record approach described by Vogel and Fennessey (1994) and others. What is striking about Figure 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 Figure 1.

There are at least three hypotheses (or a combination thereof) which could explain the general increase in low flows over time illustrated in Figure 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). Figure 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 Harr, 1995) with major well closures in 1979, possibly contributing to the sharp decline from 1979-1981. Most public water supply for the town is supplied 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.

The decrease in well withdrawals after 1980 could explain some of the increase in low flows during the 1980-90 period shown in Figure 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.

Figure 3 compares empirical cumulative distribution functions of annual evapotranspiration (ET) for the same twenty year periods reported earlier in Figure 1. Here annual ET is computed as the difference between annual precipitation P and annual streamflow Q where the precipitation record was reconstructed using records from Boston Logan International Airport. This gage was used to enable the longest possible record length. Figure 3 documents that annual ET has steadily decreased from one twenty year period to the next, with the largest changes occurring in those years in which ET is highest over each 20 year period.

Figures 1, 2, and 3 indicate that it is possible that low to average streamflows in this basin increased over the period 1940-1999 due to the early increase in groundwater withdrawals combined with the general decrease in evapotranspiration during wet years. However, there was a general increase in P and Q which also occurred over the period 1940-1999, which is shown in Figure 4. 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. In the next section we introduce a new methodology for evaluating generalized changes in hydromorphological regimes using the concept of elasticity. It is exactly these multivariate interactions among land use, climate and water use which form the basis of a hydromorphological investigation.
Multivariate Elasticity Results

This section describes the application of the multivariate elasticity approach introduced in equations (1)-(6 for determining the impact of climate, land use and water use on the complete range of streamflows on the Aberjona River. Equation (6) was fit to a time series of annual maximum $Q_{max}$, annual average daily streamflow $Q$, 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 three independent time series for climate, land use and water use in (6) were annual average basin precipitation (in inches), annual population (in thousands), 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 watershed population as a surrogate for the percentage of residential and urban land use. Several investigators have developed relationships between population density and urban/residential area for individual watersheds (Standowski, 1972; Gluck and McCuen, 1975) and for 51 watersheds across the northeastern U.S. (Dow and DeWalle, 2000). Rather than use these relationships directly, which require an assumption that the relationships are constant over time, we simply use the watershed population (in thousands) as the independent land use surrogate variable.

Estimates of the elasticity’s in (6) were obtained using ordinary least squares regression. Model residuals were tested to assure 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 estimates. 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 ($s_e$) 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. In addition, Table 1 also contains the percentage of the model sum of squares
corresponding to each explanatory variable (%SS) and the variance inflation factor (VIF).
The %SS may be used to compare the importance of climate, land use and water use in
explaining variations in each streamflow statistic. The VIF is an indicator of correlated
explanatory variables (i.e. multicollinearity); a VIF $\geq 10$ typically indicates a
multicollinearity problem. We do not report $R^2$ values because each model was fit
without an intercept term as is required in (5), and $R^2$ values for regression models fit
without an intercept can be misleading. Note that in Table 1 we have omitted regression
variables who related elasticities were not significantly different than zero, using a 5%
level test.

A number of conclusions may be drawn from the results in Table1:

(1) **Climate Elasticity:** The precipitation elasticity of streamflow $\varepsilon_P$ is 0.71, 1.6 and
1.1 for flood, average flows and low flows, respectively. A value for $\varepsilon_P = 0.71$ for flood
flows is consistent with Lins and Cohn (2003) who found that precipitation elasticity of
floods is usually lower than unity in the U.S. A value of $\varepsilon_P$ equal to 1.6 for average
annual streamflow is consistent with other estimates for undeveloped basins in New
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 precipitation will tend to exacerbate average annual streamflows and droughts more than floods.

(2) **Land Use Elasticity**: The population (residential land use) elasticity of streamflow $\varepsilon_L$ is 0.94 and 4.6 for flood flows and low flows, respectively. The value of $\varepsilon_L$ associated with average flows was not significantly different from zero, hence we did not report it in Table 1. Apparently, for this basin, changes in residential land use, as evidenced by population growth, have had their greatest impact on low flows and floods, with the 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, land use and water use all play key roles, due to the relatively equal fractions of model sum of squares explained by each of 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 $\varepsilon_W$ is -0.3, and -2.1 for average flows and low flows, respectively. Water use elasticity of flood flows were not significantly different from zero hence it is not reported in Table 1. As expected, well withdrawals lead to decreases in streamflows. Once again, low flows are much more sensitive to changes in water use than either floods or average flows.

(4) **Variability of Elasticity Estimates**: The relative variability of an elasticity estimate can be measured by its coefficient of variation $C_v$, which is the inverse of the t-ratio from
which the p-value reported in Table 1 is derived. All the models are fit using the same number of samples, in which case smaller p-values indicate model coefficients with low variability (i.e. low p-values correspond to high t-ratios which implies low Cv associated with model coefficients). Interestingly, the variability of all elasticity estimates in Table 1 are proportional to their associated elasticity values. In other words, the higher elasticity values always had lower p-values and thus less variability (lower coefficient of variation) than the lower values of elasticity. Thus, as streamflow sensitivity to climate, land use and water use increases, so does our confidence in the results!

(5) Streamflow Sensitivity: The most statistically significant elasticity’s (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 tremendous and highly significant impact on low flows. For example, an increase in population of 1% will lead to a 4.56% increase in low flow. Similarly, a 1% annual increase in well withdrawals will lead to 2.12% decrease 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 (Small et al., 2006).

(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. To highlight this point, elasticity’s were computed for $Q_{99}$, based on simple regressions between each explanatory variable, separately. In other words, the elasticities were estimated from the following three bivariate equations

$$q = \varepsilon_p \cdot p, \quad q = \varepsilon_L \cdot l \quad \text{and} \quad q = \varepsilon_w \cdot w$$

individually, instead of the single multivariate
expression in (6). The resulting estimates of $\varepsilon_p$, $\varepsilon_L$ and $\varepsilon_w$ for $Q_{99}$ were 1.11, 1.15 and 0.526, respectively, compared to the values of 1.13, 4.56, and -2.12, respectively, reported in Table 1. It makes little sense for the value of $\varepsilon_w$ to be greater than zero because this would imply that an increase in water withdrawals leads to an increase in low flow. We conclude, as did Claessens et al. (2006), that it is necessary to account for the multivariate interactions among land use, climate and water use to fully understand their impacts on streamflow.

**Conclusions**

Hydromorphology is defined as the structure and evolution of hydrologic systems. 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 thousands of previous studies which have dealt with the nonstationary structure and evolution of hydrologic systems. This is simply the first study to identify this class of problems as a new subfield of hydrology which we term hydromorphology.

To address hydromorphological problems, a new approach was introduced. A generalized multivariate 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 including: (1) no model assumptions are required yet exact confidence intervals and hypothesis tests are available, (2) any number of explanatory variables may be included in the analysis and both their relative and absolute impacts on streamflow can be assessed, and perhaps most
importantly (3) 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) or a system of watersheds (in space). The multivariate elasticity approach introduced here in equation (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, 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 precipitation for this basin will tend to 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 both Lins and Cohn (2003) and Sankarasubramanian et al. (2000).

(2) Our results indicate that low flows for this basin were extremely sensitive to changes in residential land use measured by watershed population, 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 Brandes et al. 2005). Further studies for a much wider class of basins are needed to support and generalize this new result.

(3) As expected, well withdrawals led to decreases in streamflows over all flow regimes and low flows are much more sensitive to changes in water use than either floods or average flows in this basin. The higher elasticity values always had lower p-values and thus lower coefficients of variations. Thus, as streamflow sensitivity to climate, land use and water use increases, so does our confidence in the results.

(4) Of the three factors considered for their impact on streamflow regimes, climate, land use and water use all have a tremendous and highly 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 (Small et al., 2006).

(6) 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 must 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.
References


Table 1 – Estimated Climate, Land Use and Water Use Elasticities for Flood, Average, and Low Streamflow for the Aberjona River Watershed near Winchester, MA.

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<td>Land Use $\varepsilon_L$</td>
<td>Water Use $\varepsilon_W$</td>
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<td>$p$ 0.000</td>
<td>$p_L$ 0.043</td>
<td>$p_W$ 0.043</td>
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<td>%SS 98%</td>
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<td></td>
<td>VIF 1.1</td>
<td>VIF 1.1</td>
<td>VIF 1.1</td>
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<tr>
<td>Drought – $Q_{99}$</td>
<td>$\varepsilon$ 1.13</td>
<td>$\varepsilon_L$ 4.56</td>
<td>$\varepsilon_W$ -2.12</td>
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<td>$s_\varepsilon$ 0.41</td>
<td>$s_L$ 0.83</td>
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<td>VIF 1.1</td>
<td>VIF 6.2</td>
<td>VIF 6.0</td>
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</tbody>
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Notes:

The variables $\varepsilon$, $s_\varepsilon$, $p$, are the elasticity estimate, its standard deviation and p-value, respectively, and the variables %SS and VIF denote the percentage of the overall model sum of squares and the variance inflation factor corresponding to each explanatory variable.
Figure 1. Flow duration curves based on the three different twenty year periods for the Aberjona River watershed.
Figure 2  Well withdrawals and watershed population from 1940-1999
Figure 3 – Empirical cumulative distribution function of annual evapotranspiration over three twenty year periods
Figure 4 – Annual precipitation and streamflow over the period 1940-1999