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Modeling Landscape Influence on Stream Baseflows for Watershed Conservation

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Abstract: Instream flows are vital to the ecology of riverine and riparian systems. The influence of watershed characteristics on these systems is helpful in developing landscape policies to maintain these flows. Watershed characteristics like precipitation, forest cover, impervious cover, soil drainage, and slope affect baseflows. Spatial analysis using GIS and nonlinear regression analysis is used to analyze spatial and temporal information from gauged watersheds in Massachusetts to quantify the relationship between baseflows and watershed metrics. The marginal functions of landscape factors that reflect changes in baseflow are quantified. This information is then applied to watershed policy toward improving base flows. The interactions of three fixed attributes, soil drainage, rainfall incidence, and slope, are analyzed for the manageable landscape attributes of impervious and forest cover. Developing watershed policy to protect baseflows involves evaluating the complex interactions and functional relationships between these landscape factors and their use in watershed conservation planning.

Keywords: watershed systems; landscape factors; baseflows; hydrology; conservation policy

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1. Introduction

Maintaining instream flows is vital to riverine and riparian ecosystems [1,2]. With increasing land-use changes in watersheds and higher demand for offsite uses of water for human consumption, irrigation, and industrial services, maintaining instream flows is challenging in water resource management [3]. Land use is critical in stream hydrology, particularly its influence on baseflows [4]. Urbanization affects both runoff and baseflow by reducing infiltration [5,6]. Impervious surfaces in urban areas impact baseflows [7–9].

The critical hydrological paths for maintaining these flows in rivers and streams are the gradual discharges or baseflows that enter streams from subsurface soils [10]. Since these baseflows moderate the amount and rate of instream flow, they attenuate floods and streams' extreme flows or flashiness. Baseflows ensure minimum stream flows, which are essential for sustaining instream water uses, protecting aquatic ecosystems, and providing a healthy habitat for macro-invertebrates and aquatic organisms [11]. Reducing baseflows can degrade water quality through increased concentrations of particulates, nutrients, chemical contaminants, and microorganisms, affect riparian habitats, and interfere with navigable waterways [12]. Low summer baseflows can cause fish mortalities through flow velocity, cross-sectional area, and water depth [13,14]. Baseflows also influence summer water temperatures that, in turn, impact the health and mortality of fish and aquatic ecosystems [15]. Understanding the relationship between landscape and climatic factors and their impact on baseflow helps develop management policies for instream baseflows. Therefore, this study aims to assess the relationship between watershed characteristics and baseflows for watershed policy [5,16].

Baseflows result from functional interactions involving several factors in the watershed system [17]. While much research has focused on hydrograph analysis to quantify baseflows, there is also a need to assess this component on a systems scale to quantify watershed-scale factors and influences [4,18]. This study is unique in studying baseflow variation using a watershed system as a framework to quantify interactions among ecological and hydrologic variables. The resulting multiattribute method for supporting the development of incentive policies appropriate to the watershed scale is also limited in the literature and is a valuable tool for policy planners. By using measurements of baseflows and relating to their watershed characteristics, we develop a nonlinear model to quantify causality. The results will help develop watershed policies that reduce impacts on their baseflows that can be useful in managing flow conditions in river systems.

While baseflows are recognized as essential to stream ecology and instream uses, there is limited research on the contribution of system-wide (watershed) landscape factors to variation in baseflow. This study fills this gap in research by examining the effect of watershed factors (impervious surface, forest cover, soil drainage class, precipitation, slope, and aspect) on baseflow using spatial and statistical modeling of data from several monitored streams in Massachusetts. The general objective of this study is to assess the relationship between watershed attributes and baseflows for developing watershed policies. The specific objectives of the study are (i) to evaluate various landscape characteristics of watersheds that may influence baseflow; (ii) to assess baseflow changes and levels in multiple watersheds; (iii) to estimate the nonlinear relationship between watershed characteristics and baseflow levels; and (iv) to develop landscape-based, multi-attribute policy to manage baseflows.

2. Methodology

2.1. Study Area

The study watersheds are from the Commonwealth of Massachusetts, located in the northeast region of the USA. To assess baseflow characteristics, streamflow information was initially collected from all gauging stations within the Commonwealth of Massachusetts (Figure 1). The watersheds of the selected gaging stations are identified in the figure as HUC 12 watersheds. All stations shown in the figure were reviewed for consistency. Some were eliminated for data issues if the watershed was (1) located on large river main-stems that had subbasins already accounted for, (2) crossed the Commonwealth's borders to avoid data inconsistency from different GIS data in multiple states, (3) associated with estuaries since these areas have tidal flows which would skew their gauging station results (4) within one county (Franklin) that did not have digitized soil information, (5) located on sub-watersheds with built components which may not be representative of naturally occurring watersheds, and (6) when invalid values were found in the gauging stations' data. The final sample consisted of twenty-eight gauging stations throughout the Commonwealth of Massachusetts. The sampled gauge stations and their watersheds are presented in Figure 1.

2.2. Background

A literature review assesses the landscape characteristics of watersheds that may influence baseflows [17–22]. Impervious cover and forest cover directly affect stream baseflows. Natural watershed characteristics, including soil characteristics, slope, slope aspect, forest cover, and precipitation volume and duration, have a varied effect on infiltration and the resulting base flow [19,23,24].

Soil type can play a large role in base flow hydrology. Soils in a watershed vary in porosity and thus have varying infiltration rates [25]. Macro-pores play a major role in infiltration [26] and provide rapid subsurface water movement routes to surficial aquifers and stream channels [26]. The characteristics and condition of soil are a primary determinant of the rate of water movement [27]. Sands and gravels have a high infiltration rate and low runoff, while clays have low infiltration and high runoff [14,28]. The effect of soil porosity is exacerbated by slope characteristics, which alter flow velocity to reduce or enhance infiltration [14].

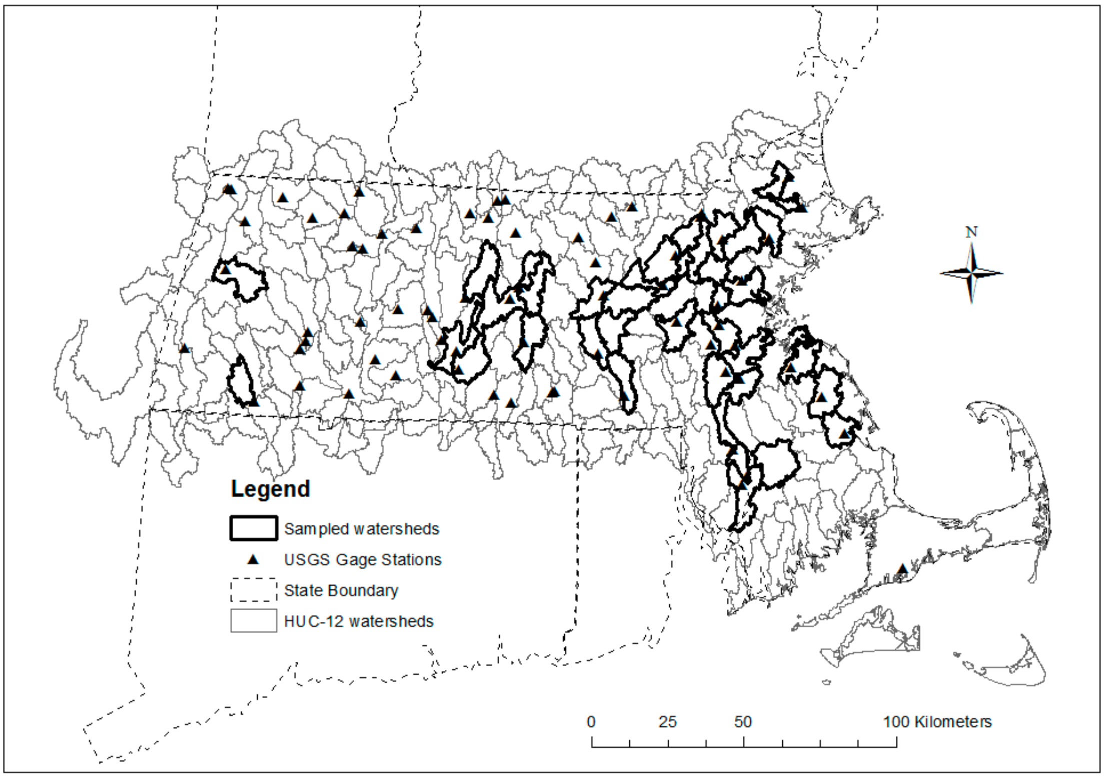

Figure 1. Sampled streamflow gage stations and their watershed boundaries.

Land slope can substantially influence the level of base flow. High slope angles reduce the time that rainwater sits on the land, thus reducing the available time to infiltrate. Steeper slopes cause narrower and deeper stream basins with near-parallel rills, while flatter surfaces produce wider basins [29]. The resulting high water velocities in high slope areas can also cause more damage to streams when there is a lack of stream roughness through large woody debris and boulders that provide a microhabitat for aquatic ecosystems [14], a common result of deforestation.

The slope aspect affects base flow levels in snow-dominated systems by its effect on stream runoff levels [30]. The slope aspect affects the amount of solar incidence contrast between the energy inputs for north- and south-facing slopes [31]. The intensity of incoming solar radiation affects snow accumulation, the timing and intensity of snowmelt, and the extent of snowpack. Slope aspect (flow direction) can also affect infiltration since north-facing aspects in middle latitudes have larger snowmelt and therefore create more groundwater downstream [32]. Since snowmelt accounts for a large percentage of recharge waters in snow-dominated systems [31], aspect exerts a larger control on spatial variations in snowmelt [32]. However, when weighing the influences of various factors, Mitchell and DeWalle [33] found little consistent difference in snow cover for different slope-aspect zones and concluded that elevation and land use were more important factors in the Towanda Creek Basin of central Pennsylvania.

While baseflows are recognized as important to stream ecology and instream uses, there is limited research on the contribution of system-wide (watershed) landscape factors to variation in baseflow. This study fills this gap in research by examining the effect of watershed factors (impervious surface, forest cover, soil drainage class, precipitation, slope, and aspect) on base flow using spatial and statistical modeling of data from several monitored streams in Massachusetts.

2.3. Methods

Spatial analysis using Geographic Information Systems (GIS) is used to quantify levels of model variables [17]. A multiple regression model [13,34] is specified to quantify the direction and magnitude of impacts using a sample of various watersheds. A nonlinear baseflow function of watershed attributes (linear and interaction terms) is specified as (1).

$$B_t = \alpha + \beta_1 x_1 + \ldots + \beta_n x_n + \beta_{1,k} x_1 x_k + \ldots + \beta_{k,l} x_k x_l \quad (1)$$

This can be rewritten as (2).

$$B_t = \alpha + \sum_i \beta_i x_i + \sum_{i \neq j} \beta_i x_i x_j \quad (2)$$

The influence of factor x_i on B_t can be derived by taking the first derivative as in (3).

$$\frac{dB}{dx_i} = \beta_i + \sum_{i \neq j} \beta_{ij} x_j \quad (3)$$

Multiple regression analysis is used to determine the effect of the various watershed factors on baseflows in sub-watersheds. The daily baseflow values were aggregated into annual average baseflow values for 2005, 2006, and 2007. The average yearly baseflow values were then used as the dependent variables for multiple regression analyses that included the following independent variables: (1) percent impervious surface, (2) percent forest cover, (3) soil drainage class, (4) slope, and (5) precipitation. The regression analysis was performed using observations from twenty-eight sub-watersheds.

To calculate direct and indirect effects, the regression equation included terms for each independent variable and five interaction terms for each pair of independent variables. A multivariate scatter analysis is used in checking collinearity and in the selection of independent variables. The nonlinear regression model is specified as in (4).

$$\begin{aligned} Y = \alpha + \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_3 + \beta_4 x_4 + \beta_5 x_5 + \beta_6 x_1 x_2 + \beta_7 x_1 x_3 + \beta_8 x_1 x_4 + \beta_9 x_1 x_5 \\ + \beta_{10} x_2 x_3 + \beta_{11} x_2 x_4 + \beta_{12} x_2 x_5 + \beta_{13} x_3 x_4 + \beta_{14} x_3 x_5 + \beta_{15} x_4 x_5 \end{aligned} \quad (4)$$

where Y = average annual baseflow; β_1 to β_5 are coefficients of direct influence, β_6 to β_{15} are coefficients of interaction terms, x_1 = percent impervious surface in watershed, x_2 = percent forest cover, x_3 = area-weighted soil drainage class, x_4 = weighted precipitation, and x_5 = area-weighted watershed slope. The equation includes both the direct and interaction effects of independent variables on baseflows. Square terms were not included in the analysis as they were found insignificant.

2.4. Data and Methods

Streamflow data were obtained from the United States Geological Survey's (USGS) National Water Information System (NWIS), which maintains historical and real-time observations [35]. Sub-basins of each gauging station were created using GIS using data layers available in a state database [36]. Daily streamflow data from 2005 through 2007 were used to evaluate the mean flow condition of the stream. While long-term data analysis is advantageous, we focused on the selected period for data limitation and to coincide with available land-use and watershed data, which are not available on a continuous basis.

GIS data layers for each factor influencing baseflow are compiled from MassGIS, USDA-NRCS, and USEPA's BASINS. GIS layers from the MassGIS include (1) the 2007 impervious surface layer, (2) the 2005 land-use layer that was used to derive the forest cover layer, and (3) the 2010 NRCS-SSURGO-Certified Soils layer that was used to prepare the slope layer [36]. The soil layer was obtained from the NRCS Soil Data Mart [37]. The precipitation values (x_4) for weather stations for the flow period were compiled from NCDC and BASINS [38]. Finally, the nonlinear regression functions were fitted using SYSTAT 13 (Systat Software, Inc., San Jose, CA, USA).

To assess baseflow levels (Y), a baseflow analysis was conducted to separate baseflow and surface runoff components of streamflow using a baseflow separation algorithm in Hydrograph Separation—HYSEP—software v2.2 [28,39,40]. A local-minimum method [28] was used to estimate the average annual baseflow in each watershed, similar to the approach Hodgkins and Dudley [15] used for baseflow analysis in New England. The HYSEP model was used because of its consistent estimation method for separating baseflow from storm flow components. The local minimum method represents the overall trend of the baseflow more precisely than other methods [39]. For the HYSEP local-minimum method, the gauging stations were classified according to the observation period (n-interval). The n value was based on the sub-watershed area associated with each gauging station. The area was taken to the two-tenths power, $n = A^{0.2}$, for the nth interval.

Spatial information on various factors was quantified for the sub-watershed using GIS. Hard impervious cover was used, including buildings, roads, parking lots, bricks, asphalt, concrete, and compacted soils such as mined areas or unpaved parking lots without vegetation [36]. The impervious surface layer (x_1) was represented as impervious (one) and pervious (zero) values for each one-meter square cell (raster) for the Commonwealth of Massachusetts. The forest coverage (x_2) was derived from the 2005 land-use layer for Massachusetts and expressed as percent area for urban and rural land-use types in subbasins. The slope layer was based on the Natural Resource Conservation Service (NRCS) SSURGO-Certified Soils, a MassGIS layer, and area weighted for each watershed.

The BASINS 4.0 (Better Assessment Science Integrating Point and Nonpoint Sources) program was used to compile the precipitation data from the NCDC of the National Oceanographic and Atmospheric Administration (NOAA) for thirteen precipitation-monitoring sites in Massachusetts. GIS was used to create an interpolated precipitation surface using spline interpolation for each watershed. The 2010 soil data from the Natural Resource Conservation Service (NRCS) were used to derive the soil drainage class for each watershed. Seven drainage classes, defined by the NRCS GIS Soil Data Viewer extension, included excessively drained, somewhat excessively drained, well-drained, moderately well-drained, somewhat poorly drained, poorly drained, and very poorly drained. The drainage classes were assigned integer values from 1 (very poorly drained) to 7 (excessively drained). The soil drainage classes (x_3) for each watershed were calculated through area-weighted aggregation.

Annual baseflows of each watershed (Y) were assessed using scatter plots for the presence of any outliers and to specify the overall functional form. No severe outliers were observed, and the relationship was nonlinear. Thus, a multiple regression equation with a nonlinear form (linear and interaction terms) was identified as the best model to explain the data. The significance of the F-statistic is used to assess the goodness of fit to identify the best multivariate specification.

3. Results

The attribute levels in each watershed in the study varied widely across the 29 watersheds of the state (Table 1). Study watersheds ranged in size from 1.14 square miles (sq. mi.) or 2.95 Km^2 (Miscoe watershed) to 260 sq. mi. or 673.40 Km^2 (Taunton watershed). They varied in their level of urbanization characterized by a low, 2.04%, impervious surface in the West Farmington watershed to a high, 26.35%, surface in the Old Swamp watershed, and a low, 0.24%, forest cover in the East Swift watershed to 94% in the Ware River watershed. As a result of these variations and the variations in soils, slopes, precipitation, and drainage, the daily means of baseflow ranged from 0.49 cubic feet per second (cfs) or 0.014 m^3/s (Mine Brook watershed) to 3.08 cfs or 0.087 m^3/s (Jones watershed).

The results of the nonlinear multiple-regression model for these watershed factors are presented in Table 2. The adjusted R^2 value is estimated at 0.62, indicating an explanatory power of 62% of the variation in the average annual baseflow. The percent impervious surface and the interaction between impervious cover and precipitation are highly significant at 1%. The coefficient of the slope is significant at a 5% level. Interactions between forest coverage and soils, soil and precipitation, and precipitation and slope are significant at 10%. The F-statistic (Table 3) is significant at a 1% level and confirms that at least one of the independent variables is statistically significant [41]. The modeled equation predicts baseflow at mean levels of independent variables in the study watersheds. The model prediction is compared to observed values and presented in Figure 2. The figure shows that the predictive model performs well concerning the observed data, with an R^2 value of 0.83. The distribution showed a reasonable correlation and explanatory power between the observed and simulated values. The Shapiro–Wilk test [42] (Shapiro and Wilk, 1965) was used to test the normality of residuals. The results confirmed the normality of residuals.

Table 1. Watershed attributes and baseflows.

Subwatershed	Area (sq. mi)	Baseflow (Daily mean)	Impervious Cover (%)	Forest Cover (%)	Soil Drainage (Mean)	Precipitation (inches)	Slope (%)
Aberjona	27.11	2.01	32.87	24.11	2.46	40.67	6.18
Assabet	117.30	1.49	11.97	49.31	3.41	40.67	7.70
E Housa	57.51	1.52	3.59	73.32	3.42	41.67	14.07
E Neponset	27.21	1.75	27.54	17.27	3.33	41.03	5.86
Eswift	43.66	1.35	1.66	0.24	3.40	42.95	14.77
Indian Head	29.89	2.21	19.75	33.02	3.03	45.13	4.14
Jones	13.73	3.08	10.41	43.32	3.53	47.28	5.81
MineBrook	5.99	0.49	8.69	52.16	3.89	38.88	8.00
Miscoe	1.14	0.72	5.85	60.53	3.36	40.67	7.75
Nashoba	12.86	0.83	10.73	51.34	3.22	40.67	6.75
Neponsett	32.77	1.66	23.93	40.93	3.23	39.96	6.20
Old Swamp	4.47	1.26	26.35	34.05	3.60	43.83	7.11
Parker	21.39	1.75	7.26	51.67	2.98	40.67	9.06
Quaboag	150.18	1.68	4.63	64.69	3.35	42.95	10.27
Quinsigamond	25.63	1.53	20.39	34.86	3.15	40.67	7.43
Segreganset	10.60	1.33	7.10	2.14	2.57	45.24	4.16
Stillwater	30.38	1.68	3.95	73.76	3.81	41.90	11.10
Tauton	260.16	1.53	22.38	37.69	2.88	45.38	4.32
Wfarm	91.24	1.54	2.04	80.61	3.28	43.78	14.97
Ware	54.96	1.40	3.44	94.05	3.05	42.95	10.90
Ipswich	45.37	1.20	15.93	37.25	2.94	40.67	5.96
Wading	43.45	2.08	22.62	44.54	3.24	53.04	4.89
3Mile	85.47	1.37	20.72	47.84	0.61	43.47	4.48
Ipswich29	126.67	1.45	12.22	44.10	2.93	41.21	7.81
SevenMile	8.69	2.30	3.21	0.92	3.46	42.95	10.80
Shawsheen	31.40	1.52	19.70	29.82	2.90	40.61	5.25
Sudbury92	105.21	1.35	16.82	40.71	3.03	38.86	6.96
Ware2	198.17	1.38	3.45	33.49	3.61	42.95	13.37

Table 2. Regression results.

Variable	Effect	Coefficient	Significance
α	Intercept	−0.785	
x_1	Impervious Surface	0.941	***
x_2	Forest Cover	−0.056	
x_3	Soil Drainage Class	−8.392	
x_4	Precipitation	−0.077	
x_5	Slope	2.994	**
$x_1 \times x_2$	Impervious and Forest	0.001	
$x_2 \times x_3$	Forest and Soil	−0.031	*
$x_2 \times x_4$	Forest and Precipitation	0.003	
$x_2 \times x_5$	Forest and Slope	0.003	
$x_1 \times x_3$	Impervious and Soil	−0.045	
$x_3 \times x_4$	Soil and Precipitation	0.250	*
$x_3 \times x_5$	Soil and Slope	0.014	
$x_1 \times x_4$	Impervious and Precipitation	−0.019	***
$x_4 \times x_5$	Precipitation and Slope	−0.075	**
$x_1 \times x_5$	Impervious and Slope	−0.003	

*** 1% level of significance; ** 5% level of significance; * 10% level of significance.

Table 3. Analysis of variation results.

ANOVA	Degrees of Freedom	Sum of Squares	Mean Square	F Statistic	F Significance
Regression	15	5.606	0.374	3.961	0.011
Residual	12	1.132	0.094		
Total	27	6.738			

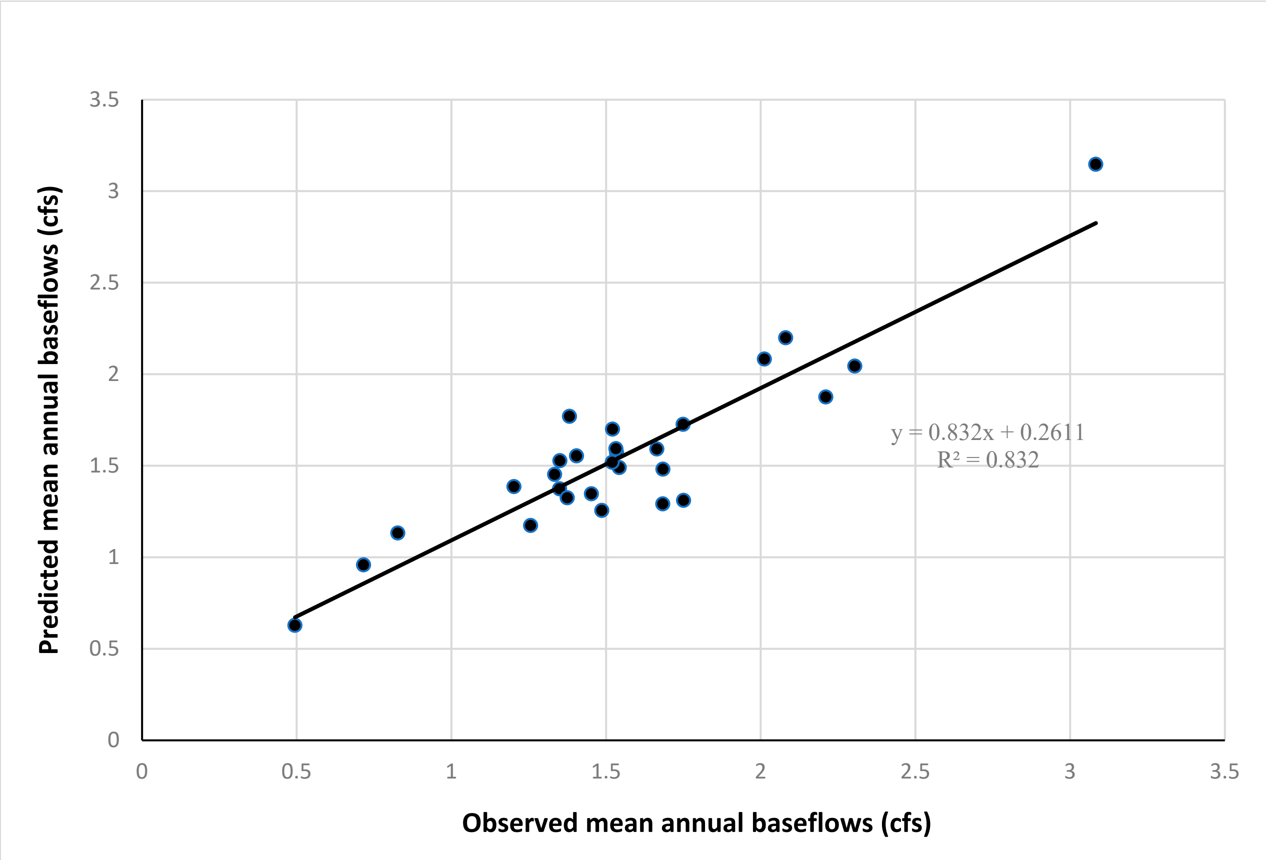

Figure 2. Observed and predicted base flow values.

The observed and predicted values of baseflows in each watershed are presented in Table 4. Deviations from observed values range from −0.44 cfs (0.012 m^3/s) to +0.39 cfs (0.011 m^3/s) in the study watersheds. The predicted values are higher in 15 of 28 watersheds, with an average incremental deviation of 0.15 cfs (0.004 m^3/s). The deviation is negative (lower than observed) in the rest of the watersheds, with an average deviation of 0.17 cfs (0.005 m^3/s). The average deviation in all watersheds is less than 0.01 cfs (0.00003 m^3/s). In general, the model performed well in explaining changes in baseflow in most of the study watersheds.

Marginal Influence of Landscape Variables

The regression function consists of the landscape factors' direct and interaction effects on baseflows. To derive the marginal effect, the first derivative of the equation is used to define the change in the average baseflow for the change in the level of each independent variable. These first derivatives' (marginal) functions are presented in Table 5.

Table 4. Observed and predicted mean annual baseflow values (cfs).

Sub-Watershed	Observed	Predicted	Error
Aberjona	2.01	2.08	+0.07
Assabet	1.49	1.26	−0.23
E Housatonic	1.52	1.7	+0.18
E Neponset	1.75	1.73	−0.02
E Swift	1.35	1.37	+0.02
Indian Head	2.21	1.88	−0.33
Jones	3.08	3.15	+0.06
Mine Brook	0.49	0.63	+0.13
Miscoe	0.72	0.96	+0.24
Nashoba	0.83	1.13	+0.3
Neponset	1.66	1.59	−0.07
Old Swamp	1.26	1.17	−0.08
Parker	1.75	1.31	−0.44
Quaboag	1.68	1.48	−0.2
Quinsigamond	1.53	1.57	+0.04
Segreganset	1.33	1.45	+0.12
Still Water	1.68	1.29	−0.39
Tauton	1.53	1.59	+0.06
W Farmington	1.54	1.49	−0.05
Ware	1.4	1.55	+0.15
Ipswich	1.2	1.39	+0.18
Wading	2.08	2.2	+0.12
Three Mile	1.37	1.32	−0.05
Ipswich Two	1.45	1.35	−0.11
Seven Mile	2.3	2.04	−0.26
Shawsheen	1.52	1.52	0
Sudbury	1.35	1.53	+0.18
Ware Two	1.38	1.77	+0.39

Table 5. Marginal effects of watershed variables on baseflow.

Equation #	Independent Variable (x_i)	$\frac{dB}{dx_1}=\beta_i+\sum_{i\neq j}\beta_{ij}x_j$
(5)	Impervious Surface	$\frac{dB}{dx_1} = 0.941 + 0.001x_2 - 0.045x_3 - 0.019x_4 - 0.003x_5$
(6)	Forest Cover	$\frac{dB}{dx_2} = -0.056 + 0.001x_1 - 0.031x_3 + 0.003x_4 + 0.003x_5$
(7)	Soil Drainage Class	$\frac{dB}{dx_3} = -8.392 - 0.045x_1 - 0.031x_2 + 0.249x_4 - 0.014x_5$
(8)	Precipitation	$\frac{dB}{dx_4} = -0.077 - 0.019x_1 - 0.003x_2 + 0.249x_3 - 0.074x_5$
(9)	Slope	$\frac{dB}{dx_5} = 2.993 - 0.003x_1 + 0.003x_2 - 0.014x_3 - 0.074x_4$

In Equation (5) in Table 5, the marginal effect of impervious cover (x_1) on baseflow is dependent on the levels of forest cover (x_2) in the watershed, as evident from the interaction effect of impervious surface and forest coverage. To enable a more straightforward interpretation, we represent the influence of factors on baseflows using Figure 3. The positive coefficient of the interaction effect shows that an increase in urban forests can increase baseflows in a watershed and mitigate the impact of impervious surface cover. The negative coefficient of interaction variables shows that impervious cover interacts with soil drainage, precipitation, and slope level and can reduce baseflows. Therefore, the adverse effects of impervious surfaces on baseflows exacerbate the reduction that increased soil drainage, increased precipitation, and high slope angles have on baseflow. The influence of impervious cover in soils with high drainage can be through an additional reduction in recharge rates, contributing to lower baseflows. The impact of impervious cover in high precipitation areas also increases runoff, reducing infiltration and reducing baseflows. A similar effect of the impervious surface in high slope areas can be deduced as resulting in lower baseflows, an effect noted by Harbor [43]. In general, forests in impervious areas contribute to increased baseflows, while increased slope, precipitation, and drainage in impervious regions are associated with decreased baseflows.

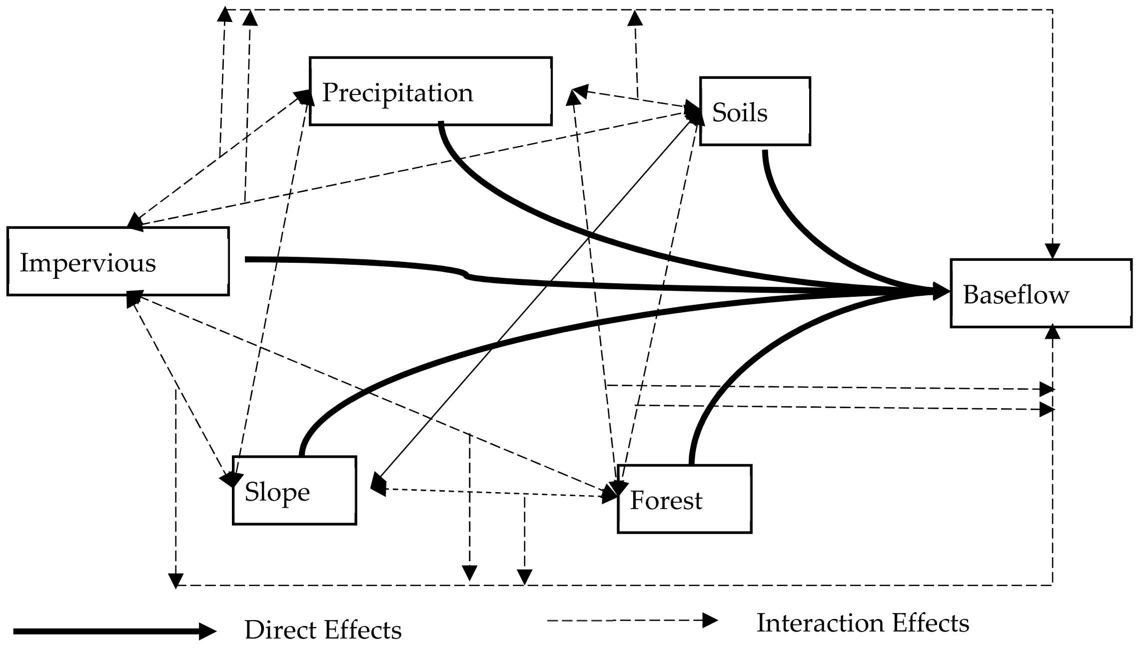

Figure 3. Influence of landscape factors on baseflows.

The marginal function of forest cover (Equation (6), Table 5) shows increased baseflow with increased impervious surface, precipitation, and slope. However, the marginal change in baseflow resulting from an increase in forest cover is negatively influenced by an increase in drainage. This effect can be attributed to vegetation uptake and the shift in subsurface hydrology in forested landscapes. The benefit of forest cover in increasing baseflow is higher in impervious areas because of a change from runoff to infiltration. The influence of forest cover on baseflow is also greater in regions with higher precipitation. The interception process of the forest cover improves infiltration and can increase baseflows in areas with higher precipitation that would otherwise result in storm runoff. Therefore, the effectiveness of forest cover to enhance baseflows is also higher in high-slope watershed systems.

The marginal function of soil drainage (Equation (7), Table 5) shows increased baseflow with increasing precipitation. In watersheds with soils with higher drainage, the influence of soil drainage in increasing baseflow increases with precipitation. This is because of higher input into the infiltration process in the watershed system. A decrease in the influence of soil drainage on baseflow with the impervious area can be because of an increase in runoff components that contribute to stormflow rather than baseflow. A similar decrease in the influence of forest cover can result from vegetation uptake and storage, which reduce baseflow. Slope decreased the effectiveness of soil drainage in influencing baseflows because of an increase in runoff and reduced infiltration. The Soil Conservation Service [25] observed increased baseflow in areas with higher soil drainage.

The marginal function of precipitation (Equation (8), Table 5) is similar to soil drainage. It shows an increase in baseflow with slope. In watersheds with higher precipitation, the influence of soil drainage in increasing baseflow increases with precipitation. This is because of higher input into the infiltration process and higher drainage that contributes to the rise in baseflow. A decrease in the influence of precipitation on baseflow with the impervious area can be because of an increase in the runoff component of the water budget that contributes more to stormflow rather than baseflow. A similar decrease in the influence of forest cover on the marginal effect of precipitation can result from vegetation uptake and vegetation storage, which reduce baseflow. Slope decreased the effectiveness of precipitation in influencing baseflows because of an increase in runoff and reduced infiltration with a higher slope. A similar observation of an increase in baseflow with precipitation was found by Groisman, et al. [44].

The marginal function of slope (Equation (9), Table 5) shows an increase in baseflow with forest cover. In watersheds with higher slopes, the influence of slope in increasing baseflow increases with forest cover. This is because higher input into the infiltration process and higher drainage could increase baseflow. A decrease in the influence of slope on baseflow with the impervious area can be because of an increase in the runoff component of the water budget that contributes more to stormflow than to the baseflow. A similar decrease in the influence of drainage on the marginal effect of slope can result from changes in the infiltration component that affects baseflow. Precipitation decreased the effectiveness of the slope in influencing baseflows because of increased runoff and reduced infiltration with higher precipitation. Castelltort, Simpson, and Darrioulat [45] also observed a decrease in baseflow with increased slope.

4. Discussion

Landscape factors, including soil characteristics, slope, aspect, forest cover, and precipitation volume and duration, also affect infiltration and the resulting baseflow [19,23,24]. Land slope also substantially influences the level of baseflow. High slope angles reduce rainwater's time on the land, thus reducing the available time to infiltrate. Steeper slopes can cause narrower and deeper stream basins with near-parallel rills, while flatter surfaces produce wider basins [29]. The resulting high water velocity in high-slope areas can also cause more damage to streams when there is a lack of stream roughness through large woody debris and boulders that provide microhabitats for aquatic ecosystems [14,45], a typical result of deforestation.

The aspect affects baseflow levels in snow-dominated systems by affecting stream runoff levels [30]. In addition, the aspect affects the amount of solar incidence contrast between the energy inputs for north- and south-facing slopes [31]. The intensity of incoming solar radiation affects snow accumulation, the timing and intensity of snowmelt, and the extent of the snowpack. The slope aspect (flow direction) can also affect infiltration since north-facing aspects in middle latitudes have larger snowmelt, creating more groundwater downstream [32]. Since snowmelt accounts for a large percentage of recharged waters in snow-dominated systems [31], the aspect exerts a larger control on spatial variations in snowmelt [32]. However, when weighing the influences of various factors, Mitchell and DeWalle found little consistent difference in snow cover for different slope aspect zones. They concluded that elevation and land use were more important factors in the Towanda Creek Basin of central Pennsylvania [33].

Finally, precipitation volume and duration affect baseflow [46]. If the precipitation occurs over an extended time, there is a greater chance of filtering into the ground. On the other hand, a sudden deluge of precipitation typically runs off surfaces quickly, reducing infiltration and associated stream baseflow and creating erosion and other flooding problems downstream.

These three characteristics (soil porosity, slope, and precipitation) are fixed landscape factors, meaning they can only be minimally modified by human intervention. On the other hand, the landscape factors of impervious surface and forest cover are mutable and can easily be modified by human intervention. The effects of soil porosity, slope, slope aspect, precipitation, and impervious surface on watersheds and their baseflows can be mitigated by forest cover, particularly mature forest stands. Typically, forest floors are covered with a thick layer of duff that absorbs rainfall and encourages infiltration. However, forest cover can also have a mixed effect on infiltration and baseflow since trees increase transpiration, reducing the amount of groundwater available for baseflow [27,47,48].

This study's most significant policy implication for watershed managers is that stream baseflow must be managed with multiple landscape factors accounted for in the analysis [17]. This is a substantial change from the focus in watershed planning on the single indicator of impervious surface. While the study results support the importance of impervious surfaces as an indicator of watershed impacts, management of those impacts must be more nuanced.

Historically, stormwater management in urban areas focused on diversions that channeled excess water away rather than allowing it to infiltrate [49,50]. While this approach was suitable for removing surface water and avoiding flooding, infiltration was affected, leading to reduced evapotranspiration and altered baseflow regimes. To mitigate this approach while removing unwanted surface water from urban environments, structural stormwater best management practices (BMPs) such as vegetated swales and infiltration, detention, and retention basins have been used to increase infiltration and stabilize baseflows [11]. In addition, Hamel et al. [51] suggest stormwater source control methods to mitigate the impacts of urbanization on baseflows.

An approach to the development of landscape factor-based policy recognizes a variety of techniques based on two levels of management: first, the two discrete variables of impervious surface and forest cover within the watershed, which can be addressed through human action, and second, the dominant fixed attribute or attributes that must be factored into the management of the impervious surface and forest cover balance, particularly as they relate to the stabilization of baseflows in the watershed: (i) soil drainage, (ii) precipitation, and (iii) slope (Figure 3) [17].

The operationalization of this approach must include mapping the fixed landscape factors of the watershed: soils, slopes, and precipitation. By assigning a weighted numerical score to each fixed landscape factor, each landscape subarea of the watershed can be given a weighted score reflective of its fixed characteristics. An increase in impervious cover can be managed through appropriate incentive structures like impervious tax through stormwater utility [52]. Using conservation contracts, cost-sharing to protect forest cover could be used to manage forest cover in watersheds. Settlement policy needs to explicitly consider the service costs of new settlements through increased runoff from urban developments. Infrastructure planning thus needs to incorporate infiltration-enhancing components in the design. Finally, forest management could focus on resilience-enhancing strategies like diverse plant species and urban forestry.

Based on these sub-area scores, watershed zoning can be based on their capacity to accommodate a higher level of impervious surface or their need for a higher land area devoted to forest stands. But, more importantly, these zones can be spatially assigned according to the specific attributes of the sub-watershed, resulting in closer achievement of targeted baseflow goals.

While this study did not explore the impacts of specific site-level BMPs, the guiding zones of effects for the watershed created by this model can then be modified by using selected best management practices tailored to the conditions of the sub-area of the watershed. For example, suppose a greater degree of urbanization is desired in an area of the watershed with steep slopes, low soil permeability, and high precipitation. In that case, development permits can be issued based on a series of best management practices designed to increase on-site infiltration. A further study would be helpful in this respect to quantify the impacts that BMPs have in the watersheds, given the various landscape factors.

The approach is also appropriate for already highly urbanized watersheds, but the goal is to improve the existing baseflow. For example, increased forest stands can be targeted to areas of low soil permeability, high slopes, and high precipitation. Likewise, best management practices to increase infiltration can be targeted to moderate to low soil permeability and high pitches. In contrast, appropriate and larger capacity retention ponds and basins can be targeted in areas of high precipitation.

Rather than a one-size-fits-all, pan-watershed strategy, this approach targets watershed areas where the intervention will produce the highest gain in stabilizing or increasing baseflow. While not strictly an incentive-based policy, the approach provides incentives for encouraging development to locate areas that will cause the most negligible impact on baseflow.

5. Conclusions

Aquatic ecosystems and river geomorphic functions depend on the baseflows in watershed systems. Understanding the influence of landscape factors on baseflows helps manage river flows using policies targeted at specific watershed development practices. Baseflows have received less attention in stormwater management studies because of the complexity and heterogeneity of watershed-scale processes that produce baseflow [53]. This study is unique in quantifying the multi-attribute landscape factors that influence baseflows at a regional watershed scale, a need identified in analyzing baseflows [18,53].

The study analyzes the relationship between watershed characteristics and baseflow using GISs and statistical analyses of streamflow data from twenty-eight watersheds in the Commonwealth of Massachusetts. A multiple regression analysis used to study the influence of soil drainage class, slope, percent impervious surfaces, precipitation, and forest cover on baseflows at the watershed scale found a variety of impacts. The results determined that percent imperviousness and precipitation were the most significant factors affecting baseflow. However, the marginal effect of each landscape factor is derived through the first derivative of the predictive equation, which indicates that the interaction between factors had a substantial impact on baseflows.

Natural land-use features such as open land, wetlands, forests, agriculture, and recreation promote infiltration and increase baseflow. However, regions with characteristic land uses such as high-density/multi-family residential, industrial, and commercial areas are impervious to infiltration and exhibit reduced baseflow. Depending on fixed landscape attributes of their soil drainage class, localized rainfall regime, and slope characteristics, these impacts have differential effects on flows. Developing sub-watershed and area-specific development standards can effectively address baseflows, often resulting from a complex, system-wide process. In addition, education policies could increase the awareness of the benefits of site-specific strategies and are vital to encouraging the voluntary implementation of appropriate, targeted BMPs in sensitive watershed areas.

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