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## Sustaining Environmental Flows in Southern New England Rivers: Effects of Watreshed Factors and Land Use

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**SUSTAINING ENVIRONMENTAL FLOWS IN SOUTHERN NEW ENGLAND RIVERS:  
EFFECTS OF WATERSHED FACTORS AND LAND USE**

**BY**

**ALISA MORRISON**

**A DISSERTATION SUBMITTED IN PARTIAL FULFILLMENT OF THE  
REQUIREMENTS FOR THE DEGREE OF DOCTOR OF PHILOSOPHY**

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OF  
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## ABSTRACT

Rivers and river systems serve as conduits for nutrients and organisms, function as corridors for fish and wildlife passage, and provide resources for humans. Streamflow has been called the master variable in a river because it affects habitat diversity and availability through its impact on physical factors that influence habitat quality. However, land use changes such as urbanization and irrigation, can have major effects on stream hydrology. Modifications of the land surface due to urbanization alters natural stream hydrographs by increasing flood peaks, decreasing time to peak flows, and causing higher runoff velocities. Irrigation may produce the opposite effects.

In order to preserve a spectrum of stream functionality, rivers must maintain seasonally adequate flows. For example, low flows can affect stream connectivity, restrict movement of aquatic organisms, concentrate prey into limited areas, purge invasive species from riparian corridors, and enable recruitment and evolution of floodplain plants. State agencies throughout the Northeast U.S. are considering policies linked to low-flow thresholds that sustain these ecosystem services. Methods that set minimum flow standards often result in conflicting values, due to differing environmental goals and levels of protection they aim to achieve. Two such methods, the USFWS Aquatic Base Flow (ABF) method and the Wetted Perimeter method have been widely used. The USFWS ABF method recommends using the median of August flows and has been refined for Rhode Island (RIABF). The wetted

perimeter method uses stream cross-sections at riffle locations to determine critical flow values to maintain flow based on the wetted perimeter of the channel. In addition to setting flow standards, methods to minimize the adverse effects of urbanization have also been proposed. Low impact development (LID) has emerged as a strategy to reduce the hydrologic impacts of urbanization on aquatic ecosystems by combining site planning and design processes with runoff reduction and treatment practices.

Within a given climatic region, water resource managers seeking to optimize stream ecosystem services need a clear understanding of the importance of land use, physical/climatic characteristics, and hydrography on different components of stream hydrographs. Within 33 Southern New England watersheds (average area 80 km<sup>2</sup>), we assessed relationships between watershed variables and a set of low flow parameters: *1-, 7- and 30- day minimum flows*. We used an information theoretical approach to develop regression models to identify relationships between landscape attributes and parameters that describe different components of the flow regime. The key variables identified by the AIC weighting factors as generating positive relationships with median annual minimum flow events included percent stratified drift (greater infiltration and storage), mean elevation (likely related to higher snowfall), drainage area and mean August precipitation. The extent of wetlands in the watershed was negatively related to low flow magnitudes likely due to the capacity of those ecosystems to remove water from the basins via evapotranspiration during drought conditions. Of the various land use variables, the percent developed land was found to have the highest importance, but it was less

important than wetlands and physical/climatic features. The extent of impervious cover in the study watersheds was primarily less than 10% and the study watersheds were generally larger than watersheds used in other studies relating impervious cover to stream health. Our results suggest that even with watersheds located within close spatial proximity, strategies focused on balancing water extraction to sustain low flows in fluvial systems can benefit from attention to select watershed features. We draw attention to the finding that streams located in watersheds with high proportions of wetlands may require more stringent approaches to withdrawals to sustain these ecosystems during drought periods.

We then determined the minimum flow requirements at three locations (riffle zones) along the Beaver River, located in southern Rhode Island, using both the wetted perimeter method and the RIABF method. In order to determine stream flow at ungaged locations, runoff was modeled using the HEC-HMS rainfall/runoff model.

To assess biological conditions, we reviewed macroinvertebrate, fish and temperature data obtained within the watershed. Biological conditions of the Beaver River indicated that the Beaver River is a well-functioning stream habitat.

Minimum stream flow requirements using ABF and WP methods were investigated. Stream flows were found to be below the ABF value between six to 21% of the time and below the WP flow between 37 to 72% of the time.

Physical and biological sampling done in the watershed indicate the river is a well-functioning, river, comparable to pristine sites; however minimum flow criteria set by the wetted perimeter method suggest that the river is flowing below critical

flow values over 50% of the time. Our results suggest that minimum flow values obtained from the wetted perimeter method for southern New England rivers should be approached with caution and should be compared to results obtained from other methods to determine the accuracy and applicability of the critical flows prior to using these values for any type of instream flow regulations.

We also assessed the effect of increased impervious cover for both conventional and LID-based urbanization on low flow metrics and flow depths in riffle habitats in a small, relatively undeveloped watershed located in southern Rhode Island. We employed a hydrologic model to simulate stream flow, base flow and storm flows under different land cover scenarios and then compared these results to the effects of direct stream withdrawals from agricultural irrigation.

We found baseflow to be negatively correlated to impervious area. On pervious surfaces, direct runoff is likely to be infrequent during the summer months, when most of the precipitation that falls is utilized for the soil moisture deficit. In contrast, connected impervious area (IA) will generate immediate runoff to streams from rainstorms that would have otherwise infiltrated the soil. During periods of excess precipitation, the falling limbs of those hydrographs generated prolonged periods of comparatively elevated flows.

Combining baseflow and storm flow shows that increased values of IA can generate higher flow values during the summer months during periods with excess precipitation. As IA increases through the different land use scenarios, storm related runoff increases immediately following precipitation events, causing higher stream

flows. The small decreases in base flow input to the stream due to increased IA are negated by the impacts of the higher storm flows, causing summer stream flows to be higher under the developed land use scenarios than existing conditions. Changes to the channel depth of the riffles were also relatively minor.

During a year with median precipitation, the model predicted a lower frequency of low flows with both conventional development and with LID compared to the predictions for the limited development present in current conditions. Both conventional development and LID also display fewer low flow periods during a dry year, but the pattern reverses, with LID predicted to have slightly lower frequencies of low flows than the conventional development. Over the summer, storm runoff and the associated falling limb of the runoff hydrograph that results from connected impervious cover occurs with enough frequency to influence the low flow thresholds we use for metrics. During the dry year, rainfall occurrences were very infrequent and the higher baseflow associated with LID accounts for the slight increase in flows compared to the conventional development. Irrigation scenarios decreased both flows and depths. Changes in land use generally increase river flows while water withdrawals decrease river flows. The occurrence of low flows within the Beaver River was found to be relatively resilient to the extent of development and water withdrawals simulated by this study.

These analyses will help inform future water management decisions in watersheds with the diversity of land uses that occur in southern New England.

## ACKNOWLEDGEMENTS

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I would also like to thank the undergraduate students who surveyed the Beaver River riffle zones during the summer of 2009; Caitlyn Johnson, Matt Lautenberger, Lauren Creamer and Erin Markham. I also thank the exceptional people in the Department of Natural Resource Science as well as Naomi Detenbeck and Nathan Smucker from USEPA AED for many helpful conversations and technical advice. Matt Fleming from the USACE was extremely helpful with his knowledge of the HEC-HMS model and providing me with the latest version after he discovered a bug in Version 3.5 which was causing severe errors in my modeling.

I am so grateful for the lasting friendships I made during this journey. The support and friendship of Kelly Addy, Julia Lazar, Peg Pelletier and Eivy Monroy made this experience fun and rewarding.

Most importantly, however, I am grateful for the love and patience of my husband, Rusty, who did all the gardening while I worked on my research. Lastly, my two beautiful daughters, Libby and Sarah, who helped me in the field surveying riffles on their long weekends, kept me going when total frustration set in.

## PREFACE

This dissertation is written in manuscript format with three chapters corresponding to the format of journal articles.

Hypotheses addressed by my dissertation were:

- Hypothesis I: Low flow characteristics of flow regimes in lower-order streams are greatly influenced by anthropogenic watershed attributes.
- Hypothesis II: Methods to develop minimum flow requirements in streams vary widely in their assessment of stream conditions.
- Hypothesis III: As development within a watershed increases, the magnitude, occurrence and duration of low flow conditions will all increase. Irrigation in a watershed will reduce stream flows in the summer. Implementation of low impact development strategies can offset the effects of development within watersheds during low flow stream conditions.

Objectives of my dissertation included:

- Assess which landscape attributes describe the variability of key components of the flow regime.
- Provide insight into the importance of specific variables for explaining the variance in the different flow parameters.
- Use field work to establish estimates of low flow thresholds

- Combine field work with simulation models to examine the capacity of a river to sustain habitat quality during low flow periods.
- Investigate the effects of land use change and irrigation on low flows to the Beaver River (Washington County, Rhode Island) and relate changes in land use to reduction in available habitat within the riffle zones along the length of the river during low flow events.
- Assess mitigating effects of low impact development on low flows.

The first manuscript addresses Hypothesis I and the second manuscript addresses Hypothesis II. The first two manuscripts have been accepted for presentation at the American Water Resources Associations 2013 Summer Specialty Conference on Environmental Flows to be held on June 24-25<sup>th</sup>, 2013.

The third manuscript addresses Hypothesis III and will be submitted to the journal *Ecological Applications*.

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## Chapter 1

### **Evaluating key watershed components of low flow regimes in New England streams**

by

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## Abstract

Rivers and river systems serve as conduits for nutrients and organisms, function as corridors for fish and wildlife passage, and provide resources for humans. In order to preserve a spectrum of stream functionality, rivers must maintain seasonally adequate flows. For example, low flows can affect stream connectivity, restrict movement of aquatic organisms, concentrate prey into limited areas, purge invasive species from riparian corridors, and enable recruitment and evolution of floodplain plants. State agencies throughout the Northeast U.S. are considering policies linked to low-flow thresholds that sustain these ecosystem services. Within a given climatic region, water resource managers seeking to optimize stream ecosystem services need a clear understanding of the importance of land use, physical/climatic characteristics, and hydrography on different components of stream hydrographs. Within 33 Southern New England watersheds (average area 80 km<sup>2</sup>) we assessed relationships between watershed variables and a set of low flow parameters: *1-, 7- and 30- day minimum flows*. We used an information-theoretical approach to develop regression models to identify relationships between landscape attributes and parameters that describe different components of the flow regime. The key variables identified by the Akaike Information Criteria (AIC) weighting factors as generating positive relationships with median annual minimum flow events included percent stratified drift (greater infiltration and storage), mean elevation (likely related to higher snowfall), drainage area and mean August precipitation. The

extent of wetlands in the watershed was negatively related to low flow magnitudes likely due to the capacity of those ecosystems to remove water from the basins via evapotranspiration during drought condition. Of the various land use variables, the percent developed land was found to have the highest importance, but it was less important than wetlands and physical/climatic features. The extent of impervious cover in the study watersheds was primarily less than 10% and the study watersheds were generally larger than watersheds used in other studies relating impervious cover to stream health. Our results suggest that even with watersheds located within close spatial proximity, strategies focused on balancing water extraction to sustain low flows in fluvial systems can benefit from attention to select watershed features. We draw attention to the finding that streams located in watersheds with high proportions of wetlands may require more stringent approaches to withdrawals to sustain these ecosystems during drought periods.

## **Introduction**

Rivers and river systems serve as conduits for nutrients and organisms, corridors for fish and wildlife passage, and provide resources for humans; such as fresh water, food, and opportunities for recreation (Puth and Wilson, 2001). In order to preserve stream functionality, rivers must maintain seasonally adequate flows. Richter et al. (1997) defined a natural flow paradigm where “the full range of natural intra- and inter-annual variation of hydrological regimes and associated characteristics of timing, duration, frequency and rate of change are critical in sustaining the full native biodiversity and integrity of aquatic ecosystems.” These characteristics affect the integrity of a stream through their effects on water quality, energy sources, physical habitat, and biotic interactions (Bunn and Arthington, 2002).

Although annual flow in a stream is largely controlled by the amount and timing of precipitation and evapotranspiration within its watershed, the amount of water at any given time (generally measured by stream flow) may also be influenced by watershed characteristics such as mean elevation, basin slope, hydrography, geology, soils, and land use. Landscape attributes can be classified as land use/land cover variables; physical/climatic variables, including features such as drainage area, geology, precipitation across the watershed, and slope; and hydrography which includes the extent of open water and wetlands within a watershed. Land use changes occur on a rapid temporal scale, are largely driven by human activity and management actions, and can have major effects on stream hydrology. For example, intensive urbanization can increase runoff, cause larger storm peaks, and reduce low

flows (Leopold, 1968; Meyer et al., 2009). Agriculture can exert a variety of effects on flow regimes based on cropping systems and management (Poff et al. 1997; Meybeck, 2003). In contrast, physical/climatic variables may have large impacts on stream flow but are relatively resistant to change due to human activities. Allan (2004) found that when anthropogenic and physical features covary and are used for evaluation, the influence ascribed to land use can be overestimated.

Arthington et al. (2006) argue that management of flow regimes can benefit from analyses that focus on classifying river into management units that have comparable climatic and physiography attributes. Within a given unit, water resource managers can then engage in analyses that further the understanding of the effects of land use, physical/climatic characteristics, and hydrography on different components of the flow regime and related ecological conditions.

Stream flow is often statistically analyzed to characterize the magnitude and probability of various components of the flow regime such as low flows, high flows, and average or median discharges (Richter et al., 1996; Allan, 1995; Olden and Poff, 2003). In this study we focused on the low flow portion of the annual flow regime. Within a set of watersheds with similar climate and physiography, low flows can affect stream connectivity, restrict movement of aquatic organisms, concentrate prey into limited areas, purge invasive species from riparian corridors, and enable recruitment and evolution of floodplain plants (Nilsson and Svedmark, 2002). In particular, extreme events, such as those caused by drought, can be particularly important to the vitality of biotic communities (Naiman et al., 2008). While a number

of approaches have been recommended to establish sustainable flow regimes (Arthington et al., 2006; James et al. 2012), state agencies throughout the Northeast U.S. are considering policies linked to low-flow thresholds that sustain these ecosystem services (CTDEEP, 2011; Richardson, 2005).

We used model selection procedures to assess relationships between watershed basin characteristics and the following parameters of the flow regime: *magnitude of minimum flows* (such as the one day minimum flow) and the *magnitude of low pulse (25<sup>th</sup> flow percentile)*. Minimum flows (i.e., annual seven day low flow) represent conditions that are understandable to local and state decision makers and occur with enough frequency to generate meaningful statistics from 30 years of data (James et al., 2012).

Specifically, we examined the importance of various landscape variables in predicting variations in daily flows for low flow components of flow regimes within 33 Southern New England watersheds during the same 30 year period (1980-2009). We used an information theoretical approach (Burnham and Anderson, 2002) to develop regression models to identify relationships between landscape attributes and flow components, with the flow components as the dependent variable and the watershed characteristics as the explanatory or independent variables. Exploring the strength of relationships between specific watershed variables and flow regime can contribute to the development of land use and water extraction policies that sustain fluvial ecosystems.

## Methods

### *Site Selection*

Study sites were selected using NHDPlus StreamGageEvent data ([www.horizon-systems.com](http://www.horizon-systems.com)) and from the United States Geological Survey (USGS) National Water Information System (NWIS) Real Time Water Data website (<http://waterdata.usgs.gov/nwis/rt>). Site selection focused on watersheds that were similar in size (area), physiography, dates of continuous flow data, and within a single ecoregion. Ecoregions combine biotic and abiotic phenomena that are expected to influence ecological integrity and environmental quality (Olson, et al., 2001). There are 766 stream gages located in New England in the NHDPlus StreamGageEvent data set. We eliminated the 279 gages located to the west of the Connecticut River to restrict the physiography to settings dominated by glacial deposits. The surficial geologic materials in eastern New England are primarily glacial. These unconsolidated glacial deposits vary in thickness across the region. The most common glacial deposit in New England is glacial till, a well-graded material with grain sizes ranging from clay to large boulders. Glacial stratified deposits occur in the coastal or valley areas and consist of layers of sand and gravel. Till deposits have a much lower permeability than the coarse-grained stratified deposits and often have restrictive layers that generate seasonal wetness. We further eliminated 92 gages that had drainage areas under 5 mi<sup>2</sup> (12.95 km<sup>2</sup>) and 189 gages that had drainage areas over 75 mi<sup>2</sup> (194.25 km<sup>2</sup>). To establish a common set of long-term flow

patterns the number of potential gages was reduced by 165 as we sought watersheds that had the same 30 year period of daily stream continuous flow gaging data, from January 1, 1980 to December 31, 2009, by the USGS. Lastly, sites were selected from watersheds within the Northeast Coastal Ecoregion (Omernik, 1995). Using these criteria, 33 sites (Table 1, Figure 1) were selected for analysis. Watersheds for the selected stream gages were delineated using NHDPlus Basin Delineator software and were visually checked for accuracy using USGS 7.5 minute quadrangles (1:24,000) and associated NHDPlus catchment areas (1:100,000).



USGS Site Number	Station Name	Drainage Area	Site Longitude	Site Latitude	Min Flow	Average Daily Flow
1117420	USQUEPAUG RIVER NEAR USQUEPAUG, RI	93.50	-71.6048	41.4768	0.03	2.17
1117350	CHIPUXET RIVER AT WEST KINGSTON, RI	24.84	-71.5512	41.4823	0.01	0.61
1117468	BEAVER RIVER NEAR USQUEPAUG, RI	22.97	-71.6281	41.4926	0.03	0.60
1118000	WOOD RIVER AT HOPE VALLEY, RI	187.51	-71.7165	41.4982	0.28	4.38
1117800	WOOD RIVER NEAR ARCADIA, RI	91.17	-71.7206	41.574	0.12	2.14
1117000	HUNT RIVER NEAR EAST GREENWICH, RI	59.31	-71.4453	41.6412	0.00	1.33
1123000	LITTLE RIVER NEAR HANOVER, CT.	77.70	-72.0523	41.6718	0.10	1.59
1116000	SOUTH BRANCH PAWTUXET RIVER, WASHINGTON, RI	162.65	-71.5659	41.6901	0.08	3.70
1192500	HOCKANUM RIVER NEAR EAST HARTFORD, CT.	190.10	-72.5873	41.7832	0.03	3.31
1114000	MOSHASSUCK RIVER AT PROVIDENCE, RI	59.83	-71.4112	41.834	0.05	1.13
1109070	SEGREGANSET RIVER NEAR DIGHTON, MA	27.45	-71.1428	41.8404	0.00	0.62
1121000	MOUNT HOPE RIVER NEAR WARRENVILLE, CT.	74.07	-72.169	41.8437	0.01	1.47
1114500	WOONASQUATUCKET RIVER AT CENTERDALE, RI	99.20	-71.4873	41.859	0.06	2.08
1184490	BROAD BROOK AT BROAD BROOK, CT.	40.14	-72.55	41.9139	0.05	0.70
1109000	WADING RIVER NEAR NORTON, MA	112.15	-71.1767	41.9476	0.01	2.07
1111300	NIPMUC RIVER NEAR HARRISVILLE, RI	41.44	-71.6859	41.9812	0.00	0.85
1105870	JONES RIVER AT KINGSTON, MA	51.28	-70.7336	41.9909	0.02	0.94
1105730	INDIAN HEAD RIVER AT HANOVER, MA	78.48	-70.8225	42.1007	0.01	1.77

Table 1 – Summary statistics of watersheds included in study. Flow values represent minimum, maximum and average daily flows for the period between 1980 and 2009. Drainage area is in square kms and flow values are in cubic meters per second ( $\text{m}^3 \text{s}^{-1}$ )

USGS Site Number	Station Name	Drainage Area	Site Longitude	Site Latitude	Min Flow	Average Daily Flow
1123360	QUINEBAUG RIVER AT FISKDALE, MA	162.13	-72.1237	42.1087	0.06	3.70
1105500	EAST BRANCH NEPONSET RIVER AT CANTON, MA	70.45	-71.1459	42.1545	0.02	1.46
1105000	NEPONSET RIVER AT NORWOOD, MA	89.87	-71.2009	42.1776	0.02	1.59
1110000	QUINSIGAMOND RIVER AT NORTH GRAFTON, MA	66.30	-71.7109	42.2304	0.00	1.16
1175670	SEVENMILE RIVER NEAR SPENCER, MA	22.82	-72.0048	42.2651	0.00	0.42
1174500	EAST BRANCH SWIFT RIVER NEAR HARDWICK, MA	113.18	-72.2387	42.3934	0.00	2.03
1172500	WARE RIVER NEAR BARRE, MA	142.71	-72.0245	42.4251	0.00	2.68
1102500	ABERJONA RIVER AT WINCHESTER, MA	63.97	-71.1389	42.4473	0.01	0.85
1097300	NASHOBA BROOK NEAR ACTON, MA	33.15	-71.4042	42.5126	0.00	0.57
1100600	SHAWSHEEN RIVER NEAR WILMINGTON, MA	94.53	-71.2148	42.5681	0.02	1.66
1101500	IPSWICH RIVER AT SOUTH MIDDLETON, MA	115.25	-71.027	42.5695	0.00	1.82
1094400	NORTH NASHUA RIVER AT FITCHBURG, MA	166.28	-71.7881	42.5762	0.07	3.38
1096000	SQUANNACOOK RIVER NEAR WEST GROTON, MA	170.68	-71.6578	42.6343	0.06	3.17
1101000	PARKER RIVER AT BYFIELD, MA	55.17	-70.9456	42.7529	0.00	1.05
1073000	OYSTER RIVER NEAR DURHAM, NH	31.34	-70.9651	43.1487	0.00	0.55

Table 1 (cont.)– Summary statistics of watersheds included in study. Flow values represent minimum, maximum and average daily flows for the period between 1980 and 2009. Drainage area is in square kms and flow values are in cubic meters per second ( $m^3s^{-1}$ )

### *Watershed Variables*

The United States Geologic Survey has tailored sets of state-specific regression equations that can be used to determine components of the flow regime based on physical and climatic features. These equations emerge from long-term USGS daily flow data of gaged watersheds and the state-specific equations often estimate different aspects of the flow regime. For example, Connecticut (Ahearn, 2004) has developed regression equations for the flood magnitude of the 2-, 10-, 25-, 50-, 100- and 500-year recurrence intervals. Massachusetts (Ries and Friesz, 2000) has developed equations for a broader spectrum of the flow regime, the 99-, 98-, 95-, 90-, 85-, 80-, 75-, 70-, 60-, and 50-percent duration flows as well as for the 7-day 2-year and the 7-day 10-year low flows. In addition, each state used different sets of watershed variables to develop the regression equations. Connecticut regression equations for nonurban watersheds used drainage area, 24-hour rainfall for the selected recurrence interval, and mean basin elevation (Ahearn, 2004). In contrast, Massachusetts regression equations used drainage area, area of stratified drift normalized to total stream length, mean basin slope, and a regional coefficient based on the location of the basin in either the eastern or western portion of the state (Ries and Friesz, 2000). For this study, we developed regression models using the collection of all variables that were used in the final regression equations for those states within the study area - Massachusetts, Rhode Island, New Hampshire (Olson, 2009), and Connecticut (Table 2). The variables were elevation difference (used to represent the variables of mean basin slope and mean channel slope), percent

stratified drift, drainage area, mean April precipitation, mean August precipitation, mean basin elevation, and drainage density (the ratio of the total stream length to the watershed area, referred to as stream density in the RI models).

Channel slope (used in New Hampshire) and mean basin slope (used in Massachusetts) were not included in the regression models due to their high correlation ( $p < 0.001$ ) with elevation difference. The regional factor used in Massachusetts was also not included as it could not be used across our study region. In addition to these physical and climatic variables, we also included land use variables and one additional hydrographic variable (extent of open water) in the models. Additional land use categories were aggregated into five groups -- developed, impervious, forest, cultivated, and pasture/hay -- and the percent cover for each category was tabulated and then normalized by area for each watershed. The extent of open water was also calculated and normalized by basin area for each watershed. Metrics of watershed attributes were calculated using ArcGIS 9.3 (Environmental Systems Research Institute, Redlands, CA).

Basin characteristics were tabulated in ArcGIS from datasets from the National Hydrography Dataset, the 2001 National Land Cover Data (Multi-resolution Land Characteristics Consortium, 2003), soil geographic database (STATSGO; U.S. Geologic Survey, 1995), and the National Wetlands Inventory (U.S. Fish and Wildlife Service, 2007). Average April and August rainfall data were obtained from PRISM (Parameter-elevation Regressions on Independent Slopes Model; PRISMGroup, Oregon State University, 2006).

To assess the stability of land use within the watersheds over the study period, we used the 10 year retrofit land cover change product compiled from the 1992 and 2001 National Land Cover Datasets (30 m resolution) (Fry et al., 2009). The NLCD 1992/2001 Retrofit Land Cover Change Product was developed to provide an accurate change analysis, using a specially developed methodology to provide land cover change information at a regional by relying on decision tree classification of Landsat satellite imagery from 1992 and 2001. Unchanged pixels between the two dates are coded with the class code, while changed pixels are labeled with a "from-to" land cover change value. This data set assures that comparisons in land cover change for all the watersheds were derived from the same methods and time period. Based on these data, there was little land use change between 1992 and 2001 within the watersheds. On average, the amount of land use change within the study watersheds was 2.5% with the majority of change, approximately 1% of watershed land use, shifting from forested land to agricultural land.

All watershed variables were evaluated using Pearson Product Moment correlation (Ott and Longnecker, 2010) to minimize the use of redundant variables in the analyses of the relationship between watershed variables and the individual components of flow regime. The correlation between percent total developed area and percent forested area within a watershed was found to be highly significant ( $p < 0.001$ ) and negatively correlated ( $r = -0.92$ ), so percent forested area was not included in the final regression models (Table 3). Additionally, the correlation

between percent impervious cover in the watersheds and percent total developed area was found to be highly significant ( $p < 0.001$ ) and positively correlated ( $r = 0.94$ ).

	Variables used in Regression Equations
New Hampshire (Olson, 2009)	<ul style="list-style-type: none"> <li>• Drainage Area</li> <li>• Mean April Precipitation</li> <li>• Percent of wetlands</li> <li>• Channel Slope</li> </ul>
Connecticut (Ahearn, 2004)	<ul style="list-style-type: none"> <li>• Drainage Area</li> <li>• 24 hour rainfall corresponding to flood frequency of interest</li> <li>• Mean basin elevation</li> </ul>
Massachusetts (Ries and Friesz, 2000)	<ul style="list-style-type: none"> <li>• Drainage Area</li> <li>• Stratified Drift per unit total stream length</li> <li>• Regional factor (East or West)</li> <li>• Mean Basin Slope</li> </ul>
Rhode Island (G. Bent, Personal Communication, Dec. 12, 2011)	<ul style="list-style-type: none"> <li>• Drainage Area</li> <li>• Stream Density</li> </ul>

Table 2 – Variables used in regression equations for New Hampshire, Connecticut, Massachusetts and Rhode Island

Variable	Mean	Std Dev	Minimum	Maximum
Developed	0.24	0.21	0.04	0.79
Pasture/Hay	0.06	0.041	0.018	0.19
Cultivated	0.01	0.03	0.00	0.19
Drainage Density	1.22	0.24	0.67	1.64
Wetlands	0.11	0.05	0.02	0.20
Open Water	0.02	0.015	0.001	0.07
Elevation Difference	167.71	100.10	56.28	490.30
Mean Elevation	15.94	85.27	25.61	304.52
Drainage Area	87.62	49.88	22.82	190.10
Stratified Drift	0.51	0.26	0.004	1.000
Mean April Precipitation	10.50	1.74	10.25	11.75
Mean August Precipitation	10.49	.81	8.67	11.63

Table 3 –Summary Statistics for Landscape variables included in regression models. April and August precipitation variables are annual mean values, in centimeters. Drainage Density (km of stream length/watershed area) is in km/km<sup>2</sup>. Elevation difference and mean elevation are in meters. Drainage area is in square kilometers. Land use and geologic variable (Forest, Developed, Stratified Drift, Wetlands, Open Water, Pasture/Hay, and Cultivated) are normalized by watershed area.

### *Flow Components*

Flow components (Table 4) were calculated using Indicators of Hydrologic Alteration software v7.1 (Smythe Scientific Software, 2010). This software uses stream gage data and statistically characterizes hydrologic variations within each year and across a range of years for a set of flow components. Each IHA/EFC (Indicator of Hydrologic Alteration/Environmental Flow Components) component is analyzed for five characteristics of hydrologic systems: magnitude, timing, frequency, duration, and rate of change. The software calculates each flow statistic for each year and then calculates the median for an overall value for each flow component for the analysis period. For any year, the one day minimum flow is the lowest single daily value occurring during the year and the multi-day minimum is the lowest multiday average occurring during the year. The 1-day, 7-day (weekly), and 30-day (monthly) minimum flows were used. A low flow pulse threshold was defined for this analysis as the 25<sup>th</sup> percentile of all daily values (often referred to as the  $Q_{75}$ ) for the entire flow record. This suite of values representing low water conditions and low flow extremes provides a measurement for environmental stress that occurs during various time periods throughout the years of record.

	One day min	Seven day min	Thirty day min	Low pulse threshold
ABERJONA RIVER AT WINCHESTER, MA	0.07	0.10	0.16	0.27
BEAVER RIVER NEAR USQUEPAUG, RI	0.09	0.10	0.13	0.22
BROAD BROOK AT BROAD BROOK, CT.	0.23	0.28	0.32	0.40
CHIPUXET RIVER AT WEST KINGSTON, RI	0.07	0.10	0.14	0.26
HOCKANUM RIVER NEAR EAST HARTFORD, CT.	1.02	1.13	1.33	1.70
HUNT RIVER NEAR EAST GREENWICH, RI	0.13	0.16	0.24	0.43
INDIAN HEAD RIVER AT HANOVER, MA	0.12	0.14	0.24	0.54
IPSWICH RIVER AT SOUTH MIDDLETON, MA	0.03	0.03	0.08	0.43
JONES RIVER AT KINGSTON, MA	0.19	0.22	0.28	0.43
LITTLE RIVER NEAR HANOVER, CT.	0.18	0.20	0.27	0.45
MOSHASSUCK RIVER AT PROVIDENCE, RI	0.16	0.20	0.28	0.37
MOUNT HOPE RIVER NEAR WARRENVILLE, CT.	0.06	0.07	0.16	0.36
NASHOBA BROOK NEAR ACTON, MA	0.02	0.03	0.05	0.14
EAST BRANCH NEPONSET RIVER AT CANTON, MA	0.17	0.20	0.28	0.48
NEPONSET RIVER AT NORWOOD, MA	0.12	0.16	0.24	0.51
NIPMUC RIVER NEAR HARRISVILLE, RI	0.03	0.03	0.05	0.15
NORTH NASHUA RIVER AT FITCHBURG, MA	0.26	0.37	0.54	1.07
OYSTER RIVER NEAR DURHAM, NH	0.02	0.03	0.05	0.12
PARKER RIVER AT BYFIELD, MA	0.01	0.01	0.03	0.22
SOUTH BRANCH PAWTUXET RIVER AT WASHINGTON, RI	0.78	0.85	0.99	1.56
QUINEBAUG R BL E BRIMFIELD DAM AT FISKDALE, MA	0.27	0.33	0.45	1.10
QUINSIGAMOND RIVER AT NORTH GRAFTON, MA	0.04	0.06	0.18	0.40
SEGREGANSET RIVER NEAR DIGHTON, MA	0.00	0.00	0.01	0.07
SEVENMILE RIVER NEAR SPENCER, MA	0.01	0.02	0.03	0.11
SHAWSHEEN RIVER NEAR WILMINGTON, MA	0.08	0.15	0.30	0.49
SQUANNA COOK RIVER NEAR WEST GROTON, MA	0.33	0.36	0.47	0.88
EAST BRANCH SWIFT RIVER NEAR HARDWICK, MA	0.12	0.13	0.26	0.66
USQUEPAUG RIVER NEAR USQUEPAUG, RI	0.35	0.41	0.51	0.85
WADING RIVER NEAR NORTON, MA	0.11	0.14	0.20	0.51
WARE RIVER NEAR BARRE, MA	0.08	0.10	0.22	0.70
WOOD RIVER NEAR ARCADIA, RI	0.33	0.36	0.41	0.74
WOOD RIVER AT HOPE VALLEY, RI	0.72	0.79	0.92	1.66
WOONASQUATUCKET RIVER AT CENTERDALE, RI	0.24	0.28	0.39	0.68

Table 4 – Low flow components for the selected watersheds. Components were generated from the IHA software version 7.1. Results are the median annual flow component for the watershed over the time period 1980-2009. Minimum flows and low flow threshold are measured in cubic meters per second ( $m^3 s^{-1}$ ).

## *Statistical Methods*

Multiple linear regression models between the flow components and landscape variables were developed using PROC REG in SAS 9.1 (SAS Institute 2002-2003). Multiple regression techniques provide mathematical equations to describe the empirical relationship between a dependent or response variable, such as one day minimum flow, and two or more independent, or explanatory, variables, such as drainage basin characteristics and land use. Multiple linear regressions were used to determine sets of variables that explained the variations in observed flow regime components. Akaike Information Criteria (AIC) was then used to evaluate the relative strength of the models and provide insight into the importance of specific variables for explaining the variance in the different flow parameters.

Regression equations for flood frequency and hydrologic characteristics are generally log-normally distributed. The variables were transformed to logarithms prior to inclusion in the models in order to satisfy the assumptions of regressions, such as linearity of the relationship between the independent and dependent variables and equality of variance about the regression line.

Instead of using a null hypothesis method, we used a model selection approach where many competing hypotheses are tested to identify a set of possible models. Those models are then compared by evaluating relative support for each model as well as each included variable. Model selection approaches are becoming more widespread among ecologists and are ideal for making inferences from observation data (Johnson and Omland, 2004). Model selection criteria, such as AIC,

account for both model complexity and fit. These approaches do not simply compare models by calculating a measure of fit, such as  $R^2$ , and then maximizing that value. They also recognize that parsimony is a bias-variance tradeoff. Using too few parameters in a model can underfit the model and may fail to identify all important variables, while conversely, using too many variables or overfitting a model may lead to spurious correlations. Because  $R^2$  will always increase with the addition of more variables, simply maximizing  $R^2$  will always favor fuller, more variable-rich models. This approach, however, ignores problems with overfitting and parsimony. AIC is a measure of goodness of fit where lower values indicate that less information is lost.

Regression models were developed from all possible combinations of available independent variables. Once the full suite of regression analyses were run, rather than selecting a single “best” predictive model, our objective was to use the model results to evaluate the relative importance of individual independent variables for different characteristics of the flow regime components (Burnham and Anderson 2002). Models were initially selected using Mallows’s  $C_p$  (Dowdy and Wearden 1985), a penalized least squares statistic. Mallows’s  $C_p$  is an estimate of the standardized least mean square error of prediction.  $C_p$  statistic is a compromise between maximizing the explained variance by including all relevant variables and minimizing the standard error by keeping the number of variables as small as possible. The fifty models with the lowest  $C_p$  value were used to determine relative importance of individual independent variables and AIC (Agresti 1996), a penalized log-likelihood statistic, was calculated for these models. Models were compared based on the

differences in AIC, correcting for small sample sizes ( $AIC_c$ , Burnham and Anderson, 2002). The best models have the lowest  $AIC_c$ . Ranking of competing models is based on the relative difference between the lowest  $AIC_c$  value and the  $AIC_c$  value of the competing model. For each flow component,  $\Delta AIC_c$  was computed ( $\Delta AIC_c = AIC_{\text{individual model}} - AIC_{\text{min}}$ ). The weight of each model,  $AIC_w$ , is calculated as  $AIC_w = \exp(-\frac{1}{2} * \Delta AIC_{\text{individual model}}) / \sum \exp(-\frac{1}{2} * \Delta AIC_{\text{all models}})$ . Summing weights across all competing models ( $w_i$ ) that include a particular variable gave an estimate of relative importance of each independent variable in explaining variation in the dependent variables (Burnham and Anderson 2002).  $w_i$  values vary from 0 to 1, with a variable that appears in every model having an  $w_i$  equal to 1. We used a  $w_i$  value greater than 0.8 as a threshold to highlight important predictors of flow components.

Within the field of water resources, AIC weights have been used to assess stream flow characteristics (Wen et al., 2011; Hawley and Bledsoe, 2011) and the relative importance of watershed features on fluvial fish populations. (Roy et al. 2007; Kanno and Vokoun, 2010)

## Results

In comparing the components of the low flow regime across the top five models (Table 5), we found all models were significant at the  $p < 0.001$  significance level. Selected physical/climatic variables and the percentage wetlands were the most important variables (Table 6) for explaining the variability of the magnitude of the most extreme low flow events (1, 7 and 30 day minimum flow rates). The key

variables identified by the AIC weighting factors as generating positive relationships with median annual minimum flow events included percent stratified drift, mean elevation, drainage area, and mean August precipitation. The extent of wetlands in the watershed was negatively related to low flow magnitudes. Of the various land use variables, the percent developed land was found to have the highest importance in explaining the variability of the more extreme low flow events and, similar to the wetlands, was negatively related to flow magnitude.

		Land Use Variables			Hydrographic Variables		Physical/ Climatic Variables									
Obs	Flow Regime Variable	Percent Developed	Percent Pasture /Hay	Percent Cultivated	Percent Open Water	Percent Wet-lands	Elev. Diff.	Percent Stratified Drift	Drainage Area	Apr Precip	Aug Precip	Mean Elevation	Drain-age Density	R2	Adj. R <sup>2</sup>	Pr>F
1	One Day Min	x				x	x				x	x		0.78	0.73	<.0001
2	One Day Min	x		x		x	x				x	x		0.79	0.73	<.0001
3	One Day Min	x			x	x	x	x			x	x		0.78	0.72	<.0001
4	One Day Min	x				x	x	x			x	x	x	0.78	0.72	<.0001
5	One Day Min	x				x	x	x	x		x	x		0.78	0.72	<.0001
1	Seven Day Min	x				x	x				x	x		0.79	0.74	<.0001
2	Seven Day Min	x		x		x	x				x	x		0.80	0.74	<.0001
3	Seven Day Min	x			x	x	x	x			x	x		0.79	0.73	<.0001
4	Seven Day Min	x		x	x	x	x	x			x	x		0.80	0.73	<.0001
5	Seven Day Min	x	x	x		x	x	x			x	x		0.80	0.73	<.0001
1	Thirty Day Min			x		x	x	x			x	x		0.82	0.78	<.0001
2	Thirty Day Min	x		x		x	x	x			x	x		0.83	0.78	<.0001
3	Thirty Day Min	x				x	x	x			x	x		0.82	0.78	<.0001
4	Thirty Day Min		x	x		x	x	x			x	x		0.82	0.78	<.0001
5	Thirty Day Min			x	x	x	x	x			x	x		0.82	0.77	<.0001
1	Low Pulse Threshold			x	x		x	x	x		x	x		0.93	0.91	<.0001
2	Low Pulse Threshold	x			x	x		x	x		x	x		0.93	0.91	<.0001
3	Low Pulse Threshold			x			x	x	x		x	x		0.93	0.91	<.0001
4	Low Pulse Threshold			x		x		x	x		x	x		0.93	0.91	<.0001
5	Low Pulse Threshold	x				x		x	x		x	x		0.93	0.91	<.0001

Table 5 – Top five models for each low flow regime variable, ranked by adjusted R<sup>2</sup>. x indicates variable appeared in model.

The model results for low pulse thresholds ( $Q_{75}$ ) exhibited the same tendencies as other low flow magnitude variables with the exception that percent wetlands and percent developed lands were not an important predictor for the low pulse threshold. No other variables were found to be important in explaining variability in the low pulse threshold.

		One Day Min	Seven Day Min	Thirty Day Min	Low Pulse Threshold
Land Use Variables	Percent Developed	0.69 (-)	0.53(-)	0.21(-)	0.15(-)
	Percent Pasture/Hay	0.12 (-)	0.12(-)	0.15(-)	0.13(+)
	Percent Cultivated	0.34 (+)	0.44(+)	0.41(+)	0.44(+)
Hydro- graphic variables	Percent Open Water	0.12 (+)	0.12(+)	0.12(+)	0.15(+)
	Percent Wetlands	<b>0.97 (-)</b>	<b>1.00(-)</b>	<b>1.00(-)</b>	0.22(-)
Physical/ Climatic Variables	Elevation Difference	0.16 (+)	0.13(+)	0.14(+)	0.26(+)
	Percent Stratified drift	<b>1.00 (+)</b>	<b>1.00(+)</b>	<b>1.00(+)</b>	<b>1.00(+)</b>
	Drainage Area	<b>1.00 (+)</b>	<b>1.00(+)</b>	<b>1.00(+)</b>	<b>1.00(+)</b>
	Mean April Precipitation	0.09 (+)	0.10(+)	0.11(+)	0.06(+)
	Mean Aug Precipitation	<b>1.00 (+)</b>	<b>1.00(+)</b>	<b>1.00 (+)</b>	<b>1.00(+)</b>
	Mean Elevation	<b>0.85 (+)</b>	<b>0.81(+)</b>	<b>0.88 (+)</b>	<b>0.82(+)</b>
	Drainage Density	0.12 (-)	0.11(-)	0.11(-)	0.05(+)
Range of R <sup>2</sup>		0.71- 0.79	0.72- 0.80	0.77- 0.83	0.90- 0.93

Table 6– Summed AIC<sub>c</sub> weights (w<sub>i</sub>) for watershed variables across 50 competing minimum flow models. (+/-) indicate direction of regression relationship. w<sub>i</sub> values vary from 0 to 1, with a variable that appears in every model having an w<sub>i</sub> equal to 1. Summing weights across all competing models (w<sub>i</sub>) that include a particular variable gave an estimate of relative importance of each independent variable in explaining variation Flow regime data represent median annual values for 30 years of record. Bold values indicate important predictors of flow components. (w<sub>i</sub> >0.8)

## **Discussion**

### *Minimum Flows*

Prolonged low flow periods reduce plant cover and diminish plant diversity (Taylor, 1982). Low flows help eliminate invasive species from the floodplain by reducing soil moisture and nutrients, restrict movement of aquatic organisms, and concentrate prey into smaller available habitats (Mathews and Richter, 2007). Low flows are not expected to represent storm-related runoff but rather reflect summer base flow, a product of inputs from groundwater or wetland storage and potential evapotranspiration losses from phreatophytes associated with wetlands connected to the stream network.

The landscape variables assessed in this study can be grouped into two general categories - anthropogenic or natural. The anthropogenic variables consist of watershed characteristics that may be altered by human activities. These attributes include watershed land cover, such as developed area and cultivated area, as well as drainage density, which can be altered by increased development. Elevation difference, precipitation values, stratified drift, drainage area, and mean elevation are natural variables that are not easily altered by human activities. Open water and wetlands were historically subject to change due to dams or artificial drainage, but the rate of change in these variables has diminished markedly due to regulations governing wetland loss, flooding associated with new reservoirs and the complexities associated with dam construction or removal.

For low flow magnitudes, natural features, such as percent stratified drift, drainage area, mean August precipitation, mean elevation, and percent wetlands, were found to be most important predictors for the more extreme low flow events (the 1, 7 and 30 day minimum flows) with only one anthropogenic variable, the percent of developed lands, found to be important but of lesser consequence. Wetlands and developed lands were not found to be important for explaining the variability in the low pulse threshold, the flow that represents the lowest 25<sup>th</sup> percentile flow or the lowest flows over roughly 90 days. Mean April precipitation, although found to be important in the New Hampshire regression equations, was not found to be an important explanatory variable for any descriptors of low flows examined in this study, likely due to the fact that the minimum flow for the study area streams was usually found to occur during September, thus August precipitation values would be expected to exert more influence on the minimum flows.

Stratified drift, which comprises most of the deep productive aquifers within the study region, was positively correlated to minimum flow magnitudes. There are many substantial groundwater withdrawals for cropland irrigation as well as municipal supplies occurring within stratified drift deposits on some watersheds within the study area. However, even with these withdrawals, the proportion of stratified drift was positively correlated with higher summer flows. Stratified drift has much higher infiltration and permeability rates than glacial till and is often located in valleys and coastal regions. Stratified drift deposits can store considerable volumes of recharge during wet periods through water table rise. In the summer

months, groundwater flow from the stratified drift contributes to stream base flow, resulting in higher low flows than streams located in areas of till (Wandle and Randall, 1994).

Mean watershed elevation was found to be positively correlated to minimum flow magnitudes, indicating higher elevation watersheds are likely to have higher values of minimum stream flows. Mean monthly precipitation, as well as snow depth increases with elevation in the study region. Dingman (1981) has shown that both floods and low flows increase with mean basin elevation and suggested that the effects of elevation are so strong in portions of New England that it can be used as the only dependent variable in estimating many stream flow statistics.

The percent of wetlands within the watershed was negatively correlated to the more extreme minimum flows that are associated with drought conditions. As the amount of wetlands increased in a watershed, the minimum flows for the 1-, 7- and 30- minimums decreased. Evidence from many studies (Bullock et al. 2003) suggests that wetlands generate substantially more summer evapotranspiration than other land uses, such as upland forests or pasture during dry periods. During dry periods, the elevated water tables and soil wetness of wetlands promote conditions that permit these areas to meet evaporative demand, while upland ecosystems undergo a number of changes that constrict evapotranspiration (e.g., stomatal closure, declines in soil upwelling due to low levels of unsaturated hydraulic conductivity). Kellogg et al. (2008) found that riparian wetland forests in southern New England intercepted virtually all groundwater flow during drought conditions,

essentially starving the rivers of baseflow during those periods. For the low pulse threshold, however, the extended time frame may encompass time periods that are not entirely within the period of highest evaporation stress, thus reducing the relative importance of wetlands on seasonal low flows under these conditions.

In many locales, watershed management is focused on reducing the extent of impervious cover to protect or restore stream health (Finkenbine et al., 2007; Snyder et al., 2005). Our finding that the extent of development in the watershed (which was strongly related to % impervious cover) was not as important as other factors for explaining the variability of flow regimes parameters is in line with the features, scale, and focus of our study. A meta-analysis conducted by Schueler et al. (2007) found few studies which researched the effects of impervious area on hydrologic factors, and those studies were either contradictory or ambiguous. Specifically, they found that an inverse relationship between impervious cover and base flow to streams was not always present. Most papers that confirmed hydrologic effects related to impervious cover mainly studied small watersheds (between 5 to 50 km<sup>2</sup>). Contradictory studies sampled watersheds that were generally larger (between 75 and 100 km<sup>2</sup>). The average watershed size of our study was 87 km<sup>2</sup> generally larger than watersheds where other studies found strong relationships between impervious cover and hydrologic effects. In addition, 29 out of the 33 watersheds in our study had % impervious cover less than 10%, the frequently used threshold for degradation in stream health. The extent of impervious cover is not unexpected for watersheds of this size in southern New England, where outside of the Boston and New York City

metro regions, the land use patterns typically encompass extensive amounts of open space and lower density suburbia.

### **Management Implications**

Our results were obtained from watersheds with a number of similar characteristics (e.g., similar size, ecoregion, and geomorphology). Yet even with these similarities, important differences emerged suggesting that management of water extraction to sustain low flows can benefit from attention to select watershed features. Based on our analyses of regression models, minimum flow components of the flow regime are more likely to be governed by natural features of the watershed. For example watersheds with high proportions of stratified drift were less likely to have extremely low minimum flow levels, while in watersheds where wetlands comprise a relatively high proportion of the watershed minimum flows tend to decrease. Management insights that follow from these findings may imply that watersheds with high proportion of stratified drift may be less susceptible to summer withdrawals for irrigation or municipal uses. In contrast, more stringent requirements on water extraction during drought conditions may be warranted in watersheds with high proportions of wetlands to avoid pushing those fluvial systems into extreme drought stress. Although the importance of development on low flows during drought were weaker than natural watershed features, we expect that the large area and low proportion of development within the study watersheds may mask the effects that can occur in smaller, more developed watersheds. Our analyses did not include the proximity of wetlands to fluvial systems; thus, we were

not able to distinguish the role of isolated wetlands (Leibowitz, 2003) versus riparian wetlands and floodplains on the low flow components of the flow regime. Effects of wetlands proximity to fluvial systems is a critical question for future research, particularly given recent interests in the courts related to regulatory questions on the extent of connections between wetlands and “navigable” waters (Nadeau and Rains, 2007).

Our study suggests that we need to recognize that a variety of watershed factors can that influence low flows. The increasing availability of geospatial data can assist in future, management decisions regarding environmental flow recommendations that will, ultimately, support healthy river ecosystems and communities.

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## Chapter 2

### **Evaluating the efficacy of low flow thresholds in a southern New England river**

by

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## **Abstract**

Streamflow has been called the master variable in a river because it affects habitat diversity and availability through its impact on physical factors that affect habitat quality. There are over 200 methods that set minimum flow standards, resulting in conflicting values due to differing environmental goals and levels of protection they aim to achieve.

Two such methods, the USFWS Aquatic Base Flow (ABF) method and the Wetted Perimeter (WP) method have been widely used. The USFWS ABF method recommends using the median of August flows and has been refined to develop more representative hydrographs for Rhode Island using monthly flow values as well as accounting for physiographic differences. The wetted perimeter method uses stream cross-sections at riffle locations to determine critical flow values to maintain flow based on the wetted perimeter of the channel.

We determined the minimum flow requirements at three locations (riffle zones) along the Beaver River, located in southern Rhode Island, using both the wetted perimeter method and the RI-ABF method. Field surveys of stream characteristics at each of the three riffle zones were conducted for evaluating the wetting perimeter method. In order to determine stream flow at ungaged locations, runoff was modeled using the HEC-HMS rainfall/runoff model.

To assess biological conditions, we reviewed macroinvertebrate, fish, and temperature data at locations within the watershed. Biological condition of the Beaver River indicated that the condition of the Beaver River, in terms of

macroinvertebrate taxa, is equal to or better than the reference site. Fish sampling locations showed an abundance of fluvial specialists and fluvial dependent species indicating for fish species, the Beaver River is a well-functioning stream habitat. Temperature readings in the Beaver River show stream temperatures never exceeded 22 °C, indicating suitable temperature for the maintenance of a brook trout population.

Minimum stream flow requirements using RI-ABF and WP methods were investigated during a wet year and a dry year for the modeling time interval. During the wet year, stream flows were below the ABF value between 6% to 12% of the time and below the WP flow 37% to 46% of the time. During the dry year, stream flows were below the RI-ABF value 18% to 21% of the time but below the WP flow 46% to 72% of the time.

Based on physical and biological sampling done in the watershed, the river is, comparable to pristine sites; however minimum flow criteria set by the WP method suggest that the river is flowing below critical flow values over 50% of the time. Critical flow values as determined by the RI-ABF method suggest that the river flows below critical flow values under 10% of the time. Our results suggest that minimum flow values obtained from the wetted perimeter method for southern New England rivers should be approached with caution.

## **Introduction**

Streamflow has been called the master variable in a river because it affects habitat diversity and availability through its impact on stream geomorphology, channel substrate, water depth, velocity, and other factors that, in turn, affect habitat quality, such as water temperature and water quality (Poff et al., 1997; Wilding and Poff, 2008; Poff and Zimmerman, 2009). Flow also influences habitat variables, such as the shape and size of channels, as well as distribution of riffle and pool habitats. Physical conditions within a habitat mediate levels of food resources available (Rabeni and Minshall, 1977) and may constrain the roles of predator competition (Peckarsky and Dodson, 1980). Minimum flow requirements for rivers aim to provide protection to habitat. Currently, there exists a wide variety of methods that result in conflicting minimum flow standards, largely due to differing environmental goals and levels of protection they aim to achieve. There are currently over 200 methods for determining low flow instream flow requirements (Annear and Conder, 1984), ranging from simple methods that use historical flow data to field-based reconnaissance for critical aspects of stream morphometry. More complex simulation models can link flow, velocity, and stream depth to habitat requirements.

Standard setting methods set limits to define a threshold flow regime or minimum flows, below which water cannot be diverted. Examples of standard setting methods include the United States Fish and Wildlife Service Aquatic Base Flow method (USFWS ABF). To define minimum flow requirements, the USFWS used

historical flow records for New England to describe stream flow conditions that will sustain and perpetuate indigenous aquatic fauna. The USFWS ABF method assumed that the most critical flows occur in August when the metabolic stress to aquatic organisms is at its highest due to high water temperatures, diminished living space, low dissolved oxygen, and low or diminished food supply. Where adequate records exist, the USFWS recommends using the median of the monthly means of August flows as a minimum threshold to sustain benthic organisms.

Field-based hydraulic methods use the hydraulic geometry of stream channels to estimate low-flow discharge thresholds. The hydraulic geometry is based on surveyed cross-sections, from which parameters such as width, depth, velocity, and wetted perimeter are determined. Hydraulic models can predict water depth and velocity within a specific habitat (i.e. riffles) (Gippel and Stewardson, 1998) or throughout a reach (i.e PHABSIM) (Milhous et al., 1984). These are then compared with habitat suitability criteria to determine the area of suitable habitat for the target aquatic species. When this is done for a range of flows, it is possible to see how the area of suitable habitat changes with flow.

The WP method (Gippel and Stewardson, 1998), one type of hydraulic method, uses stream cross-sections - typically at riffle habitat - to determine critical flow values expected to maintain flow based on the wetted perimeter of the channel. The wetted perimeter is the distance along the bottom and sides of a channel cross-section in contact with the water. The wetted perimeter method assumes that the fish carrying capacity of a stream is related to food production and that food

production is related to the amount of wetted perimeter in riffle sections. As discharges decrease, riffle habitats are often the first locations to be exposed or go dry. For a specific cross-section, the flow rates that cover a reasonable proportion of bed area of riffles with flowing water are determined in order to provide adequate minimum flows for benthic macroinvertebrates communities and allow for fish passage. The method uses plots of wetted perimeter vs. discharge to identify a break or inflection point. Critical discharge corresponds to this inflection point (Gippel and Stewardson, 1998). At this inflection point, food production is assumed to approach optimum levels (Gippel and Stewardson, 1998). Below the inflection point, aquatic habitat will decline and thus support lower populations of benthic species. Above the upper inflection point, the flow regime is expected sustain thriving benthic aquatic populations which then contribute to a robust food web.

We compared the two approaches for estimating the minimum flow requirements for a third order stream network in Rhode Island. Rosenblatt et al. (2001) found that first and second order streams compose 70% of total stream length in RI based on digitized hydrographic data from the 1:24,000 scale USGS 7.5 minute topographic quadrangle maps. In addition, headwater streams have smaller average flows, resulting in low flow stress more frequently occurring in headwater streams (Richardson and Danehy, 2007). Third order watersheds, therefore, may have many ramifications for low flow management.

We used the wetted perimeter method and the Rhode Island Aquatic Base Flow(RI-ABF) method in combination with a daily flow simulation model (Hydrologic

Engineering Center Hydrologic Model system (HEC-HMS) (Davis, CA) to evaluate the long-term probabilities of not exceeding minimum flow thresholds at select riffle habitats within the stream. The RI ABF and the wetted perimeter method are among the easier methods for estimating low flow thresholds and in conjunction with historical flow data (simulated or from gauging stations) have potential for widespread applications related to water withdrawals. To gain insight into the efficacy of these methods for their intended goal of protecting the biological integrity of the study stream, we then compared the recommendations of these two methods with indicators of stream conditions, such as fish, macroinvertebrate and temperature, surveys of the river.

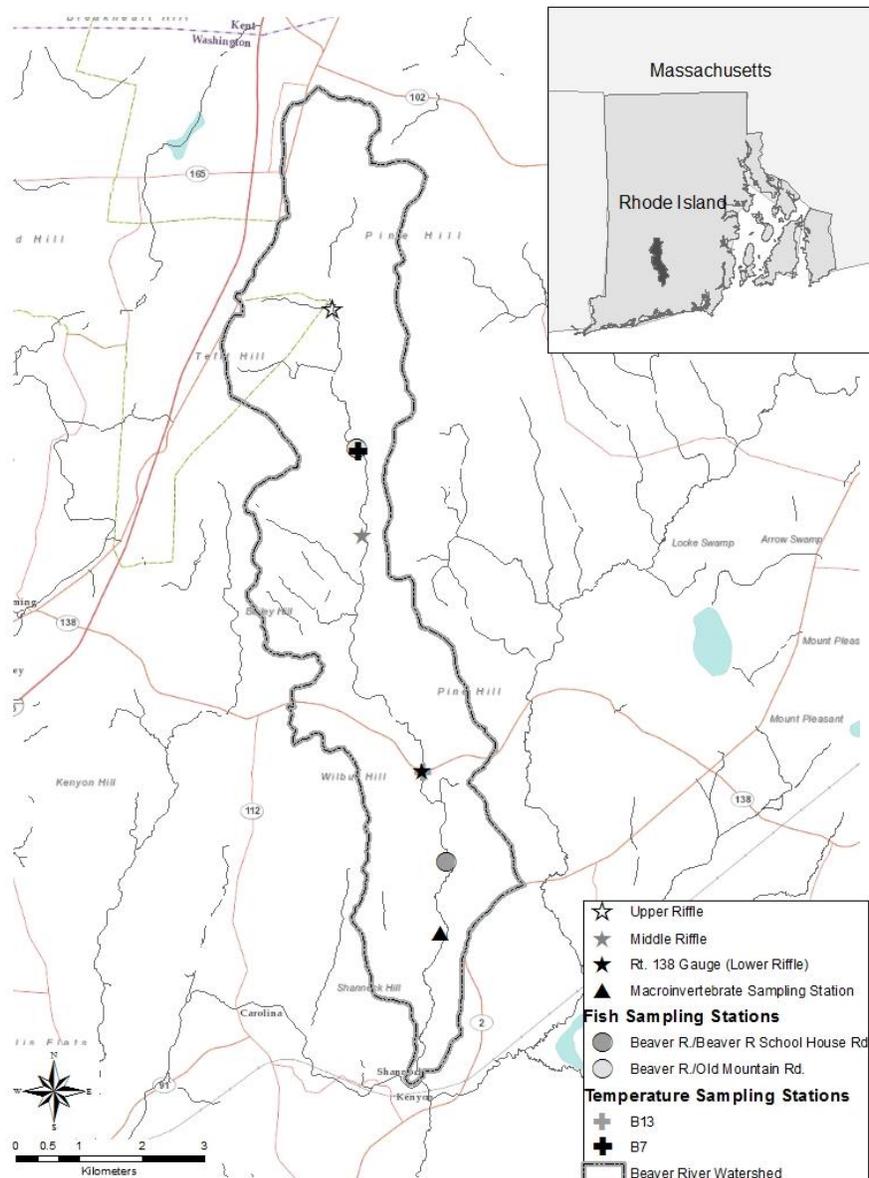
## **Methods**

### **Study Watershed**

The study area is the 32 km<sup>2</sup> Beaver River watershed, a third-order stream located in southern Rhode Island (Figure 1). This watershed is a sub-watershed of the, Pawcatuck-Wood Subbasin, in the New England Region (Rhode Island Digital Atlas, <http://www.edc.uri.edu/atlas/>). Richardson (2005) classifies the watershed within the Coastal Lowland physiographic subregion (Denny, 1982; Patton 1988) of Southern New England, which is characterized by areas of low relief, Cenozoic sedimentary deposits and deep stratified drift. Current land use in this rural watershed is approximately 82% forested, 9% agricultural, 6% residential housing, with the balance in recreational use, open land, water and wetlands (Rhode Island

Digital Atlas, [www.edc.uri.edu/atlas](http://www.edc.uri.edu/atlas)). The watershed is lightly developed with approximately 2.4 % impervious area (IA) (Rhode Island Digital Atlas, [www.edc.uri.edu/atlas](http://www.edc.uri.edu/atlas)). The slopes in the watershed vary from flat – majority of watershed between 0% to 3 % - to a maximum of 14.7%. The soils in the watershed are generally moderately drained with 66% of the soils falling within USDA-NRCS hydrologic soil group B (Rhode Island Digital Atlas, [www.edc.uri.edu/atlas](http://www.edc.uri.edu/atlas)). To assess the stability of land use within the watershed over the study period, we used the 10 year retrofit land cover change product compiled from the 1992 and 2001 National Land Cover Datasets (30 m resolution) (Fry et al., 2009). The amount of land use change within the Beaver River watershed was 1.84% with the majority of change, approximately 1.2% of watershed land use, shifting from forested land to agricultural land. One U.S. Geological Survey (USGS) long term, continuous stream gage, Gage 01117468, is located within 5.7 km of the outlet of the Beaver River Watershed.

Figure 1-Location Map of Beaver River Watershed showing sampling site locations. The USGS Gage 01117468 is located at the intersection of Kingstown Road with the Beaver River.



## Field Based Measurements

Riffles along the Beaver River were field located during the summer of 2009. USGS standard methodology (Rantz, 1982) was used to measure discharge at the riffle locations at each subbasin outlet (Buchanan and Somers, 1969). At each riffle location, the stream channel cross section was divided into one-foot (0.3048 m) subsections. In each subsection, the depth at the center of the subsection was measured with a surveyor's rod (Figure 2), and the area was estimated by multiplying the depth times the width (0.3048 m). Water velocity was determined using a Global Water Flow Probe FP101 current meter. Stream bed elevations were determined using a CST/berger automatic level (Figure 3). Stream discharge was then calculated using the mid-section method:

$$Q = \sum_{i=1}^n (X_{i+1} - X_i) (U_i Y_i + U_{i+1} Y_{i+1}) / 2$$

where the  $X_i$  are the distances to successive measurement points along the transect, where stream velocity ( $U_i$ ) and water depth ( $Y_i$ ) are measured, starting with  $X_1$  being the initial point on one bank and  $X_n$  being the final measuring point on the opposite bank.

A slope-area method was used to determine Mannings roughness coefficient ( $n$ ) for each riffle location by rearranging Mannings Equation to solve for  $n$ :

$$n = \frac{1.49}{Q} R^{\frac{2}{3}} S^{\frac{1}{2}} A$$

Where  $A$  is the cross sectional area of the stream measured from survey data,  $n$  is Mannings  $n$  which is an index of the roughness of the stream bed,  $R$  is the hydraulic

radius which is the ratio of the cross section area of the stream to its wetted perimeter (which is the cross-sectional distance along the stream bed and banks that is in contact with the water), and  $S$  is the change in elevation of the stream over a specified distance. Stream bed elevations and water surface elevations for points about 7m upstream and downstream of the riffle section were measured with a CST/berger automatic level and the energy slope ( $S$ ) was calculated as the ratio of the difference in water surface elevations to the distance between these points.

The roughness coefficient ( $n$ ) for each riffle location was then calculated for each subsection from Mannings Equation. Once Mannings  $n$  was calculated for each riffle location and the stream cross-sections measured, the stage-discharge relationship of each cross-section was determined, as well as the wetted perimeter-discharge relationship.



Figure 2-Cross-section survey procedure. Steel tape is extended across stream channel and elevation and velocity are measured at one-foot increments.



Figure 3-Surveyors CST/berger automatic level is used to determine cross-section elevations at one-foot intervals.

## Wetted Perimeter Breakpoint Analysis

The channel in the Beaver River is roughly rectangular throughout its length. Gippel and Stewardson (1998) found that for a hypothetical rectangular cross-section, the relationship between wetted perimeter and discharge was logarithmic and had the general form:

$$WP = a \ln(Q) + 1$$

Where WP is wetted perimeter, Q is the discharge and  $a$  is a constant.

Gippel and Stewardson (1998) use the point of maximum curvature of the wetted perimeter-discharge curve to determine the breakpoint of the wetted perimeter-discharge curve. The breakpoint is the point where the slope of the tangent is equal to one for the fitted line. This point equates to the point where  $\frac{\Delta WP}{\Delta Q} = 1$ , or the first derivative,  $dy/dx = 1$ . In order to determine this point for each riffle location, both discharge and wetted perimeter were normalized to the corresponding bankfull values, logarithmic curves were fitted to each measured wetted perimeter-discharge relationship. The equation for the slope of the logarithmic function is  $dy/dx = a/Q$ . For a slope equal to one (the critical flow value, or breakpoint), the equation becomes  $Q_{crit} = a$ .

## **Aquatic Base Flow**

The United States Fish and Wildlife Service (USFWS) used historical flow gage records for New England from 48 unregulated rivers to prescribe stream flow conditions that will sustain and perpetuate indigenous aquatic fauna (Lang, 1999). This policy has been widely used in New England. Richardson (2005) further refined the USFWS ABF recommendations to develop more representative hydrographs for Rhode Island using the median of monthly flow median values (rather than the USFWS approach of using median of monthly means) at gaged rivers as well as accounting for physiographic differences between watersheds (Figure 4, Table 1). For the study area the RI-ABF varied substantially over the course of the year, from a low in August and September of  $0.006 \text{ m}^3 \text{ s}^{-1} \text{ km}^{-1}$  of watershed area to a high in April of  $0.033 \text{ m}^3 \text{ s}^{-1} \text{ km}^{-1}$  of watershed area.

### RI-ABF Monthly Instream Flow Values (Coastal Lowlands)

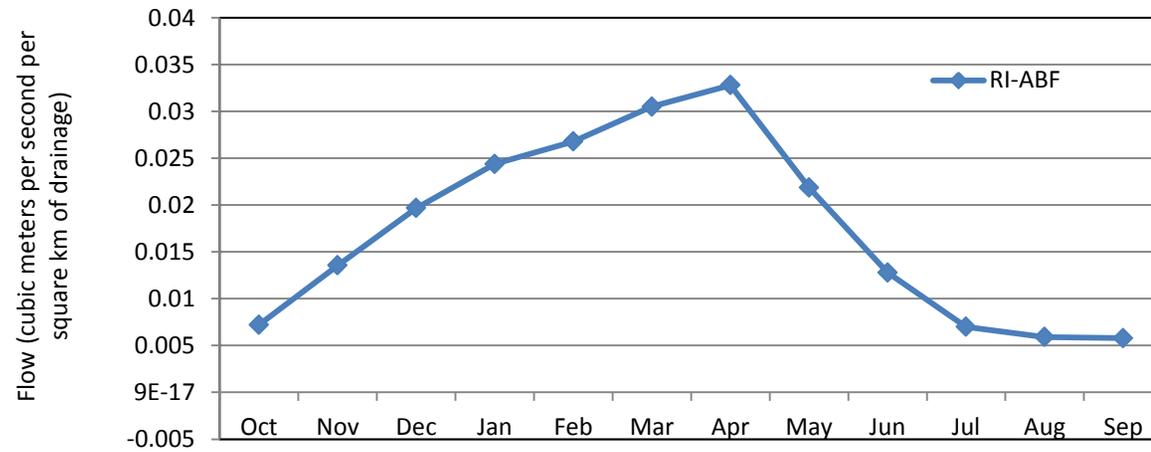


Figure 4- RI-ABF values in cubic meters per second per square km of drainage area. (from Richardson, 2005), These represent the median of the monthly median flow values derived from gaged watersheds within the Coastal Lowland physiographic unit of Southern New England.

	Area (km <sup>2</sup> )	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep
Upper	5.31	0.038	0.072	0.105	0.130	0.142	0.162	0.174	0.116	0.068	0.037	0.031	0.031
Middle	13.78	0.099	0.187	0.271	0.336	0.369	0.420	0.452	0.301	0.176	0.096	0.081	0.080
Outlet	23.33	0.168	0.316	0.459	0.569	0.625	0.712	0.765	0.510	0.298	0.163	0.138	0.135

Table 1-Monthly ABF values for subbasins within the Beaver River watershed, Richmond, RI. Area is cumulative area of watershed. Flow values are in cubic meters per second.

## **Assessment of Benthic Macroinvertebrate Condition**

To assess biological conditions, we used benthic macroinvertebrate data that were collected each summer within the Beaver River over a 11 year period (1991-2001) (Gould, 1999; Pomeroy, 2000; Da Silva, 2002). A single evaluation score of biological condition was derived by scoring a set of metrics according to the type, abundance and diversity of taxa found at each site and ranking each sample in comparison to the metrics of a reference sample station taken during the same year from the Wood River in Richmond, RI (Figure 1). The Wood River is mostly surrounded by the Arcadia Management Area, and thus receives minimal human impacts. Scoring criteria for each metric were derived from Plafkin et al. (1989) and modified according to specifications for the region (Jessup, 2000). A maximum score of 50 represents excellent biological condition.

## **Assessment of Fish Condition**

Fish were collected by electrofishing in August, 1998 by the Rhode Island Division of Fisheries and Wildlife (Libby, 2013) (Figure 1) and were identified and enumerated. Fish species were then classified as fluvial specialists, fluvial dependent or macrohabitat generalists (Bain and Meixler, 2008). The Beaver River was sampled at two locations (School House Road and Old Mountain Road) with a Smith-Root Model 12-A or Coffelt Model BP-4 backpack electrofishing unit during the daytime when flows were low. The electrofishing crew consisted of an operator and two netters. A single pass was carefully conducted in the streambed in an upstream

direction which included all types of microhabitats such as beds of aquatic macrophytes, woody debris, and undercut banks when present. In an attempt to maximize the number of fish species collected at a station, the length of stream surveyed was at least 35 times its mean width (Lyons 1992).

### **Temperature Data**

Temperature data were obtained from the Wood-Pawcatuck Watershed Association ([www.wpwa.org](http://www.wpwa.org)) at two locations within the study watershed area during the summer of 2004 (Figure 1). Summer air temperatures during 2004 approximate the long-term median summer temperatures for the watershed, based on data from the Kingston, RI weather station. DS1921G Thermochron® iButtons were used to monitor hourly temperature readings during the summer of 2004. The iButtons were attached to a piece of steel rebar with duct tape, labeled, and then deployed directly into the stream substrate. The iButtons were installed in flowing pools to ensure they would be submerged during the summer months. The loggers were deployed from the end of June to the end of September, in order to capture the warmest water temperatures. The sites were checked at least once during the deployment to ensure that the iButtons were functioning correctly and remained submerged.

### **HEC-HMS Model**

In order to determine stream flow at ungaged riffle locations, runoff was modeled using the Hydrologic Engineering Centers Hydrologic Modeling System

(HEC-HMS; Davis, CA) rainfall/runoff model. For this modeling effort, the overall watershed was divided into three subbasins, ranging in size from 5.1 km<sup>2</sup> to 9.4 km<sup>2</sup>, corresponding to the locations of each measured riffle habitat (Figure 1). Flows were modeled cumulatively down the basin. The flow for the upper watershed included flow from only the upper watershed; flow for the middle basin included both flow from the upper and from the middle basin. HEC-GeoHMS (Fleming, 2010) was used to develop hydrologic modeling inputs for HEC-HMS model. For hydrologic modeling within HEC-HMS, we generated the following components: (1) runoff volume by initial deficit and constant loss infiltration, (2) Clark's unit hydrograph, (3) linear reservoir for subsurface flow and (4) kinematic wave routing for channel flow (Feldman, 2000).

### **Model calibration and validation**

Initial model parameters were estimated using the guidelines given in the HEC-HMS Technical Reference Manual (Feldman, 2000). The automatic parameter optimization tools, available in the HEC-HMS model, were used to find the optimum set of parameters (groundwater storage coefficients for the linear reservoirs) for each sub-basin.

Nash-Sutcliffe efficiency (NSE) (Nash and Sutcliffe, 1970) was used to determine "goodness of fit" of the model. NSE ranges from  $-\infty$  to 1.0 with values between 0 and 1 being acceptable levels of performance (Moriassi et al., 2007).

Root mean square error (RMSE) is also a commonly used error index statistics (Singh et al., 2005). Singh et al. (2005) stated that RMSE values less than half the standard deviation of the observed data may be considered appropriate for model evaluation. Based on the recommendation by Singh et al. (2005), a model evaluation statistic, RMSE-observations standard deviation ratio (RSR), was developed. RSR standardizes RMSE using the standard deviation of the observed values, and it combines both an error index and the additional information recommended by Legates and McCabe (1999). RSR varies from the optimal value of 0, which indicates zero RMSE or residual variation - perfect model simulation - to large positive values. In general, models can be considered “very good” if  $0.75 < NSE < 1.00$  and  $0.00 < RSR < 0.50$ , (Moriasi et al., 2007), while models are considered “satisfactory” if  $0.60 < NSE < 0.75$  and  $0.50 < RSR < 0.60$ .

### **Flow Analysis**

Stream discharge data is a continuous variable that is often summarized by frequency distributions. The values for the streamflow were first ranked from smallest to largest, and then plotted using a Weibull distribution (Weibull, 1951) where:

$$F(x) = \frac{i}{d + 1}$$

Where  $F(x)$  is the non-exceedance probability,  $i$  is the rank of the flow observation and  $d$  is the total number of flow observations. Cumulative distribution functions

(CDF), or flow duration curves, show magnitude of stream flow against the probability the flow is not exceeded.

### **Climate Data**

Rainfall data were obtained from the National Weather Service Cooperative Observer Station 37-4266-01, Kingston, Rhode Island, located approximately 11.4 km to the east of the watershed. Historic monthly average evaporation data was obtained from the National Weather Service (Farnsworth and Thompson, 1982) as well as from the National Weather Service Cooperative Observer Station 37-4266-01 . Both rainfall and evaporation were assumed to be constant over the entire watershed. For the years 1982 to 2007, the modeling time interval, 1983 was the wettest year with an annual precipitation of 1783 mm (Figure 5). The driest year was 1993 with 1110 mm of precipitation. Average summer temperature values ranged from 24.48 °C in 1992 to 27.81°C in 2005.

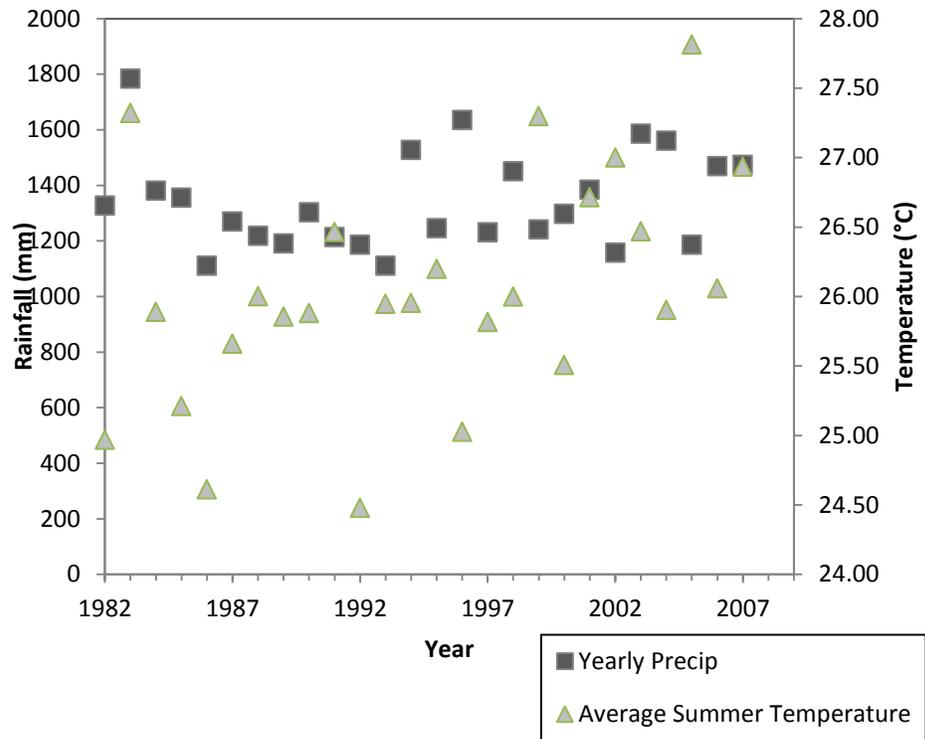


Figure 5-Annual precipitation depth and average summer temperatures for the 1982 through 2007.

## **Results/Discussion**

### **Model Calibration and Validation**

Statistical indices of NSE and RSR, for both the calibration and the verification periods, were calculated using the results of daily time steps (Table 2). Typically, model simulations are better for longer (monthly) time steps than for shorter time steps (daily) (Engel et al., 2007). For example, in a study conducted by Fernandez et al. (2005), NSE values were 0.395 and 0.656 for daily and monthly, respectively, for model calibration and 0.536 and 0.870 for daily and monthly, respectively, for model validation. In our simulation, model calibration statistics for the calibration period, the validation period and overall time period can be classified as “very good” or “satisfactory” indicating the generated model was acceptable.

	NSE	RSR
Calibration period (1982-1992)	0.83	0.42
Validation period (1993-2007)	0.72	0.52
Overall (1982-2007)	0.78	0.46

Table 2- Model calibration and validation values for daily time steps. NSE >0.75 are classified as very good and values between 0.5 and 0.75 are considered satisfactory. RSR values < 0.5 are classified as very good and values between 0.5 and 0.7 indicate satisfactory models (Moriassi, 2007).

## **Breakpoint Analysis**

For each riffle section, normalized discharge vs. normalized wetted perimeter, calculated from the field cross-section data, was plotted, and the breakpoint of the resulting curve was determined (Figure 6, Table 3). Moving down the watershed, the stream increased in both depth and width, and the critical flow value also increased from  $0.131 \text{ m}^3 \text{ s}^{-1}$  in the upper watershed to  $0.400 \text{ m}^3 \text{ s}^{-1}$  in the lower watershed.

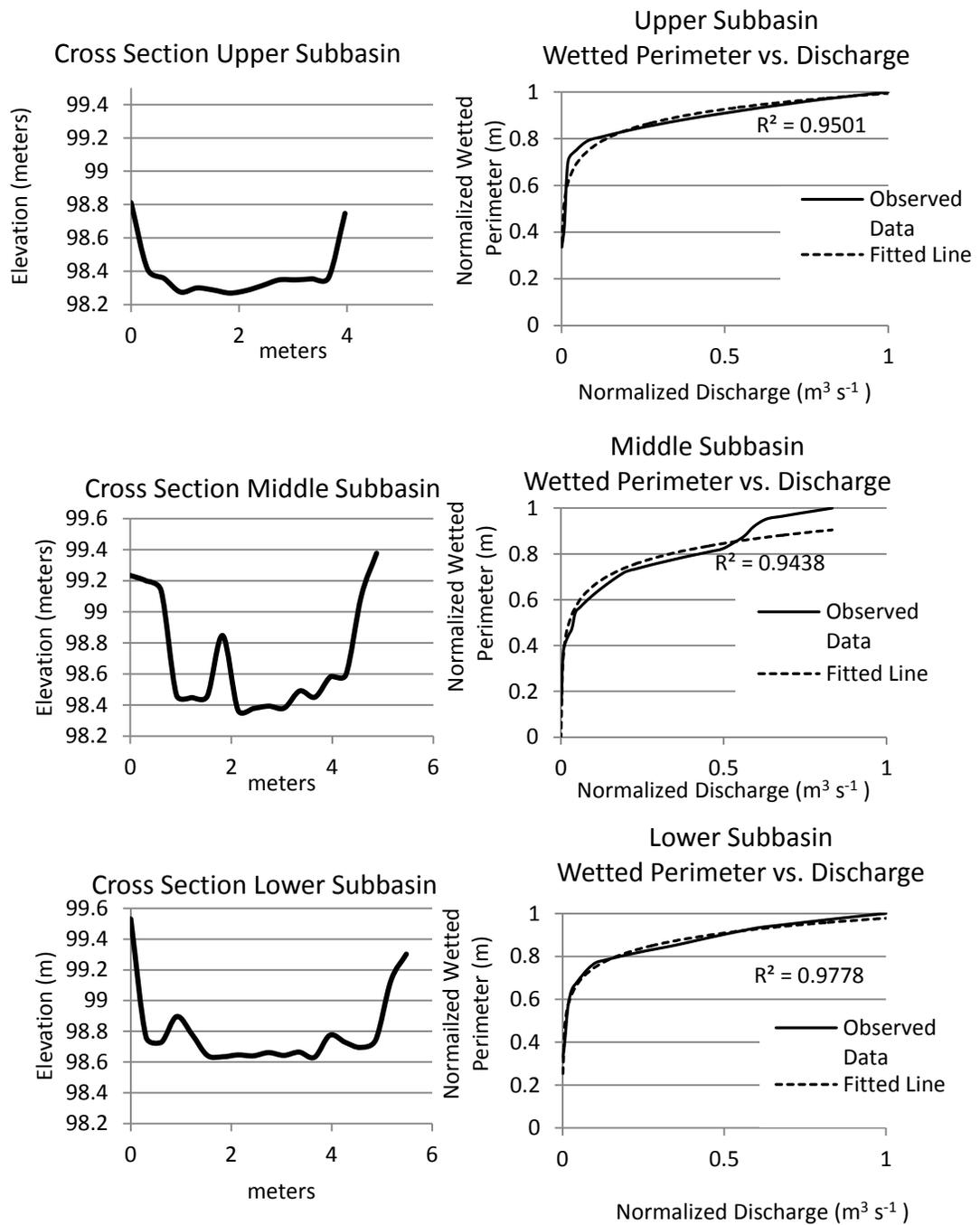


Figure 6 – Cross section and discharge vs. wetted perimeter for a) upper subbasin b) middle subbasin and c) lower subbasin. Elevations are assumed for each cross-section.

	Fitted Line	$F > p$	Wetted Perimeter Critical Flow Value ( $m^3 s^{-1}$ )
Upper Watershed	WP=.0980 lnQ+.994	$p < .001$	0.131
Middle Watershed	WP=.1150 lnQ+.905	$p < .001$	0.316
Lower Watershed	WP=.0994 lnQ+.978	$p < .001$	0.400

Table 3-Equations of fitted lines for discharge vs. wetted perimeter function, along with critical flow values for each subbasin.

## **Stream Condition**

### ***Macroinvertebrates***

Indicator species are taxa that are highly sensitive to pollution or anthropogenic disturbance and are the first to disappear with disturbance or pollution. Biological condition based on macroinvertebrate taxa from riffle sites was compared between the Beaver River and a pristine river site on the Wood River that is used as a reference station for all Rhode Island benthic macroinvertebrate assessments. Over the 10 years of sampling, the Beaver River had a median score of 36, with an interquartile range of 27 to 38, while the Wood River had a median score of 24, with an inter-quartile range between 20 and 36 (Figure 7) (Da Silva, 2003). These values indicate that the biological condition of the Beaver River is comparable to a pristine river in terms of macroinvertebrate taxa and is likely to be very capable of sustaining high levels of biological integrity.

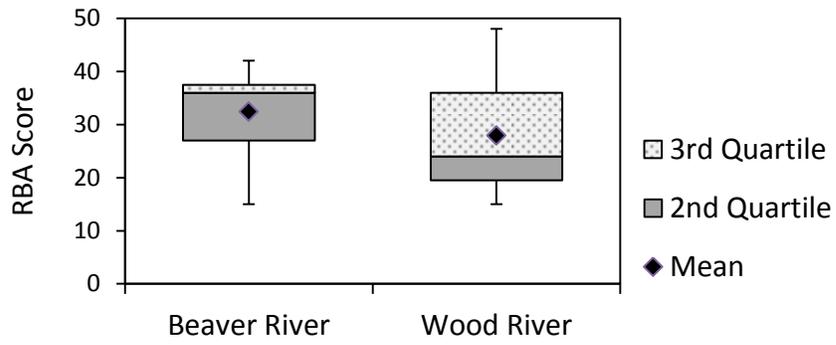


Figure 7 Rapid bioassessment scores of the Beaver River and the pristine (state reference) Wood River site for 1991 to 2001 (from DaSilva, 2003). Higher scores reflect higher biological conditions.

### ***Fish Abundance***

Fish samples show 83% of the fish sampled were fluvial specialists at the Old Mountain Road site and 73% of the fish at the Schoolhouse Road site were fluvial specialists as compared to 10% and 17% of the fish at both sites being macrohabitat generalists. A fish community with substantial numbers of fluvial specialists, such as found in the Beaver River, indicates well-functioning stream habitats expected for flowing waters (Bain et al., 2000).

Both fish sampling locations showed an abundance of brook trout, a fluvial specialist species that requires flowing water for most or all of its life cycle (Figure 8). Steedman (1988) found brook trout to be a suitable indicator species for measures of stream quality. The Schoolhouse Road site also had tessellated darter present, also fluvial specialists. Atlantic salmon and white suckerfish, both fluvial dependent species were present at both sites. Fluvial dependent species require flowing water for a portion of their life cycle (commonly for reproduction). Macrohabitat generalists, such as eel, redbfin pickerel, and brown trout, which are found in both lentic and lotic systems (Galat et al., 2005) and were found in lower numbers at both sites.

To provide additional context on the status of the Beaver River fish communities, the results were compared to the Ipswich River (Figure 9) (Armstrong et al., 2003). The Ipswich target fish community is used to show a healthy fish community in a small coastal river (Armstrong et al., 2003). Fish in the Ipswich River have a population of 49% fluvial specialists, 19% fluvial dependents and 32%

macrohabitat generalists, suggesting that the Beaver River, with a substantially higher proportion of fluvial specialists, sustains a healthy fish community relative to its location and physiography.

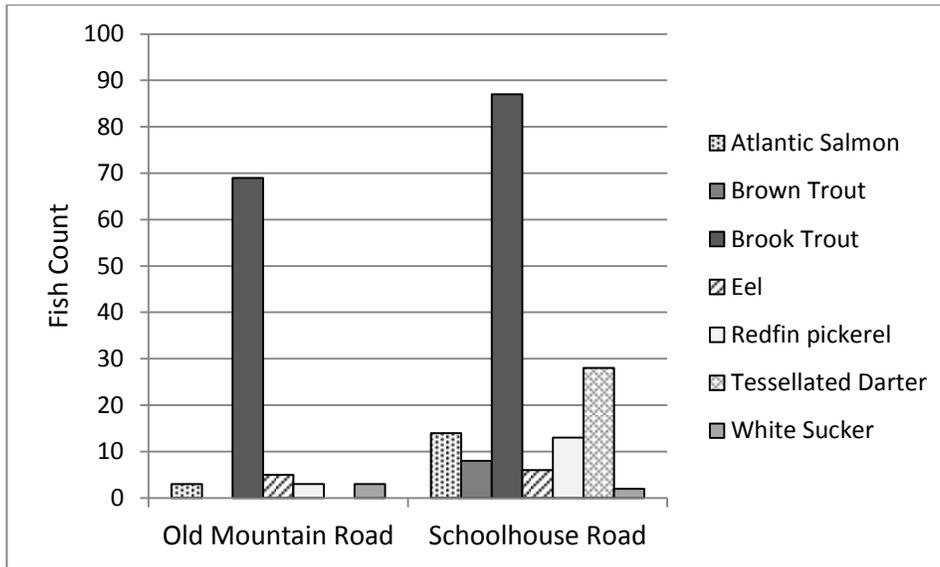
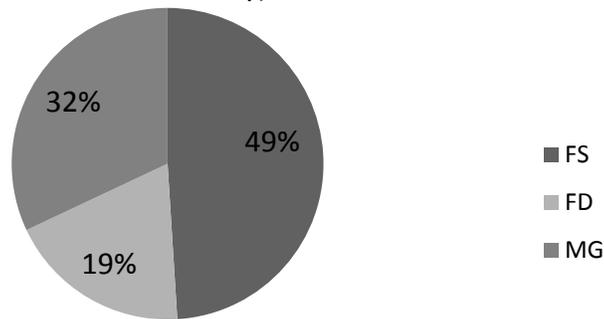
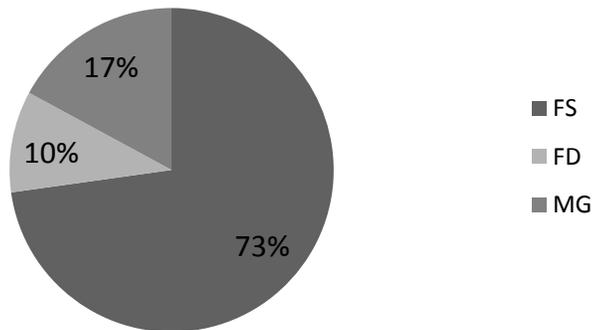


Figure 8-Fish counts at Old Mountain Road and Schoolhouse Road in the Beaver River. Fish were sampled in August 1998 (Libby, 2013).

Ipswich River, MA (used as an example of a coastal lowland river with healthy fish community)



Schoolhouse Road Site



Old Mountain Road Site

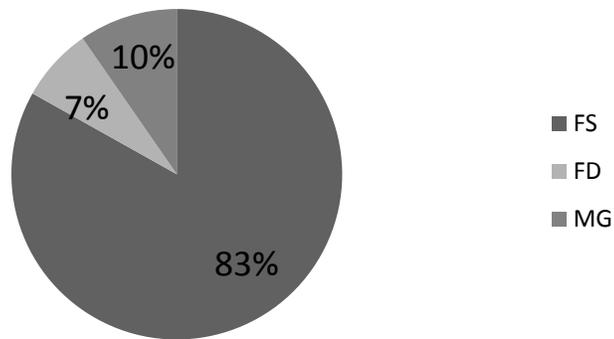


Figure 9 – Target fish communities for the Ipswich River, Massachusetts (Armstrong et al., 2003); Schoolhouse Road and Old Mountain Road, Beaver River, Rhode Island. FS (Fluvial Specialist), FD (Fluvial Dependent) and MG (Macrohabitat Generalist) (Libby, 2013)

### ***Temperature Data***

Water temperature is a key factor affecting fish (Fry 1971). Temperature regimes influence such life cycle stages as migration, egg maturation, spawning, incubation success and growth as well as resistance to disease, parasites and pollutants (Armour, 1991). In warmer streams, trout populations have been found to be almost nonexistent (Barton et al., 2002). Brook trout, the native trout for New England and Vermont's official cold-water fish, are found primarily in streams with maximum weekly average water temperatures less than 22 °C (Barton et al., 2002). Sustained water temperatures over 25.3 °C are considered to be lethal for brook trout (Mullen, 1958).

The Beaver River maintained stream temperatures conducive to brook trout, with daily maxima temperatures at or below 22 °C and sustained average temperatures of 17 °C for the two sites monitored during 2004 (Figure 10). These temperatures are substantially lower than the average summer air temperature of 25.8 °C.

For lower order streams, phreatic groundwater inputs and riparian shade have the highest influence on sustaining cool summer water temperature (Poole and Berman, 2001). Virtually the entire stream network within the Beaver River is shaded by forested riparian zones, and the extensive forest cover and minimal extent of impervious cover enhances the potential for excess rainfall to enter the stream as baseflow, rather than as storm-generated overland flows.

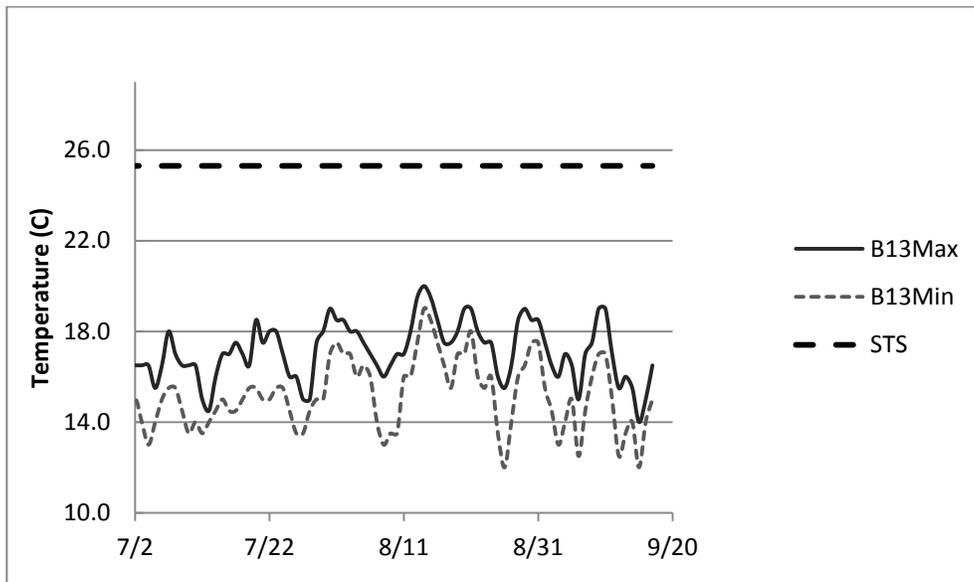
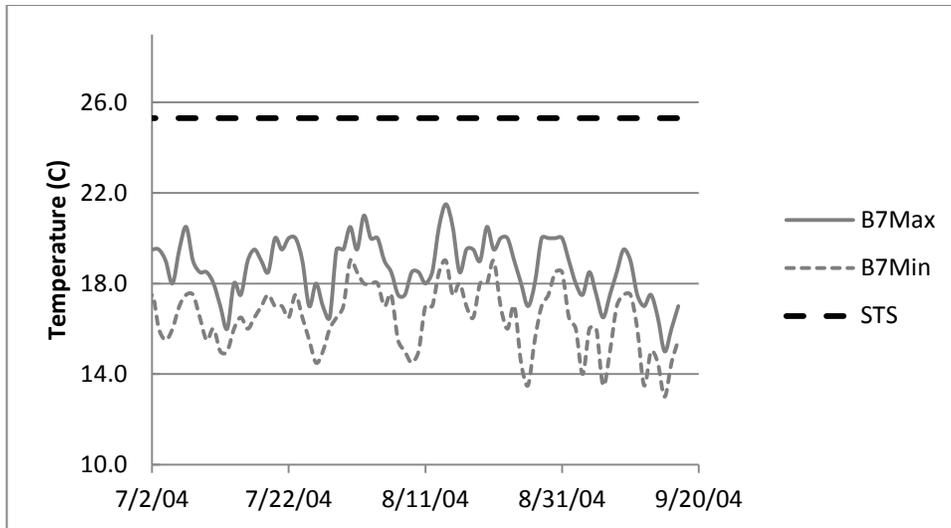


Figure 10-Daily maximum and minimum temperature readings for sites B13 and B7 (Figure 1) on the Beaver River during the summer of 2004 along with short term survival (STS) temperature above which brook trout cannot survive.

## Minimum Flows

Minimum stream flow requirements using ABF and WP methods were investigated during a wet year (1983) and a dry year (1993) for the modeling time interval (Figure 11). We focused our attention on the summer months, when flow is at its lowest, since our goal was to examine the efficacy of these methods for establishing minimum flow requirements. Marked differences between the two methods were observed in the summer non-exceedance flow probabilities predicted for the riffles targeted in our study. Summer flows were usually below the minimum thresholds determined by Wetted Perimeter method for both wet and dry years. At the riffles located in the upper and middle subbasins, the flows met or exceeded the minimum WP thresholds less than 20% during the summer for both wet and dry year (Table 4). At the lower subbasin riffles during a wet year the WP minimum threshold was still exceeded less than 40% of the time during summer. In contrast, summer flows were nearly always above the minimum flow threshold for the RI ABF during a wet year and met or exceeded the RI ABF threshold from 68% to 77% of the summer during a dry year.

Location	Method	Threshold flows ( $\text{m}^3 \text{s}^{-1}$ )	1983 (Wet Year)	1993 (Dry Year)	1982- 2007
Upper	ABF	0.031	1.9%	32.1%	11.2%
Subbasin	WP	0.131	87.5%	93.0%	61.3%
Middle	ABF	0.080	0.0%	23.4%	8.4%
Subbasin	WP	0.316	80.3%	91.0%	54.0%
Lower	ABF	0.135	0.0%	26.6%	11.1%
Subbasin	WP	0.40	63.8%	84.1%	41.9%

Table 4 – Non-exceedance probabilities for ABF and WP flows for the upper, middle and lower subbasins for summer months (Jun 1 to Sep 30).

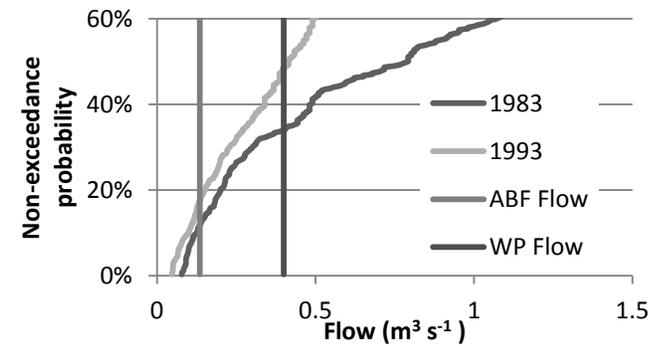
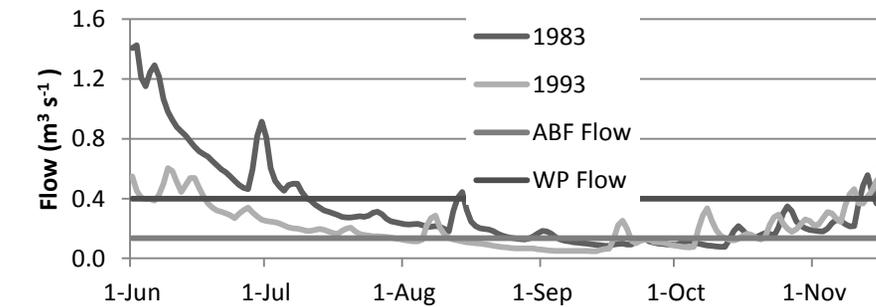
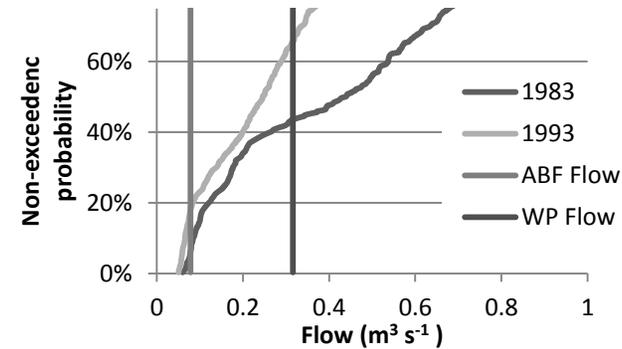
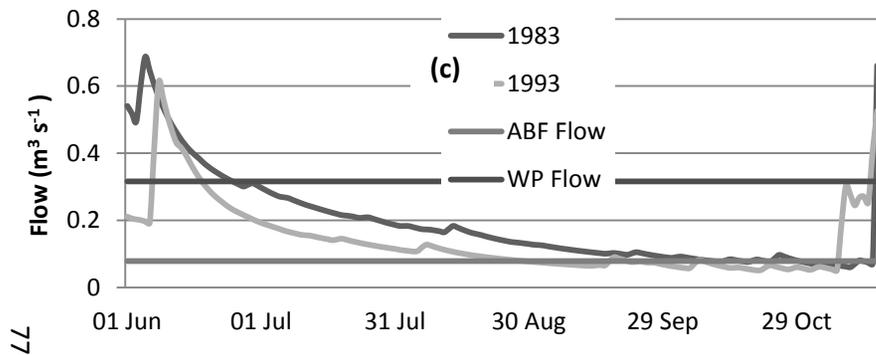
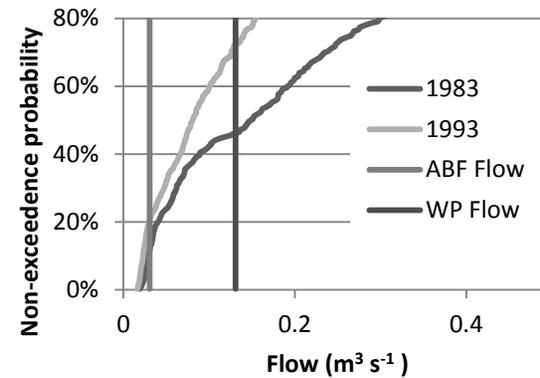
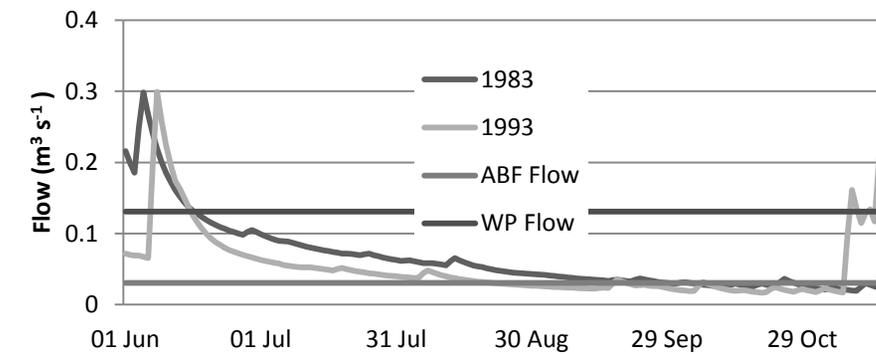
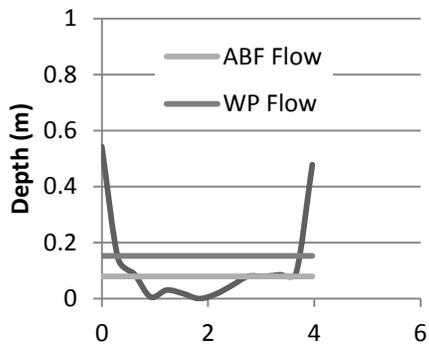
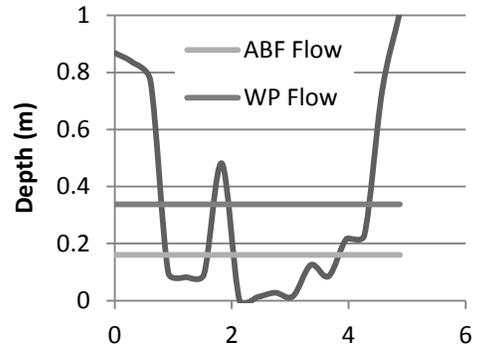


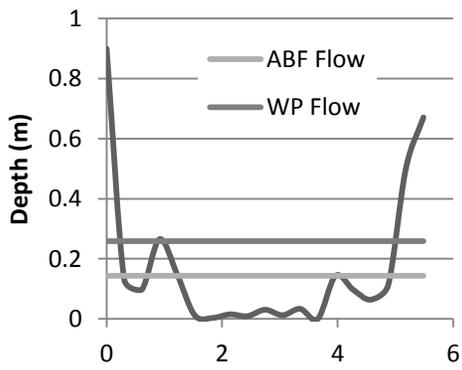
Figure 11-Hydrographs and CDF curves for June 1-Nov 15<sup>th</sup> a) upper subbasin b) middle subbasin and c) lower subbasin during 1983 (wet year) and 1993 (dry year). Upper and middle subbasin values are from modeled data. Outlet values are from USGS gage data.



(a)



(b)



(c)

Figure 12-Cross sections of riffles at outlets of a) upper subbasin b) middle subbasin and c) lower subbasin, with ABF and WP flow lines.

Given the many indications that the Beaver River sustains a healthy cold-water fishery, we suggest that the current flow regime is not generating impairment. The thresholds set by the WP method resulted in high frequencies of summer flows that failed to meet those thresholds, thus it appears that this method may be far too conservative. In contrast, summer flows in the Beaver River routinely meet the minimum thresholds determined from the simpler RI ABF, which may be more suited as a low flow threshold method that can reflect the required minimum flow conditions of the river.

In addition to minimum flows predicted by the two methods, we also examined the minimum flow depths at riffle habitats that would be expected for each method. These findings were obtained by plotting ABF flow values and WP flow values, along with the cross-section data to determine maximum depth of flow under both criteria (Figure 12, Table 5). USDA (1975) suggests that a stream depth of at least 0.12 m is required for trout passage. Except for the upper subbasin, the threshold flows predicted by the ABF method would provide adequate depth for trout passage at the riffle sites (e.g., the riffles located on the outlet and middle watersheds). The WP method will provide at least twice the minimum depth required for trout passage in the lower two watersheds, suggesting that the WP method produces extremely conservative estimates of minimum flow depths for this river system.

	Flow Depth (m)  ABF Flow for September	RI-ABF Flow for September  ( $\text{m}^3 \text{s}^{-1}$ )	Flow Depth (m)  WP Flow	Wetted Perimeter Critical Flow Value ( $\text{m}^3 \text{s}^{-1}$ )
Upper Subbasin	0.08	.031	0.15	0.131
Middle Subbasin	0.16	.080	0.34	0.316
Lower Subbasin	0.14	.135	0.26	0.400

Table 5 - Maximum depth of stream at surveyed riffle habitats based on ABF and WP critical flow values.

## Conclusions

Based on stream temperature, macroinvertebrate and fish, sampling the Beaver River is a well-functioning river supporting a naturally reproducing healthy cold-water, indigenous fishery. This finding contrasts with what might be expected based on methods used for assessing low flow thresholds. The in-streams flows suggest that the wetted perimeter method might not a useful approach for the low gradient streams of southern New England.

Stream temperatures for the river enable it to remain a cold water fishery as defined by the Rhode Island Department of Environmental Management (RIDEM) which defines cold water fisheries as waters in which naturally occurring water quality and/or habitat allow the maintenance of an indigenous coldwater fish populations (RIDEM, 2006).

Macroinvertebrate data obtained from a riffle habitat on the Beaver River also indicate that the Beaver River maintains high biotic integrity – comparable to the results obtained at the pristine reference site in the Wood River, which is surrounded by the Arcadia Management area and has almost no anthropogenic alterations in its watershed.

Despite these indicators that the river is currently in excellent condition, minimum flow criteria set by the wetted perimeter suggest that the river is flowing below critical flow values for approximately 50% of the time during the summer months based on a 25 year evaluation. Critical flow values as determined by the RI-ABF method suggest that the river flows below critical flow values approximately 10%

of the time during summer over a 25 year period. In addition, depths of flow in the riffle locations under wetted perimeter critical flow values indicate that the critical flow values result in depths that exceed minimum depth requirements for trout habit and often result in depths that are over twice what may be required for summer trout passage. Our results suggest that the use of the wetted perimeter method is not appropriate for the Beaver River. For southern New England, minimum flow values obtained from the wetted perimeter method should be compared to results obtained from other methods to determine the accuracy and applicability of the critical flows prior to using these values for any type of instream flow regulations.

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## Chapter 3

### **Effects of Low Impact Development and irrigation on sustaining environmental flows in a southern New England river**

by

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## **Abstract**

Land use changes such as urbanization and irrigation can have major effects on stream hydrology. Modifications of the land surface due to urbanization alters natural stream hydrographs by increasing flood peaks, decreasing time to peak flows, and causing higher runoff velocities, while irrigation may produce the opposite effects. Low Impact Development (LID) has emerged as a strategy to reduce the hydrologic impacts of urbanization on aquatic ecosystems by combining site planning and design processes with runoff reduction and treatment practices.

In this study, we assessed the effect of increased impervious cover for both conventional and LID-based urbanization on low flow metrics and flow depths in riffle habitats in a small, relatively undeveloped watershed located in southern Rhode Island. We employed a hydrologic model to simulate stream flow, base flow and storm flows under different land cover scenarios and then compared these results to the effects of direct stream withdrawals from agricultural irrigation.

We found baseflow to be negatively correlated to impervious area (IA). On pervious surfaces, direct runoff is likely to be infrequent during the summer months, when most of the precipitation that falls is utilized for the soil moisture deficit. In contrast, connected IA will generate immediate runoff to streams from rainstorms that would have otherwise infiltrated the soil. During periods of excess precipitation, the falling limbs of those hydrographs generated prolonged periods of comparatively elevated flows.

Combining baseflow and storm flow showed increased values of IA can generate higher flow values during the summer months during periods with excess precipitation. The small decreases in base flow input to the stream due to increased IA are negated by the impacts of the higher storm flows, causing summer stream flows to be higher under the developed land use scenarios than existing conditions. Changes to the channel depth of the riffles were relatively minor.

During a year with median precipitation, the model predicted a lower frequency of low flows with both conventional development and with LID compared to the predictions for the limited development present in current conditions. Over the summer, storm runoff and the associated falling limb of the runoff hydrograph that results from connected impervious cover occurs with enough frequency to influence the low flow thresholds we use for metrics. During the dry year, rainfall occurrences were very infrequent and the higher baseflow associated with LID accounts for the slight increase in flows compared to the conventional development. Irrigation scenarios decreased both flows and depths.

The occurrence of low flows within the Beaver River was found to be relatively resilient to the extent of development and water withdrawals simulated by this study. The analyses will help inform future water management decisions in watersheds with the diversity of land uses that occur in southern New England.

## Introduction

Riverine systems serve as conduits for nutrients and organisms, corridors for fish and wildlife passage, and provide resources for humans; such as fresh water, food, and opportunities for recreation (Puth and Wilson, 2001). In order to preserve stream functionality, rivers must maintain seasonally adequate flows (Richter et al. 1998). Characteristics, such as the duration and frequency of flow, affect the integrity of a stream through their effects on water quality, energy sources, physical habitat and biotic interactions (Bunn and Arthington, 2002). Although flow in a stream is controlled by the amount and timing of precipitation and evapotranspiration, the amount of streamflow at any given time is also influenced by watershed characteristics, such as elevation, hydrography, drainage area, water abstractions for irrigation and domestic uses.(Richter et al., 1998; Allan, 1995; Olden and Poff, 2003; Piao et al., 2007). Land use changes such as urbanization can have major effects on stream hydrology, generating changes in both low flow and flood conditions (Brabec, 2002; Walsh et al., 2009). Modifications of the land surface due to urbanization alters natural stream hydrographs by increasing flood peaks, decreasing time to peak flows, and causing higher runoff velocities (Paul and Meyer, 2008). Urbanization can also generate higher frequencies and durations of low flow conditions (Leopold, 1968; Meyer, 2005). Direct water withdrawals for agricultural use from streams and rivers has become a common occurrence in Rhode Island since the 1980's when center pivot and linear move irrigation systems were introduced by turf growers (Gold et al., 1988).

Increasingly, states in the Northeast are developing management strategies to protect riverine ecosystems against stresses imposed by low flow conditions (CT DEEP, 2011; RI WRB, 2011). Low flows can affect stream connectivity, restrict movement of aquatic organisms, concentrate prey into limited areas, purge invasive species from riparian corridors, and enable recruitment and evolution of floodplain plants (Cushman 1985; Gehrke et al., 2006; Scheidegger and Bain, 1995; Mathews and Richter, 2007; Nilsson and Svedmark, 2002; Humphries and Baldwin. 2003). Low flows are expected to reflect summer baseflow and can be reduced by evapotranspiration of riparian wetlands (i.e., phreatophytes) and withdrawals for irrigation and other uses (Winter, 2007).

Low impact development (LID) has emerged as a strategy to reduce the hydrologic impacts of urbanization on aquatic ecosystems. It combines site planning and design processes with runoff reduction and treatment practices (Dietz, 2007; Coffman and France, 2002; Davis et al., 2009). LID is intended to mimic the natural hydrology of a site by collecting and infiltrating stormwater runoff close to the source and extending the rapid overland flow travel times that typically occur with urbanization. It is used to facilitate baseflow and groundwater recharge, as opposed to traditional stormwater strategies which focus on mitigating flood risks through control structures located at the downstream end of a development (RIDEM, 2010). LID site designs often preserve much of the site in an undisturbed condition by mandating increased open space and riparian buffers. Post construction techniques are utilized to reduce a development's impact to the soils, vegetation, and aquatic

systems. These practices promote disconnecting IA from the stream network by utilizing onsite infiltration from roofs and impervious areas (IA) through the use of detention areas, such as grassed swales, rain gardens and other bioinfiltration devices (Booth and Jackson 1997). Effective IA, or connected IA, is the proportion of IA that is directly connected to the stream network. There have been many studies that show connected IA affects changes in runoff much more than total IA (Brabec et al. 2002).

Stream flow is often statistically analyzed to characterize the magnitude and probability of various components of the flow regime, such as low flows, high flows, and average or median discharges (Richter et al., 1998; Allan, 1995; Olden and Poff, 2003). In this study, we assessed the effect of increased impervious cover for both conventional and LID-based urbanization on statistical metrics related to low flow in the Beaver River, a small, relatively undeveloped watershed located in southern Rhode Island. We also evaluated the flow depths associated with these low flow metrics at specific riffle habitats where abnormally low flows is expected to degrade aquatic habitat. In order to assess the flow depths, we performed field surveys of riffle sections at three locations along the Beaver River to determine cross-section morphometry. We employed a hydrologic model using HEC-HMS (USACE, Hydrologic Engineering Center, Davis, CA) to simulate stream flow, base flow and storm flows under different land cover scenarios over a 26-year period. We then compared these results to the effects of direct stream withdrawals from agricultural irrigation. The

analyses were undertaken to inform future water management decisions in watersheds with the diversity of land uses that occur in southern New England.

## **Methods**

### **Study Watershed**

The study area is the 23 km<sup>2</sup> Beaver River watershed, located in southern Rhode Island (Figure 1). This watershed is a sub-watershed of the Pawcatuck River, which drains into the ocean at Little Narragansett Bay. Current land use in this rural watershed is approximately 82% forested, 9% agricultural, 6% residential housing, with the balance in recreational use and open land, and has approximately 2.4 % impervious area (IA) (RI Digital Atlas, [www.edc.uri.edu](http://www.edc.uri.edu)). The Beaver River sustains macroinvertebrate and fish communities associated with some of the most pristine rivers in the State of Rhode Island (Chapter 2) . The slopes in the watershed vary from 0 % to 14.7 % with the majority of the watershed exhibiting a slope between 0 % to 3 % (RI Digital Atlas, [www.edc.uri.edu](http://www.edc.uri.edu)). The soils in the watershed are generally moderately drained with 66 % of the soils classified within NRCS hydrologic soil group B (RI Digital Atlas, [www.edc.uri.edu/atlas](http://www.edc.uri.edu/atlas)). Approximately 15 % of the watershed is characterized by hydric soils (RIGIS, 2013). The watershed is underlain by two major geologic units; bedrock and stratified drift. The stratified drift aquifer is highly permeable, comprises approximately 25 % of the watershed (RIGIS, 2013) and consists of interbedded lenses of gravel and sand within the Beaver River valley, formed by meltwater streams flowing south from retreating glaciers (Dickerman and

Ozbilgin, 1985). One U.S. Geological Survey (USGS) long term stream gage, Gage 01117468, is located near the outlet of the Beaver River Watershed.

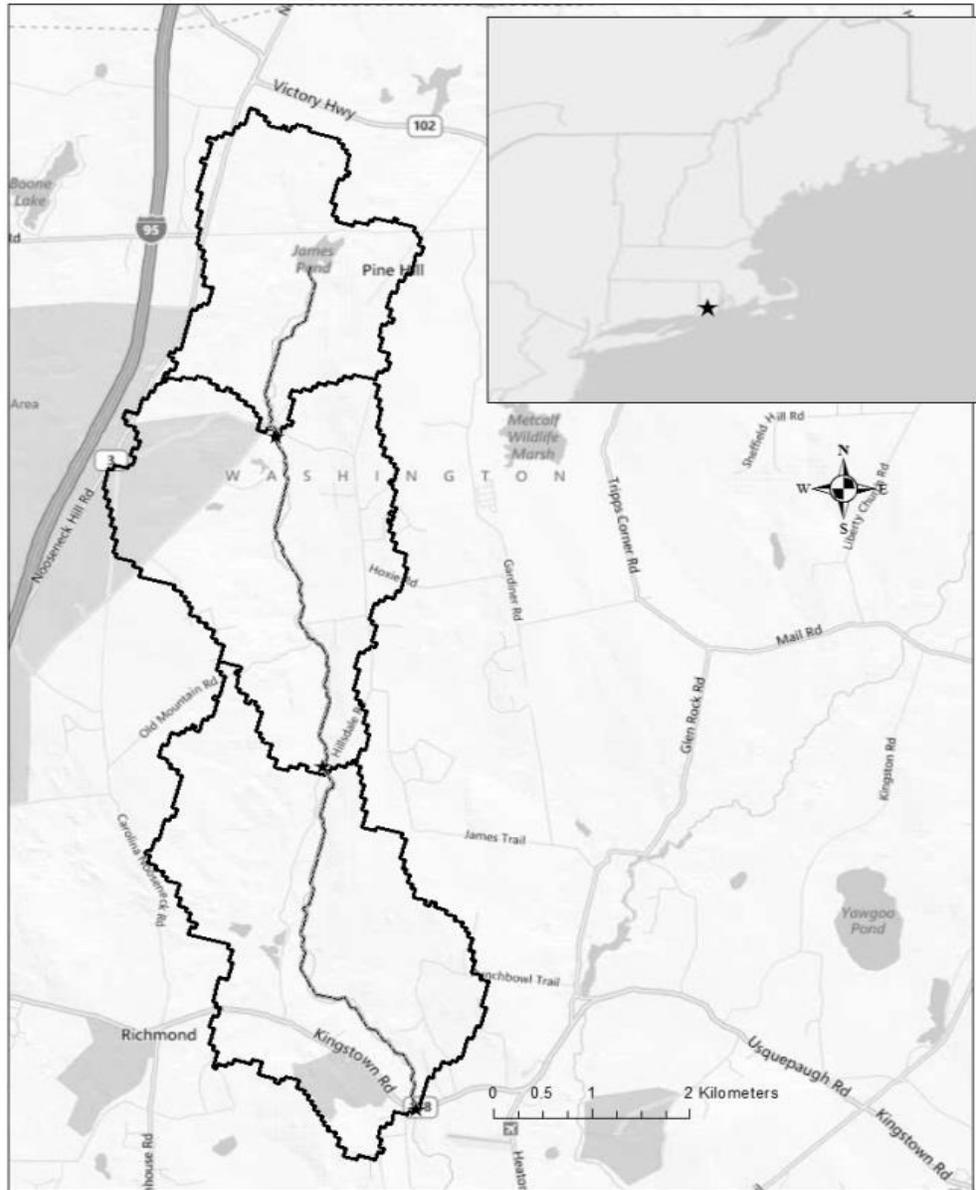


Figure 1- Location map of study area showing Beaver River watershed along with USGS gage at Rt. 138. Subbasins used in HEC-HMS are also displayed

## Stage-Discharge Relationships at Riffle Cross-Sections

At each riffle location that corresponded to the outlet of each subbasin a stage-discharge relationships was developed to relate simulated discharge from the various scenarios to minimum flows and depths at riffle habitats. To generate the stage-discharge relationships, the stream channel cross section was divided into one-foot (0.3048 m) subsections. In each subsection, the depth at the center of the subsection was measured with a surveyor's rod, and the area was estimated by multiplying the depth times the width (0.3048 m). Water velocity was determined using a Global Water Flow Probe FP101 current meter. Stream bed elevations were determined using a CST/berger automatic level. Stream discharge was then calculated using the mid-section method:

$$Q = \sum_{i=1}^n (X_{i+1} - X_i) (U_i Y_i + U_{i+1} Y_{i+1}) / 2$$

where the  $X_i$  are the distances to successive measurement points along the transect, where stream velocity ( $U_i$ ) and water depth ( $Y_i$ ) are measured, starting with  $X_1$  being the initial point on one bank and  $X_n$  being the final measuring point on the opposite bank.

A slope-area method was used to determine Manning's roughness coefficient ( $n$ ) for each riffle location by rearranging Manning's Equation to solve for  $n$ :

$$n = \frac{1.49}{Q} R^{\frac{2}{3}} S^{\frac{1}{2}} A$$

Where  $A$  is the cross sectional area of the stream measured from survey data,  $n$  is Manning's  $n$ , which is an index of the roughness of the stream bed,  $R$  is the hydraulic

radius, which is the ratio of the cross section area of the stream to its wetted perimeter (i.e., the cross-sectional distance along the stream bed and banks that is in contact with the water), and  $S$  is the change in elevation of the stream over a specified distance. Stream bed elevations and water surface elevations for points about 7m upstream and downstream of the riffle section were measured.

### **Model Selection**

Criteria for selecting a basin scale model for this study was ease of use, compatibility of model parameters with available site-specific data, ease of calibration, model availability, and lastly, whether the model is commonly used for hydrologic studies. An integrated, physically based, distributed model (MIKE SHE; DHI, [www.dhisoftware.com](http://www.dhisoftware.com)) was given extensive attention, since it is intended to simulate most major hydrological processes of water movement, including canopy and land surface interception after precipitation, snowmelt, evapotranspiration, overland flow, channel flow, unsaturated subsurface flow, and saturated ground water flow, including exchanges between surface water and ground water. However, the MIKE SHE modeling system required extensive parameterization with high-resolution data and a large number of parameters, such as detailed soil and vegetation attributes. For the Beaver River watershed, a number of key model parameters are either not available or not available at the required scales, negating the value of many of the process-oriented, distributed aspects of the model (Beven, 1989; Jakeman and Hornberger, 1993). In addition substantial complications with

model calibration was encountered when default values for required parameters were estimated or used.

### **HEC-HMS Model**

The Hydrologic Engineering Centers Hydrologic Modeling System (HEC-HMS) model, developed by the Army Corps of Engineers was then selected for use. HEC-HMS is a lumped parameter model that incorporates the spatial pattern of development by subdividing the watershed into areas that are approximately homogeneous in land use, soil type, and slope. The HEC HMS model has been used for a variety of different hydrological studies, such as studying the effects of urbanization on runoff (Hejazi and Markus, 2009; Du et al., 2012) and flood modeling (Harris, 2007; Amengual et al., 2007)

Runoff was modeled using the HEC-HMS rainfall/runoff model to simulate continuous stream flow for the Beaver River Watershed. The daily discharge simulated by the model was calibrated and validated to data obtained from a USGS real-time gauging station (USGS 01117468) located on the right bank of the Beaver Rivergauge, approximately 3 meters downstream from the Beaver River Bridge on Route 138 in Richmond, RI. The gage has a drainage area of approximately 23.8 km<sup>2</sup> and has a continuous period of daily flow records from December 1974 to the present.

Since the Beaver River watershed is fairly homogeneous, the watershed was subdivided into just three subbasins to simulate development in the upper, middle and bottom third of the watershed. The resultant subbasins ranged in size from 5.1

km<sup>2</sup> to 9.4 km<sup>2</sup> (Figure 2). Flow regimes were modeled cumulatively down the basin. That is, the flow for the upper watershed included flow from only the upper watershed; flow for the middle basin included both flow from the upper and from the middle basin and flow for the outlet basin included flow from all upstream basins. The outlet of each subbasin corresponds to a riffle habitat where stage-discharge curves were established.

HEC-GeoHMS (Fleming and Doan, 2010) was used to develop hydrologic modeling inputs for HEC-HMS model. The program created background map files, which contain stream alignments and subbasin boundaries along with physical parameters, such as stream and basin slope and stream length – derived from input elevation data – as well as IA coverage.

The 30-m digital elevation model from NHDPlus ([www.horizon-systems.com](http://www.horizon-systems.com)) was used as input for the elevation model. Impervious surface coverage for Rhode Island was obtained from the RIGIS website ([www.edc.uri.edu/rigis](http://www.edc.uri.edu/rigis)) based on 2007 two-meter grid. A lumped basin model was then created that contained subbasin areas, hydrologic elements and their connectivity to represent the movement of water through the drainage system.

For hydrologic modeling, HEC-HMS utilized the following components: (1) runoff volume by initial deficit and constant loss infiltration, (2) Clark unit hydrograph, (3) linear reservoir for subsurface flow and (4) kinematic wave routing for channel flow.

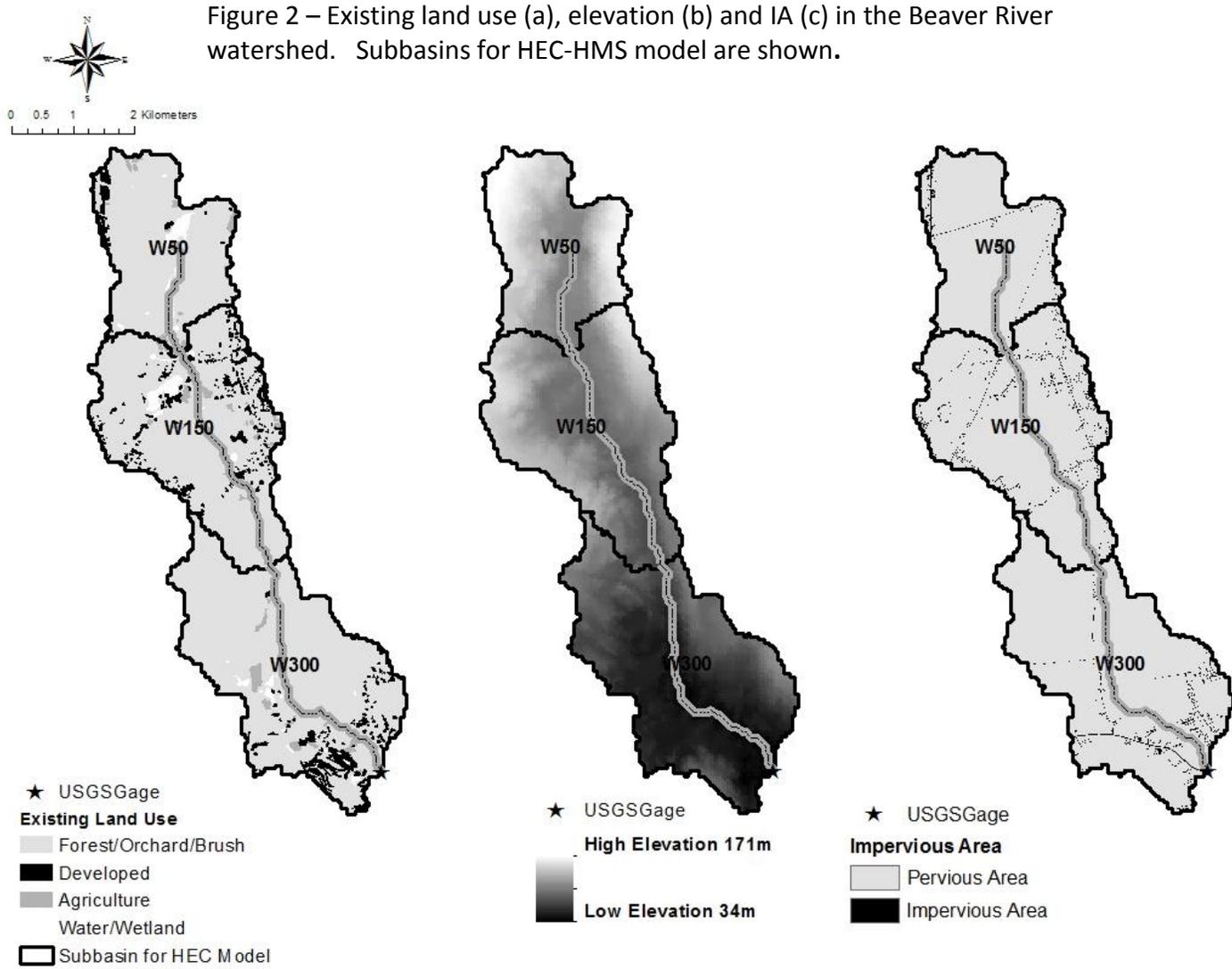
### ***Runoff volume***

Daily runoff volume was computed by the deficit and constant rate loss model. The model simulates connected impervious areas by assuming that all rainfall onto “connected” impervious surfaces results in direct surface runoff to the stream. Connected impervious surfaces, also known as effective impervious cover (Brabec et al., 2002) include only those areas that drain directly into a storm conveyance system that discharges to surface water (Brabec et al., 2002).

For pervious areas, the deficit constant loss method employs a quasi-continuous model of precipitation loss that uses a single soil layer to account for daily changes in moisture content. This method has been widely validated in many studies, it is easy to use and is parsimonious, requiring only a few input parameters . The deficit constant loss method for pervious surfaces employs a daily soil water balance to assess the depth of water storage capacity, known as the deficit field. Infiltration represents the input to the daily soil water balance. Evapotranspiration and soil percolation to the groundwater are the outputs. Rainfall onto pervious surfaces first fills the initial soil deficit until the maximum storage depth is reached at which point runoff can occur.

The initial daily soil deficit at the beginning of the modeling simulation indicates the amount of water that is required to saturate the soil to the maximum storage and reflects the topography, land use, hydrologic soil group, type, infiltration capacity and antecedent moisture condition. This combination of interception, the precipitation required to fill the soil water deficit, and depression storage are

considered watershed losses and is also termed the initial loss ( $I_a$ ). The potential evapotranspiration computed by the meteorological model of HEC-HMS is used to dry out the soil layer between precipitation events. Evapotranspiration was based on monthly average values for Rhode Island (Farnsworth and Thompson, 1982). The maximum potential rate of precipitation loss due to infiltration, referred to as the constant loss rate ( $f_c$ ) was assumed to be constant throughout an event. The loss rate is the long-term infiltration capacity of the soil. Skaggs and Khaleel (1982) published estimates for  $f_c$  based on hydrologic soil types. Both the  $f_c$  and  $I_a$  values in the validated model were determined by calibration (Feldman, 2000).



Precipitation excess ( $pe_t$ ) is obtained by subtracting all soil and watershed losses ( $I_a$  and infiltration) from precipitation. The precipitation excess ( $pe_t$ ) during the time interval  $t$  to  $t+\Delta t$  was then calculated as follows:

$$pe_t = \begin{cases} 0 & \text{if } \sum P_i < I_a \\ P_t - f_c & \text{if } \sum P_i > I_a \text{ and } P_t > f_c \\ 0 & \text{if } \sum P_i > I_a \text{ and } P_t < f_c \end{cases}$$

The direct runoff was then generated from  $pe_t$  by using Clark's unit hydrograph model.

### **Clark's Unit Hydrograph**

The Clark's Unit Hydrograph (UH) model was used to perform runoff simulations. This model derived the subbasins' UHs by representing two critical processes in the transformation of  $pe_t$  to runoff: (1) the movement of  $pe_t$  from its origin through the drainage area to the outlet and (2) attenuation, the storage effect of the stream channel (Feldman 2000). Short-term storage of water in the watershed was represented using a linear reservoir approach, represented by the equation:

$$\frac{dS}{dt} = I_t - O_t$$

Where  $dS/dt$  = time rate of change of water storage at time  $t$ ;  $I_t$  = average inflow to storage at time  $t$ ; and  $O_t$  = outflow from storage at time  $t$ .

Along with the linear reservoir model for groundwater flow, the storage at time  $t$  is related to outflow as:

$$S_t = RO_t$$

Where  $R$  is a constant linear reservoir parameter (storage coefficient). These equations are combined and solved using a simple finite difference approximation, yielding:

$$O_t = C_A I_t + C_B O_{t-1}$$

Where  $C_A$  and  $C_B$  are routing coefficients and were calculated as follows:

$$C_A = \frac{\Delta t}{R + 0.5\Delta t} \quad \text{and} \quad C_B = 1 - C_A$$

The average watershed storage outflow for each time interval was:

$$\bar{O}_t = \frac{O_{t-1} + O_t}{2}$$

Conceptually, the reservoir for the watershed was located at the outlet of each subbasin and represents the aggregate impacts of all watershed storage (Feldman, 2000). Clark's UH model also accounted for the time required for water to move to the watershed outlet by using a linear channel model that routed the water from remote locations to the linear reservoir at the outlet without attenuation. The time delay was represented implicitly with a time-area histogram, included within HEC-HMS. If the area is multiplied by unit depth and divided by  $\Delta t$ , the result is the inflow to the linear reservoir. Since the unit depth for the simulation was  $pe_t$ , solving for the reservoir outflow ordinates generated the Unit Hydrograph (Feldman, 2000). The other parameter required for by HEC-HMS for the Clark's UH simulation was the storage coefficient, or  $R$ .  $R$  is an index of the temporary storage of  $pe_t$  in the

watershed as it drains to the outlet, estimated for this study using the autocalibration feature of the model (Feldman, 2000).

### ***Linear reservoir for subsurface flow***

Base flow was modeled using a linear reservoir approach, which simulated the storage and movement of subsurface flow as water moving between two linear reservoirs and is used along with Clark's UH. The initial baseflow was specified for the beginning of the simulations. The groundwater storage coefficient was a time constant, measured in hours, giving a sense of the response time of the subbasin. Groundwater flow was the sum of volumes of groundwater from each layer and is computed by:

$$GwFlow_{t+1} = \frac{ActSoilPerc + CurGw_tStore - \frac{1}{2}GwFlow_t * TimeStep}{RoutGw_tStore + \frac{1}{2}TimeStep}$$

Where  $GwFlow_t$  and  $GwFlow_{t+1}$  were the groundwater flow rates at the beginning of the time interval  $t$  and  $t+1$ ,  $ActSoilPerc$  was the actual soil percolation from the soil profile to the groundwater layer, computed from the constant infiltration rate input in the deficit and constant loss method and obtained from model calibration.

$CurGw_tStore$  was the calculated groundwater storage for the groundwater layer,

$RoutGw_tStore$  was the groundwater flow routing coefficient from groundwater

storage,  $TimeStep$  was the simulation time step.

### ***Kinematic wave routing for channel flow***

Channel flow was modeled using a kinematic wave routing model, based on a finite difference approximation of the continuity equation and a simplification of the momentum equation. Values for Manning's  $n$  (roughness coefficient of the channel) were estimated from visual inspection, field measurements and comparison to other channels (Barnes, 1967). The cross-sectional area of the channels were approximated by rectangles.

### **Model calibration and validation**

Initial model parameters were estimated using the guidelines given in the HEC-HMS Technical Reference Manual (Feldman, 2000). The automatic parameter optimization tools, available in the HEC-HMS model, were used to find the optimum set of parameters (groundwater storage coefficients for the linear reservoirs) for each sub-basin.

Model calibration was based on 10 years of continuous flow data at the USGS Beaver River gauging station and validation was performed on a separate 15 years of daily runoff records at the same location. Validation was also examined for just the summer months to assess the low flow performance of the calibrated model. Both Nash-Sutcliffe efficiency (NSE) and root mean square ratio (RSR) were used to determine "goodness of fit" of the model (Nash and Sutcliffe, 1970). The NSE is a normalized statistic that determines the relative magnitude of the residual variance compared to the measured data variance.

NSE indicates how well the plot of observed versus simulated data fits a 1:1 line and was computed as:

$$NSE = 1 - \left[ \frac{\sum_{i=1}^n (Y_i^{obs} - Y_i^{sim})^2}{\sum_{i=1}^n (Y_i^{obs} - Y^{mean})^2} \right]$$

Where  $Y_i^{obs}$  is the  $i^{th}$  observation for the stream flow,  $Y_i^{sim}$  is the  $i^{th}$  simulated value and  $Y^{mean}$  is the mean of the observed data and  $n$  is the total number of observations. NSE ranges from  $-\infty$  to 1.0 with values between 0 and 1 being acceptable levels of performance (Moriasi et al., 2007)

Root mean square error (RMSE) is also a commonly used error index statistics (Singh et al., 2005). Singh et al. (2005) stated that RMSE values less than half the standard deviation of the observed data may be considered appropriate for model evaluation. Based on the recommendation by Singh et al. (2005), a model evaluation statistic, RMSE-observations standard deviation ratio (RSR), was developed. RSR standardizes RMSE using the standard deviation of the observed values, and it combines both an error index and the additional information recommended by Legates and McCabe (1999). RSR was calculated as the ratio of the RMSE to the standard deviation of observed data:

$$RSR = \frac{RMSE}{STDEV_{obs}} = \left[ \frac{\sqrt{\sum_{i=1}^n (Y_i^{obs} - Y_i^{sim})^2}}{\sqrt{\sum_{i=1}^n (Y_i^{obs} - Y^{mean})^2}} \right]$$

RSR varies from the optimal value of 0, which indicates zero RMSE or residual variation, perfect model simulation, to large positive values. In general, models can be considered “very good” if  $0.75 < NSE < 1.00$  and  $0.00 < RSR < 0.50$ , (Moriasi et al.,

2007) while models are considered “satisfactory” if  $0.60 < NSE < 0.75$  and  $0.50 < RSR < 0.60$ .

### **Climate Data**

Daily precipitation data were obtained from the National Weather Service Cooperative Observer Station 37-4266-01, Kingston, Rhode Island, located approximately 11.4 km to the east of the watershed. Monthly average evaporation data was obtained from the National Weather Service (Farnsworth and Thompson, 1982). Both rainfall and evaporation rates were assumed to be constant over the entire watershed. For the modeling time interval (1982 to 2007), the median annual precipitation was 1300 mm, with 1983 the wettest year with an annual precipitation of 1783 mm. The driest year was 1993 with 1110 mm of precipitation.

### **Conventional Development Land Use Scenarios**

Two conventional development scenarios at each of the three subbasins were modeled, reflecting increasing amounts of urbanization. In each subbasin the additional development was modeled by assuming that it occurred only on areas with hydrologic soil group B. The extent of urbanization was simulated through increased amounts of connected impervious area. Existing IA within the watershed was all assumed to be connected. Scenario A proposed that 25% of the watershed undergoes development into ½ acre building lots. For ½ acre building lots, approximately 25% of each lot is converted to connected IA (Kauffman and Brant, 2000). Under Scenario A, approximately nine percent of each subbasin became

connected IA (Table 1). Scenario B represented a situation where half the watershed undergoes development into ½ acre lots resulting in approximately 14% of each subbasin becoming connected IA (Table 1).

Basin	Existing IA %	Total Area (ha)	Scenario A		Scenario B	
			(9% IA)		(14% IA)	
			IA (ha)	% IA	IA (ha)	% IA
Upper	1.76%	531.6	33.3	8.1%	66.48	14.3%
Middle	2.75%	846.3	52.9	9.0%	105.8	15.2%
Lower	2.25%	955.5	59.8	8.5%	119.5	14.5%

Table 1 – Summary of development scenarios for the upper, middle and lower subbasins, including total IA and percent IA.

## Low Impact Development Land Use Scenarios

To develop alternate land use scenarios with LID, zoning regulations of local municipalities were examined for building requirements of both conventional subdivisions and subdivisions with LID design practices, such as increased required open space in exchange for reduced lot sizes and road lengths. A variety of terms were related to these subdivisions, such as “cluster subdivisions”, “open space subdivisions”, and “conservation subdivisions”. These types of developments conserve at least 50% of the site as open space, concentrating development density into one portion of the site to protect natural features, such as wetlands, steep slopes, and surface waters (RIDEM, 2011). In addition to preserving natural features, disconnecting impervious area and promoting infiltration are also encouraged. Applying these practices to conventional zoning for subdivisions with ½ acre lots, IA can be reduced from approximately 25% IA per lot to between 11 and 18% per lot (CWP, 1998).

The upper watershed using Scenario B was used to evaluate the potential impacts of LID on stream flow in the Beaver River. The developed area was reduced by half, but the housing density was doubled to 1/4 acre lots and the connected IA per lot was increased from 25% to 38%. The RI Stormwater design manual (RIDEM, 2010) was used to guide assumptions in the LID scenario. It requires that IA be disconnected and that a portion of the IA runoff (based on the NRCS Soil Hydrologic Group at the site) be directed to recharge structures. Given the soil attributes of the developed areas, a recharge factor of 35%, was used. This was reflected in the

simulation by reducing the percent connected IA under LID scenarios by 35%. The combination of less area in development and partial recharge of runoff from disconnected IA resulted in a substantial change in connected impervious area from 14.3% to 7.9%.

### **Irrigation Scenario**

The effects of direct river withdrawal for irrigation on the probability of low flows in the upper subbasin of the Beaver River was explored. The irrigation scenario represents the daily water withdrawals from a 50 ha turf field in summer (mid-June through August) when potential evapotranspiration is most elevated (average month ET of 0.126-0.144 m/month). Withdrawals from a linear move system that traverses the field in 22 hours and operates seven days a week were modeled. Irrigation was assumed to occur for a total of 40 days between mid-June and August 31, (representing dry periods punctuated by occasional rains). This level of irrigation does not represent a worst case drought situation. For the 66 days between June 1 and August 7, 1999, the Kingston RI weather station recorded a total of 41.2 mm of rainfall, warranting much more extensive periods of irrigation. An application rate of 0.035 m/day was selected to meet the daily ET demand fully. Irrigation was scheduled for 5 consecutive days followed by 5 days without rainfall to mimic intermittent rainfall. Withdrawals could be substantially higher in some watersheds where the area of irrigated agriculture is higher. In addition, irrigation systems are usually not operated continuously, since time is needed for maintenance and repair,

so irrigation demand is satisfied through somewhat higher rates of pumping and withdrawal.

### **Flow Analysis**

Stream flow data is a continuous variable often summarized by frequency distributions. The values for the streamflow were ranked from smallest to largest and plotted using a Weibull distribution (Weibull, 1951) where:

$$F(x) = \frac{i}{n + 1}$$

Where  $F(x)$  is the non-exceedance probability,  $i$  is the rank of the flow observation and  $n$  is the total number of flow observations. Cumulative distribution functions (CDF), or flow duration curves, show the magnitude of stream flow verses the probability the flow is not exceeded. These statistical flows are frequently expressed in the complementary form; for example, Q99 is the flow that is exceeded 99% of the time.

Defining low flows often involves setting an arbitrary upper limit (flow rate per contributing catchment area) to the stream flow record, below which is classified 'low flows'. Other approaches to establishing low flows thresholds include the base flow index (BFI), defined as the average annual ratio of the lowest daily flow to the mean daily flow; the number of zero flow days; and a variety of exceedance levels such as the Q90, the flow that corresponds to discharge equaled or exceeded 90% of the time (Smakhtin, 2001) or the Q95 or Q96 (Pyrce, 2004; Shokoohi and Hong,

2011), while the Q99 is often used to quantify more extreme drought conditions. (Price et al, 2011). In this study two exceedance levels of low flows, Q90 and Q95 were assessed. These exceedance levels were used as metrics to compare the flow regime of the various land development scenarios to the flow regime that is expected under current watershed conditions.

## **Results/Discussion**

### **Model Calibration and Validation**

The observed and model predicted stream flow hydrographs for the calibration period of January 1982 to December 1992 are shown (Figure 3a). The calibrated model was then applied to predict the stream flow for the validation period of January 1993 to December 2007 (Figure 3b).

Statistical indices of NSE and RSR, for both the calibration and the verification periods were calculated using the results of daily time steps (Table 2). In our simulation, model calibration statistics for the calibration period, the validation period and overall time period were classified as “very good” or “satisfactory” and indicated that this generated model was acceptable. The results would likely improve if longer time steps were used, i.e., monthly (Engel et al., 2007); however the focus was on daily flow metric for management applications. For example, in a study conducted by Fernandez et al. (2005), NSE values were 0.395 and 0.656 for daily and

monthly time steps, respectively, for model calibration and 0.536 and 0.870 for daily and monthly time steps respectively, for model validation.

	NSE	RSR
Calibration period (1982-1992)	0.83	0.42
Validation period (1993-2007)	0.73	0.52
Overall (1982-2007)	0.78	0.46

Table 2- Model calibration and validation values for daily time steps. NSE >0.75 are classified as very good and values between 0.5 and 0.75 are considered satisfactory. RSR values < 0.5 are classified as very good and values between 0.5 and 0.7 indicate satisfactory models (Moriasi, 2007).

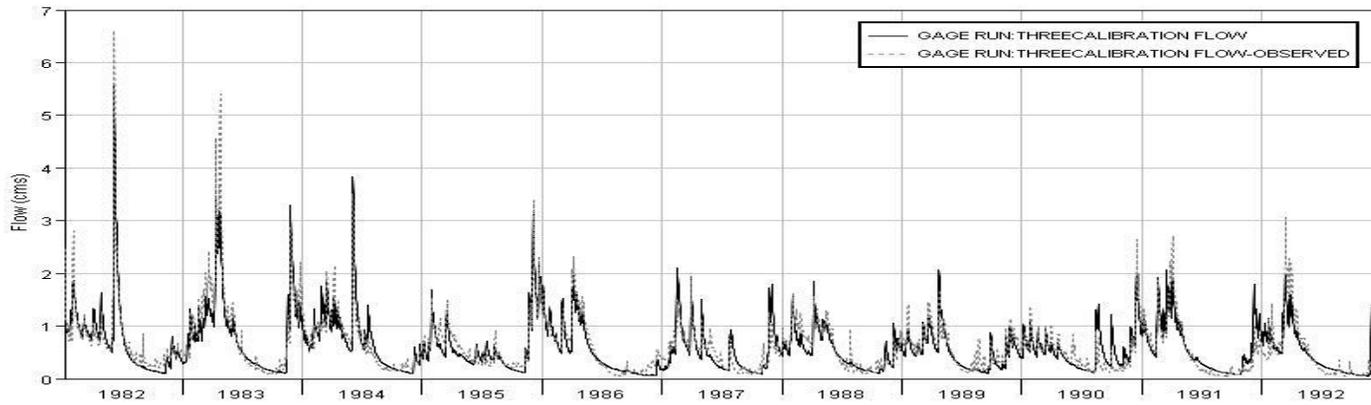


Figure 3 (a) Observed vs. modeled values for daily stream flow during calibration period, 1982-1992.

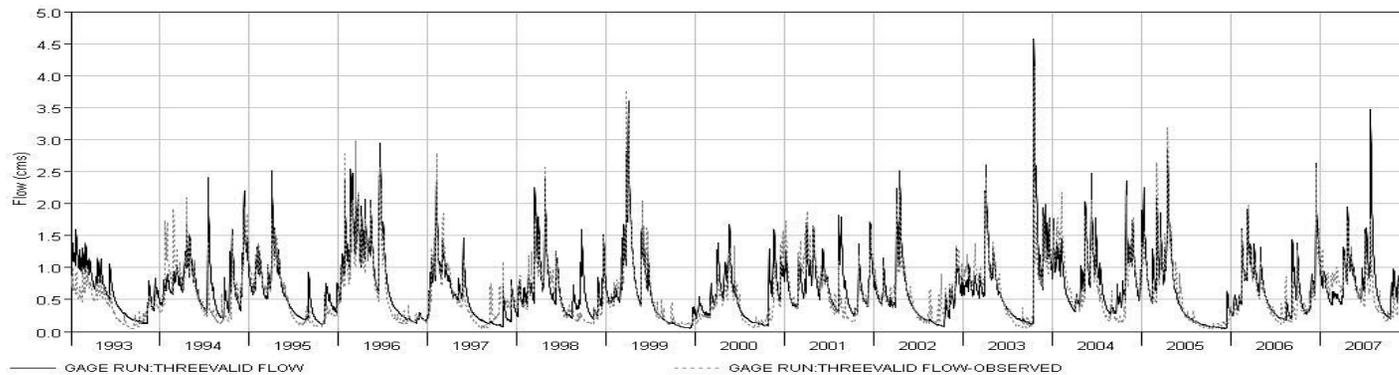


Figure 3 (b)-Observed vs. modeled values for daily stream flow during validation period, 1993-2007.

## Changing Land Use

In order to quantify the changes in flow conditions due to changing impervious area, the model results were examined in two ways. First, the flows associated with the Q90 and Q95 for each of the scenarios were obtained. This permits comparison of changes in the actual flow rates between different scenarios (Table 3). Second, the flow associated with each exceedance (and companion non-exceedance) metric (e.g., Q95, Q90) from the current watershed development condition was used as the basis for comparison. This is referred to as the “basis” flow rate. Then the exceedance (and companion non-exceedance) probabilities for each land use scenario were determined for the “basis” flow in each land use scenario (Table 4).

Upper  
Watershed

Flow probability metric	<b>Existing condition</b> (m <sup>3</sup> s <sup>-1</sup> )	Scenario A - 9% IA (m <sup>3</sup> s <sup>-1</sup> )	Scenario B- 14% IA (m <sup>3</sup> s <sup>-1</sup> )
Q95	0.022	0.028	0.032
Q90	0.029	0.037	0.041

Middle  
Watershed

Q95	0.065	0.083	0.096
Q90	0.084	0.106	0.120

Outlet  
Watershed

Q95	0.107	0.143	0.167
Q90	0.138	0.181	0.208

Table 3 - Daily Flow rate associated with Q95 and Q90 for existing conditions and development scenarios for each of the three subbasins.

Upper  
Watershed

Existing Flow Statistics	Basis Flow for existing conditions at exceedance probability in left column ( $m^3s^{-1}$ )	Existing conditions (probability that flow < basis) %	Scenario A - 9% IA (probability that flow < basis) %	Scenario B- 14% IA (probability that flow < basis) %
Q95	0.022	5	2.3	1.6
Q90	0.029	10	5.2	3.7

Middle  
Watershed

Q95	0.065	5	2.1	1.4
Q90	0.084	10	5.1	3.2

Outlet  
Watershed

Q95	0.107	5	1.8	0.9
Q90	0.138	10	4.5	2.5

Table 4 - Non-exceedance probabilities for subbasins using daily flow rate computed for existing conditions as baseline.

The model indicates slightly higher levels of flow for the low flow metrics with increasing impervious cover. Changes to the channel depth of the riffles were also relatively minor (Table 5). Increasing impervious cover was found to generate fewer days below low flow thresholds than what was simulated for the current, relatively undeveloped watershed conditions. For example, while daily flows of  $\leq 0.029 \text{ m}^3\text{s}^{-1}$  occurred 10 % of the time (Q90) in the upper sub-basin under current conditions. In Scenario B with 14% impervious area within the watershed this level of daily flow occurred less than 4 % of the time (Table 4). The relative effects of development were more pronounced at the lower flows. For example, in the upper watershed the model results show that during 5% of the year flows will be less than  $0.022 \text{ m}^3\text{s}^{-1}$  for the existing conditions compared to  $0.032 \text{ m}^3\text{s}^{-1}$  for scenario B (with 14% impervious cover). Based on hydraulic measurements taken at the riffle cross section at the outlet of the upper basin, this change in flow will raise the water depth from 7.18 cm with present conditions to 8.00 cm with scenario B (Table 5).

Upper  
Watershed

Flow probability metric	<b>Existing condition</b> (cm)	Scenario A - 9% IA (cm)	Scenario B- 14% IA (cm)
Q95	7.18	7.74	8.00
Q90	7.77	8.43	8.74

Middle  
Watershed

Q95	14.80	16.47	18.47
Q90	16.56	17.63	19.96

Outlet  
Watershed

Q95	12.91	14.71	16.56
Q90	14.52	15.93	17.85

Table 5 - Stream height (above thalweg) associated with Q95 and Q90 for existing conditions and development scenarios for each of the subbasins.

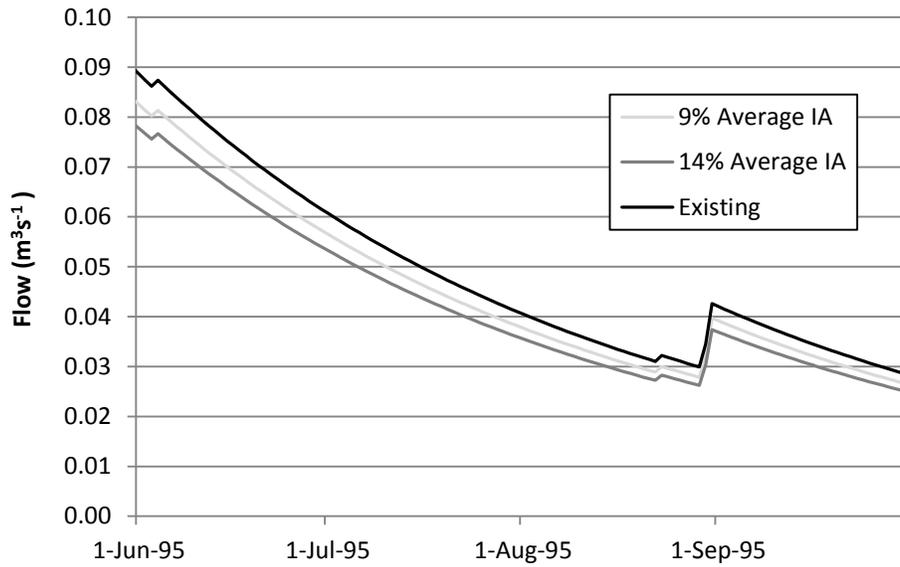
To gain further insight into the simulated summer stream flow predictions with varying land use and impervious cover scenarios, we examined summer baseflow and storm flow hydrographs. We focused just on the upper watershed, which exhibited the largest response to land use change, for the years 1995 and 1993, representing a year that had annual precipitation close the median and a dry year based on the 26 years of record.

Numerous studies suggest that base flow will be negatively correlated to connected impervious area (Klein, 1979; Finkenbine et al., 2007). Our modeled scenarios agreed with these findings (Figure 4; Table 6). In the HEC-HMS model baseflow originates as percolation from the soil profile to the groundwater. Connected impervious areas within HEC-HMS do not contribute to the baseflow. On pervious surfaces, percolation from the soil profile reflects both the extent of the soil moisture deficit and the magnitude of daily rainfall. During the summer in the study region, monthly evapotranspiration usually exceeds precipitation and soil moisture can be depleted substantially. In 1995, soil moisture depletion dropped to 53% of its full storage capacity (Figure 5), while in 1993, soil moisture depletion dropped to less than 30% of its full storage capacity. Baseflow from LID-based development is higher than from conventional development and this difference is most pronounced during a median year, with less differences noted for a dry year when the soil moisture deficit is expected to be higher.

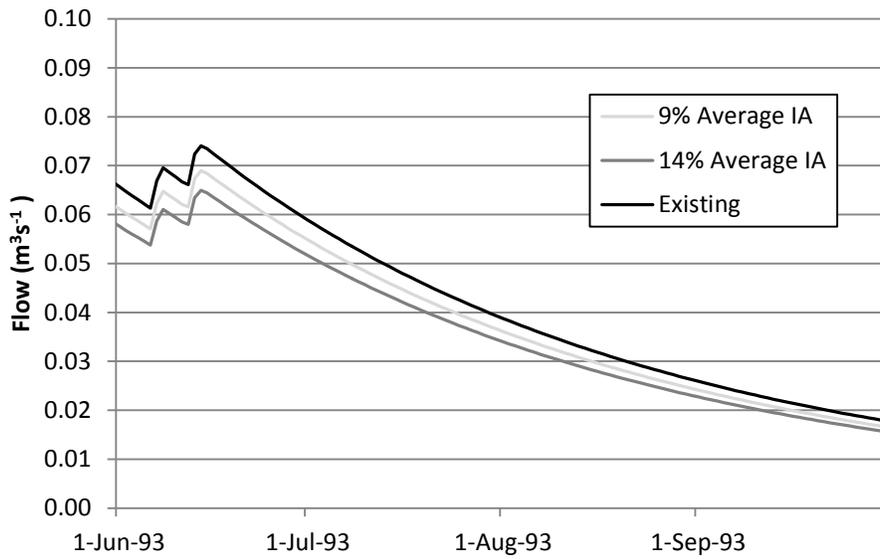
On pervious surfaces in the study region, direct runoff (storm runoff) is likely to be infrequent during the summer months, when most of the precipitation that

falls is utilized for the soil moisture deficit. As seen in Figure 6, direct runoff for the study watershed, with its current condition of 2% IA, was negligible during much of the summer of both a median and a dry summer. Summer rainfall must fill the soil voids of the pervious areas before runoff begins. In contrast, connected IA will generate immediate runoff to streams from rainstorms that would have otherwise infiltrated the soil when those areas were in pervious surfaces (Lull and Sopper, 1969). It is noteworthy that at least one period of excess precipitation occurred in the summers of both the median and dry years and the falling limbs of those hydrographs generated prolonged periods of comparatively elevated flows (Figure 6).

Total flow to the stream is the total of baseflow and direct runoff. The combined hydrograph for the summer of 1995 shows that increased values of IA can generate higher flow values during the summer months during periods with excess precipitation (Figure 7). When connected IA is low, there are prolonged periods in the summer with very little storm-related runoff generated. As IA increases through the different land use scenarios, storm related runoff increases immediately following precipitation events, causing higher stream flows. Since precipitation events occur, on average, every third day, the small decreases in base flow input to the stream due to increased IA are negated by the impacts of the higher storm flows, causing summer stream flows to be higher under the developed land use scenarios (Figure 7) than existing conditions.



a) Base flow for the upper subbasin for 1993



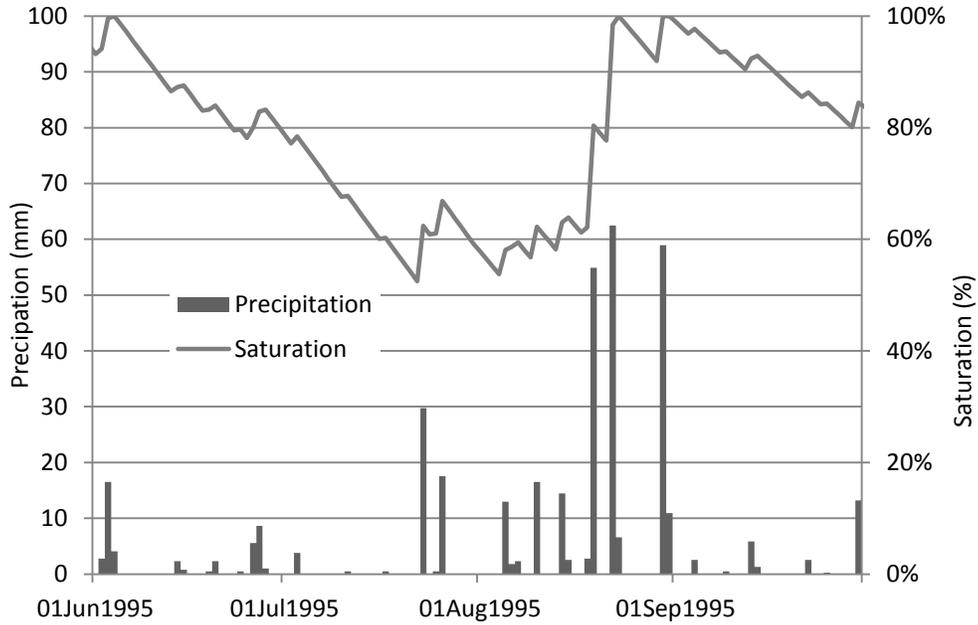
b) Base flow for the upper subbasin for 1995

Figure 4- Base flow for the upper subbasin for a) 1993 (dry year) and b) 1995 (median year). Baseflow was found to decrease with increasing percentages of IA.

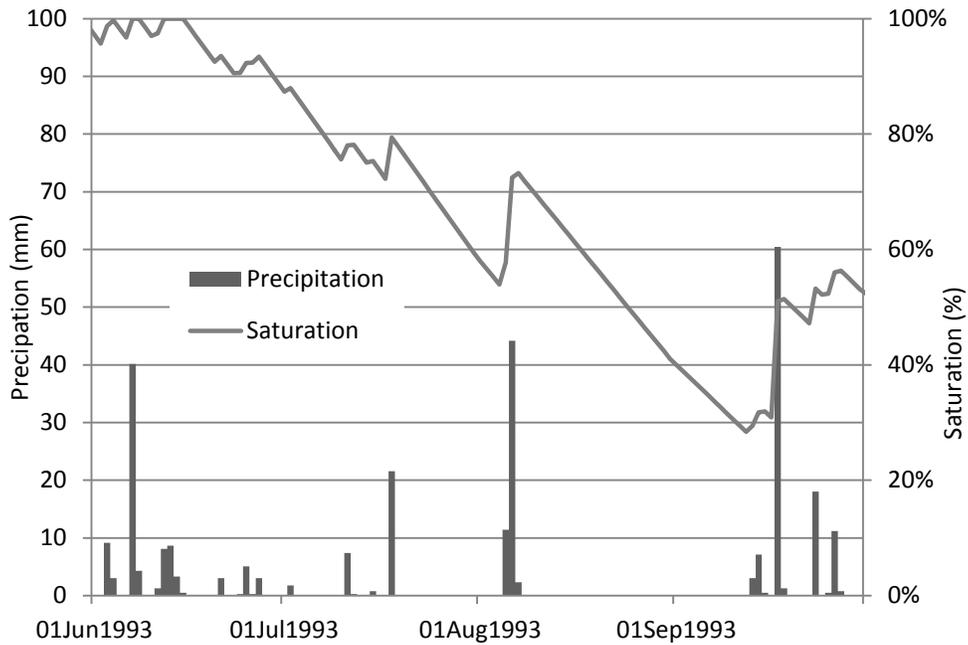
Existing Flow Statistics ( $m^3 s^{-1}$ )	Existing Flow conditions – flow occurs <% of time	Baseline flow values for existing conditions ( $m^3 s^{-1}$ )	Scenario A -9% IA	Scenario B-14% IA	Scenario B-with LID-8% IA
Q95	5	0.023	7.7%	9.0%	7.5%
Q90	10	0.028	12.6%	16.6%	12.0%

Existing Flow Statistics ( $m^3 s^{-1}$ )	Existing Flow conditions – flow occurs <% of time	Baseline flow values for existing conditions ( $m^3 s^{-1}$ )	Scenario A -9% IA	Scenario B-14% IA	Scenario B-with LID-8% IA
Q95	5	0.014	6.4%	7.7%	6.1%
Q90	10	0.017	12.5%	13.8%	12.2%

Table 6 – Baseflow non-exceedance probabilities for upper subwatershed using existing conditions as baseline for a) 1995 –median year and b) 1993- dry year.

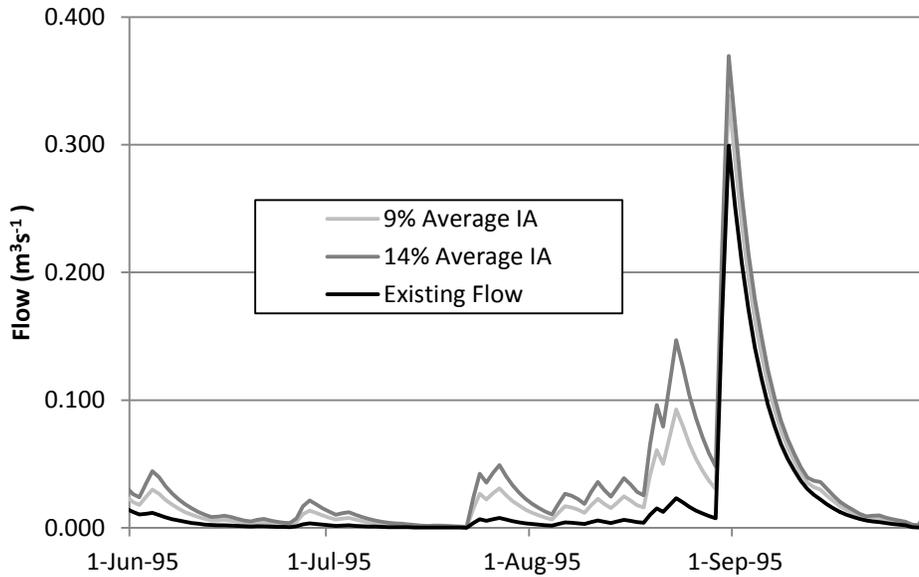


a) Precipitation and percent soil saturation for summer 1995

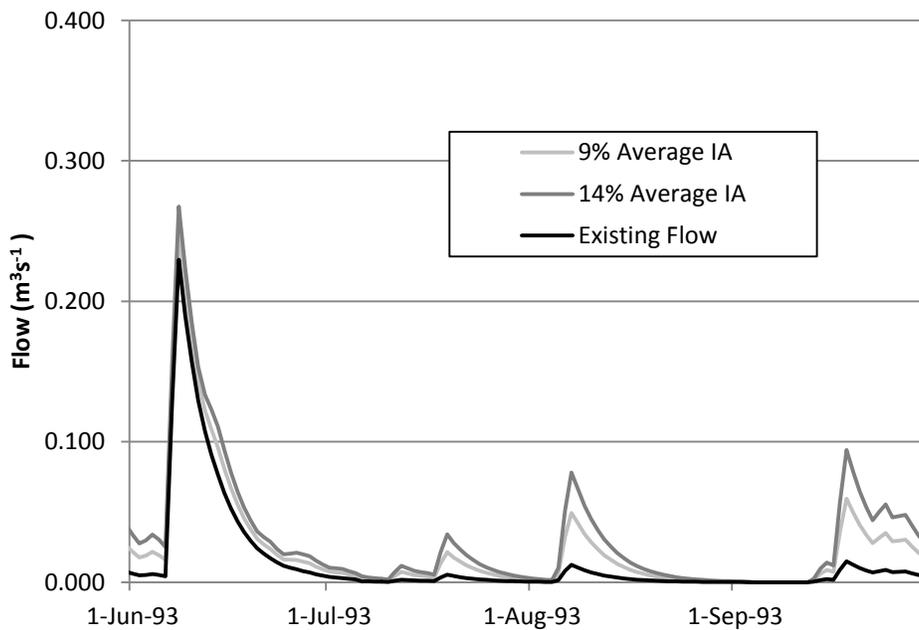


b) Precipitation and percent soil saturation for summer 1993

Figure 5-Precipitation and percent soil saturation for summer a) 1995 and b) 1993

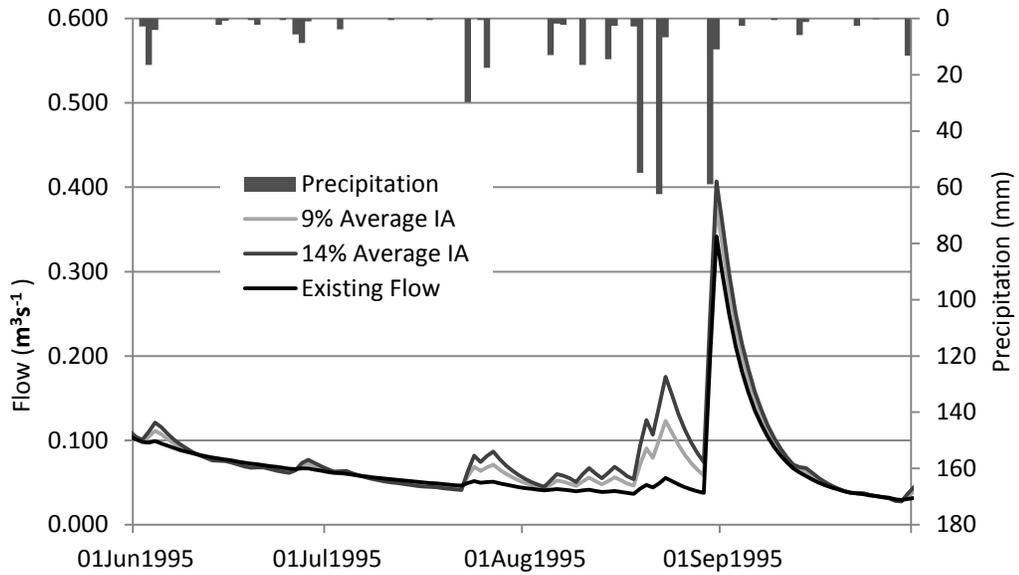


a) Hydrograph of direct runoff for summer 1995

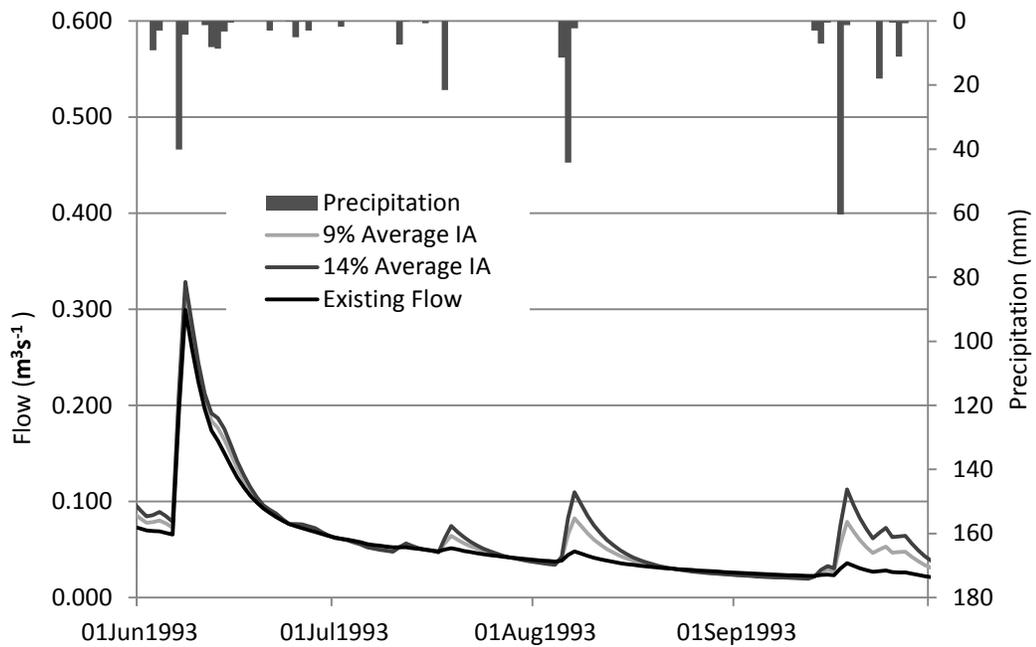


b) Hydrograph of direct runoff for summer 1993

Figure 6-Hydrograph of direct runoff for summer a) 1995 and b) 1993 for different land use scenarios. Direct runoff is derived from storms and does not include baseflow. Direct runoff was found to be higher for increased IA and more pronounced in the summer months.



a) Total hydrograph and precipitation for upper basin for 1995



b) Total hydrograph and precipitation for upper basin for 1993

Figure 7-Total hydrograph and precipitation for upper basin for a) 1995, a year with median precipitation values and b) 1993, a dry year. Hydrograph combines base flow and storm flow. Total flow was found to increase with increasing IA.

## **Comparative Effects of Impervious Cover, Irrigation and LID**

Table 7 includes the low flow metrics for the 1995 (median year) and 1993 (dry year) of the upper watershed for current conditions, Scenario B (14% impervious), LID and irrigation. Changes in flow conditions due to either implementing LID or accounting for potential irrigation losses were examined as before, comparing the flows associated with the Q90 and Q95 for each of the scenarios as well as comparing the exceedance (and companion non-exceedance) probabilities for each land use scenario based on existing probabilities.

During 1995, a year reflecting median rainfall conditions, the flow predicted to occur with 10% non-exceedance probability under the existing conditions decreased to 5.7% under Scenario B (conventional development with 14% IA) and to 6.7% under an LID scenario (Table 7). In other words, during a year with median precipitation, the model predicts a lower frequency of low flows with both conventional development and with LID development compared to the predictions for the limited development present in current conditions. Both conventional development and LID also display fewer low flow periods during a dry year, but the pattern reverses, with LID predicted to have lower frequencies of low flows than the conventional development (Table 7). As noted above, connected impervious cover generates more storm-generated flow, but lower baseflow. Over the summer, storm runoff and the associated falling limb of the runoff hydrograph that results from connected impervious cover occurs with enough frequency to influence the low flow thresholds used for metrics (i.e., the flow rate that coincides with the lowest 18th or

37<sup>th</sup> day of a year). During the dry year, rainfall occurrences were very infrequent and the higher baseflow associated with LID accounts for the slight increase in flows compared to the conventional development.

Irrigation within the upper watershed was the only scenario that resulted in a decrease in flows compared to current conditions. Irrigation scenarios decreased both flows and depths. For example, while daily flows of  $\leq 0.032 \text{ m}^3\text{s}^{-1}$  occurred 10 % of the time (Q90) in the upper sub-basin under current conditions in a dry year, during the irrigation scenario, this level of daily flow occurred more than 15 % of the time (Table 7). Based on hydraulic measurements taken at the riffle cross section at the outlet of the upper basin, this change in flow will lower the water depth from 7.2 cm with present conditions to 6.9 cm with irrigation (Table 8).

Changes in land use generally increase river flows while water withdrawals decrease river flows (Gerten et al, 2008). Eheart and Tornil (1999) found both surface water and groundwater withdrawals have the potential to deplete streams to dangerous levels. Caldwell et al. (2012) found that water withdrawals decreased river flows by an average of 1.4% nationwide.

Existing Flow Statistics	Existing Flow conditions – flow occurs <% of time	Daily stream flow values for existing conditions ( $m^3s^{-1}$ )	Scenario B-14% IA	Scenario B-with LID-8% IA	Irrigation Scenario
Q95	5	0.026	3.8%	3.9%	8.5%
Q90	10	0.032	5.7%	6.7%	15.9%

a) Daily flow non-exceedance probabilities for different management scenarios in the upper subbasin for 1995

Flow Statistics	Existing Flow conditions – flow occurs <% of time	Daily stream flow values for existing conditions ( $m^3s^{-1}$ )	Scenario B-14% IA	Scenario B-with LID-8% IA	Irrigation Scenario
Q95	5	0.020	0.5%	0%	8.0%
Q90	10	0.023	3.1%	2.6%	13.2%

b) Daily flow non-exceedance probabilities for different management scenarios in the upper subbasin for 1993

Table 7 - Daily flow non-exceedance probabilities for different management scenarios in the upper subbasin a) 1995 (median year) and b) 1993 (dry year). The flow corresponding to the Q95 and Q90 for existing conditions is used as a as basis for comparison.

Flow probability metric	Existing condition (m <sup>3</sup> s <sup>-1</sup> )	Scenario B-14% IA (m <sup>3</sup> s <sup>-1</sup> )	Scenario B-With LID 8% IA (m <sup>3</sup> s <sup>-1</sup> )	Irrigation
Q95	0.026	0.030	0.029	0.024
Q90	0.032	0.041	0.038	0.028

Daily Flow rate associated with Q95 and Q90 for existing conditions and development scenarios. 1995

Flow probability metric	Existing condition (m <sup>3</sup> s <sup>-1</sup> )	Scenario B-14% IA (m <sup>3</sup> s <sup>-1</sup> )	Scenario B-With LID 8% IA (m <sup>3</sup> s <sup>-1</sup> )	Irrigation
Q95	0.020	0.027	0.025	0.018
Q90	0.023	0.034	0.030	0.021

Daily Flow rate associated with Q95 and Q90 for existing conditions and development scenarios. 1993

a) Daily flow rates associated with Q95 and Q90

Flow probability metric	Existing condition (cm)	Scenario B-14% IA (cm)	Scenario B-with LID 8% IA (cm)	Irrigation
Q95	7.54	7.81	7.78	7.33
Q90	8.06	8.81	8.55	7.66

Stream height (above thalweg) associated with Q95 and Q90 for existing conditions and development scenarios. 1995

Flow probability metric	Existing condition (cm)	Scenario B-14% IA (cm)	Scenario B-with LID 8% IA (cm)	Irrigation
Q95	7.03	7.58	7.45	6.86
Q90	7.28	8.26	7.87	7.12

Stream height (above thalweg) associated with Q95 and Q90 for existing conditions and development scenarios. 1993

b) Stream height above thalweg for development scenarios

Table 8 – Flow metrics for upper watershed for Scenario B, Scenario B with LID and existing conditions with irrigation. a) daily flow rates associated with Q95 and Q90; b) stream height above thalweg for development scenarios

## Conclusions and Limitations

The occurrence of low flows within the Beaver River was found to be relatively resilient to the extent of development and water withdrawals simulated by this study. Generally, any changes observed in the Q90 and Q95 flow values due to different land use scenarios were not dramatic. A meta-analysis conducted by Schueler et al. (2007) found few studies which researched the effects of impervious area on hydrologic factors, and those studies were either contradictory or ambiguous. Specifically, they found that an inverse relationship between impervious cover and base flow to streams was not always present. Winter (2007) found that base flow is more sustained in watersheds with extensive aquifers, like the Beaver River aquifer (Dickerman and Ozbilgin, 1985), but transpiration from riparian vegetation can cause notable loss of stream flow. Morrison et al., in a statistical study of the importance of watershed attributes to low flow metrics in 33 watersheds in southern New England (Chapter 1), found that the proportion of developed areas (which was highly correlated with IA) was not as important to the magnitude of low flows as natural attributes within a watershed i.e., the proportion of wetlands (negatively correlated to low flow magnitudes) and the extent of stratified drift which was positively correlated to low flow magnitudes. These natural attributes were unchanged for all scenarios investigated in this chapter.

The Beaver River study watershed has approximately 14% wetlands soils and 60% of the length of the river abuts riparian wetlands. In riparian areas, groundwater

is closer to the land surface and riparian vegetation will derive most of its water from the groundwater. During spring and summer months when evapotranspiration is high, riparian vegetation will draw water from the stream and reduce streamflow (Winter, 2007). In a meta-analysis of wetland functions, Bullock and Acreman (2003) found that floodplain wetlands reduce the flow of water in streams during dry periods. Evaporation was also found to be higher in wetlands than in non-wetland portions of a watershed. In a study of riparian wetlands in southern Rhode Island on soils similar to those found in our study site, Kellogg et al. (2010) found that transpiration from riparian wetlands intercepted virtually all base flow to the river during the summer months. Rowe (1963) found that streamflows are greatly increased when woody riparian vegetation is removed, which would suggest that the vegetation was drawing water from the streams.

A lumped parameter model, such as HEC-HMS does not differentiate location of soil types within subbasins, but rather calculates an overall value for soil properties such as infiltration rate. Also, the HEC model does not account for losses due to increased water demand from riparian vegetation, perhaps overestimating stream flow during summer months when the evapotranspiration demands are highest. However, the simulations relied on a calibration step which may have partially accounted for the role of riparian zone on the flow regime of the stream.

In addition to the lack of explicit representation and modeling of riparian wetlands, there are other limitations to the HEC-HMS model as well as factors that were not included in the changing land use scenarios which may affect the results of

the low flow analysis. That is, the simulated scenarios did not consider the increased well water usage that typically coincides with increased development. Depending on the location of the wells, distance from the river, withdrawal rates and hydrogeologic setting, installation of wells will have differing impacts on the river. Long term studies of stream discharges have found groundwater withdrawals have decreased stream flow significantly as well as to become disconnected from downstream reaches or dry up altogether (Wahl and Wahl, 1988; Sophocleous, 2000).

The effects of increased effluent from septic systems were also not investigated. Burns et al. (2005) found that base flow during dry periods was higher in high density residential areas, perhaps due to discharge from septic systems. They suggest that while development and increased IA will increase peak magnitude and accelerate the conveyance of storm runoff to streams, the combined effects of natural landscape features such as wetlands and human alterations can change the expected effects of human development on both storm runoff and groundwater recharge. In addition, Hirsch et al. (1990) suggest that the effects of septic system effluent may mitigate the effects of increased impervious area on baseflow recharge. The effects of groundwater withdrawals for human consumption coupled with septic system groundwater recharge and reinfiltration from lawn watering may be insignificant as overall, they may negate each other (Foster, 1990).

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