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Effects of Urbanization on Stream Flashiness in the I-85 Corridor of the Southeastern Piedmont

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EFFECTS OF URBANIZATION ON STREAM FLASHINESS IN THE I-85 CORRIDOR OF THE SOUTHEASTERN PIEDMONT

By

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Under the Direction of Katie Price, PhD

ABSTRACT

The metro areas of the southeastern Piedmont are rapidly expanding, bringing changes to the hydrology of the watersheds within them. Increased urbanization can have significant effects on stream hydrology within a watershed, including large fluctuations of flow in streams referred to as “stream flashiness”. Increased stream flashiness has numerous consequences, including water quality degradation, flooding, and destruction of aquatic habitats. This thesis quantifies stream flashiness in urban and rural streams and investigates the relationship between flashiness and watershed land cover, particularly the amount and spatial distribution of impervious surfaces. Results show a strong relationship between urbanization and peak flows, but indicate that the underlying geology and other natural/anthropogenic factors complicate the relationship between R-B index and percent impervious surface cover. Results also indicate regional patterns within the southeastern Piedmont, most notably flashier streams in North Carolina compared to Georgia.

INDEX WORDS: Hydrology, Flashiness, Urban, Impervious Surface, Richards-Baker Index, Land cover

EFFECTS OF URBANIZATION ON STREAM FLASHINESS IN THE I-85 CORRIDOR OF THE SOUTHEASTERN PIEDMONT

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ELI KOSLOFSKY

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DEDICATION

I dedicate my thesis to my parents. They provided mental support/advice for me throughout the process of obtaining my master's degree and I am very greatful for their help.

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I would like to express my acknowledgment here to my advisor, Katie Price. In my time working under her I expanded my knowledge greatly. I would like to thank her for providing me the avenue in which to do so, through my coursework with her, our discussions regarding this thesis, and through her guidance of my personal research.

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1 INTRODUCTION

Significant change has occurred to the natural landscape of the United states in the last century. Since the 1950s, metropolitan areas in the United States have rapidly expanded. With the invention of the automobile and the expansion of paved road networks, people gained the ability to live further and further from the urban core. These new types of landscapes required significant infrastructure, including roads and highways paved with concrete and asphalt, shopping centers with large expansive parking lots, and buildings with impervious roofs (Hanson & Giuliano, 2004).

These changes to the landscape greatly alter hydrologic systems (Booth, 1991; Hey, 2001). In urban settings, during storm events, flow is quickly "flushed out" from the system. Because of the dominance of overland flow, the water during a storm event flows to the stream very quickly, causing the water levels to rise rapidly (Hollis, 1975). This phenomenon is referred to as "stream flashiness" (Baker et al., 2004; Tomer et al., 2013).

These rapid fluxes of stormwater can have numerous environmental consequences. Increased stream flashiness can lead to water quality degradation in streams, as the increased runoff from storm events contains all the anthropogenic contaminants that occur on these surfaces (Olson et al., 2013). If the stream feeds into a drinking water reservoir, these pollutants will have to be treated to drinking water standards at the expense of the local taxpayers and/or utility customers. The changing flows and recurrence of floods associated with increased impervious surfaces in a watershed also have significant geomorphological impacts (Paul & Meyer, 2001). Larger floods create more capacity for erosion, leading to increased sedimentation during storm events. These changes greatly impact the habitat conditions for the aquatic life in these streams, especially due to siltation of spawning and food production areas for fish (Bledsoe, 2002). These effects can lead to a significant reduction of fish and invertebrate diversity in streams (Paul & Meyer, 2001). With the sprawling suburban landscape that has come to characterize southeastern cities (Hamidi et al., 2014), investigation of these effects is increasingly important, especially in the rapidly expanding cities along the I-85 corridor of the southeastern Piedmont.

1.1 Hydrology of Forested Watersheds

In forested watersheds, flow overland flow is rare, and stream discharge is fed significantly by subsurface baseflow given the ability of forests to allow infiltration. In humid, forested areas, streamflow is dominated by groundwater inputs, with additional storm sources from interflow, variable source area runoff, and occasional Hortonian overland flow (Dunne et al., 1975; Sklash, & Farvolden, 1979). The layer of leaf litter/biomass below the forest has the ability to slow the speed by which water moves over the surface, and will also trap water and promote infiltration (Li et al., 2014). This effect is such that overland flow will hardly ever occur in forests (Price et al., 2010). Infiltration is also increased in these environments by burrowing animals/organisms through “macropores” (Lee & Foster, 1991). In a hypothetical ‘untouched’ watershed in the Eastern United States, the land cover would be nearly entirely forested with ample precipitation (MacCleery, 1993).

1.2 Hydrology of Urban Watersheds

Human impact is now seen in virtually all watersheds in the Eastern United States (MacCleery, 1993). Various land covers affect the infiltration capacity of soils in different ways, and all of them reduce the infiltration capacity in comparison to forested land cover (Price et al., 2010). Row-crop agriculture removes the litter below the forest canopy and replaces it with exposed soils with heavy potential for runoff (Arnhold, et al., 2014). In these cases, overland flow will dominate over the throughflow and baseflow that occurs in forests (Kirkby & Chorley, 1967). In urban areas, lawns, golf courses and other non-concrete land covers may greatly reduce the infiltration capacity of surfaces. Roads and parking lots have almost no infiltration capacity at all (Hsu et al., 2000). In watersheds with large amounts of impervious cover, stormwater is forced to run off to the streams with no chance of infiltration. In heavily urbanized areas, land cover is dominated by these human-altered surfaces, and thus is dominated by these rapid flow paths.

The effects of urbanization on baseflow can be quite complicated. With much of the water being flushed out of the system due to low capacity for infiltration, it would be theoretically expected for these urbanized watersheds to have abnormally low baseflows as a result (Klein, 1979). All the flow would enter the channel network during and immediately after the storm event, and once the storm event is over, there would be little water flowing through the slower pathways of throughflow and baseflow to feed the stream (Konrad & Booth, 2005). However, leaking subterranean infrastructure may dampen, or even reverse, the relationship of more urban watersheds having reduced baseflows (Lerner, 2002; Brandes et al., 2005). Additionally, if the direction of the sewer lines flow across watershed boundaries, this would cause precipitation that fell in one watershed to feed baseflow in another watershed. These inter-basin transfers via leaking infrastructure bring water to watersheds it normally would have never reached, altering the water budget of both watersheds. Various studies have shown highly variable baseflow responses to urbanization, indicating baseflow responses to urbanization are highly dependent on specific local factors, including leaking infrastructure and cross-basin transfer of water (Price et. al, 2011).

The distribution of impervious surfaces, rather than simply its total quantity, is also significant in determining how much overland flow will occur in a watershed (Alley & Veenhuis, 1983; Booth & Jackson, 1997). Impervious surfaces that are disconnected are less "effective" than those that are connected. Connected impervious surfaces allow a pathway for stormwater to flow and gain speed, whereas disconnected impervious surfaces route water to permeable areas where they can infiltrate (Figure 1) (Yao, et al., 2016). This paper will, in part, explore these topics.

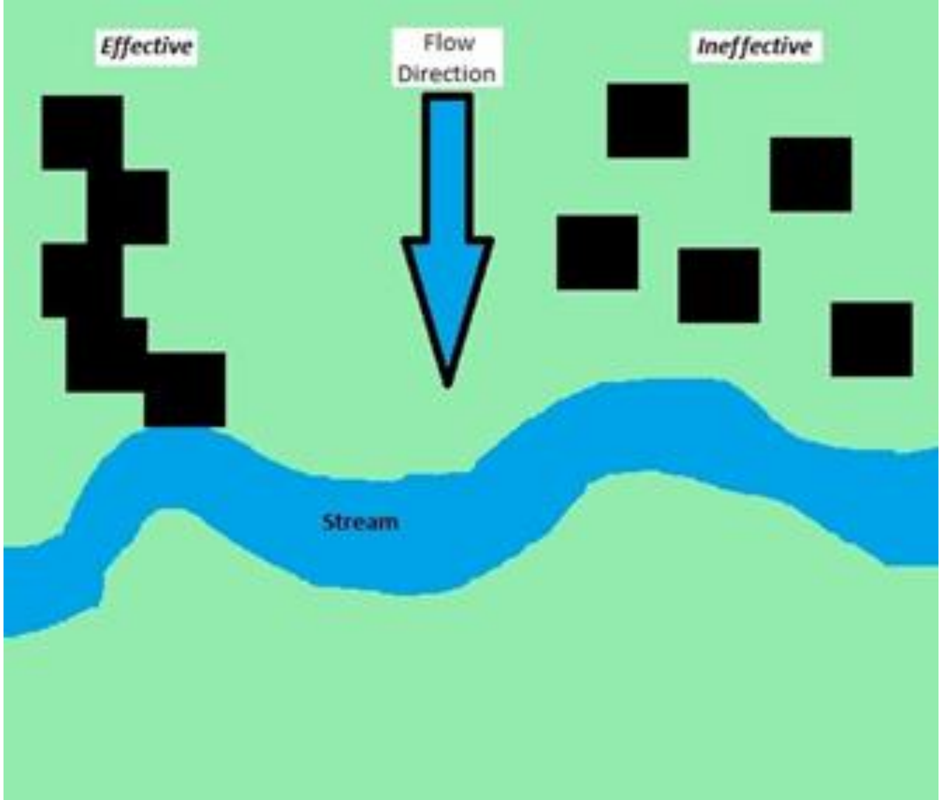

Figure 1. Effective vs. ineffective impervious surface

1.3 Other Relevant Hydrology

Another factor that can complicate both urban and rural watersheds are impoundments. The increased storage in open, uncovered water bodies can lead to increased evaporation (Craig et al., 2007) Dams also have an effect on flooding, altering the stream response to storm events (Graf, 1999). It can be very difficult to quantify the hydrology of a watershed if it is heavily impounded, as one would need to know what amount of water is being trapped and what the frequency and mechanism for release is downstream from the dam. Furthermore, information is rarely available regarding the mechanisms and timings of dam releases.

One more complicating factor that must be accounted for is the evapotranspiration/infiltration tradeoff hypothesis. Trees are known to use large amounts of water and reduce streamflows if no other factors are present (Brown et al. 2005). However, forest soils promote infiltration, which can increase baseflows (Price et al. 2011). The interaction between these two factors and how they can balance each other out has been termed the “infiltration-evaporation tradeoff hypothesis” (Brujinzeel, 2004). It is yet another factor that must be considered when analyzing urban hydrology, and the role it plays in urban areas that contain (or lack) forest cover must be considered.

1.4 Geology/Surficial Hydrogeology

The Southeastern Piedmont region is underlain mostly by bedrock composed of igneous and metamorphic rocks, mostly gneiss and schist, and in some areas by metavolcanic and metasedimentary rocks (Hack, J. T., 1982). Above the bedrock lies a layer of saprolite, a material that forms from in-situ chemical weathering of bedrock, and retains many of the structural characteristics of its unweathered, parent bedrock (Chapman, et al., 1993). The Piedmont features mostly utisols, in which A and B horizons lie above the saprolite, with the B horizon consisting of mostly red clay and at A horizon mostly of organic matter (Markewich et al., 1990). However, due to rampant erosion that occurred from poor agricultural practices during the cotton farming era, many areas of the Piedmont have eroded down to the red-clay B-horizon (Trimble, 1974; Brown, 2002). The underlying bedrock in the Piedmont typically has very little porosity, although it has some capacity to transmit water if it is fractured (Chapman, et al., 1993). Saprolite retains many of the structural characteristics of unweathered bedrock, however due to having been chemically weathered it has increased porosity as compared to the lithified bedrock below (Hoven et al., 2003). Soil infiltration rates in the Piedmont are relatively low as compared to the coastal plain, although they are significantly higher than in the unweathered bedrock (Markewich et al., 1990).

There are two key factors in determining the speed with which water infiltrates and travels via throughflow. In groundwater systems with a confining layer near the surface, flow patterns tend to be more lateral and local than in deeper systems, with shorter times from recharge to discharge (Tóth, 1963; Zhou & Li, 2011). In the Piedmont, the boundaries between the soil/saprolite, saprolite/bedrock and soil/bedrock typically yield lateral flow (Markewich et al., 1990). Thus, with a relatively impermeable bedrock layer below it, residence times of water via throughflow in the Piedmont are dictated by the hydraulic conductivity, the ability of water to move through pore spaces/fractures in rocks, and thickness of the soil/regolith it travels through.

1.5 Research Objectives

The concept that urban development has a significant effect on the hydrology of a watershed has been understood for quite some time. However, the complexity of urban/suburban landscapes, the permeability of the different types of surfaces found within them, and the distribution of these surfaces makes it difficult to predict the exact streamflow responses (Alley & Veenhuis, 1983; Booth & Jackson, 1997; Price et al., 2011). This paper explores how flashy southeastern Piedmont streams actually are, and to what extent the amount and distribution of impervious surfaces and other land covers affect this. This was achieved by analyzing hydrograph responses in urban/rural paired watersheds to storm events, through spatial analysis of the distribution of land cover in these watershed, and through analysis of the underlying geology of the watersheds.

This study features two main objectives:

1. Quantifying stream flashiness in urban and rural streams, using varied metrics
2. Determining the relationship between flashiness and watershed land cover, particularly the amount and spatial distribution of impervious surfaces

Southeastern cities tend to follow similar patterns, characterized by sprawling, post-1950's growth (Hamidi et al., 2014), but each city is unique and will have different specific local factors. An additional objective is to determine whether specific watersheds within this region behave as expected given the percent impermeable surface found within them, and what factors could be causing variability.

1.6 Study Area

The population of the southeastern Piedmont is projected to grow rapidly, which will inevitably be associated with urban sprawl (Conroy et al., 2003). Thus, evaluating the effects of these land cover changes on the hydrology of the region is increasingly relevant to a large population. Within the Piedmont, the I-85 corridor specifically provides a range of urban to rural areas, through a relatively uniform physiographic and climatic region. These characteristics provide an ideal study area for comparing the effects of varying degrees of urbanization on stream flashiness (O'Driscoll et al., 2010).

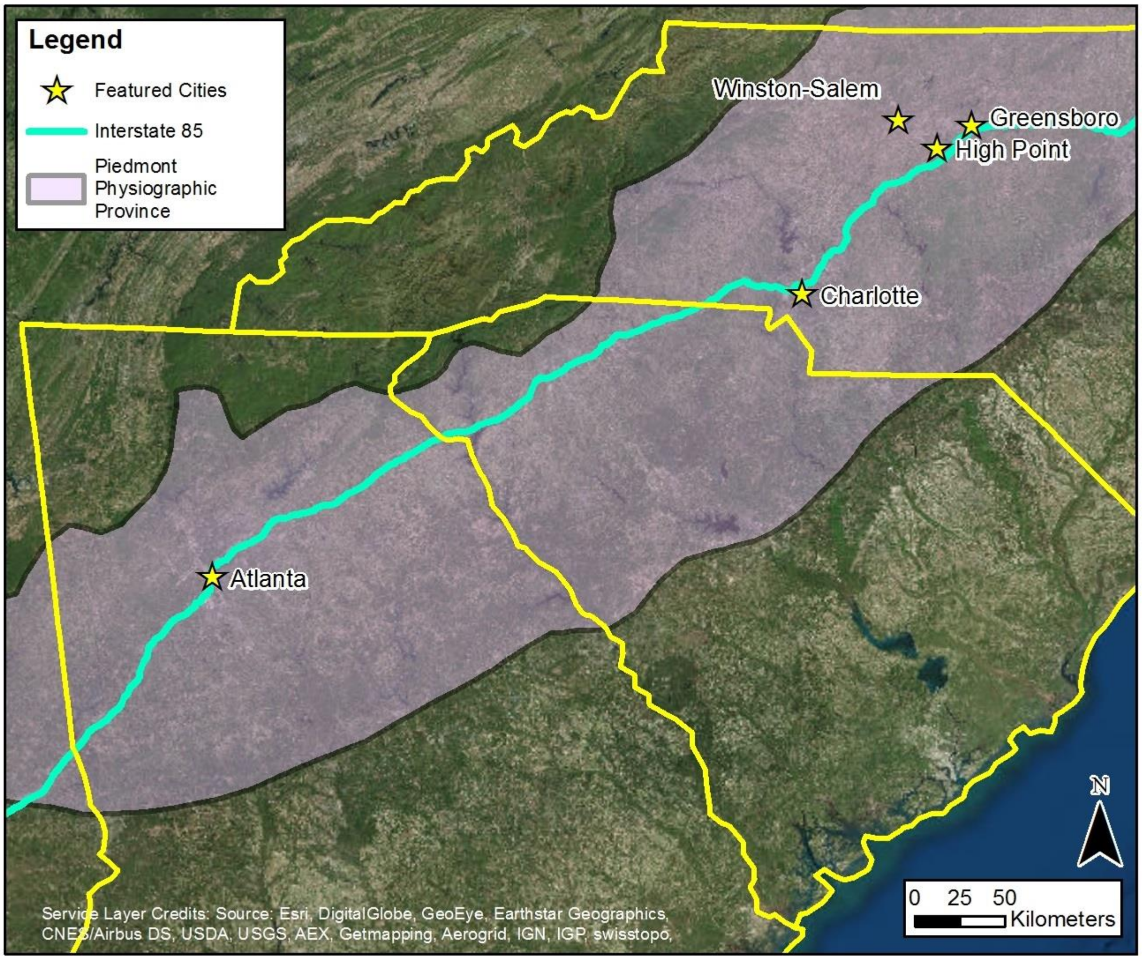

Figure 2. Study area

2 METHODOLOGY

2.1 Site Selection/Categorization

USGS stream gages were identified within the Atlanta, Charlotte, and Greensboro-Winston-Salem-High Point metro areas. Sites were selected in pairs for the purpose of comparing urban and rural differences within the same metro area, with sites as similar in drainage area as possible.

Each metro area features two urban-rural pairs, consisting of a site within the urban core and a site in rural areas in the far reaches of the metro area. Additionally, two "moderate" pairs, one in metro Atlanta and one in metro Charlotte, were selected. These sites featured moderate levels of impervious cover and were meant to represent moderate urban or suburban land cover. No pairs were selected in the Greensboro-Winston-Salem-High Point metro area due to lack of data availability.

Sites were selected based upon four criteria:

1. Sites must feature USGS streamflow gauge with nearly continuous daily data from 2005 to 2014
2. Pairs were chosen to be relatively close in watershed area. All sites were between 35 and 100 square kilometers (13 - 39 square miles), and each pair were within 13 square kilometers of each other in area.
3. The watershed that drains to every site must fall completely within the Piedmont Physiographic province.
4. Sites selected also were required not to feature any large impoundments on the main stem of the stream.

Some metro-areas along the I-85 corridor straddle the boundary between the Piedmont and the Blue Ridge or Coastal Plain provinces. Lack of sites falling completely within the Piedmont, the region selected due relative geologic and climatic uniformity and significance as a growing population region, in addition to lack of sites with the 10-year minimum of discharge data, led to the exclusion of metro Greenville, SC and Raleigh, NC. Given that the goal of this study was to examine the effect of different land covers on the streamflow patterns, sites with dams artificially releasing water in intervals that don’t correspond to natural flow dynamics, thus having no value in this comparative framework. Each potential study watershed was individually screened for main stem impoundments using National Hydrography Database (NHD) water body data and also cross checked with the most recent ESRI satellite imagery for any impoundments that may have been excluded from the NHD dataset. While most sites still feature some small impoundments on tributaries, their effect on downstream hydrology is assumed to be minimal as small tributaries don’t drain large areas and thus impound minimal quantities of water. Nearly all watersheds featured at least some impoundments, and thus it would have been impossible to select sites that feature no impoundments at all and still do this study.

While these paired analyses are useful for making comparisons, sites were also evaluated along a gradient based on impervious surface cover. These analyses were done by comparing all 16 sites as a whole, and also by splitting them up, via Jenks natural breaks, into three categories: less than 9% impervious cover, 20 and 26% impervious cover, and 29 to 41% impervious cover.

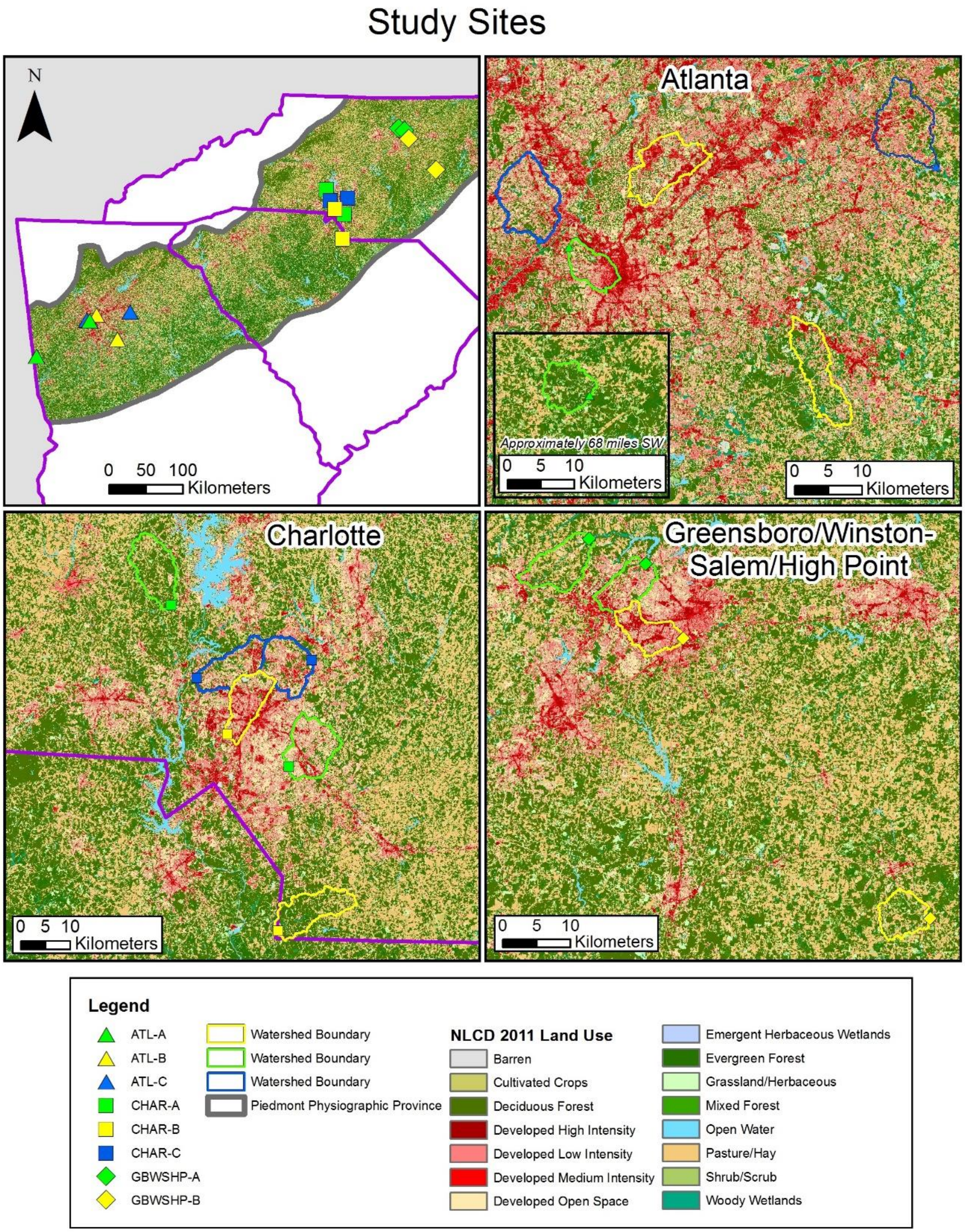

Figure 3. Study sites and locations

2.2 Quantifying Land Cover/Impervious Surface Cover

Land cover can be quantified for each watershed using a variety of tools. One of these tools is simply comes estimating the amount of impervious surfaces from looking at satellite imagery. Historically, delineations of impervious surfaces and other land covers were performed manually (Zhou & Wang, 2008). The National Land Cover Database (NLCD), a database that is updated every five years and freely available to the public, has become the standard for assessing land cover (Xian & Homer, 2011). The resolution, however, is only 30 meters. Thus when attempting to estimate impervious surfaces at smaller scales, it may be more useful to manually delineate localized areas in the field or from high-resolution aerial photography.

Quantifying the true permeability of different land covers is especially challenging. The permeability of surfaces such as row-crop agriculture or suburban lawns can vary, however, and this isn’t accounted for by the NLCD (Price et al., 2010; Xian & Homer, 2011). If soil or land cover type is used solely to estimate permeability without knowledge of whether or not previous practices have compacted the soil, the permeability can be greatly overestimated (Booth & Jackson, 1997; Pitt et al., 2008). It can be difficult to find the history of each individual lot within an entire watershed. Nonetheless, use of NLCD has become common practice, given the operational impracticality of manual delineation of impervious surfaces over large areas. In investigating the effects of land cover on the hydrology of the study sites, the total percentage of watershed area covered in impervious surface was calculated by extracting this data from the NLCD 2011 imperviousness raster file for each watershed. NCLD impervious surface data is also available for 2006. Impervious surface values were also run for this year for comparison, however the 2011 NLCD data were used all of the analyses, given that 2011 is near the middle of the record and thus is a better summary of the impervious surface values that would be present during the time period of focus for the study.

2.3 Flow Analyses

When quantifying how an urban stream responds to storm events, variability of discharge will almost always be analyzed. This can be achieved through analysis of peak flows and low flows. If the main consequence of increased impervious surface in a watershed is increased runoff, this should manifest itself in larger peak flows during storm events, given that stormflow reaches the stream so quickly (Hollis, 1975; O'Driscoll, et al., 2010). Forested watersheds should have lower peak flows given that much more of the stormwater infiltrates and is allowed to enter the stream via slower pathways. Likewise, low flows would be expected to be lower in urban watersheds given that impervious surfaces inhibit infiltration which supports low flows (Klein, 1979). However leaking subterranean pipes have been shown to complicate this relationship (Lerner, 2002; Brandes et al., 2005; Price et. al, 2011).

For each watershed, a "peak flow" and "low flow" were assigned by taking the USGS stream gauge discharge value that occurred at the 95th and 5th percentiles for the entire record. These values indicate what a typical high and low flow are for the watershed, but eliminate abnormally low or high values that could be outliers if the absolute lowest and highest flows for the record were used. Flow values were also normalized by watershed area, by simply dividing each flow value by the watershed area, given that larger watersheds yield proportionally more flow due to being drained by larger areas (Hornberger, 1998).

It should also be noted that individual storm events can be used to assess stream flashiness. Forested watersheds generally respond more slowly than developed watersheds, given the predominant flow paths, while urban watersheds respond much more quickly, with a much steeper spike in stream stage (Smith et al., 2013). For individual storm analyses, one would need hourly or even sub-hourly discharge data. These types of studies can also prove difficult in practice given that similar storm events of similar magnitudes must be compared, which aren’t always easy to identify. The distribution of rainfall over the watershed may also influence how rapidly the stream responds, and this information will not generally be available when using rain gauge data (Brooks, 1997). Given sparse data availability, radar data provides more information of the spatial distribution of precipitation, but requires significant processing time and introduces other errors (Price et al., 2014). Given these limitations, analyses of individual storm events were not included in this study.

2.4 R-B Index

Perhaps one of the most commonly used metrics for assessing stream flashiness is the Richards-Baker Flashiness Index, hereafter, “R-B Index” (Equation 1). Since its publication in 2004, it has been widely used to quantify flashiness in urban hydrology studies (Dow, 2007; Nagy et al., 2011; Tomer et al., 2013). The numerator of the equation subtracts the sum of all the discharge values for a single day from the discharge on the previous day. This captures the day-to-day difference in discharge. The denominator is simply the sum of all the daily discharge values.

$$\mathrm{R-B\ Index} = \frac{\sum_{i=1}^{n} |q_i - q_{i-1}|}{\sum_{i=1}^{n} q_1}$$

Equation 1. R-B Index

R-B index normalizes the day-to-day change in discharge by the total discharge during the period, providing a metric of the overall ‘up and downedness’ of the hydrograph (Baker et al., 2004). It would be expected that more urbanized streams would have higher R-B Index values than non-urban streams, given the tendency to have more peak flows that quickly recede (Hollis, 1975). The greater a peak flow, the greater the change in discharge from one day to another, leading to a higher overall R-B Index value. Since it is unitless, the index can be used over any time-scale. Although often used with daily discharge data, R-B Index can be used with daily or hourly data, as it is simply as measure of the change from one time-step to another (Baker et al., 2004). To test for differences in R-B index among the three Jenk’s Natural Break’s defined classes (defined in section 2.1), two-sample student’s t-tests assuming unequal variances were run comparing each class with each other.

2.5 Spatial Distribution of Impervious Surfaces

At the scale of moderately sized to large watersheds, it can be very difficult to determine impervious surface connectivity. It can be done in the field by individually measuring the connectivity of each surface, however this is extremely time consuming and labor-intensive. There are empirically-based equations derived from USGS data in the Pacific Northwest, however these only provide an approximation, and they cannot be assumed to apply to other regions (Sutherland, 2000). There are GIS tools available as well, but their results must still be verified in the field to determine true accuracy (Janke & Gilliver, 2011). Thus, it is not practical to attempt to quantify exactly where stormwater is flowing over all types of surfaces if one’s goal is to study a large range of sites or across large spatial scales.

In this study, the effects of the distribution of the impervious surface within each watershed were analyzed using multistep GIS methods. Distance values of impervious surface pixels were calculated to the pour point, and to the streams. In this context, a pour point refers to the point to which the watershed drains, coinciding with the location of the USGS stream gauge. Distance to the pour point essentially looks at the idea that if most of the impervious cover is concentrated far away from the pour point, overland flow will have more opportunity (spatially and temporally) to infiltrate en route to the pour point. Conversely, if the impervious surface cover is mostly concentrated near the pour point, its effects on the flashiness of the streams could be pronounced, given the lack of time and space for water to infiltrate. This concept was similarly applied to distance to the perennial/intermittent stream network (as defined by the NHD). Here, the thinking is that varying distances of impervious cover to the streams will allow for more time for infiltration, altering runoff loads and stream response to storm events.

2.5.1 Generation of Flow Cost Path Raster

In order to calculate these distances, first a ‘cost path’ raster was generated for each site. In GIS, cost path represents a preferred path of travel from a start point to an end point. A raster must be generated assigning a “cost” to each cell. To find the “least cost path”, the shortest route traveling through the “cheapest” cells are taken to find a path that adds up to the lowest cost. Given that water in a watershed does not flow ‘as the crow flies’, a raster containing a dense network of every possible flow conduit was generated. These flow conduits, essentially topographic low points, represent the paths that that water would follow on its way down-gradient (Figure 4).

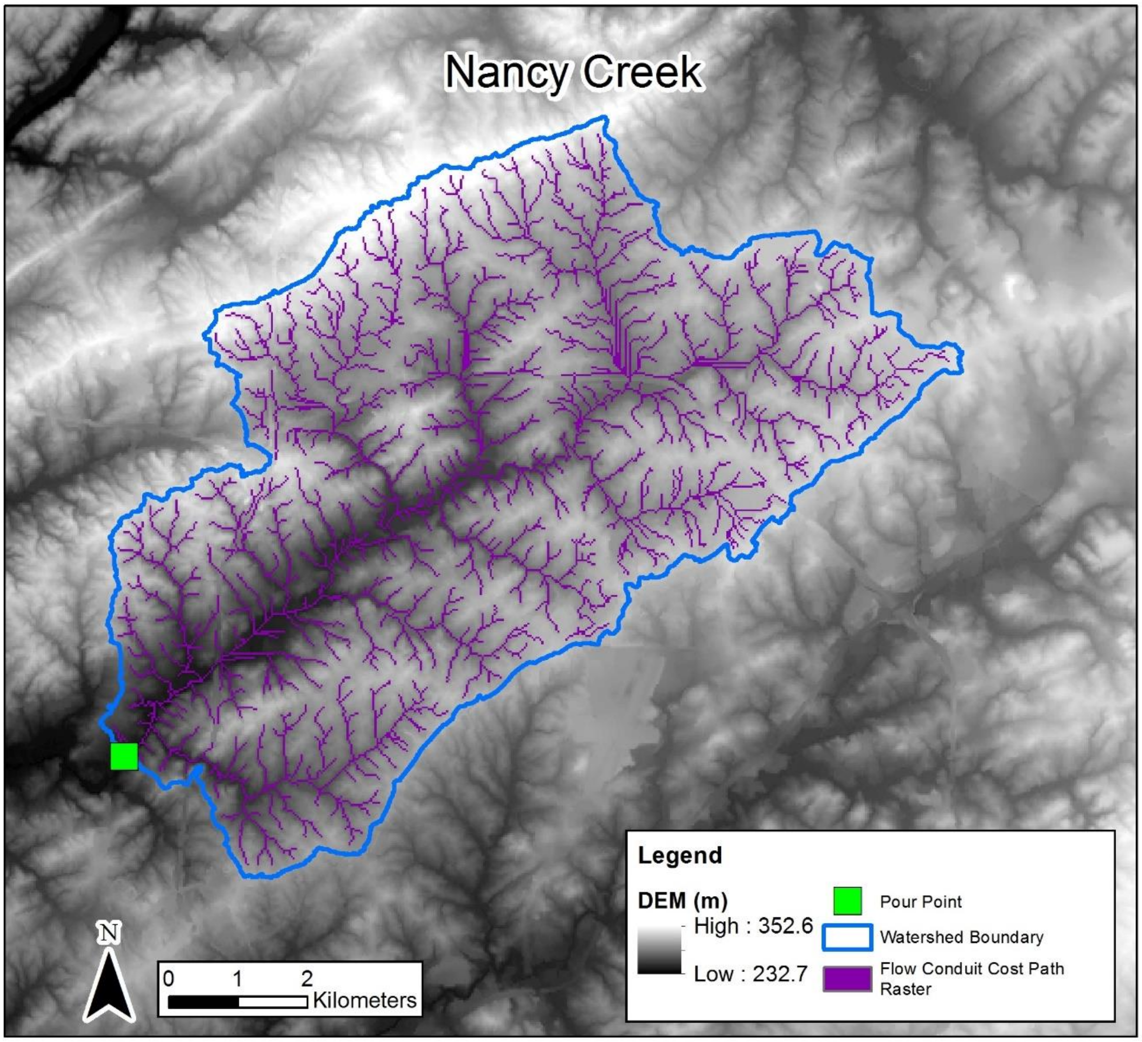

Figure 4. Flow conduit cost path and DEM

2.5.2 Flow Path Distance to Pour Point and Stream Network

The flow conduits were then used to calculate the distance water falling on each cell would travel on its way to the pour point and the streams. These distances (Figures 5 and 6) were generated for every 30x30 meter cell in the watershed, and then assigned to each cell containing over 50 percent impervious cover, as determined by the NLCD. These values were then averaged, giving the average distance of each cell with over 50% impervious cover in each watershed (Figure 7), along the flow path, to both the pour point and perennial/intermittent stream network. These values will be referred to hereafter as "Pour Point Distance" and "Stream Network Distance".

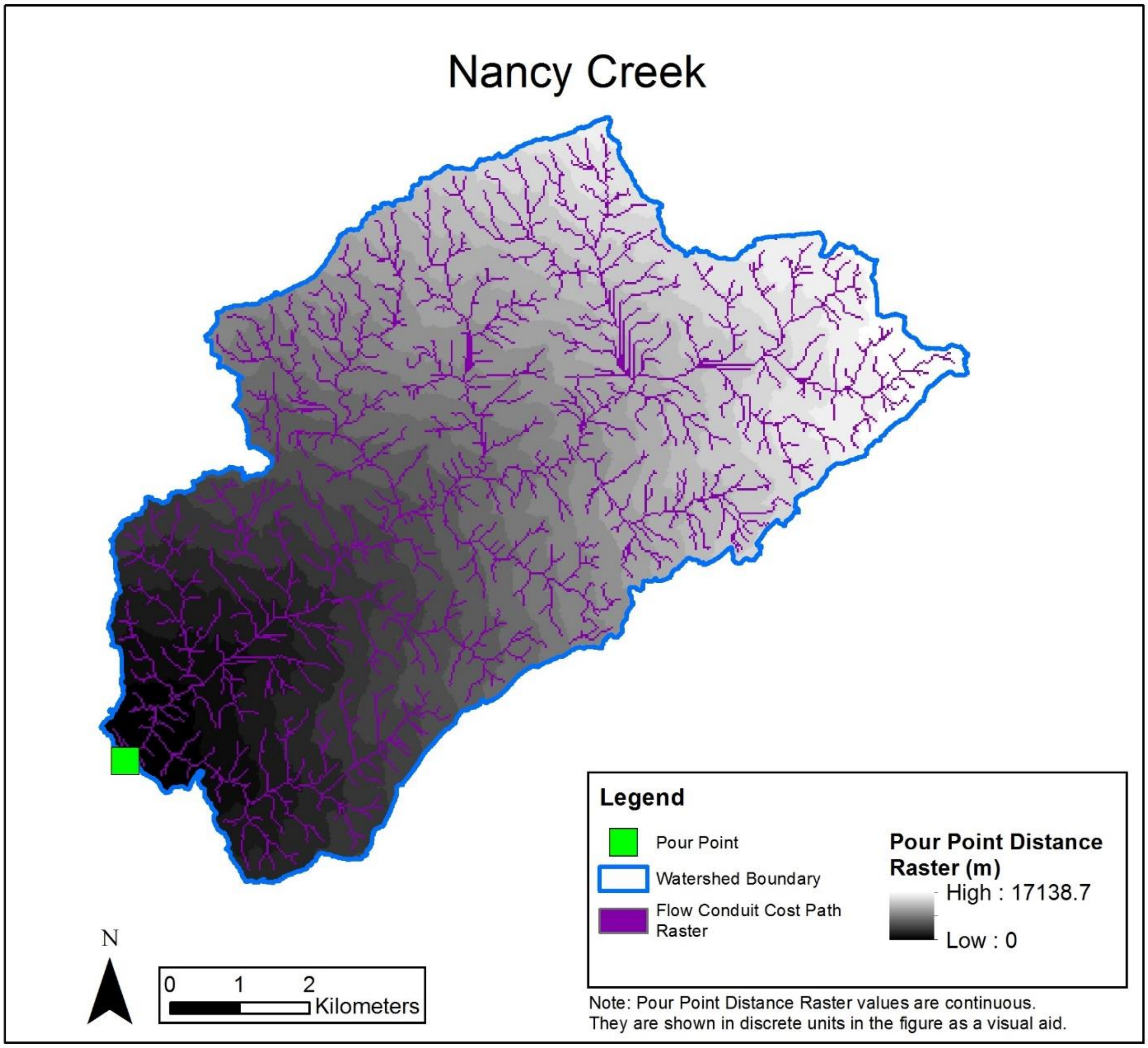

Figure 5. Flow path distance to pour point

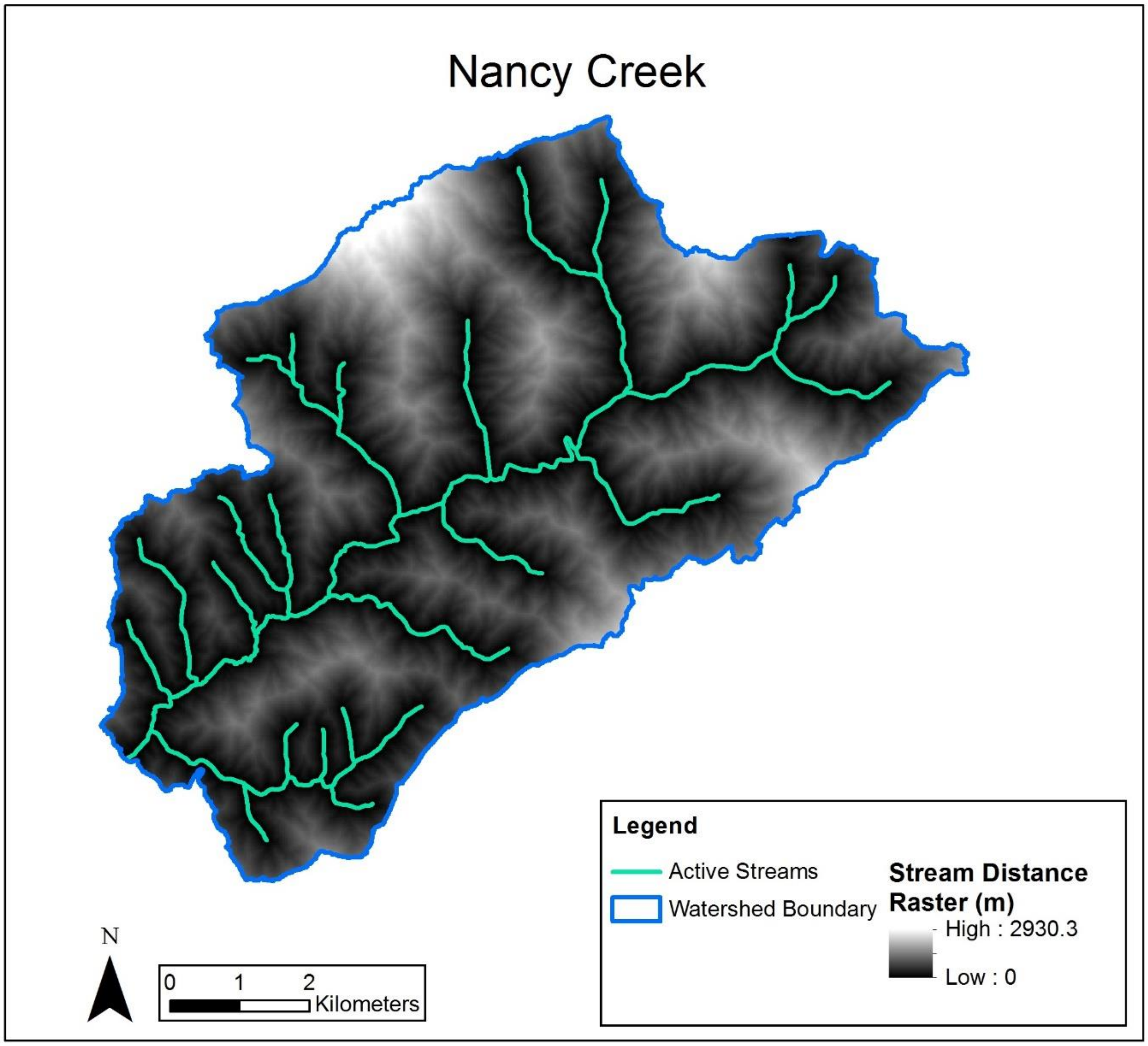

Figure 6. Flow path distance to stream network

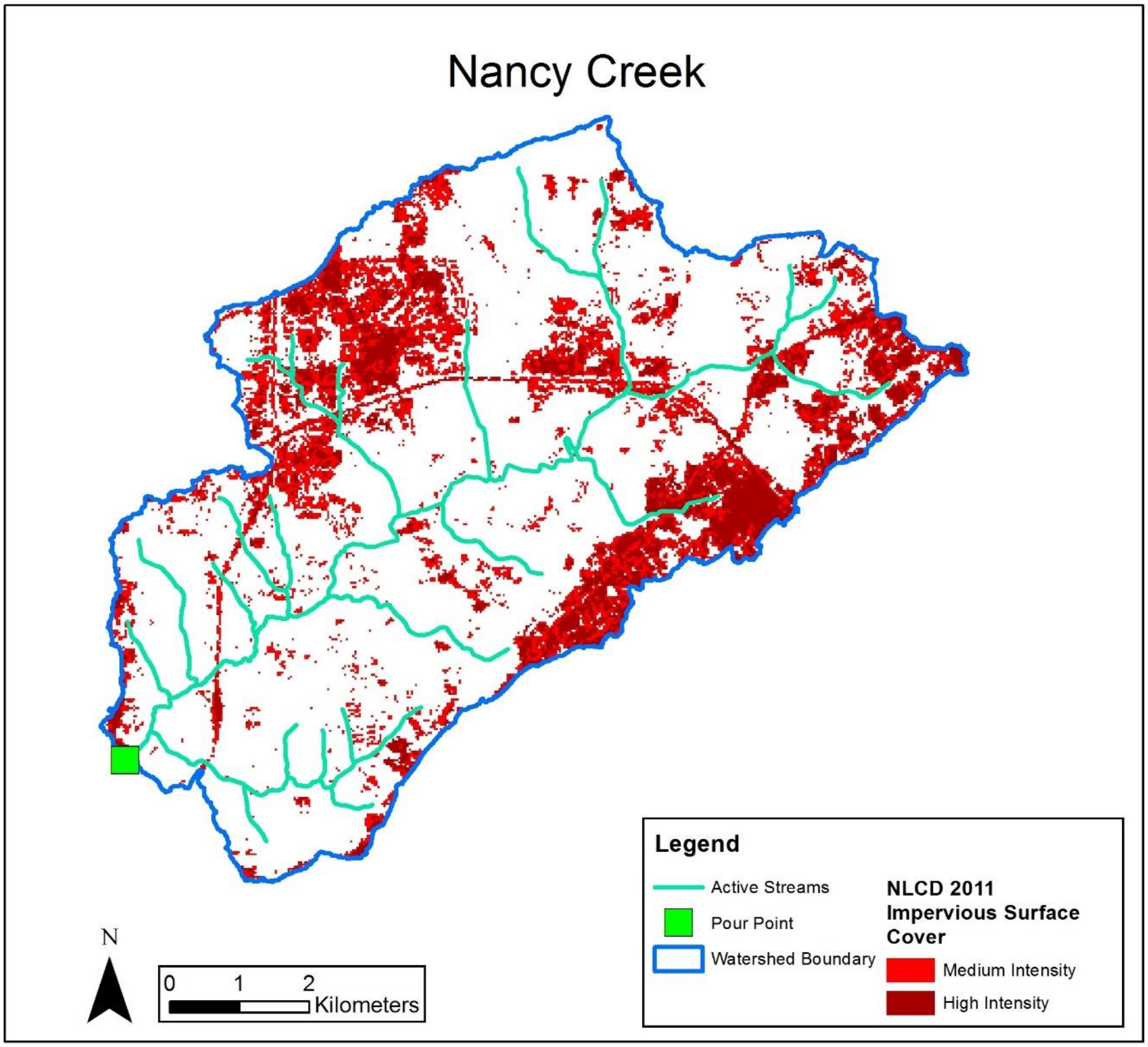

Figure 7. Medium/high intensity urban cells to be extracted to cost path distance values

2.6 Geology

Two sets of data regarding the surficial geology of the study watersheds were obtained, the saturated hydraulic conductivity (Ksat) and depth to lithic bedrock. Both sets of data were obtained from the Natural Resources Conservation Service (NRCS) Web Soil Survey dataset (websoilsurvey.nrcs.usda.gov). Ksat measures the ability of a saturated soil to transmit water, and is useful in determining how effective a soil will be in allowing infiltration during a storm event (Mcdonnell, 1990). The purpose of using Ksat values is to examine the ability of areas not covered with impervious surface to be infiltrated, and thus urban areas are excluded. The Ksat values of the soils underneath concrete are not relevant, as water will simply run off along the concrete, and the NRCS doesn't record Ksat values for urban land anyway. The Ksat values for the non-urban land in each watershed were averaged, producing an average Ksat value for each watershed.

Depth to bedrock is significant, as areas with shallow bedrock will have reduced residence times of throughflow, as greater depths to confining units yield longer flow paths in groundwater (Tóth, 1963; Zhou & Li, 2011). The NRCS doesn't collect data depth to bedrock greater than 2 meters, however this information is still useful. The percent of land area with depth to bedrock less than 2 meters was calculated for each watershed, identifying watersheds with larger areas of shallow bedrock.

2.6.1 Outliers

Due to lack of available data, Proctor Creek was excluded from all analyses involving NRCS data. The NRCS classifies some areas as "urban land" and does not record Ksat or depth to lithic bedrock for these areas. Most of the watersheds don't feature sizable areas classified this way, even in the more urbanized areas. However, Proctor Creek features almost all of its land classified as "urban land", despite the fact that there is quite of bit of area in the watershed within these large swaths of land that have plenty of exposed soil/forest not covered with impervious surface. Proctor Creek has 95% of its land area classified as urban land, a significant outlier from the other sites. Even among the other urbanized sites, values ranged from 4% to 44% percent of their land area classified as urban land and reported Ksat and depth to bedrock values in the majority of their land area. Additionally, Proctor Creek's average Ksat value for the watershed is over 4 standard deviations from the mean, with all other values within 2 standard deviations. This is due to the fact that the only Ksat values reported in the watershed are found within the stream floodplains, as nearly all other land is classified as “urban” and doesn’t record any Ksat values. For these reasons, Proctor Creek was excluded from all analyses featuring NRCS data.

2.7 Water Budget

Lastly, the “discharge/precipitation ratio” was calculated, a value representing the ratio of discharge observed in a watershed compared to the amount of precipitation inputs it receives. To determine this, precipitation totals for each site were estimated using data from the nearest rain gauges to each watershed, selected from the National Oceanic and Atmospheric Administration National Climatic Data Center online database (https://gis.ncdc.noaa.gov/map/viewer/#app=cdo). Annual precipitation totals (2004 – 2015) were averaged for each site. Years with missing data for any month were excluded, as not to overly emphasize any seasonal precipitation trends. Annual average precipitation totals (m/year) were then multiplied by watershed area (m2) to estimate the flow input from precipitation for each watershed (m3/year). The observed mean annual flows for each watershed (m3/sec) were then divided by the input flow from precipitation values (converted from m3/year to m3/sec), producing a unitless ratio. This value gives a sense of the water budget, as with the major known input (precipitation) and the output (discharge), we can then make educated guesses as to what factors, such as rate of evapotranspiration, baseflow inputs from leaking infrastructure, etc., contribute to differences in these ratios among watersheds.

2.7.1 Water Budget Effects on R-B Index

R-B Index and impervious surface would be expected to show correlation, due to concept that watersheds with higher percentages of impervious surfaces would be flashier (O'Driscoll, et al., 2010). By normalizing the R-B Index values and impervious surface values, their differences can be compared directly. This is done by simply dividing each watershed's R-B Index value by the highest R-B Index and each watershed's impervious surface value by the highest impervious surface value, setting both to a scale of 0 to 1. If the variables were perfectly correlated, their differences would all be zero. By comparing the differences between each site's normalized R-B Index value and normalized impervious surface value to its discharge/precipitation ratio, we can determine whether water budget effects complicate the relationship between R-B Index and impervious surface.

2.8 Multiple Linear Regression Model

Percent impervious surface, along with the geology and spatial distribution of impervious surface variables, were used as dependent variables in a multiple linear regression (MLR) model to explain R-B Index. The method of choosing the final variables for the MLR model was backwards elimination, where an initial model is run that includes all the variables. Subsequent models are then produced, eliminating one variable at a time, until a specific, formula derived criteria is met (Hocking, 1976).

3 RESULTS

Table 1. Summary Table

Site Name	Pair	Drainage Area (sq km)	Percent Impervious Surface Cover (2011)	Percent Forest	R-B Index	Discharge/ Precipitation ratio	Average Ksat (micro meters/ sec)	Percent Area with Shallow Bedrock	Area-Adjusted Low Flow	Area-Adjusted Peak Flow	Impervious Surface Distance to Pour Point	Impervious Surface Distance to Stream Network
HILLABAHATCHEE CREEK	ATL-A	43.2	0.4%	68.1%	0.3	0.34	27.3	0.0%	0.17	3.1	0.41	8.4
TICK CREEK	GBWSHP-B	39.1	0.6%	52.4%	0.9	0.17	8.4	14.3%	0.00	1.8	0.49	2.7
WAXHAW CREEK	CHAR-B	90.6	0.6%	66.1%	0.9	0.14	9.6	16.2%	0.00	1.3	0.47	13.6
KILLIAN CREEK	CHAR-A	94.4	1.5%	60.3%	0.5	0.24	10.4	0.3%	0.12	1.5	0.42	12.0
REEDY FORK	GBWSHP-A	53.4	5.7%	40.6%	0.5	0.30	13.2	0.9%	0.12	2.3	0.35	12.4
HONEY CREEK	ATL-B	66.7	8.7%	46.2%	0.5	0.30	15.1	15.8%	0.07	3.3	0.63	15.6
LONG CREEK	CHAR-C	82.5	19.8%	23.4%	1.1	0.37	10.0	16.6%	0.06	4.0	0.34	13.3
MCALPINE CREEK	CHAR-A	100.0	20.2%	14.8%	1.2	0.34	10.2	14.8%	0.03	4.4	0.32	7.9
MALLARD CREEK	CHAR-C	89.8	20.6%	21.1%	1.1	0.37	9.1	23.5%	0.06	4.2	0.31	7.0
ALCOVY RIVER	ATL-C	79.9	21.5%	25.4%	0.5	0.34	13.9	14.2%	0.21	3.3	0.40	11.9
NICKAJACK CREEK	ATL-C	81.9	21.7%	23.1%	0.7	0.40	14.1	0.0%	0.20	4.4	0.58	9.9
HORSEPEN CREEK	GBWSHP-A	41.3	25.3%	13.5%	0.8	0.35	9.5	0.3%	0.11	3.6	0.39	7.2
NANCY CREEK	ATL-B	68.9	29.6%	17.6%	0.9	0.37	14.0	1.1%	0.12	5.5	0.75	10.2
PROCTOR CREEK	ATL-A	34.9	34.6%	13.2%	1.1	0.34	---	---	0.10	5.0	1.66	8.5
IRWIN CREEK	CHAR-B	79.1	35.1%	8.5%	0.9	0.47	10.2	2.7%	0.27	5.2	0.38	8.7
SOUTH BUFFALO CREEK	GBWSHP-B	39.9	40.7%	2.5%	1.2	0.43	8.3	0.0%	0.08	6.0	0.36	7.3

It should be noted here that while most sites didn’t record a notable change in impervious surface cover from 2006 to 2011, the change in impervious surface among the watersheds between 2006 and 2011 was as high as 2.7%. Two sites featured change in impervious surface over 2.4%, five sites featured a change between 1 and 1.6%, and the remaining 9 sites featured a change less than 0.7%.

3.1 Flow Analyses

As percent imperviousness increased in watersheds, area-adjusted 95th percentile flows increased linearly (Figure 8). The relationship between area-adjusted 5th percentile flows with percent imperviousness, while still showing a somewhat linear trend, was much weaker (Figure 9). It is also worth noting that this relationship was weakly positive, featuring a weak trend of higher low flows in the more urbanized watersheds.

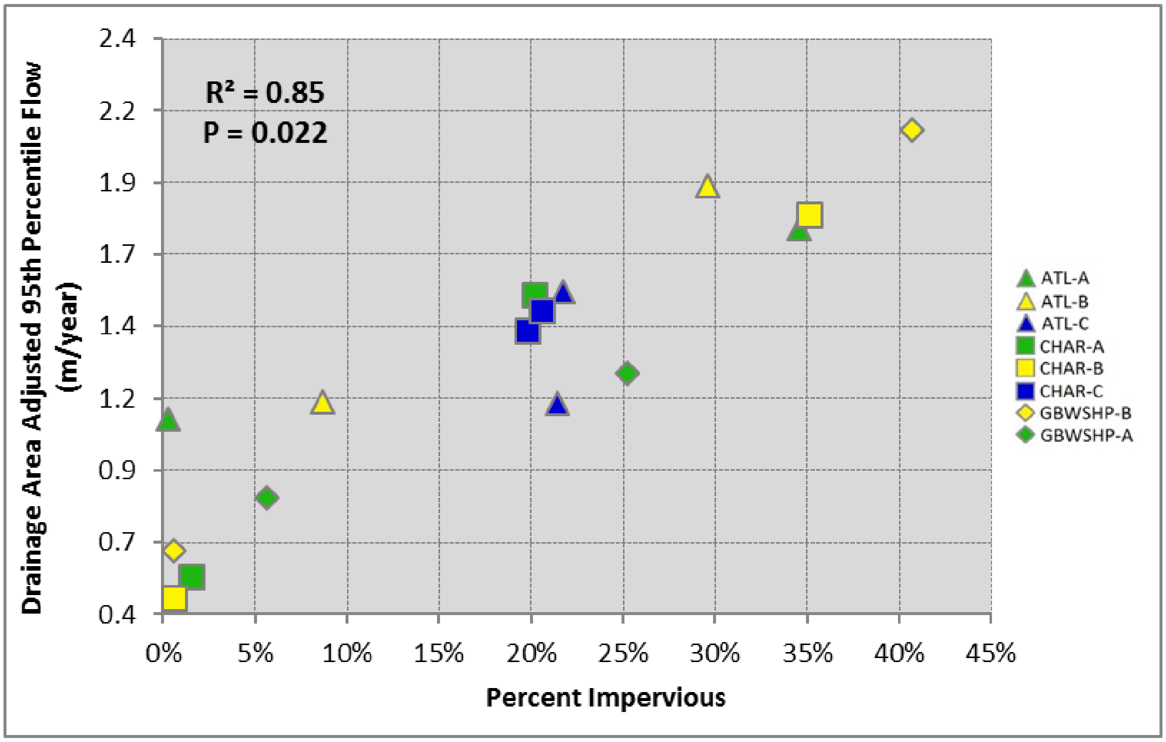

Figure 8. Drainage area adjusted 95th percentile flow vs. percent impervious surface cover

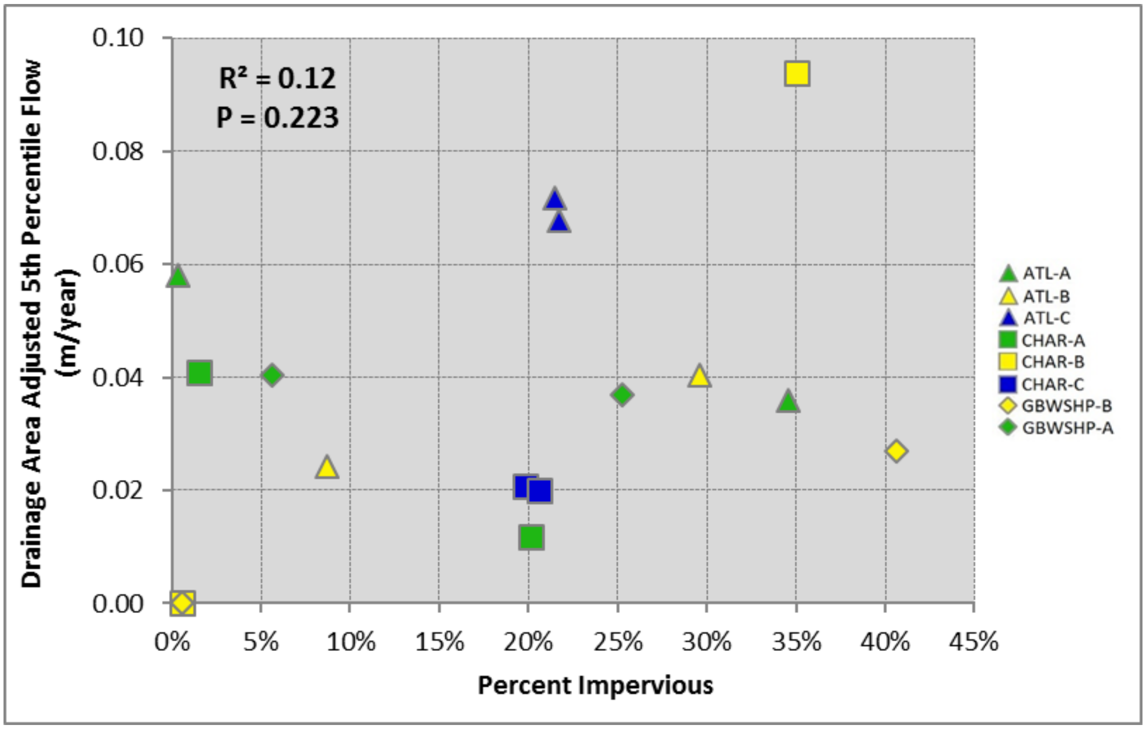

Figure 9. Drainage area adjusted 5th percentile flow vs. percent impervious surface cover

3.2 R-B Index

The relationship between watershed impervious cover and R-B Index was of weak to moderate strength, but statistically significant (R2=0.35, p=0.016), showing a general trend in increased R-B Index and increased impervious surface (Figure 10). There were also some seasonal trends in R-B index. Sites in metro-Atlanta, metro-Charlotte, and the Greensboro-Winston-Salem-High Point metro area all showed a dip in R-B index around May and a peak in July or August (Figure 11).

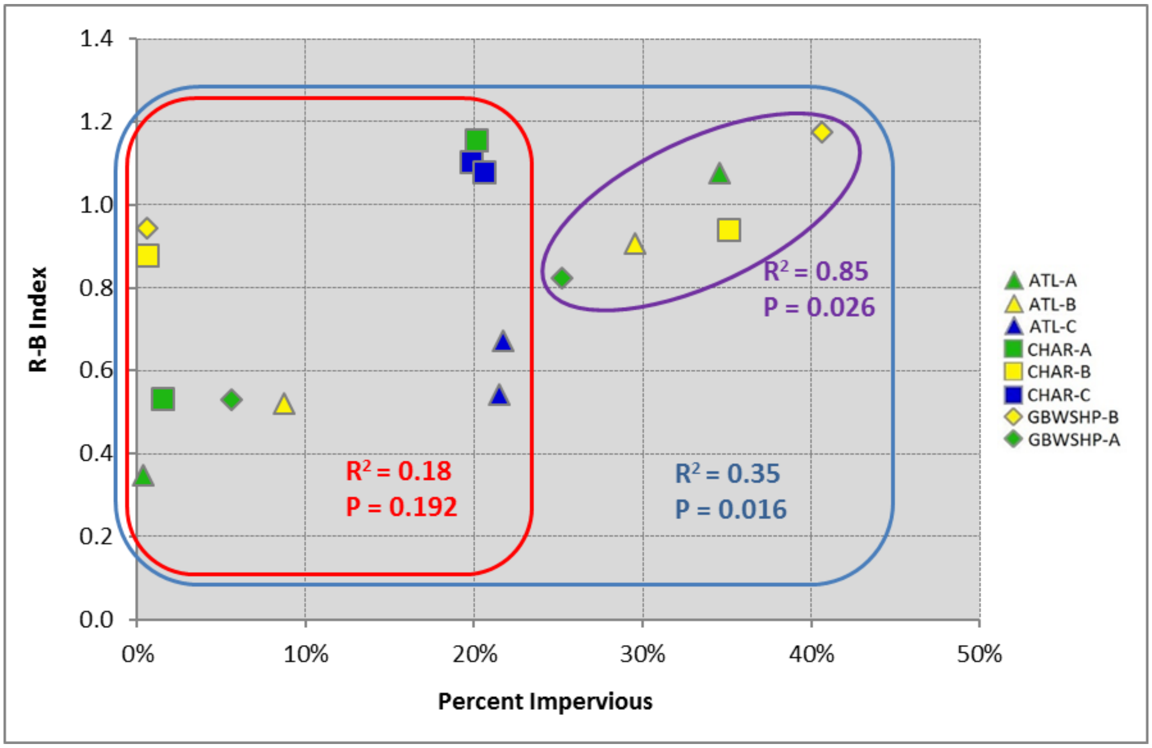

Figure 10. R-B index vs. percent impervious surface cover

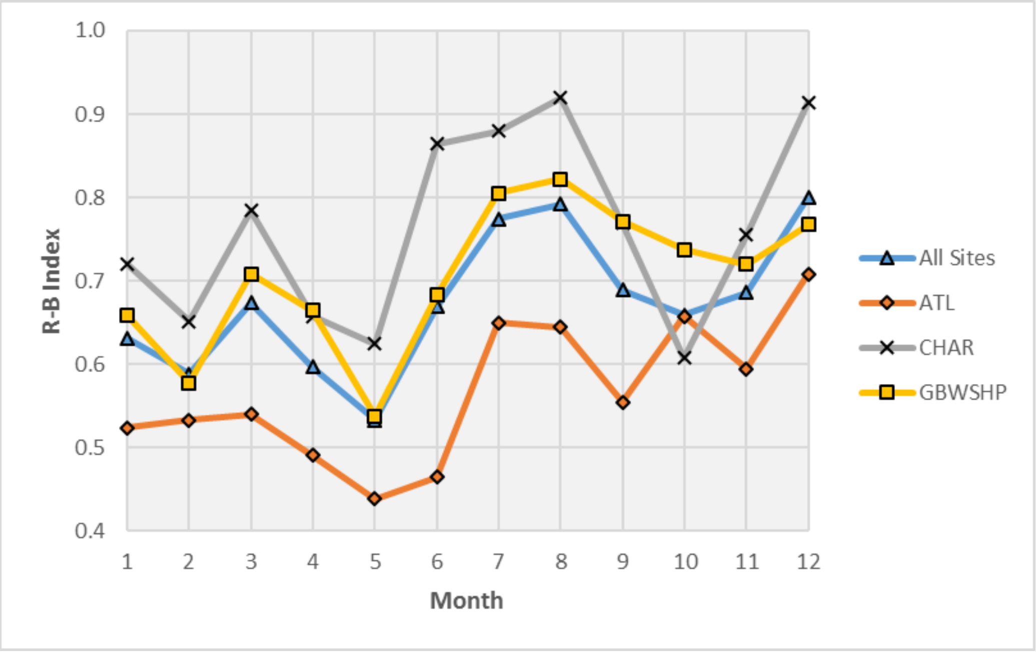

Figure 11. Average monthly R-B index values

3.2.1 Paired Analysis of R-B Index vs. Impervious Surface

While every urban site had a higher R-B Index than its rural pair, there was still quite a bit of unexplained variability. Some sites, specifically the pairs of CHAR-B and GBWSHP-B, showed small differences in their R-B Index values despite larger differences in percent impervious surface. The CHAR-B pair had a 34.6% difference in percent impervious surface, yet showed almost no difference in R-B Index. GBWSHP-B had the highest difference in impervious surface of all the site pairs (40.1%), yet showed less of a difference in R-B Index than GBWSHP-A, which had only a 19.6% difference in R-B Index. Both of these pairs had their respective rural pair exhibit high R-B Index values. The two moderate pairs (ATL-C and CHAR-C) also showed some variation in this respect. It can also be noted that the metro-Atlanta sites had the lowest R-B Index values, the Charlotte sites the highest, and the Greensboro-Winston-Salem-High Point sites in between.

3.2.2 Jenks Natural Breaks Class Analysis of R-B Index vs. Impervious Surface

According to the student's t-tests, R-B index values in sites with 25 to 41% impervious surface were significantly statistically different from R-B index values in sites with 0 to 9% impervious surface values at less than the 0.05 level. R-B index values in sites with 19 to 22% impervious surface were not statistically different in a significant way from either the sites in the highest or lowest class of impervious surface values. Among the most urbanized sites (greater than 25% impervious cover), the relationship of R-B index to impervious surface was much stronger (R2=0.85, P=0.02) than in the sites with less than 25% impervious surface cover (R2=0.18, P=0.19) (Figure 10).

3.3 Spatial Distribution of Impervious Surface

There was no significant relationship between R-B Index and distance to stream network (R2= 0.018, P= 0.62). The relationship between R-B Index and distance to pour point was weak and not statistically significant at the 0.05 level (R2= 0.17, P= 0.11), but it was stronger than the relationship between R-B index and distance to pour point.

3.4 Geology

The relationship of average Ksat to R-B index was of moderate strength and statistically significant at the 0.01 level (R2=0.51, P=0.00). When breaking the relationship down into Jenks classes, the relationship was strongest in the moderate and less urbanized sites and weakest in the most urbanized sites (Figure 12). The relationship percent area with shallow bedrock to R-B index was much weaker than average Ksat and not statistically significant at the 0.05 level (R2=0.12, P=0.20). While not statistically significant at the 0.05 level, it is worth noting that the relationship of percent shallow bedrock and R-B index was strongest in the least urbanized sites and weakest in the most urbanized sites (Figure 13). All of these values are summarized in Table 2.

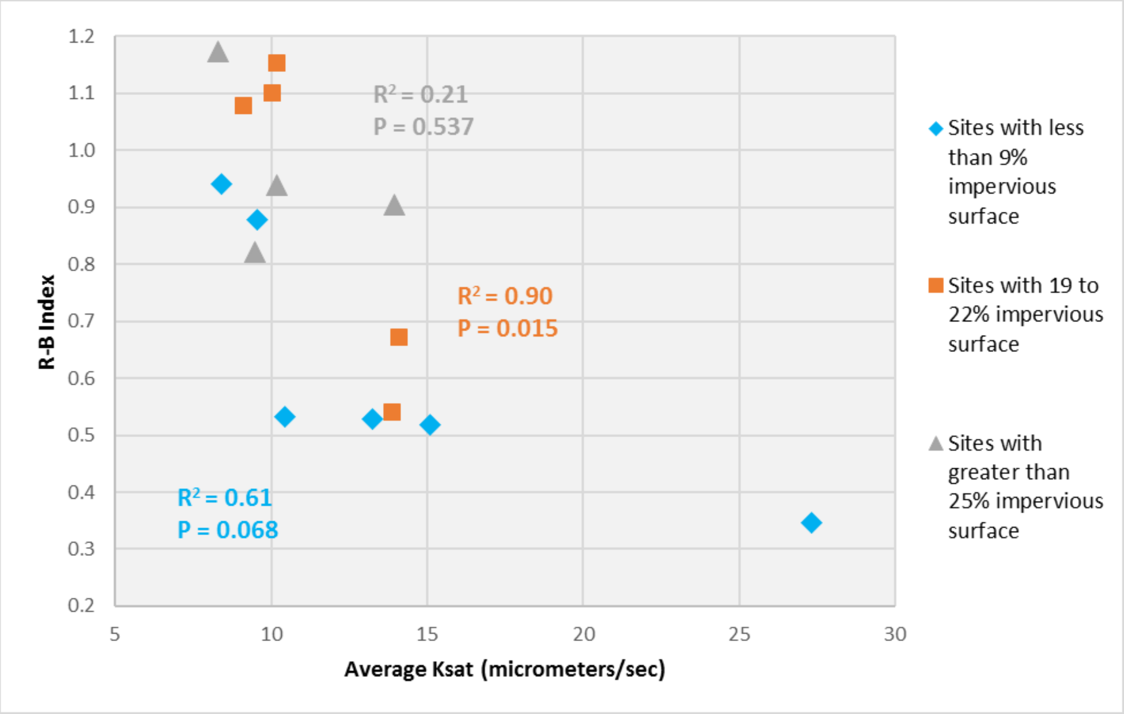

Figure 12. R-B index vs. Average Ksat

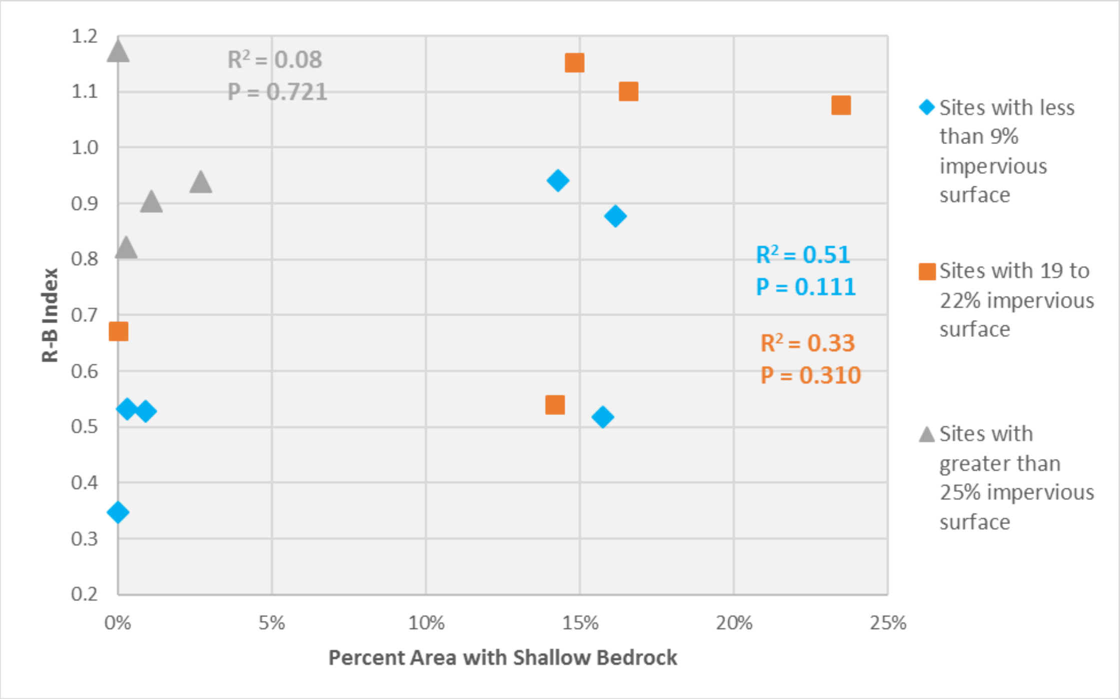

Figure 13. R-B index vs. percent area shallow bedrock (less than 2 meters depth)

Table 2. Regression relationships of geology variables with R-B index

		Average Ksat		Percent area with shallow bedrock	
	n	R^2	P	R^2	P
Sites with less than 9% impervious surface	6	0.61	0.068	0.51	0.111
Sites with 19 to 22% impervious surface	*5*	0.90	0.015	0.33	0.310
Sites with greater than 25% impervious surface	*4*	0.21	0.537	0.08	0.721
All sites	*15*	0.51	0.003	0.12	0.203

3.5 Water Budget

3.5.1 Water Budget Relationship with Land-Cover

There was a moderately strong, positive relationship (R2=0.65) between percent impervious surface cover and discharge/precipitation ratio that was significant at the 0.01 level (Figure 13). Relative to the amount of precipitation they received, more urbanized sites yielded more discharge than more rural sites, with the highest amount of variation occurring in sites with less than 10 percent impervious surface cover. The opposite relationship was seen with percent forest cover and discharge/precipitation ratio, with more forested sites yielding less discharge relative to their precipitation inputs (Figure 14). This relationship was also moderately strong (R2=0.62), and significant at the 0.01 level. It should also be noted here that sites with higher percent impervious surface cover featured less forest. There was a strong inverse relationship (R2=0.90) between percent forest cover and percent impervious surface that was significant at the 0.01 level.

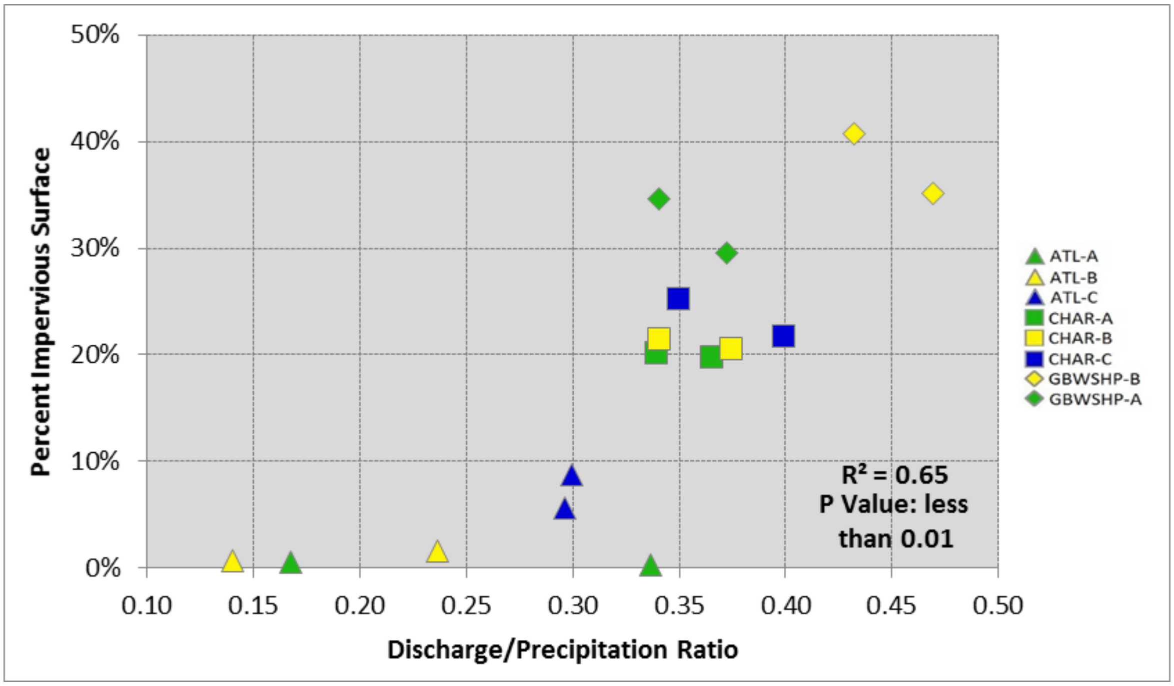

Figure 14. Percent impervious surface cover vs. discharge/precipitation ratio

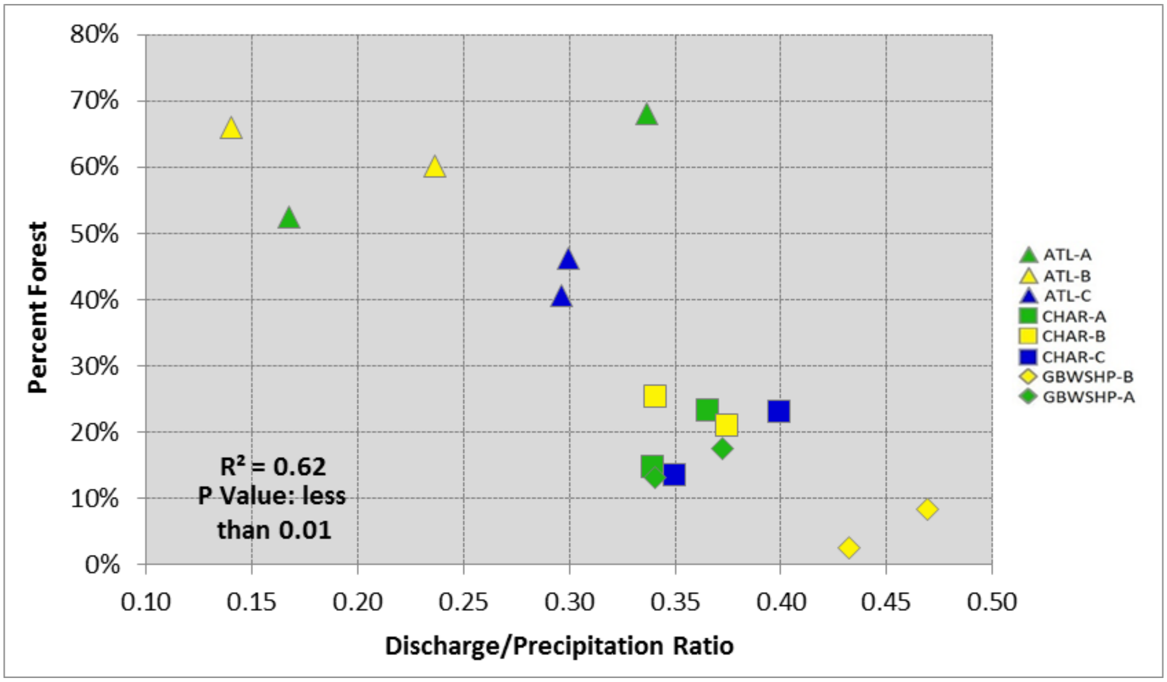

Figure 15. Percent forest cover vs. discharge/precipitation ratio

3.5.2 Water Budget Effects on R-B Index

Among sites with less than 10 percent impervious surface, there was a strong, positive relationship between R-B index and discharge/precipitation ratio (Figure 15). In these sites, the higher the total discharge yielded relative to precipitation the higher the R-B index value was. There was a moderately strong, inverse relationship (R2=0.63) between difference in normalized R-B index and normalized impervious surface and discharge/precipitation ratio that was significant at less than the 0.01 level (Figure 16). Put another way, sites with the largest difference between normalized R-B index and normalized impervious surface values featured the lowest amount of discharge relative to their precipitation.

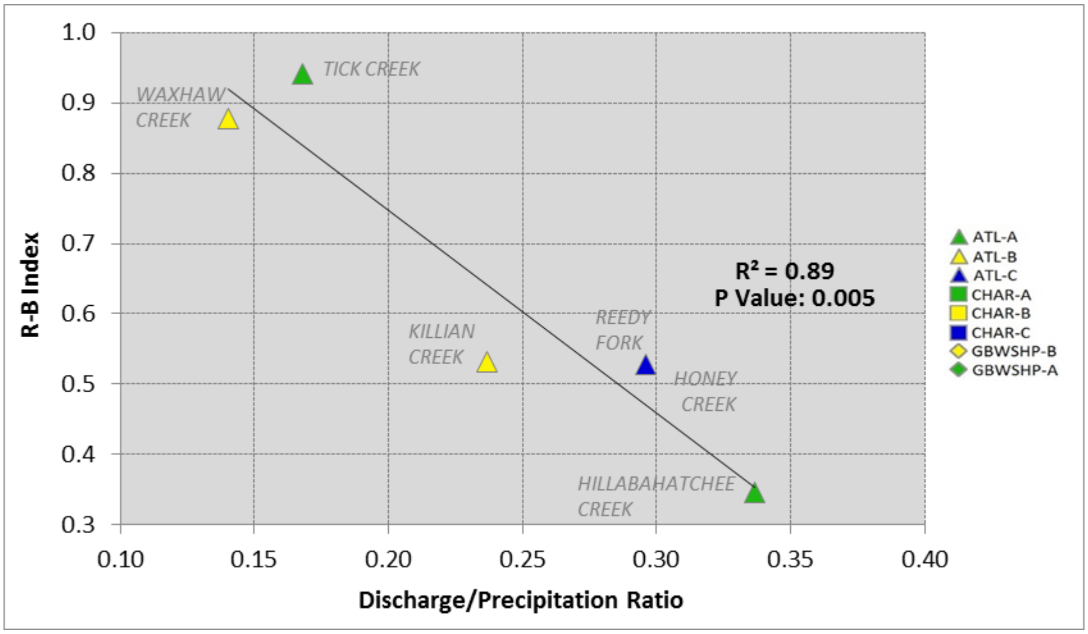

Figure 16. R-B index vs. discharge/precipitation ratio in sites with less than 10% impervious surface cover

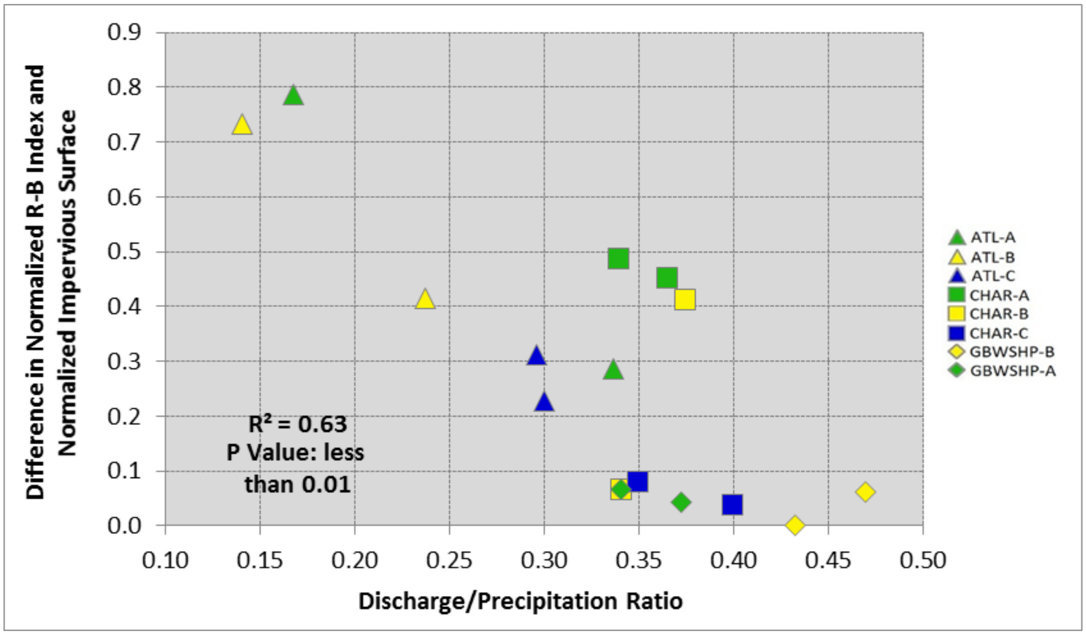

Figure 17. Difference in normalized R-B index and normalized percent impervious surface cover vs. discharge/precipitation ratio

3.6 Multiple Linear Regression Model

The initial model, including all the variables, produced an R2 and was significant at the 0.01 level. However many of the variables featured high P values, with impervious surface distance to stream network's p-value at 0.9 and all others above 0.05 except percent impervious surface cover, ranging from 0.06 to 0.15. The final model featured only two variables, average Ksat and percent impervious surface cover. This model featured an R2 of 0.63 and was significant at less than the 0.01 level. Average Ksat featured a p value significant at the 0.01 level while percent impervious surface cover was not significant at this level in the model, with a p value of 0.08.

Table 3. Initial and final MLR models produced with backwards elimination method

Model	R^2	Variables	Coefficients	P	VIF
Initial Model	*0.77*	---	---	*0.01*	---
Variables	---	Intercept	1.10	0.00	---
	---	Percent Impervious Surface Cover	0.87	0.04	1.28
	---	Average Ksat	-0.02	0.06	1.40
	---	Depth to Shallow Bedrock	1.04	0.11	1.29
	---	Distance to Pour Point	-0.02	0.15	1.12
	---	Distance to Stream	-0.05	0.90	1.13
Final Model	*0.63*	---	---	*0.00*	---
Variables	---	Intercept	1.09	0.00	
	---	Average Ksat	-0.03	0.01	1.12
	---	Percent Impervious Surface Cover	0.73	0.08	1.12

4 DISCUSSION

4.1 Flow Analyses

The results indicate a clear relationship between peak flow and increased urbanization. This relationship agrees with the literature, given that watersheds with higher amounts of impervious surfaces allow less infiltration of precipitation, and the flow during storm events is flushed directly to the stream (Hollis, 1975). This is seen in peak flows, as high precipitation events have almost no capacity for infiltration in these urbanized watersheds, and thus, most precipitation makes its way into the stream as immediate discharge (O'Driscoll, et al., 2010). That low flows show a weaker relationship to impervious surface percentage is also consistent with the literature (Price et. al, 2011). Despite the notion that, in theory, less infiltration would lead to lower baseflows (Klein, 1979), the reality tends to be complicated by leakages in subterranean infrastructure and inter-basin transfers and complicates the relationship (Lerner, 2002; Brandes et al., 2005; Price, 2011).

4.2 R-B Index

Despite R-B Index and percent impervious not being as related as R-B Index and peak flows, every urban site still exhibited a higher R-B Index than its rural counterpart. This indicates that more urbanized sites feature, for the most part, a greater day-to-day change in flow and are "flashier" in this sense. Still, the variations found here leave further questions that need to be addressed.

4.3 Water Budget

The sites that showed the greatest deviation from the linear relationship of R-B Index and percent impervious surface cover (Figure 16) are also the sites that produced the lowest amount of discharge relative to their precipitation inputs. Tick Creek and Waxhaw Creek featured much lower discharge relative to their precipitation inputs than other sites with similar impervious surface cover. In sites with less than 10% impervious surface percentage, there was a significant, negative relationship between discharge relative to precipitation inputs and R-B Index as well (Figure 15), showing that sites that produce low amounts of discharge relative to their inputs of precipitation are also flashier. This suggests that there is a link between sites losing their precipitation inputs somewhere in their water budget and flashier streams.

4.4 Role of Anthropogenic Effects on Southeastern Piedmont Hydrology

4.4.1 Total Imperviousness

While there was still a moderate overall relationship between R-B index and percent impervious surface, there relationship was strongest among sites with greater than 25% impervious surface percentage, with an R2 value of .085 that was significant at the 0.05 level. This suggests that the presence of impervious surface cover has its greatest effect on stream flashiness in more urbanized sites, with natural factors or perhaps other anthropogenic factors playing a greater role in less urbanized sites.

4.4.2 Spatial Distribution of Imperviousness

It is possible that the distribution of the impervious surface within these watersheds could also be contributing to R-B Index variability. While the relationship of distance to pour point wasn't strong, it still suggests that this may be a factor among many, and can't be easily isolated. In theory, it makes sense that impervious surface distances to the stream network would also be a factor, despite no significant relationship being seen in the data. The fact that no significant relationship was seen doesn't necessarily negate this idea. It is likely that the resolution of the DEM and NLCD data (both 30m) could have had an influence on how significant these distances are in determining the ability of runoff to infiltrate. For example, riparian buffer laws in Georgia only require 7.62 m, and the resolution of the DEM and land cover is nearly four times that. Impervious surface distribution, in addition to unknown withdrawals, leaking pipes, and inter-basin transfers, all have reasonable amounts of evidence behind them to suggest that they are at least factors influencing the day-to-day changes in discharge in these streams (seen in the R-B Index values).

While it's always important not to over-engineer a study so that it is no longer applicable to the real world, it could be interesting to conduct a study to try to get some empirical values regarding different patterns of impervious surface connectivity, and how they affect stream discharge response to storm events. Perhaps a hillslope with different patterns of concrete surfaces could be designed, and responses to storm events measured. This study was able to touch on the effects these distributions may have, but without designing a study to specifically address this, it is impossible to truly isolate this variable.

4.4.3 Leaking Pipes/Inter-basin Transfers

While leaking subterranean infrastructure is certainly a valid explanation for the weakness of the relationship between R-B index and low flows (Lerner, 2002; Brandes et al., 2005; Price et. al, 2011), it's unlikely to explain the flashiness seen in the rural watersheds as rural areas with low population density tend not to feature much stormwater infrastructure and thus lack pipes with potential to leak in the first place. However, unaccounted groundwater withdrawals could be a potential anthropogenic influence. These withdrawals wouldn't affect the relationship between percent impervious cover and peak flows, as it's unlikely that any significant withdrawal would occur during a storm. Withdrawals tend to be the largest during times of drought when water is scarce, and have the greatest effect on streamflow during drier periods (Eheart et al.,1999; Wang et al., 2009). Determining if water withdrawals are a significant factor in producing flashier streams in these sites would require an in-depth investigation into local water use, which is beyond the scope of this study.

4.5 Role of Natural effects on Southeastern Piedmont Hydrology

4.5.1 Geology

While unaccounted withdrawals could potentially be having an effect on the day-to-day changes in discharge, Tick and Waxhaw Creek both fall within the Carolina Slate Belt, which feature some of the lowest groundwater yielding rock units to wells in the state. Low flows ranging from 0.001 – 0.005 ([ft3/sec]/mi2) are typical in this region (Giese & Mason 1993). A more valid explanation than unaccounted withdrawals for the flashiness and low discharge seen in these sites may simply be the inability of the underlying material to recharge groundwater, causing flow to be flushed out of the system in a manner similar to what would be seen in a heavily urbanized watershed.

The stark differences between the R2 values in the high impervious sites versus the low impervious sites also contributes to the idea that geology is a heavier influence on stream flashiness in less urbanized sites, and impervious surface cover is more influential in more urbanized sites. Given the small sample sizes of the regression analyses comparing R-B index to the two geological variables, the results should certainly be taken with a grain of salt. Defining a clear threshold would require more data, however with the data available in this study this transition appears to occur somewhere are 22% impervious surface cover. These results are close to what has been seen in other studies, as thresholds where impervious cover has significant effects on water quality degradation begins have been defined previously in the ranges of 10 to 20% (Kim et al., 2016).

4.5.2 Evaporation/Infiltration Hypothesis

Tying back to the concept of the evapotranspiration/infiltration tradeoff hypothesis, more forested watersheds produced less runoff given their precipitation inputs, likely attributed to greater evapotranspiration losses (Zhang et al., 2001). The increased losses in more forested watersheds would suggest that the role of evapotranspiration rather than infiltration is more significant here. This could possibly be due to the age of the forest cover and the erosion of Piedmont soils (Cowell, 1998)). During the cotton-farming era, much of the Piedmont topsoil eroded away, the portion of the soil that is best for root growth and where earthworms and other organisms thrive (Trimble, 1974, Brown, 2002). These are the drivers of increased macropores in soil that have the potential to fuel increased infiltration in forests (Lee & Foster, 1991). Many

Piedmont forests are also relatively new, and have sprung up as cropland has converted to forest, and may not have had time to develop much of an understory to facilitate increased infiltration (Connor, 2004).

The seasonal trends in R-B index may also potentially be explained via naturally occurring processes. The dip in R-B index in the spring may be in part due the role deciduous trees may play in water budget as they take up water to grow their leaves, and the spike in the summer months may be due to increased thunderstorms during that season. In depth analysis into the seasonal trends of stream flashiness could potentially be the focus of a future study, but would likely require analysis of individual storm events, and is beyond the scope of this study.

4.6 Multiple Linear Regression Model

Producing a model that could accurately predict R-B index/stream flashiness based upon the land cover and geology present can't be done with the information available in this study due to multiple assumptions of regression being violated (Berry, 1985). The production of these models is still an interesting practice, however, as it can be seen how these variables, in conjunction with one another, could be potentially used to make these predictions. Clearly, with the final model produced via the backwards elimination method featuring average Ksat and total impervious surface cover, a combination of anthropogenic and natural factors must be considered when trying to predict stream flashiness. It wasn't possible for the spatial distribution of impervious surface to be included in the model, but perhaps with a larger dataset, or another method to gauge spatial distribution of impervious cover, a more meaningful relationship that could fit into an MLR model could be found.

4.7 Limitations

Streamflow response to urbanization, like all intense anthropogenic impacts, can be very difficult to quantify. This study certainly has its limitations. One limitation of the study was operating under the assumption that the Piedmont Physiographic region was geologically uniform. While sites are geologically similar as far as being predominately metamorphic rock overlain by saprolite (Hack, J. T., 1982), still quite a bit of variability in soil ksat and depth to bedrock in Piedmont. Still, this was best that could be done with the available sites.

Without a detailed inspection into each watershed, it's difficult to know exactly which specific anthropogenic factors were present in specific watersheds, and to get an in-depth summary of the geology and soil properties. Given that the nature of this study was to use existing data and methods that could be easily replicated, doing so is outside the scope of this study, and also wouldn't be possible given the regional-scale analysis on which this paper sought to focus.

5 SUMMARY AND CONCLUSIONS

This study had two main objectives: to quantify flashiness in urban and rural streams using a variety of metrics, and to determine the relationship between watershed and land cover, particularly the amount and distribution of percent impervious cover. An additional goal was to investigate patterns and variability between the three cities focused on in the study.

In investigating these topics it was found that:

- Peak flows increased with increasing amounts of impervious cover, while low flows showed a much weaker relationship (and weakly positive instead of negative)
- R-B Index values tended to increase with increasing levels of impervious surface cover, although there was quite a bit a variability
- Urban sites yielded more discharge relative to their precipitation inputs, while more forested sites showed the opposite trend
- The underlying geology appears to play a significant role in stream flashiness in more urban sites, while impervious surface cover is more significant in urbanized sites
- Impervious surface distribution, unknown withdrawals, and leaking pipes, all have reasonable amounts of evidence behind them to suggest that they are at least factors influencing R-B Index and contributing to the unexplained variability seen in these study watersheds

Additionally, there were some patterns among cities. The most notable being that sites in North Carolina, in particular Charlotte, featured high R-B Index values relative to Georgia. This is likely due to geologic variability found in the Piedmont.

Urban hydrology is a complex subject, with many variables that must be examined. Not only must the amount of impervious surface be considered, the permeability of other surfaces and their distribution must be looked at. All of these bring a series of challenges regarding their quantification, as these systems can be very complex and the variables can be difficult to isolate. With the increased urbanization impending in the United States, and elsewhere in the world, a better understanding of urban hydrology is necessary in order to properly manage the problems associated with its processes. By expanding our knowledge of how urban watersheds function, hopefully we can reduce the negative impacts of urban expansion on water quality, flooding, and habitat loss.

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