THE INFLUENCE OF IMPERVIOUS SURFACE LOCATION ON WATER QUALITY IN THE HEADWATERS OF THE SOUTHERN APPALACHIAN MOUNTAINS

A Thesis
by
E. CAMERON CARLYLE

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APPROVED BY:

Jeffrey D. Colby
Chairperson, Thesis Committee

Chuanhui Gu
Member, Thesis Committee

Kathleen Schroeder
Member, Thesis Committee

Kathleen Schroeder
Chairperson, Department of Geography and Planning

Edelma D. Huntley
Dean, Cratis Williams Graduate School

Abstract

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E. Cameron Carlyle
B.S., University of North Carolina at Asheville
M.A., Appalachian State University

Chairperson: Jeffrey D. Colby

Determining where critical areas in watersheds exist, and how land cover in these critical areas influence water quality is vital. Impervious land cover has been shown to have a negative influence on water quality; however, the influence of impervious surface location within individual watersheds is poorly understood. This study examined the effects of impervious surfaces on water quality in 23 headwaters catchments in the Southern Appalachian Mountains of Western North Carolina. An effective method for generating impervious surface classifications from aerial photography is presented. Using these impervious surface classifications, the influence of impervious surface position was examined. Additionally, using a functional definition of a riparian area, this study presents a methodology for delineating potential riparian zones from adjacent hillslopes along Southern Appalachian headwater streams. Impervious surface percentages were correlated with water quality (specific conductance) at the watershed outlet. The results indicate that impervious surface in potential riparian zones and low-order streams (i.e., $\leq 3^{rd}$ order) are dominant controls of specific conductance measured at the watershed outlet.

Acknowledgments

First and foremost, I would like to acknowledge Dr. Colby. Without our many, many, long conversations the idea for this thesis would not have come about. Thanks for being patient while I tried to articulate my often inarticulate ideas. I will miss working with you on a regular basis, but I look forward to the opportunity to work with you more in future.

Second, I would like to acknowledge Dr. Gu. Your comments and critiques have consistently been insightful. I'm certain that the quality of my work has been greatly improved under your advisement. I also look forward to working with you in the future.

Third, I would like to acknowledge Dr. Schroeder. Thanks for stepping up to fill in on committee. I appreciated comments and observations during my defense. Moreover, my time in the Department of Geography has been wonderful, which is due in no small way to the work that you do for department on a daily basis. Thank you what you do for the department, and for making my time in the department as good as it was.

Finally, I would like to thanks my family and friends for all their support during my time at Appalachian. It really has been great experience. It would not have nearly as great without the consistent love and support of my girlfriend, Flannery. You are truly wonderful. Thank you.

Dedication

To

Flannery, with all my heart,

to

My Parents, without your love and support I would not be where I am today,

and to

Grandma Mable, your endless thirst for knowledge continues to inspire me.

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Foreword

The organization and formatting of the thesis main body strictly follows the instruction to authors for manuscript submission to the journal *Water*.

Introduction

1.1 Importance of Mountains and Headwaters

Understanding the interactions between humans and the environment, and specifically the hydrologic components of the environment, is a critical and complex issue at the core the discipline of geography. In Carol Harden's 2011 Presidential Address to the Association of American Geographers (AAG), she identified what she viewed as "… gaps at the core of what we have defined as our intellectual space." Harden [1] called for geographers to focus their research on the intersection of human activities and the environment and "…the complex web of interactions and feedbacks that are involved." If the nexus of human and environmental processes can be viewed as a critical domain of geographers, then perhaps the mountain landscape can be viewed as a critical area of study within that domain. Richard Marston, in his Presidential Address to the AAG in 2008, commented, "… it is difficult to conceive of landscapes where opportunities for geographic understanding are as great and as urgently needed, as in the mountains of the world." Indeed, mountain environments provide geographers with a dynamic laboratory for studying the way in which physical processes impact human activities, and the way in which human activities impact physical processes. As Marston [2] points out, in mountain environments "…physical processes can operate at ferocious rates and ecosystems are sensitive to rapid degradation by climate change, resource development, and land use and land cover change." Viewed in this light, mountain environments can be seen as ideal environments in which to study the effects of change on both the physical and human environments. Perhaps nowhere is this more critical than in the relationship between humans and water. Studying the hydrologic processes at work in the mountains and the human activities interacting with those processes provides researchers with a central position from which to engage nearly all of the processes at work in and on the mountain landscape.

A continued understanding of the hydrologic processes of mountain environments is of critical importance not only to those living within the localized mountain landscape, but also to those living at lower elevations and farther downstream. Research suggests that headwater streams could play a significant role in downstream water quality. Alexander *et al.* [3] found that 1st order streams contributed about 70% of the total water volume to second-order streams, and about 55% to 4th order and higher streams. In addition, Dodds and Oakes [4] also found that headwater streams could have a significant impact on downstream water quality, and that riparian buffers on 1st order streams could significantly explain variance in water quality parameters of 4th order streams. Moreover, Dodds and Oakes [4] found that watershed and 1st order stream riparian land cover explains water quality variability with greater statistical significance than more localized riparian buffers on the 4th order streams. The direct source of some water quality threats can be traced to single point sources, such as discharge from a waste water treatment facility or an industrial site; however, other non-point sources, such as runoff from agricultural fields or developed areas, are more difficult to identify and model directly. The human activities that produce non-point source threats to water quality can be identified on the landscape, as these activities often alter the composition of the land cover [5]. The influence of land cover on water quality has been well researched, and much focus has been directed at studying the influence of runoff from impervious surfaces on water quality [6-7]. However, little research has focused on how impervious surfaces in headwater streams influences water quality downstream.

One way that regulators and water resources managers have tried to maintain water quality standards in streams and rivers is through the use of conservation buffers. Traditionally, conservation buffers have been sited along banks of streams and rivers at state and federally regulated widths; however, Walter et al. [8] identified a “new paradigm” in the sizing and placement of riparian buffers. Walter et al. [8] suggested that riparian buffers should target areas of the watershed that are most prone to generating runoff. This concept is a direct outgrowth the concept of variable source area (VSA) hydrology. This new paradigm, along with the linkages between headwater and downstream water quality, suggests that management practices in headwaters should be reevaluated in light of the new paradigm. One way in which management practices could be reevaluated is through the use of variable width buffers that better reflect the hydrologic and geomorphic processes at work in headwater watersheds. This thesis was motivated by this need to revaluated management practices in headwater watersheds. The overarching goal of this thesis was to better understand how land cover, particularly impervious surfaces, and the location of land cover in headwater watersheds influences water quality downstream.

1.2 Author’s Role in the Article Section of this Thesis

To accomplish the goal above, the research presented in the article section of this thesis was conducted by me, with the help of Dr. Colby and Dr. Gu. All of the methods described in the article were performed by me; however, Dr. Colby and Dr. Gu contributed significant advice, conceptual knowledge, domain expertise, and edits to article. The advice and domain expertise of Dr. Colby and Dr. Gu contributed primarily to the conceptual framework for the article, and directed the actions and methods that I performed in conducting the research. Specifically, I performed all of the watershed and hydrographic modeling, including the delineation of all the watersheds in the study area, and derivation of the stream network used in the article. I preformed all of the preprocessing on the NAIP imagery. I developed an effective impervious surface classification routine for large areas by extending earlier work by other graduate students in the Department of Geography and Planning, Chris Coffey [9], Ashleigh Turner, and Mark Jenkins. I performed all of the impervious surface classifications and accuracy assessments of the classifications, including the work with Feature Analyst and all of the manual editing. I developed the initial idea for the RipZone presented in the article. The idea was refined with help from Dr. Colby and Dr. Gu. I developed conceptual model for the RipZone algorithm, wrote all of the Python code referenced in the article, and implemented the code for each watershed in the study area. I performed the accuracy assessment of RipZone and the associated field work with the help of Mark Jenkins. I performed all of the GIS analysis associated with the watershed segmentation and calculation of percent impervious surface. I derived all of the statistics presented in article, and, finally, wrote the initial draft of the article.

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Article

The Influence of Impervious Surface Location on Water Quality in the Headwaters of the Southern Appalachian Mountains

E. Cameron Carlyle [1],* Jeffrey D. Colby[1], Chuanhui Gu[2]

[1] Department of Geography and Planning, Appalachian State University, Boone, NC 28607; E-Mails: carlyleec@appstate.edu (E.C.); colbyj@appstate.edu (J.C)
[2] Department of Geology, Appalachian State University, Boone, NC 28607; E-Mails: guc@appstate.edu (C.G.)

* Author to whom correspondence should be addressed; E-Mail: carlyleec@appstate.edu (E.C.); Tel.: +1-828-808-0265;

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Abstract: Determining where critical areas in watersheds exist, and how land cover in these critical areas influence water quality is vital. Impervious land cover has been shown to have a negative influence on water quality; however, the influence of impervious surface location within individual watersheds is poorly understood. This study examined the effects of impervious surfaces on water quality in 23 headwaters catchments in the Southern Appalachian Mountains of Western North Carolina. An effective method for generating impervious surface classifications from aerial photography is presented. Using these impervious surface classifications, the influence of impervious surface position was examined. Additionally, using a functional definition of a riparian area, this study presents a methodology for delineating potential riparian zones from adjacent hillslopes along Southern Appalachian headwater streams. Impervious surface percentages were correlated with water quality (specific conductance) at the watershed outlet. The results indicate that impervious surface in potential riparian zones and low-order streams (i.e., ≤ 3rd order) are dominant controls of specific conductance measured at the watershed outlet.

Keywords: impervious; headwaters; water quality; riparian; Appalachian; mountains; classification;

1. Introduction

Understanding the interactions between humans and water quality is a critical and complex issue. Water quality managers need effective tools for determining where critical areas in watersheds exist, and how land cover in these critical areas influence water quality. The direct source of some water quality threats can be traced to single point sources, such as discharge from a waste water treatment facility or an industrial site; however, other non-point sources, such as runoff from agricultural fields or developed areas, are more difficult to identify and model directly. The human activities that produce non-point source threats to water quality can be identified on the landscape, as these activities often alter the composition of the land cover [5]. The influence of land cover on water quality has been well researched, and much focus has been directed at studying the influence of runoff from impervious surfaces on water quality [6-7]. The percent of impervious surface within a watershed has been shown to be an important predicator of water quality, with higher percentages of impervious surface resulting in lower levels of water quality [5]. Although this relationship is widely accepted, Brabec [10] points out that the influence of the location of impervious surfaces within individual watersheds is poorly understood.

Research suggests that headwater streams could play a significant role in downstream water quality. Alexander *et al.* [3] found that 1st order streams contributed about 70% of the total water volume to second-order streams, and about 55% to 4th order and higher streams. In addition, Dodds and Oakes [4] also found that headwater streams could have a significant impact on downstream water quality, and that riparian buffers on 1st order streams could significantly explain variance in water quality parameters of 4th order streams. Moreover, Dodds and Oakes [4] found that watershed and 1st order stream riparian land cover explains water quality variability with greater statistical significance than more localized riparian buffers on the 4th order streams. Little research has focused on how impervious surfaces in headwater streams influences water quality downstream.

One way that regulators and water resources managers have tried to maintain water quality standards in streams and rivers is through the use of riparian buffers. Traditionally, riparian buffers have been sited along banks of streams and rivers at state and federally regulated widths; however, Walter *et al.* [8] identified a “new paradigm” in the sizing and placement of riparian buffers, and suggested that riparian buffers should target areas of the watershed that are most prone to generating runoff. This concept is a direct outgrowth the concept of variable source area (VSA) hydrology [11-15]. This new paradigm along with the linkages between headwater and downstream water quality suggest that management practices in headwaters should be re-evaluated in light of the new paradigm. In addition, McGlynn and McDonnell [15] found that riparian zones were able to alter the chemistry of shallow subsurface runoff from hillslopes. Based on this research, McGlynn and Seibert [16] described a rationale for segmenting the landscape of a watershed into riparian and hillslope zones. Jencso et al. [17] reinforced this concept of riparian buffering capacity, finding that the relative size of the riparian area to the hillslope determined the effectiveness of the riparian zone at buffering hillslope runoff. As such, the effectiveness of a riparian area to chemically buffer hillslope water can be expressed as a ratio of riparian contributing area to hillslope contributing area for a particular point on a stream, or the riparian buffering ratio. One of the aspects of the riparian buffering ratio approach that is lacking is a methodology for effectively delineating the extent of riparian zone landscape units without extensive fieldwork.

Due to its position in the landscape, riparian areas have been studied from a number of perspectives, including geomorphological [18], hydrological [15], biological [19], and natural resources perspectives [20]. As such, a number of definitions for riparian areas exist in the literature. Verry et al. [21] provide an excellent summary of some 40 years of such definitions of riparian areas. Based on the conclusions of Verry et al. [21] and Gregory et al. [22], a functional definition for riparian areas along Southern Appalachian headwater streams is a three dimensional ecotone ranging vertically from rooting depth or the depth of a restrictive layer to the top of the canopy including the stream, the floodplain, and any adjacent hillslopes that provide a riparian function. To move from definition to delineation, the riparian area could be characterized geomorphically as relatively flat flood prone areas adjacent to streams; distinct from surrounding steeper hillslopes. Accordingly, several studies have used breaks in slope as a method for identifying riparian-hillslope transition points [15, 18].

To better understand how land cover in critical areas of watersheds influences in-stream water quality, this study examined the effects of impervious surfaces on stream specific conductance (SC), as an integrated water quality index, in 23 headwaters catchments in the Southern Appalachian Mountains of Western North Carolina. To quantify the extent of impervious surface, this study presents a method for generating highly accurate, high-resolution impervious surface classifications from aerial photography. Using the impervious surface classifications, the influence of impervious surface location was examined by segmenting each of the watersheds in the study area based on distance from the stream and stream order. Additionally, using the functional definition of a riparian area described above, this study presents a methodology for delineating potential riparian zones from adjacent hillslopes along Southern Appalachian headwater streams. Within each watershed, the percent impervious surface was calculated in each of the segments, and the percentages were correlated with SC at the watershed outlet. The results indicated that the location of impervious surfaces within a watershed determines the degree of influence that impervious surfaces have on in-stream SC measured at the watershed outlet.

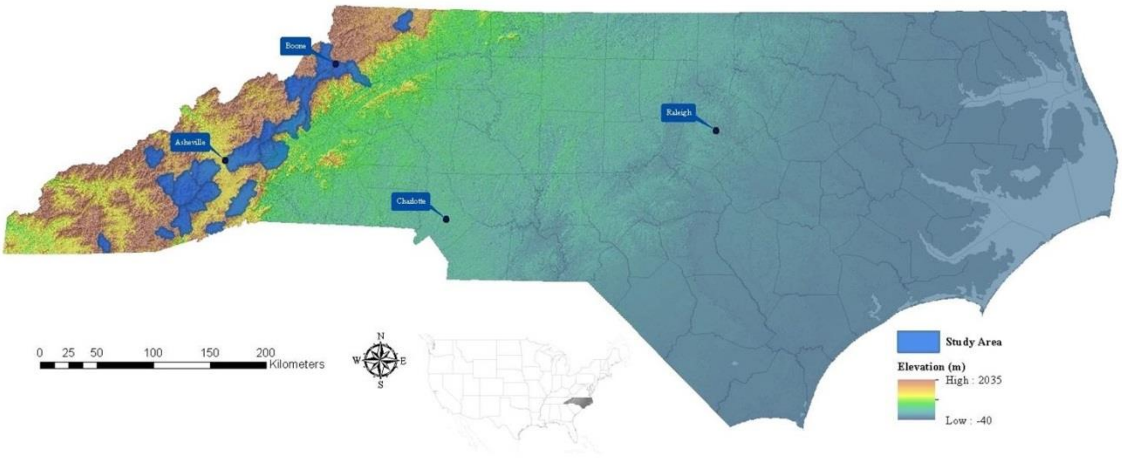
2. Data and Methods

2.1 Study Area

In the Southern Appalachian Mountains of Western North Carolina, 23 watersheds were selected as a study area (Figure 1). These watersheds were selected based on the availability of data and watershed characteristics. Watershed selection was limited to the mountains in Western North Carolina to ensure that the study area shared the same general ecosystem, bedrock geology, and climate. By holding these factors generally constant across the study area, the influence of land cover could be isolated as a primary control on SC at the landscape scale. The location of in-stream water quality sampling locations was the primary criteria in watershed selection within the study area. For each of the selected watersheds, a minimum of 20 water quality samples were collected by the North Carolina Division of Water Quality over a two year period of time from 2005 to 2006. In addition to the availability of water quality sampling locations, the availability of aerial imagery for each watershed of sufficient quality during the time period the water quality data was collected was also a deciding factor in watershed selection. For each of the selected watersheds, it was determined that the 2005 National Agriculture Imagery Program (NAIP) [23] imagery provided effective coverage with minimal cloud cover occlusions. Watersheds were also selected based on similarity in size and stream order at the watershed outlet. The selected watersheds ranged in size from 57.8 – 336.7 km^2, with a mean area of 168.5 km^2. The total area of the watersheds that were studied was 3675.5 km^2. Streams at the watershed outlets varied between 5th or 6th order streams.

The study area watersheds were predominately forested, with an average percent of forested area of 80% across all of the selected watersheds [24]. Elevation in the study area ranged from 327.4 to 2036.7 m, with a mean slope of 19.2 degrees. Lower order streams in the study area were characterized by steep valley walls, and narrow riparian areas along streams, whereas higher order streams in the study area tended to have wider more established floodplains. Asheville, NC is the largest population center in the region with a 2012 population of 85,712. Two watersheds in the study area had outlets within Asheville's city limits; however, these outlets did not receive direct runoff from the most urban sections of Asheville. The largest population center to be contained with a single watershed in the study was the town of Boone, NC, with a 2012 population of 17,774. Several other towns with populations of approximately 10,000 were contained within other watersheds within the study area [25].

Figure 1. Locations of the study area watersheds in western North Carolina, USA.



2.2 Water Quality Data Sources and Summary Statistics

Water quality data was downloaded from the EPA Storet website [26] for 23 water quality sampling locations across Western North Carolina. These locations were sampled by the North Carolina Division of Water Quality (NC DWQ) ambient monitoring system [27-28] during the years 2005 and 2006. The grab-samples were collected approximately monthly, with an average of 21 and minimum of 20 samples per location. Of the water quality parameters collected and measured at each sampling location, SC was selected as the sole indicator of water quality as SC gives a good estimate of the total amount of dissolved solids (such as salt) in the water and is primarily controlled by non-point source pollution. Several studies have shown a relationship between SC and imperviousness [29-31]. A mean SC value was derived for each sampling location using all available samples from the two year period for each location. There was a wide range in SC values collected across the study area, ranging from 13.5 to 142 mS (Table 1 and Figure 2).

Figure 2. Histogram of mean Specific Conductance (mS) measurements collected during 2005-2006 for each monitoring location in the study area.

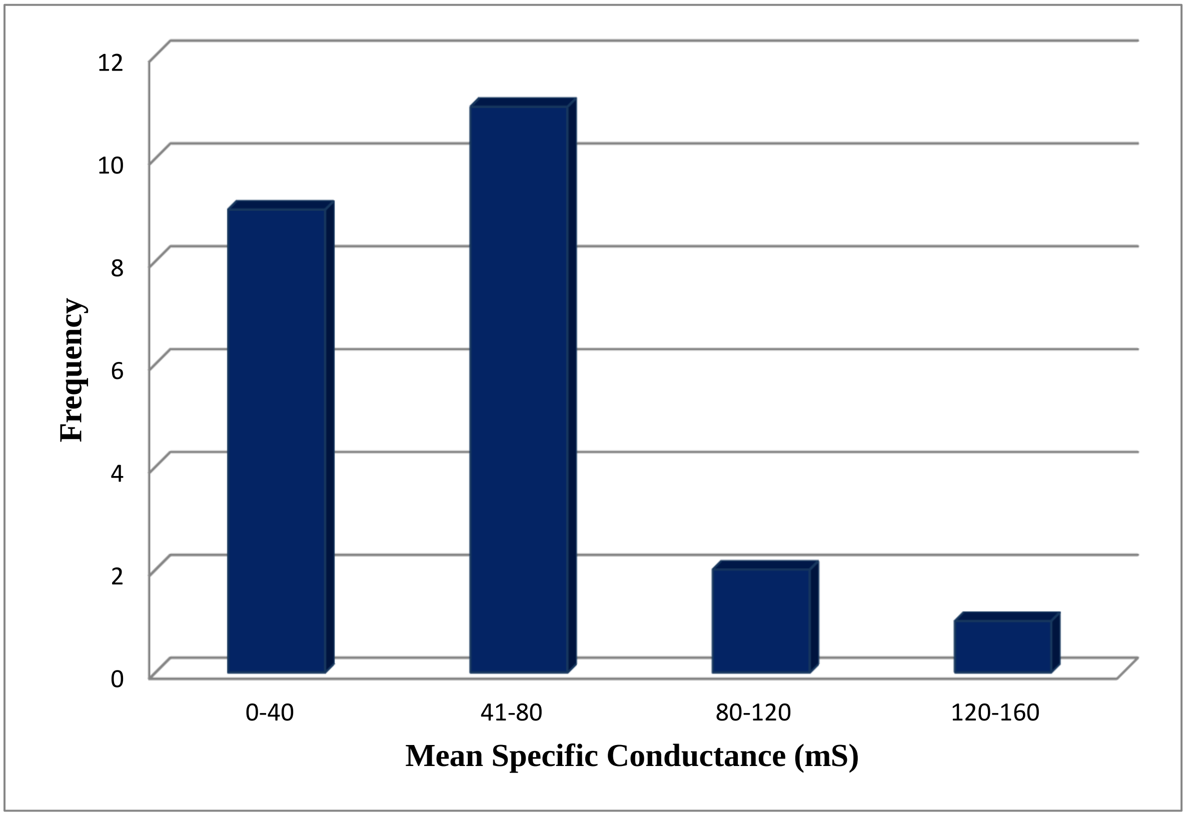


Table 1. Summary statistics of Specific Conductance measurements.

Median	Mean	Max	Min	Standard Deviation
47.0	44.6	142.0	13.5	30.6

2.3 Watershed Delineation and Hydrographic Modeling

Light Detection and Ranging (LiDAR) derived 6.1 m (20ft) resolution Digital Elevation Models (DEMs) for the 13 counties in Western North Carolina that contained the study area were downloaded from the NC Department of Transportation (NC DOT) Connect website [32]. The LiDAR data used in the preparation of the DEMs was collected as part of the North Carolina Floodplain Mapping Program (NCFMP) in the study area in 2005 and 2006 (except for Watauga County in 2003) [33]. Using the geographic information system (GIS) ArcGIS (Environmental Systems Research Institute; Redlands, CA, USA), the DEMs from each county in the study area were mosaicked into one DEM. Hydrographic datasets for the study area were downloaded from the NC Stream Mapping Program (NCSMP) [34]. The NCSMP hydrographic datasets were an effort by the NC Center for Geographic Information and Analysis (NCCGIA) to improve upon the National Hydrographic Dataset (NHD) [35] available from the United States Geologic Survey (USGS). All but one of the watersheds in the study area were covered by the NC SMP hydrographic datasets. The NHD was used for the remaining watershed. The hydrographic datasets were clipped using ArcGIS by the county boundary shapefiles downloaded from the NC One Map Geospatial Portal [36]. Coordinates for each of the sampling locations were provided with the data downloaded from EPA Storet. The sampling locations were verified using ArcGIS's imagery base maps and drainage lines from the NCSMP datasets, and adjusted slightly in some cases to ensure that sampling points were located on the drainage line.

The ArcHydro [37-38] extension for ArcGIS was used to perform hydrographic processing in the study area. Using the ArcHydro toolset, the mosaicked DEM was reconditioned using the drainage lines from the hydrographic datasets. Sinks in the reconditioned DEM were filled, and a D8 [39] flow direction layer was generated. From the flow direction layer, a flow accumulation layer was derived. Using the flow accumulation layer, a stream raster was defined using an accumulation threshold of 0.0728 km^2, based on research by Coffey [9], who found that this accumulation threshold produced the most accurate drainage network in the Upper South Fork of the New River (USFNR), one of the watersheds in the study area. The stream raster was segmented into stream links, and sub-catchments were delineated using ArcHydro tools. Using ArcGIS's Hydrology tools, which are part of the Spatial Analyst extension, the watershed draining into each of the sampling locations was delineated. Using ArcGIS's Raster Calculator, the watersheds were separated into distinct raster layers representing the extent of each watershed. Sub-catchment and stream raster layers were generated for each watershed. The stream order of each sub-catchment was calculated for each watershed using the Strahler method [40]. Additionally, the Euclidean distance from the stream of each 6.1 m (20 ft) grid cell within 182.88 m (600 ft) of the stream in each of the watersheds was calculated.

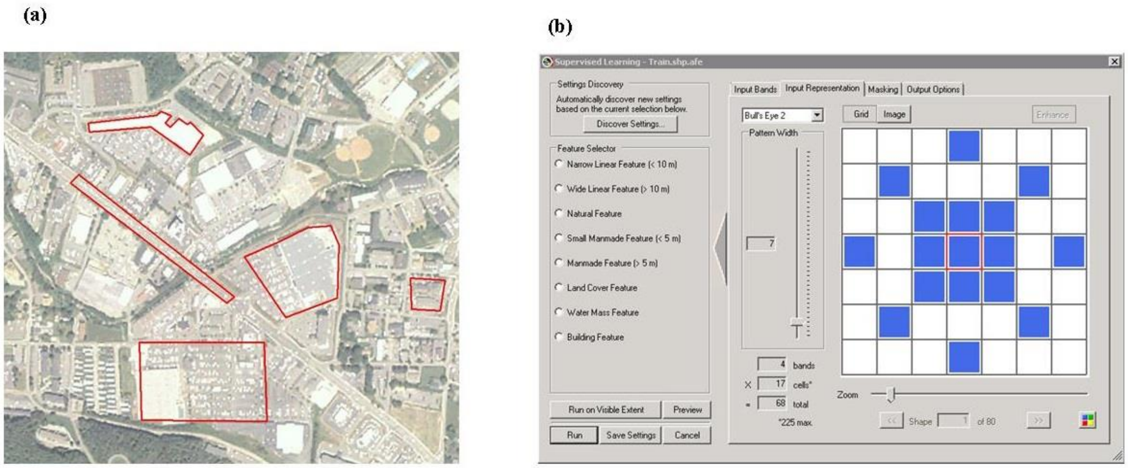
2.4 Aerial Imagery Data Sources and Preprocessing

Aerial imagery collected as part of the NAIP was downloaded from the United States Department of Agriculture (USDA) Geospatial Gateway [41] for the year 2005 for the 13 counties in Western North Carolina that contained the study area. The resolution of the imagery was 2 m, and was acquired during the growing season; as such, vegetation was full-leaf on. Several of the watersheds in the study area overlapped the boundaries of multiple counties. The watershed boundaries were clipped by county boundary shapefiles downloaded from the NC One Map Geospatial Portal [36] using ArcGIS. Using ArcGIS's Extract By Mask tool the imagery for each county was extracted by either the clipped or complete watershed boundaries as appropriate. The extracted imagery from each clipped watershed was merged with the extracted imagery from the other clipped sections using ArcGIS's Mosaic to New Raster tool.

2.5 Impervious Surface Classification

For each watershed, impervious surface was classified from the 2 m resolution NAIP imagery using the Feature Analyst extension for ESRI ArcGIS [42-43]. Approximately 50 training sites were created for each watershed by heads-up digitizing polygon features around impervious surfaces visible in the imagery. The Feature Analyst supervised learning routine was then implemented using a gridded input representation of Bull's Eye 2 with a pattern width of 7 (Figure 3).

Figure 3. Training sites and statistical filter used in the classification of impervious surface: **(a)** Example training sites, as digitized on the aerial photography; **(b)** Feature Analyst's Bull's Eye 2 statistical filter used in the supervised learning classification routine.



Bull's Eye 2

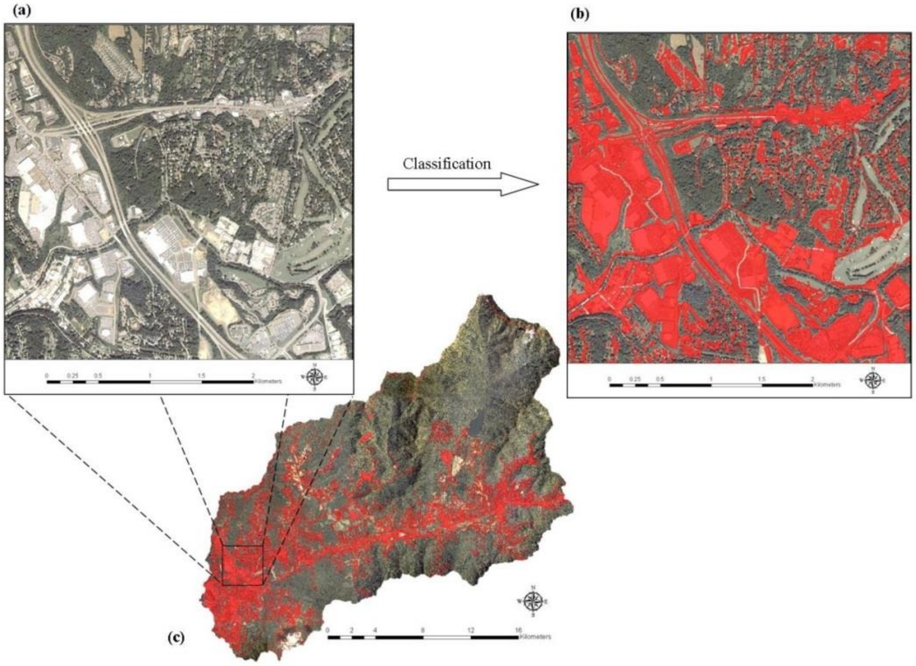
Pattern Width 7

4 bands
× 17 cells*
= 68 total
*225 max.

Previous research by Coffey [9] determined that Bull's Eye 2 input representation and pattern width were highly effective at extracting impervious surface for imagery. Although

Feature Analyst has the capability to utilize hierarchical learning to improve classifications, the hierarchical learning features of Feature Analyst were not used in this study. Instead, if the initial supervised learning routine was deemed effective, the initial classification was then manually improved through heads-up digitizing to reduce omission and commission errors. To augment each impervious classification, the NC Integrated Statewide Road Network (ISRN) [44] dataset was buffered by 3m, and appended to the impervious surface layer in each watershed. The final impervious layer was resampled to the 20 ft resolution to ensure congruency with the information products derived from the 20 ft resolution DEMs. An accuracy assessment of the impervious classification in each watershed was conducted by generating 50 random points within a 10m buffer of the classified impervious surfaces.

Figure 4. Impervious surface classification from aerial imagery: **(a)** 2005 NAIP Imagery of a section of the Swannanoa watershed; **(b)** Impervious surface classification (shown in red) of a section of the Swannanoa watershed; **(c)** Impervious surface classification of the Swannanoa watershed.



2.6 RipZone description

A new geomorphometric, called RipZone, was developed in this study to calculate the potential topographic extent of riparian areas in Southern Appalachian Mountain headwater watersheds. The new metric segments the landscape into two distinct zones: riparian areas and hillslopes. As a geomorphometric, RipZone is calculated directly from the land surface represented by a digital elevation model (DEM). Landcover and soil were not considered, but could be used to refine the extent predicted using RipZone. The riparian extent depicted by RipZone represents the geomorphic extent of the riparian area, or the extent of the watershed that has a topographic character consistent with the definition of the riparian area given in the introduction. RipZone is computed on elevation profiles perpendicular to a stream or valley centerline, and the transition point between the riparian area and the adjacent hillslope is defined as the maximum perpendicular distance between the land surface and a straight line extended from the stream to the nearest point on the land surface with a height of 5 m above the stream (Figure 5).

To delineate the RipZone, the elevation values were first converted to heights above the stream. Using the heights above the stream, the upper bound of the profile is limited to 5m above the stream. This is done for two reasons. First, in the Southern Appalachian Mountains roads are often cut into the hillslope immediately adjacent to the floodplain/riparian area. The road cut into the hillslope creates a break in slope that has not been formed by fluvial processes and, therefore, can lead to false predictions of the riparian extent. By selecting a height of 5 m above the stream, the break in slope created by the road cut becomes less pronounced along the profile reducing its influence on the metric. The second reason for selecting a maximum height of 5 m above the stream was based on the assumption that the functioning geomorphic extents of riparian areas do not extend beyond 5m above the stream, which was confirmed with fieldwork. It is important to note that the 5m height limit refers only to the land surface, and not to vegetation. In addition to limiting the maximum height of the profile, the minimum height of the profile must also be restricted to 0 m. Depressions in riparian areas that have a height less than 0 m below the stream lead to false riparian extent predictions. Using the RipZone, the transition point between the riparian area and the adjacent hillslope is defined as the maximum perpendicular distance between the land surface and a straight line extended from the stream to the nearest point on the land surface with a height of 5 m above the stream.

Figure 5. A representation of the riparian zone as modeled using RipZone: **(a)** The maximum perpendicular distance between land surface and a line extended from the stream to a point on the land surface 5m above the stream; **(b)** The transition point between the riparian zone and the hillslope.

2.7 Accuracy assessment of the RipZone metric

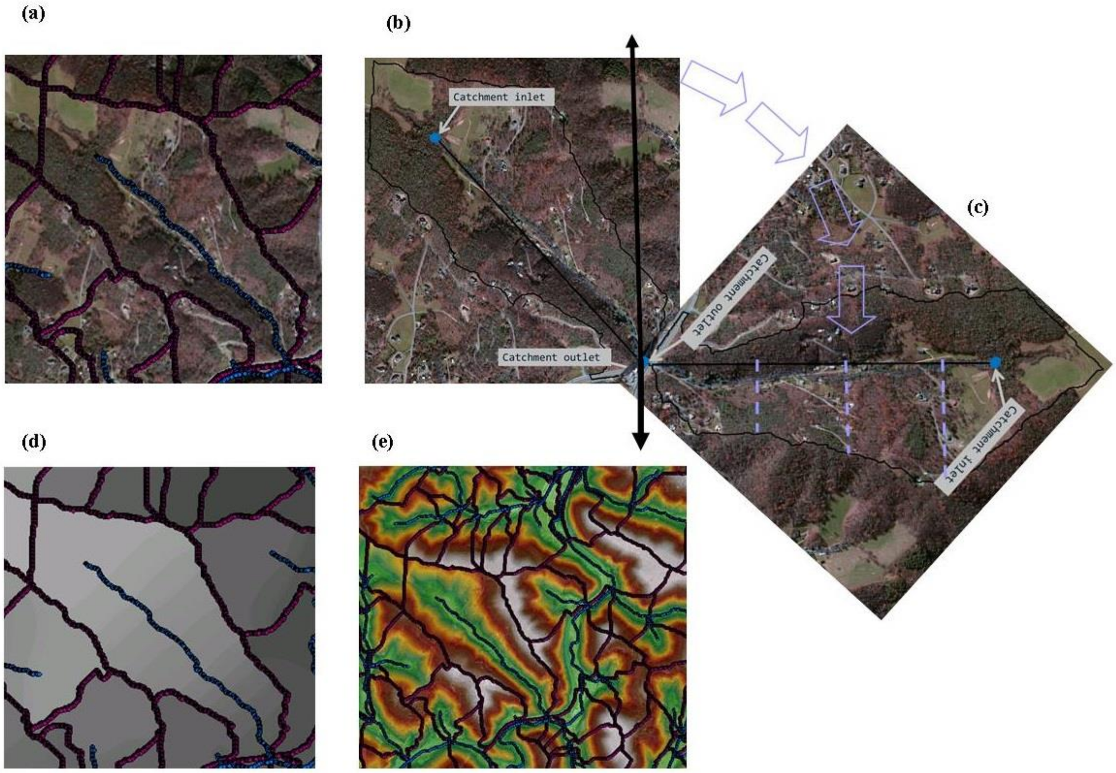
An accuracy assessment of the metric was conducted by measuring the extent of 31 riparian areas in the USFNR watershed using a Trimble Geo XT and 6 inch aerial photography. At each sample location, a coordinate point was acquired at the stream bank and at the break in slope perpendicular to the stream. The distance between the two points was measured in ESRI's ArcMap. Additionally, using the 3D Analyst extension in ArcMap, elevation profiles corresponding to the sampled point locations were extracted from a 5m DEM. A Python script was used to calculate the metric along these extracted elevation profiles. The predicted and measured riparian extent distances from the 5m DEM were statically analyzed.

2.8 Implementation of the RipZone on a watershed scale

RipZone was implemented for each watershed in the study area with the Python [45] programming language using the open source library OGR [46], as well the ArcPy module available with ArcGIS. The RipZone algorithm takes a DEM, a polygon shapefile of the sub-catchments, a raster layer representing the location of streams in the watershed, and a stream link raster as inputs. The RipZone was separated into three Python scripts. The first script used the ArcGIS ArcPy module to perform some initial preprocessing and reformatting of the data inputs. Elevation values from the input DEM were assigned to the grid cells of the input stream raster creating a stream elevation raster. The stream elevation raster were converted into a point shapefile, such that each grid cell in the stream raster is represented as a discrete point in the shapefile. The coordinates of each stream grid point were added to the attribute table of the stream elevation point shapefile, and the shapefile was returned as output. The sub-catchment polygon shapefile was converted into a polyline shapefile representing the boundary of each sub-catchment. This polyline was converted into a raster at the same resolution as the input DEM, and then converted into a point shapefile. The coordinates of each point in the sub-catchment point shapefile were added to the attribute table, along with a blank elevation field (Figure 6a).

The second Python script calculated the height above river (HAR) using the stream elevation point shapefile and sub-catchment point boundary shapefile returned from the first script. The script looped over the sub-catchments, and selected the stream elevation points and sub-catchment points within each sub-catchment. With each iteration, 2D arrays of the stream elevation points and the sub-catchment boundary points [id, *x*, *y*, *z*] within the selected sub-catchment were generated. The arrays were sorted by elevation values. The point with the lowest elevation value in the array was considered to the be the sub-catchment outlet, and the point with highest elevation value was considered to be the stream initiation point in 1st order streams or the in-flow point where a lower order stream flowed into the selected sub-catchment. A line connecting these two points was considered to be the valley centerline for the sub-catchment (Figure 6b). To prevent the overlapping of transects, all transects were generated perpendicular the valley centerline, rather than perpendicular to the tangent of each stream point. To collect sub-catchment points along the perpendicular transects, the direction of flow and angle of the valley centerline was calculated. All of the *x* and *y* coordinates in the stream elevation and sub-catchment arrays were rotated by the angle of the valley centerline using a rotational matrix and translated by the new *y* value of the stream outlet; such that the valley centerline was congruent with the *x* axis in the coordinate system of input layers (Figure 6c).

Figure 6. A conceptual diagram of the second script used in the RipZone calculation: (a) Stream elevation and sub-catchment points; (b) The valley centerline extended from the sub-catchment inlet to sub-catchment outlet; (c) Conceptual rotation of the stream and sub-catchment points, such that the valley centerline is congruent with the *x*-axis; (d) Natural neighbor interpolation of stream elevation extending up the sub-catchment; (e) Height above river raster layer with green indicator areas of low height above river



The resulting array was then sorted by the rotated *x* values. As shown by blue dashed lines in Figure 6c, the rotation resulted in all of the sub-catchment points perpendicular to a stream point sharing the same *x* value, except for sub-catchment points with a greater *x* value than stream initiation point (or in-flow point from another sub-catchment). These upper sub-catchment points were collected into a separate array and in a similar manner as described above, 180 rotations were performed on the upper sub-catchment points, so that transects fanned out from the highest stream point in the sub-catchment in 1 degree increments. The elevation of each sub-catchment point was assigned the mean elevation value of each perpendicular stream point. This resulted in stream elevations being assigned to the boundary of each sub-catchment. These arrays were converted into a single shapefile, containing both stream and sub-catchment boundary points. The elevation values from the point shapefile were then interpolated using a natural neighbor interpolation. The interpolation created a raster layer of stream elevation values extending perpendicular away from each stream (Figure 6d). The natural neighbor interpolation was then subtracted from the original DEM to produce a height above river (HAR) raster layer.

The final script used the ArcPy module to calculate the maximum perpendicular distance from the land surface, represented by the HAR shapefile, to a line extending from the stream to a point on the land surface 5 m above the stream. The distance between any point (x_1,y_1) and a line $y = mx + b$, where m is the slope and b is the y intercept, can be determined by using the formula:

$$\frac{|y_1 - mx_1 - b|}{\sqrt{m^2 + 1}} \tag{1}$$

In the case of the RipZone calculation, the formula can be rewritten to perform a raster calculation as:

$$\frac{|HAR - LINE_{HEIGHT}|}{\sqrt{\left(\frac{LINE_{HEIGHT}}{EUDIST}\right)^2 + 1}} \tag{2}$$

In the RipZone calculation the y-intercept occurs at the stream, and was therefore zero. *HAR* as a natural neighbor interpolated surface generated from the input HAR shapefile. $LINE_{HEIGHT}$ was a raster surface generated by first creating a raster of all the points less than or equal to 5 m above the stream. This raster was then converted to a polygon, and then into a polyline representing a boundary around the streams in the watershed that contains the entire land surface less than or equal to 5 m above the stream. This polyline was then converted back into a raster at the same resolution of the input DEM, and assigned a value of 5. This raster was then converted into a point shapefile, such that each point represents a point 5 m above the stream. The elevation values in the input stream elevation shapefile were set to zero, and then appended to the 5 m boundary shapefile. This appended shapefile was then interpolated using a natural neighbor interpolation, which produced an approximately straight line between each stream point and a natural neighbor point on the 5 m height boundary. The interpolated values represented a surface of heights extending away from the stream to points on the land surface 5 m above the stream, and were used as the $LINE_{HEIGHT}$ values in the equation above. The *EUDIST* values were derived from a Euclidean distance raster representing distances from the stream. This calculation was performed for every sub-catchment in the watershed, and was output as a distance surface.

After performing the distance calculation above, the maximum distance for each transect was calculated using a watershed delineation technique. Since greater distances have higher values, maximum distances form ridges on the distance surface. The techniques used to delineate watersheds from topographic surfaces represented by DEMs can be used to delineate the riparian zone from the distance surface calculated above. Sinks in the distance surface were filled, and a D8 flow direction surface was generated. Then using the same stream link raster used in the delineation of the actual watershed, combined with the flow direction raster generated from the filled distance surface, the riparian “watershed” was calculated. The resulting raster was reclassified to a value of 1, representing the riparian extent (Figure 7). Using the methods outlined above, the RipZone was calculated for each watershed in the study area. A watershed scale visualization of RipZone can be seen in Figure 8.

Figure 7. Comparison of the distance surface with the final RipZone product: (a) Raster surface that represents the perpendicular distance between the land surface and lines perpendicularly extended from every point on the stream to points on the land surface 5m above the stream; (b) The final RipZone raster layer overlain on the distance raster.

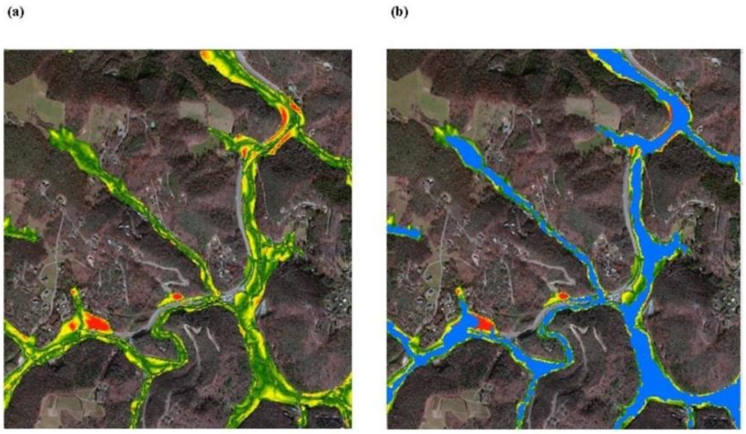
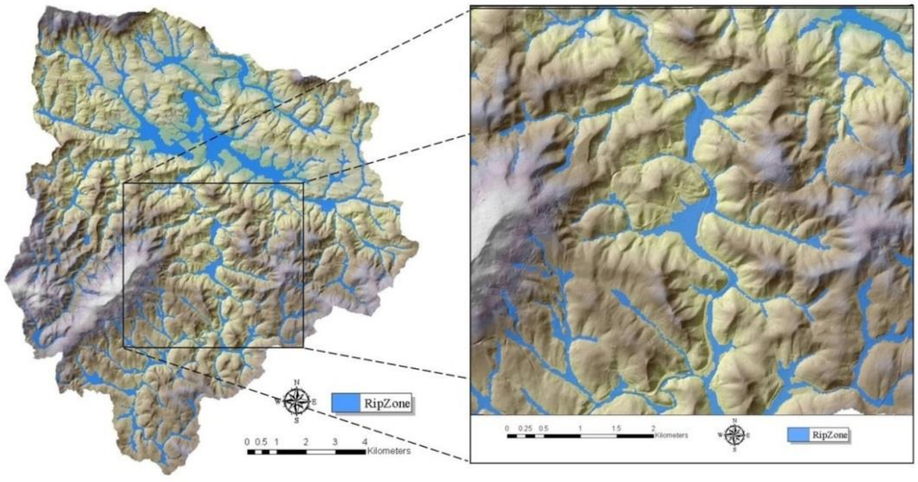


Figure 8. The riparian area in the Upper South Fork of the New River as calculated using RipZone.



2.9 Watershed Segmentation, Percent Impervious Calculations, and Regression Analysis

Total percent impervious (TPI) was first calculated for each watershed as a whole, and then within 162 defined segments of each watershed. Each watershed was segmented by stream order, the RipZone calculated riparian area, and by distance from the stream in 6.1 m (20 ft) linear increments from 0 - 182.9 m (600 ft) of each stream. Table 2 details the manner in which each watershed was segmented.

Table 2. Watershed segmentation.

Total Area	**RipZone**	**Distance in 6.1 m (20ft) increments-182.88m (0-600ft) of each stream**
Watershed TPI	RipZone TPI	Within each distance TPI
1st Order TPI	1st Order within RipZone TPI	1st Order within each distance TPI
2nd Order TPI	2nd Order within RipZone TPI	2nd Order within each distance TPI
3rd Order TPI	3rd Order within RipZone TPI	3rd Order within each distance TPI
4th Order TPI	4th Order within RipZone TPI	4th Order within each distance TPI
5th Order - Outlet TPI	5th Order- Outlet within RipZone TPI	5th Order- Outlet within each distance TPI

For each of the watershed segments above, linear regression analysis was completed using the mS values at each watershed outlet, and the TPI from each watershed segment.

3. Results and Discussion

3.1 Accuracy assessment of the impervious surface classification

The accuracy assessment of the impervious surface classification of the 2005 NAIP Imagery using the Feature Analyst extension for ArcGIS resulted in a total accuracy of 89% after significant manual editing (Table 3). Considering the entire size of the study area (3675.5 km^2) and the resolution (6.1 m) of the final classification this was an exceptional level of accuracy. There were more errors of commission than omission, and overall classification tended to over-classify visible impervious surface. For instance, the grey trunks of dead or dying sands of Hemlocks (*Tsuga Canadensis*), were often classified as impervious, resulting in sections of forested improperly classified. In some instances, the imagery was “washed out” resulting in extremely bright reflectance from features such as barren fields and water bodies. These features were often classified as impervious, as they appeared spectrally similar to the spectral values of impervious surface training sites. Although, Feature Analyst tended to over classify impervious surface, it should be noted that the imagery was collected during the growing season, and some impervious surface was occluded by canopy cover. Due to instances as listed above, the need for manual editing was required; however, the manual editing was very tedious and time consuming.

Table 3. Results of the Impervious Surface Classification Accuracy Assessment.

Minimum Accuracy	Total Accuracy	Percent Error: Omission	Percent Error: Commission
82%	89%	3%	8%

3.2 Accuracy assessment of the RipZone metric

The riparian extents predicted by RipZone were not significantly different from the riparian extents measured in field according to the Wilcoxon Signed Rank Test (Table 4). While the horizontal root mean square error (RMSE) was almost 10 m, this error was only a small percentage of the total distance of the riparian extents analyzed. The mean predicted height above the stream of 1.31 meters indicated the threshold of 5 m above stream used in the RipZone is well above the mean riparian height in the area surveyed. In some instances it was difficult to accurately identify breaks-in-slope in the field, the RipZone metric could aid in better identifying these transitions in future studies.

Table 4. Results of the RipZone Accuracy Assessment.

Statistic	**Result**
Wilcoxon Signed Rank Test (Sig. Level .05)	0.71
Mean Absolute Error	6.65 m
Maximum Absolute Error	28.26 m
Minimum Absolute Error	0.39 m
STD of Absolute Error	7.22 m
Percent Error of Total Distances	0.37%
RMSE	9.73 m
Mean Predicted Height Above Stream	1.31 m

3.3 Linear regression of total watershed impervious surface

The results of the linear regression of SC measured at the watershed outlet and total watershed TPI can be seen in Figure 9. The coefficient of determination (R^2) for watershed TPI and SC was 0.54, which indicates a moderate-strong correlation between impervious surface and in-stream water quality at the watershed outlet. The R^2 values for SC and TPI for the total watershed separated by stream order are reported in Table 5. The results in Table 5 indicate that the total percentage of impervious surface in the watershed has a stronger influence than TPI within individual stream orders; however, TPI in each stream order exerts some influence on water quality at the watershed outlet, with impervious surface in 1st through 3rd order sub-catchments exerting the most. A perceptible break can be observed in the influence impervious surface from the 3rd to 4th to 5th stream orders, indicating that the percent of impervious surface in higher order streams has a lesser influence on water quality at the watershed outlet than lower order streams. One possible explanation for the gradient of impervious surface influence across stream orders could be the relative area drained by each stream order. The watersheds in the study area were dominated by 1st order streams, followed distantly by 2nd and 3rd order streams. As can be seen in Table 6, almost 90% of the total area in study area was covered by sub-catchments of 3rd order streams and below.

Figure 9. Linear regression of watershed TPI and SC measured at the watershed outlet.

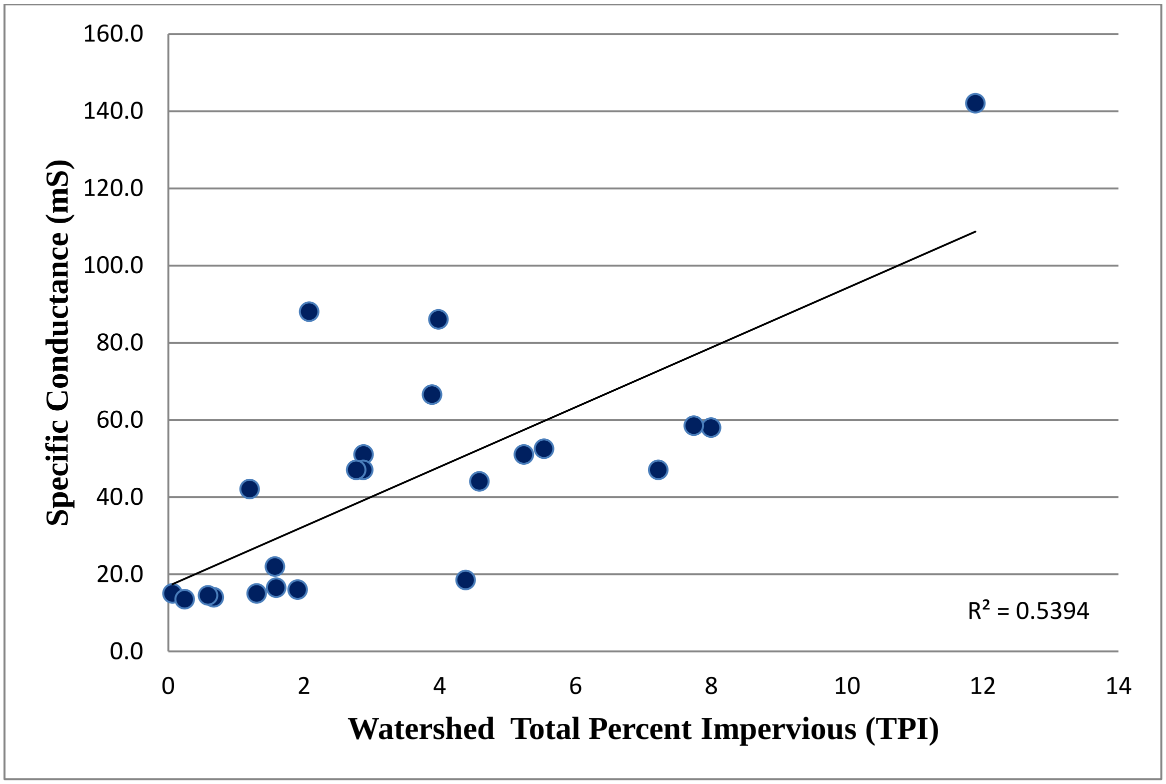


Table 5. The R^2 values for SC and TPI for the total watershed separated by stream order.

1st Order	2nd Order	3rd Order	4th Order	5th Order to Outlet	Watershed
0.26	0.27	0.28	0.19	0.09	0.54

Table 6. Percent of total watershed area by stream order.

1st Order	**2nd Order**	**3rd Order**	**4th Order**	**5th Order to Outlet**
61.5	17.7	9.4	5.8	5.1

3.4 Linear regression of riparian impervious surface

In addition to stream order, topographic setting relative to the stream was also found to affect the influence that impervious surface has on in-stream water quality. Figure 10 shows the results of the linear regression of SC measured at the watershed outlet and total riparian TPI, as calculated using RipZone. The R^2 value for RipZone TPI and SC was 0.52. This R^2 value was only slightly less than the value for watershed TPI, and the value indicates a moderate-strong correlation between impervious surface and in-stream water quality at the watershed. The R^2 values resulting from the combination of stream order and RipZone can be seen in Table 7. The influence of impervious surface is dramatically increased in the potential riparian areas identified by RipZone, with R^2 values doubling and even tripling in some stream orders. The same gradient in impervious surface influence across stream orders can be observed within the RipZone, with 2nd and 3rd stream order RipZone impervious surface almost twice as influential as 4th order streams. Again, this gradient could be attributed to relative area of the RipZone in each stream order as seen in Table 8. It should be noted that the total RipZone area represents less than 10% of the total area in the study area, yet the influence of impervious surface within the RipZone exerts substantially greater influence across all stream orders than TPI within each stream order as a whole.

Figure 10. Linear regression of total Riparian TPI and SC.

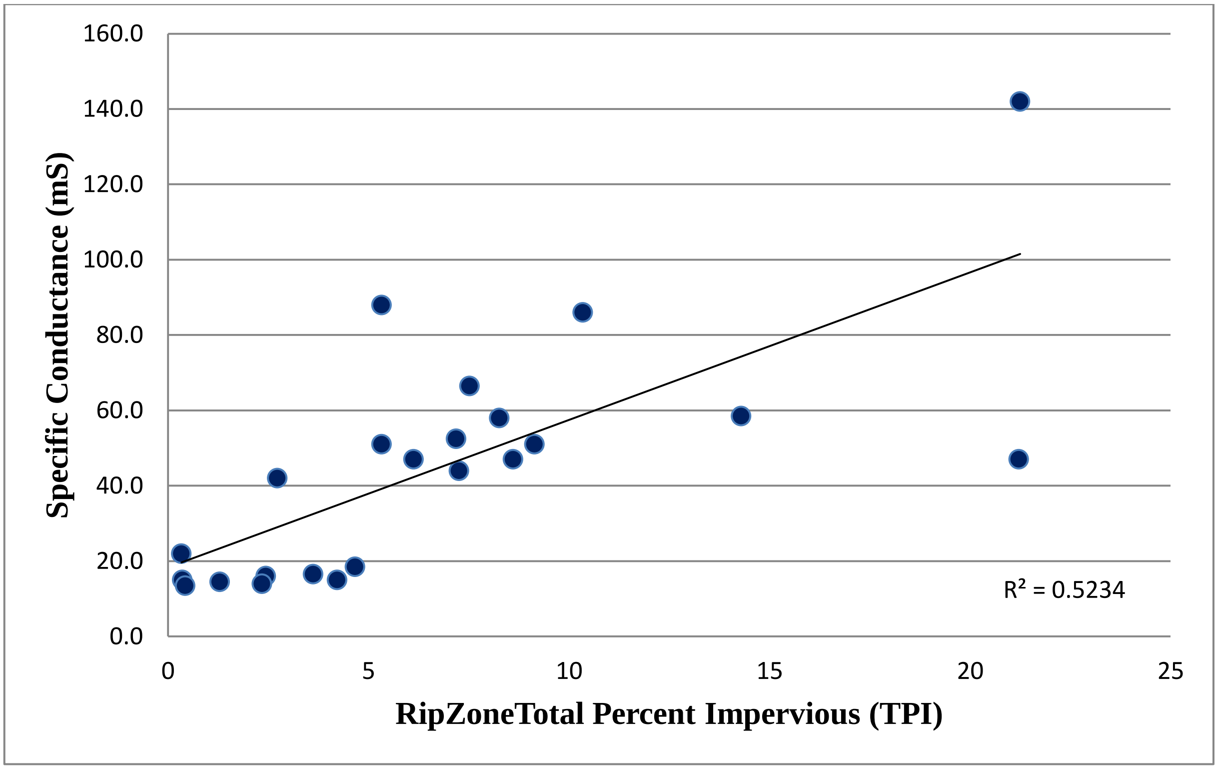


Table 7. The R^2 values for SC and TPI for the total RipZone separated by stream order.

1st Order	2nd Order	3rd Order	4th Order	5th Order to Outlet	Total RipZone
0.49	0.61	0.59	0.33	0.26	0.52

Table 8. Percent of total watershed area within RipZone within each stream order.

1st Order	2nd Order	3rd Order	4th Order	5th Order to Outlet	Total RipZone
4.0	2.0	1.3	0.88	1.1	9.2

Although impervious surface within the RipZone for each stream order has a stronger correlation with water quality at the watershed outlet than total impervious surface within each stream order, impervious surface outside of the RipZone still has an effect on in-stream water quality. As seen in Table 9, non-RipZone areas can have a strong influence on in-stream water quality in 1st and 4th order streams, and equal influence in 3rd order streams; however, the percent of total watershed area outside of the RipZone was much greater. For example, in 1st order streams the area outside of the RipZone account for 96% of the total area of the stream order. If a proportional comparision is made based on R^2 values and the area inside and outside the RipZone, the area inside the RipZone is proximate to the stream and more influential per unit area than the area outside of the RipZone. The slight increase in the influence of impervious surface outside of the RipZone in 1st order streams could potentially be explained by the geomorphology of the study area. In the study area, riparian areas in lower order stream are often narrow and bounded by steep valley walls, as such, the potential buffering capacity of the riparian area relative to steep adjacent hillslopes is limited. In these geomorphic settings, runoff from impervious surfaces on the adjacent hillslopes or flatter areas above the hillslopes may substantially be influencing in-stream water quality. This does not discount the utility of the RipZone as method for identifying riparian areas. However, it does point to a need for future research into the influence of the hillslope runoff on the RipZone delineated riparian areas, and the development of methods for determining how much of the adjacent hillslope that must be protected to facilitate effective riparian buffering.

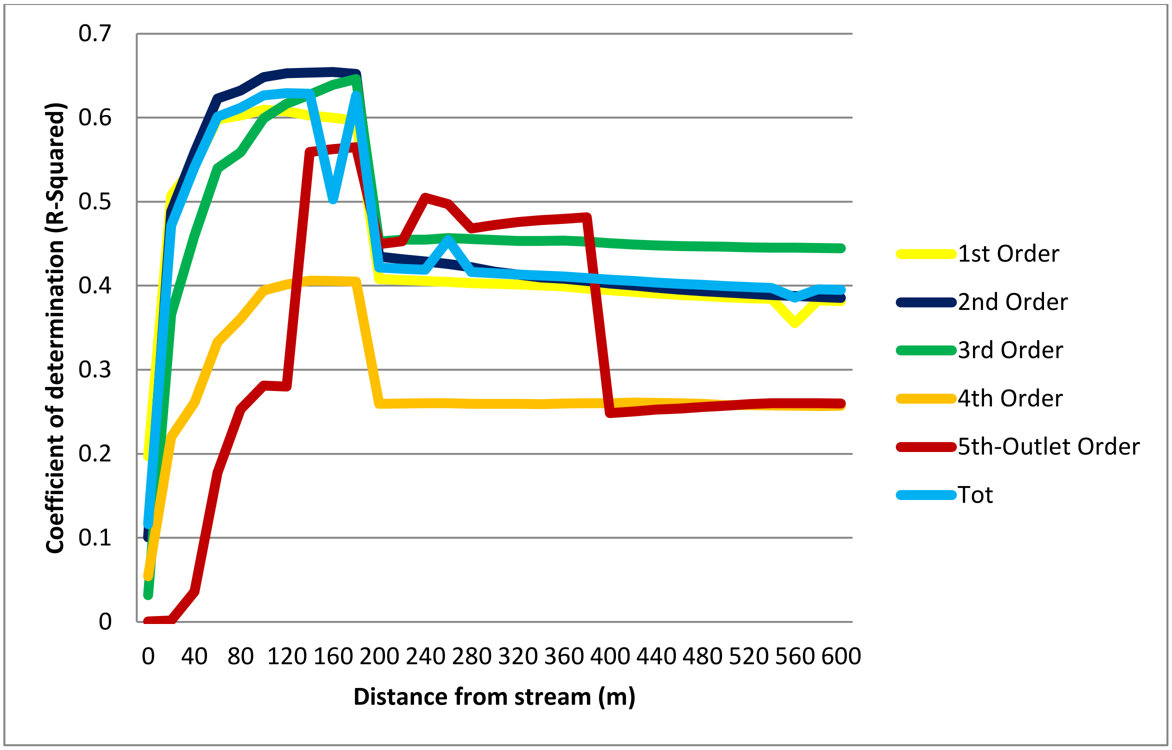
Table 9. The R^2 values for SC and TPI for the total Non-RipZone separated by stream order.

1st Order	**2nd Order**	**3rd Order**	**4th Order**	**5th Order to Outlet**	**Total non-RipZone**
0.51	0.52	0.59	0.38	0.04	0.49

3.5 Linear regression of watershed impervious surface segmented by distance and stream order

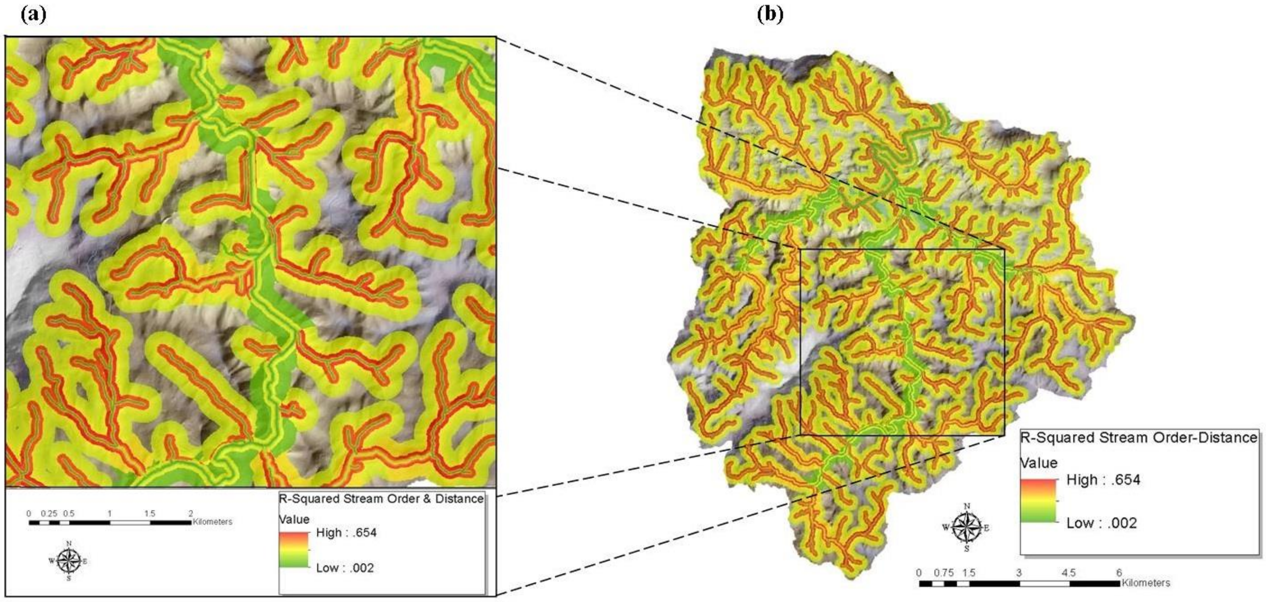
As indicated by the discussion above, proximity to the stream affects the influence of the impervious surface on in-stream water quality; however, it is also clear that the influence extends beyond the RipZone. Figure 11 depicts R^2 values for SC and TPI for each stream order within linear distances between 0 and 182.9 m (0-600ft) from each stream in the study area in 6.1 m (20ft) increments. The same gradient across stream orders can be observed in the vertical separation of the lines, with 1st through 3rd order streams and total watershed being closely grouped. The most interesting point to note is the precipitous drop in the influence of the impervious surface on in-stream water quality at around 55 m from the streams, which occurs across all stream orders. Beyond 55 m from the streams, the influence of impervious surface remains relatively constant to 182.9 m. It should be noted that the steep initial rise in each line can most likely be attributed to the width of the stream, since the distances from the stream were measured from the stream centerline.

Figure 11. Results of linear regression of TPI within 6.1 m distance increments from the stream and SC. The results are separated by stream order.



Utilizing the R^2 values from Figure 11 as a guide, specific areas in the study area could be identified as locations where impervious surface will most likely influence water quality at the watershed outlet. The R^2 values from Figure 11 can be mapped to produce a raster surface illustrating the varying influence of impervious surface on waters quality at the watershed outlet (Figure 12). Analysis of this type and visualizations such as shown in Figure 12, could be a powerful tool for regulators and policy makers, as well as environmentally conscious landowners and developers. Both figures paint a clear picture of where the influence of impervious surface is greatest in Southern Appalachian headwater catchments.

Figure 12. Visualization of the R^2 values from the analysis in Figure 8 map on the associated segment of the Upper South Fork of the New River watershed.



4. Conclusions

This study presented an accurate method for classifying impervious surface and a new method to delineate variable width riparian areas, and examined the influence of impervious surface location on stream water quality, as indicated by measurements of SC. The classification of impervious surface presented in this study was highly accurate. Although the methodology was also very labor intensive, the resulting data set provided an impervious surface classification over a large area, 3675.5 km^2, at a much finer resolution, 6.1 m (20 ft), than is typically available for this type of analysis. Using finer resolution classifications of impervious surface calls into question the comparability of classifications calculated at varying resolutions using a variety of methods. In order to effectively communicate results of impervious surface research, such as those presented by this study, results must be comparable. Future work should investigate the variance of percent impervious surface calculations computed at different scales and using different methodologies.

The RipZone algorithm was shown to be highly effective at predicting the potential extent of riparian areas in watersheds located in the Southern Appalachian Mountains. Impervious surface within potential riparian areas predicted by the RipZone, had a greater influence on water quality when separated by stream order, than total impervious surface within each stream order. The influence of impervious surface outside the RipZone was found to be relatively strong compared to the influence of impervious surface within the RipZone; however, when comparing the relative small are near the stream delineated by the RipZone with the relatively large area outside of the RipZone, the RipZone proved very influential. Future work should be directed at investigating the role that adjacent hillslopes and flatter areas above the hillslopes play in determining the effectiveness of riparian buffering.

Multi-scale factors may play a role in the influence that drainage area exerts on SC at the watershed outlet. When comparing the influence of 1st through 3rd stream order impervious surface with 4th and greater, the relative size of the stream order drainage areas seem to influence the relationship between TPI and SC. However, when comparing the influence between 1st, 2nd, and 3rd order drainage areas, the relative sizes of the stream orders were inversely proportional in terms of their influence on the relationship between TPI and SC. The influence of stream order area needs to be investigated further.

Impervious surface in 1st through 3rd order streams clearly plays a significant role in water quality at the watershed outlet. These headwater streams drain a large majority of the land surface in the Southern Appalachian Mountains, and thereby, account for a large majority of the water volume and contaminants being discharged into higher order streams. Impervious surface within 55 m of the streams and within the potential riparian areas as delineated by the RipZone had a strong influence on water quality, as measured by SC. Focusing development beyond these thresholds and further away from these streams would improve the quality of downstream water.

Conflicts of Interest

The authors declare no conflict of interest.

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Vita

Cameron Carlyle grew up in the mountains of western North Carolina, and served with the US Army overseas from 2001 to 2005, including deployments in support of Iraqi Freedom and NATO operations in Kosovo. He completed a BS in Environmental Studies at the University of North Carolina at Asheville in 2010. He studied Geography at Appalachian State University gaining an MA in Geography in December 2013. His research interests included GIS, geocomputation, headwaters, computer vision, UAVs, and data visualization. Research projects have included generating 3D point clouds from UAVs using computer vision, and well as the collection and maintenance of water quality data in support of the Upper South Fork of the New River Project. He hopes to continue his education in a doctoral program in the near future. Currently, Cameron Carlyle works as a Software Engineer at Locus Technologies in Asheville, NC developing cloud based environmental software solutions.