IMPERVIOUS SURFACE AND WATER QUALITY IN WAKE COUNTY: AN ANALYSIS OF RECENT DEVELOPMENT, IMPACTS, AND OPPORTUNITIES

By

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To Mark and Carrie Petrosky, two of the greatest parents in the world

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Abstract of Thesis Presented to the Graduate School
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By

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Wake County, North Carolina has experienced significant growth over the last twenty years. Between 1996 and 2006 the population of Wake County has grown from 423,380 to 790,007 people. The population is expected to double in the next 30 years. Studies have shown a correlation between urban growth and degraded water quality. This study quantifies impervious surface in selected watersheds within Wake County using Feature Analyst, feature extraction software by Visual Learning Systems, which uses hierarchical learning techniques to extract features based on color, shape, and adjacency. The study determines increases in impervious surface in the study areas and compares these changes with trends in monthly water quality data. Impervious surface rates by land use were produced for the study areas. These rates are compared to impervious surface rates developed in previous studies to evaluate if current development trends remain compatible with these measures. The effectiveness of alternative design techniques, such as green rooftops and pervious pavements are estimated.

This study proves that typical suburban development outside of rapidly growing areas in the North Carolina Piedmont can result in a substantial increase in impervious surface. Results of the water quality data analysis, using a Mann-Kendall test for trend, indicate statistically

significant trends of decreasing water quality in the study areas. The study estimates that 47% of all new impervious surface constructed in the study areas between 1999 and 2005 could have been mitigated by incorporating green roofs and pervious pavements in new development.

CHAPTER 1
INTRODUCTION

Introduction

It is essential for planners, elected officials, and the private sector to understand the impacts local land use decisions and development policies have on water quality. Impervious surface has been linked to degraded water quality, however, there is limited research detailing the amount of impervious surface growth, trends in the built environment, and water quality effects in the Piedmont region of North Carolina and the Southeastern United States. This paper details the use of Geographic Information Systems (GIS) and remote sensing technologies to quantify impervious surface coverage (ISC) in five watersheds in Wake County, North Carolina. Actual, measured, impervious surface coverage rates by land use were compared to ISC rates by land use from a variety of sources that are often used to forecast and estimate impervious surface. The result of this analysis provides insight on current development patterns and trends in the built environment. These results may enable more accurate forecasts of ISC. Growth of impervious surface has been quantified in each watershed and has been compared to historical water quality data in order to provide insight on the relationship between urban growth and water quality in urbanizing areas of the southeastern piedmont.

The Built Environment and Urban Land Use Change

Humans have impacted the natural environment for thousands of years, but never has human induced change occurred at such a scale and at such remarkable speed (Turner and Meyer 1994, p. 4). Between 1982 and 2003 35.2 million acres of the United States have been developed for urban uses (National Resources Conservation Service 2007, p. 5). On average over 1.7 million acres is converted from farm and forest every year. Humans are a primary driver of these changes in land use and land cover.

Land use is an anthropocentric term used to describe how people use a parcel or area of land (Turner & Meyer 1994, p. 5). Land cover is a term generally used by the natural sciences to describe the "physical state of the land," including, "the quantity and type of surface vegetation, water and earth materials" (Turner and Meyer 1994, p. 5). Growth and development on the fringe of suburbanizing America is an example of human induced land use and land cover change. This change has many direct and secondary impacts on the natural environment. Direct effects occur during the land transformation process. These effects include the immediate loss of tree canopy, wetlands, habitat and individual organisms that occurs when land is converted from field to subdivision or forest to shopping center. Secondary impacts occur subsequent to the initial land transformation and are cumulative in nature. Examples of secondary impacts include habitat, water quality, and soil degradation in areas adjacent to the initial land cover change (Turner and Meyer 1994, p. 6).

Urban land use change results in growth of the built environment. The built environment can be defined as, "everything humanly created, modified, or constructed, humanly made, arranged, or maintained (Bartuska 2007, p. 5)." This definition aggregates virtually every square meter of Earth into the built environment, including areas modified by humanity such as once logged forests, fields of grain, and even the atmosphere. For the purpose of this research the built environment will be limited to products and structures that people build, or the "built-up areas" mentioned by Grubler when referring to the area covered by buildings and infrastructure (Turner and Meyer 1994, p. 323). If this more narrow definition of the built environment is used then the human built environment began with the construction of mud huts in the Fertile Crescent to house a population that was beginning to farm. The built environment has increased in size dramatically since its early beginnings.

> “Within the last 10,000 years, man has invented an environment which is almost altogether artificial, with the consequence that he now lives in a world of his own devising (Lenihan and Fletcher 1987, p. 125).”

Settlements begat villages, villages evolved into towns and cities, and cities now connect to form megalopolises—urban landscapes that stretch for hundreds of miles. Only relatively recently has man embarked on such audacious endeavors as the construction of freeways, skyscrapers, and the less enthralling, but cumulatively impressive, network of strip development, warehouses, condos and subdivisions that dominate the American landscape.

It is the nature of typical urban change and occupation that leads to detrimental effects—it is the things that are built—and what people do when they live among them, that disrupt natural systems. Impacts are not limited to cities themselves and range from the minute to the incredible. Land cover change related to urbanization can lead to reductions and fragmentation of wildlife habitat, changes in wind patterns, temperature, climate, and hydrology. It is true that “in the places where man’s activities are most densely concentrated—his settlements—the environmental impact is greatest and the risks of environmental damage are most acute” (United Nations 1974, p. 12). However, the impacts are not restricted to local areas, but can impact natural systems downstream, downwind, and across the globe.

Impacts to hydrological systems can be particularly substantial and can include increases in runoff, erosion, non-point source pollution and reduced low flows (Paul and Meyer 2001, pp. 337-347). Certain aspects of man’s artificial environment—the rooftops, sidewalks, asphalt, brick and lawns individually and cumulatively provoke changes to natural processes. These tangible, quantifiable facets of the built environment combined with other side effects of modern life (i.e. auto emissions, sewage effluent, nonpoint source pollution, etc.) result in reduced water and air quality.

The hydrological cycle involves evaporation, rainfall, canopy interception, stemflow, overland flow, infiltration, and groundwater recharge. In urban areas this cycle is altered. Instead of tree canopy and groundcover, rainfall strikes concrete, brick and asphalt. These textures and surfaces, products of human ingenuity, are inventions derived from organic products. Whether these products are "natural" is debatable. It cannot be debated that these materials and other types of impervious surface are ubiquitous in cities and suburban areas. It has been proven that these man-made surfaces interfere with the hydrological cycle by altering the processes of interception, stemflow and overland flow and increasing the volume and speed of runoff, while reducing rates of infiltration and groundwater recharge. In addition to quantity related effects, growth in impervious surfaces has been correlated with decreases in water quality (Paul and Meyer 2001, Arnold and Gibbons 1996). Increases in runoff and degraded water quality can cause negative economic and public health impacts to urbanizing communities (SCS 1975, p. 1-1).

Though impervious surface has been directly linked to water quality degradation, planners do not usually measure existing impervious surface or project the impervious surface potentially resulting from the build out of land use plans (Brabec et al.2002, p. 500). This is unfortunate, as it is essential to quantify changes in and the distribution of, impervious surface in growing areas, in order to better understand how land use decisions result in changes in the built environment that may negatively impact the natural environment. As noted by Morisawa and LaFlure (1979), "stream hydrology and function are dependent on five variables: climate, geology, soils, land use, and vegetation (Brabec et al.2002, p. 500)." Accordingly it is important for planners to understand the impacts local land use decisions are having on the two variables that they can influence: land use and vegetation.

Urban growth and development are not necessarily the harbinger of environmental degradation. Indeed, there are instances where ecosystems have been improved in tandem with development. It is not necessarily simply human occupation that leads to significant problems. It is the responsibility of society and those that plan, design, and construct the built environment to reduce impacts on the natural environment. This will become more important if population projections hold true and the cities of the world absorb an additional three billion people.

Study Area

Land use change and resulting changes in the built environment have been particularly profound in the southeastern United States. According to the U.S. Census Bureau, the South Atlantic division, composed of Deleware, D.C., Florida, Georgia, Maryland, North Carolina, South Carolina, Virginia and West Virginia, has added over 31 million people between 1960 and July of 2007. This increase is larger than any other Census defined division.

North Carolina has doubled in population between 1960 and 2007, swelling from 4.5 million people to over 9 million. A disproportionate amount of this growth has occurred in the piedmont region and particularly the metropolitan areas in what has been called North Carolina's Urban Crescent. The Urban Crescent, as shown in Figure 1-1, is a number of urbanized counties and metropolitan areas that begins in the city of Charlotte located in Mecklenburg County, and then continues northward along I-85 to Greensboro in Guilford County, then eastward along I-40 to Durham and Raleigh in Wake County. Railroad networks once connected this area of the state. These rails were used to transport tobacco, cotton and textiles. The rails remain, but have been augmented by interstates which now move commuters to hubs of economic activity. This area has also been called the "Rich Crescent" and North Carolina's Main Street.

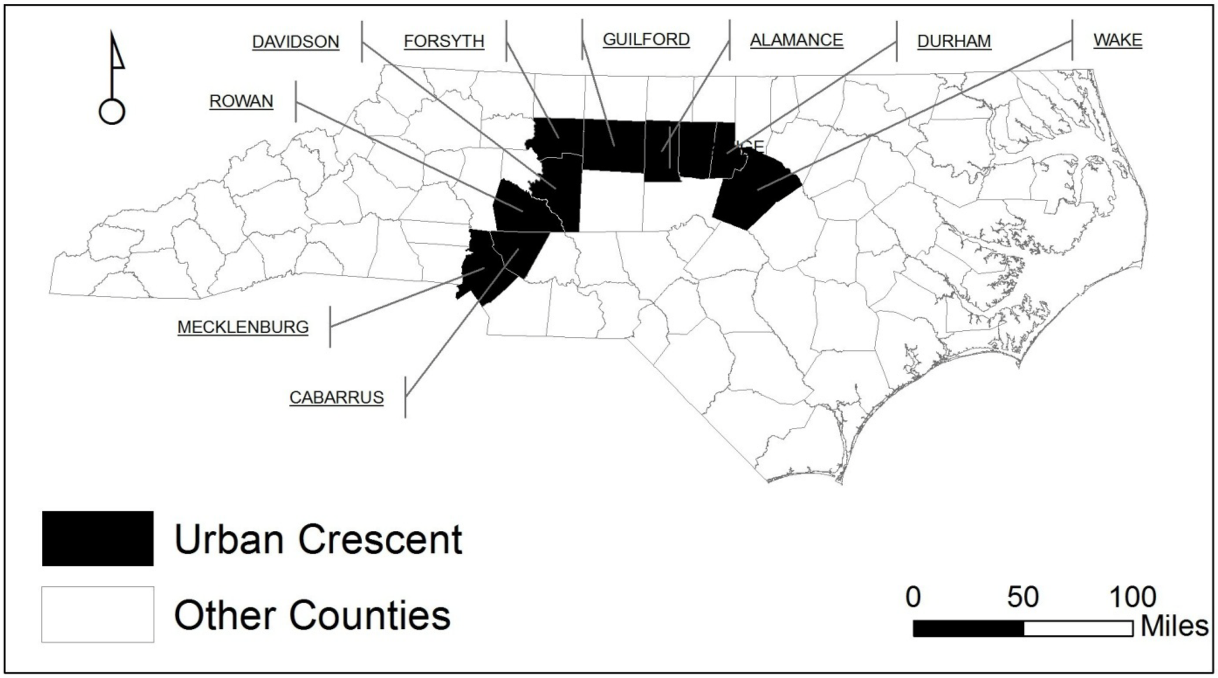

Figure 1-1. Map of North Carolina's Urban Crescent

Since 1980, the ten counties that compose the Urban Crescent, Alamance, Cabarrus, Davidson, Durham, Forsyth, Guilford, Mecklenburg, Orange, Rowan, and Wake County, have grown by nearly 1.6 million residents. Fifty percent of North Carolina's population growth between 1980 and July of 2007 has occurred in these counties, which comprise only 10% of the state's land area. Wake County, which anchors the eastern end of the Urban Crescent, has experienced rapid growth during the last twenty-five years. Wake County also forms the eastern edge of the Research Triangle, composed of Raleigh, Durham and Chapel Hill. Home to a number of major universities, the Research Triangle Park, and a benign climate, the area has experienced significant in-migration. Spurred by a growing economy and residential development in bedroom communities outside of Raleigh, the county has added 204,466 residents between 1990 and 2000 (Wake County 2005, p. 1). Since 2000, Wake County has grown from 627,846 residents to its present population of 790,007 (Wake County 2005, p. 1 and North Carolina State Demographics 2007).

Conceptual Model

Land use decisions are driven by polices of local governments and regional economic realities. Demand, be it for "McMansions" or donut shops is perceived and enacted upon by the private sector. Anthropogenic change, resulting from this demand is marked by land cover change and an increase in the built environment. Development in the rapidly urbanizing area on the urban/rural fringe of Wake County is driven by growth in residential subdivisions and is followed by commercial development along major arterials. Suburban growth in the study area has been enabled by the continued public investment in transportation infrastructure, primarily focused on increasing capacity on arterials and reducing commute times through the construction of major highways. Increases in impervious surface, stream crossings and road densities are products of this growth. Currently 63% of the watersheds in Wake County are considered impaired or degraded (Wake County 2003, p. ES-6). It is anticipated that drivers of development have led to increases in impervious surface coverage within the study watersheds and has contributed to degraded water quality (See Figure 1-2). Information from this study will provide a better understanding of the relationship between the built environment and the natural environment.

Existing rates of average impervious surface coverage, including those available from studies conducted by the Soil Conservation Service (SCS), are regularly used to estimate and forecast ISC in watersheds. Due to the changes in regional development patterns and trends, these rates may not provide an accurate representation of average ISC rates by land use in Wake County. Accordingly, SCS ISC rates were compared to those measured in the study area. This methodology is suggested as being critical to ensuring the accuracy in impervious surface studies (Brabec, Schulte, and Richards 2002, p. 503). The results of this study will allow for the forecasting of impervious surface in Wake County to occur based on coverage rates based on local data. Once change in impervious surface coverage is determined in the study areas it can be estimated how much impervious surface could be avoided by using innovative designs such as pervious pavements and green roofs.

Objectives

This research has specific aims:

1. Determine how many square feet of impervious surface is attributable to new development in the study areas.

2. Compare established rates of average impervious surface by land use to measured impervious surface rates by land use in development that has occurred between 1999 and 2005.

3. Determine how innovative design techniques can employed and encouraged to decrease impervious surface in new development (i.e. pervious pavement and green roofs).

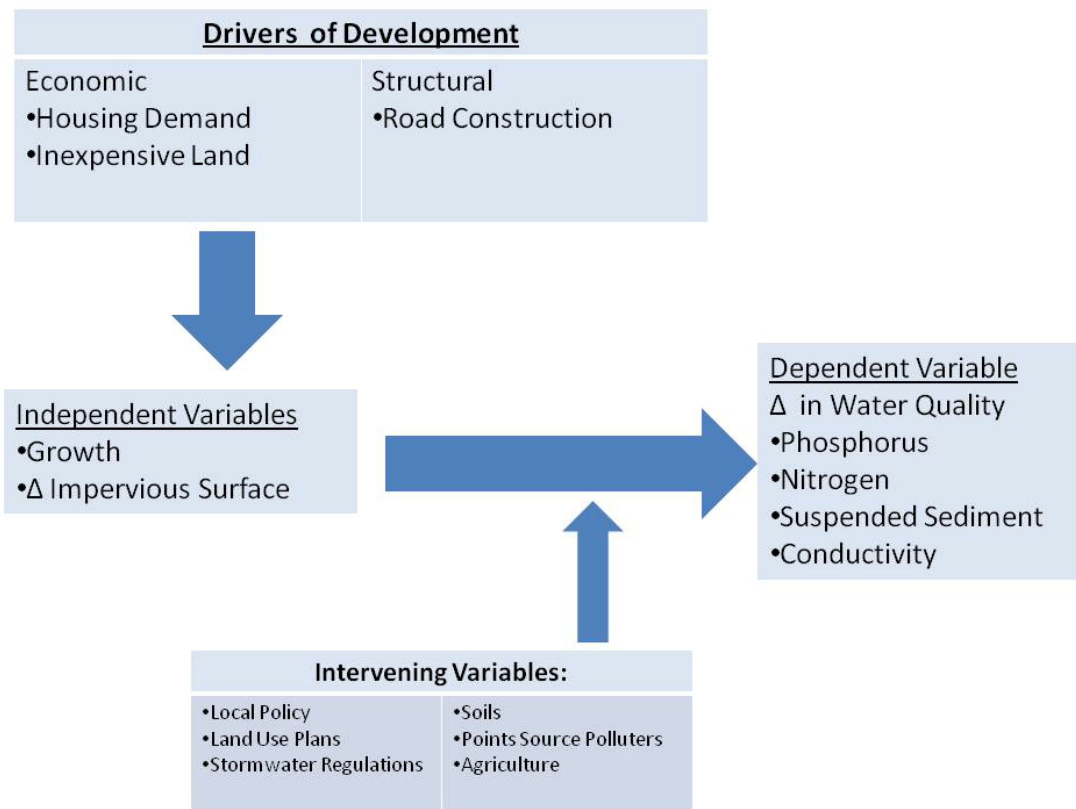

Figure 1-2. Conceptual model

CHAPTER 2
LITERATURE REVIEW

Trends

It has been estimated that there is 1454 million km^3 of freshwater in the global hydrosphere (Roger 1994, p. 234). Of this seemingly infinite amount, only $0.6189e^{-8}$% is readily available for human use (Ibid., 236). As of 1970, it was estimated that 3,500 km^3 of the 9,000 km^3 of available freshwater was utilized and 5,800 km^3 was polluted by human action (Ibid., 234). Between 1970 and 2003 the world population has grown from 4.07 billion to 6.465 billion people (United Nations 2005, p. 4). World population is predicted to peak at 9.22 billion in 2075 (World Pop to 2030 United Nations 2004, p. 1). Levels of use will rise as the developing world adopts more modern lifestyles. Freshwater will become more important as the realities of population growth and consumption trends become apparent. On a local level, in Wake County, pending population growth jeopardizes water supplies as well. Falls Lake was added to EPA's list of impaired waters in 2008 due to excessive nutrients and algal growth (Rawlins 2009). Growth and development, combined with wastewater outfalls from municipalities upstream from the lake have contributed to elevated nitrogen and phosphorus levels. This may force municipalities in Wake County to spend more on water treatment. The proposed Little River Reservoir in Eastern Wake County may be destined to join Falls Lake on the list of impaired reservoirs. Wake County commissioners recently rejected a proposal to limit residential development adjacent to the proposed reservoir to lower densities than currently allowed adjacent to Falls Lake (Bracken 2009).

Urban Growth in the U.S.

Urban growth was spurred by the industrial revolution and further enabled by the development of new modes of transportation. The horse and buggy gave way to railroads and the street car, both of which were replaced with the automobile. These new transportation technologies allowed cities to grow outward. Housing followed expanded transportation networks, strip development of commercial establishments tagged along. The resulting auto-oriented society results in a development pattern that follows arterials with little regard for habitats or hydrological features.

Urbanization Impacts on Hydrology

As early as the 1960s the United States Geological Survey (USGS) was studying the hydrologic effects of development (Rome 2001, p. 192). Scientists working for the agency found that there was a, “dramatic increase in flood potential in the wake of suburban growth (Ibid., 194).” Studies showed that as land uses changed from undeveloped to developed, the volume of runoff could quadruple and the speed of runoff also increased (Ibid.). In addition to increases in flows, urbanization can cause physical changes in the size of channels in streams (Hammer 1972, p. 1540). Thomas Hammer studied watersheds outside of Philadelphia and concluded that land uses within and adjacent to streams can have significant impacts on the structure of stream channels. The study found that the presence of streets, sidewalks, and contiguous impervious surfaces exceeding one acre can cause the enlargement of stream channels and, thereby cause, “a serious reduction in the aesthetic and recreational value of the stream (Ibid., 1530).” In 1975, the Soil Conservation Service (SCS), part of the U.S. Department of Agriculture detailed the impacts of urbanization on hydrology in Technical Release No. 55 entitled, “Urban Hydrology for Small Watersheds.” The SCS acknowledged that, “As population density and land values increase, the effects of uncontrolled runoff become an economic burden and a serious threat to the health and well-being of a community and its citizens (Ibid., 1-1).” Urbanization reduces the time of concentration, or the time it takes for water to pass through a watershed from point of origin to outlet (Ibid., 3-1). Increases in impervious surface lead to higher peaks and lower baseflow (Paul and Meyer 2001, p. 335). This is due in part to channelization and the construction of conveyance structures and partly due to reduced depressional storage from predevelopment grading.

Impervious Surface and Water Quality

The construction of new homes, roads, driveways and parking lots increases impervious surface, which, has been shown to serve as a key indicator for the health of aquatic ecosystems (Arnold and Gibbons 1996). Impervious surface affects the hydrology of a watershed, the geomorphology of stream beds, temperature, fish populations, macro invertebrates, microbes, algae, and macrophytes (Paul and Meyer 2001, p. 337-347). Impervious surface acts as a conduit through which pollutants are injected into surface water. In a sense, the impervious surface acts as an enabler to non-point source pollution. Non-point source pollution, as opposed to point source pollution, is described by the Environmental Protection Agency as pollution composed of, “natural and human-made” pollutants carried by runoff and deposited in bodies of water (EPA 2008). Stormwater runoff can carry sediment from farms and cleared land, chemicals and fertilizers from residential lawns, and toxins from streets or industrial sites to streams, wetlands, lakes, rivers, estuaries and oceans downhill or downstream. Nutrients, toxins and sediment disrupt aquatic ecosystems and contribute to degraded water quality. Non-point source pollution is the number one threat to water quality in the United States (Arnold and Gibbons 1996, p. 245). The waters of the Southeastern states are in imperiled due to anthropocentric causes. As of 1998, 45% of the rivers assessed in the Southeast were found to be impaired (Potter et al.2004, p. 62). It has been found that “between 1988 and 1998, 70% of stream degradation in the southeast was caused by nonpoint source pollutants (Ibid.).”

The abundance and diversity of fish and macro invertebrate populations is harmed as ISC increases (Paul and Meyer 2001). Certain species of fish and invertebrates are more susceptible to increases in urbanization and impervious surface than others. A study in the Tennessee River drainage system in Western North Carolina and Tennessee found that rare endemic fish species decreased in abundance as development increased and forest cover decreased (Scott 2006). The Maryland Department of the Environment found that water temperature of Piedmont streams increased as total percentage of impervious surface increases (Galli 1990, p. 28). Higher temperatures were determined to be the cause of declining native trout populations throughout headwater streams in the Maryland Piedmont (Ibid.). The study found that impacts from impervious surface were noticeable even in lightly developed watersheds with total impervious surface coverage of 12% (Ibid.). For more developed watersheds, the increase in average temperature can be substantial. In the Maryland study researchers found that with a watershed with over 60% impervious surface the average temperatures can be 4-15% higher than a similar undeveloped watershed. It should be noted that the extent of riparian vegetation was also found to have a significant impact on temperatures (Ibid., 44). Impervious surface coverage also has significant impacts on species other than much sought after trout and other gamefish. Invertebrates, the ubiquitous and essential prey of charismatic aquatic denizens, are also negatively impacted by impermeable surfaces. The Maryland study found that stoneflies (Plecoptera) and caddisflies (Trichoptera), two favorite foods of trout, were more abundant in habitats that enjoyed cooler waters-habitats more likely to occur in watersheds with limited development. A study of 20 catchments in Maine found that species richness of insect and invertebrate prevalence “showed an abrupt decline” as percent total impervious surface area (PTIA) rose over 6% (Morse et al.2002, p. 95). Indeed, there are many studies that have shown that urbanization decreases density and diversity of aquatic insects (Ibid., 96).

The Southern United States has the, “fastest rate of urbanization of any region in the country (Scott 2005, p. 302). Urbanization’s effect on water quality in North Carolina’s piedmont is well documented. A study, funded by the North Carolina Division of Environmental Management’s Water Quality Section and the United States Geological Survey’s Water Resources Division monitored the effect of land use on water quality in three streams in the piedmont. Water quality testing and biological sampling were conducted in streams where land use was mostly forested, agricultural, or urban. The study found that an urban stream, Marsh Creek, in east Raleigh, had the highest levels of suspended sediment, and the highest recorded levels of metals (Lenate and Crawford 1994, p. 185). The study also found that Marsh Creek had the lowest percentage of gamefish of all of the streams sampled (Ibid., 191). In addition, the study found that fish and invertebrate species richness, biomass and presence of intolerant species were lowest in the urban stream. Salamanders, considered a species which indicates water quality, have been shown to decrease in prevalence as impervious surface increases from 0 to 26% (Miller and Hess 2005, p. 12). The 2004 study of 43 streams in Wake County found that the amount of impervious surface in a watershed had negative effects on larval E. cirrigera, a species of salamander (Ibid.).

Impervious Surface as an Indicator

Studies suggest that levels of degradation correspond to ranges of impervious surface ranging from 0 to 10% (Sensitive), 11-25% (Impacted) and above 25% (Non-supporting) (Schueler 2000). This was recently revised from a previous classification range which classified 0-10% as Protected, 10-30% as Impacted and greater than 30% as Degraded (Arnold and Gibbons 1996). Arnold and Gibbons (1996) argue that years of scientific inquiry has firmly established impervious surface coverage is a “reliable and integrative indicator of the impact of development on water resources (246)."   This combined with the fact that impervious surface is measurable, makes it an ideal proxy for gauging water quality in an urban environment.

Measurement Techniques

Impervious surface is a "simple attribute" that is easy to measure and forecast (Barbec et al.2002, p. 500). Impervious surface measurement techniques can range from in situ measurement at the site level, to interpretation of aerial photos, to interpolation of impervious percentages from satellite imagery or other land use/land cover inventories.

Two types of impervious surface area have been measured. Total impervious area is a measure of all impervious surfaces in an area. Effective impervious surface area is a measure of only those areas that are connected hydraulically to drainage channels in the landscape, or connected to other impervious surface which is connected to the drainage network (Alley and Veenhuis 1983, p. 313). Both measures have been found to be related to water quality degradation. Measurement of effective impervious surface has been found to be "labor intensive and inherently subjective," accordingly it is not used in this study (Ibid., 314).

Estimation of total impervious surface is possible based on a number of methods. Researchers have developed estimation techniques based on readily available census information, including population, households and employment (Brabec et al.2002, p. 503). Average impervious surface coverage rates have been measured by land use category in a number of studies (Arnold and Gibbons 1996, 247). The Soil Conservation Service (SCS) was among the first to develop average impervious surface rates by land use. They found that impervious surface in residential uses varied significantly based on lot size and that industrial uses typically had the most impervious surface, only exceeded by commercial and shopping center land uses (Ibid.). This study was updated in 1986. A summary of these rates and rates from additional studies are shown in Table 2-1. Studies in Northern Virginia and Denver found residential ISC rates generally lower than the SCS study. The ISC rates for commercial and industrial parcels in both the Northern Virginia study and the Denver study were close to those published in the 1986 SCS report.

Table 2-1. Impervious surface percentages by land use

Land Use	Dwelling Units/Acre	Source: NVPDC, Northern Virginia (1980)	Source: SCS (1986)	Source: SCS (1975)	Source: Alley and Veenhuis, Denver (1983)
Low Density Residential	<0.5	6	-	-	-
	0.5	-	12	-	-
	1	12	20	20	15
Medium Density Residential	2	18	25	25	15-26
	3	20	30	30	26
	4	25	38	38	26
High Density Residential	5-7	35	-	-	39
Townhouse	>7	35-50	65	65	60
Industrial	--	60-80	72	75	60
Commercial	--	90-95	85	85	88
Shopping Centers	--	-	-	95	--

Sources: Stormwater Manager's Resource Center 2009, SCS 1975, SCS 1986, Alley and Veenhuis 1983, p. 314

Rates by land use can be used to estimate impervious surface if an accurate land use inventory is available. However, it has been suggested that land use patterns have changed significantly since the development of standard percentages and the collection of new rates based on local data may provide a greater level of accuracy (Brabec et al. 2002, p. 503).

It is important to note that studies of impervious surface have not been limited to studies of total impervious surface, but also delve into quantifying the types of impervious surfaces in developments. In 1995, the City of Olympia, Washington measured impervious surface on 11 sites that were classified as high density residential, multi-family residential or commercial. The study detailed area associated with different elements of the built and natural environment of each site, including sidewalks, streets, parking/driveways, roofs, lawns/landscaping, and open space (Arnold & Gibbons 1996, p. 248). The amount of impervious surface attributable to these elements varied based on the type of land use. For instance, in residential development with densities between 3 and 7 dwelling units per acre, rooftops accounted for 15% of total impervious area, or 37.5% of the total site area, whereas for residential development with dwelling units densities between 7 and 30 units per acre, rooftops accounted for 17% of the impervious surface, and 35.4% of the total site area. The study found that road related impervious surface accounted for more than 60% of all impervious area (Ibid.).

Remote sensing technologies have enabled the use of satellite imagery to measure urban sprawl and changes in the built environment. Physical properties of land cover types result in unique spectral signatures that can be classified using various remote sensing software packages. The availability of higher resolution (>1m) satellite imagery from IKONOS, QuickBird, and Worldview satellites as well as aerial photography has enabled the extraction of features or objects. Until recently this was a manual process that took a great deal of time (ERDAS 2008, 11). The time and expense of manual digitization typically prevented large scale remote sensing studies using aerial photography. Methods of interpreting aerial photography have become more sophisticated over the years. Feature Analyst, an extension for ArcGIS, created by Visual Learning Systems, offers an interface that allows users to manually digitize training samples. The software uses the training samples and hierarchical learning to develop algorithms that determine the presence of desired features based on the shape, color, and adjacency of the features. The software allows users to refine the methodology to extract features using an iterative process of training and correcting the extraction procedure. Feature Analyst has been used to extract impervious surface inventories using high resolution aerials with accuracies over 90% (Miller and Hess 2005, p. 10). It has been shown that feature extraction with Feature Analyst is 5 to 10 times quicker than manual digitization (O'Brien, p. 1). The availability of up to date high resolution aerial photography combined with the availability of the Feature Analyst extension can potentially enable researchers to accurately quantify impervious surface over large watersheds.

Statistical Analysis of Water Quality

Urban growth, and particularly impervious surface, has been proven to have detrimental effects on certain aquatic species in Wake County (Miller and Hess 2005). This study attempts to clarify whether impervious surface growth has had measurable detrimental effects on water quality as measured in the study areas.

Statistical analysis of water quality data presents a number of problems. Significant issues analyzing water quality data include seasonal variations in the data, the presence of outliers, or exceptionally high or low values, and missing values (or values below the reporting limit), and the non-parametric nature of the data, which is primarily due to the lack of negative values, positive skewness and outliers (Helsel and Hirsch 2002, p. 2).

The mean and median of data are two common methods for measuring the distribution and central tendency of data. The mean, or average, is calculated by summing all data values and then dividing by the sample size. The mean is heavily influenced by, "the presence of, or to changes in the magnitudes" of outliers (Ibid., 5). The median is defined as, "the central value of the distribution when the data are ranked in order of magnitude (Ibid., 5)." The median is much more resistant to outliers or extreme instances of large or small values (Ibid., 6). A trimmed mean is calculated by removing high and low values in a dataset and calculated the mean based on the remaining values (Ibid., 7). A common method for calculating a trimmed mean, also known as the “25% trimmed mean” is accomplished by calculating the mean after removing 25% of highest values and 25% of the lowest values (Ibid.). A study published in 1997 of the River Tweed, located on the border of England and Scotland, used a 5% trimmed mean to exclude outliers in water quality data collected on a variety of nutrients over a ten year period (Robson and Neal 1997, p. 176, 190).

Trend detection in water quality data is possible through the use of the Nonparametric Mann-Kendall test. This test for trend was first by Henry B. Mann in 1945 in a paper entitled “Nonparametric Tests Against Trend” published in the journal *Econometrica*. The test ranks datasets against one another and uses time as the x variable when determining the significance of Kendall’s tau (Helsel and Hirsch 2002, p. 326). Mann proposed that a benefit of the test was to allow for the detection of trends even when, “quantities cannot be measured, as long as it is possible to rank them (Mann 1945, p. 247).” Mann thought it would be helpful in instances where measures of sensory experiences, such as pleasure or pain could not be directly measured (Ibid.). The test has since been used by researchers attempting to determine trends in time series water quality data (Sheng 2001, p. 254).

The Seasonal Mann Kendall test, as suggested by Hirsch et al.(1982), improves results of the Mann-Kendall test by accounting for seasonal changes in water quality data. The Seasonal Mann Kendall test was used in this study; however, the results are not reported due to the fact that they were nearly identical to the results of the Mann Kendall test.

Alternative Stormwater Design

Negative impacts on hydrologic systems and water quality can be mitigated using alternative stormwater design techniques. Stormwater has long plagued human settlements. Traditional methods of stormwater engineering sought to herald stormwater offsite as soon as possible (Randolph 2004, p. 434). This was accomplished by the construction of curb and gutter, and by channelizing existing drainage pathways. It has since been proven economical and more environmentally friendly to retain stormwater, closer to where it falls on the landscape using techniques that include rain gardens, rain barrels, and larger cisterns fed by rainwater falling on roofs and other surfaces (Forman 2005, p. 329)." Stormwater management occurring in the headwaters of drainage networks, or "headwater management," is preferable to the traditional practice of "outlet management," where costly engineering projects, in the form of large scale retention basins and sewer systems are the norm. An intermediate form of stormwater management known as "enroute management" is more likely. In this form of stormwater management water is detained temporarily in many dispersed basins, stormwater wetlands, and other structures that allow infiltration to occur enroute (Ibid., 329).

New technologies and design alternatives at the site and neighborhood level may be aid in reducing impervious surfaces and their effects on water quality and aquatic ecosystems. Among the site specific technologies that promise to make headwater and enroute management of stormwater more feasible are green roofs and pervious pavements.

Low Impact Development

Low impact development (LID) is a general term used to describe a development philosophy that seeks to minimize impacts on the natural environment. Stormwater management is a key element of the LID approach. Traditional stormwater management practices focus on controlling runoff for a design storm, usually a 1, 10 or 100 year 24 hour storm (Randolph 2004, p. 436). LID attempts to limit runoff volume, discharge, frequency and duration to predevelopment conditions for all storms (Ibid., 437). LID practices include preserving vegetative cover, limiting impervious surfaces, preserving multiple drainage pathways, maintaining groundwater recharge and a general shift from outlet management toward integrated stormwater design. LID is an example of an alternative design technique for neighborhoods that can potentially mitigate negative hydrologic effects of development.

Green Roofs

Although green roofs have been in existence for millennia as elements of the vernacular architecture of Scandinavia and parts of the Middle East, they have recently grown in popularity in cities all over the globe (Dunnett 2005, p. 15, 21). Frank Lloyd Wright, Walter Gropius, and Le Corbusier were among the first architects to employ roof gardens in the modern age (Ibid., 14). Germany serves as the epicenter of green roof technology in the modern world (Ibid., 22). Early research into the merits of green roofs began in the 1950s and continued in the 1960s and 1970s (Ibid., 19). This research combined with a growing interest in environmental and economic benefits of green roofs has led to many governments in Germany and the rest of the world to embrace and encourage the construction of green roofs. Green roofs have many environmental benefits, including increasing opportunity for biodiversity and urban habitat, reducing quantity and quality of stormwater runoff, filtering urban air of pollutants, reducing urban heat island effect, and reducing noise pollution (Ibid., 41-67). Economic benefits of green roof technologies include increased roof life and reduced energy costs through improved insulation (Ibid., 68-76). In addition to economic and environmental benefits, green roofs can provide passive recreation opportunities and provide aesthetic benefits to urban residents often surrounded by concrete and steel.

Researchers in the U.S. have noted benefits of rooftop gardens since the 1970s. In a publication in 1975, the SCS noted the benefits of rooftop gardens included reduction in runoff, decreased noise levels, benefits to wildlife and an improvement the aesthetics of roofs (SCS 1975, p. 7-3). The SCS also pointed out disadvantages of rooftop gardens including in increased loadings on the structure and increased maintenance and installation costs (Ibid.).

Green roofs can have a significant impact on reducing the negative hydrological impacts of impervious surface growth. The amount of stormwater retained by green roofs varies between type of roof, climate, and season. In general, studies show that green roofs can reduce runoff between 40-60% (Dunnett 2005, p. 58). In addition, the quality of stormwater runoff entering aquatic ecosystems can be improved by implementing green roof technology. It has been found that green roofs can reduce nitrate loadings in streams and rivers, which can cause algal blooms (Ibid., 61). It has also been found that green roofs can increase the pH of runoff, which may counteract the impacts of acid rain (Ibid). If employed on a wide scale, green roofs could potentially counteract the increases in runoff due to increases in impervious surfaces. A study of Brussels predicted that runoff could be decreased by 2.7% if 10% of the buildings in the City were retrofitted with vegetated roofs (Ibid., 60). Although green roofs address some of the negative impacts of impervious surfaces, they are not a panacea to the negative impacts of urban development. Reducing runoff and water pollution from rooftops is beneficial; however, reduced infiltration and subsequent groundwater recharge resulting from increased impervious surface will not be addressed by constructing and/or retrofitting existing buildings with green roofs.

Pervious Pavements

A significant portion of the impervious surface in urban areas is due to paved portions of developments including streets, driveways, sidewalks, and paved plazas. As previously mentioned, a study by the City of Olympia, WA found that road related impervious surface accounted for more than 60% of all impervious area (Arnold & Gibbons 1996, p. 248). Pervious pavement has been identified as a measure that is effective at mitigating negative hydrological effects of urbanization (SCS 1975, p. 7-2). Pervious pavements can reduce runoff by increasing the amount of infiltration and alternatively, delay runoff by retaining stormwater in cisterns and other catchment devices (Ibid.). Pervious pavements are created by processes that have been developed whereby concrete and asphalt are created using aggregate that is larger than traditional methods. This combined with a lack of sand provides for a porous material that water can percolate through at relatively high rates (National Ready Mix Concrete Association 2009) This pervious pavement lacks the strength of traditional pavements; however it can be substituted for traditional pavements in many circumstances where high traffic and heavy loads are not the norm.

Headwater Streets

Transportation related components of the built environment are ubiquitous. Everywhere humans go, they are accompanied by paved pathways. This is no doubt due to our reliance on, and the adoption of, the automobile as our primary mode of transport. Richard Forman, in *Road Ecology*, claims road surfaces make of 10 to 20% of the suburban land cover and over half of the ISC (2003). This is corroborated by the City of Olympia study in 1994 that found that transportation related ISC made up 63-70% of total impervious surface (Schueler 1995, p. 19).

Disruptions caused by road construction and maintenance can lead to degraded aquatic ecosystems. Roads have numerous hydrological effects including the direct effect of filling wetlands, changing flow patterns of surface water, increased erosion and deposition, stream channelization and a loss of riffle and pool structure (Forman 2003, p. 229). Roads are one of the largest contributors to non-point source pollution (Ibid., 248). It has been suggested that reducing the width of residential feeder roads would have a significant impact on ISC (Ibid., 251). Advocates for narrow, “headwater streets,” or streets that serve small numbers of residential units and have low traffic volumes claim that roads in many residential areas are overbuilt.

> "Road networks resemble stream systems in many respects. For example, they are connected in a hierarchial network that is quite similar to stream order. Small access streets generate the traffic that is routed to collector streets that in turn connect with arterial roads, that ultimately feed freeways. Like streams, the capacity and width of roads tend to increase in a downstream direction. And just like headwater streams, local streets comprise the majority of the road length of the entire road network in a community. Recent studies indicate that they represent between 50 and 65% of the length of the entire road network (Carrol County 1992)(Schueler 1995, p. 129-130)."

AASHTO requires residential streets to be 26 ft minimum width, and ITE recommends 22-35 ft, depending on dwelling unit density, terrain and on street parking (Ibid., 131). Schueler recommends lower design speeds, more limited right-of-way, no curb and gutter, reduced culdesac radii, and reduced width (Ibid.). Recommended width is based on anticipated ADT with the following thresholds; >100 ADT-16 ft, 100-500 ADT-20 ft, 500-3,000 ADT-26 ft, >6du/acre-32 ft (Ibid.). Average daily traffic (ADT) was analyzed and it was found that headwater street design could be employed to different degrees depending on traffic volume. Streets could be 16 ft for roads that serve less than 100 cars per day and 22 to 28 ft if ADT was between 1,000 and 3,000 (Ibid., 135).

The City of Olympia plans to reduce impervious surface in new development by 20%. Reductions will be made by reducing the size of parking areas, reducing street widths required in residential development, retrofitting culdesacs with vegetated depressions that will hold stormwater, constructing narrow sidewalks where there is limited use, building sidewalks on only one side of the street, building taller and clustering development.

Summary

More people are going to be living in urban areas. Human activities that result in substantial land cover change such as timber harvesting, agriculture and urban development can be contribute significantly to the impairment of surface waters. Given this reality, it is imperative that the amount of water that is rendered useless due to anthropogenic pollution be minimized by implementing policies that limit negative effects on water quality. Studies have shown a correlation between impervious surface, and degraded water quality. Accordingly, it is essential to understand the trends in the built environment related to impervious surface growth as well as trends in water quality on a local level. This will provide justification for planners and elected officials who wish to safeguard the water supplies of growing areas by encouraging responsible developments that incorporate low impact development design features and alternative stormwater design techniques.

CHAPTER 3
METHODOLOGY

Methodology Overview

This study measures increases in impervious surface in four watersheds in Wake County, NC. The study quantifies the amount of impervious surface by land use classification and compares these rates to identified average ISC rates from previous studies. The study estimates the amount of ISC attributable to roads and potential reductions attainable through the implementation of new residential roadway design standards. The study estimates the amount of impervious surface from buildings and the potential reduction attainable by retrofitting buildings with green roofs. The study seeks to identify the effects new development has on water quality, impervious surface and non-point source pollution. The study will contribute to the understanding of the correlations between land use changes, increases in impervious surface and reductions in water quality. The findings of the study enable the accurate forecasting of future impervious surface based on adopted land use plans of local governments in the study areas. The study will enable the drafting of recommendations for local governments consisting of implementation steps, including ordinances and site design guidelines that will reduce impervious surface and the impervious surface of new development, limiting the ability to conduct pollutants, thereby reducing impacts on water quality.

Time Frame and Study Area Selection

Land cover change resulting from urbanization, and its derivatives, has significant impacts on water quality throughout the rapidly growing Sunbelt in the southeastern United States. Urbanization in the piedmont region of North Carolina, South Carolina, and Georgia has been especially prolific. Wake County is located in the piedmont region of North Carolina and has experienced rapid suburban growth over the past 26 years. Between 1990 and 2006, Wake

County has grown from 423,380 people to 832,970 people (U.S. Bureau of Census 2009). It has been documented that urbanization can have a negative impact on water quality, invertebrate populations and fish communities (Lenat and Crawford 1994, Booth and Jackson 1997). Accordingly, land use change and its effects on water quality in Wake County can be seen as representative of a larger trend occurring on the edges of cities throughout the Piedmont.

The study will measure changes in the built environment between 1999 and 2005. This time frame was selected due to the availability of aerials for Wake County.

There are 81 watersheds in Wake County identified in the Wake County Watershed Management Plan (Wake County, 2003, p. ES-5). Of these, 30 are classified as "healthy," 38 are classified as "impacted" and 13 are classified as "degraded (Ibid., ES-6)." These classifications are based on in stream data and habitat data collected by the North Carolina Division of Water Quality (DWQ) and other agencies. It has been determined that sediment from construction sites and, "increased stream bank erosion caused by increased storm water runoff volumes from additional impervious surfaces in developing areas" are the two primary causes of degraded water quality (Ibid.).

Study Area Selection Process

Within Wake County watersheds or sub-basins were selected based on an attempt to minimize the potential interference of intervening variables by selecting small basins. Preference was given to those basins that begin and end in Wake County, due to the variability of aerial photography. Preference was also given to those areas with available water quality data.

A shapefile of the river basins and sub-basins (14 digit hydrologic units) for North Carolina was downloaded from the North Carolina Center for Geographic Information & Analysis (NC CGIA) download page on July 12, 2008. This inventory was created through a cooperative effort involving the United States Department of Agriculture-Natural Resources

Conservation Service (USDA NRCS), NC CGIA, and the North Carolina Department of Environment, Health and Natural Resources-Division of Water Quality (NC DENR DWQ). ArcGIS 9.1 was used to select the 45 hydrologic units that intersected the boundary of Wake County and export them as a new layer. The watersheds were cross checked with aerials and water quality data inventories of the United States Geological Survey and the Lower Neuse River Basin Association.

The size of the catchment, availability of water quality data, and land use mix, were evaluated. Four watersheds were selected. Each of the study areas are medium size streams located in urbanizing areas outside the city core. Perry Creek, Poplar Creek, Upper Middle Creek, and Smith Creek watersheds were chosen. The study areas are shown in Figure 3-1.

Delineating Watersheds

The watersheds that were selected included parts of the watershed downstream from water quality monitoring stations. In order to ensure that the water quality data were influenced only by impervious surface upstream from the monitoring stations it was necessary to revise study areas to include only the area upstream from the monitoring stations. This was accomplished using Terrain Analysis Using Digital Elevation Models (TauDEM) and ArcHydro for ArcGIS 9 Version 1.2 Beta. The methodology is explained below.

Downloaded 10 meter digital elevation models (DEM) from the USGS's seamless data distribution site, http://seamless.usgs.gov/.

Used the Extracted by Mask tool in ArcGIS to extract pixels within the study area watersheds defined in the EPA watershed layer

Filled Pits using TauDEM to get rid of depressions in DEMs

Calculated Flow Direction Grid with ArcHydro

Calculated Flow Accumulation Grid with Arc Hydro

Defined Streams based on a stream initiation threshold of 3500 cells which is the equivalent of 0.202663 square kilometers (based on extent of 24k "blueline" streams) in Arc Hydro

Calculated Stream Segmentation Grid in Arc Hydro

Delineated Catchment Grid in Arc Hydro to identify areas draining to each stream link

Catchment Polygon Processing in Arc Hydro to create catchment polygons out of the catchment grid

Drainage Line Processing in Arc Hydro to create streamlines

Adjoint Catchment Processing in Arc Hydro to create simplified catchments

Used the Point Delineation command to delineate the watershed above the location of the water sampling station

Measurement of Variables

Impervious Surface in 2005

Measurement of independent variables was conducted using Geographic Information Systems (GIS) technology and aerial photography, tax parcel records and road inventories maintained by Wake County. Feature Analyst, an extension for ArcGIS developed by Visual Learning Systems, was used to extract impervious surface coverage from high resolution aerial photography for 2005. The aerials had a resolution of 6 inches and were flown in April of 2005 and downloaded from Wake County's website. Each aerial tile was in Mr. Sid format and represented roughly 144 acres. For the study watersheds 357 tiles were processed.

Tax parcel records were acquired from Wake County for April of 2005, in order to correspond with the timeframe in which the aerials were taken.

The resulting impervious surface polygons were corrected using post processing tools available in the Feature Analyst software and revised based on manual inspection. The basic process used for impervious surface extraction is outlined below.

1. Create Pervious Surface Training Set/Create Impervious Surface Training Set

2. Prepare Multi-class Input Layer (Vector Tools/Prepare Multi-Class Input Layer)
    a. Add pervious_train and impervious_train

3. Set Up Learning
    a. Optimized Results from Learning
        i. Used Bulls Eye 2 9” for the input representation
        ii. Resample of 1/Histogram Stretch/Aggregate at 100 pixels

4. Run Extraction Pass
    a. Use Learning to Resolve Ambiguity/Classify Background

5. Split Out Pervious Class (Vector Tools/Split Out Classes)

6. Remove False Positives From Pervious Features
    a. Hierarchical Learning/Begin Removing Clutter
    b. Select/Digitize correct and incorrectly classified features

7. Set Up Learning
    a. Optimized Results from Learning
        i. Used Manhattan 5 input representation
        ii. Resample of 4/Histogram Stretch/Aggregate at 50 pixels

8. Run Extraction Pass

9. Split Out Impervious Class (Vector Tools/Split Out Classes)
    a. Select impervious class

10. Remove False Positives From Impervious Features
    a. Hierarchical Learning/Begin Removing Clutter
    b. Select/Digitize correct and incorrectly classified features

11. Set Up Learning
    a. Optimized Results from Learning
        i. Used Bulls Eye 2 9” input representation
        ii. Resample of 1/Histogram Stretch/Aggregate at 100 pixels

12. Combine Feature Layers (Vector Tools/Combine Features)
    a. Use Learning to Resolve Ambiguity/Classify Background
    b. Optimized Results from Learning
    c. Used Manhattan 5 input representation
    d. Resample of 4/Histogram Stretch/Aggregate at 50 pixels

A unique extraction model was built for each study watershed. Originally one model was built and applied to all watersheds, but this resulted in inaccurate results. An alternate method was used in which an extraction model was built for each study area. Training images and training sets, as shown in Figure 3-2, were selected in order to account for the variety of land cover found in each study area.

Once training sets were produced, the sets were combined into a Multi-class input layer. Then the Set Up Learning options were adjusted. After a number of iterations of experimenting with different learning options it was found that an initial extraction pass based on the Bulls Eye 2 9" input representation resulted in the most accurate initial extraction. Results from an initial Multi-class extraction are shown in Figure 3-3.

After initial Multi-class Results were developed, the impervious and pervious classes were split out and clutter was removed using the hierarchical learning functions within Feature Analyst. Incorrectly classified groups of pixels were selected as well as correctly classified pixels. See Figure 3-4 for an example.

After clutter was removed from pervious and impervious classes, an extraction pass was set up. For the impervious class the Bulls Eye 2 9" input representation was used with a resample of 1, approach setting 2, and an aggregation level of 100 pixels. For the pervious class, the Manhattan 5 input representation was used with a resample of 4, approach setting of 1, and an aggregation level of 50 pixels. After the clutter removal results were processed, the resulting layers were combined and learning was used to solve ambiguity between the classes and classify the background. See Figure 3-5 for an example of the results from the final extraction.

Once the feature extraction models were developed for each watershed, the remaining tiles in the watersheds were processed using the batch classification option. Each tile required 15-20 minutes to process. This process was lengthened due to a “Memory Exception” error message occasionally received in the middle of processing, which required a reboot and resetting of the batch process. After the tiles were processed the results were merged and the impervious surface was selected and manually edited to remove clutter and misclassified groups of pixels. Corrections included removing false positives created by gray tree trunks and masses of branches in leaf-off deciduous forests, and in bare fields grayish in color. In some instances weathered roofs and red roofs were added to the impervious results. Approximately 8 hours per study area was spent on manually correcting the resulting classification.

Impervious Surface 1999

Impervious surface in 1999 was “back casted” by netting out ISC on parcels that had a built year, of 1999, 2000, 2001, 2002, 2003, 2004, and 2005. All parcels were selected where "YEAR_BUILT" in (2005, 2004, 2003, 2002, 2001, 2000, 1999), and the ISC on these parcels was summed and subtracted from the total ISC measured.

Impervious surface associated with roadways was estimated by overlaying the derived impervious surface polygons and road inventories developed by Wake County. An archival roadway inventory from Wake County Geographic Information Services was buffered by 12 feet and unioned with the extracted impervious surface polygons. A buffer width of 24 feet (12 feet on each side of road) was chosen based on the average width at a random sampling of 20 points on the road network in the Middle Creek Study Area. This post processing step ensures that roadways ensconced by tree cover are included in the impervious surface totals.

Accuracy was determined by generating a statistically significant number of random points and visually inspecting the results of the feature extraction, after post processing, to determine if the methodology resulted in successfully identifying areas as pervious or impervious. Congalton

(1991) recommends at least 50 samples per land use category (43). For this study 152 random points were generated for each class and verified for correct classification.

Analysis Methodology

Impervious surface coverage rates by land use were produced for the study areas. This was accomplished by querying the tax parcel information to determine the land use of individual parcels based on American Planning Association Land Based Classification System (APA LBCS) codes maintained by the Wake County Department of Revenue. Impervious surface rates by land use were quantified by merging the impervious coverage output and the parcel information then summarizing by land use type. These were compared to SCS impervious surface coverage rates often used to forecast impervious surface. Estimates of impervious surface coverage attributable to certain facets of the built environment were produced, including square footage of non-permeable surface from roads, driveways, and rooftops. In the future it may be possible to extract these three features separately by experimenting with hierarchical learning capabilities within Feature Analyst by developing specialized training sets after the initial impervious surface extraction has been successfully completed, however, this was not done during this research. From these totals, estimates will be produced that indicate what percentage of impervious surface can be reduced by incorporating green rooftops and pervious pavements in all new developments.

The GIS steps taken to quantify ISC by land use are included in the list below.

1. Union ISC extraction with streets
2. Dissolve
3. Calculate ISC by watershed
4. Clip Parcel Classified by SCS LU by Study Areas
5. Recalculate Parcel Acres

6. Union ISC with Parcel Classified by SCS LU
7. Select ISC and calc Area Acres field
8. Summarize based on PIN in Parcels (summing ISC acres, first AreaInSA, first NRCS)
9. Join with Parcel layer
10. Calculate Percent ISC by Parcel
11. Select where "Per_ISC" >0 AND "BLDG_VAL" >0 and "YEAR_BUILT" in (2005, 2004, 2003, 2002, 2001, 2000, 1999)
12. Summarize based on SCS LU
13. Calculate Mean ISC by SCS LU

Quantifying Land Use by Watershed

A Wake County tax parcel database from April 2005 was received from Wake County. Each parcel was classified using a lookup table (See Appendix A), which translated the APA Activity codes to simplified land use types that were used in previous impervious surface studies.

The queries used to classify land uses are also included in Appendix A.

Parcels with SCS categories were summed by Study Area. Only those parcels that were completely in the study area were selected.

The following queries were used to select and calculated dwelling units built prior to 2000 and between 2000 and 2005:

"NRCS_USDA_" in ('Multi-family Residential', 'Single Family Residential') AND
"YEAR_BUILT"<2000

"NRCS_USDA_" in ('Multi-family Residential', 'Single Family Residential') AND
"YEAR_BUILT" >= 2000

Quantifying Road Density

Road density has been determined to be correlated with impervious surface and water quality degradation (Forman 2005). The number and proximity of roads corresponds with the intensity of land uses. Road density in 1999 and 2005 was measured in this study. Wake County maintains a GIS-based road inventory for emergency services. An archived copy of the Wake County streets shapefile was received from Wake County Geographic Information Services for 1999 and April of 2005. These two files were clipped based on the study watershed boundaries and an overall road density was calculated by dividing total roadway miles by total square miles of the watersheds.

Water Quality Analysis

Once increase in impervious surface coverage was quantified, these changes were compared to changes in water quality in the study areas. It was hypothesized that increases in impervious surface would correlate closely with degraded water quality.

Water quality data was collected for Smith Creek, Middle Creek, and Poplar Creek by the Lower Neuse Basin Association. The data was part of the Ambient Water Quality Monitoring Data records maintained by the North Carolina Division of Water Quality. The data included measurements of a variety of parameters including temperature, PH, dissolved oxygen (DO), conductance, turbidity, suspended residue, Total Kjeldahl Nitrogen (TKN), nitrate (NO_3) + nitrite (NO_2), and total phosphorus. The data was collected between 1995 and 2006 (1996 and 2006 for the Middle Creek watershed). Prior to clean up, the datasets contained 193 records for Smith Creek, 198 records for Poplar Creek and 182 for Middle Creek. There were multiple sampling dates for some months which were averaged to create a single value representative of the conditions for that month. In some months where there was not a reading. These missing values were interpolated based on a linear curve.

The data for Perry Creek was compiled by the Stormwater Management Division of the City of Raleigh Public Works Department. This dataset consisted of 30 samples that were taken between 1998 and 2008. The low number of samples prevented statistical analysis.

Water quality indicators that will be measured will include Conductance, Suspended Residue, TKN, Nitrate + Nitrite, and Total Phosphorus (TP). A 25% trimmed mean was calculated for each parameter by year, except Perry Creek where limited data was available. In addition, a Mann-Kendall Trend Test was conducted using the monthly water quality values for all study creeks, except Perry Creek, where limited data was available. A Mann-Kendall Test for trend was used due to the non-parametric nature of water quality data and its applicability for use with time series water quality data. Results of the Mann-Kendall Test include a value for tau and a 2-sided p-value. Positive tau values indicate a positive trend; negative values indicate a negative trend. A p-value below 0.05 indicates a statistically significant trend.

Mann-Kendall in R

R is free software that is essentially a, "language and environment for statistical computing and graphics (The R Foundation for Statistical Computing 2009)." R allows for a variety of data processing, statistical analysis and graphics production. Time series analysis is possible within the R environment. Data tables can be inputted as a time series layer (See Figure 3-6). The R environment can be extended by downloading and installing a variety of packages. In order to conduct the Mann Kendall trend test it is necessary to download the Kendall package. For this study the Kendall Package, version 2.0 was downloaded and installed. The package was authored by A.I. McLeod.

For the three study areas with ample reading, the datasets were pre-processed by averaging multiple readings per month and filling in missing months based on a linear curve. Once the data was pre-processed, the following steps were used to run the Mann Kendall trend test in R.

1. Create comma delimited file for each variable
2. Import variable into R using the command
   a. poplarcond=ts (scan("C:/R/Poplar_cond.csv"), start=1995, frequency=12)

3. Run Mann Kendall Test (See Figure 3-7 for an example of output results)
    a. MannKendall(poplarcond)

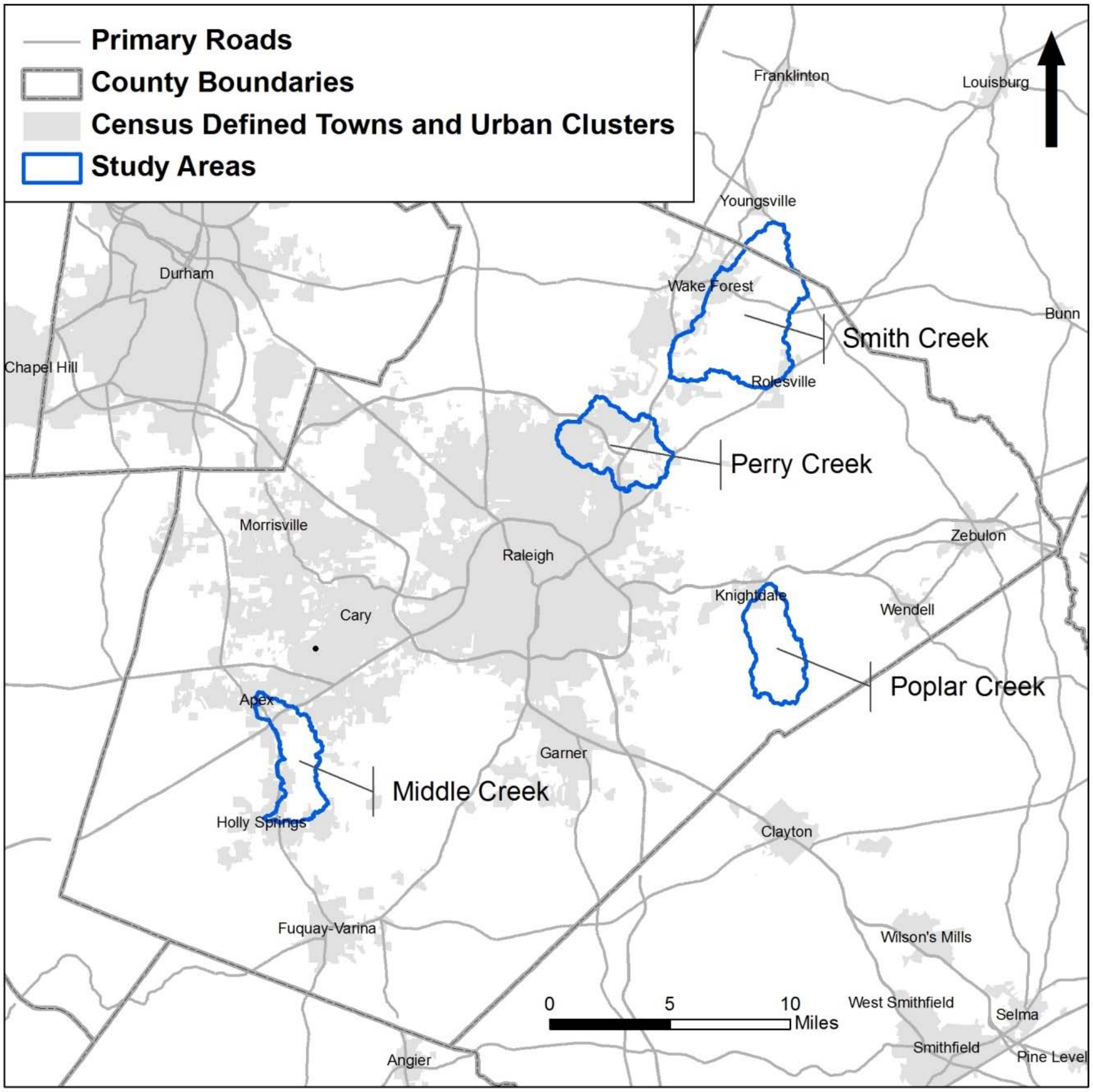

Figure 3-1. Study watersheds

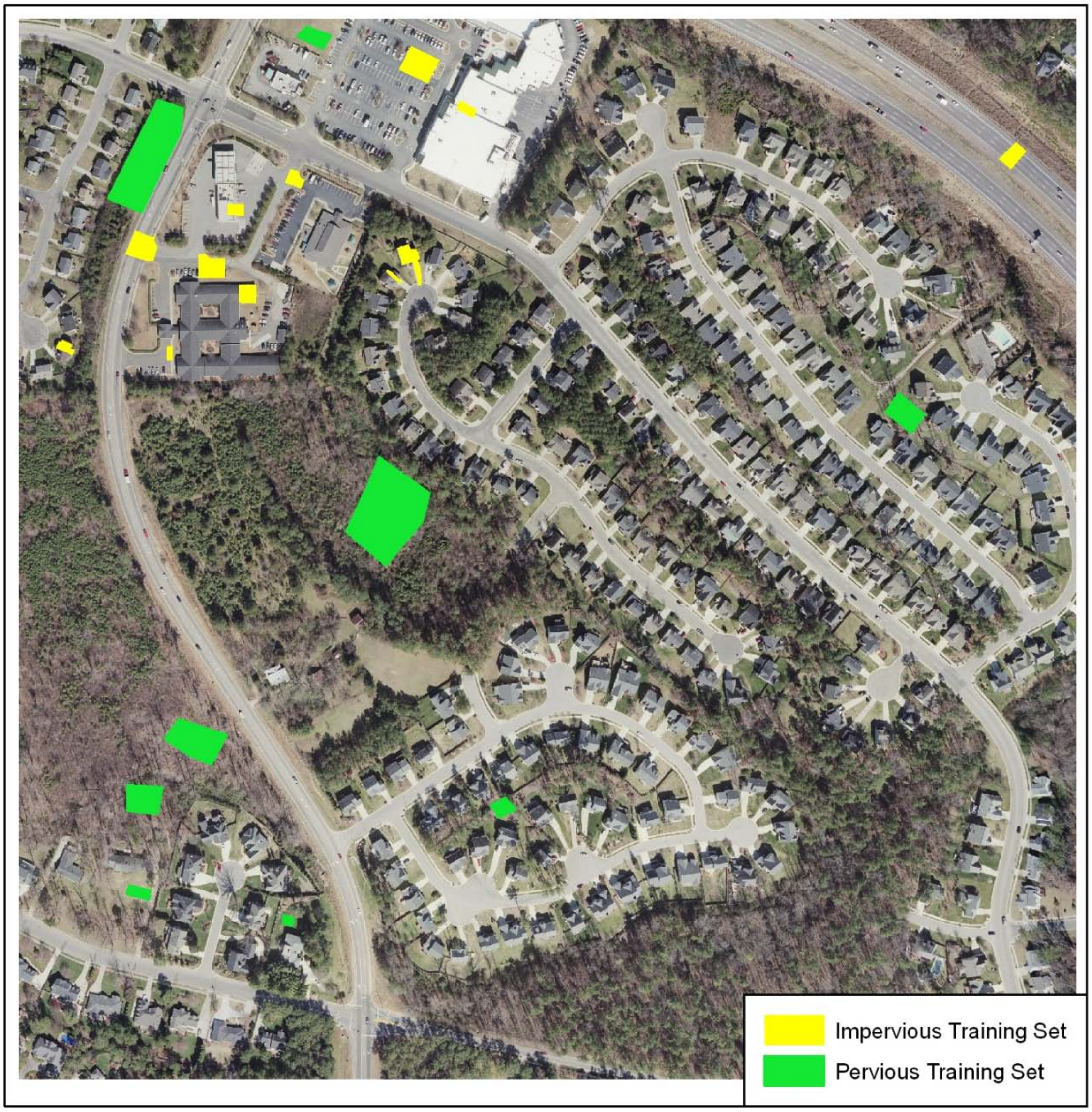

Figure 3-2. Perry Creek training sets

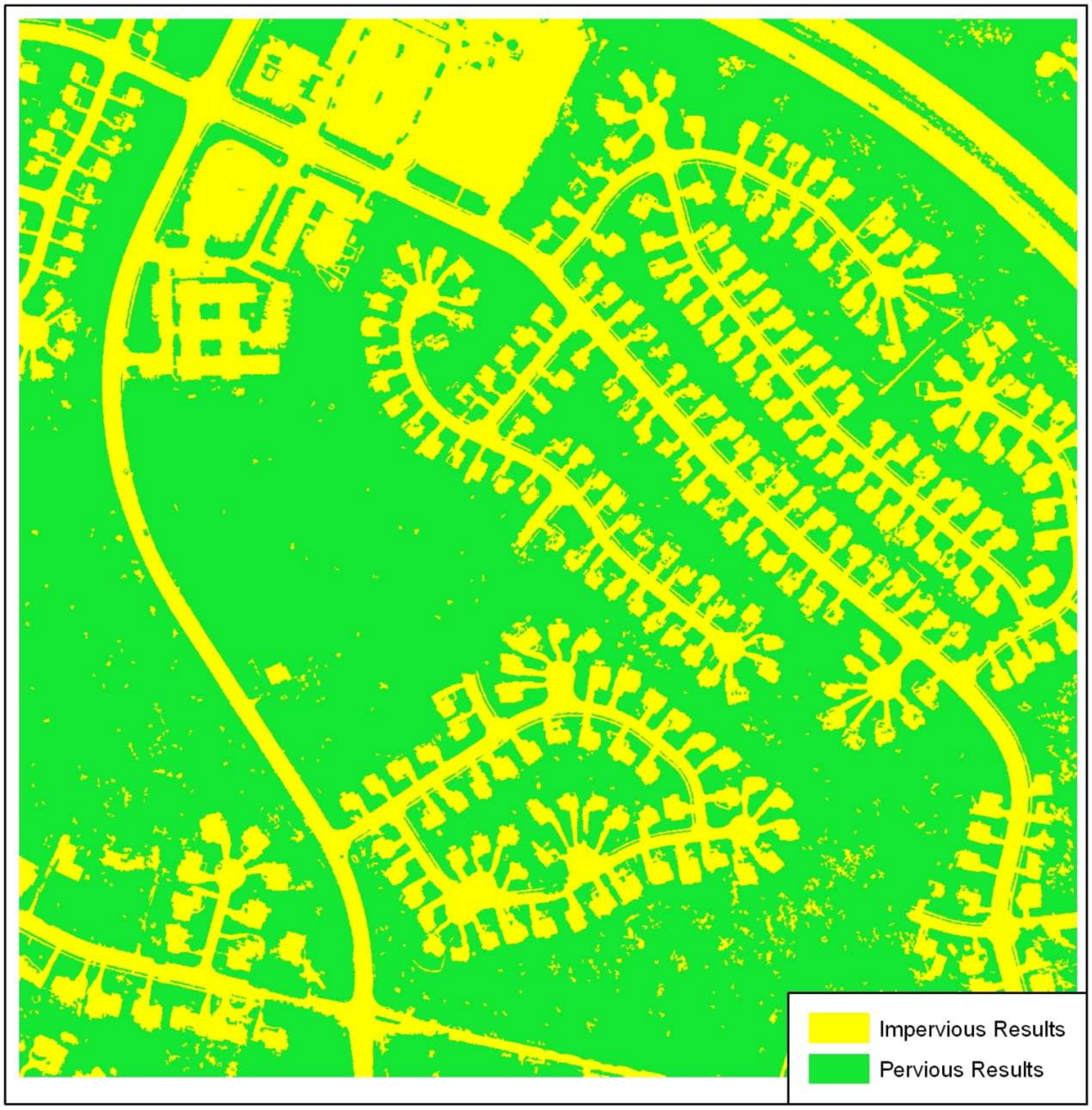

Figure 3-3. Perry Creek initial multi-class results

Figure 3-4. Perry Creek remove clutter training

Figure 3-5. Perry Creek final model results

```
      Jan   Feb   Mar   Apr   May   Jun   Jul   Aug   Sep   Oct   Nov   Dec
1995 116.0  63.0  50.0  60.0  55.0  50.0  60.0  80.0  90.0  90.0  20.0  60.0
1996  80.0  50.0  50.0  70.0  60.0 115.0 135.0  65.0  60.0  40.0  60.0  60.0
1997 100.0  60.0  82.0  67.0  55.5 115.5 137.0 167.0 176.5 125.0 100.0  98.0
1998  83.0  71.0  74.0  71.0  82.5  84.0  84.0 122.0  83.5 128.0 139.0 112.0
1999  79.0  87.0 101.0 101.0 116.0 139.5 156.5 128.0  94.5  87.5  82.0 102.0
2000  63.0  52.0  82.0  79.0 108.0 117.5 110.0 110.0 115.0 105.0 120.0 122.0
2001 109.0 104.0  87.0  99.0 111.5 100.0 110.0 127.0 130.0 134.0 125.0 124.0
2002 103.0  90.0 101.0 108.0 130.5 159.0 160.0 133.0 148.5 176.0  89.0  94.0
2003  59.0  81.0  72.0  82.0  90.0 102.5  90.0  82.0  90.5 101.0 103.0  90.0
2004  90.0  96.0  89.0  96.0 103.5 108.5 110.0   3.0 119.0  85.0  92.0  97.0
2005 108.0 117.0 139.0 168.0 148.0 120.0 125.0 125.0 126.0 194.0 148.0 131.0
2006 112.0 143.0  97.0 112.0 111.0 152.5 127.5 195.5 147.5 140.0 118.0 112.0
>
```

Figure 3-6. After inputting Poplar Creek conductance into a time series

```
> poplarcond=ts (scan("C:/R/Poplar_cond.csv"), start=1995, frequency=12)
Read 144 items
> MannKendall(poplarcond)
tau = 0.362, 2-sided pvalue =1.5408e-10
```

Figure 3-7. Example Mann-Kendall test results

CHAPTER 4
DESCRIPTION OF WATERSHEDS

Overview

The majority of land area in study watersheds is located in Wake County. Smith and Perry creeks are located on the northeastern side of the City of Raleigh, and enter the Neuse River just south of the Falls Lake Reservoir. Poplar Creek is on the east side of Raleigh and flows from Knightdale south to the Neuse River. Middle Creek is located southeast of Raleigh on the outskirts of Cary, Apex and Holly Springs. Digital elevation and context maps are included as Figure 4-1 through 4-4.

Smith Creek, Perry Creek, and Poplar Creek are in the Neuse River Subbasin 02 as defined the North Carolina Department of Environment and Natural Resources Division of Water Quality Environmental Services Section in the Basinwide Assessment Report for the Neuse River Basin (NCDWQ 2006, p. 29). It has been noted that nonpoint source pollution and agricultural runoff impact water quality in Subbasin 02. There are six large permitted wastewater discharge sites in the Subbasin, but none discharge into the study creeks. In the Smith Creek Study Area, “three minor NPDES dischargers lie within five miles upstream: Whipporwill Valley WWTP, Wake Forest WTP, and Jones Dairy Farm (Ibid., 32).” Middle Creek is located in the Neuse River Subbasin 03 as defined in the Report (Ibid., 43).

Middle Creek

The Middle Creek watershed drains 56 square miles in southern Wake County. The Middle Creek Study Area covers only 8.4 square miles of the total watershed and is comprised of land that drains into Middle Creek before it reaches the ambient water quality monitoring station at Holly Springs Road. Middle Creek has its headwaters in downtown Apex and drains rapidly growing residential areas east of Apex. The riparian corridor has been fragmented by small subdivisions with low residential densities. There is some newly constructed industrial development in the northern part of the watershed near US-1. More than a third of the 2,900 homes in the watershed were built between 2000 and 2005. A detailed summary of land uses, density, and age of housing stock in this watershed is included in Table 4-1.

Perry Creek

Perry Creek begins in the northern part of Raleigh and drains in a northeasterly direction to the Neuse River. It has been described as a, “small, sandy, shallow” creek approximately 4 meters in width (NCDWQ 2006, p. 33). The Perry Creek Study Area is 11 square miles in area. The Study Area is divided into four quadrants by two major transportation corridors. US 1, also known as Capital Boulevard travels through the center of the watershed in a north/south alignment and I-540, also known as the Outer Beltline, traverses the Study Area in an east to west direction. The section of I-540 west of US 1 was constructed during the study timeframe. The southeast quadrant of the study area is dominated by Triangle Town Center, a regional mall that was constructed between 2000 and 2005.   The southwest quadrant is composed of commercial and industrial outparcels near US 1, and residential uses to the west.   A number of the residences in this area are part of established low density residential neighborhoods built prior to 1990. The northwest quadrant is composed of medium density residential uses to the west, between 3 and 5 units per acre, and industrial uses near US 1. The northeast quadrant is composed of residential uses of varying densities and large vacant tracts near the I-540 corridor. Much of the established and new residential development in this watershed is due to high density apartments units. A detailed summary of land uses, density, and age of housing stock in this watershed is included in Table 4-1.

Poplar Creek

Poplar Creek has its headwaters in the Town of Knightdale, which is located just east of Raleigh. The creek drains south to the Neuse River. The Poplar Creek Study Area covers nearly all of the 9 square miles of the watershed. Poplar Creek is the most rural of all the study areas. As of 2001 there was a significant amount of cultivated crops and pasture land. There has been some suburban development in the watershed; the majority of the residential development has been low and medium density development built prior to 2000. A detailed summary of land uses, density, and age of housing stock in this watershed is included in Table 4-2.

Smith Creek

Smith Creek drains an area of 29.2 square miles. The Smith Creek Study Area comprises only 21.5 square miles due to the fact that 2.1 square miles are located in Franklin County and necessary aerial photography was not available for the study timeframe and a portion of the watershed drains land that is not hydrologically connected to the water quality sampling point on Burlington Mills Road. The portion of land in the watershed which drains Franklin County is rural in character; because of this it was assumed that development in this area does not substantially affect the overall health of the stream. Smith Creek watershed has its headwaters in the Town of Wake Forest and Sanford Creek and smaller streams that drain the north side of the Town of Rolesville. The watershed is bordered by Main Street in Wake Forest to the northwest and Main Street in Rolesville to the southeast. The creek drains south to its confluence with the Neuse River downstream from the Falls Lake Dam. The watershed has experienced significant growth as development has extended northward from Raleigh along US-1 and subdivisions have been built on the outskirts of Wake Forest and Rolesville. Out of the 4,531 dwelling units, 31.1%, or 1,409 dwelling units were built between 2000 and 2005. The majority of these have been medium density between 2 to 4 units per acre. A detailed summary of land uses, density, and age of housing stock in this watershed is included in Table 4-2.

In the 2006 Neuse Basin Assessment Report, produced by the North Carolina Department of Environment and Natural Resources Division of Water Quality Smith Creek was assigned a Good-Fair classification based on benthic macroinvertebrate data in 2005 (Ibid., 30). This was one of only two creeks in Subbasin 02 to show improvements in the benthic macroinverterate community. In contrast sampling shows that the fish community in this creek has declined between 2000 and 2005. In 2000 it received an Excellent rating, in 2005 it received a Fair rating.

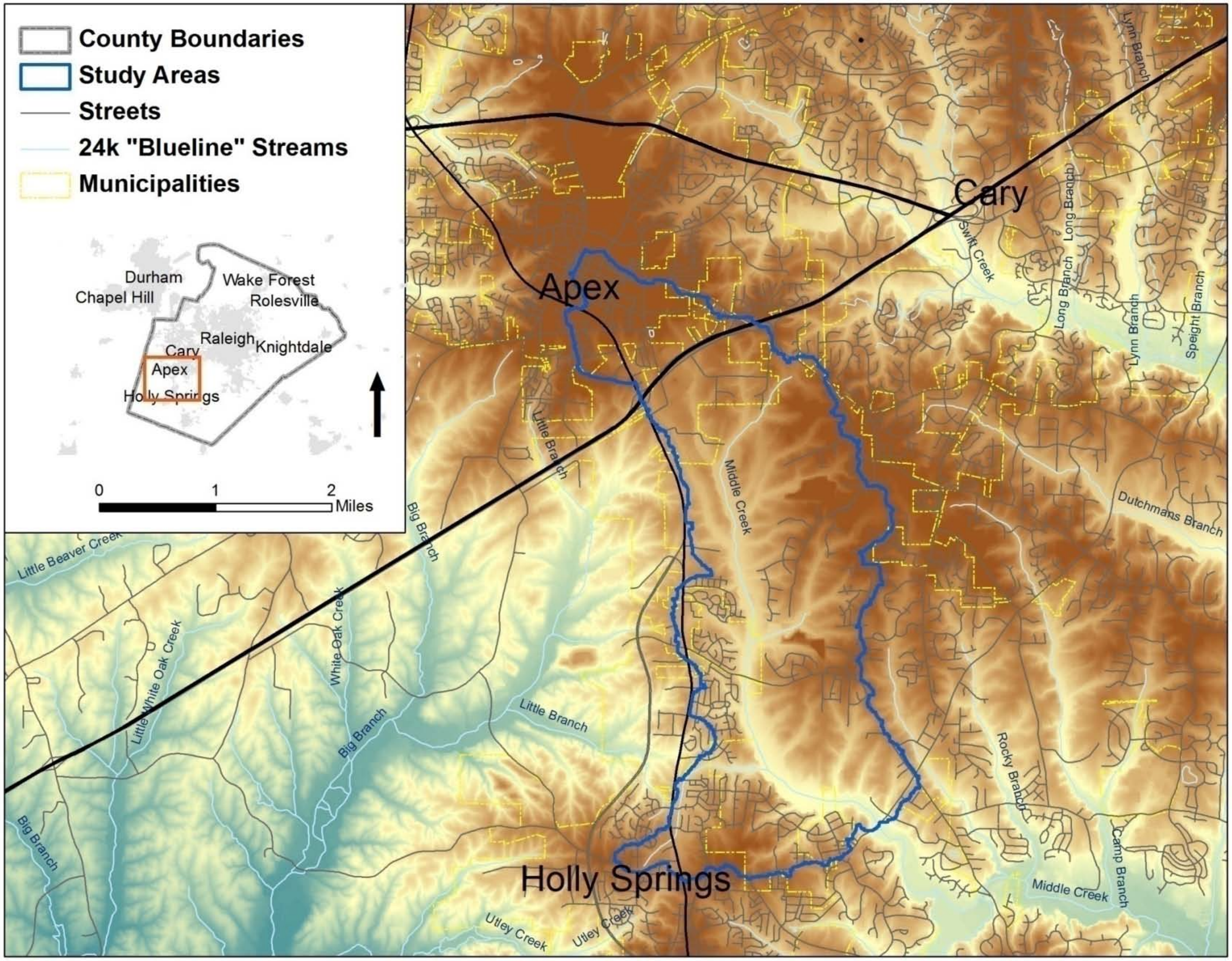

Figure 4-1. Middle Creek digital elevation model and context map

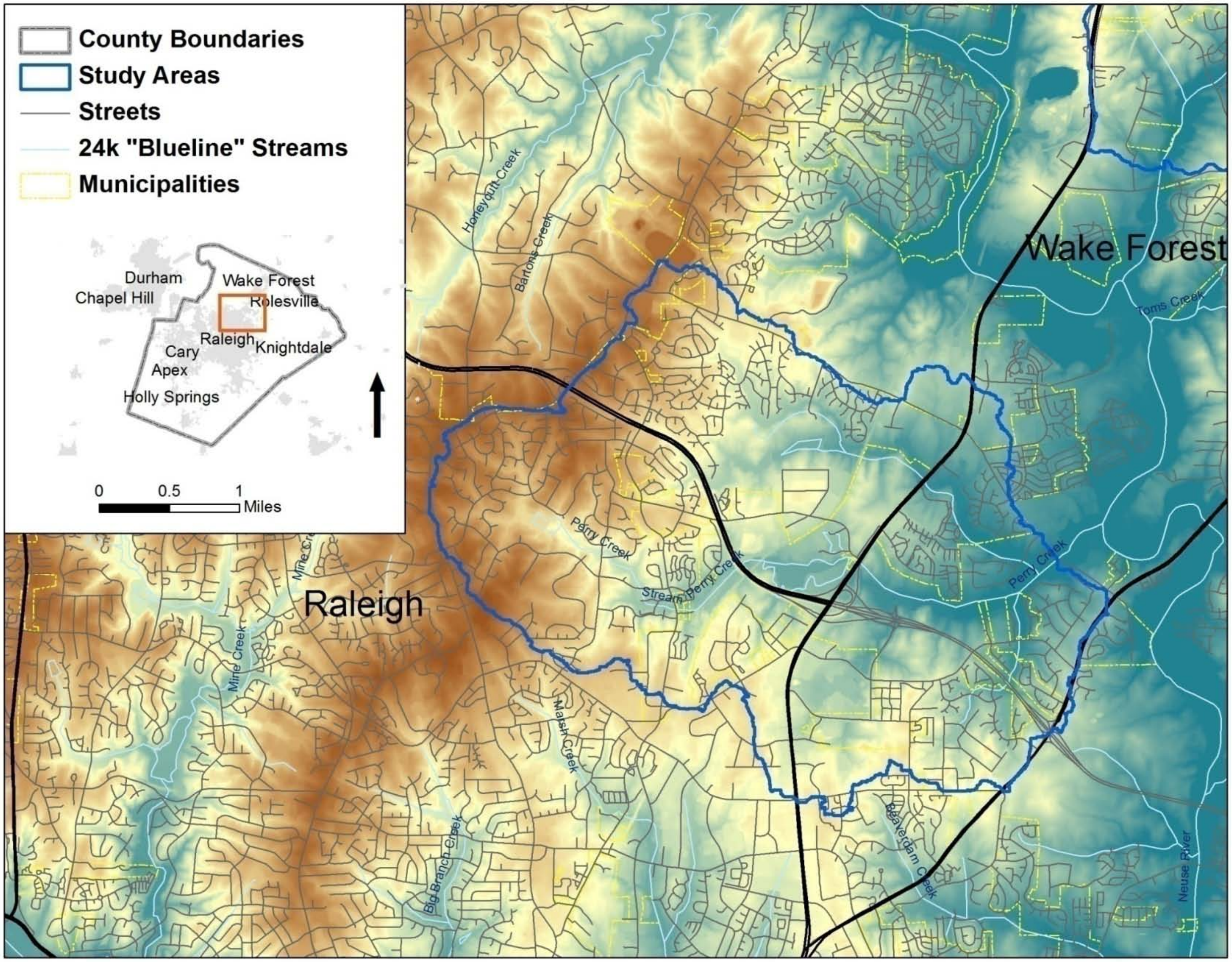

Figure 4-2. Perry Creek digital elevation model and context map

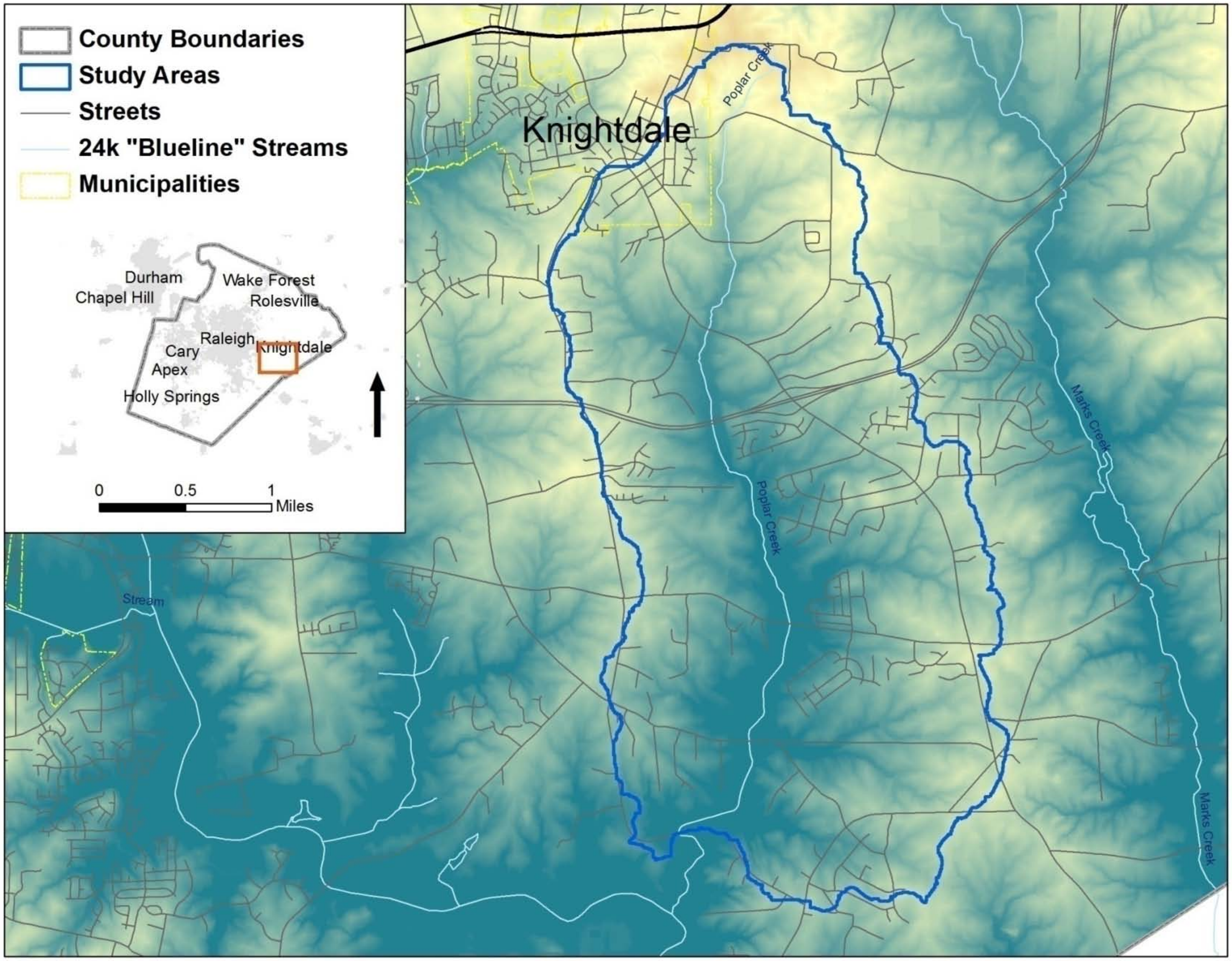

Figure 4-3. Poplar Creek digital elevation model and context map

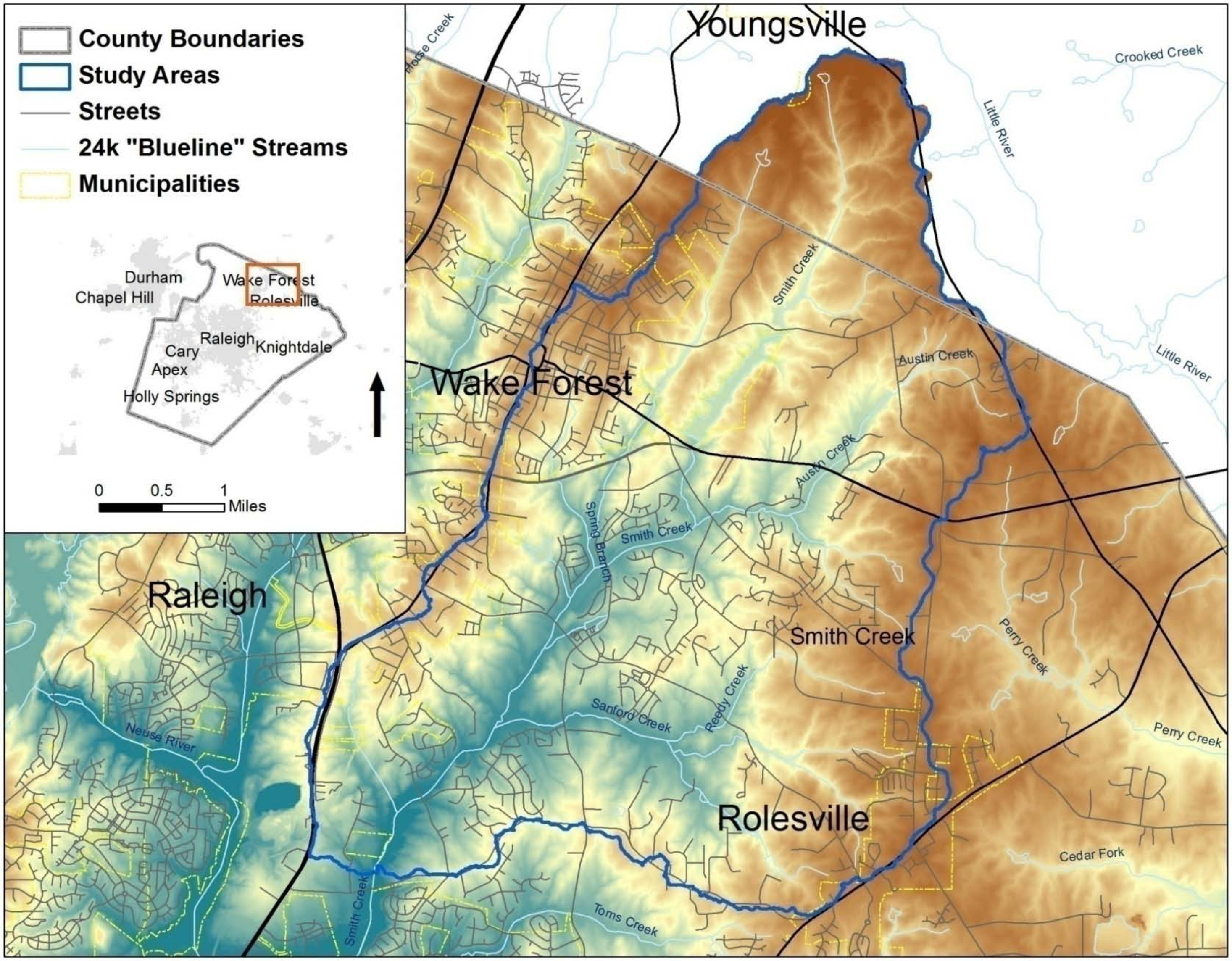

Figure 4-4. Smith Creek digital elevation model and context map

Table 4-1. Middle Creek and Perry Creek land uses, density, and age of housing stock

Land Use and Density		Middle Creek					Perry Creek				
				Dwelling Units					Dwelling Units		
Land Use	Dwelling Units/Acre	Parcels	Acres	Built Before 2000	2000-2005	Total Units	Parcels	Acres	Built Before 2000	2000-2005	Total Units
Unclassified		861	2,504	-	-	-	636	1642	0	0	-
Low Density Residential	<0.5	44	444	43	4	47	27	511	34	1	35
	0.5	300	119	132	168	300	99	128	100	0	100
	1	300	210	185	150	335	924	606	917	9	926
Medium Density Residential	2	334	132	265	77	342	1236	536	1272	4	1,276
	3	341	98	212	80	292	941	274	941	21	962
	4	288	66	306	134	440	1032	234	1024	22	1,046
High Density Residential	5-7	427	75	43	4	47	1093	247	1380	52	1,432
	>7	432	107	691	383	1,074	1337	239	1976	927	2,903
Commercial		33	51	-	-	-	79	334	0	0	-
Industrial		58	257	-	-	-	91	327	0	0	-
Totals		3,418	4,064	1,877	1,000	2,877	7,495	5,078	7,644	1,036	8,680

Table 4-2. Poplar Creek and Smith Creek land uses, density and age of housing stock

Land Use and Density		Poplar Creek					Smith Creek				
				Dwelling Units					Dwelling Units		
Land Use	Dwelling Units/Acre	Parcels	Acres	Built Before 2000	2000-2005	Total Units	Parcels	Acres	Built Before 2000	2000-2005	Total Units
Unclassified		398	1592	0	0	-	1,740	7,331	-	-	-
Low Density Residential	<0.5	93	1558	88	13	101	269	2,011	238	38	276
	0.5	223	287	181	43	224	283	401	246	45	291
	1	526	387	484	46	530	664	484	541	128	669
Medium Density Residential	2	296	129	297	1	298	974	389	709	289	998
	3	103	30	100	7	107	616	214	341	400	741
	4	252	56	242	10	252	375	87	167	213	380
High Density Residential	5-7	255	44	229	32	261	238	44	148	104	252
	>7	167	27	82	154	236	254	59	732	192	924
Commercial		9	33	0	0	-	77	199	-	-	-
Industrial		4	7	0	0	-	37	147	-	-	-
Totals		2,326	4,151	1,703	306	2,009	5,527	11,368	3,122	1,409	4,531

CHAPTER 5
FINDINGS

Impervious Surface Area

The semi-automated impervious surface extraction process utilized Feature Analyst to classify high resolution images, an estimation of roadway impervious surface using a county maintained GIS roadway inventory, and manual cleanup based on visual inspection.

Accuracy

An accuracy assessment was conducted by generating 252 random points using the Generate Random Points Tool within Hawth's Analysis Tools for ArcGIS. Half of the points (126) were generated within the pervious extraction layer and half were generated within the impervious extraction layer. Each point was inspected to determine if the resulting classification was correct. It was found that the overall accuracy of this semi-automated classification method was 94%. The impervious surface classification was found to be correct 90.32% of the time, and the pervious surface classification were found to be correct 97.62% of the time. This resulted in an overall accuracy of 94%.

Findings

The percentage of ISC varies by study area, as shown in Table 5-1. The Poplar Creek watershed had the lowest amount of impervious surface, with 7.56% of the watershed. Perry Creek had the highest level of ISC with 26.51%. The percentage of ISC attributable to roads ranged from 18.24% for Perry Creek to 32.84% for Poplar Creek.

If the receiving streams in the study areas were classified according to thresholds indicating stream health, Middle Creek would be considered "Impacted" with over 10% impervious surface, Perry Creek would be considered "Non supporting" since it exceeds the 25% threshold which indicates a stream degraded to the point that it does not support a variety of aquatic life. Both Poplar Creek and Smith Creek would be considered “Sensitive,” since total ISC in these watersheds is below 10%.

Table 5-1. Impervious surface coverage by study area in 2005

Watershed	Area of Watershed (Acres)	ISC (Acres)	% ISC	Street ISC (Acres)	% Street ISC
Middle Creek	5,404.62	740.85	13.71%	166.60	22.49%
Perry Creek	7,064.96	1,873.10	26.51%	341.70	18.24%
Poplar Creek	5,546.55	419.18	7.56%	137.64	32.84%
Smith Creek	14,511.34	1,370.88	9.45%	314.70	22.96%

Impervious Surface Growth

Impervious surface growth was most pronounced in the Perry Creek Study Area, where substantial commercial growth in and around Triangle Town Center and the completion of a portion of I-540, the outer beltline, increased the amount of impervious surface dramatically. Over five percent of the total land area in the Perry Creek watershed was converted to impervious surface between 1999 and 2005. This is a low estimate, as the estimate was based on an assumption that new roads were 24 ft wide. The outer beltline exceeds this width, but more research needs to be done in order to develop a more accurate methodology to estimate ISC growth attributable to roads. In the Middle Creek Study area ISC growth between 1999 and 2005 resulted in the watershed crossing the threshold from “Sensitive” to “Impacted.” Although, in both the Poplar Creek and Smith Creek study areas impervious surface grew by smaller amounts, the watersheds are approaching 10% impervious surface. At the current rate of growth, the Smith Creek watershed will be classified as “Impacted” and exceed 10% ISC by 2011. See Table 5-2 for detailed estimates of impervious surface growth between 1999 and 2005 by watershed.

Table 5-2. Impervious surface growth estimates

Watershed Information		Estimated ISC Growth 1999-2005			
Name	Area in Acres	On Parcels	From Roads	Total	% of Land Area
Middle Creek	5,404.62	157.76	47.82	205.58	3.80%
Perry Creek	7,064.96	325.06	77.60	402.66	5.70%
Poplar Creek	5,546.55	30.05	8.78	38.83	0.70%
Smith Creek	14,511.34	261.96	87.84	349.80	2.41%
Total	32,527.47	774.83	222.04	996.87	3.06%

Impervious Surface Rates by Land Use of Recent Development

Impervious surface resulting from construction on parcels that had a built year of 1999, 2000, 2001, 2002, 2003, 2004, and 2005 was summarized by land use. The average rates of impervious surface attributable to new development in different land use categories in each watershed are shown in Table 5-3. Although the average rates of impervious surface on residential parcels varied between watersheds, the average rates of impervious surface in the study as a whole are close to the average rates of ISC by residential densities produced by the SCS. The average rates of ISC for commercial and industrial properties in the study (59% and 56%) were much lower than the SCS rates for commercial and industrial land uses (85% and 72%).

Table 5-3. Impervious surface rates by land use comparison

Land Use	Perry Creek	Poplar Creek	Middle Creek	Smith Creek	N	Average	SCS
<0.5 DU/Acre	24.16%	8.10%	10.21%	8.57%	99	9.34%	-
0.5 DU/Acre	-	10.43%	16.65%	14.06%	281	15.12%	12.00%
1 DU/Acre	24.66%	15.51%	22.93%	17.12%	401	19.71%	20.00%
2 DU/Acre	28.38%	12.76%	23.22%	24.50%	474	24.30%	25.00%
3 DU/Acre	27.74%	21.47%	27.93%	31.11%	577	30.13%	30.00%
4 DU/Acre	33.87%	27.50%	31.67%	34.88%	521	33.15%	38.00%
5-7 DU/Acre	39.98%	34.12%	19.19%	40.69%	284	39.00%	-
>7 DU/Acre	58.74%	39.37%	47.67%	72.96%	1,130	55.30%	65.00%
Commercial	65.74%	42.54%	52.23%	56.66%	63	59.56%	85.00%
Industrial	62.49%	0.00%	57.36%	49.10%	60	56.51%	72.00%

Statistical Analysis of Water Quality Data

Results of Mann-Kendall Test

The Mann-Kendall trend test showed that there was a statistically significant positive trend in total phosphorus readings in Middle Creek, conductance and total nitrogen readings in Poplar Creek, and conductance and total phosphorus readings in Smith Creek. Interestingly, the test showed a statistically significant negative trend in total nitrogen readings in Smith Creek. This could be a result of reduced amounts of fertilizer application due to the abandonment of farming. The majority of the remaining variables showed positives trends that were not statistically significant (See Table 5-4). Overall there were five statistically significant positive trends, indicating increasing pollutant loads, and one statistically significant negative trend, indicating a decreasing pollutant load. The strongest trends were in conductance values in Poplar Creek and Smith Creek, which had tau values of 0.351 and 0.56, respectively.

Table 5-4. Mann-Kendall trend test results

Study Area	Variable	Tau	P Value
Middle Creek	Conductance	-0.057	0.33
	Suspended Residue	-0.086	0.15
	TKN	0.0753	0.21
	NO2/NO3	0.008	0.89
	Total Phosphorus	0.149	*1.16E-02
Poplar Creek	Conductance	0.361	*1.77E-10
	Suspended Residue	0.0396	0.49
	TKN	0.03	0.60
	NO2/NO3	0.275	*1.05E-06
	Total Phosphorus	-0.057	0.32
Smith Creek	Conductance	0.56	*2.22E-16
	Suspended Residue	0.0411	0.47
	TKN	-0.053	0.36
	NO2/NO3	-0.25	*9.81E-06
	Total Phosphorus	0.125	*0.03

Annual Trimmed Mean Calculations

A 25% trimmed mean was calculated for each water quality parameter per year. Tables 5-6 through 5-9 and Figures 5-1 through 5-5 show the trimmed means from the study areas for conductance, suspended residue, turbidity, TKN, Nitrite + Nitrate, and Total Phosphorus by year of sample. Annual trimmed means for 2006 were compared to annual trimmed means for the base year. In eight cases the annual trimmed mean increased, indicating decreasing water quality (See Table 5-10). In seven cases the annual trimmed mean decreased, indicating improving water quality (See Table 5-10).

Road Density

Road density in the study watershed has increased substantially between 1999 and 2005. Smith Creek, Perry Creek, and Middle Creek have experienced increases in excess of 20% (See Table 5-5). Increases in miles of roadway results in more stream crossings, culverts and, ultimately, disrupted hydrologic systems.

Table 5-5. Road density in study watersheds

Study Area	Area (square miles)	Miles of Roads 1999	Miles of Roads 2005	Road Density 1999	Road Density 2005	Percent Change
Smith Creek	22.67	88.53	116.96	3.91	5.16	32.1%
Poplar Creek	8.67	51.47	53.48	5.94	6.17	3.9%
Perry Creek	11.04	99.89	127.55	9.05	11.55	27.7%
Middle Creek	8.45	53.74	67.08	6.36	7.94	24.8%

Effectiveness of Green Roofs and Pervious Pavements

Using rates of impervious surface for roofs and parking areas/driveways by land use developed by the City of Olympia, WA, estimates can be developed for the amount of ISC that would be eliminated if new development were to incorporate green roofs and pervious pavements into site plans. If it is estimated that parking lots and driveways make up 15% of all

ISC in residential development under 7 units per acre, 31.3% of ISC in residential development greater than 7 units per acre, and 61.6% of ISC in commercial and industrial development, then it can be estimated that the parking lots and driveways constructed as components of all new development in the study areas between 1999 and 2005 add up to 178.43 acres of impervious surface. If it is assumed that roofs make up 37.5% of ISC in residential development under 7 units per acre, 35.4% of ISC in residential development greater than 7 units per acre, and 30.2% of ISC in commercial and industrial development, then it can be estimated that rooftops make up 130.20 acres of impervious surface built between 1999 and 2005. Together it can be estimated that rooftops, driveways and parking areas accounted for 308.63 acres (47.4%) of new impervious surface built between 1999 and 2005, not including ISC attributable to streets. If every house, strip center, and warehouse built included pervious pavements and green roofs, nearly 13.5 million square feet of impervious surface could be eliminated. More realistically, encouraging green roofs and pervious pavements to be utilized during the design and construction of certain types of development can have a significant impact on the amount of ISC. For instance, if new industrial and commercial buildings were required to have green roofs, eco-roofs, or some type of vegetated roof, over 4 million square foot of impervious surface would have been eliminated in the Perry Creek watershed alone. Alternatively if residential development was required to have pervious pavement installed in driveways and parking areas, roughly 400,000 square feet of impervious surface would have been avoided in Perry Creek, Middle Creek and Smith Creek in developments constructed between 1999 and 2005.

Table 5-6. Trimmed mean of Poplar Creek water quality readings

Year	Conductance	Suspended Residue	Turbidity	TKN	NO2 + NO3	TP
1995	63.00	7.83	NA	0.42	1.10	0.18
1996	62.50	5.33	NA	0.50	1.04	0.13
1997	103.42	5.83	NA	0.41	1.12	0.14
1998	88.17	8.17	NA	0.41	0.91	0.16
1999	100.33	6.45	6.63	0.36	1.04	0.17
2000	105.00	3.80	5.73	0.37	0.43	0.17
2001	113.92	6.00	8.27	0.48	1.45	0.18
2002	120.67	4.95	7.37	0.45	1.16	0.22
2003	89.25	5.78	9.87	0.50	1.14	0.10
2004	87.42	11.28	16.92	0.47	1.34	0.12
2005	127.67	10.45	12.72	0.41	1.73	0.15
2006	125.42	6.10	7.13	0.46	1.94	0.13

Table 5-7. Trimmed mean of Middle Creek water quality readings

Year	Conductance	Suspended Residue	Turbidity	TKN	NO2 + NO3	TP
1996	136.67	5.83	NA	0.56	0.85	0.19
1997	260.92	6.17	NA	0.70	1.62	0.26
1998	225.50	12.17	NA	0.79	2.66	0.47
1999	246.08	12.12	9.42	1.02	0.57	0.42
2000	265.42	8.50	11.60	0.65	0.08	0.34
2001	276.00	4.83	11.73	0.68	1.38	0.58
2002	366.25	3.48	7.92	0.85	1.68	0.68
2003	111.17	9.98	21.00	0.63	1.08	0.30
2004	113.00	5.62	13.50	0.77	1.44	0.46
2005	169.42	9.10	20.67	0.73	1.30	0.37
2006	203.33	5.33	8.08	0.74	1.06	0.42

Table 5-8. Trimmed mean of Smith Creek water quality readings

Year	Conductance	Suspended Residue	Turbidity	TKN	NO2 + NO3	TP
1995	63.00	7.83	NA	0.42	1.10	0.18
1996	62.50	5.33	NA	0.50	1.04	0.13
1997	103.42	5.83	NA	0.41	1.12	0.14
1998	88.17	8.17	NA	0.41	0.91	0.16
1999	100.33	6.45	6.63	0.36	1.04	0.17
2000	105.00	3.80	5.73	0.37	0.43	0.17
2001	113.92	6.00	8.27	0.48	1.45	0.18
2002	120.67	4.95	7.37	0.45	1.16	0.22
2003	89.25	5.78	9.87	0.50	1.14	0.10
2004	87.42	11.28	16.92	0.47	1.34	0.12
2005	127.67	10.45	12.72	0.41	1.73	0.15
2006	125.42	6.10	7.13	0.46	1.94	0.13

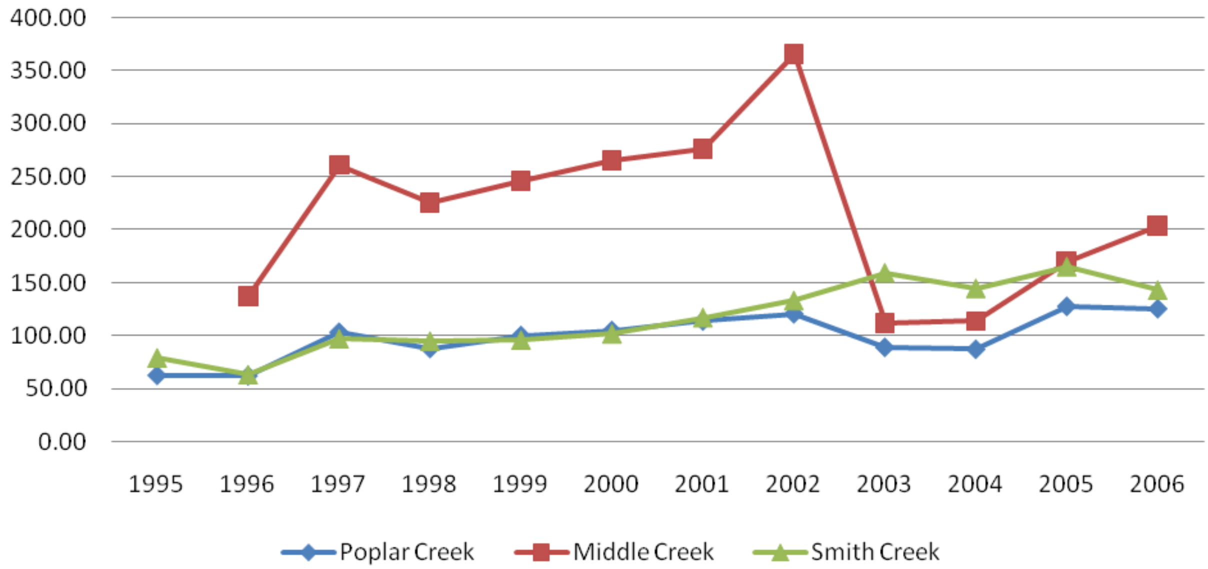

Figure 5-1. Trimmed mean results graph: Conductance

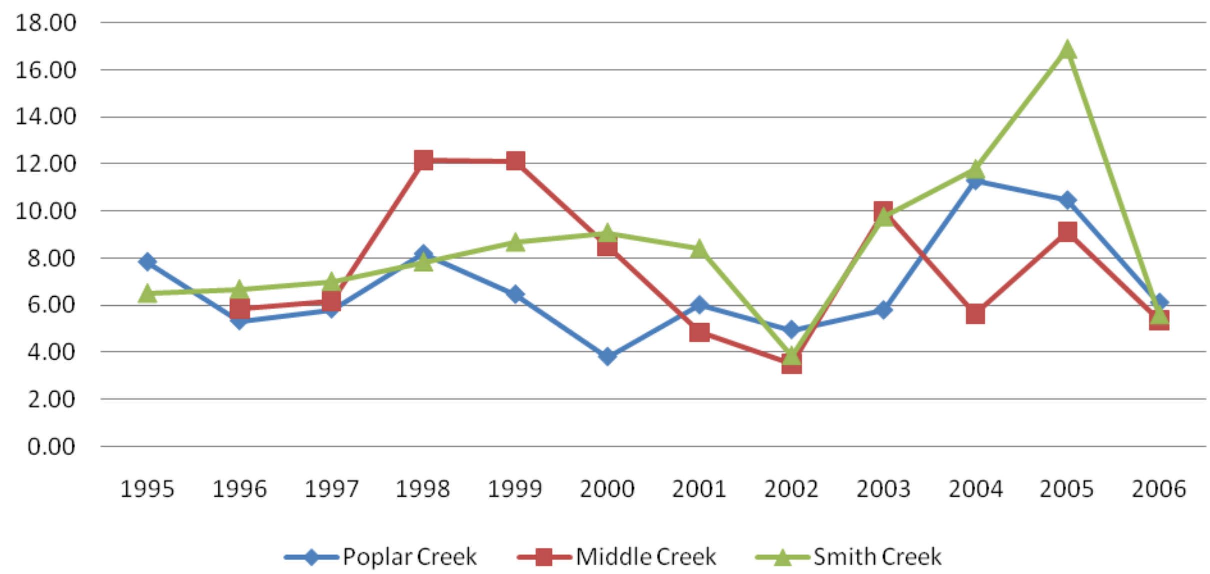

Figure 5-2. Trimmed mean results graph: Suspended Residue

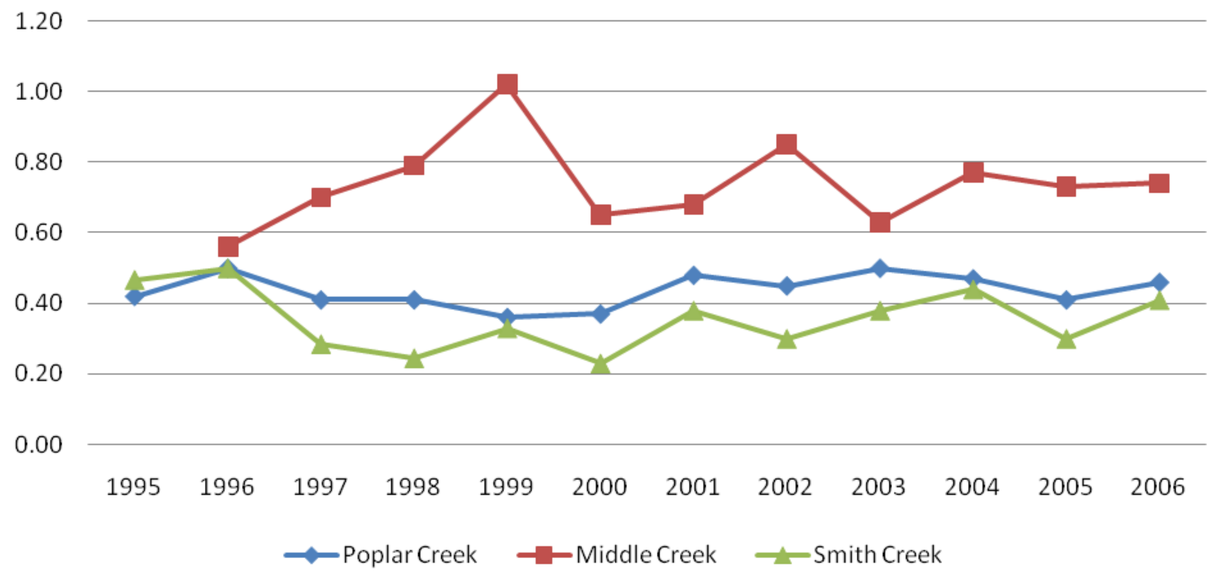

Figure 5-3. Trimmed mean results graph: Total Kjeldahl Nitrogen (TKN)

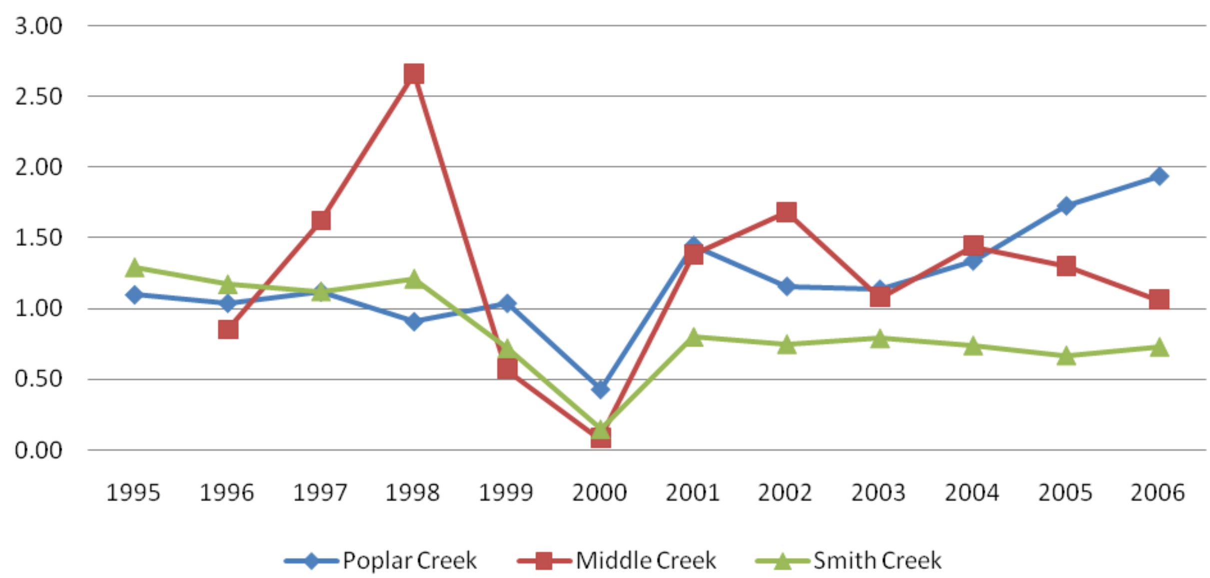

Figure 5-4. Trimmed mean results graph: Nitrite (NO2) + Nitrate (NO3)

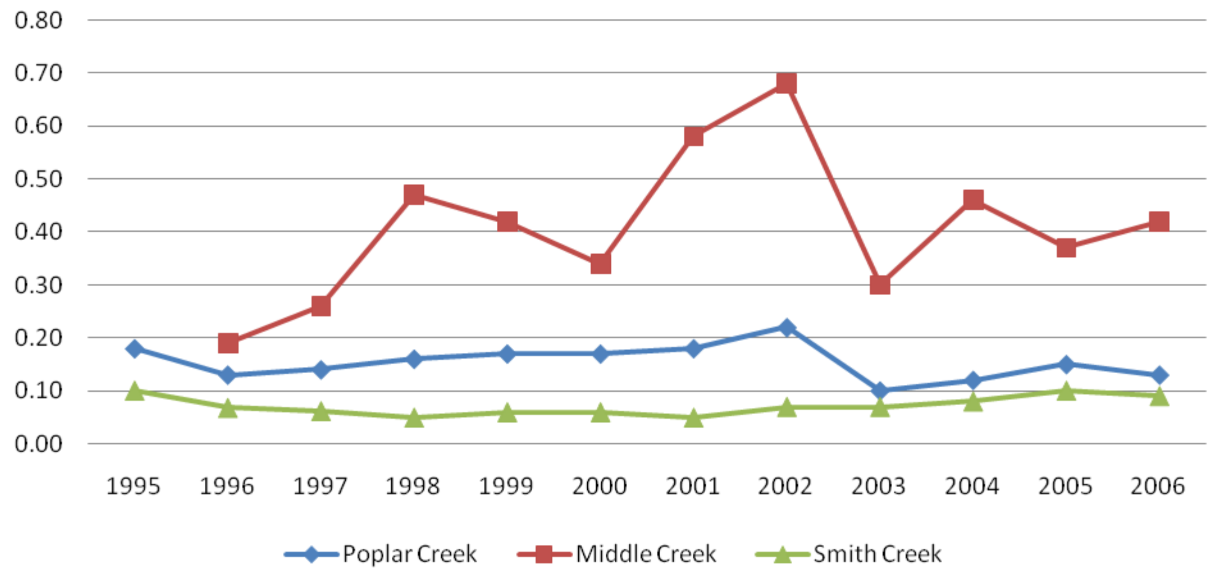

Figure 5-5. Trimmed mean results graph: Total Phosphorus (TP)

Table 5-10. Trimmed mean analysis results

Variable	Increasing Trimmed Mean Base Year to 2005	Decreasing Trimmed Mean Base Year to 2005
Conductivity	Poplar Creek, Middle Creek, Smith Creek	None
Suspended Residue		Poplar Creek, Middle Creek, Smith Creek
TKN	Poplar Creek, Middle Creek	Smith Creek
NO3 + NO2	Poplar Creek, Middle Creek	Smith Creek

CHAPTER 6
DISCUSSION

Discussion of Findings and Methods

This study has quantified the growth of impervious surface resulting from development in four watersheds in rapidly urbanizing parts of Wake County, North Carolina. Local information has been collected regarding the average rates of impervious surface by land use in development between 1999 and 2005. In addition, this study has shown that certain facets of the urban environs, including rooftops and pavement for driveways and parking lots are principal contributors to the amount of impervious surface in suburban watersheds. Significant reductions in the amount of impervious surface in new developments are achievable by encouraging the incorporation of pervious pavements and green roofs in new developments.

Quantifying Impervious Surface Growth

This study found that urban growth in developing areas of Wake County, North Carolina has lead to significant increases in impervious surface. It was found that 13.54%, or 4,404.01 acres of land in the study areas is covered by impervious surface. Of this, it was estimated that at least 996.87 acres of impervious surface was constructed between 1999 and 2005. In the four urbanizing watersheds that were investigated there was a 22.6% growth in impervious surface between 1999 and 2005. Literature suggests that this growth, 43.4 million square feet of impervious surface, will have significant impacts on the hydrology of the watersheds and the health of aquatic ecosystems.

Comparison of Impervious Surface Rates by Land Use

The study also has shown that impervious surface rates developed by the SCS are accurate estimations of residential impervious surface rates in Wake County, NC. Impervious surface rates by land use were quantified for development that took place between 1999 and 2005. For five residential land use categories the average impervious surface rates as measured in the study areas were within a few percentage points of the impervious surface rates found by the SCS. Only for three classes—residential land use with a density greater than 7 units per acre, commercial and industrial—were impervious surface rates significantly different. The differences in these rates may be due to the fact that the study areas were suburban in character. Measuring ISC rates in more urban areas may affirm the SCS figures. Also the study areas were primarily residential in nature, with only 63 commercial parcels and 60 industrial parcels. A sampling of more commercial and industrial parcels may result in different impervious surface rates for those land use categories.

Benefits of Encouraging Green Roofs and Pervious Pavements

Using information collected by the City of Olympia, WA this study estimated the amount of impervious surface growth that can be attributed to rooftops and driveways or parking areas in the study areas. It was found that 308.63 acres of impervious rooftops, driveways and parking areas were constructed between 1999 and 2005. This accounts for 7% of all impervious surfaces in the study areas. If all new residential development was required to use pervious pavement, pavers or concrete for parking areas and driveways, impervious surface growth between 1999 and 2005 would have been reduced by nearly 1.4 million square feet. If just 20% of all rooftops were required to be vegetated, it would have reduced the total amount of impervious surface in the study areas by 1.1 million square feet. This data shows that local governments can have a significant impact in the amount of runoff generated by new developments by adopting policies that provide incentives to developers that utilize construction methods that have the potential to mitigate increases in impervious surfaces.

Roads and Impervious Surface

Impervious surface increases in tandem with road density (see Figure 6-1). In three out of four watersheds road density increases of over 20% corresponded with an increase in impervious surface of over 20%. Roads contribute directly to this growth in ISC due to the face that transportation related impervious areas can account for 70% of total impervious surface area (Arnold & Gibbons 1996, p. 248). Not only do roads contribute directly to ISC growth, as roads get built, there is better access to parcels of land which enables more intense development. Larger shopping centers and more dense residential developments are enabled by the reduced travel times resulting from more connectivity. The fact that transportation planners seek to increase connectivity and capacity, in order to reduce congestion, conflicts with the need to limit impervious surfaces in order to protect water quality.

This study did not directly measure the amount of impervious surface that could be saved using alternative design standards such as headwater streets. Although additional study is needed to quantify the benefits of adopting alternative design standards, it can be assumed that impervious surface attributable to new streets constructed to serve recently constructed residential neighborhoods contributes significantly to the total amount of ISC in a watershed. Accordingly it would be beneficial for growing municipalities in the Piedmont to investigate the adoption of revised street standards that allow for narrower street widths on low volume residential feeder roads.

Water Quality and Impervious Surface

Research has proven that impervious surface is a good indicator of the health of aquatic systems. This study used water quality data collected between 1995 and 2005 to detect trends in readings of key parameters, including conductivity, TKN, Nitrate + Nitrite, suspended residue, and total phosphorus. There were statistically significant positive trends found in total phosphorus readings in Middle Creek, conductance and total nitrogen readings in Poplar Creek, and conductance readings in Smith Creek. The study found only one statistically significant negative trend. This analysis supports the hypothesis that water quality is negatively impacted by urban growth. As this research was limited to investigating trends in levels of water quality measurements, it does not address impacts to the biotic community. Analysis of invertebrate and fish community sampling data collected by the Division of Water Quality could provide more insight into changes that may be detectable only through measuring the subtle effects of increases of impervious surface over a relatively short timeframe.

Feature Extraction Using Feature Analyst

This study demonstrated that Feature Analyst, an extension to ArcGIS created by Visual Learning Systems can be used to extract impervious surface from large watersheds. The semi-automated extraction process used in the study included automated extraction based on a watershed specific model followed by manual editing. This method enabled the investigation of larger study areas than would be possible if manual digitization was employed.

Using one training set to develop a model used to extract features from a number of large watersheds led to a significant amount of clutter. Watershed specific model improved results, however classification still required manual cleanup, which added time to the processing. Even with the added time for manual cleanup, this study illustrates that extraction of impervious surface using Feature Analyst is faster than manually digitizing. Classification results could potentially have been improved to the point that manual cleanup was not required by improving training sets, or developing training sets over multiple images. Alternatively, the study watersheds could have been subdivided into catchments and individual models could have been developed for these catchments. Time was a factor due to hardware limitations on the computer used for model development. Rather lengthy delays (~5 minutes) resulted when selecting incorrect and correct classification results using the Remove Clutter Tool in Feature Analyst.

It was difficult to develop a model that would correctly classify weathered rooftops and red rooftops. These problems were due to the fact that the color signatures of these features resembled those found in natural features. Bare fields and leaf-off stands of deciduous trees also presented problems due to the fact that these features were shades of gray also found in parking lots, sidewalks and rooftops. These false classifications could potentially have been removed by perfecting training sets. Time constraints did not allow for this to be explored in this study.

Opportunities for Future Research

Although this study determined that using Feature Analyst could increase the area in which impervious surface could be quantified, it remains to be seen if extraction models can be produced that result in a high level of accuracy when applied to large watersheds. The mixes of land use and land cover in rural areas of watersheds seem to result in misclassifications. Ideally a methodology for developing impervious extraction models for large watersheds could be researched in order to enable the expeditious development and revision of models and subsequent application to new sets of high resolution aerials.

This study estimated the amount of impervious surface growth due to roads (See Figure 6-1). Available datasets may have limited results. Spatial accuracy of existing road inventories produced and maintained by Wake County may have caused inaccuracies. In addition, an underestimation of ISC due to roads may have resulted from the lack of available road width data. A focused study of ISC growth resulting from expansion of road networks would be beneficial.

Additional research is needed regarding ISC rates of commercial and industrial properties. This study investigated impervious surface rates on a limited number of commercial and industrial parcels. A focused study which details the rates of impervious surface on these land uses in different contexts would provide insight on trends and potential differences between industrial and commercial properties in rural, suburban and urban areas.

Finally, there is a need for refined percentage of impervious surface attributable to different facets of the built environment. This study used estimates produced by the City of Olympia, WA and generalized to match land use categories used by the Soil Conservation Service. Although these figures can be used to estimate percentages of impervious surface in the form of transportation related facilities and rooftops, they were produced based on a small sample size. In addition, there may be regional differences in building trends which would prove the use of the estimation technique employed in this study inaccurate. It is possible that a feature extraction software package, such as Feature Analyst could be trained to classify ISC in individual developments by distinguishing between rooftops, driveways and streets. This would enable the efficient analysis of building trends in a city or region. Accordingly the percentages of ISC found in the Olympia, WA study, as well as the methodology employed in this study could be validated or refined.

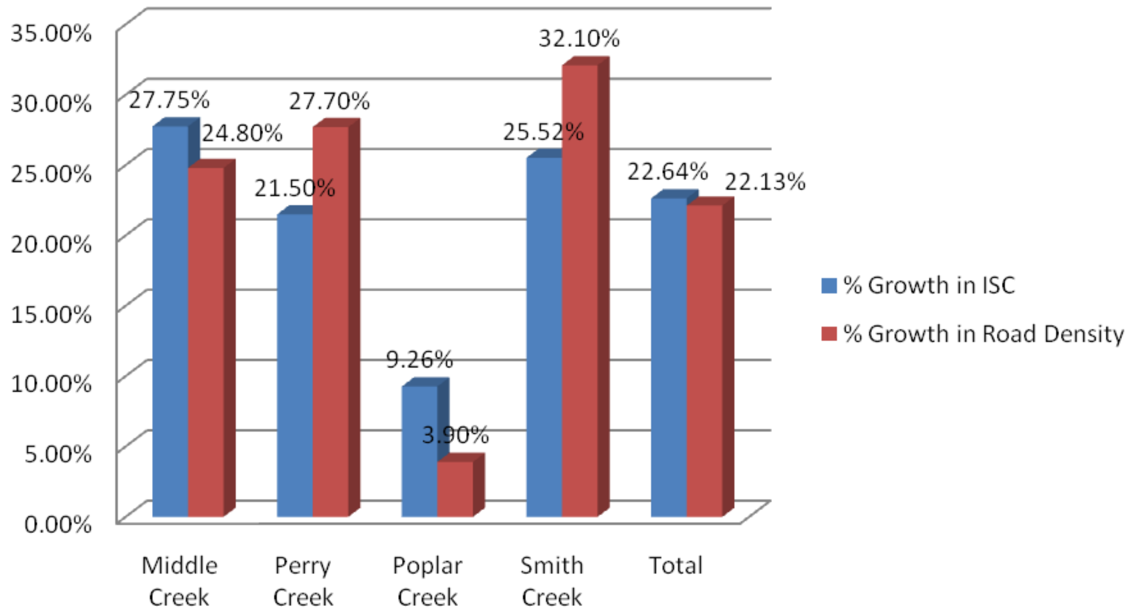

Figure 6-1. Growth in impervious surface and road density

CHAPTER 7
CONCLUSION

This study has analyzed recent development in four watersheds in Wake County. Growth in impervious surface was measured using Feature Analyst, water quality trends were measured using a Mann-Kendall test and monthly water quality data, and opportunities to incorporate green roofs and pervious pavements to mitigate negative impacts were identified. Suburban development can rapidly increase impervious surface coverage. In a period of seven years, 1999-2005, impervious surface in the study areas grew by 996 acres. Development in the study areas resulted in as much impervious surface as building a parking lot a mile and a half wide. This study has determined that impervious surface rates developed by the Soil Conservation Service can be used to accurately estimate impervious surface for most land uses in existing or proposed developments in the North Carolina Piedmont, particularly in areas on the urban/rural fringe on the edge of North Carolina's Main Street. This finding can be helpful to local and regional governments tasked with estimating current or future impervious surface.

The water quality analysis conducted as a component of this thesis found five instances of decreasing water quality and one instance of improving water quality. This supports the initial hypothesis that impervious surface growth negatively impacts water quality. Further studies that investigate the relationship between impervious surface growth, road density, and biological indicators of the health of aquatic communities in the North Carolina Piedmont would be helpful.

Design will be an important determinant of the built environment's future effects on aquatic systems. This study has shown that the incorporation of green roofs and pervious pavements in new development can significantly reduce the amount of impervious surface in new development. Local government policy can encourage the incorporation of green roofs and pervious pavements by providing incentives or amending ordinances to require these types of low impact development features. Ideally local governments could require that a certain percentage of pavements in residential neighborhoods be porous pavement or pervious pavers. Sidewalks and driveways rarely bear extreme loads and would be ideal candidates for these features. Commercial and industrial buildings could be required to incorporate green roofs on a certain percentage of buildings. Requirements and incentives could vary based on percentage of impervious surface on site, current health of the watershed, and additional factors that affect the development's potential impacts on stormwater. Implementing such policies may be problematic due to the fact that additional technical expertise and cost may be accrued. However, a departure from existing trends is necessary in order to mitigate the impacts of projected growth.

The method of feature extraction employed in this study could be expanded and applied to a larger geographic region, but may require additional time for model development and manual editing. One of the drawbacks of using Feature Analyst is the amount of time it requires to create and improve extraction models. Depending on the land use mix and the quality of training sets utilized there may be a need for manual editing to remove false positives, as in this study. Using a Mann-Kendall trend test on a larger body of water may require adjustments in order to account for intervening variables. A larger drainage area could result in more point source polluters upstream of sampling stations. Significant nutrient inputs from point source polluters, including municipal wastewater treatment plants would have to be taken into account.

The methods employed in this study could be applied successfully in many different geographic regions in the United States. Areas with limited tree cover, similar soils, and hydrology would be ideal candidates. Although the effect of tree cover on accuracy of feature extraction was not investigated in this study, a cursory inspection of extraction results indicates increased tree cover may result in reduced accuracy when using Feature Analyst and color aerial photography. This may be able to be avoided by using color infrared imagery. The methodology employed assumed that soils and topography of the study areas result in predictable overland flow, channel initiation and stream formation. It is also assumed that all impervious surface is hydrologically connected to stream networks and impacts water quality in the streams sampled. This assumption would not necessarily hold true in a region with different soils and hydrologic patterns. For instance, areas of northern Florida have soils of a mixture of sand and clay as well as hydrologic systems similar to the North Carolina Piedmont, whereas other areas of Florida, including the west side of Alachua County and other areas of Florida have karst topography and rapidly drained sandy soils which result in limited surface flow. Accordingly, effects of impervious surface on water quality and runoff patterns will be significantly different and methods used to determine the relationship between impervious surface and water quality need to be adjusted accordingly.

APPENDIX A

PARCEL CLASSIFICATION DOCUMENTATION

APA Activity Codes to NRCS Land Use Category Lookup Table

DESC	NRCS_USDA_1986
Residential Activities	Residential
Household Activities	Residential
Transient Living	Residential
Institutional Living	Residential
Household With Business Use	Residential
Shopping, Business, Or Trade Activities	Commercial
Shopping	Commercial
Goods-Oriented Shopping	Commercial
Service-Oriented Shopping	Commercial
Retail Combination	Commercial
Restaurant-Type	Commercial
Restaurant-Type With Drive-Through	Commercial
Office Activities	Office
Office Activities With High Turnover Of People	Office
Office Activities With High Turnover Of Automobiles	Office
Industrial, Manufacturing, And Waste-Related Activities	Industrial
Plant, Factory, Or Heavy Goods Storage Or Handling Activities	Industrial
Primarily Plant Or Factory-Type Activities	Industrial
Primarily Goods Storage Or Handling Activities	Industrial
Laundry Activities	Commercial
Solid Waste Management Activities	Industrial
Solid Waste Collection And Storage	Industrial
Landfilling Or Dumping	Other
Waste Processing Or Recycling	Industrial
Construction Activities (Grading, Digging, Etc.)	Industrial
Research Or Laboratory Activities	Office
Social, Institutional, Or Infrastructure-Related Activities	Civic
School Or Library Activities	Education
Classroom-Type Activities	Education
Training Or Instructional Activities Outside Classrooms	Education
Other Instructional Activities Including Those That Occur In Libraries	Education
Child Day Care Activities	Commercial
Emergency Response Or Public-Safety-Related Activities	Civic

DESC	NRCS_USDA_1986
Fire And Rescue-Related Activities	Civic
Police, Security, And Protection-Related Activities	Civic
Emergency Or Disaster-Response-Related Activities	Civic
Activities Associated With Utilities (Water, Sewer, Power, Etc.)	Industrial
Water-Supply-Related Activities	Other
Sewer-Related Control, Monitor, Or Distribution Activities	Other
Power Generation, Control, Monitor, Or Distribution Activities	Industrial
Power Generation, Storage, Or Processing Activities	Industrial
Telecommunications-Related Control, Monitor, Or Distribution Activities	Industrial
Natural Gas Or Fuels-Related Control, Monitor, Or Distribution Activities	Industrial
Mass Storage, Inactive	Other
Water Storage	Other
Storage Of Natural Gas, Fuels, Etc.	Other
Storage Of Chemical, Nuclear, Or Other Materials	Other
Health Care, Medical, Or Treatment Activities	Commercial
General Medical Care	Commercial
Veterinary Medical Care	Commercial
Interment, Cremation, Or Grave Digging Activities	Other
Military Base Activities	Other
Ordnance Storage	Other
Range And Test Activities	Other
Travel Or Movement Activities	Transportation
Pedestrian Movement	Transportation
Vehicular Movement	Transportation
Vehicular Parking, Storage, Etc.	Transportation
Drive-In, Drive Through, Stop-N-Go, Etc.	Commercial
Truck Transport Terminal	Industrial
Trains Or Other Rail Movement	Transportation
Rail Maintenance, Storage, Or Related Activities	Industrial
Sailing, Boating, And Other Port, Marine And Water-Based Activities	Transportation
Boat Mooring, Docking, Or Servicing	Transportation
Port, Ship-Building, And Related Activities	Industrial
Aircraft Takeoff, Landing, Taxiing, And Parking	Other
Spacecraft Launching And Related Activities	Other

DESC	NRCS_USDA_1986
Mass Assembly Of People	Other
Passenger Assembly	Other
Spectator Sports Assembly	Recreation and Entertainment
Movies, Concerts, Or Entertainment Shows	Recreation and Entertainment
Gatherings At Fairs And Exhibitions	Recreation and Entertainment
Mass Training, Drills, Etc.	Other
Social, Cultural, Or Religious Assembly	Other
Social Assembly	Other
Religious Assembly	Other
Gatherings At Galleries, Museums, Aquariums, Zoological Parks, Etc.	Commercial
Historical Or Cultural Celebrations, Parades, Reenactments, Etc.	Recreation and Entertainment
Leisure Activities	Recreation and Entertainment
Active Leisure Sports And Related Activities	Recreation and Entertainment
Running, Jogging, Bicycling, Aerobics, Exercising, Etc.	Other
Equestrian Sporting Activities	Other
Hockey, Ice Skating, Etc.	Recreation and Entertainment
Skiing, Snowboarding, Etc.	Recreation and Entertainment
Automobile And Motorbike Racing	Recreation and Entertainment
Golf	Recreation and Entertainment
Tennis	Recreation and Entertainment
Track And Field, Team Sports (Baseball, Basketball, Etc.), Or Other Sports	Recreation and Entertainment
Passive Leisure	Recreation and Entertainment
Camping	Recreation and Entertainment
Gambling	Recreation and Entertainment
Hunting	Recreation and Entertainment
Promenading And Other Activities In Parks	Recreation and

DESC	NRCS_USDA_1986
	Entertainment
Shooting	Recreation and Entertainment
Trapping	Recreation and Entertainment
Flying Or Air-Related Sports	Recreation and Entertainment
Water Sports And Related Leisure Activities	Recreation and Entertainment
Boating, Sailing, Etc.	Recreation and Entertainment
Canoeing, Kayaking, Etc.	Recreation and Entertainment
Swimming, Diving, Etc.	Recreation and Entertainment
Fishing, Angling, Etc.	Recreation and Entertainment
Scuba Diving, Snorkeling, Etc.	Recreation and Entertainment
Water-Skiing	Recreation and Entertainment
Natural Resources-Related Activities	Recreation and Entertainment
Farming, Tilling, Plowing, Harvesting, Or Related Activities	Agriculture and Timber
Livestock Related Activities	Agriculture and Timber
Pasturing, Grazing, Etc.	Agriculture and Timber
Logging	Agriculture and Timber
Quarrying Or Stone Cutting	Extraction
Mining Including Surface And Subsurface Strip Mining	Extraction
Drilling, Dredging, Etc.	Extraction
No Human Or Unclassifiable	Other
Not Applicable To This Dimension	Other
Unclassifiable	Other
Subsurface	Extraction
To Be Determined	Other
To Be Determined	Other

Parcel Queries

The following query was used to extract single family residential land uses from the Wake County parcel layer:

"NRCS_USDA_" = 'Residential' AND "TOTUNITS" = 1

The following query was used to extract multi-family residential land uses from the Wake County parcel layer:

"NRCS_USDA_" = 'Residential' AND "TOTUNITS" > 1

The following query was used to extract unclassified residential (where parcel layer may be incorrect) from the Wake County parcel layer:

"NRCS_USDA_" = 'Residential' (where "TOTUNITS" =0)

These parcels were filled with "Unclassified Res"

To split residential NRCS into specific lot sizes the following queries were used:

"NRCS_USDA_" = 'Single Family Residential' and "DU_DEN" < 0.5

"NRCS_USDA_" = 'Single Family Residential' and "DU_DEN" >= 0.5 and "DU_DEN"<1

"NRCS_USDA_" = 'Single Family Residential' and "DU_DEN" >= 1 and "DU_DEN" < 2

"NRCS_USDA_" = 'Single Family Residential' and "DU_DEN" >= 2 and "DU_DEN" < 3

"NRCS_USDA_" = 'Single Family Residential' and "DU_DEN" >= 3 and "DU_DEN" < 4

"NRCS_USDA_" = 'Single Family Residential' and "DU_DEN" >= 4 and "DU_DEN" < 5

"NRCS_USDA_" = 'Single Family Residential' and "DU_DEN" >= 5 and "DU_DEN" <= 7

"NRCS_USDA_" = 'Single Family Residential' and "DU_DEN" > 7

"NRCS_USDA_" = 'Multi-family Residential' and "DU_DEN" < 0.5

"NRCS_USDA_" = 'Multi-family Residential' and "DU_DEN" >= 0.5 and "DU_DEN" <1

"NRCS_USDA_" = 'Multi-family Residential' and "DU_DEN" >= 1 and "DU_DEN" < 2

"NRCS_USDA_" = 'Multi-family Residential' and "DU_DEN" >= 2 and "DU_DEN" < 3

"NRCS_USDA_" = 'Multi-family Residential' and "DU_DEN" >= 3 and "DU_DEN" < 4

"NRCS_USDA_" = 'Multi-family Residential' and "DU_DEN" >= 4 and "DU_DEN" < 5

"NRCS_USDA_" = 'Multi-family Residential' and "DU_DEN" >= 5 and "DU_DEN" <= 7

"NRCS_USDA_" = 'Multi-family Residential' and "DU_DEN" >7

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BIOGRAPHICAL SKETCH

Jake Petrosky was born in Ft. Lauderdale, Florida in 1981. He grew up in Raleigh and Knightdale, North Carolina and graduated from East Wake High School with honors in 1999. Jake attended Appalachian State University and graduated in December of 2003 with university and departmental honors and a degree in community and regional planning, a minor in geography, and a minor in sustainable development. After graduating Jake worked at the Capital Area MPO as a Planning Technician and GIS Analyst/Programmer conducting multi-modal transportation planning, socio-economic forecasting, and environmental analysis for three years prior to attending the University of Florida. As a graduate student at the University of Florida in the Department of Urban and Regional Planning Jake worked at an joint assistantship with the Gainesville Metropolitan Transportation Planning Organization (GMTPO) and the GeoPlan Center. At the GMTPO Jake served as the Efficient Transportation Decision Making (ETDM) coordinator and as project manager for the development of the socio-economic forecasts for the upcoming Long Range Transportation Plan update. During his time at the University of Florida Jake was awarded the WRS Infrastructure & Environment Inc. Award In Memoriam of Mario Ripol for Outstanding Achievement for Planning Information and Analysis. During his spare time he volunteered for the Conservation Trust for Florida and acted as safety coordinator for the University of Florida Outdoor Adventure Recreation Club (OAR).