THE EFFECT OF URBANIZATION ON STREAM-FLOW PATTERNS ON BIG CREEK WATERSHED, ALPHARETTA, GEORGIA

by

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A professional paper submitted in partial fulfillment
of the requirements for the degree

of

Master of Science

in

Land Resources and Environmental Sciences

MONTANA STATE UNIVERSITY

Bozeman, Montana

August 2020

DEDICATION

This work is dedicated to my parents, who immigrated to the U.S from Mexico to provide a better opportunity for their children. Without their sacrifice, I would not have achieved this goal.

To my nieces and nephews, for understanding my constant absence while I completed this degree, may this inspire you to reach your dreams.

To my dog Indy, who sacrificed many walks and always remained by my side, thank you for always being a loyal and faithful companion.

And finally, this is dedicated to my father, who always remained strong and fearless until his passing on May 27, 2019. Witnessing his strength gave me the motivation to continue this to the finish line.

ACKNOWLEDGEMENTS

I would like to acknowledge Dr. Paul Hook for his guidance and support on this project. His expertise knowledge and teachings on the subject of applied watershed hydrology has allowed me to explore the topic of water dynamics and urbanization.

I would like to thank my supervisors for allowing me the opportunity to pursue higher education.

I would also like to thank my colleagues, Tori J. Goehrig, for always providing her support and Michael Perkins for creating my GIS maps for this project.

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ABSTRACT

The natural flow regime, defined as the characteristic pattern of discharge variation in streams and rivers not altered by humans, plays an important role in the ecosystem. The increase in urban development in the U.S. is an important environmental change that alters the landscape and affects the flow regime of streams and rivers. Previous hydrological studies have used different methods to investigate the effects of urbanization on stream flow; these studies have found that urbanization can often lead to an increase in peak flow (largest instantaneous magnitude occurring in a water year), increased flashiness (rapid change in magnitude), and reduced baseflow (relatively steady stream-flow primarily maintained by groundwater between storm runoff events). With increasing urbanization in the southern U.S., my study focused on Big Creek watershed, located in one of the most populated cities, Metro-Atlanta. Several studies have investigated urbanization effects on stream-flow in Metro-Atlanta, but these studies have focused on the Peachtree Creek watershed, a highly urbanized watershed located near downtown Atlanta. In contrast, the Big Creek watershed is a less intensively developed area about 20-35 miles from downtown Atlanta. I used a paired watershed approach with a nearly 60-year period of record to characterize Big Creek discharge before and after urban development and to compare changes in Big Creek to a non-urban reference watershed, Snake Creek. Several hydrological trend analyses and pre- versus post-urbanization comparisons revealed that urbanization altered some features of the flow regime. The post-urban period in Big Creek resulted in an 11% increase in high flow (defined as 5% annual exceedance probability), 25% decrease in low flow (90% annual exceedance probability), 27% decrease in average peak flow, 14% decrease in average baseflow, and a flashier discharge. Current stormwater management strategies within Big Creek target minimizing peak flow events by requiring facilities to control for the 2-year to 100-year flood event. The findings indicate that stormwater management strategies should also aim to restore baseflow and reduce flashiness within the watershed.

INTRODUCTION

Rivers and streams play an important role in ecosystems. Water movement through rivers and streams is the main process that connects the landscape through multiple pathways (Coles et al., 2012). The flow of rivers and streams provides important benefits such as transport of sediment and nutrients, life-cycle cues to aquatic fauna, transport of merchandise, and drinking water supply (USGS, n.d. and EPA, 2012). Stream-flow, also referred as discharge, is the amount of water moving through the watershed in the stream channel (USGS, n.d.). Stream-flow is always changing and is primarily affected by weather (USGS, n.d.). The dynamic interaction between discharge, channel slope, sediment load and sediment size constantly change the shape of rivers and streams (Wampler, 2012). A stream's dynamic equilibrium reflects its characteristic patterns of stream-flow, known as the natural flow regime (Poff et al., 1997). The natural flow regime is comprised of five main characteristics: *magnitude, frequency, duration, timing*, and *rate of change or flashiness* (Poff et al., 1997).

- *Magnitude* is the amount of water moving past a fixed location per unit of time in any given interval. The maximum and minimum magnitude of flow varies with watershed size and climate.
- *Frequency* is how often a flow above a given magnitude recurs over a specified time interval. For any specific stream, the frequency of occurrence of high flows is inversely related to flow magnitude.
- *Duration* is the period of time associated with a specific flow condition.

- *Timing* or *predictability* of flows of defined magnitude refers to the regularity in which they occur. The regularity can be defined formally and informally and in reference to different time scales.
- *The rate of change* or *flashiness* is how quickly flow changes from one magnitude to another. "Flashy" streams have a rapid rate of change whereas "stable" streams have a slow rate of change.

Human-mediated activities such as hydroelectric power generation, water diversion, and water withdrawal can directly alter the five critical components of the natural flow regime (EPA, 2012), which results in a shift in sediment transport and deposition, floodplain land use, and high and low stream flow (EPA, 2012). However, other forms of human mediated activities such as urbanization can directly and indirectly alter the natural flow regime by altering runoff processes.

Urban development has vastly increased and has been described as an important environmental change in the United States (Coles et al., 2012). The percentage of the U.S. population living in urban areas is projected to increase to 84% by the year 2030 (Rosburg et al., 2017). Urban development can indirectly affect the natural flow regime by developing alongside rivers, contributing to the loss of wetlands and floodplains, and by expanding the total impervious area in watersheds (Driscoll et al., 2010). The conversion of naturally vegetated areas to urban development can have significant implications on the landscape (Rosburg et al., 2017). Landscape changes from an urbanized environment include reduced vegetation, increase in engineered storm drainage networks, and increase in impervious surface (Martin et al., 2012). By altering the watershed hydrology through urbanization, the stream flow magnitude, timing, and rate of change are affected (EPA, 2012). The effects of urbanization on watershed hydrology can result in increased runoff, larger flood peaks, increased stream bank erosion, decreased

infiltration, and decreased elapsed time between rainfall and runoff, also known as lag time (Martin et al., 2012; Rosburg et al., 2017; and Peters et al., 2001). Other effects of urbanization on watershed hydrology include altered groundwater levels and altered stream channel morphology (Martin et al., 2012; Rosburg et al., 2017; and Peters et al., 2001). These hydrologic changes from urbanization can affect ecosystem benefits and processes.

In the U.S., the southern region is considered one of the most rapidly urbanizing areas in the nation (O'Driscoll et al., 2010). In year 2000, urban residents made up 72% of the total population of the southern U.S. (O'Driscoll et al., 2010). Metro-Atlanta is one of the more populous metropolitan areas in the southern region (O'Driscoll et al., 2010). Due to its large population growth and shift from rural land to urban land over large areas (Wight et al., 2012), my study examined the effects of urbanization on stream-flow in a Metro-Atlanta watershed.

Hydrologic studies analyzing stream-flow changes in urbanized environments tend to compare runoff event hydrographs, peak flow, flashiness, baseflow, and stream-flow variability in urbanized versus non-urbanized environments (Rosburg et al., 2017) while attempting to account for the confounding effects of precipitation differences. The hydrologic studies discussed below use several different methodologies to evaluate the effects of urbanization on streamflow.

Rosburg et al. (2017) investigated the effect of urbanization by analyzing eight urban and rural watersheds that were less than 200 km^2 in size with mean elevations less than 300 m above sea level. In the study, trends in annual flow duration curves, the 99%, 98%, 95%, 90%, 75%, 50%, 25%, and 10% annual exceedance probabilities, an index in flashiness, and baseflow in urban and rural watersheds in the Puget Sound region of Washington were evaluated for the years 1960 to 2010. The flow duration curves in the urban watersheds were characterized by

increased high flows and low flow for each flow duration curve, but trends were only statistically significant in two of the four urban watersheds (Rosburg et al., 2007). Additionally, all four urban watersheds had statistically significant increases in flashiness (Rosburg et al., 2007). Three of the four urban watersheds showed a statistically significant decreasing trend in baseflow, likely due to increasing trends in storm event runoff (Rosburg et al., 2007). The rural watersheds generally showed decreasing trends in flows for each exceedance probability, decreased baseflow, and increased flashiness, although most trends were not significant (Rosburg et al., 2017). The authors concluded that the hydrologic changes within the urban watersheds were likely due to increased impervious surface area from urbanization, whereas changes in the rural watersheds were likely due to reductions in stream-flow from groundwater extraction for agricultural and municipal purposes, which also affected the flashiness index (Rosburg et al., 2017).

Peters & Rose (2001) also used a multiple watershed approach. They analyzed annual runoff, peak flow, low-flow discharge, and baseflow discharge in four watersheds ranging from urbanized to less urbanized, and non-urbanized watersheds in Metro Atlanta from 1958 to 1996. The study found that baseflow, the relatively steady flow maintained between runoff events, decreased in response to urbanization. In support of baseflow findings, the daily mean groundwater levels from two long-term urban wells were compared to a non-urban well. The ground-water data indicated that monthly ground-water levels within the urban watershed correlated with the ground-water seasonal variability with the non-urbanized watersheds (Peters & Rose, 2001). However, the groundwater level in the urban wells decreased overall compared to the non-urban well, suggesting that urbanization and increased storm event runoff decreased groundwater recharge (Peters & Rose, 2001). Baseflow is often derived from groundwater. The

reduction of baseflow in some urban watersheds is thought to occur through reduced infiltration of water from precipitation into subsurface soil and rock due to impervious surfaces which cause increased storm runoff and reduced groundwater recharge (USGS, n.d.; Rosburg et al., 2017; O'Driscoll et al., 2010;and Liu et al., 2013). However, baseflow changes in response to urbanization have not been completely consistent. Artificial mechanisms such as stormwater infiltration basins, detention ponds, leaky sewer pipes, and leaky water mains can lead to an increase in groundwater recharge following urbanization (O'Driscoll et al., 2010).

Others investigating the effects of urbanization have incorporated a 'pre-urban' and 'post-urban' contrast. For example, Sheng and Wilson (2008), analyzed 20 watersheds in the Los Angeles Metropolitan region that were less than 300 km^2, had more than 20 years of discharge data, and were not affected by dams or reservoirs. The study analyzed flood behavior, quantified as annual peak flow, from 1921 to 2000 (Sheng and Wilson, 2008). Similar to Rosburg et al. (2017), the degree of urbanization of the watersheds was determined using population density data and impervious surface landcover data. This study compared the nearly 80-year period of record in a 'prior' and 'post urban' development timeframe for three of the most developed watersheds and incorporated trend analysis (Sheng and Wilson, 2008). To establish that stream-flow changes were not due to precipitation changes, Sheng and Wilson (2008) used the Mann-Kendall non-parametric statistical test to identify significant trends in annual rainfall and peak discharge. There were no significant trends in annual rainfall in the 80-year time period with the exception of one watershed (Sheng and Wilson, 2008). Four of the five urban watersheds, including a moderately urbanized watershed, showed a statistically significant increasing trend for peak discharge (Sheng and Wilson, 2008). The prior versus post-urban comparison analyzed peak flow frequency distributions for years before and after 1960. The

three most urban watersheds had increases in magnitudes of peak discharge at 2, 10, and 50-year recurrence intervals compared to the prior-urbanization period of record (Sheng and Wilson, 2008). Long-term increases in annual peak flows were correlated with increases in population density, which were correlated with impervious areas. Because a significant trend in precipitation was not detected, Sheng and Wilson (2008) concluded that changes in streamflow patterns were due to urbanization and were not due to precipitation.

In contrast to studies that compare multiple watersheds, some hydrological studies focus on a single urban watershed either because there is only one watershed with adequate stream-flow data in a given urban area or because management questions focus on a specific watershed. For example, Chung et al. (2019) examined one urbanized watershed with four stream gauges in Seoul, South Korea and evaluated storm runoff as a fraction of precipitation, runoff lag times, and baseflow using various hydrograph analysis and modeling methods.

Paired watershed studies have also been used to compare water balance and hydrology between two watersheds. A paired watershed study involves using neighboring or nearby watersheds, one as a control and the other as the treatment (Van Loon et al., 2019). The purpose of comparing nearby watersheds over the same period of record is to account for climatic variability so that differences in hydrology can be attributed to the disturbance treatment (Van Loon et al., 2019). Some paired watershed studies have also incorporated a pre-disturbance period to ensure similarity in hydrology between the watersheds before the disturbance treatment (Van Loon et al., 2019). In their paired watershed study, Boggs and Sun (2011) found that the urban watershed had higher annual water yield, peak flow, storm flow, and baseflow compared to the forested watershed. They noted that although the watersheds were located in different counties and therefore not considered “neighboring” watersheds, the confounding effects of

differences in soil types and geology were likely minimal since overall watershed drainage and permeability were similar (Boggs and Sun, 2011). This study illustrates a basic challenge with paired watershed studies that use existing gauged watersheds that were not originally set up as experimental watersheds, are not replicated, and did not have land use treatments assigned randomly. It is up to the researchers to find two watersheds that are as comparable as possible except as affected by land use and to convince readers that the comparison is reasonable.

Finally, flashiness is an important criterion used to characterize urban watersheds and a central concept to this study. Flashiness is the amount of rapid short-term changes in stream-flow and is quantified with the Richards-Baker Flashiness Index (R-B Index) (Fongers, 2012). Fongers (2012) investigated flashiness on 308 stream gauges in Michigan watersheds and found that the R-B flashiness values within the watersheds ranged from 0.005 to 1.009. The flashier streams (i.e. higher R-B index values) were located near the southeastern portion of the Lower Peninsula and less flashier streams were located in the northern portion of the Lower Peninsula; flashier streams coincided with developed land-use and heavy soils and vice versa for less flashier streams (Fongers, 2012). Rosburg et al. (2017) also found that flashiness had an increasing relationship with population density. Despite these findings, Fongers (2012) noted that developed land does not always correlate with flashier streams. Fongers (2012) concluded that the relationship between impervious cover and stream quality is not fixed, but rather variable. In fact, stream quality was found to be more variable in watersheds with less than 10% impervious cover (Fongers, 2012).

Objective:

My study analyzed the effects of urbanization on the flow regime in an urban watershed, Big Creek watershed, located in Metro-Atlanta near Alpharetta, Georgia. I selected Big Creek

watershed for study due to the quality of available data and documented history of land-use change.

Several previous hydrological studies have investigated urbanization effects on stream-flow in Metro-Atlanta, but these studies have focused on Peachtree Creek watershed, a highly urbanized watershed located near downtown Atlanta. For example, Ferguson and Suckling (1990) analyzed rainfall-runoff relationships in Peachtree Creek watershed. Following Ferguson and Suckling (1990), Peters and Rose (2001) analyzed annual runoff, peak flow, low-flow discharge, and baseflow in four Metro-Atlanta watersheds, with Peachtree Creek as the highly urbanized watershed and Big Creek watershed as the less urbanized watershed. In a more recent study, Diem et al. (2018) investigated trends in stream-flow patterns in eight Metro-Atlanta watersheds, including Peachtree Creek and Big Creek watershed in a 20-year period from 1986 to 2015. At the time of these studies, Big Creek watershed was either categorized as a 'less urbanized' watershed in comparison to Peachtree Creek or the investigated time period did not capture the complete transition from less urban to urban environment.

Therefore, the objective of my study was to characterize Big Creek watershed by using a paired watershed approach with data spanning a six decade period of increasing development. I compared Big Creek to a non-urban reference watershed, Snake Creek, using Snake Creek as a control when comparing Big Creek discharge before and after urban development. I hypothesized that the increase in urban development in Big Creek watershed would lead to an increase in high flow and reduced low flow as represented by the flow duration curve, increased peak flows, reduced base flow, and flashier discharge compared to the non-urban watershed. The results from the hydrological assessments are intended to improve understanding of altered

hydrological patterns in Big Creek watershed and improve current stormwater management strategies to minimize impacts from urbanization.

METHODS

The paired watersheds were selected to be similar in climate, soils, and geology and only differ in the landcover treatment or disturbance within the watershed (Van Loon et al., 2019). Snake Creek watershed was selected as the "control" watershed due to the near similarity to Big Creek watershed and available corresponding data for the same period. The methods used in this study included Landsat satellite images to characterize the transition of development through time and precipitation data to analyze its influence on stream-flow changes. Several stream-flow metrics were used to evaluate changes in discharge that may result from changes in land-use within the watersheds. Complete and available discharge data for Big Creek was from 1960 to 2019, while Snake Creek records began in 1954; therefore, this study analyzed the 1960-2019 period.

Watershed Description

Big Creek watershed is an urbanized watershed located within north Metro-Atlanta and is approximately 189 km^2 (73 mi^2) at the USGS 02335700 Big Creek stream gauge, which is treated as the watershed outlet in this study (USGS, 2016) (Figure 1). The watershed is primarily located within Fulton and Forsyth counties (CDM, 2000). The northern portion of the watershed, approximately 60%, is within Forsyth County and the southern portion of the watershed is located in Fulton County (CDM, 2000). Approximately 73% of the watershed is urbanized (USGS, 2016 and CDM, 2000).

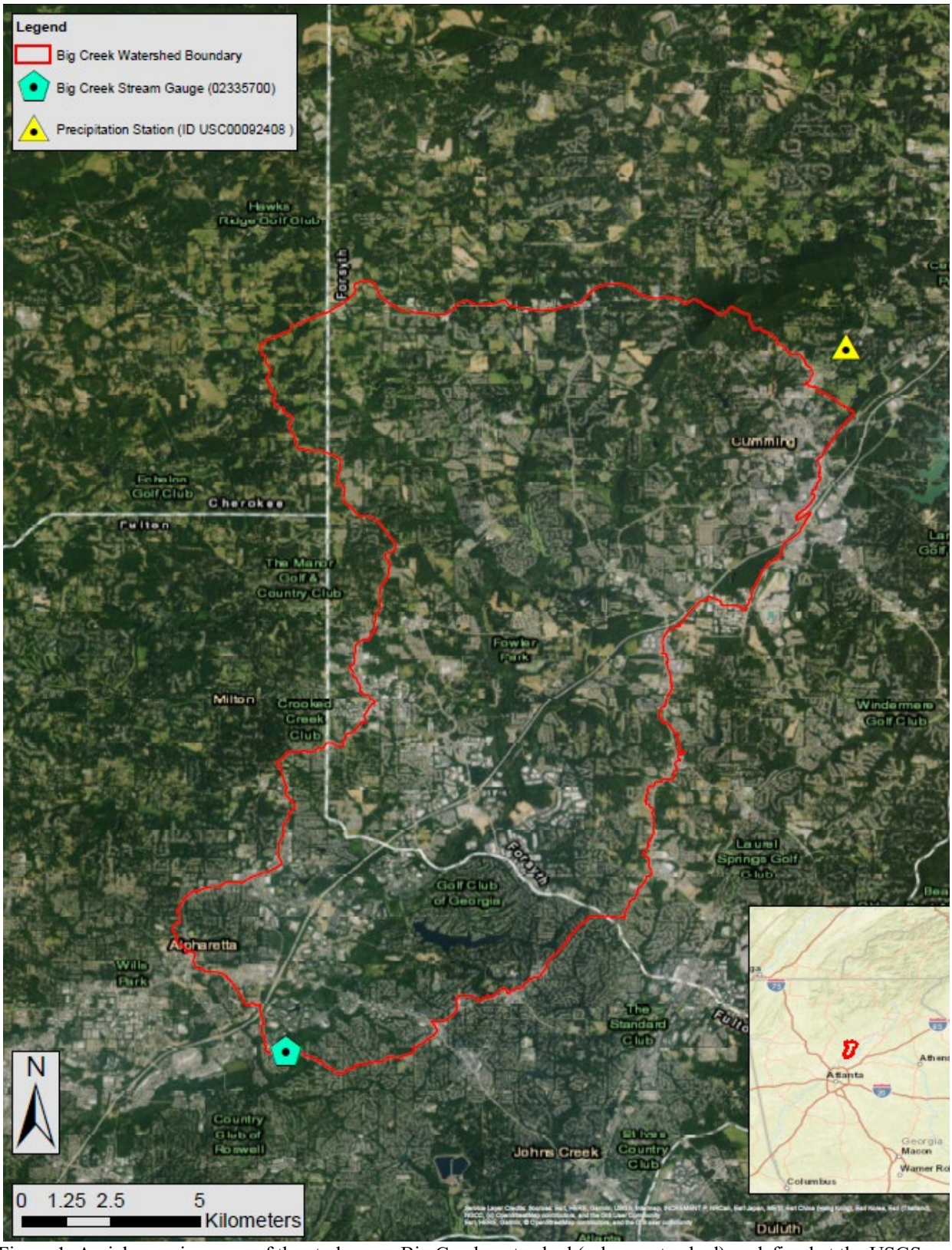

Figure 1. Aerial overview map of the study area, Big Creek watershed (urban watershed) as defined at the USGS stream gauge.

Snake Creek watershed is a rural watershed located east of Carrollton, Georgia, and is approximately 92 km^2 (35.5 mi^2) at the USGS 02337500 Snake Creek stream gauge (USGS, 2016) (Figure 2). Snake Creek watershed is located within Carroll County and is located approximately 30 miles west of Metro-Atlanta and approximately 50 miles southwest of Alpharetta. According to StreamStats, approximately 22.8% of the watershed is urbanized land, but this is likely an overestimate (USGS, 2016).

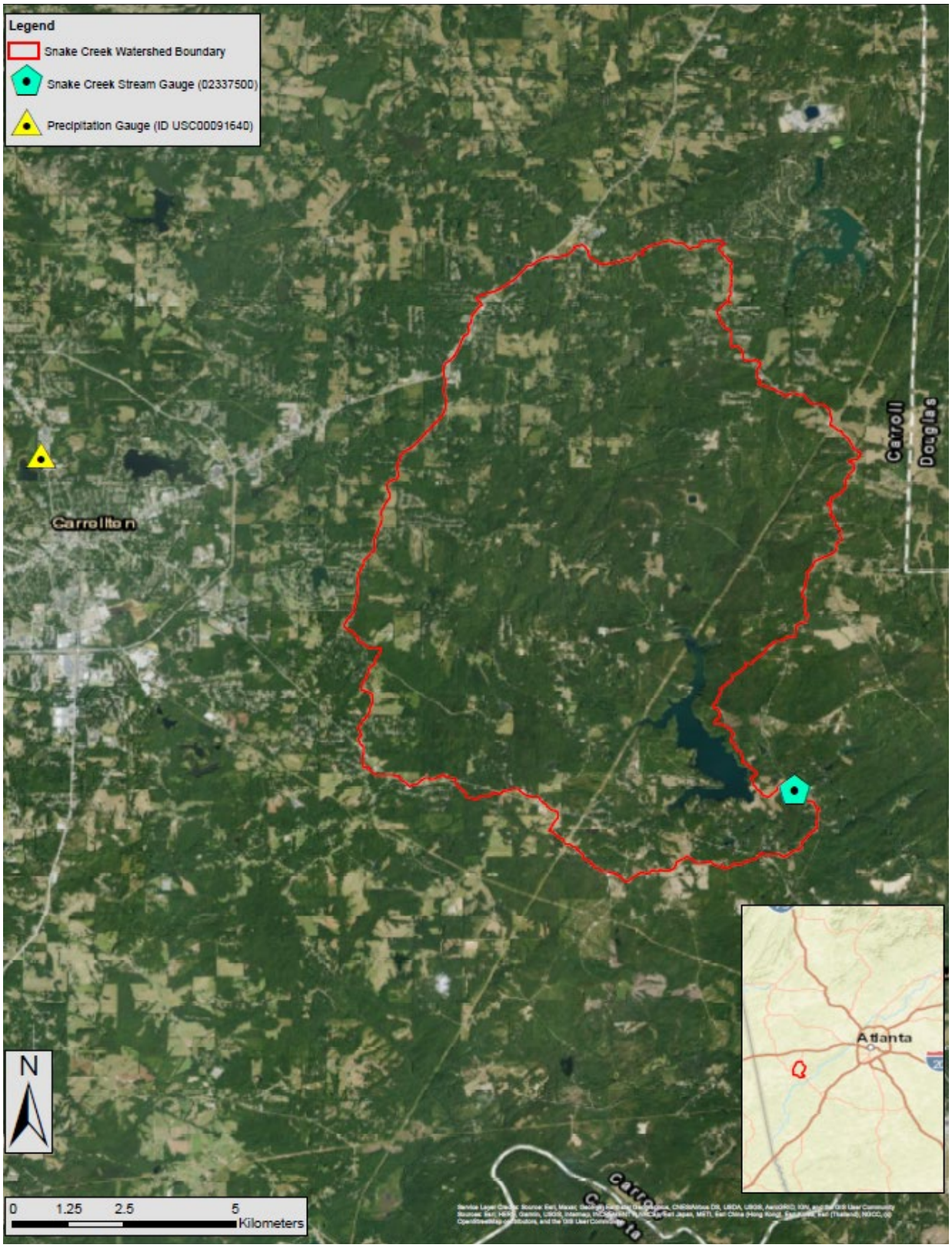

Figure 2. Aerial overview map of the study area, Snake Creek watershed (non-urban watershed) as defined at the USGS stream gauge.

Physical Geography: Big Creek and Snake Creek watershed are located within the Piedmont Mountains of Georgia. The Piedmont physiographic province is characterized by rolling hills with many valleys and upland tributaries (Georgia Info, 2004). The typical natural vegetation within the Piedmont consists of oak and hickory forests while the lower Piedmont region is used primarily for agriculture (Georgia Info, 2004). The elevation within the Piedmont can range from 1700 feet above sea level near the southern boundary of the Blue Ridge Mountains to 500 feet above sea level near the northern boundary of the Coastal Plain (Georgia Info, 2004). The streams and rivers in the Piedmont region generally flow from the north to south and are characterized by shallow bedrock and may have rapids or waterfalls (Georgia Info, 2004). Big Creek is an unregulated stream that originates near Sawnee Mountain in Forsyth County at an elevation of 1,300 feet and flows through the city of Alpharetta (population estimate of 67,213 in 2019; census.gov) before draining into the Chattahoochee River near Roswell. The elevation within the watershed ranges from 1,965 feet to 962 feet with a mean elevation of 1,119 feet (USGS, 2016) (Figure 3).

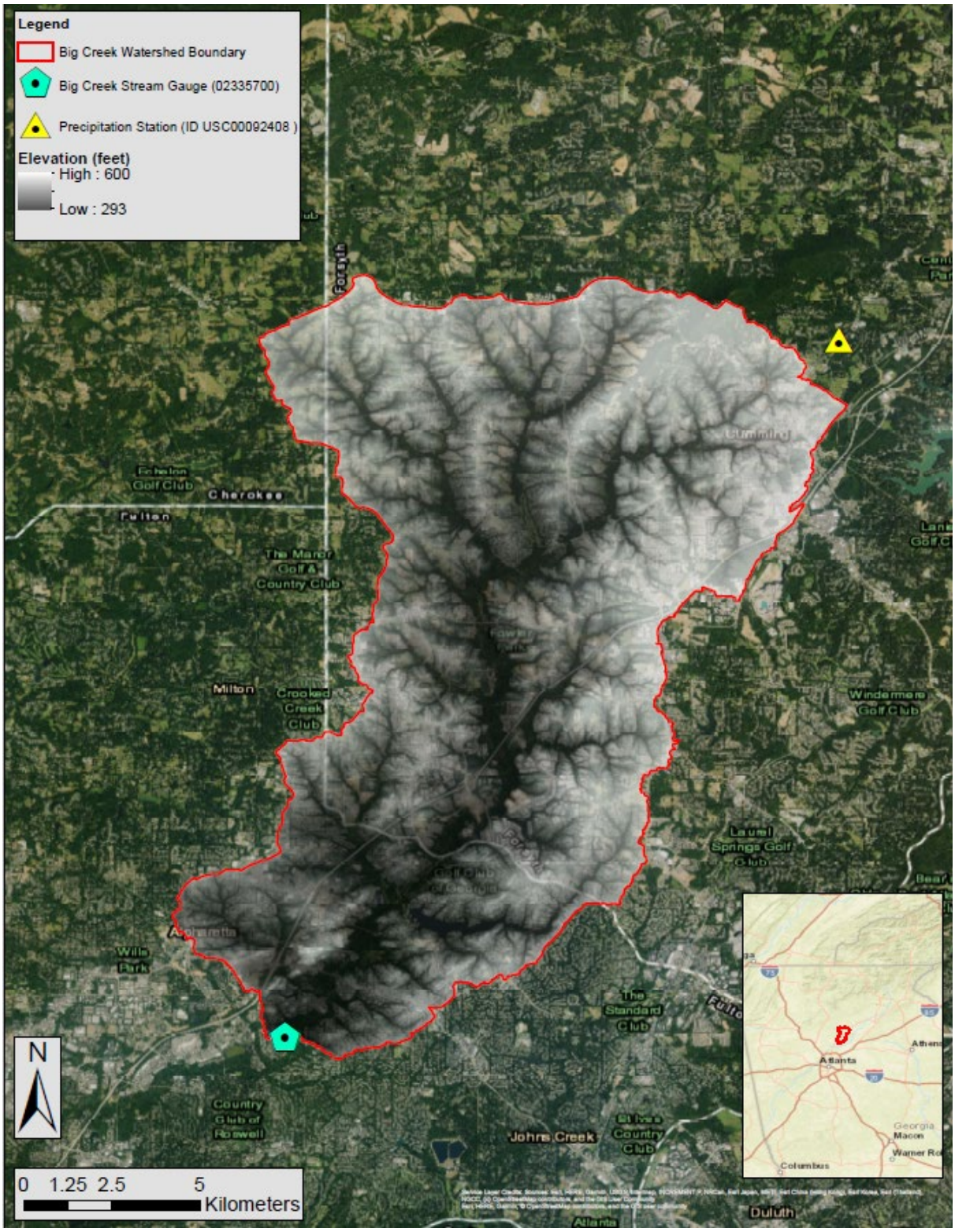

Figure 3. Digital elevation map of Big Creek watershed.

Snake Creek originates at Law Lake at an elevation of 1,045 feet. The stream flows south then east through rural Carroll County ultimately draining into the Chattahoochee River near Whitesburg. The Snake Creek Reservoir, built in 2001, is located in the southeastern portion of the watershed, about 1.5 miles above the gaging station. The elevation within the watershed ranges from 1,300 feet to 838 feet with a mean elevation of 1,087 feet (USGS, 2016) (Figure 4).

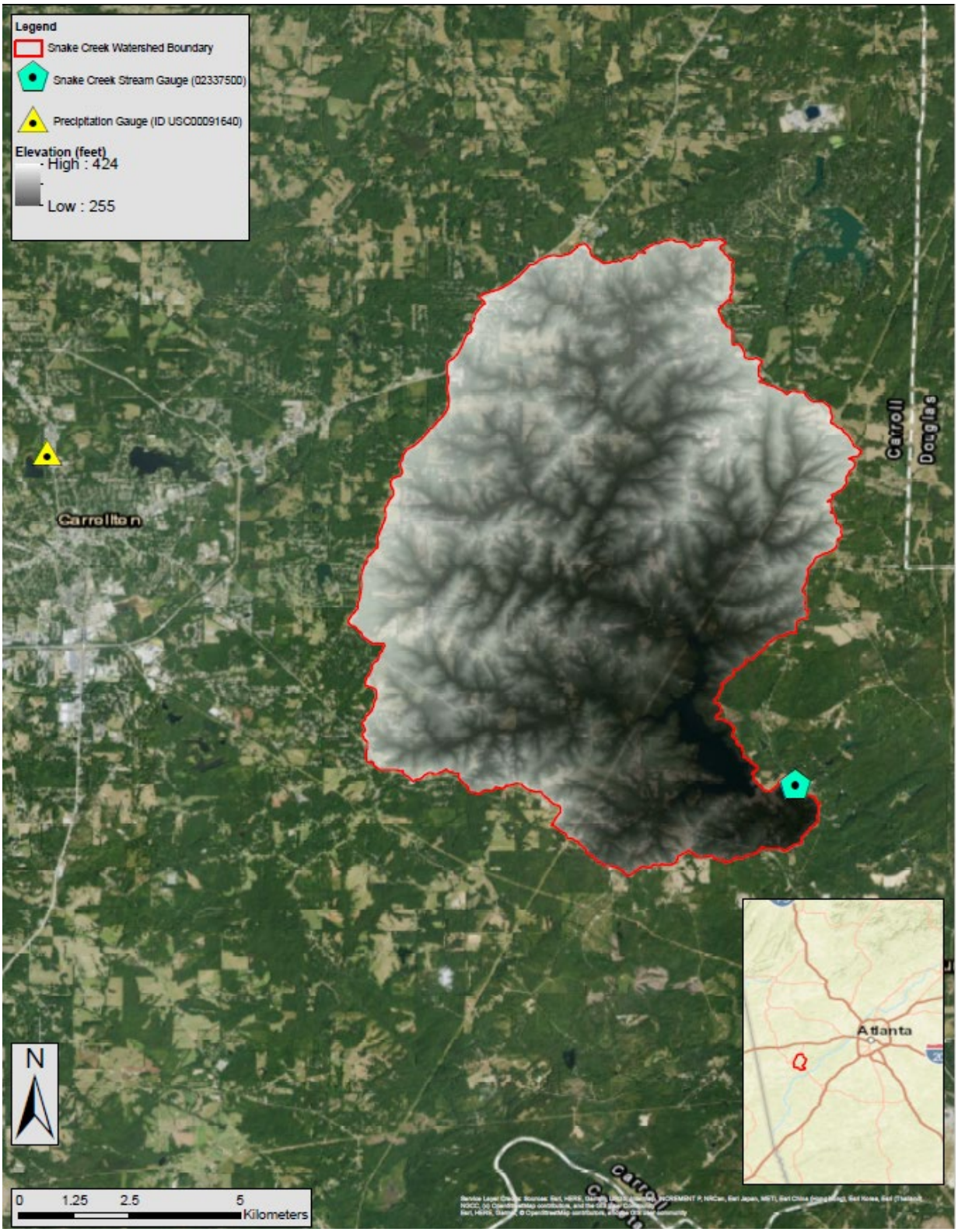

Figure 4. Digital elevation map of Snake Creek watershed.

The geology in the Piedmont region consists of metamorphic rocks such as gneiss and marble and igneous rocks such as granite. Areas of bedrock outcrops are found along hillsides and riverbeds (Georgia Info, 2004). The majority of the geology in Big Creek watershed consist of biotitic gneiss, mica schist, amphibolite with minor components of quartzite and aluminous schist (Georgia Info, 2004).

Similar to Big Creek watershed, the major geologic components of Snake Creek watershed include mica schist and gneiss and minor components of granite undifferentiated and garnet mica schist (Georgia Info, 2004).

The predominant soil type in the Piedmont region is the Ultisols soil order, which is characterized by a clay-rich B-horizon and typically occurs in wet tropical and subtropical climates (Chapin et al., 2012). Given the warm and wet climate, the soils within this region are prone to high rates of chemical weathering (Chapin et al., 2012 and Georgia Info, 2004). The majority of the soils within Big Creek watershed consist of Cecil-Madison, Lloyd Cecil-Madison, and Cecil-Lloyd Appling soils; these soils are found on ridges or gently sloping side slopes of the Piedmont uplands and consist of deep, well-drained soils with moderate moisture holding capacity (CDM, 2000 and USDA NRCS, n.d.). The Congaree and Chewacla soils are found along the floodplains of Big Creek and are somewhat poorly drained soils, occasionally flooded, and runoff is negligible (CDM, 2000 and USDA NRCS, n.d.).

The major soil type in Snake Creek watershed consist of Madison gravelly fine sandy loam, Louisa gravelly fine sandy loam, Hulett gravelly sandy loam, Congaree soils, and Chewacla silt loam soils (USDA NRCS, n.d.). The Madison, Louisa, and Hulett soils are found on hills and side slopes, and consist of deep, well-drained soils with moderately high permeability (NRCS, n.d.).

Climate: Big Creek and Snake Creek watersheds are both located within a humid subtropical region and experience four seasons; winters tend to be short and mild, autumn is long and sunny, spring has frequent storms, and summers are hot and humid (NOAA, n.d.). The average summer temperatures in the Piedmont region range between 80 °F and 82 °F and can exceed 90 °F (NOAA, n.d.). During the summer months, the moist air provides most of the summer rainfall. The average winter temperature in the Piedmont region is approximately 32 °F and freezing temperatures can be experienced every year. The cold temperature periods tend to occur from mid-November to mid-March (NOAA, n.d.). Within Big Creek watershed, the average temperature in Forsyth County is approximately 59.2 °F and 60.4 °F in Fulton County (NOAA, 2020) (Figure 5). Within Snake Creek watershed, the average temperature in Carroll County is 59.9 °F (NOAA, 2020).

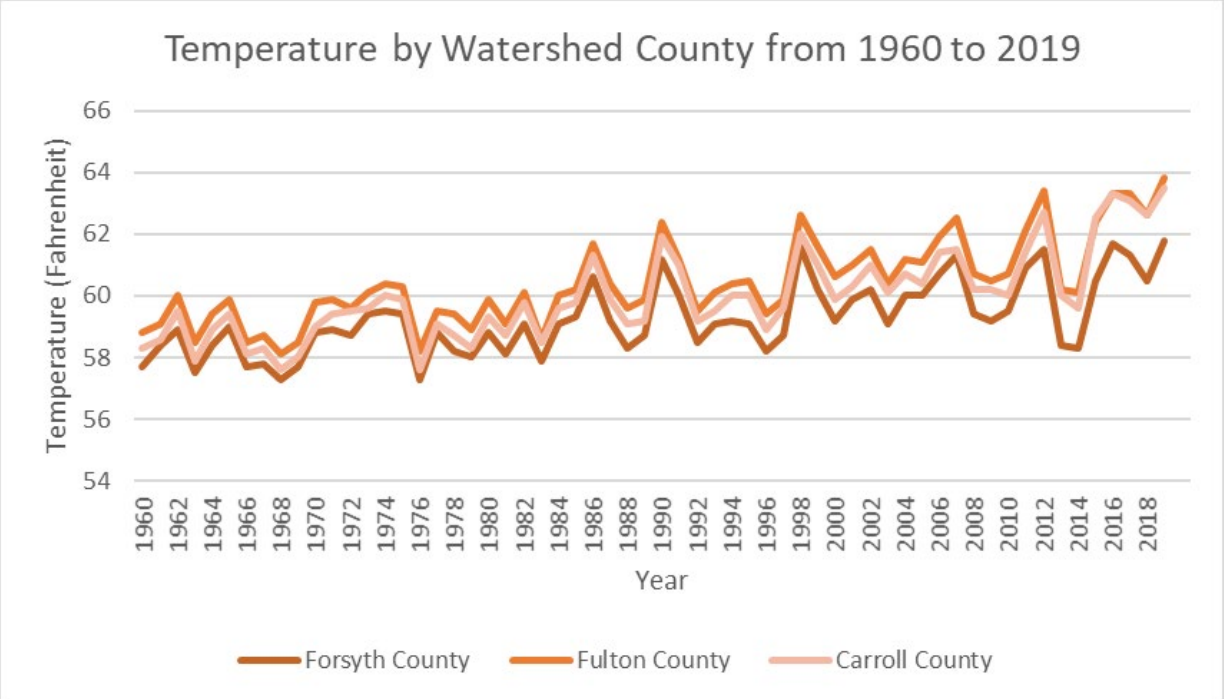

Figure 5. Average annual temperature for counties containing Big Creek and Snake Creek watersheds for 59-year period of record (NOAA, 2020).

Within the Piedmont region, precipitation is mainly received as rain, but both watersheds can receive the occasional light snow and sleet, typically during the months of January or February (NOAA, n.d.). In both watersheds, the driest season occurs during autumn with October as the driest month in the state. The wettest month tends to occur in December, January or March with additional peaks during midsummer. The greatest flood events occur during winter and spring months. Tropical storm rainfall peaks in September and tends to mainly affect coastal Georgia, but widespread winds and rain can reach Metro-Atlanta (NOAA, n.d.). It should be noted that a record rainfall event occurred in Metro-Atlanta during September 15 to 22, 2009, which resulted in a historic flood event, exceeding levels of a 500-year event (Williams, 2017). Average precipitation is approximately 55.6 inches in Forsyth County, 52.4 inches in Fulton County, and 54.7 inches in Carroll County (NOAA, 2020) (Figure 6). As shown by Figure 5 and 6, the climates of the counties of the two watersheds are similar.

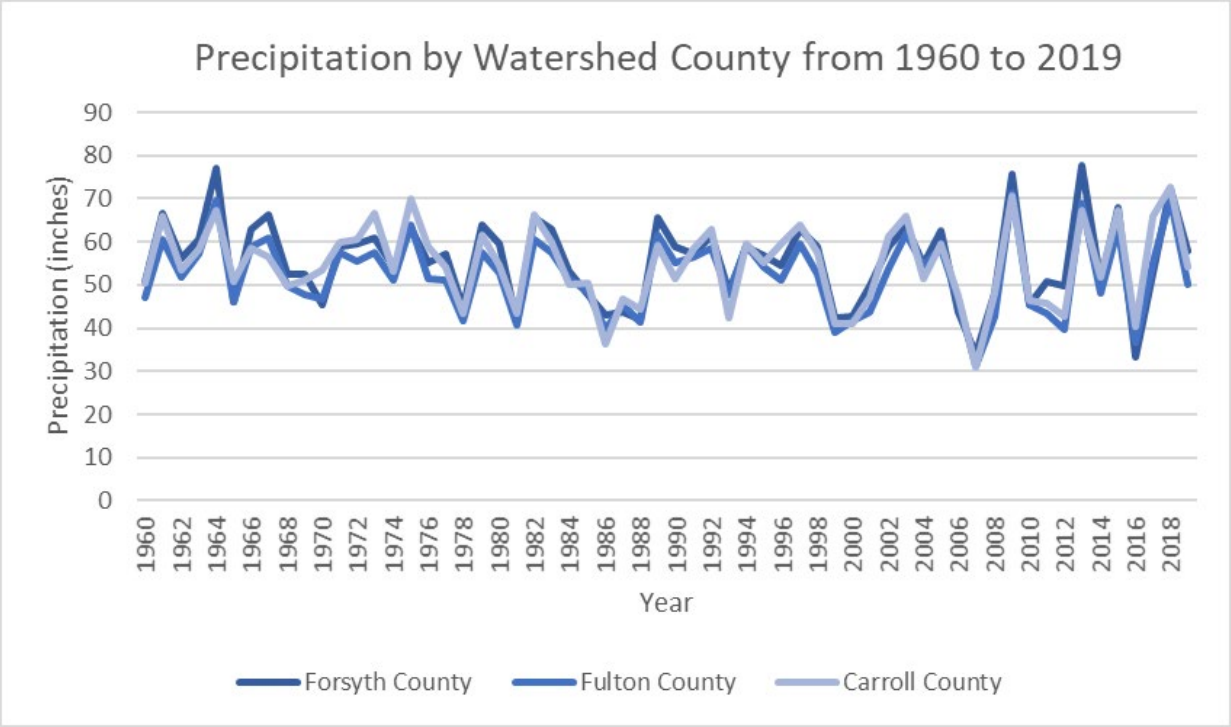

Figure 6. Average annual precipitation for counties containing Big Creek and Snake Creek watershed for 59-year period of record (NOAA, 2020).

Landcover Change: Big Creek watershed has undergone a major landcover change since the early 1950s. In 1995, approximately 56% of the watershed was estimated to be pasture/cropland and forest land; 33.6% was single family residential or townhomes; 6.0% was commercial; 1.7% was office/light industrial; 1.7% was major roads; and 0.6% was heavy industrial (CDM, 2000). According to the Atlanta Regional Commission, an estimated 61% increase in population growth occurred in Fulton County between 1970 and 2016 (ARC, 2016). Data collected from the 10 metro-counties suggest that the 1990s were "booming" and had the largest gain in population compared to other decades; a gain in population was also observed between 1950 and 1960 (ARC, 2016). Big Creek population quadrupled from 1990 to 2010 (Diem et al. 2018). Within the 10 metro counties, residential building permit activity also increased in the early 1980s, with an average of 32,570 permits a year, and peaked again in the 1990s before dropping in the 2008 economic recession (ARC, 2016). The amount of developed land doubled from 1992 to 2011. Developed areas in Big Creek watershed are concentrated in and near the city of Cumming in the north and city of Alpharetta in the south (CDM, 2000). The City of Alpharetta is a highly developed area. Based on the 2010 U.S. Census, the city's population was 57,383 and the population was expected to increase by 17.1% by 2019 (census.gov). Development type within the watershed consists mainly of single and multifamily residential use with commercial and light industrial development limited to the Georgia 400 Highway corridor (CDM, 2000). It was projected that 86% of the watershed would become urban development by 2020, and the largest increase would occur in residential and office/light industrial development (CDM 2000) (Figure 7).

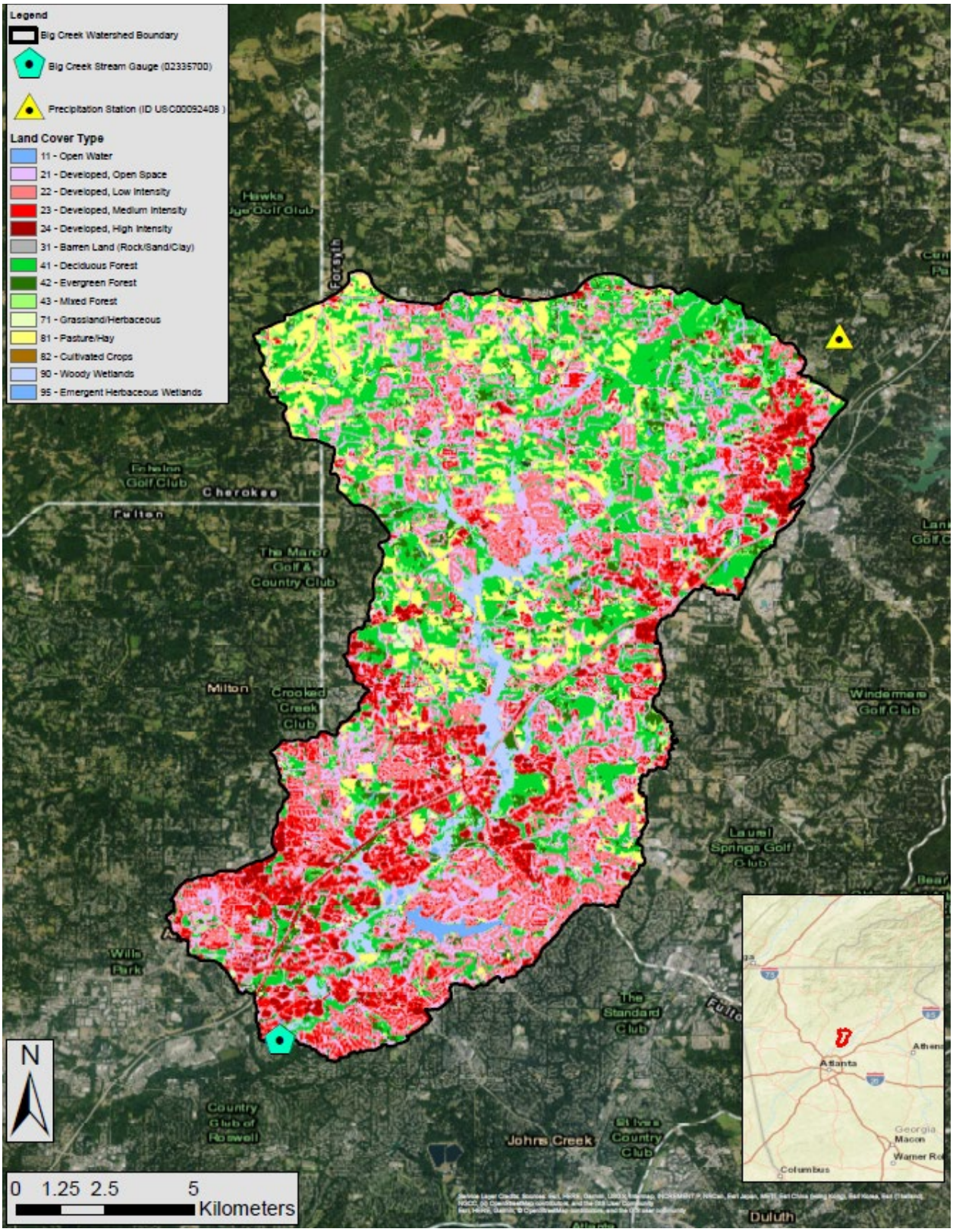

Figure 7. National landcover data 2016 for Big Creek watershed (NLCD, 2016).

Snake Creek watershed is located outside the city limits of Carrollton and is primarily occupied by wooded land and pastures. Approximately 64.9% of the watershed is forest land, 22.8% is urban/impervious surface, and 13.2% is pasture/grass (USGS, 2016). Sparse residential development and pasture areas are limited to the northern and western portion of the watershed (Figure 8). Although estimated population density within the watershed is unknown, the population of Carroll County, which it is concentrated in, was estimated at 110,570 in 2010 and was expected to increase by 8.5% by 2019 (census.gov). The most significant landcover change to occur within the Snake Creek watershed is the creation of Snake Creek Reservoir (also known as Seaton Reservoir) in 2001 by construction of an earthen dam upstream from the USGS 02337500 Snake Creek stream gauge. The Snake Creek Reservoir is approximately 2 km^2 (0.85 mi^2), can hold 12,000 acre-feet of water, and is used for recreation purposes (Ignatius, 2009).

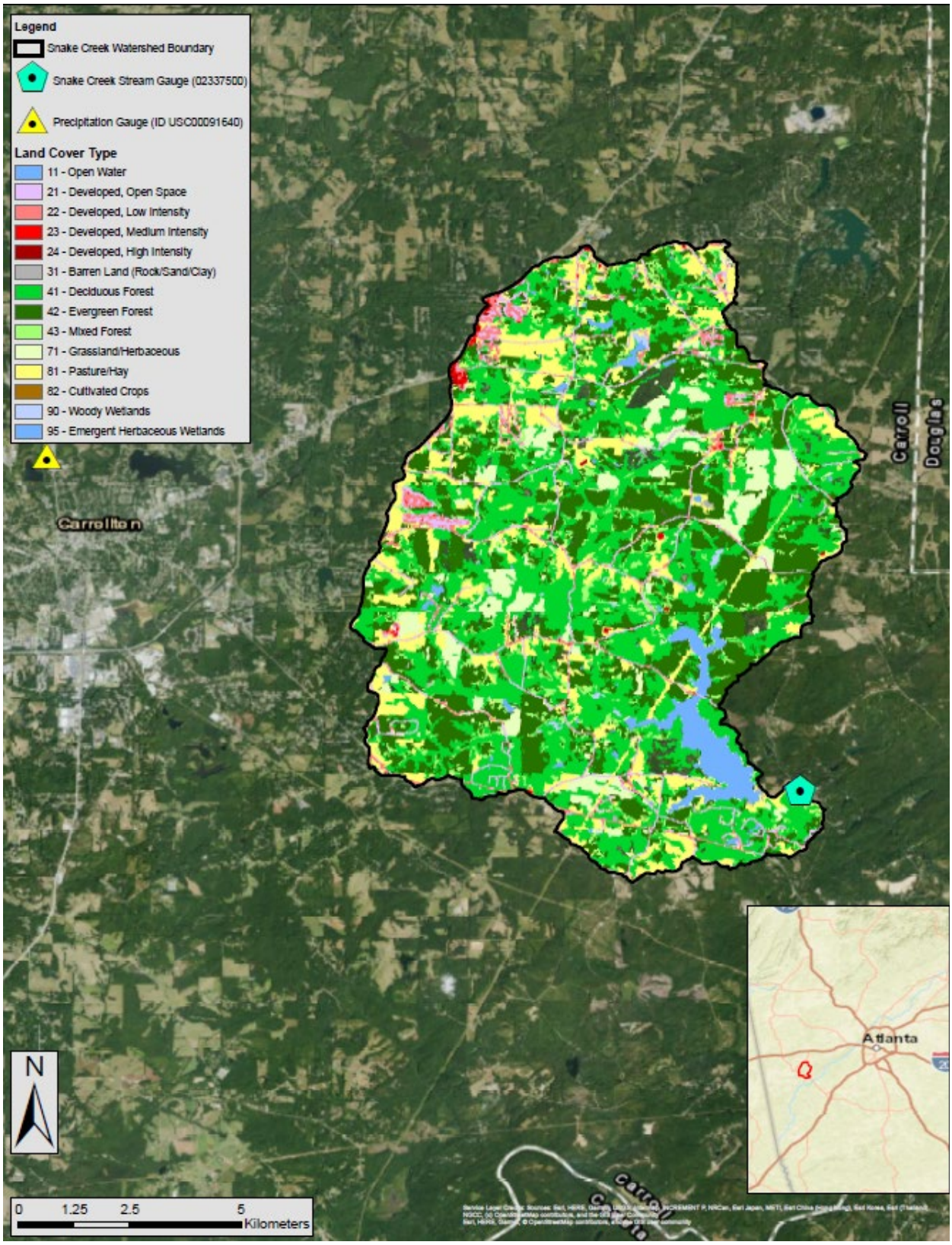

Figure 8. National landcover data 2016 Snake Creek watershed (NLCD, 2016).

LANDSAT SATELLITE IMAGES ANALYSIS

Landsat satellite images were used to determine the timing of development and to define the 'pre-urban' and 'post-urban' periods for Big Creek watershed. Landsat satellite images were acquired from USGS Global Visualization Viewer (GloVis, https://glovis.usgs.gov/). Selected satellite images from 1975 to 2019 during the months of March to June with 0-10% cloud cover were downloaded. MultiSpec (https://engineering.purdue.edu/~biehl/MultiSpec/download_win.html, a freeware multispectral image data analysis system, was used for further linking of images, cropping, and band selection. The following satellite images and band combinations were used:

1. Big Creek watershed
    a) April 21, 1975 satellite image from Landsat 1 MSS C1 Level-1; band combination 4,6,7
    b) June 4, 1984 satellite image from Landsat 5 TM C1 Level-1; band combination 4,5,1
    c) June 20, 2019 satellite image from Landsat 8 OLI/TIRS C1 Level-1; band combination 7,6,4
2. Snake Creek watershed
    a) April 21, 1975 satellite image from Landsat 1 MSS C1 Level-1; band combination 4,6,7
    b) June 6, 1984 satellite image from Landsat 5 TM C1 Level-1; band combination 4,5,1
    c) May 1, 2018 satellite image from Landsat 8 OLI/TIRS C1 Level-1; band combination 7,6,4

The Landsat satellite images were visually reviewed and compared to corresponding population data. As explained in the Results section, the pre-urban and post-urban periods in the Big Creek watershed were defined as 1960-1984 and 1985-2019.

PRECIPITATION DATA

Annual, county-level precipitation and temperature data for 1960-2019 were acquired from the National Oceanic and Atmospheric Administration (NOAA) Climate at a Glance website: https://www.ncdc.noaa.gov/cag/county/time-series. Local daily precipitation data from USC00092408 Cumming 2 N (Big Creek watershed) and USC00091640 Carrollton, GA, (Snake Creek watershed) stations were also downloaded from NOAA Climate Data Online: https://www.ncdc.noaa.gov/cdo-web/datasets. County-level annual data have no gaps and average data over areas roughly comparable to the watersheds. Data for individual stations may have gaps and may not be representative of a watershed. The 1960-2019 daily precipitation data for USC00092408 Cumming 2 N contained a data gap in 1985 as well several missing months of data in 1974, 1984, and 1986. The USC0091640 Carrollton, GA, dataset was complete and contained no data gaps.

Since precipitation influences stream-flow, changes in precipitation need to be considered when evaluating the relationship between development and stream-flow. To evaluate possible changes in total precipitation, a linear trend analysis of annual county precipitation data was performed in Excel. To evaluate changes in major storm size that might affect peak discharge, the maximum 1-day rain event was determined for each year from the local daily precipitation data for each station and analyzed for linear trends.

STREAM DISCHARGE

Daily mean discharge data were acquired for gauging stations USGS 02335700 Big Creek near Alpharetta, Georgia, and USGS 02337500 Snake Creek near Whitesburg, Georgia, from USGS Water Data website: https://waterdata.usgs.gov/ga/nwis/rt. Uninterrupted daily data were available beginning in May 1960 for Big Creek and beginning in September1954 for Snake Creek. The period with data for both sites, 1960-2019, was analyzed. Each daily mean value is the average of raw values recorded every 15 minutes.

By USGS convention, the water year (WY) is defined as the 12-month period starting October 1 of a given year and ending September 30 of the following year (USGS, n.d.). For example, the year ending September 30, 1961, is referred as WY1961 (USGS, n.d.). Therefore, the period for analysis is from October 1, 1960, to September 30, 2019, a complete 59-year record spanning WY1961-WY2019. USGS reports discharge in units of cubic feet per second (ft^3/s); these units were retained for data analysis. The pre-urban and post-urban periods used for analysis were from WY1961 to WY1984 and WY1985 to WY2019, respectively.

Seasonal Stream-flow Patterns: The daily mean data for WY1961 to WY2019 for Big Creek and Snake Creek were used to calculate average discharge for each day of the year and create a daily seasonal hydrograph: This hydrograph was used to illustrate general similarities and dissimilarities in seasonal flow between watersheds.

Flow Duration Curve Analysis: A flow-duration curve is a cumulative frequency curve that shows the percentage of time during which specific discharges were equaled or exceeded in a given period, i.e. their exceedance probabilities (Searcy, 1959). For example, flows equaled or exceeded 99% of time represent very low flows; flows equaled or exceeded 1% of time represent

very high flows; and median flows represent flows that are equaled or exceed 50% of the time. Flow-duration curves summarize long discharge records efficiently and provide a convenient method for comparing and analyzing the pre-urban and post-urban flow characteristics of Big Creek to Snake Creek.

Flow duration curves for Big Creek and Snake Creek were calculated in Excel using daily discharge data for the pre-urban and post-urban periods. A figure depicting a flow duration curve for Big Creek and Snake Creek for discharge data for WY1961 to WY2019 period can be found in Appendix A. The daily discharge data for each period was sorted and ranked from highest to lowest discharge. The following equation was used to calculate the exceedance probability of ranked daily discharge:

$$P = 100*[M/(n+1)]$$

where: P is the probability that a given flow will be equaled or exceeded (% of the time), M is the ranked discharge, n is the number of events for that period of record

The discharge values for 5%, 10%, 50% (median), and 90% exceedance probabilities for the pre-urban and post-urban period were tabulated for comparisons.

Peak Flow Frequency Analysis: The annual peak flow is defined as the maximum instantaneous flow occurring in a water year (Ahearn, 2003). Peak flow events may barely exceed the natural stream banks with minimal effects to the floodplain or may inundate the floodplain and cause extensive damage (Ahearn, 2003). An annual peak flow frequency analysis is used to estimate the percent chance that a given flow will be exceeded in any single year, the annual exceedance probability (AEP). The annual peak flow analysis also calculates the average time interval (years) during which the flow is expected to be exceeded one time. This is the

inverse of the annual exceedance probability and is referred to as the annual recurrence interval (ARI) (Ahearn, 2003).

The peak flow frequency analysis for Big Creek and Snake Creek watershed for pre-urban and post-urban periods (WY2019 was not available) were calculated using the Natural Resources Conservation Science (NRCS) Frequency Curve Determination Excel spreadsheet obtained from https://www.nrcs.usda.gov/wps /portal/nrcs/detailfull/national/water/manage/hydrology/. The NRCS spreadsheet follows the standard methods in the *Guidelines for Determining Flood Flow Frequency, Bulletin 17C*.

The NRCS Frequency Curve Excel spreadsheet automatically retrieves annual peak discharge data from the USGS water data website and calculates peak discharge by sorting and ranking the annual peak discharge from high to low discharge. The non-exceedance frequency for each peak discharge is then calculated using the Weibull equation, shown below:

$$F(x) = \frac{r}{N+1}$$

Where:

F(x) represents how often the annual peak will be less than or equal to X,

r is the rank of individual peak discharge,

N is the number of peaks,

The AEP is calculated using the following formula:

$$P(x) = 100 * F(x)$$

Where:

P(x) is the probability

The ARI for each peak discharge value is calculated using the following formula:

$$T(x) = \frac{1}{P(x)}$$

Where:

T(x) is the average expected interval between occurrences of annual peaks that equal or exceed X

The NRCS Frequency Curve Excel spreadsheet also automatically calculates the upper and lower confidence interval (labeled *Q5* and *Q95*) for peak discharge for each recurrence interval. Outputs were copied and pasted to another excel spreadsheet to plot Big Creek and Snake Creek peak discharge graphs concurrently. Recurrence interval values were tabulated for 1, 2, 50, and 100-year interval for the pre-urban and post-urban POR periods. A figure depicting peak flow for Big Creek and Snake Creek watershed for WY1961 to WY2018 can be found in Appendix A.

Baseflow Analysis: Baseflow is defined as water that enters a stream from persistent and slowly varying sources that maintains streamflow between precipitation-input events (Liu et al., 2013). The baseflow in a watershed can originate from groundwater input as well as the slow release from surface storages such as lakes, wetlands, or melting snow (Liu et al., 2013). Baseflow separation hydrographs for Big Creek and Snake Creek were generated using AquaPak software, downloaded from Jacobs Engineering Group https://www.jacobs.com/natural-resource-management. Big Creek and Snake Creek daily discharge data for WY1961 to WY2019 POR were converted to a two-column, date and discharge text file, saved as .dat files for AquaPak analysis, and opened in AquaPak. The baseflow separation hydrograph was created using a recursive digital filter algorithm with default values for “filter parameter” and “number of passes”. This method splits the hydrograph between slowly and quickly varying components labeled as baseflow and quickflow. Quickflow, also called event flow, is equal to daily total discharge minus daily baseflow discharge.

Following the baseflow separation for each stream, outputs from AquaPak were imported into an Excel spreadsheet and used to calculate average annual baseflow, quickflow, baseflow index (BFI) values, and create graphs. The baseflow index (BFI) was calculated using the following formula:

$$BFI = \frac{Baseflow\ volume}{Total\ discharge\ volume}$$

The annual BFI was calculated for Big Creek and Snake Creek by dividing the average baseflow discharge by the average total discharge flow for each year from WY1961 to WY2019. The baseflow index can range from 0 to 1 (i.e. 0 to 100% of discharge as baseflow).

Richards-Baker Flashiness Index Analysis: Rapid variations in stream discharge, known informally as "flashiness", are common in urban watersheds (Rosburg et al., 2017). The Richards-Baker (RB) Flashiness Index quantifies day to day variations in discharge (Baker et al., 2004). "Flashy" hydrographs have a high RB index, while hydrographs that exhibit a gradual rise and fall with a low RB index (Rosburg et al., 2017). The possible range is from 0 to 2 (Fongers, 2012). The following RB Flashiness Index formula was used:

$$RB = \frac{\sum_{i}^{n}=1 |qi - qi-1|}{\sum_{i=1}^{n} qi}$$

Where:

n is the number of days of discharge in the period

i is the day in the POR

q is the discharge for the day i

The RB Flashiness Index is calculated by dividing the sum of the absolute daily changes in daily discharge for each water year by the sum of all daily discharge values for each water year. Dividing the sum of daily discharge normalizes RB index values so that streams with

different average discharge can be compared. The RB Flashiness index was calculated for Big Creek and Snake Creek watershed for each year from WY1961 to WY2019.

Statistical Analysis: The Mann-Kendall non-parametric statistical test was used to identify whether the discharge time series data had a monotonic trend (increase or decrease) or no trend (Sheng et al., 2009 and Meals et al., 2011). The test compares later-measured values to earlier-measured values and assigns an integer value of either 1, 0, or -1, meaning positive, no difference, or negative difference (Meals et al., 2011). A large positive value for the "S" value indicates an upward trend because later-measured values are larger than earlier-measured values (Meals et al., 2011). A large negative value for "S" indicates a downward trend because later-measured values are smaller than earlier-measured values (Meals et al., 2011). A small absolute value of "S" indicates a no trend (Meals et al., 2011).

The null hypothesis, H_O, is that the data from a sample are have no trend (Sheng et al., 2009 and Meals et al., 2011). The alternative hypothesis, H_A is that the data follow a monotonic trend (Sheng et al., 2009 and Meals et al., 2011). When the test statistic "τ" and "S" value are significantly different than zero (p-value < 0.05), then the null hypothesis is rejected (Sheng et al., 2009 and Meals et al., 2011). Failure to reject H_O does not necessarily mean that a trend does not exist, but instead that there is not sufficient evidence to conclude with a specific level of confidence that a trend exists (Meals et al., 2011).

The Mann-Kendall statistical test analysis was conducted using XLSTAT, a Statistical excel program downloaded from https://www.xlstat.com/en/, on the following time series data: daily mean discharge for WY1961 to WY2019, peak discharge from WY1961 to WY2018, baseflow discharge from WY1961 to WY2019, and flashiness from WY1961 to WY2019.

RESULTS

LANDSAT SATELLITE IMAGES

The band combination 4,6,7 for Landsat 1 satellite image depicts vegetation in various shades of blue and urban and clear-cut areas as pink and white (USGS, n.d.). The Landsat 1 MSS 1975 image shows Big Creek watershed as wooded land and pasture-land with developed areas located in Cumming and Alpharetta, GA (Figure 9).

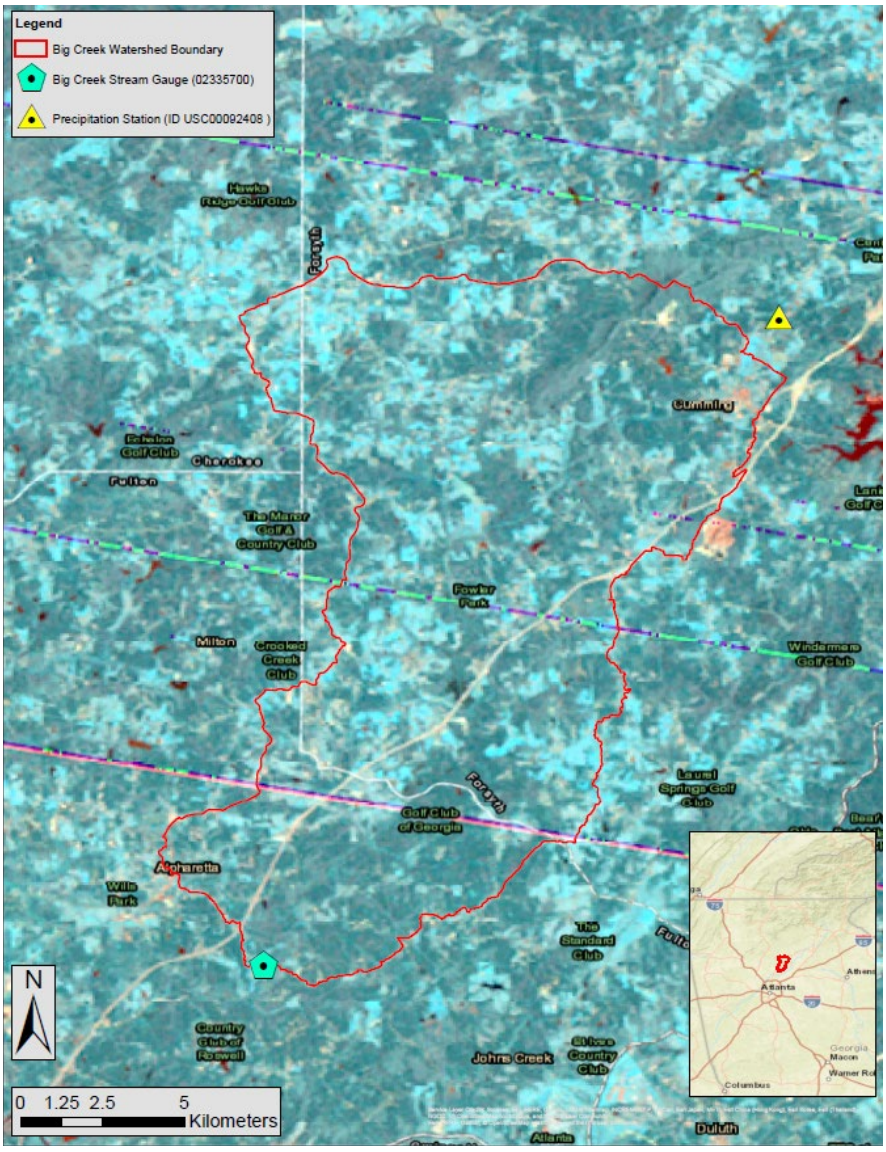

Figure 9. April 21, 1975 Landsat 1 MSS satellite image of Big Creek watershed (Band Combination 4, 6, 7). Urban areas are shown in pink and white (USGS GloVis, 2005).

The band combination 4,5,1 for Landsat 5 TM satellite image depicts vegetation in shades of reds, browns, oranges, and yellow whereas urban and clear-cut areas are depicted as white, cyan, gray, and bright blue (USGS, n.d.). From 1975 to 1984, the 1984 satellite image for Big Creek watershed displays an increase in development within Cumming and Alpharetta, Georgia (Figure 10).

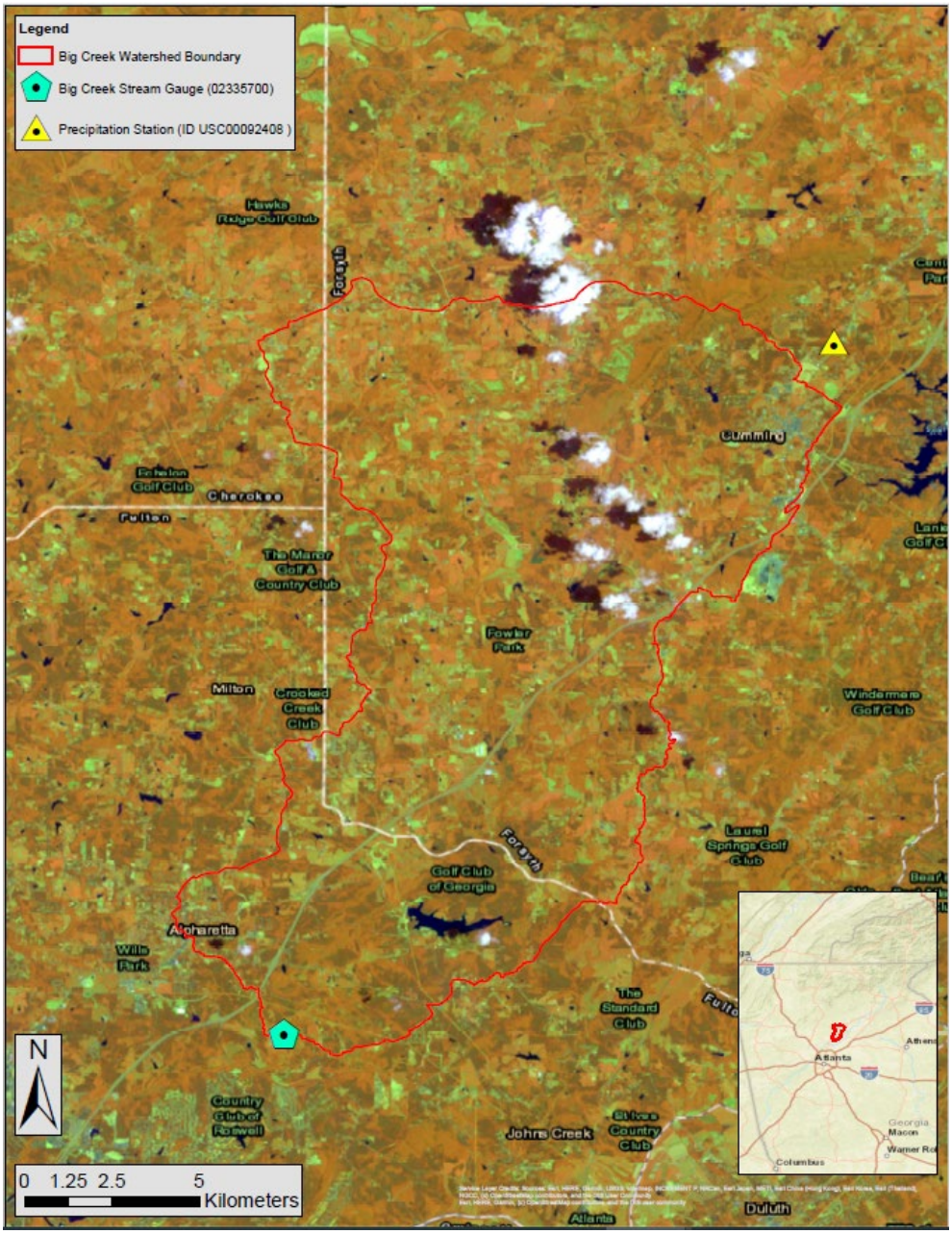

Figure 10. June 4, 1984 Landsat 5 TM satellite image of Big Creek watershed (Band Combination 4,5,1). Urban areas are show in white, cyan, gray, and bright blue (USGS GloVis, 2005).

The band combination 7,6,4 for Landsat 8 OLI satellite image depicts vegetated areas as various shades of green and urban areas as white, cyan, and purple (Butler, 2019). From 1984 to 2019, the 2019 satellite image for Big Creek shows an increase within city center areas as well as suburban expansion throughout the watershed (Figure 11). Despite an urbanized city center in the southern portion of the watershed, the northern portion of the watershed remains relatively wooded.

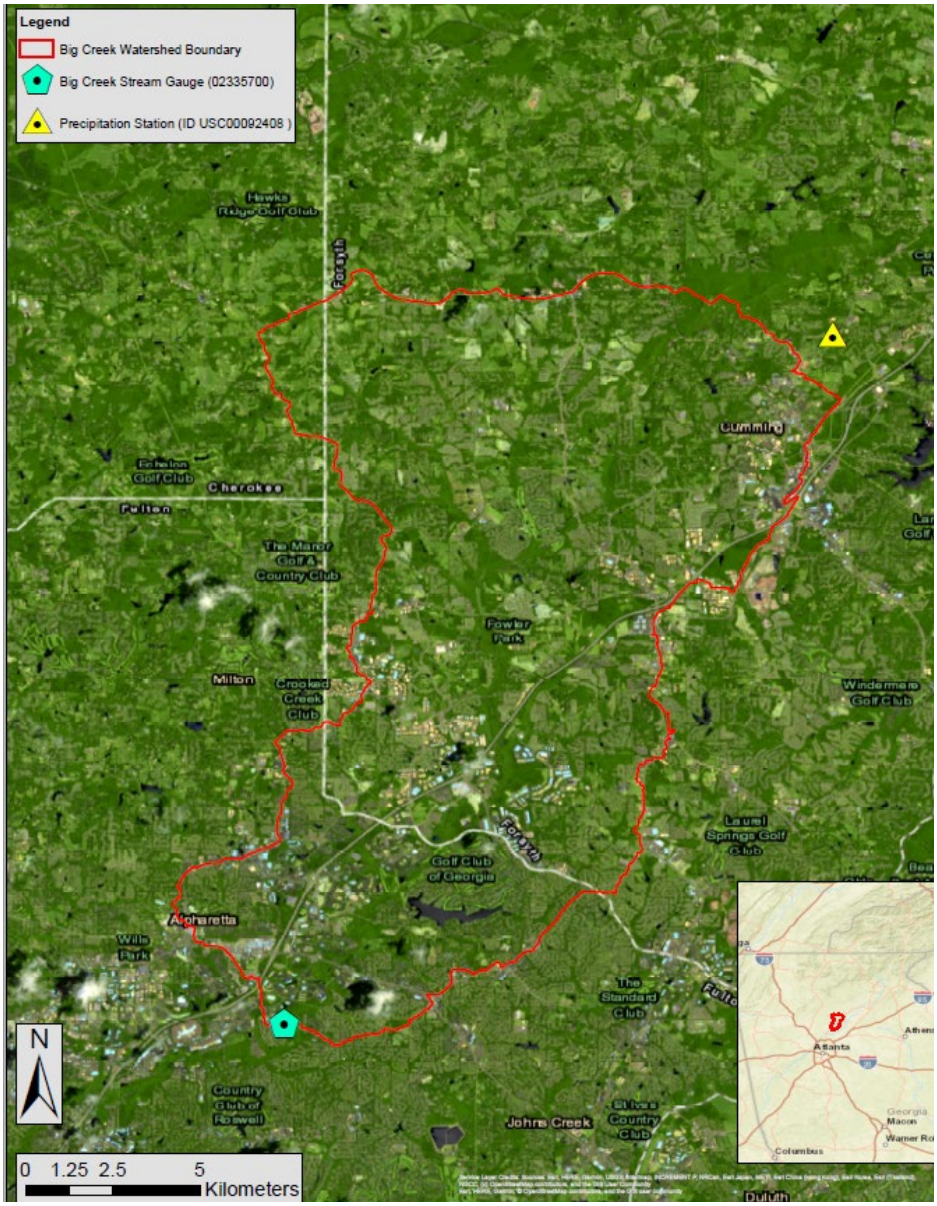

Figure 11. June 20, 2019 Landsat 8 OLI satellite image of Big Creek watershed (Band Combination 7,6,4). Urban areas show as white, cyan, and purple (USGS GloVis, 2005).

The Landsat 1 MSS 1975 satellite image for Snake Creek watershed shows the watershed as a wooded watershed, as indicated by the various shades of blue (Figure 12).

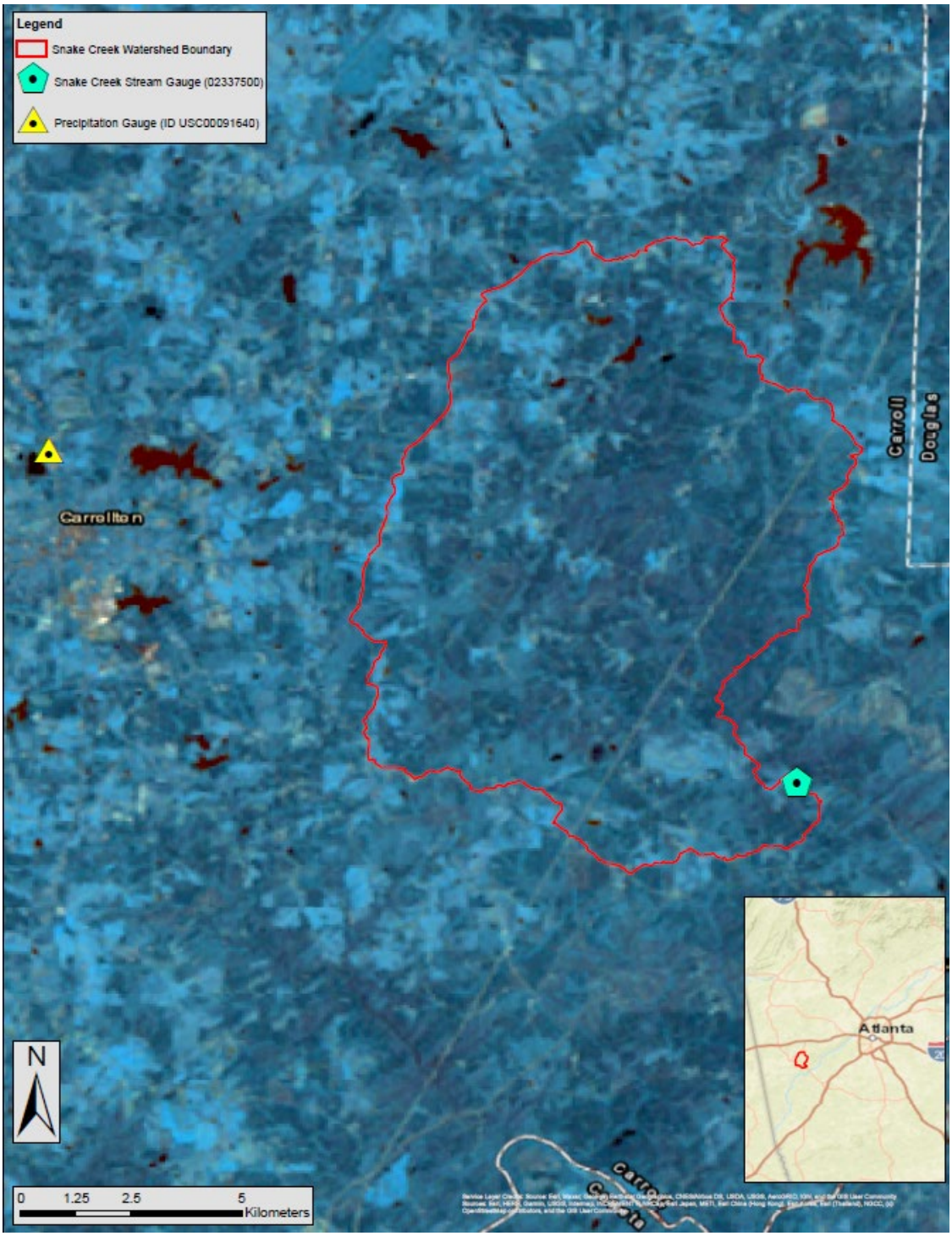

Figure 12. April 21, 1975 Landsat 1 MSS satellite image of Snake Creek watershed (Band Combination 4,6,7) (USGS GloVis, 2005).

From 1975 to 1984, the Landsat 5 TM 1984 satellite image shows rural residential development along the northern and western portion of the watershed and an increase in clear-cut areas throughout the watershed, as indicated by the various white, gray, and cyan colors (Figure 13). The remaining areas of the watershed are wooded land as depicted by the various shades of orange and brown.

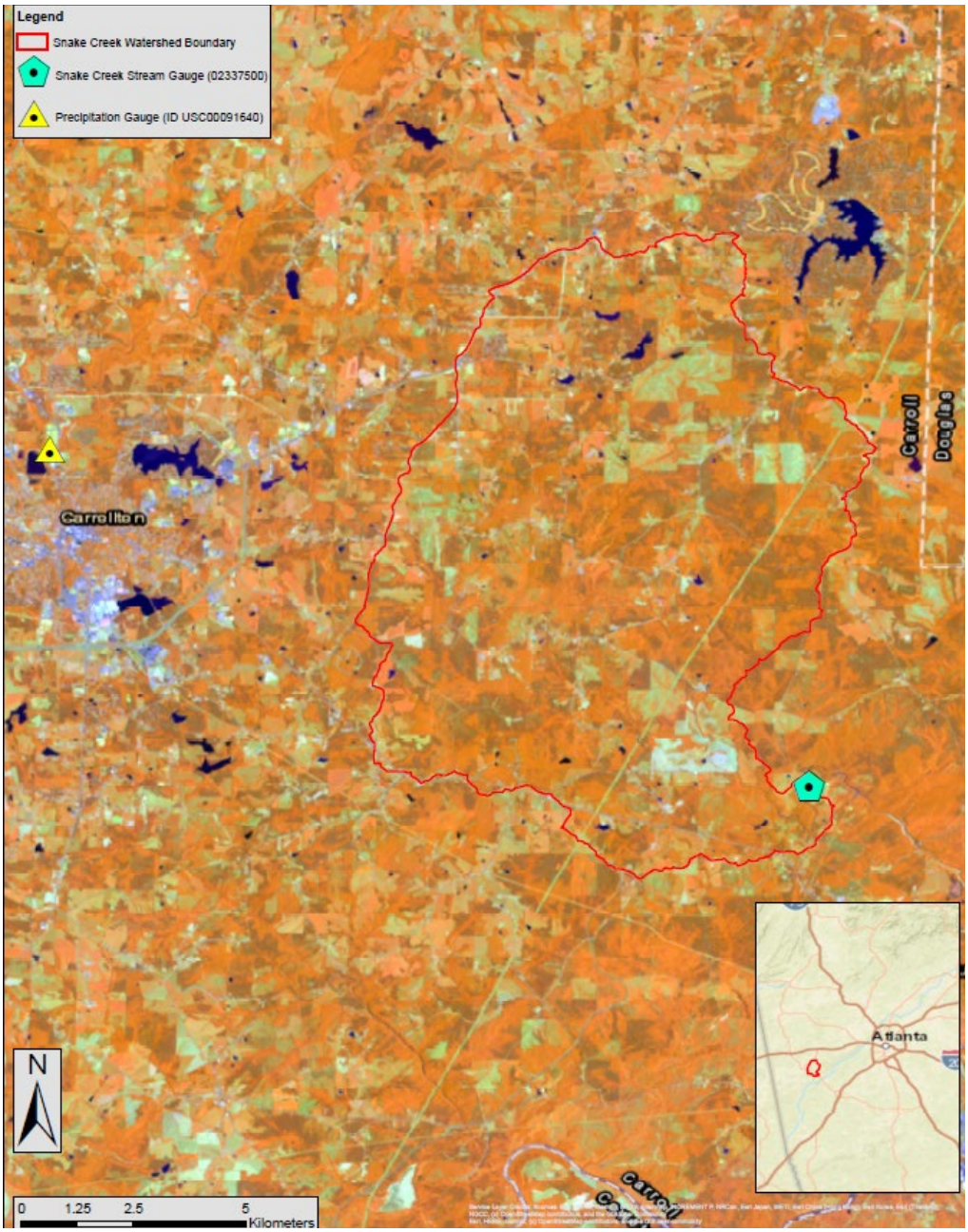

Figure 13. June 6, 1984 Landsat 5 TM satellite image of Snake Creek watershed (Band Combination 4,5,1). Urban areas shown in white, gray, and bright blue USGS GloVis, 2005).

From 1984 to 2018, the Landsat 8 OLI 2018 satellite image for Snake Creek watershed continues to show pasture areas and wooded land in shades of green (Figure 14). The rural residential development is generally limited to the north and northwest portion of the watershed. The 2018 satellite image also shows Snake Creek Reservoir within the southern portion of the watershed.

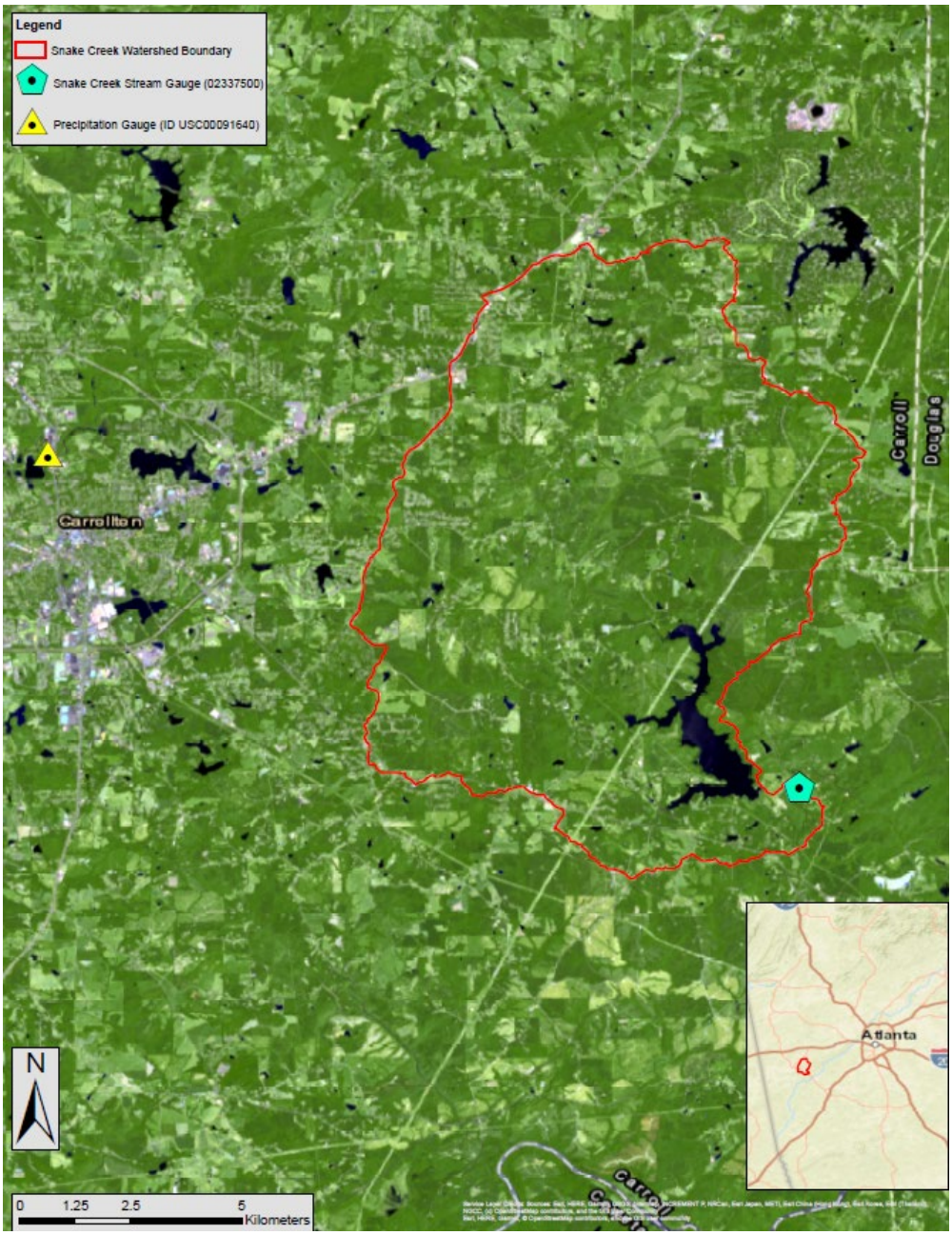

Figure 14. May 1, 2018 Landsat 8 OLI satellite image of Snake Creek watershed (Band Combination 7,6,4). Urban areas show in white, cyan, and purple (USGS GloVis, 2005).

In general, the satellite images depict an increase in urban development in Big Creek after 1984, which corresponds with population data. Population within Alpharetta was estimated at 3,128 in 1980 and increased to 13,984 in 1990 (Population U.S., "n.d."). After 1990, population grew exponentially. Therefore, as previously discussed, the pre-urban and post-urban in Big Creek was determined as WY1961-WY1984 and WY1985-WY2019. The same periods were selected for Snake Creek for comparison purposes.

PRECIPITATION DATA

The linear trend analysis for annual precipitation data by county indicates substantial precipitation variability, but no overall trends in the 59-year period of this study. Specifically, the scatter around the regression line and the low R^2 value of 0.01 in Forsyth County, 0.01 in Carroll County, and 0.01 in Fulton County indicates that variability can-not be explained by the model (Figure 15).

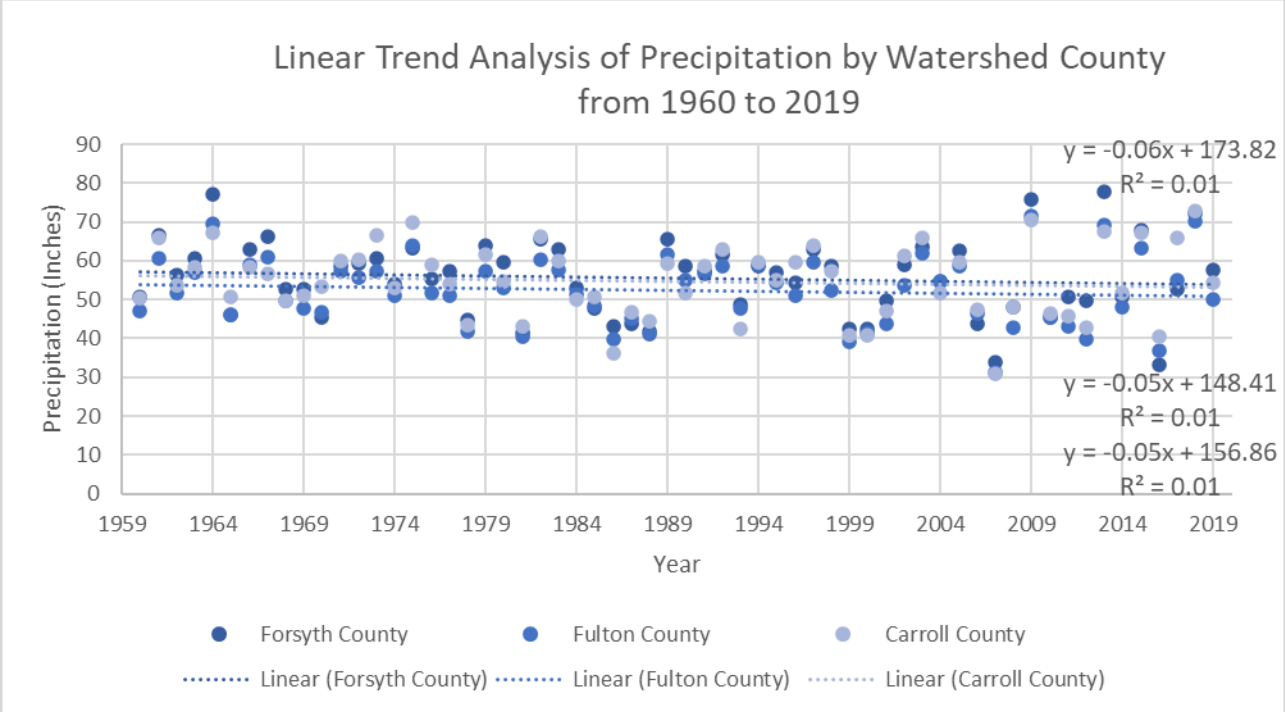

Figure 15. Linear trend analysis- annual precipitation by watershed county (Big Creek -Forsyth and Fulton Co. and Snake Creek – Carroll Co.).

The linear trend analysis for annual temperature data by county indicates an increasing trend in temperature in the 59-year period. The R^2 values of 0.58 in Fulton County, 0.59 in Carroll County, and 0.45 in Forsyth County indicate that approximately half of the observed variation in temperature is explained by the linear model (Figure 16).

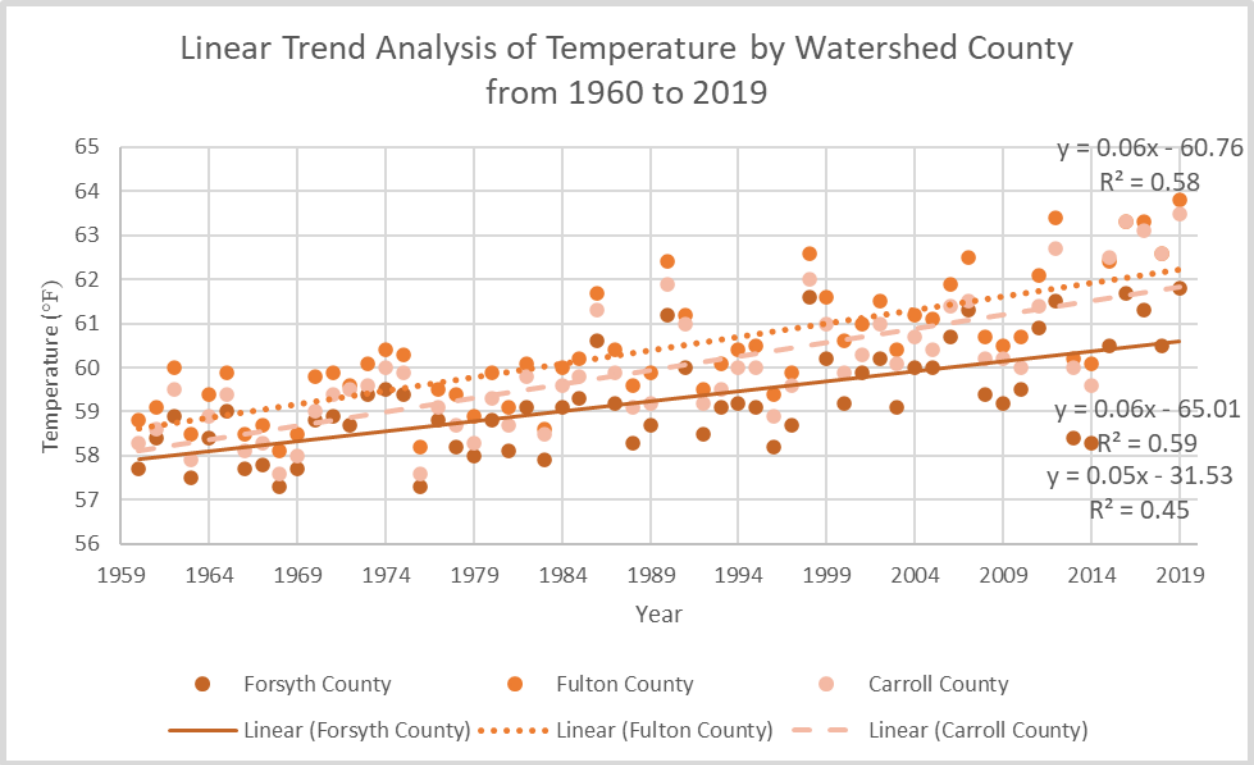

Figure 16. Linear trend analysis- annual temperature by watershed county (Big Creek -Forsyth and Fulton Co. and Snake Creek – Carroll Co.).

The linear trend analysis for annual maximum 1-day rainfall for precipitation stations USC00092408 Cumming 2 N, GA, and USC00091640 Carrollton, GA, indicates high year-to-year variability in maximum rainfall events and no clear trends in the 59-year period study. The low R^2 values of 0.04 for Cumming 2 N, GA, station and 0.00 for Carrollton, GA, station indicate that very little of the variability can be explained by the model (Figure 17).

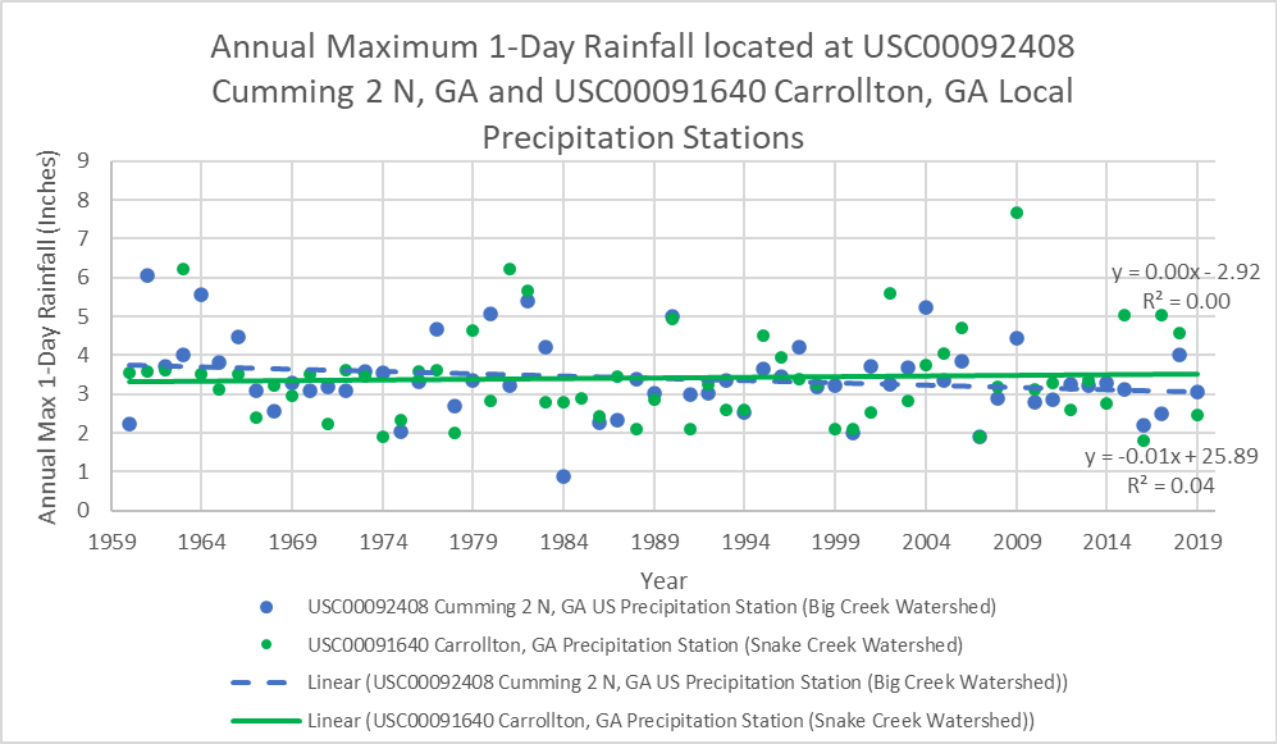

Figure 17. Linear trend analysis of annual maximum 1-day rain events (Big Creek -USC00092408 Cumming 2 N, GA Precipitation Station and Snake Creek – USC00091650 Carrollton, GA Precipitation Station).

STREAM DISCHARGE DATA

Seasonal Stream-flow Patterns: The hydrographs for daily mean data for WY1961 to WY2019 for Big Creek and Snake Creek watershed indicate similarities in seasonal discharge (Figure 18). The highest discharge in both watersheds occurs from the months of December to May and the lowest discharge occurs from June to November. Additionally, Big Creek watershed daily discharge was greater than Snake Creek discharge, with an average daily discharge of 115.4 ft^3/s compared to 50.6 ft^3/s from WY1961 to WY2019. These differences in daily discharge are due to differences in watershed size; Big Creek watershed is a larger watershed. The historic flood event recorded in Atlanta was observed in both watersheds on September 22, 2009.

The results of the Mann-Kendall statistical test on annual mean discharge for Big Creek and Snake Creek watershed from WY1961 to WY2019 indicated that there is sufficient evidence to conclude with a level of confidence (p-value <0.0001) that a decreasing trend in daily mean discharge exist for both watershed.

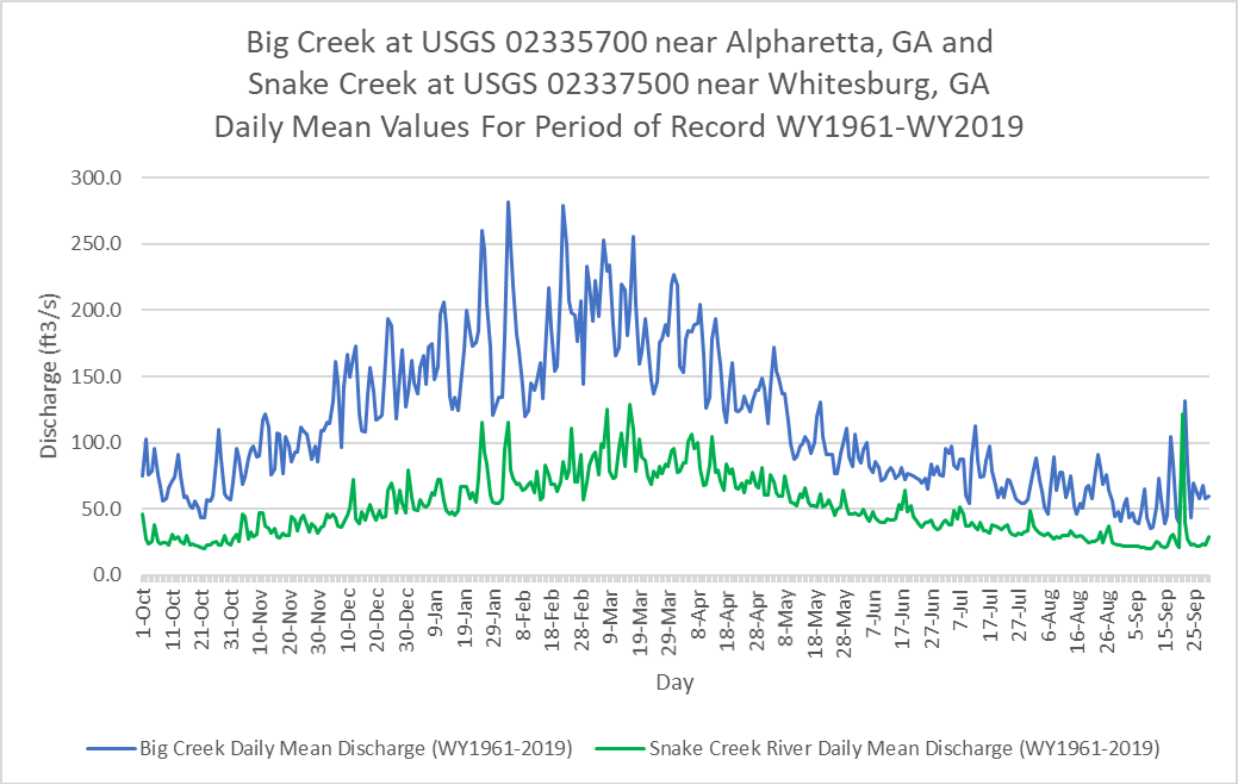

Figure 18. Daily mean discharge for Big Creek and Snake Creek Watershed.

Flow Duration Curve Analysis: The flow duration curves for the pre-urban and post-urban periods were compared for Big Creek and for the same periods for Snake Creek (Figure 19). The results indicate that from the pre-urban to post-urban period, the average discharge in Big Creek decreased by 4%, and decreases occurred for all except the highest flows (AEP less than 8%). In comparison, the average discharge for Snake Creek decreased by 33% between the two time periods, and decreases occurred across all flows including high flows. Table 1 shows discharge differences between the periods for selected exceedance probabilities.

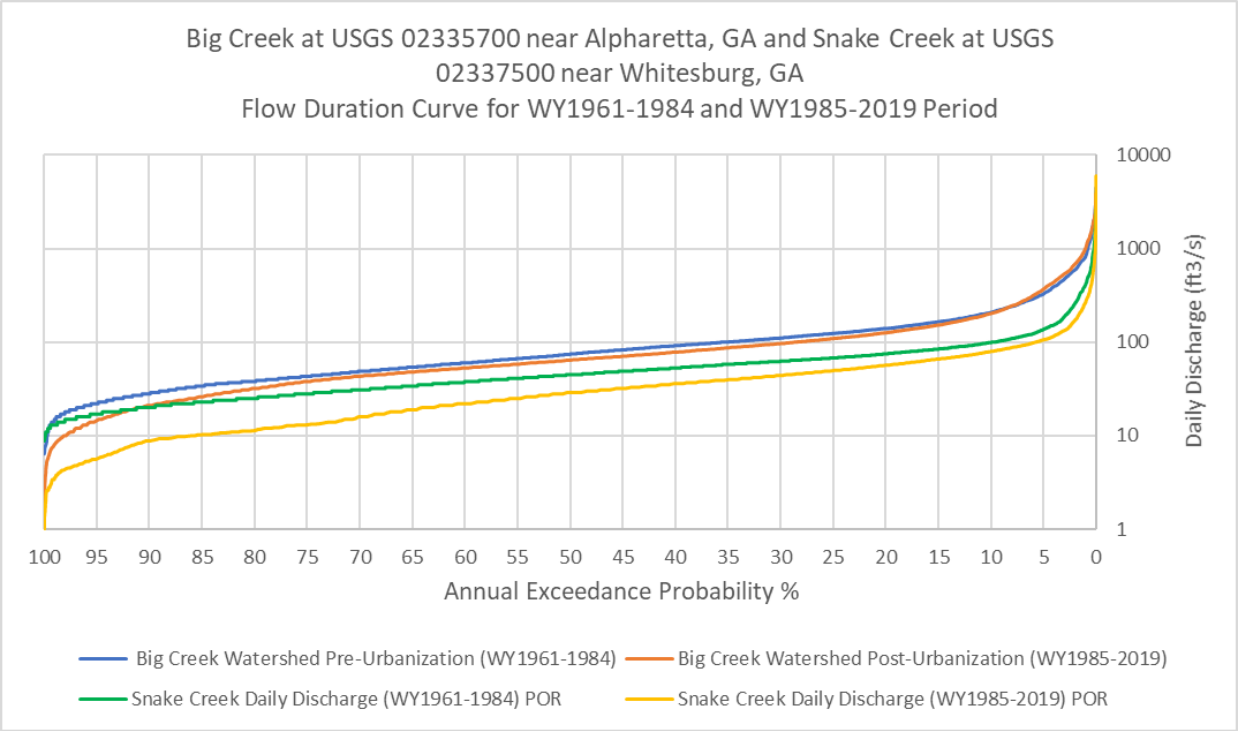

Figure 19. Comparison of flow duration curves in Big Creek and Snake Creek watershed between WY1961 to WY1984 and WY1985 to WY2019.

Table 1. Annual exceedance probabilities for Big Creek and Snake Creek watershed.

	WY1961- WY2019 Period		**WY1961-WY1984 (Pre-Urban Period)**		**WY1985-WY2019 (Post-Urban Period)**	
	Big Creek Watershed (ft^3/s)	**Snake Creek Watershed (ft^3/s)**	**Big Creek Watershed (ft^3/s)**	**Snake Creek Watershed (ft^3/s)**	**Big Creek Watershed (ft^3/s)**	**Snake Creek Watershed (ft^3/s)**
Average Discharge	115.6	50.6	118.2	62.7	113.8	42.3
5% Exceedance Probability	340.6	116.4	321.3	134.1	356.4	104.5
10% Exceedance Probability	202.6	88.2	205.4	98.7	200.2	78.8
50% Exceedance Probability	67.9	35.0	74.1	44.9	64.0	28.9
90% Exceedance Probability	23.5	10.5	28.0	20.0	20.9	8.8

Peak Flow Frequency Analysis: The peak flow comparison between pre-urban and post-urban periods for Big Creek indicates a decrease in peak flows in the post-urban period compared to the pre-urban period (Figure 20). The 99% AEP of discharge in the post-urban period decreased by 17%; the 50% AEP of discharge decreased by 19%; the 2% AEP of discharge decreased by 27%; and the 1% AEP of discharge decreased by 29%.

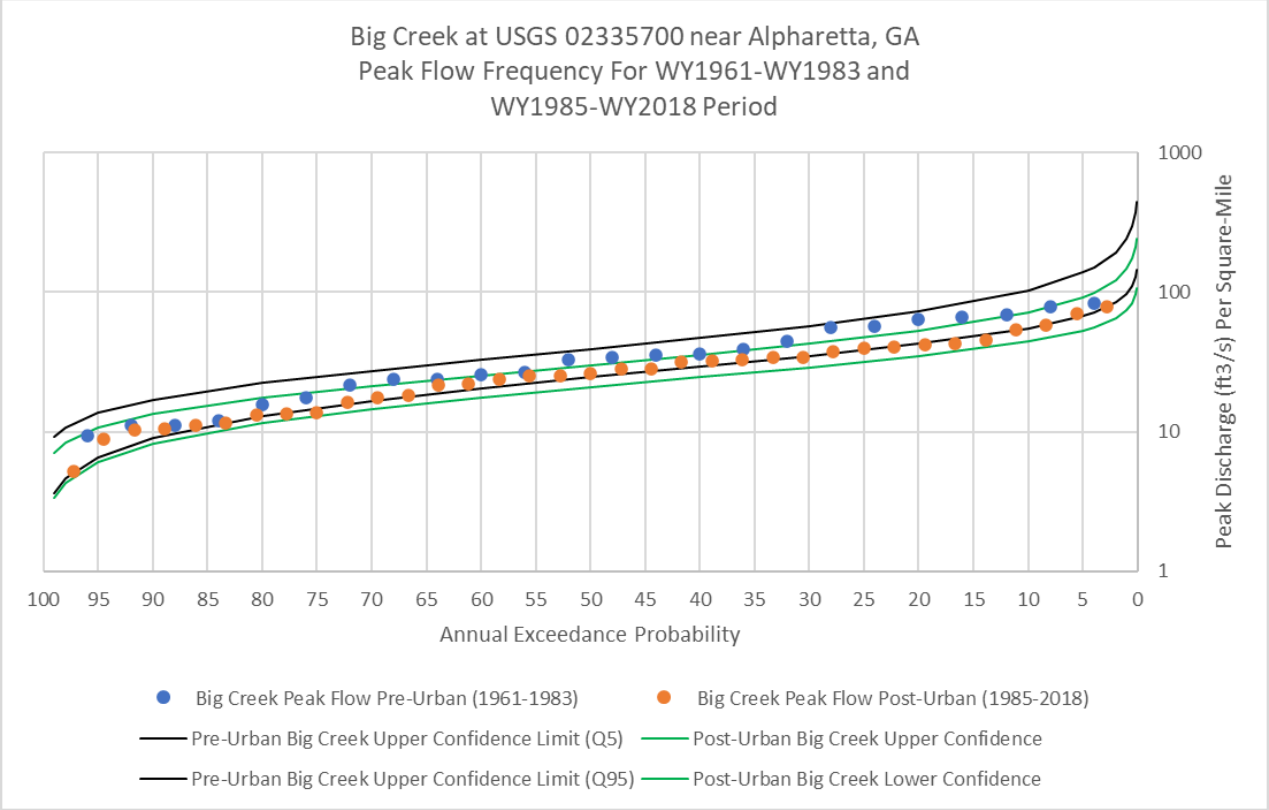

Figure 20. Comparison of peak flow discharge in Big Creek between 'Pre-Urban' and 'Post-Urban' POR.

The peak flow comparison of the same period for Snake Creek indicates an overall larger decrease in peak flow in WY1985 to WY2018 period compared to the earlier period, except for 2% exceedance probabilities and lower (Figure 21). The 99% AEP of discharge in WY1985 to WY2018 period decreased by 98% and the 50% AEP of discharge decreased by 75%. However, the 2% AEP of discharge increased by 47% and the 1% AEP of discharge increased by 81%. Extreme peak flow events increased in the later period compared to the earlier period.

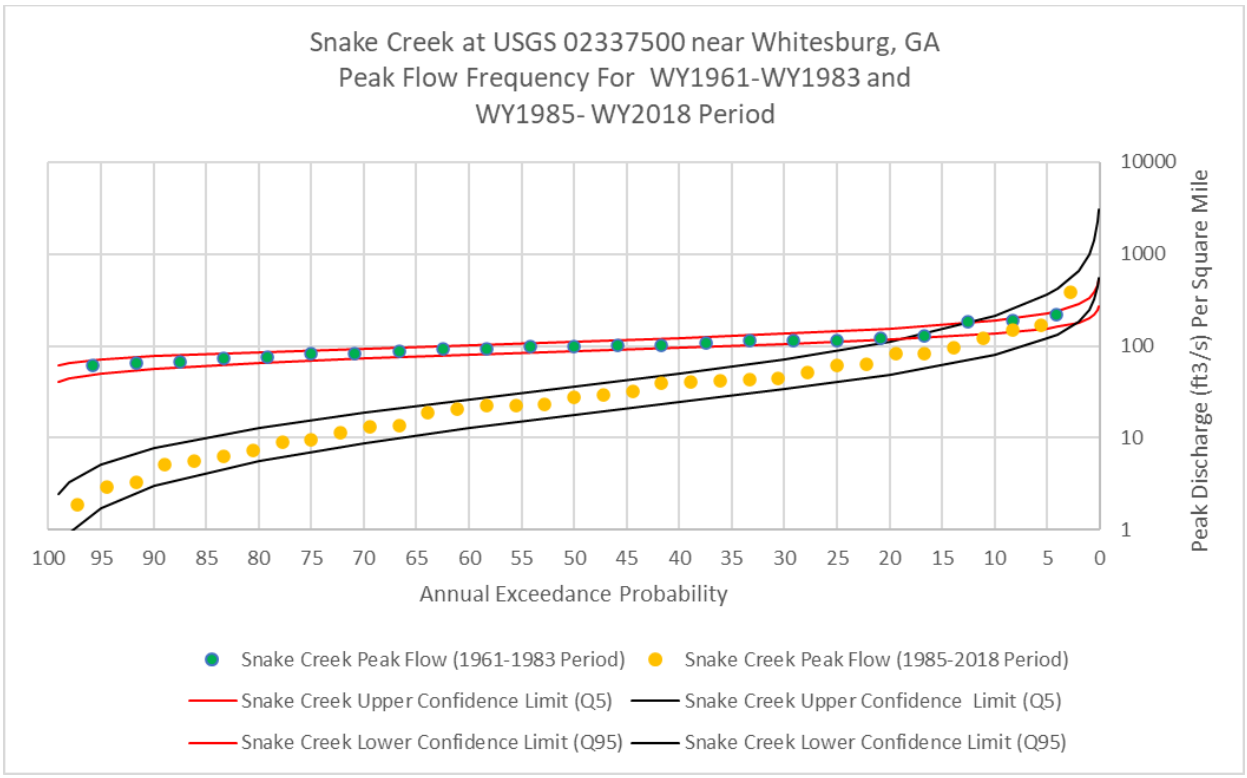

Figure 21. Comparison of peak flow discharge in Snake Creek between WY1961 to WY1983 and WY1985 to WY2018 POR.

The results of the Mann-Kendall statistical test on peak flow discharge for Big Creek watershed from WY1961 to WY2018 found that there is not enough evidence to conclude that a trend exists for peak flow at Big Creek, ($p=0.574$). The Mann-Kendall test for Snake Creek confirms that there is sufficient evidence ($p<0.001$) to conclude that there is a decreasing trend in peak flow.

Baseflow Index Analysis: The baseflow and quickflow results for Big Creek and Snake Creek indicate differences in baseflow behavior after WY1985. Baseflow discharge in Big Creek was greater than quickflow in all but a few years during the pre-urban period; however, after WY1985, quickflow discharge became greater than baseflow in many years; average baseflow decreased by 14% and average quickflow increased by 10% (Figure 22). In Snake Creek watershed, in contrast, baseflow discharge remained greater than quickflow throughout the 59-

year period, except in 2009. Additionally, annual average baseflow and quickflow discharge decreased after year 2001 (Figure 23).

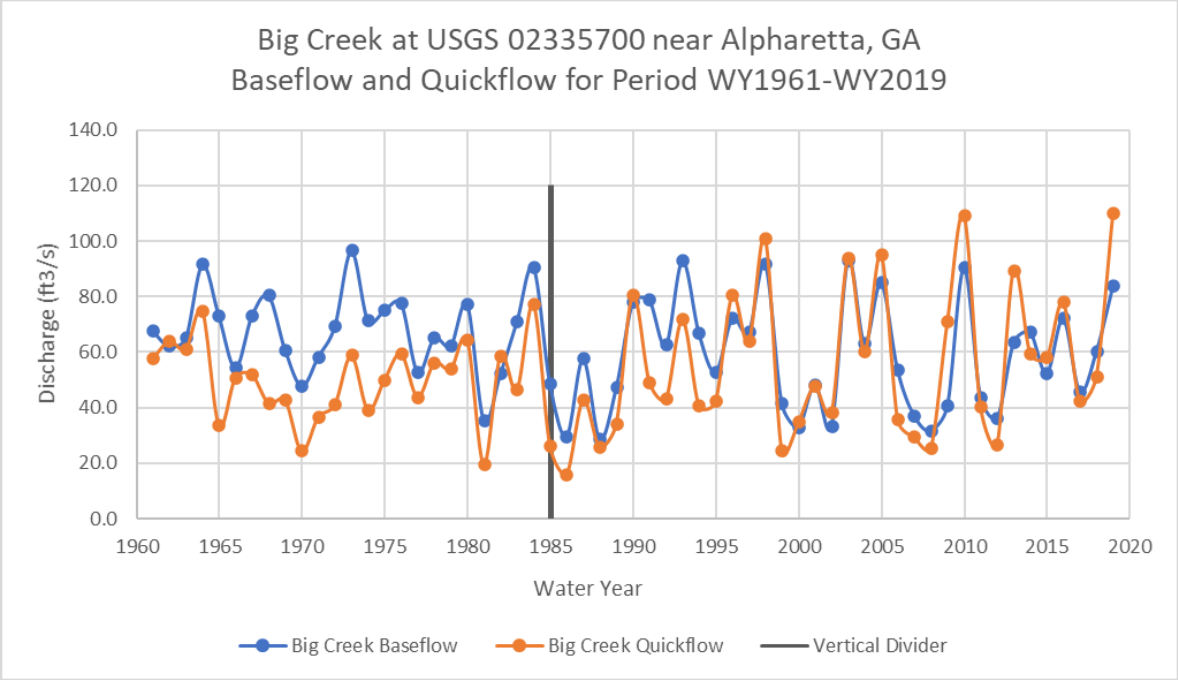

Figure 22. Annual baseflow and quickflow discharge in Big Creek watershed from WY1961 to WY2019.

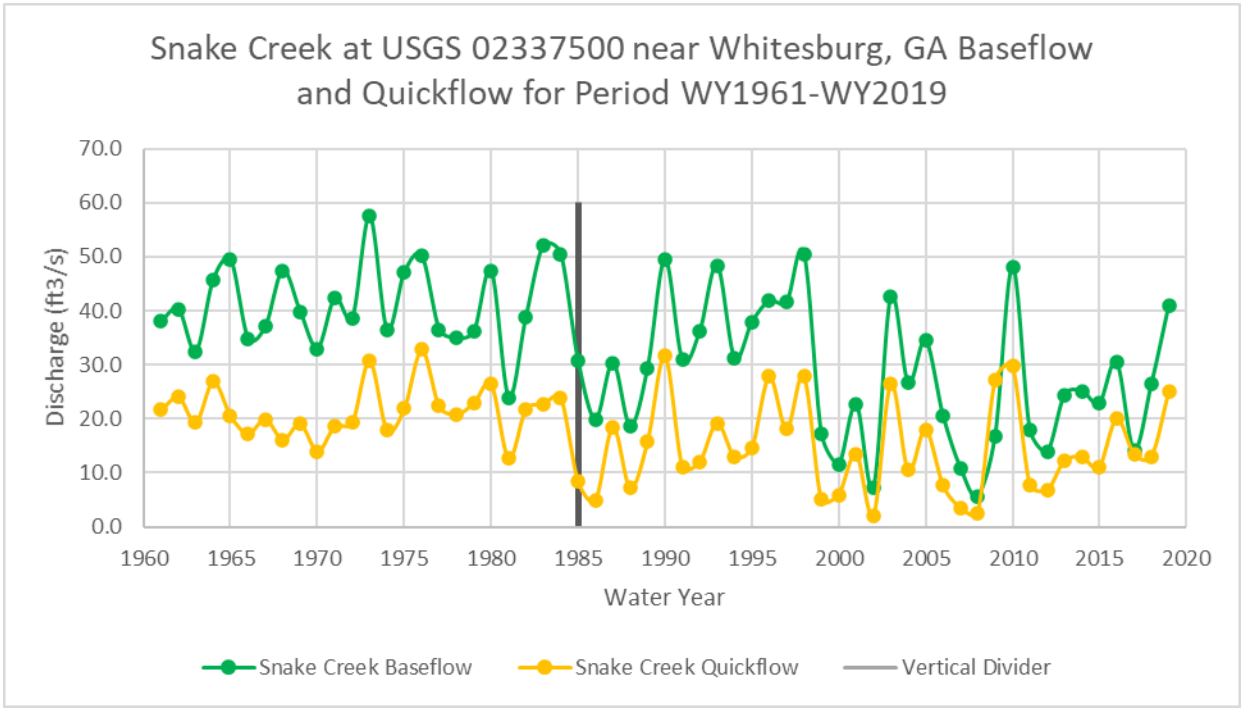

Figure 23. Annual baseflow and quickflow discharge in Snake Creek watershed from WY1961 to WY2019.

The average Big Creek BFI value in the post-urban period decreased by 11.7% compared to the pre-urban period. In comparison, the Snake Creek average BFI value for the two periods remained the same (Table 2).

Table 2. BFI Value for Big Creek and Snake Creek watershed.

	Big Creek Watershed (WY1961-WY2019	Snake Creek Watershed (WY1961-WY2019)	Big Creek Watershed Pre-urban Period	Big Creek Watershed Post-urban Period	Snake Creek Watershed (WY1961-WY1984)	Snake Creek Watershed (WY1985-WY2019)
Average Baseflow Index (BFI)	0.54	0.66	0.57	0.51	0.66	0.66

The results of the Mann-Kendall test on annual baseflow discharge for Big Creek and Snake Creek watershed from WY1961 to WY2019 indicates that there is sufficient evidence ($P < 0.0001$) that there is a decreasing trend in baseflow in Big Creek and Snake Creek. These are trends in baseflow discharge values, not baseflow index.

Richards-Baker Flashiness Index: The R-B Flashiness Index comparison between Big Creek and Snake Creek watershed for WY1961 to WY2019 POR indicates that Big Creek has become a flashier watershed compared to Snake Creek, the non-urban watershed, in recent decades (Figure 24). From WY1961 to WY1984, both watersheds exhibited similar flashiness overall, with Snake Creek exhibiting a slightly higher average R-B index than Big Creek watershed (0.36 compared to 0.34, respectively. From WY1985 to WY2019, Big Creek exhibits a higher flashiness index than Snake Creek watershed. From WY1985 to WY2019, the average R-B index value for Big Creek was 0.47 and 0.26 value for Snake Creek. The change in flashiness in Big Creek occurred in in the mid-1980s and steadily increased until the early 2000s and remained the same since then.

The 2009 historic flooding event of Atlanta resulted in an exceptionally high R-B index value for 2009 water year for Snake Creek. The historic flood event resulted in a 23% higher R-B index value for Snake Creek compared to Big Creek watershed, which was atypical for the post-urban period.

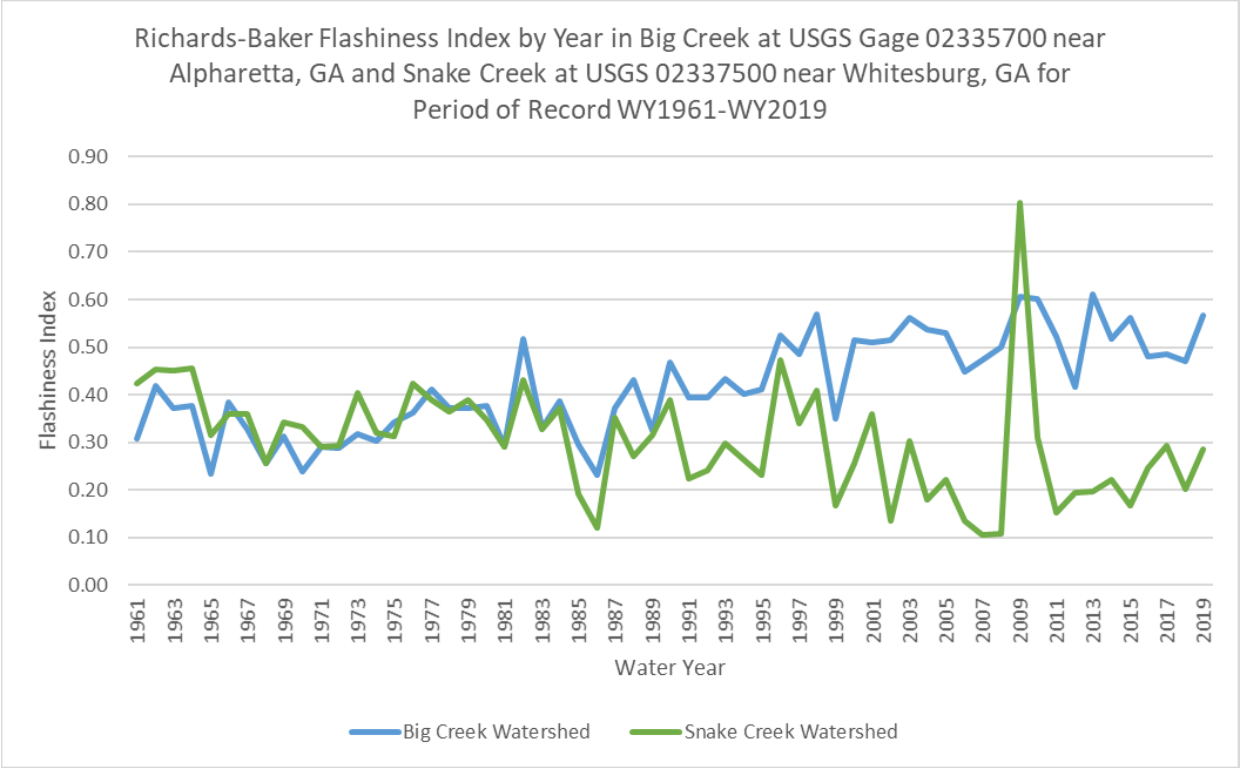

Figure 24. Annual R-B flashiness index in Big Creek and Snake Creek watershed from WY1961 to WY2019.

The results of the Mann-Kendall test on flashiness index for Big Creek indicates that there is sufficient evidence to conclude ($p<0.0001$) that there is an increasing trend in flashiness in Big Creek. For Snake Creek, there is sufficient evidence to conclude ($p<0.0001$) that a decreasing trend in flashiness exists.

DISCUSSION

A paired watershed study with complete data for 59 years was used to compare hydrological changes between two watersheds that differed in landcover type change since the 1980s. Based on previous research, I hypothesized that urban development within the Big Creek watershed would result in an increase in high flows and reduced low flows, increased annual peak flows, flashier discharge variation, and reduced baseflow compared to a non-urban watershed, Snake Creek watershed.

It should be noted that although the watersheds were selected to be as similar as possible in all factors other than landcover change, the development of the reservoir and earthen dam on Snake Creek altered and reduced stream discharge after 2001, making it a flawed "control" watershed. Because of this, the timing of urbanization and stream-flow change in Big Creek watershed is important.

The Landsat satellite images, documented land-use change and population records (ARC, 2016 and census.gov) indicated a rapid increase in urbanization in Big Creek watershed beginning around 1980 to 1985 whereas Snake Creek watershed exhibited very little landcover change over the entire study period. The almost six-decade period of record for Big Creek stream-flow includes two decades of data before major urbanization, which provides a good baseline, and four decades with increasing urbanization. Changes in Big Creek flows can be evaluated by comparing pre- and post-urbanization period or long-term trend, and conclusions can be made without completely depending on the reference watershed. However, the equally long and complete record for an undeveloped reference watershed provides a useful comparison even if it is flawed. Although differences in flows the last 19 years were affected by the dam, differences in 1980-2000 were not.

The lack of trends in total annual precipitation in the 59-year study period for the county's containing each watershed indicates that it is reasonable to assume that any increases in stream-flow observed are not due to a wetter weather regime. Additionally, significant decreasing trends in daily discharge were found for both watersheds. This could result from increasing temperature and evaporation or other causes.

Overall seasonal stream-flow did not change in either watershed, but changes in flows were observed between the two time periods. The post-urban flow duration curve for Big Creek showed an increase in high flows (5% exceedance probability), reduced median flows (50% exceedance probability), and reduced low flows (90% exceedance probability). These findings are similar to findings of other studies. Diem et al. (2018) found a 101% increase in what they called high flow days (i.e. daily streamflow above the 95th percentile for the 10,957 days) in Big Creek watershed in the 30-year period that they analyzed. Prince (1981) found that the flow duration curves in urbanized watersheds had increased in high flows and decreased in low and median flows, compared to the moderately urbanized and non-urbanized watersheds. The urbanized watershed with dense populations and sanitary sewers exhibited the maximum changes in flow duration compared to the other watersheds (Prince, 1981). In my study, however, the non-urban Snake Creek watershed flow duration curve for the later period exhibited a larger change in flow (overall decrease) compared to the Big Creek watershed post-urban period.

The analysis did not find a statistically significant trend in Big Creek annual peak flow, and a trend was not observed in annual maximum 1-day rainfall event at USC00092408 Cumming 2 N station from WY1961 to WY2019. However, when peak flow frequency curves were created for the post-urban and pre-urban periods, peak flows decreased for the 1, 2, 50, and

100-year average return intervals in Big Creek after urbanization. Despite the decrease in peak flow, the increase in RB flashiness and quickflow seem to suggest that more frequent smaller storm events have been affected by urbanization, rather than large storm events.

The decrease in post-urban peak flows in this study does not agree with other studies. Many hydrological studies have found that urbanization and other types of landcover change can increase peak flow rates by two-to tenfold depending on the severity of land disturbance (e.g. deforestation, percentage impervious surface, and soil compaction) (Sun and Lockaby, 2012). For example, Sheng et al., (2009) found that high frequency, low magnitude flood events (common floods) and low frequency, high magnitude (rare floods) increased in peak flow discharge in an urbanized watershed. Additionally, Peters and Rose (2001) found that highly urbanized watersheds in Atlanta had greater peak flow discharge compared to less urbanized watersheds and rural watersheds. Ferguson and Suckling (1990) reported that an Atlanta urbanized watershed exhibited a greater peak flow after urbanization compared to earlier less urbanized years.

Other factors such as topography and locations and sizes of urban areas can affect peak flow and potentially mask the effects of urbanization in Big Creek (Sun and Lockaby, 2012). Additionally, the year of development of any specific urban site influences the stormwater infrastructure and stormwater management practices (Hopkins et al., 2015). Development intensity and specific stormwater infrastructure could be a factor in decreased peak magnitudes observed in Big Creek. Estimating large flood events with the smaller datasets of pre-urban and post-urban periods is a limitation of the peak flow analysis and may have also played a part in the lack of increased peak flows during the urbanized years. In contrast to the urban watershed,

Snake Creek had a statistically decreasing trend in peak flow. Storage by reservoirs often reduces the magnitude of peak flows (Mitchell, 1962).

The results of the baseflow analysis indicate that stream discharge in both watersheds is dominated by baseflow under natural conditions. However, after WY1985 (post-urban period) Big Creek quickflow increased and the average baseflow index decreased. Quickflow is an estimate of the portion of runoff caused by individual storm events, whereas baseflow is an estimate of the flow sustained between events by sources such as groundwater. The proportion of runoff occurring as baseflow decreased slightly while the proportion occurring as quickflow increased slightly with urbanization of the Big Creek watershed. In Snake Creek, although a statistically decreasing trend in baseflow volume was found, the BFI value remained the same, meaning that the proportion of baseflow versus event runoff did not change.

Studies investigating effects of urbanization on baseflow have had inconclusive findings; urbanization may either increase or decrease baseflow. Peters and Rose (2001) found that an urbanized watershed in Atlanta experienced decreased baseflow. A decrease in baseflow in urbanized watersheds is likely the result of a lower water table from increased storm runoff to streams from storm sewers, which reduces ground water recharge (Spinello and Simmons 1992). They also note that precipitation, storm sewers and recharge basins, and sanitary sewers are factors that can affect baseflow. Since a trend in precipitation was not found, it is likely that urbanization and associated storm sewers resulted in a decreasing trend in baseflow and a decreased BFI index in the post-urban environment. Although the non-urban watershed exhibited a statistically significant trend in baseflow, the creation of the reservoir could be contributing to that change.

Trends in the Richards-Baker flashiness index provide the strongest evidence for changes in the flow regime of the two streams. During the pre-urban period, Big Creek exhibited a slightly lower average flashiness index than Snake Creek. The R-B flashiness index tends to decrease with increasing watershed size, and this could explain the slightly lower flashiness index for Big Creek watershed before development (Baker et al., 2004). In the post-urban period, the R-B flashiness index value for Big Creek steadily increased compared to Snake Creek watershed, especially after 1987. Although differences were greatest after Snake Creek Reservoir was built, the differences developed before the dam. Since trends in total and maximum precipitation were not detected, it can be assumed that increase in flashiness in Big Creek was not due to precipitation.

Considering the timing of changes and the results of previous studies, changes in flashiness were probably caused by the concurrent changes in landcover. Rosburg et al. (2017) and Greve (2012) found that urban areas with higher levels of impervious surface displayed greater flashiness. Additionally, Diem et al., (2018) found that Big Creek exhibited a statistically increasing trend in flashiness over 1986 to 2015 and that the average flashiness index for eight Atlanta area watersheds was positively correlated with increased developed land. Greve (2012) found that urban land cover and flashiness are linked. In their study, flashiness within an urban watershed had the strongest correlation with lot coverage, defined as the proportion of a property parcel covered by building footprints (Greve et al., 2012). The increase in flashiness observed in Big Creek watershed compared to Snake Creek watershed up to 2001 can probably be attributed to impervious surfaces. Although the development of the Snake Creek Reservoir altered stream discharge starting in 2001, flashiness index values before 2001 reflect the nearly natural flow regime of a non-urban watershed with low-intensity rural land uses.

CURRENT STORMWATER MANAGEMENT STRATEGIES

Several city and county jurisdictions are located within Big Creek watershed and each jurisdiction differs in local stormwater management ordinances and regulations (CDM, 2000). Currently, the jurisdictions have adopted the Federal Emergency Management Agency (FEMA) ordinance to combat flood events, but local jurisdictions differ in how far above the base flood elevation buildings and structures can be constructed. Additionally, some jurisdictions allow development within the floodway if a hydraulic study is conducted while others do not. Generally, development within the watershed is designed to control runoff for the 2-year to 100-year flood event, but other jurisdictions only design for the 100-year flood event. No jurisdiction explicitly manages for the frequent (many times per year), smaller events that affect flashiness and baseflow index. Several stream buffer setbacks have been adopted, but the setbacks also differ, with some jurisdictions requiring a 25-foot buffer and others requiring a 75-foot buffer (CDM, 2000).

In 2000 a technical study was conducted to estimate peak discharges in Big Creek watershed for future 2020 land-use conditions. The peak discharges were estimated using a RUNOFF and EXTRAN modeling approach and the study projected that a 25-year flood event with 1995 land-use conditions would occur closer to every 10-years with 2020 land-use conditions, if stormwater management practices are not implemented (CDM, 2000).

The results of my study found that peak flow discharge decreased in the post-urban period, which as previously discussed, could likely be due to stormwater management strategies and limitations of the peak flow analysis. My results also indicate that despite current stormwater management strategies, Big Creek watershed continues to exhibit a flashier discharge and reduced baseflow. Stormwater management practices should consider implementing strategies

aimed at restoring baseflow and reducing flashiness. Additionally, future technical studies conducted within the watershed should incorporate hydrological analyses aimed at monitoring flashiness and baseflow to monitor the effectiveness of newly implemented stormwater practices.

CONCLUSION

The results presented in my case study support the hypothesis that urbanization has altered the natural flow regime of Big Creek. However, the findings indicate that some aspects of stream discharge are affected by development whereas other are unaffected in this watershed. Similar to other studies, the results suggest that urbanization in Big Creek watershed resulted in an increase in high flow and reduced low flows, increased flashiness, and reduced baseflow; however, contrary to previous studies, an increasing trend in annual peak flow was not detected. Current management strategies within Big Creek watershed are aimed at reducing peak flow events, but my results suggest that strategies have not been able to address the flashiness and baseflow issues; therefore, strategies should also aim at reducing flashiness and increasing baseflow.

Further research is needed to explain the differences in effect of urbanization on stream-flow patterns between watersheds. The stormwater management practices, stream buffer regulations, development type, and forest cover within the urban watershed could have dampen the effects of urbanization. Future studies investigating altered stream discharge from urbanization should include population density, percent of impervious surface, stormwater management practices and stream buffer enforcements to identify and correlate factors that affect stream-flow. Given the amount of forest cover within the urban watershed and increasing temperature, future studies should also incorporate evapotranspiration rates and water balance when investigating the effects of urbanization because urbanization can alter evapotranspiration processes (Sun and Lockaby, 2012). The whole water cycle should be considered to more completely understand the alteration of stream discharge.

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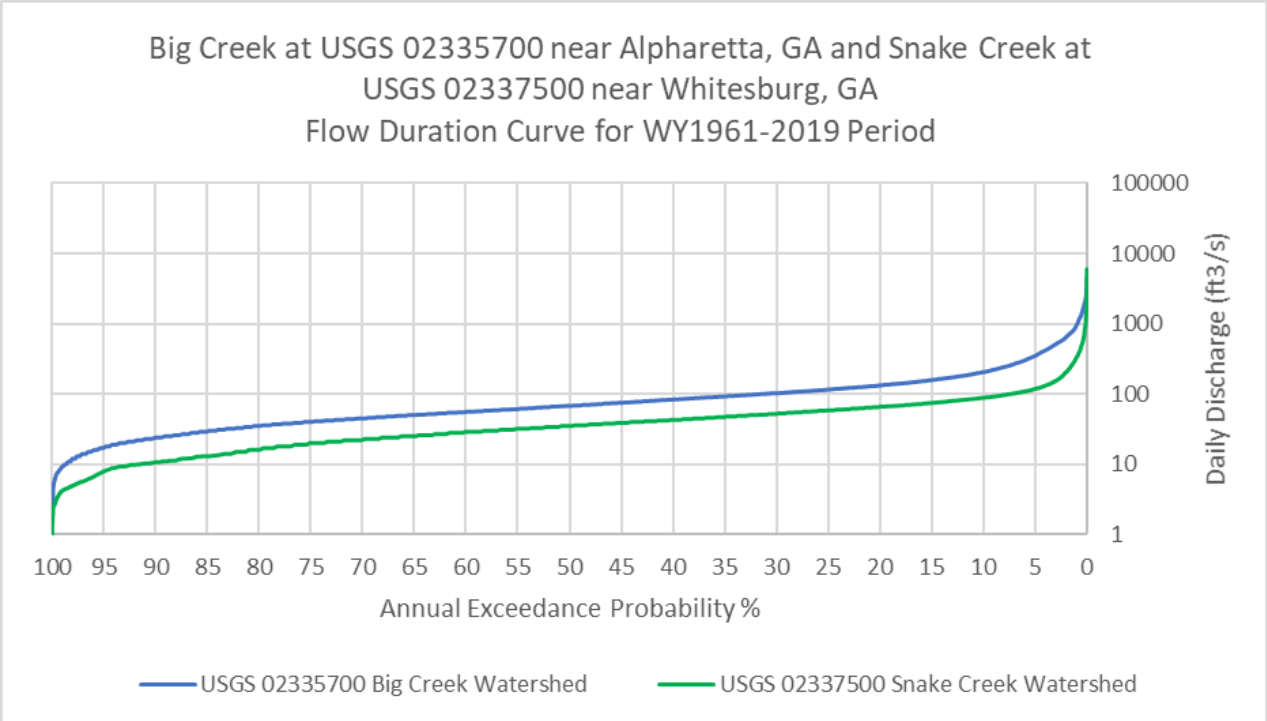
APPENDIX A

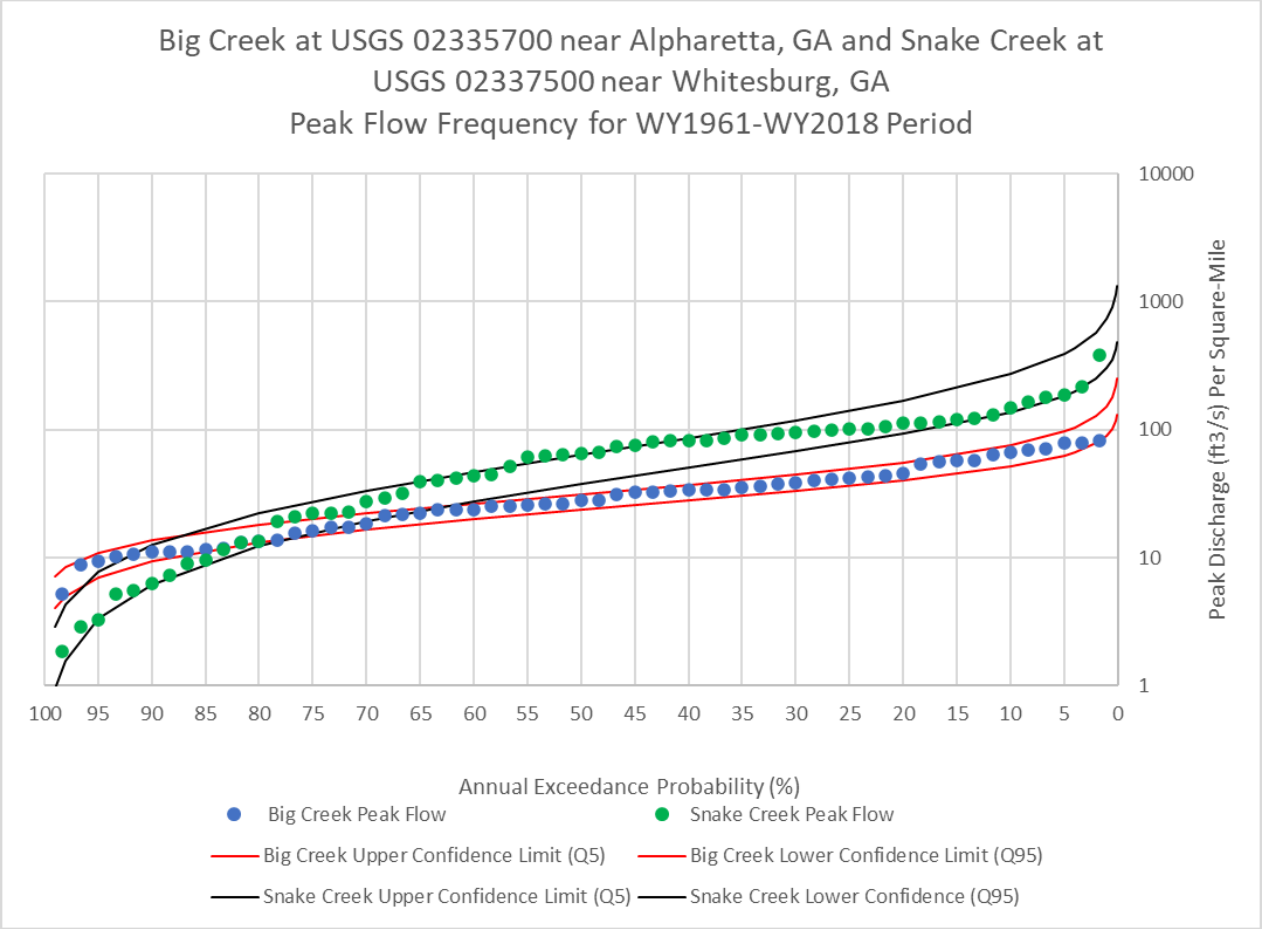
Additional Watershed Comparison

Watershed characteristics of Big Creek and Snake Creek

Stream Gauge Name/ID	Stream Gauge Coordinates	Watershed Size	Mean Basin Elevation	Min Basin Elevation	Max Basin Elevation	Mean Basin Slope	Mean Annual Precipitation	% Urbanized	Daily Mean Discharge
Big Creek near Alpharetta (02327500)	34°03'01.89"N, 84°16'09.98"W	73.4 mi^2	1119 ft	962 ft	1965 ft	9.07%	55.2 in	73%	115.6 ft^3/s
Snake Creek near Whitesburg, GA (02337500)	33°31'45.60"N, 84°55'242.02"W	35.5 mi^2	1,087 ft	838ft	1,390 ft	9.79%	53.7 in	22.8%	50.6 ft^3/s



The flow duration curve in Big Creek and Snake Creek watershed from WY1961 to WY2019. Average discharge in Big Creek is 115.6 ft^3/s and average discharge in Snake Creek is 50.6 ft^3/s.



Peak flow frequency curve in Big Creek and Snake Creek watershed from WY1961 to WY2018. The low flows (represented by the 99% AEP) in Big Creek was greater than Snake Creek; however, Snake Creek had greater peak flow (represented by the 1% AEP) compared to Big Creek watershed.