1-6-2017

Land Cover Change Impacts on Multidecadal Streamflow in Metropolitan Atlanta GA, USA

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Recommended Citation

Hill, T. Chee, "Land Cover Change Impacts on Multidecadal Streamflow in Metropolitan Atlanta GA, USA." Thesis, Georgia State University, 2017.
doi: https://doi.org/10.57709/9011550

LAND COVER CHANGE IMPACTS ON MULTIDECADAL STREAMFLOW IN METROPOLITAN ATLANTA, GA USA

by

TIFFANNIE CHEE HILL

Under the Direction of Jeremy E. Diem, PhD

ABSTRACT

Urbanization has been associated with the degradation of streams, and a consequence of forest to urban land transition is a change in streamflow. Therefore, the purpose of this thesis is to examine the impacts of land-cover change in ten different watersheds in the rapidly urbanizing Atlanta, GA USA metropolitan area. Streamflow and precipitation data for a 30-year period (1986-2016) were analyzed in conjunction with land cover data from 1992, 2001, and 2011. Big Creek and Suwanee Creek experienced the most urbanization and increases (20%) in streamflow and runoff, and high flow (>95th percentile of flow) days doubled and increased 85%, respectively. Precipitation-adjusted streamflow for Peachtree Creek and Flint River decreased about 17%. Runoff ratios for South River were the highest among all watersheds, even the Etowah River, which remained moderately forested and had the most precipitation and slope.

INDEX WORDS: Streamflow, Land cover, Urban streams, Baseflow, Watershed, Georgia, urbanization, precipitation

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TIFFANNIE CHEE HILL

A Thesis Submitted in Partial Fulfillment of the Requirements for the Degree of

Master of Science

in the College of Arts and Sciences

Georgia State University

2016

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August 2016

DEDICATION

I would like to dedicate this thesis to my very funny, loving, and supportive partner Carolina Casares, to whom I cherish given that she kept me fed and sane while writing this. I would also like to dedicate this to my now deceased father Charles Wayne Hill (1949-1985) because he taught me how to be a good, decent, and better human being.

ACKNOWLEDGEMENTS

I want to acknowledge Jeremy Diem as the one whom I could always rely on to listen to, understand, and respond to my goals for this project with great ideas and for my graduate education in general from the start to the finish - thank you very much. I also want to thank Ricardo Nogueira who was my first geography professor at Georgia State University and a member of my thesis committee. Along the process of organizing my thoughts for this project, Luke Pangle helped me narrow down my research interests to water quantities (not just flooding), and he is also a committee member.

Several other faculty and staff members (of both GSU and Ga Tech schools) have helped me to understand all the different aspects of geoscience. I could not have completed this thesis without the specialized skills I obtained in remote sensing and quantitative spatial analysis. I could not have done the research without the library, and my time serving on the Student Library Advisory Council (organized by Librarian Jennifer Jones) was helpful and interesting. I also appreciated the chance to work on the radon screening and exposure health disparities project in south DeKalb County, which was organized by Dr. Dajun Dai, Dr. Christine Stauber (School of Public Health), and Dr. Jeremy Diem. I also appreciate the last minute help from the Office of Graduate Services.

Thank you all for everything you have done for me, knowingly or not.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

1 INTRODUCTION

Forest conversions dramatically affect streamflow. Based on Earth observation satellite records from 2000 to 2012, we have lost 2.3 million square kilometers of forest land cover (Hansen et al., 2013). Meanwhile, the global extent of urban land from circa 2000 to 2030 is estimated to increase 185% (Seto, Gueneralp, & Hutyra, 2012). Across the planet from continent to continent, approximately half of the world's population now lives in urban areas as opposed to rural, and by 2050 approximately 87% of North America's population will live in urban areas (Paul & Meyer, 2001; UN Population Division, 2014). In an urbanized watershed if the a priori land use type was forest, there will be markedly consistent responses from aquatic biota (fish, macroinvertebrates, etc.) (Brown et al., 2009). As more urban land encroaches into forested land, for every 10% of trees that are removed, approximately 20 mm of water are added to the water balance budget for watersheds yielding increased peak flows and increased velocity of streamflow (Sahin & Hall, 1996). Upland compacted soil and pavement aggravates urbanizing streamflow conditions by becoming impervious to rainfall, and this sets off a beginning to an "urban stream syndrome" (D. B. Booth & Jackson, 1997; Walsh et al., 2005). Additionally, impoundments or water features in urban areas functioning as water supply reservoirs or stormwater control attempt to mitigate peakier flows and stormwater volumes but actually disrupt the natural streamflow regime (Ignatius & Jones, 2014; Poff & Allan, 1997). The purpose of this thesis is to explore the impact of urbanization on streamflow in the Atlanta metropolitan area, using 30 years of data from ten multi-basin sub-watersheds (30-1,000 km^2).

1.1 Controls of Streamflow

Precipitation is the most important control of streamflow in most watersheds, and streamflow increases with increasing precipitation. Streamflow patterns are also an indirect result of runoff behavior, infiltration, evaporation, transpiration of vegetation, groundwater inflow and outflow, and baseflow (Barlow & U.S. Geological Survey, 2002). The contribution of precipitation to streamflow has been shown to be around 1/3 streamflow (Changnon & Demissie, 1996). Likewise, it has also been shown that to achieve bankfull status an urban stream (33% urban) requires nearly 40% less precipitation to achieve the same discharge as a rural stream (13% urban) (Jennings & Jarnagin, 2002).

Increased evapotranspiration decreases streamflow. For full radiation capture, a leaf needs to remain turgid for transpiration, and that happens only when there is a steady volume of water streaming through a plant's xylem from root system all the way to leaves (Campbell, 1993). When trees like pine and hardwood trees from a natural forest use water, it is exported to the immediate air as water vapor via its stomata, and in the southeastern US where there are mostly temperate deciduous forests/woodlands (a mix of conifers and deciduous trees), the amount of water vapor flow exported each year is estimated to between 553-792 mm, which can equal almost half the amount of annual precipitation (~1,200 mm) in Atlanta, GA (Gordon et al., 2005; NOAA, 2016).

Groundwater discharge also contributes to streamflow (Figure 1). In fact, drainage density among first order streams (i.e. headwaters), large amount of colluvium deposits, and variable slope are among the most important factors when explaining groundwater or baseflow contribution to streamflow in the Blue Ridge region (Price et al., 2011). During dry seasons or drought, baseflows are sustained by subsurface groundwater, and it has been thought that lithology is the primary factor of baseflow (Bloomfield, Allen, & Griffiths, 2009). In the southeastern United States (U.S.), where hard metamorphic rock makes up the Piedmont and Blue Ridge ground water aquifers, groundwater is mainly stored in the regolith on top of bedrock (Miller & U.S. Geological Survey, 1990).

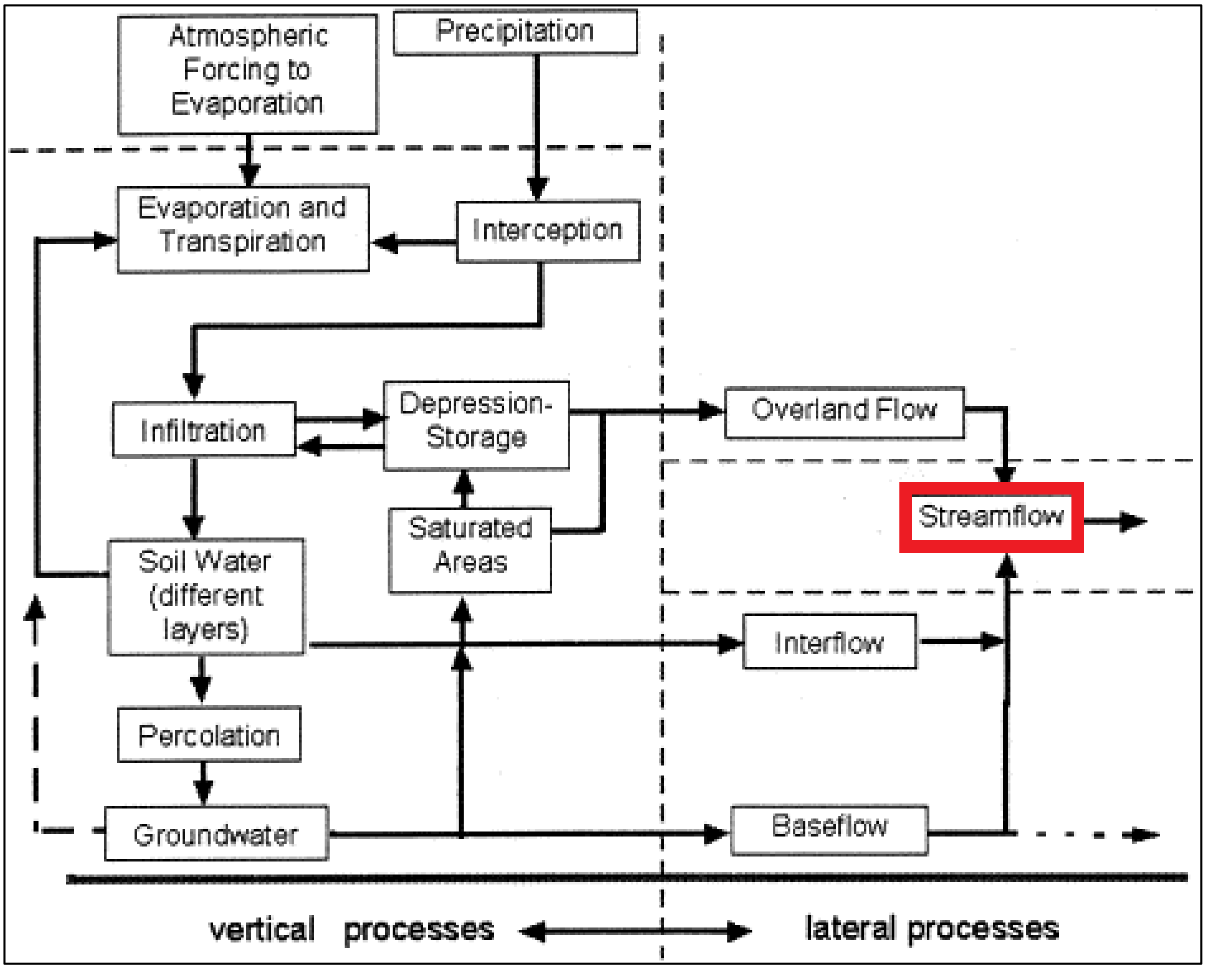

Figure 1 Hydrological vertical and lateral processes (Becker & Braun, 1999)

1.2 Urbanization Impacts on Streamflow

Impervious cover (IC) and soil compaction increase peak flows. ICs lead to much faster runoff response to rainfall and shorter times of concentration and recession times (Leopold, 1968). Baseflows have been found to mostly decrease due to high IC area in a watershed --

considering only natural groundwater influences – especially during summer seasons (Finkenbine, Atwater, & Mavinic, 2000). With just a 10% increase in IC in a watershed, peak flows have been shown to sometimes triple (Paul & Meyer, 2001). In San Diego, when increasing soil compaction urbanized land cover in a watershed grew from 9% urban to 37% urban, total runoff has been seen to increase at a rate of 4% per year (White & Greer, 2006). IC impacts can be split between isolated imperviousness and directly connected ICs (DCIA), with the latter being much more detrimental than isolated IC that may in fact allow its runoff to be infiltrated before reaching streams (Walsh et al., 2005). Increased peak flows in urban areas are more due to an improved continuity of ICs in a watershed than just the percentage of total ICs because manufactured hydrological links, such as parking lots, culverts, paved streets, and gutters are designed to drain water efficiently (Meierdiercks, Smith, Baeck, & Miller, 2010). Inevitably this urbanization of local stream morphology makes impacted streams become straight, flat, engulfed with sedimentation from eroded stream banks and still more deleterious impacts affecting stream beds can make a stream draining ICs look uniformly ugly (Derek B. Booth, Roy, Smith, & Capps, 2016).

Stormwater infrastructure adds a variety of effects to streamflow. The Clean Water Act introduced several regulations and physical infrastructure-based solutions and regulations to address stormwater management that include flood risk and water pollution mitigation at point sources in the United States. There are some critical concerns with stormwater ponds that mostly address aging of technology such as first generation stormwater ponds only worked for reducing volume versus second generation ponds were built to address quality and quantify (Anderson, Watt, & Marsalek, 2002). Also, where there are scattered rainfall events in urban areas, it has been shown that antecedent soil moisture variability reduces the effect of local rainfall variability in fully networked stormwater catchments (Smith et al., 2005). However, an examination of stormwater ponds used on a watershed-scale ensued because peak flow control structures were seen to not really reduce final downstream peak flows (Emerson, Welty, & Traver, 2005; Goff & Gentry, 2006). Conversely when analyzing different types and ages of stormwater controls, number/count of controlled stormwater detention ponds, versus scattered and dense DCIAs draining directly to streams, has been seen to in fact decrease peak flows, which could mean that the degree of stormwater treatment is more important in predicting stormwater runoff than land use (Meierdiercks et al., 2010). Where there is a combination of IC (progressing from 11% to 44% impervious) mixed with a large stormwater drainage system later added to it, peak flows have been seen to increase 400% over approximately 10 years, so stormwater management is not as effective in newly-developed areas (Miller et al., 2014). Combined sewer overflow systems are sometimes installed in urbanized watersheds for treating all waste- and stormwater (only lower frequency storms <50%), which can cause water quality problems during high flows, but up to 30% streamflow can infiltrate the system on an annual basis and ultimately cause baseflows to decrease while also doing nothing for high flows in the urban watershed (Braud et al., 2013).

Wastewater and sewer degrade streamflow in urban streams. Then, there is also the other way sewer systems affect streamflow which is called infiltration / inflow (I/I) to sewer systems via older or compromised sewer subsurface infrastructure. Sewer system pipelines are not perfectly sealed, so they do frequently take-in water because of such things as the type of pipe material, aging/weathering, location along system, toxic effluent, the way pipe segments are connected, diameter, and slope or gradient (Baur & Herz, 2002). In trying to quantify the I/I rate, it has been found that the age/condition of pipe and the infiltration of groundwater potential is a way to estimate I/I, and this was led knowing that 79% of mean I/I flow rate would affect approximately 3% of a city's sewer system pipes in the city of Dresden (Karpf & Krebs, 2011). Water supply (raw source and treated potable water) pipelines exist in urban areas as well, and their pipelines age either slower or faster than other pipe, but they do need maintenance and replacement (Herz, 1996).

Research completed in the southeastern US within the Piedmont and Blue Ridge provinces uniformly suggest that there are distinct differences in the effect of urbanization on the ecosystem in the Atlanta metropolitan area. Forests in the Piedmont are enduring significant decline and fragmentation, and it has been accelerating since 1985 with a rate faster than the Northern Piedmont (Griffith, Stehman, & Loveland, 2003). Meanwhile, lands in the southeastern plains located south of the fall line has been changing at an accelerating rate from agriculture to industrial forests (Griffith et al., 2003). Another attribute of the Piedmont is the rise in number of small water reservoirs within the Chattahoochee River basin; small reservoirs have grown from just 19 reservoirs in 1950 to 329 reservoirs in 2010, thus inundating lowland floodplain forests by constructed dams (Ignatius & Jones, 2014). Streamflow responds by increasing flows with high peaks and low lows when forest convert to either agriculture or urban areas in northwest Georgia (Isik, Kalin, Schoonover, Srivastava, & Lockaby, 2013). When comparing Piedmont streams with the urban Peachtree Creek in Atlanta, peak flows were 30-100% greater, low flows were 25-35% less, storm recession periods were 1-2 days lower, and baseflow recession constants were 35-40% lower than other less urban streams, which was attributed to decreased evapotranspiration and lower infiltration even though groundwater levels in nearby wells were just as low as the stream's, but this was attributed to less groundwater recharge due to the built-up nature of the watershed (Rose & Peters, 2001). An indicator of urbanization levels between two urban streams (built-up Peachtree Creek and half rural Sweetwater Creek in Atlanta) is the amount of total dissolved solids (TDS), and in a comparison study it was found that Peachtree Creek baseflows had a higher concentration of solutes than more rural Sweetwater Creek more so than during high flows (Rose, 2002). Later, there was another study on urban streams in Atlanta in the Chattahoochee River basin, and that study's watersheds made up a gradient of concentration of a certain solute (mostly indicating wastewater) -- the highest being watersheds with wastewater discharges and combined sewer overflows and the lowest being rural watersheds (Rose, 2007). In west Georgia, impacts of land cover on stream hydrology showed that among variables such as flow frequency, magnitude, flow duration, and flow predictability, flow frequencies were most correlated to land cover type (i.e. urban versus forest); moreover, the streamflow patterns were the same between 15-minute and daily discharge intervals (Schoonover, Lockaby, & Helms, 2006). Interestingly, there is an urban temperature connection to baseflow because in a study on the North Carolina Piedmont showed that stream baseflow temperature was directly correlated to extent of development and road density, and that storm-flow (peak flows) temperatures were strongly influenced by percent of IC in a catchment (Somers et al., 2013).

1.3 Research Question

How does streamflow change in watersheds with varying degrees of urbanization? Long-term analysis of streamflow patterns has not yet been tied to fragmenting forests in the southern Piedmont. Long-term streamflow (30 years) has not yet been used to determine impact of small reservoirs and stormwater ponds. North Georgia's forestland loss and urbanization has not yet been analyzed over a 30-year period with land-cover data spanning multiple decades. and recent studies have not yet included multiple and neighboring watersheds with varying degrees of urbanization from separate river basins. Objectives to address this research gap: (1) assess land-cover changes over several decades, (2) determine the typical characteristics of streamflow, and (3) examine interannual variations in streamflow.

1.4 Study Region

The ten study watersheds are located in metro Atlanta. The study region lies entirely in the Piedmont division that includes crystalline-rock aquifers (Fanning & Trent, 2009) (Figure 2, Figure 3). Within the Piedmont division, there are a few terranes (Cocker, 1999). In the Piedmont and Blue Ridge, natural springs are likely to be from localized water sources: shallow aquifers of precipitation filling interstitial space in regolith deposits and parallel rock fractures in the immediate area (LeGrand, 1967). The study watersheds are situated at the headwaters of major river basins, are entirely inside the Piedmont province, and are laid upon fairly impermeable geology. Associated districts and terranes per watershed are listed (Table 1). The Inner Piedmont terrane is less permeable than the Carolina terrane (south of the Towlinga fault zone), but the terranes to the north like the Blue Ridge terrane are less permeable than the Inner Piedmont terrane (Cocker, 1999). The climate in this study region is humid, with strong rainstorms occurring in Winter and Spring. During July and August, dry conditions cause water deficits. The Web-based, Water-Budget, Interactive, Modeling Program (WebWIMP) model was used to develop soil-water balance diagrams in order to show when rainy and dry seasons occur in the study region (Matsuura, Willmott, Cort J., & Legates, 2009). The southern watersheds tend to have a longer deficit duration than the northern (Figure 4, Figure 5).

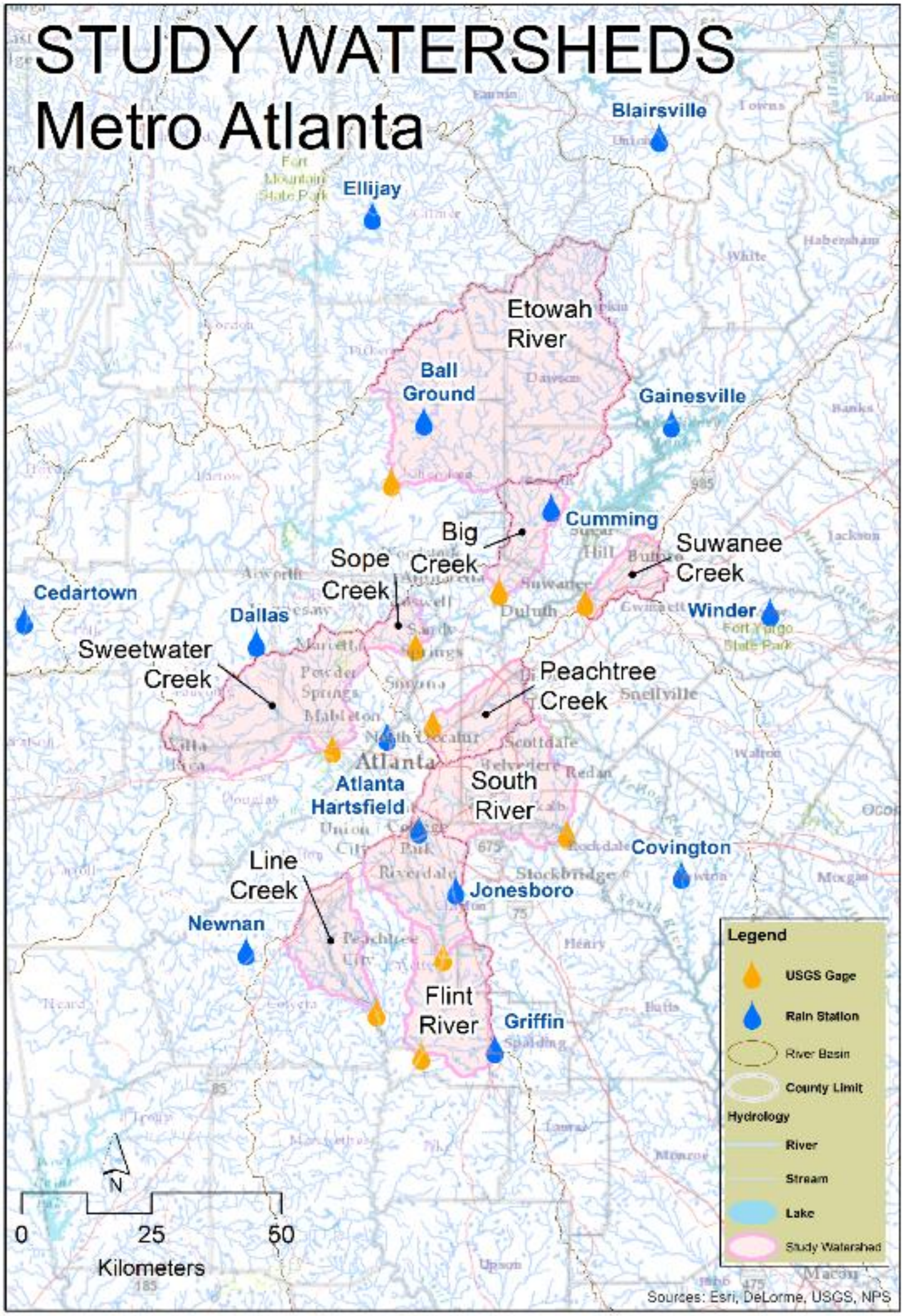

Figure 2 Streamflow study watersheds in metropolitan Atlanta, GA

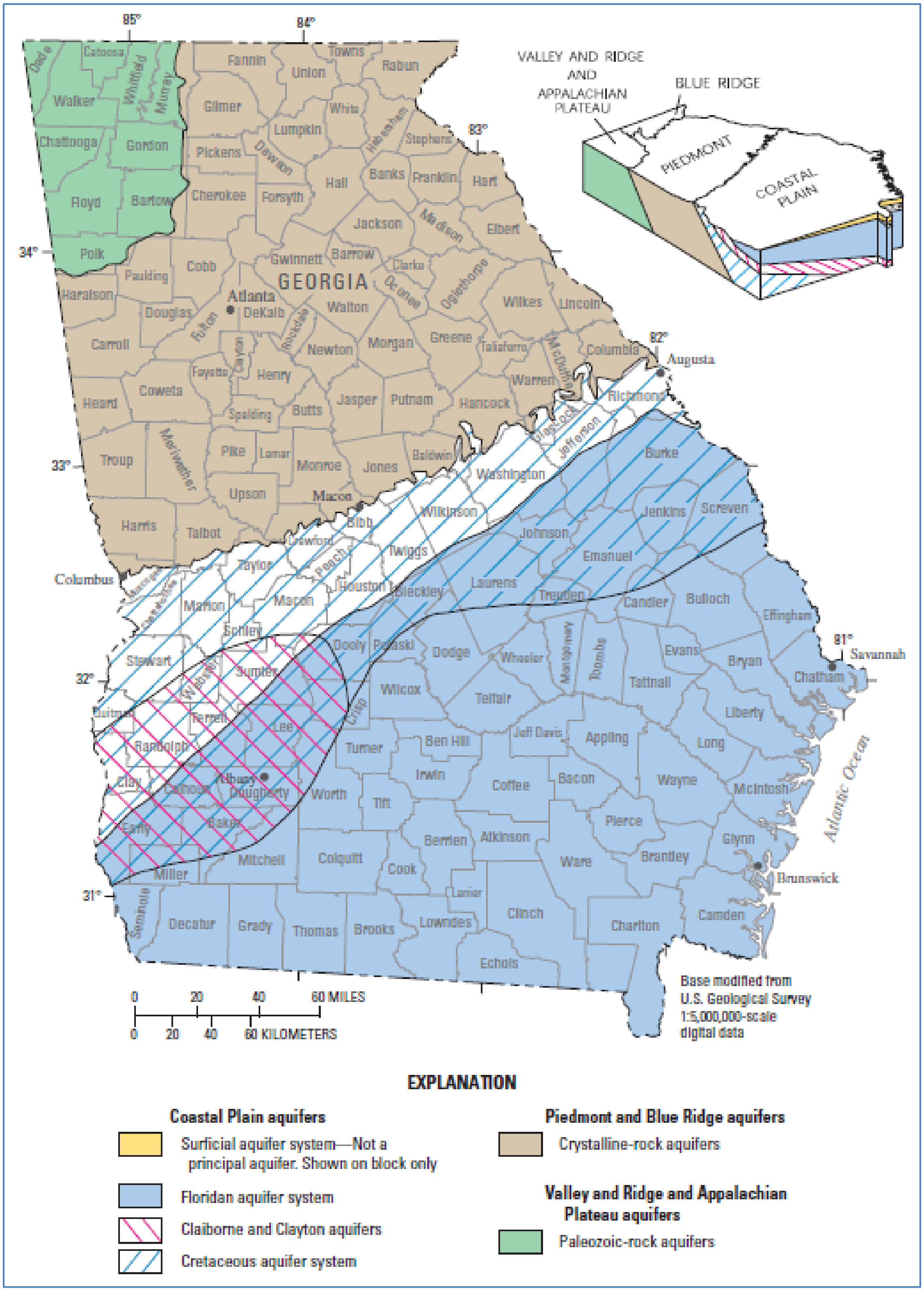

Figure 3. Aquifers and provinces of Georgia (from Fanning & Trent, 2009)

Table 1. Watershed characteristics

WATERSHED	Mean Slope (%)	Geologic District of the Piedmont	Terrane	Dominant Bedrock Type	Drainage Area (km^2)
Big Creek	7.21	Central Uplands	Blue Ridge	biotite gneiss	189.4
Etowah River	14.82	Dahlonega Upland	Blue Ridge	mica schist	1,587.3
Flint River	4.40	Greenville Slope	Inner Piedmont	biotite gneiss	696.0
Flint River (upstream)	5.00	Greenville Slope	Inner Piedmont	granitic gneiss	330.2
Line Creek	5.00	Greenville Slope	Inner Piedmont	mica schist	259.3
Peachtree Creek	6.78	Winder Slope	Inner Piedmont	biotite gneiss	222.2
Sope Creek	7.03	Central Uplands	Blue Ridge	biotite gneiss	79.2
South River	6.72	Winder Slope	Inner Piedmont	mica schist	475.8
Suwanee Creek*	7.67	Gainesville Ridges	Blue Ridge/ Inner Piedmont	Meta-sedimentary rock	125.3
Sweetwater Creek	6.29	Central Uplands	Blue Ridge	granitic gneiss	615.1

*-Dissected by Brevard Fault Zone.

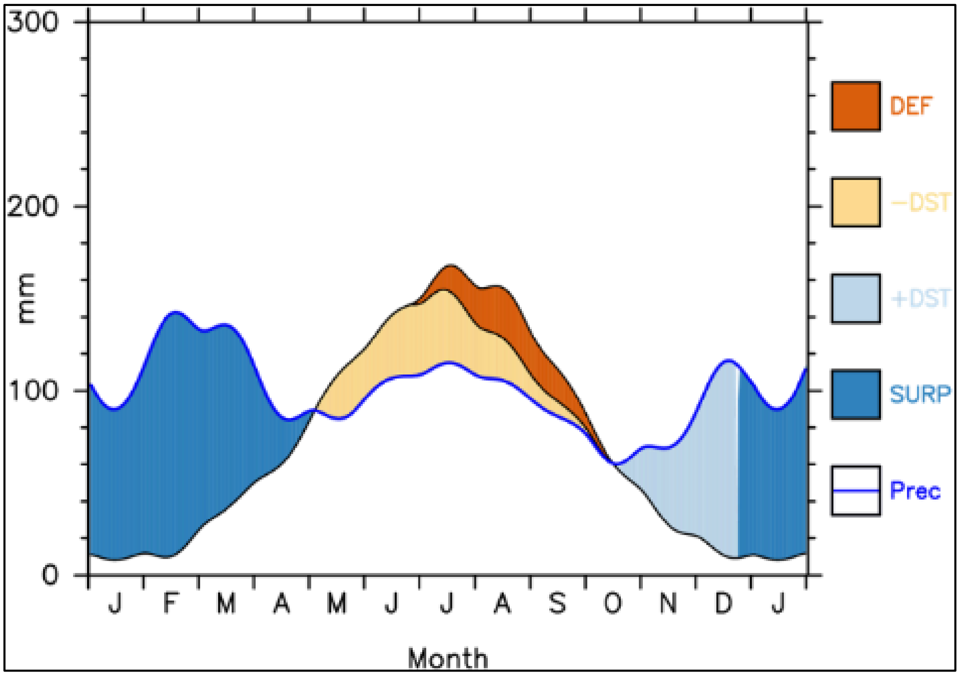

Figure 4 Water balance for southernmost watersheds (DEF is the estimated deficit (mm/month), -DST/+DST is change in monthly soil moisture (mm/month), SURP is surplus (surface runoff plus percolation below the plant root zone) (mm/month))

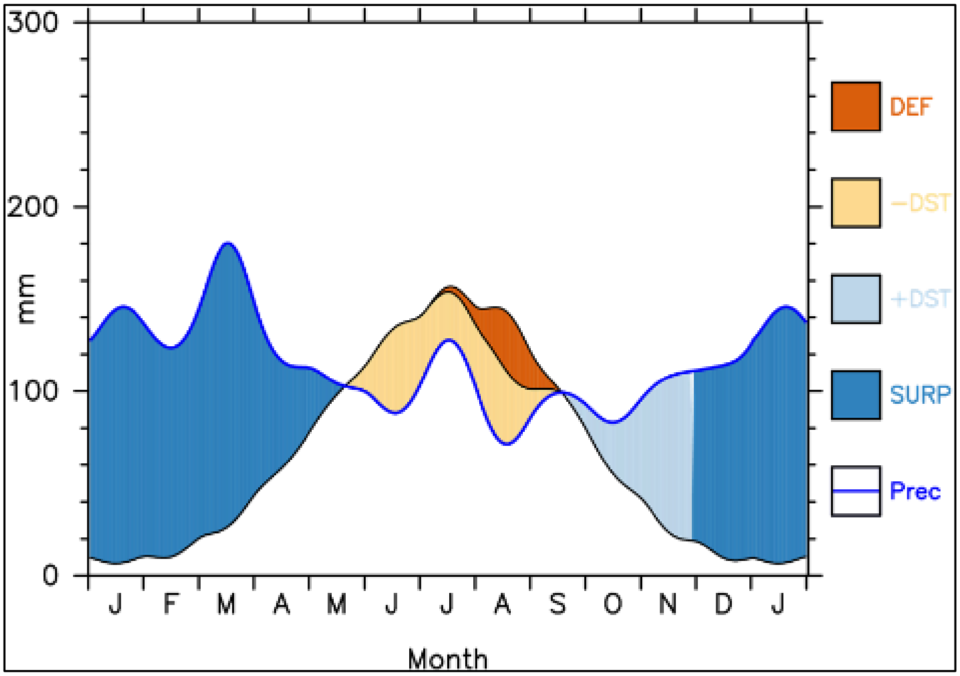

Figure 5 **Water balance for northernmost watersheds (DEF is the estimated deficit (mm/month), -DST/+DST is change in monthly soil moisture (mm/month), SURP is surplus (surface runoff plus percolation below the plant root zone) (mm/month))**

2 DATA AND METHODS

The data acquired for the study consisted of all publically-available sources. The land cover data was obtained from the National Land Cover Database (NLCD) by the consortium of federal agencies which is named the Multi-Resolution Land Characteristics Consortium (MRLC). The precipitation data were obtained by the National Oceanic and Atmospheric Administration (NOAA) National Climate Data Center (NCDC) Cooperative (Co-Ops) stations. The discharge data was from the United States Geological Survey (USGS), and the baseflows were obtained by the program Web-based Hydrograph Analysis Tool (WHAT). The digital elevation models (DEMs) were used as well, and they were downloaded from the USGS land cover web site.

Table 2. Project Data

DATA NAME	TYPE	SOURCE
NLCD 1992, 2001, 2011	Georeferenced Raster	www.mrlc.gov
NCDC/COOP Precipitation	Monthly Total Table	https://www.ncdc.noaa.gov/data-access/land-based-station-data/land-based-datasets/cooperative-observer-network-coop
Streamflow discharges	Table	USGS
Baseflow Separation	Table	Engineering.purdue.edu/mapserve/WHAT/
Digital Elevation Model	Raster	USGS

2.1 NLCD 1992, 2001, and 2011

The NLCD is a land cover mapping product that covers the entire U.S. and is based on Landsat Thematic Mapper (TM) 30-meter satellite images. It was developed for the MLRC (www.mrlc.gov) (Stehman, Wickham, Smith, & Yang, 2003; Wickham, Stehman, Fry, Smith, & Homer, 2010). The processes for getting the digital images to a seamless conterminous U.S. raster database involved many steps and much research (Vogelmann et al., 2001). Well after 1992 in 2000, the first NLCD was produced with certain methods including ground control points, terrain-correction, and a classification comprehensive change-detection method based on Landsat 5 TM satellite images taken in 1992 (Vogelmann et al., 2001). In subsequent years, new NLCD products were developed as well.

Gathering the data for land cover analysis included simple steps. Beginning with all three NLCD products, subsets of the Atlanta metropolitan area were downloaded, projected, and clipped using all ten watershed boundaries, which were created with DEMs. Therefore, there were 30 land cover images, three NLCD products (1992, 2001, and 2011) for each of the ten study watersheds. Then, two change-detection NLCD products (1992-2001 and 2001-2011) were downloaded for the Atlanta metropolitan area, and they were projected and clipped. The final total of all land cover and change-detection images was 50 images.

Remote sensing allows one to compare multi-temporal images of the same area in order to determine what has changed about the landscape. That would then explain any land use changes. This study project attempts to compare a 1992 NLCD with a 2001 NLCD in order to do just that. However, it should be known that some mapping and comprehensive change-detection methods used between the two NLCDs were significantly different. If one were to compare 2001, 2006, and 2011, for which the same methods were used, the change-detection result would be a pure change-detection because pixel-for-pixel, they are of the same classification and the same scheme. There is a risk when comparing the older 1992 and subsequent years because of the different methods used to develop the 1992 NLCD. They do however have the same resolution.

The differences between the 1992 NLCD and the subsequent NLCD are related to different mapping, satellite, and classification systems. The first NLCD used the Landsat 5 TM satellite and the 2001-2011 used a combination of Landsat 5 and 7 TM satellites. The first NLCD used a combination classification system that basically merged the Anderson system with the NOAA Coastal Change Analysis Program (C-CAP) system (Vogelmann et al., 2001). The following NLCDs used a different classification system that caused minor legend changes (Homer et al., 2007). As far as accuracy goes, it has been estimated that for the metropolitan Atlanta area and north Georgia, there are different Level 1 and Level II accuracies. For example, when considering only Level I, the 1992 NLCD with 83% (+- 2.0) is less accurate than the 2001 NLCD with 87% (+-2.4) for the Atlanta region (Wickham et al., 2010).

The good news is that there is a way to “bridge” the divide between the two different NLCDs. In 2007, researchers were able to produce a product that compared the two eras of the NLCD products using only the Anderson Level 1 classification scheme (Homer et al., 2007). The NLCD 1992/2001 Change Retrofit Product will allow proper comparison between 1992 and 2001. The legends between 1992, 2001, and 2011 were not that complicated because the NLCD multi-consortium produced the two change products that can be used to compare.

2.2 NCDC/Co-Ops Precipitation Data

To ensure that all ten study watersheds would be covered by precipitation data from 1986-2015, several region-wide NOAA Cooperative Observer (Co-Ops) stations were considered (NOAA, 2016). This study required full sets of data (i.e. no missing precipitation data). Therefore, mean daily precipitation data from several Co-Ops were used as backup data for those missing days. The 14 stations for which data was downloaded and quality-controlled were the following: Atlanta Bolton, Atlanta Hartsfield, Ball Ground, Blairsville, Cedartown, Covington, Cumming, Dallas, Ellijay, Gainesville, Griffin, Jonesboro, and Winder. Quality control steps will be presented in Examination of Precipitation, section 2.5.

2.3 Streamflow Data

Gages within the Atlanta metro area with at least 30 years of daily discharge data were selected for analysis. As seen in Table 3, the start dates of daily data collection and other pertinent data about the gages are shown. Water data consisted of daily average discharge or flow at each gage, in the form of cubic feet per second. Data were aggregated and units were converted in order to be consistent with the precipitation data, which was in millimeters.

Discharge data was acquired from the United State Geological Service (USGS) gages in study watersheds in the Metro-Atlanta area.

Table 3 USGS Stream Gages

ID	USGS SITE CODE	LAT/LONG	NAME	DATA START DATE	DRAINAGE AREA (KM^2)
1	02335700	34°03'02"N, 84°16'10"W (NAD83)	Big Creek	1960-05-01	189.4
2	02392000	34°14'23.4"N, 84°29'41.08"W (NAD27)	Etowah River	1896-10-01	1587.3
3	02344500	33°14'39"N, 84°25'45"W (NAD83)	Flint River	1937-03-01	696.0
4	02344350	33°24'56"N, 84°23'05"W (NAD83)	Flint River upstream	1985-05-07	330.2
5	02344700	33°19'09"N, 84°31'20"W (NAD83)	Line Creek	1964-09-01	259.3
6	02336300	33°49'10"N, 84°24'28"W (NAD83)	Peachtree Creek	1958-06-20	222.2
7	02335870	33°57'14"N, 84°26'36"W (NAD83)	Sope Creek	1984-10-01	79.2
8	02204070	33°37'47"N, 84°07'43"W (NAD27)	South River	1983-10-01	475.8
9	02334885	34°01'56"N, 84°05'22"W (NAD27)	Suwanee Creek	1984-10-01	125.3
10	02337000	33°46'35.4"N, 84°36'56.2"W (NAD27)	Sweetwater Creek	1904-05-18	615.1

2.4 Land Cover Change Analysis

As mentioned in section 2.1, the official NLCD 1992–2001 Land Cover Change Retrofit Product (Retrofit) and the NLCD 2001 to 2011 Land Cover Change data (NLCD 2001/2011) were used to identify land use changes in each of the ten watersheds during the 30-year study period. The 1992/2001 Retrofit was produced because the NLCD 1992 land cover data could not appropriately be used to compare any subsequent land cover products (Fry, Coan, Homer, Meyer, & Wickham, 2008). The classification scheme used in the Retrofit was simplified to a modified Anderson Level 1 including only the following seven land covers for the Georgia region: (1) open water, (2) urban, (3) barren, (4) forest, (5) grass/shrub, (6) agriculture, and (7) wetland. The NLCD 2001/2011 used a similar modified Anderson Level I classification scheme, which is a basic numeric land cover classifying system, with little difference, but it includes the following *eight* Level I land cover classes for the Georgia region: (1) water, (2) developed, (3) barren, (4) forest, (5) shrub land, (6) herbaceous, (7) planted/cultivated, and (8) wetland (Jin et al., 2013). Since the two datasets both use an Anderson Level I scheme but also do not match exactly, it should be noted that a distinction between the two was made. The standard products from MRLC were not modified for this study. The scrub, grasses, and pastures from the NLCD 2001/2011 could not be reconciled with the more basic classification scheme in the Retrofit. Therefore, each watershed had separate land cover data, and no data were aggregated or combined other than to the first level.

2.5 Examination of Precipitation

This study required full sets of data (i.e. no missing precipitation data) spanning the time of Jan 1, 1986 to Dec 31, 2015. Therefore, mean daily precipitation data from 14 COOP stations were downloaded and for any missing data, nearby stations were used to help complete the records. If a value was missing, the average value from neighboring stations was used. The one station that needed this the most was Griffin. The precipitation totals were estimated for each watershed using a distance weighting process. All ten study watersheds were covered by precipitation data (Table 4). The precipitation totals were estimated for each watershed using a distance weighting factoring process (Diem & Mote, 2005; Xia, Fabian, Stohl, & Winterhalter, 1999). Data were converted to millimeters, mapped by station location, and then scaled into total monthly format. The total monthly data was then interpolated using simple inverse distance and weighted for factoring precipitation for each watershed by using the distance from the stations to the centroid of each watershed – see Figure 2 for Co-Ops location.

Table 4 Precipitation stations and watersheds matrix

CO-OP PRECIPITATION STATION	LAT., LONG.	BIG CREEK	ETOWAH RIVER	FLINT RIVER	FLINT RIVER (U/S)	LINE CREEK	PEACHTREE CREEK	SOPE CREEK	SOUTH RIVER	SUWANEE CREEK	SWEETWATER CREEK
Atlanta Bolton	33.798, -84.502	X					X	X	X	X	X
Atlanta Hartsfield	33.638, -84.436			X	X	X	X		X	X	
Ball Ground	34.346, -84.428	X	X					X			
Blairsville	34.837, -83.933		X								
Cedartown	33.996, -85.259										X
Covington	33.559, -83.891						X		X	X	
Cumming	34.195, -84.161	X	X				X	X	X	X	
Dallas	33.960, -84.775	X						X			X
Ellijay	34.702, -84.537		X								
Gainesville	34.342, -83.909		X							X	

Griffin	33.256, -84.277			X	X	X					
Jonesboro	33.531, -84.359			X	X	X	X		X		
Newnan	33.425, -84.793			X	X	X		X			X
Winder	34.013, -83.704	X					X		X	X	

The flow variables in Table 5 were computed from using the USGS daily mean flow values for each watershed. For converting and comparing variables with precipitation, the following equations were used

$$\mathrm{Q}\ \frac{m^3}{s} * 1\mathrm{e}+9\,\frac{mm^3}{m^3} * \frac{86{,}000\ s}{day} * \frac{D.A.km^2}{1e{+}12\ mm^2}\ =\ \mathrm{mm/day} \qquad \text{Equation 1}$$

$$\mathrm{Q}\ \frac{m^3}{s} * 1\mathrm{e}+9\,\frac{mm}{m^3} * \frac{2{,}626{,}560\ s}{month} * \frac{D.A.km^2}{1e{+}12\ mm^2}\ =\ \mathrm{mm/month} \qquad \text{Equation 2}$$

$$\mathrm{Q}\ \frac{m^3}{s} * 1\mathrm{e}+9\,\frac{mm}{m^3} * \frac{31{,}536{,}000\ s}{year} * \frac{D.A.km^2}{1e{+}12\ mm^2}\ =\ \mathrm{mm/year} \qquad \text{Equation 3}$$

where Q is discharge, D.A. is drainage area, and m^3/s is cubic meters per second. Variability among the ten different watersheds was determined by normalizing the values with the respective drainage area (D.A.) values (km^2) by division, as seen in the three equations. Runoff ratios were also computed for all watersheds based on the weight-factored process in millimeters (Diem & Mote, 2005).

Table 5 Streamflow variables

FLOW VARIABLE	**DESCRIPTION**	**UNITS**
Mean Daily Flow	Total water volume per year by averaging daily mean discharge	Gigaliters or mm per year
Mean Annual Runoff	Total water volume per year by averaging daily runoff separated from	Gigaliters or mm per year

	baseflow for each year per WHAT*	
Mean Annual Baseflow	Total water volume per year by averaging mean daily baseflow	Gigaliters or mm per year
Baseflow Index	Total annual baseflow volume ÷ total annual streamflow volume for each year	Ratio
Runoff Ratio	Total annual runoff ÷ annual precipitation for each watershed	Ratio
Low Flow	Annual occurrences of flow < 25% all daily values for each year	Integer
High Flow	Annual occurrences of flow > 95% all daily values per year	Integer

*(Lim et al., 2005)

2.6 Baseflow separation

The original daily mean streamflow values were converted to annual values and are presented as a time series of mean annual streamflow, runoff, and baseflow in the Interannual Variations in Streamflow results. Annual values were used because they were based on the daily mean discharges, and it has been shown that there is minimal difference between 15-minute interval data and daily discharge data when analyzing for general streamflow patterns (Schoonover et al., 2006). The online web-based hydrograph analysis tool (WHAT), the Web based Hydrograph Analysis Tool (WHAT) system found online at https://engineering.purdue.edu/mapserve/WHAT was used to separate baseflow from runoff for each watershed, from 1986 to 2015 (Lim et al., 2005). For this study, a recursive digital filter was used and is meant for use in studies of perennial streams with hard rock aquifers. The digital filter parameter was 0.98 minus BFI$_{max}$ 0.25 because Piedmont aquifers are made of hard-crystalline rock aquifers (Fanning & Trent, 2009; Lim et al., 2005). A mean annual baseflow index (BFI) was then calculated for each watershed using the baseflow data and the mean daily discharge. Runoff ratios were also calculated with the runoff obtained via WHAT.

2.7 Testing for Trends

All the following streamflow variables were tested for trends for the entire duration 1986-2015: runoff ratio, baseflow index, frequency of low flow days, frequency of high-flow days, precipitation-adjusted versions of mean annual flow, mean annual runoff, mean annual baseflow, and frequency of low- and high-flow days. The significance will be tested with Kendall's tau (Helsel & Hirsch, 2002). The precipitation-adjusted variables involved regressing the above variables against annual precipitation and using the residuals as the new variable (Changnon & Demissie, 1996).

Testing for trends in the above variables was performed by using one-tailed Kendall-Tau correlation assessments with a 0.01 or 0.05 significance level. To estimate changes from 1986-2015, the Kendall-Theil line for best fit was used to find out how much change there is because it estimates rate of change by calculating slope medians among all combinations of pairs in the data (Helsel & Hirsch, 2002).

3 RESULTS

3.1 Land Cover Analysis Results

Land cover data for the ten watersheds showed varying degrees of urbanization. Peachtree Creek was the most urbanized before 1992. Etowah River was the least urbanized all the way to the end of this study 2015.

3.1.1 Big Creek Watershed

The Big Creek watershed underwent massive urbanization from 1992-2001 (Figure 6, Figure 7). Big Creek was only about 27% urban in 1992, but by 2011 it was 55% urbanized (Table 6). Forest-to-urban was the dominant land-cover change over the period: approximately 12% of the watershed undergoing the change from 1992-2001 and an additional 13% of the watershed undergoing the change from 2001-2011 (Table 7). The urbanization occurred mostly in the south from 1992-2011 and then shifted northwards for 2001-2011 (Figure 6, Figure 7).

Table 6 Big Creek watershed land cover percentages

Land Cover	**1992**	**2001**	**2011**
Water	0.8	0.9	0.8
Urban	27.8	40.9	55.0
Barren	0.8	0.9	0.2
Forest	52.5	39.5	29.1
Shrubland	1.4	0.3	0.7
Grassland		1.9	1.8
Planted/Cultivated	13.2	12.0	9.1
Wetland	3.5	3.6	3.4

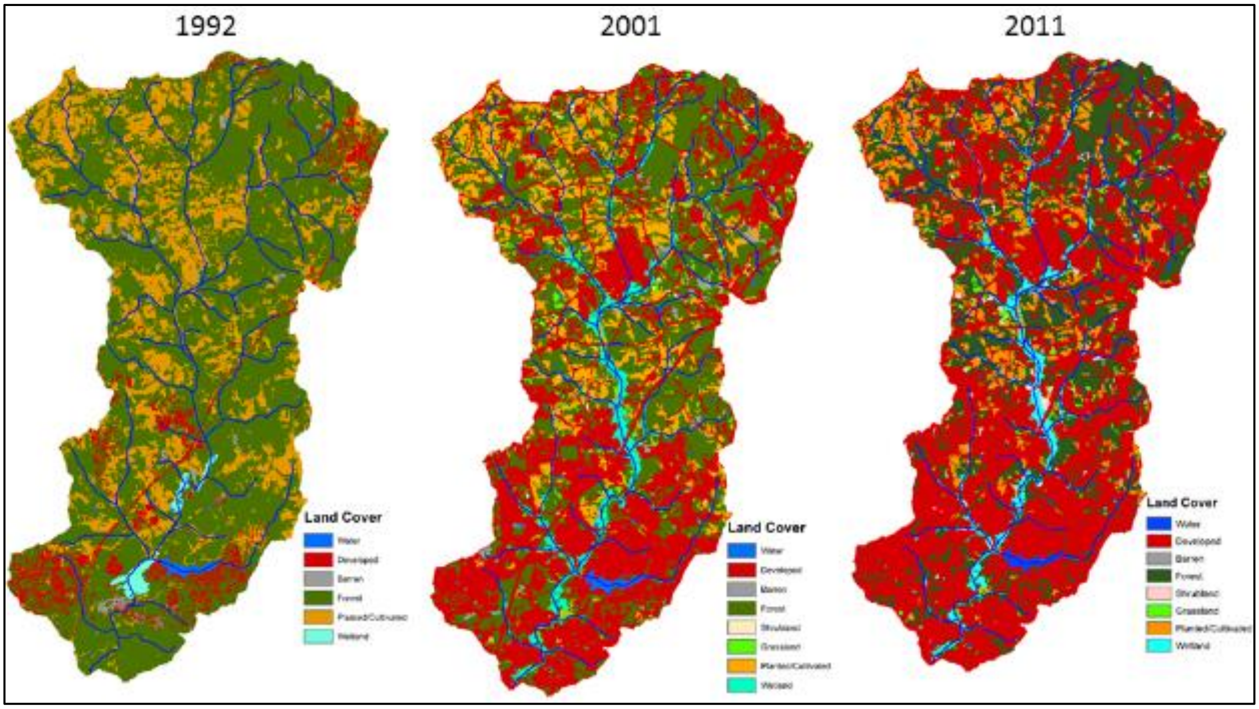

Figure 6 Big Creek watershed land cover

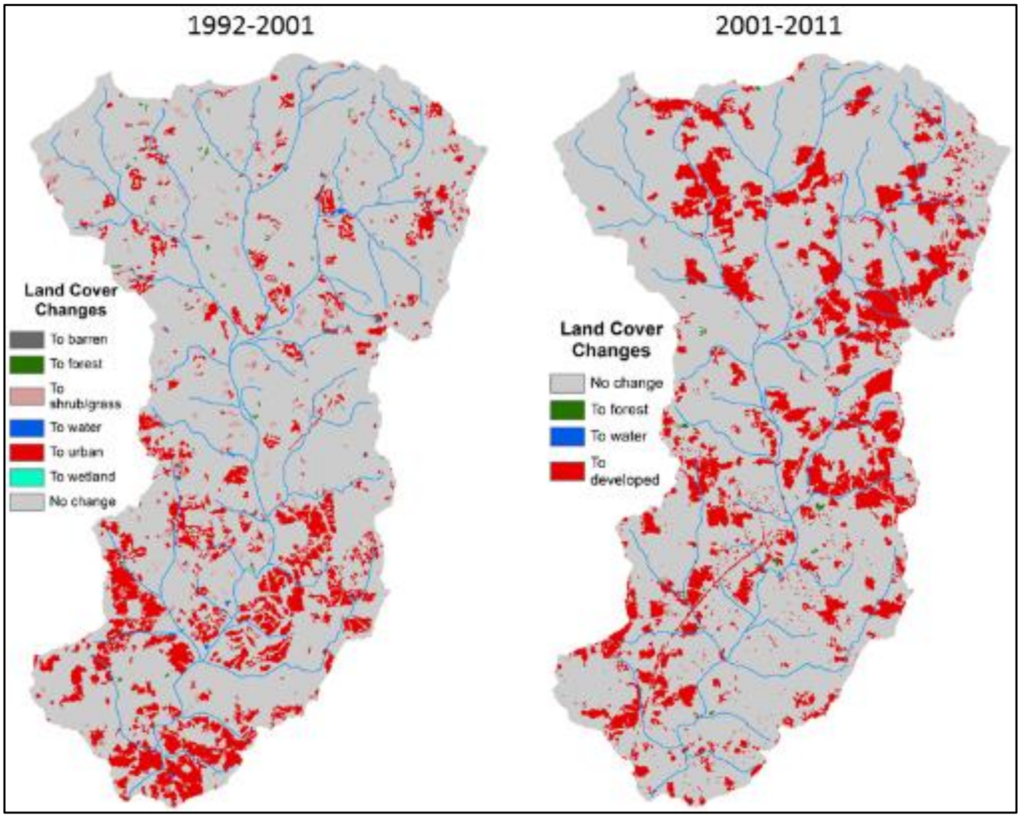

Figure 7 Big Creek watershed land cover changes

Table 7. Big Creek Watershed Changes - 1992-2001 and 2001-2011

Land Cover Changes 1992-2011	1992-2001 hectares	1992-2001 Percent (%)	Land Cover Changes	2001-2011 hectares	2001-2011 Percent (%)
Forest to urban	2302	12.2	Forest to developed	1842	9.9
Forest to agriculture	215	1.1	Pasture to developed	497	2.7
Forest to grassland/shrub	144	0.8	Barren to developed	154	0.8
Agriculture to urban	82	0.4	Grass to developed	113	0.6
Agriculture to forest	24	0.1	Forest to scrub	80	0.4
Forest to barren	20	0.1	Forest to grass	68	0.4
Forest to open water	13	0.1	Wetland to developed	40	0.2
Agriculture to grassland/shrub	5	0.0	Pasture to grass	28	0.2
Urban to agriculture	4	0.0	Scrub to developed	25	0.1
Agriculture to open water	4	0.0	Water to developed	12	0.1
Urban to forest	2	0.0	Pasture to forest	11	0.1
Open water to agriculture	1	0.0	Grass to forest	11	0.1
Agriculture to barren	1	0.0	Pasture to scrub	10	0.1
Open water to grassland/shrub	1	0.0	Forest to barren	10	0.1
Open water to wetlands	1	0.0	Scrub to forest	9	0.0
Agriculture to wetlands	1	0.0	Grass to scrub	8	0.0
Urban to grassland/shrub	1	0.0	Pasture to wetland	2	0.0
No data	No data	No data	Pasture to barren	2	0.0
No data	No data	No data	Forest to water	2	0.0
No data	No data	No data	Barren to grass	1	0.0
No data	No data	No data	Wetland to water	1	0.0
No data	No data	No data	Barren to forest	1	0.0
No data	No data	No data	Scrub to grass	1	0.0
No data	No data	No data	Forest to wetland	1	0.0

No data	No data	No data	Barren to scrub	1	0.0
No data	No data	No data	Water to forest	1	0.0

3.1.2 Etowah River Watershed

In the Etowah River watershed experienced minimal land cover change from 1992-2011 (Figure 8, Figure 9). The urbanizing changes that did take place were located in the southern part of the watershed. This watershed includes several conservation areas (e.g. GA Wildlife Management Areas, U.S. National Forest, private preserves etc.), and they account for about 17% of the watershed.

Table 8 Etowah River watershed land cover percentages

Land Cover	1992	2001	2011
Water	0.4	0.4	0.5
Developed	7.8	9.9	12.0
Barren	0.3	0.4	0.3
Forest	80.4	76.3	74.0
Shrubland	1.8	1.2	1.8
Grassland		3.0	3.2
Planted/Cultivated	8.7	8.2	7.6
Wetland	0.6	0.6	0.6

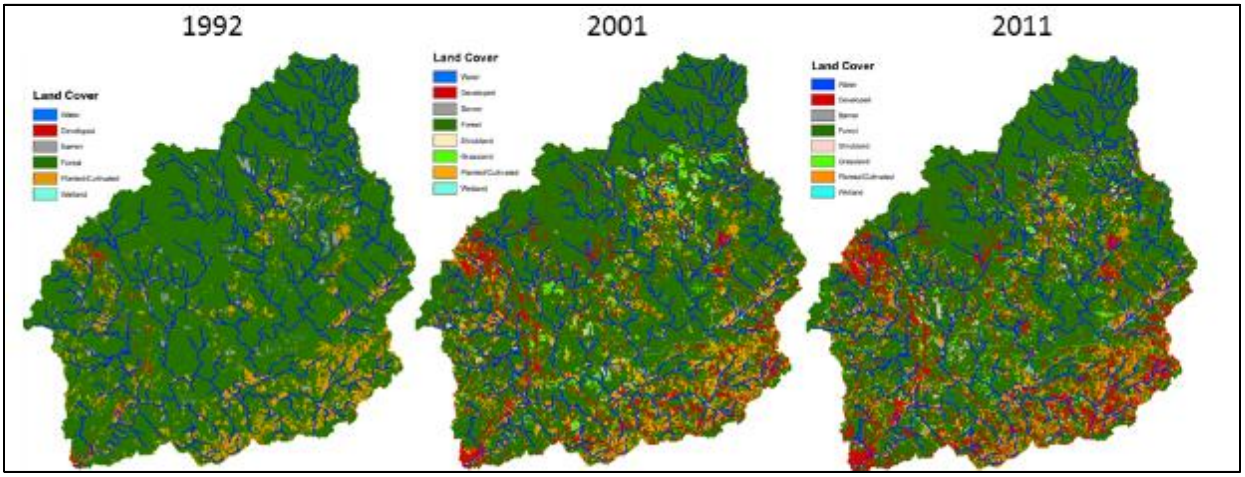

Figure 8 Etowah River watershed land cover

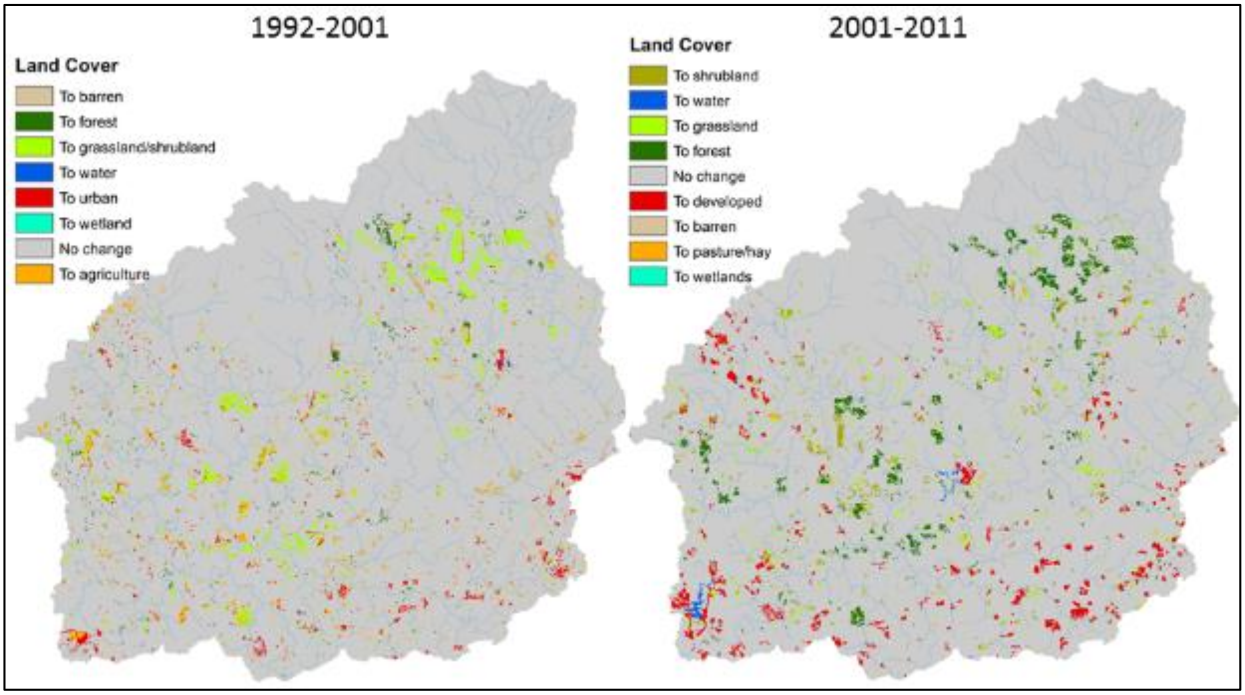

Figure 9 Etowah River watershed land cover changes

Table 9 Etowah River Watershed Changes from 1992-2001

1992-2001 Land Cover Change	1992-2001 (hectares)	1992-2001 (%)	2001-2011 Land Cover Change	2001-2011 (hectares)	2001-2011 (%)
Forest to grassland/shrub	3808	2.4	Forest to urban	2402	1.5
Forest to agriculture	2606	1.6	Forest to grass	1896	1.2
Forest to urban	1539	1.0	Forest to shrub	1643	1.0
Agriculture to forest	817	0.5	Grass to forest	1513	1.0
Forest to barren	183	0.1	Scrub to forest	822	0.5
Agriculture to urban	125	0.1	Pasture to urban	542	0.3
Forest to open water	33	0.0	Pasture to forest	280	0.2
Agriculture to grassland/shrub	31	0.0	Grass to shrub	194	0.1
Urban to forest	14	0.0	Pasture to grass	172	0.1
Agriculture to open water	13	0.0	Forest to water	171	0.1
Agriculture to barren	8	0.0	Forest to barren	143	0.1
Urban to agriculture	7	0.0	Barren to forest	134	0.1
Urban to grassland/shrub	4	0.0	Grass to urban	123	0.1
Open water to grassland/shrub	3	0.0	Barren to urban	110	0.1

Open water to urban	2	0.0	Forest to pasture	89	0.1
Urban to open water	2	0.0	Barren to grass	79	0.0
Agriculture to wetland	1	0.0	Scrub to urban	66	0.0
Open water to agriculture	1	0.0	Pasture to shrub	62	0.0
Open water to forest	1	0.0	Scrub to grass	33	0.0
No data	No data	No data	Wetland to urban	23	0.0
No data	No data	No data	Pasture to barren	20	0.0
No data	No data	No data	Barren to shrub	19	0.0
No data	No data	No data	Grass to barren	15	0.0
No data	No data	No data	Crop to urban	10	0.0
No data	No data	No data	Barren to pasture	9	0.0
No data	No data	No data	Grass to water	8	0.0
No data	No data	No data	Water to urban	4	0.0
No data	No data	No data	Forest to wetland	4	0.0
No data	No data	No data	Wetland to grass	4	0.0
No data	No data	No data	Scrub to water	4	0.0
No data	No data	No data	Pasture to water	4	0.0
No data	No data	No data	Grass to wetland	3	0.0
No data	No data	No data	Crop to grass	3	0.0
No data	No data	No data	Scrub to barren	3	0.0
No data	No data	No data	Crop to shrub	1	0.0
No data	No data	No data	Barren to water	1	0.0
No data	No data	No data	Pasture to wetland	1	0.0

No data	No data	No data	Crop to barren	1	0.0
No data	No data	No data	Wetland to water	1	0.0
No data	No data	No data	Wetland to shrub	1	0.0
No data	No data	No data	Water to shrub	1	0.0
No data	No data	No data	Crop to water	1	0.0
No data	No data	No data	Wetland to forest	1	0.0

3.1.3 Flint River Watershed (upstream and downstream)

The entire Flint River watershed from 1992-2001 went through two major changes: (1) urbanization where about 4% of the watershed changed to urban and (2) the construction of two large lakes (Figure 10, Figure 11). Flint River watershed was about 31.5% urban in 1992, and with a steady increase to about 35% in 2001 the watershed was finally 40% urban by 2011 (Table 10). Forest-to-urban was the dominant land cover change from 1992-2001 with about 3.2% of the watershed and from 2001-2011 with about 3.4% (Table 11). The land cover change pattern clearly shows that the upper more northern half of the watershed changed to urban while the downstream southern half experienced minimal changes aside from the two large lakes (Figure 11). Club Lake is on the east side of the river, and Lake Horton is on the west side of the river. They are not on the main stem of the river, so streamflow has not been regulated for all of the Flint River, only in two small portions.

Table 10 Flint River watershed land cover percentages

Land Cover	**1992**	**2001**	**2011**
Water	1.3	2.0	1.9
Developed	31.5	35.1	40.3
Barren	0.4	0.6	0.3
Forest	43.8	38.7	33.8

Shrubland	2.6	0.7	2.2
Grassland		3.2	3.0
Planted/Cultivated	12.9	13.0	11.7
Wetland	6.9	6.8	6.7

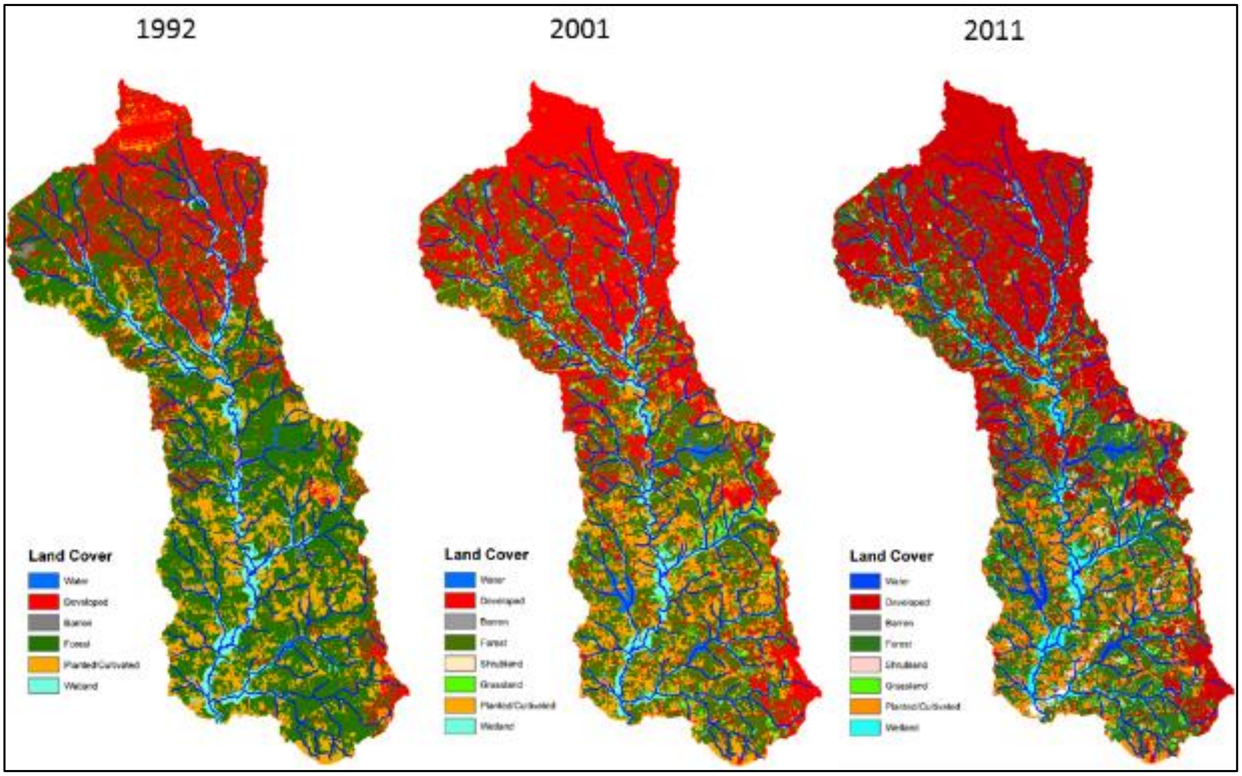

Figure 10 Flint River watershed land cover

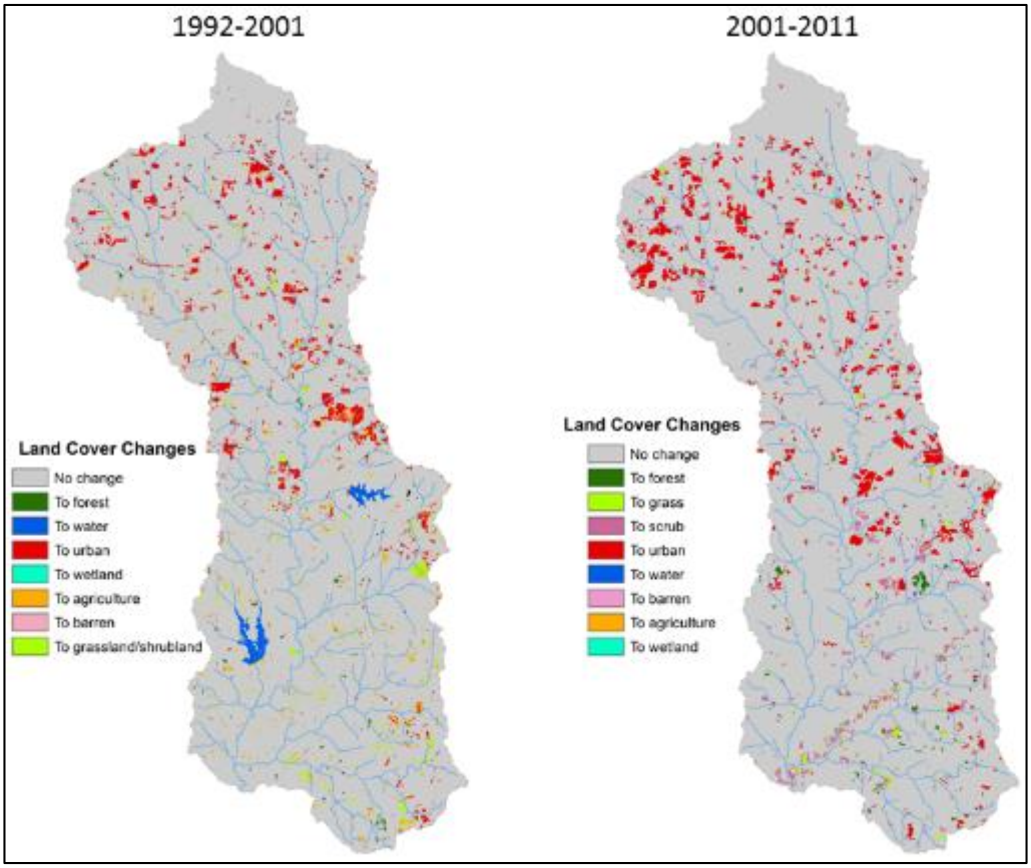

Figure 11 Flint River watershed land cover changes

Table 11 Flint River watershed changes 1992-2001 and 2001-2011

1992-2001 Land Cover Change	**1992-2001 (hectares)**	**1992-2001 Percent (%)**	**2001-2011 Land Cover Change**	**2001-2011 (hectares)**	**2001-2011 Percent (%)**
Forest to urban	2207	3.2	Forest to urban	2366	3.4
Forest to ag	930	1.3	Forest to scrub	848	1.2
Forest to grassland/shrub	734	1.0	Pasture to urban	593	0.9
Forest to open water	330	0.5	Forest to grass	372	0.5
Ag to forest	175	0.2	Grass to urban	316	0.5
Forest to barren	165	0.2	Barren to urban	195	0.3
Wetland to open water	123	0.2	Pasture to scrub	179	0.3
Ag to urban	111	0.2	Grass to scrub	144	0.2
Urban to forest	43	0.1	Grass to forest	107	0.2
Ag to open water	42	0.1	Scrub to urban	85	0.1
Urban to ag	10	0.0	Pasture to forest	84	0.1
Forest to wetland	7	0.0	Scrub to forest	63	0.1

Open water to grassland/shrub	7	0.0	Wetland to urban	50	0.1
Open water to urban	7	0.0	Pasture to grass	42	0.1
Urban to wetland	7	0.0	Forest to barren	22	0.0
Grassland/shrub to forest	7	0.0	Water to scrub	18	0.0
Barren to open water	5	0.0	Forest to water	13	0.0
Open water to wetland	5	0.0	Barren to scrub	13	0.0
Urban to grassland/shrub	3	0.0	Forest to wetland	9	0.0
Ag to wetland	3	0.0	Forest to pasture	7	0.0
Open water to ag	2	0.0	Water to urban	7	0.0
Urban to open water	2	0.0	Pasture to wetland	7	0.0
Barren to urban	2	0.0	Wetland to forest	6	0.0
Open water to forest	1	0.0	Wetland to grass	6	0.0
Grassland/shrub to ag	1	0.0	Crop to urban	6	0.0
Open water to barren	1	0.0	Barren to grass	6	0.0
Ag to barren	0	0.0	Wetland to scrub	5	0.0
Ag to grassland/shrub	0	0.0	Grass to barren	5	0.0
Grassland/shrub to open water	0	0.0	Pasture to barren	4	0.0
No data	No data	No data	Barren to water	4	0.0
No data	No data	No data	Water to forest	3	0.0
No data	No data	No data	Barren to forest	3	0.0
No data	No data	No data	Scrub to grass	2	0.0
No data	No data	No data	Pasture to water	2	0.0
No data	No data	No data	Water to barren	2	0.0
No data	No data	No data	Wetland to pasture	1	0.0
No data	No data	No data	Grass to water	1	0.0
No data	No data	No data	Grass to wetland	1	0.0
No data	No data	No data	Water to grass	1	0.0
No data	No data	No data	Wetland to water	1	0.0

3.1.4 Flint River Watershed (upstream only)

In the upper Flint River watershed nearer to the city of Atlanta, a large amount of the watershed became urbanized before 1992-2011 (Figure 12, Figure 13). The upper Flint River watershed was already about 50% urban in 1992, but the watershed became even more urbanized to 64% by 2011 (Table 12). The dominant land cover change was forest-to-urban during 1992-2001 by about 5.4% of the watershed and during 2001-2011 by an additional 5.8% of the watershed (Table 13). Spatially, urbanization took place throughout this smaller upstream watershed, not just in the north where higher intensity urban areas (e.g. Atlanta airport) are located (Figure 13).

Table 12 Flint River (upstream) watershed land cover percentages

Land Cover	1992	2001	2011
Water	0.7	0.7	0.6
Urban	50.3	56.1	64.0
Barren	0.7	0.8	0.4
Forest	35.5	29.2	22.7
Shrub	1.5	0.5	0.9
Grassland		2.0	1.7
Planted/Cultivated	5.9	5.1	4.2
Wetland	5.5	5.6	5.5

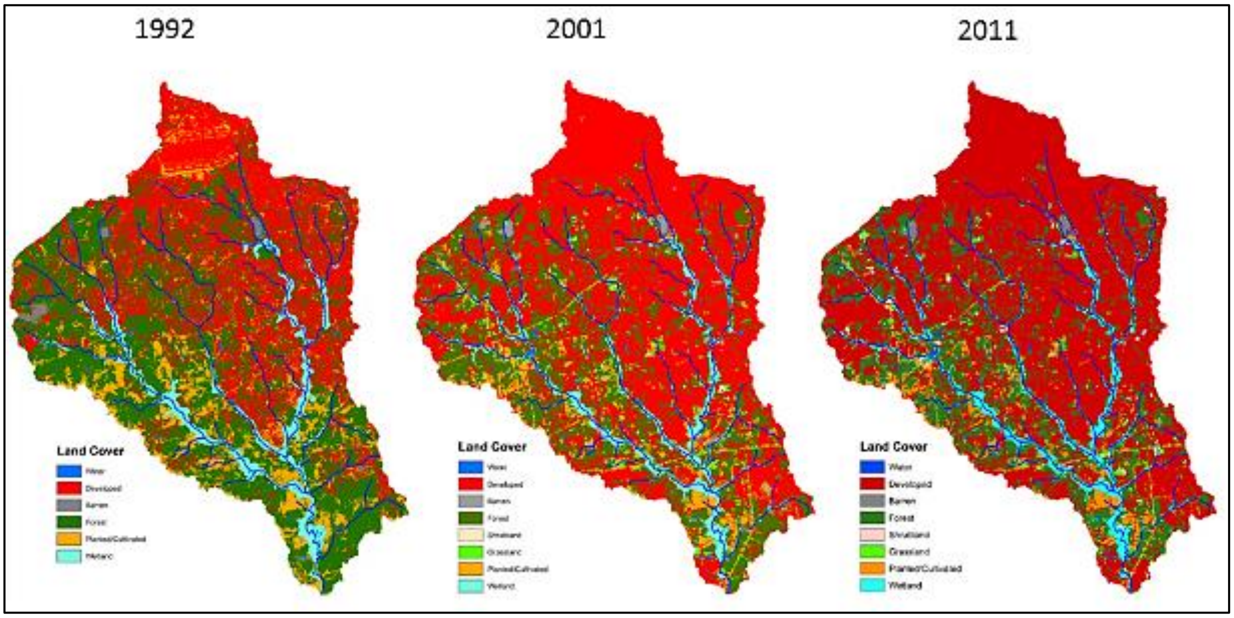

Figure 12 Flint River (upstream) watershed land cover

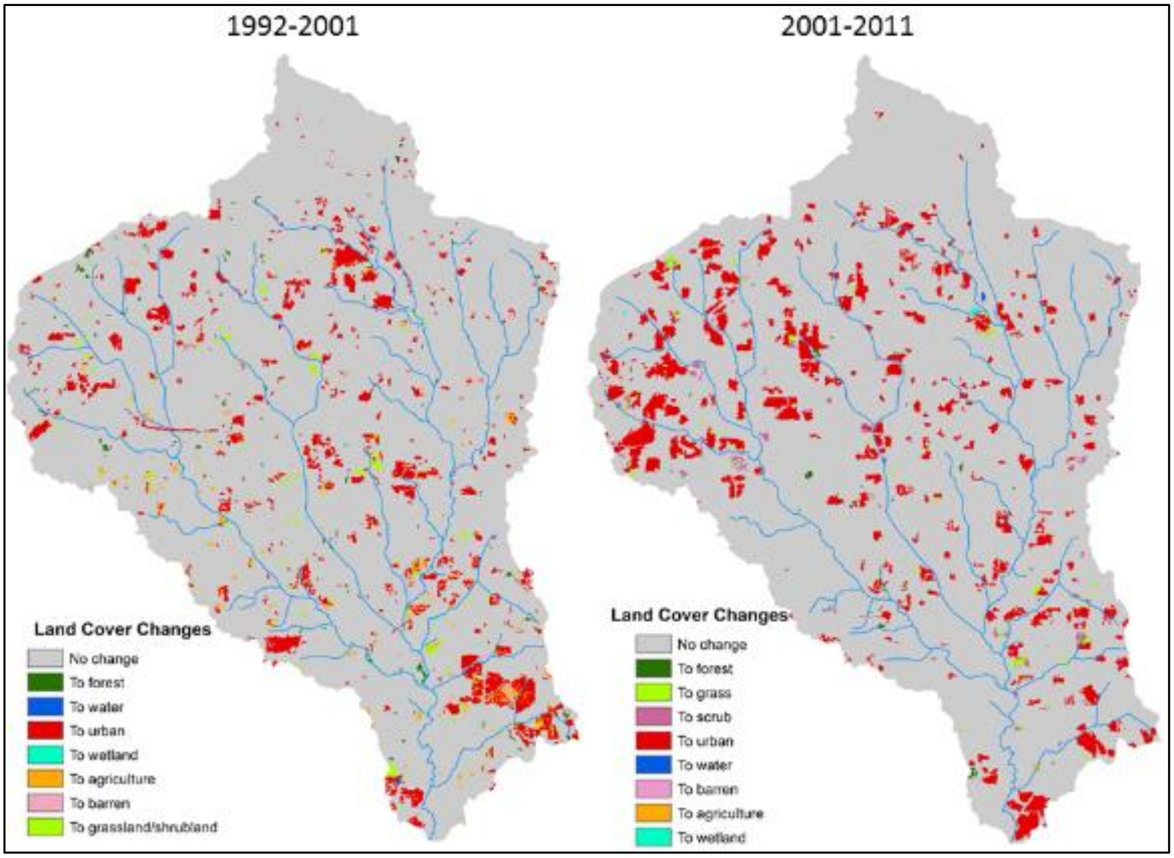

Figure 13 Flint River (upstream only) land cover changes

Table 13 Flint River (upstream only) land-cover changes 1992-2001 and 2001-2011

1992-2001 Land Cover Change	1992-2001 (hectares)	1992-2001 (%)	2001-2011 Land Cover Change	2001-2011 (hectares)	2001-2011 (%)
Forest to urban	1792	5.4	Forest to urban	1906	5.8
Forest to agriculture	274	0.8	Pasture to urban	255	0.8
Forest to grassland/shrub	228	0.7	Grass to urban	180	0.5
Forest to barren	93	0.3	Barren to urban	153	0.5
Agriculture to urban	70	0.2	Forest to scrub	142	0.4
Agriculture to forest	63	0.2	Forest grass	107	0.3
Urban to forest	30	0.1	Scrub to urban	62	0.2
Open water to urban	7	0.0	Wetland to urban	44	0.1
Urban to wetland	7	0.0	Pasture to scrub	22	0.1
Agriculture to open water	5	0.0	Grass to scrub	22	0.1
Forest to open water	4	0.0	Pasture to forest	17	0.1

Open water to grassland/shrub	4	0.0	Forest to barren	16	0.0
Urban to agriculture	4	0.0	Grass to forest	14	0.0
Open water to wetland	3	0.0	Water to scrub	12	0.0
Grassland/shrub to forest	2	0.0	Scrub to forest	11	0.0
Agriculture to wetland	2	0.0	Pasture to grass	8	0.0
Open water to agriculture	2	0.0	Water to urban	6	0.0
Urban to grassland/shrub	2	0.0	Forest to wetland	5	0.0
Open water to forest	1	0.0	Pasture to wetland	4	0.0
Forest to wetland	1	0.0	Barren to water	4	0.0
No data	No data	No data	Forest to pasture	4	0.0
No data	No data	No data	Barren to grass	4	0.0
No data	No data	No data	Crop to urban	4	0.0
No data	No data	No data	Wetland to scrub	2	0.0
No data	No data	No data	Wetland to grass	2	0.0
No data	No data	No data	Water to barren	2	0.0
No data	No data	No data	Forest to water	2	0.0
No data	No data	No data	Wetland to crop	1	0.0
No data	No data	No data	Barren to scrub	1	0.0
No data	No data	No data	Wetland to forest	1	0.0
No data	No data	No data	Scrub to grass	1	0.0
No data	No data	No data	Water to grass	1	0.0

3.1.5 Line Creek Watershed

The Line Creek watershed was 22% urbanized in 1992, and by 2011 it was about 40% (Table 14). Line Creek watershed underwent moderate urbanization from 1992-2011 (Figure 14, Figure 15). Forest-to-urban was the largest land cover change over a 19-year period from 1992-2011 with approximately 6% of the watershed undergoing the change from 1992-2001 and an additional about 4% undergoing the change from 2001-2011 (Table 15).

Table 14 Line Creek watershed land cover percentages

Land Cover	1992 Retrofit	2001	2011
Water	1.9	2.0	2.0
Urban	22.1	28.1	33.9
Barren	0.6	0.9	0.8
Forest	54.3	46.4	40.6
Shrub	2.4	0.8	2.0
Grassland		3.0	3.4
Planted/Cultivated	12.1	12.1	10.7
Wetland	6.6	6.7	6.6

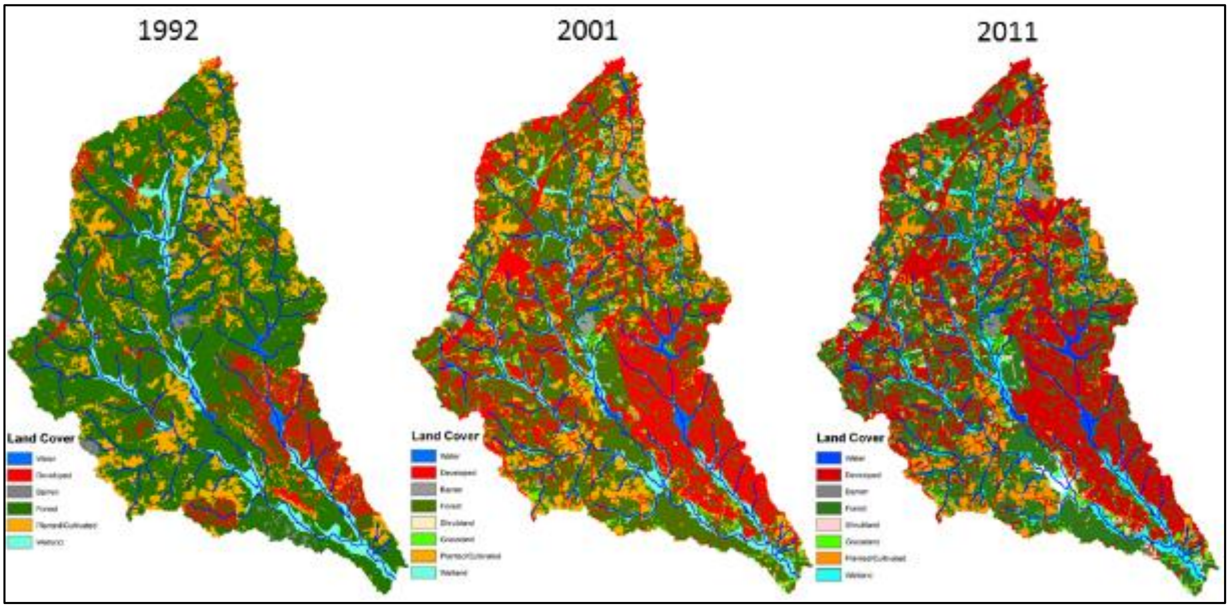

Figure 14 Line Creek watershed land cover

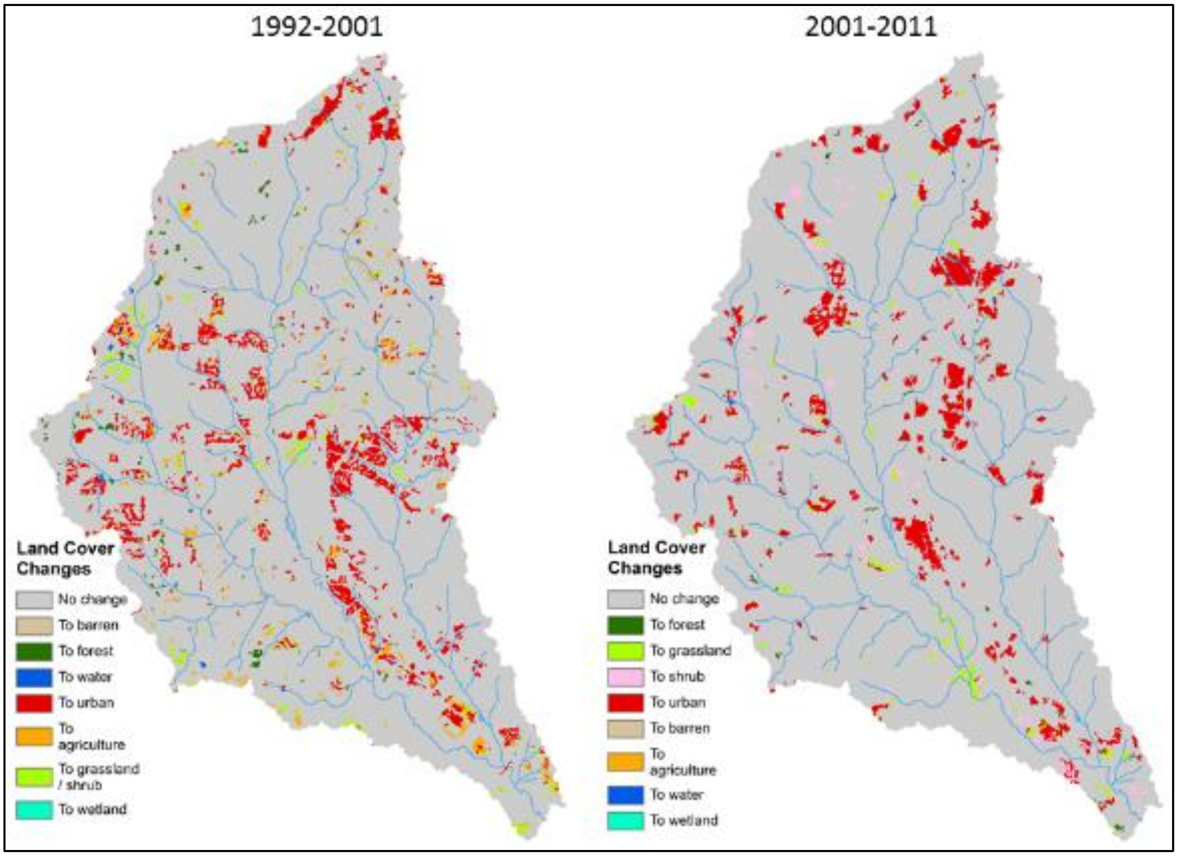

Figure 15 Line Creek watershed land cover changes

Table 15 Line Creek watershed land cover changes 1992-2001 and 2001-2011

1992-2001 Land Cover Change	1992-2001 (hectares)	1992-2001 (%)	2001-2011 Land Cover Change	2001-2011 (hectares)	2001-2011 (%)
Forest to urban	1491	5.7	Forest to urban	977	3.8
Forest to ag	495	1.9	Forest to scrub	330	1.3
Forest to grassland/shrub	291	1.1	Pasture to urban	330	1.3
Ag to forest	101	0.4	Forest to grass	235	0.9
Forest to barren	61	0.2	Grass to urban	106	0.4
Ag to urban	35	0.1	Barren to urban	45	0.2
Forest to open water	27	0.1	Scrub to urban	31	0.1
Grassland/shrub to forest	8	0.0	Grass to scrub	30	0.1
Urban to forest	6	0.0	Scrub to forest	22	0.1

Ag to barren	5	0.0	Pasture to grass	19	0.1
Ag to open water	4	0.0	Pasture to scrub	18	0.1
Open water to grassland/shrub	4	0.0	Wetland to urban	16	0.1
Open water to ag	2	0.0	Pasture to forest	16	0.1
Urban to wetland	2	0.0	Grass to forest	13	0.1
Urban to ag	2	0.0	Forest to barren	9	0.0
Urban to open water	1	0.0	Water to urban	6	0.0
Open water to barren	1	0.0	Grass to barren	5	0.0
No data	No data	No data	Scrub to grass	4	0.0
No data	No data	No data	Wetland to water	3	0.0
No data	No data	No data	Forest to wetland	3	0.0
No data	No data	No data	Barren to grass	3	0.0
No data	No data	No data	Pasture to barren	3	0.0
No data	No data	No data	Forest to water	3	0.0
No data	No data	No data	Water to forest	2	0.0
No data	No data	No data	Pasture to wetland	1	0.0
No data	No data	No data	Pasture to water	1	0.0
No data	No data	No data	Barren to scrub	1	0.0
No data	No data	No data	Water to barren	1	0.0
No data	No data	No data	Scrub to water	1	0.0
No data	No data	No data	Barren to forest	1	0.0
No data	No data	No data	Scrub to barren	1	0.0

3.1.6 Peachtree Creek Watershed

The Peachtree Creek watershed had already experienced massive urbanization by 1992, so any additional urbanization from 1992-2011 was minimal (Figure 16, Figure 17). The watershed was 80% urbanized by 1992 and increased only an additional 3% by 2011 (Table 16). Forest-to-urban was the highest land cover change type from 1992 to 2011, but it was very little (Table 17). Spatially, the changes that did occur were not in any particular pattern.

Table 16 Peachtree Creek watershed land cover percentages

Land Cover	1992	2001	2011
Water	0.3	0.3	0.3
Urban	79.9	82.3	83.2
Barren	0.1	0.1	0.0
Forest	18.8	16.6	15.7
Shrubland	0.1	0.0	0.1
Grassland		0.1	0.1
Planted/Cultivated	0.3	0.1	0.1
Wetland	0.5	0.6	0.5

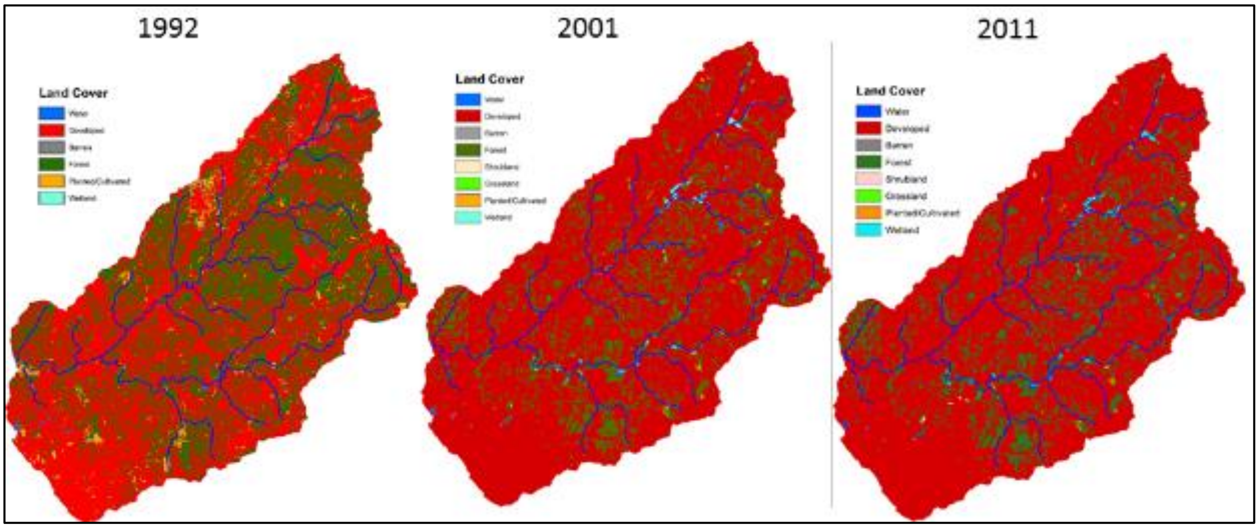

Figure 16 Peachtree Creek watershed land cover

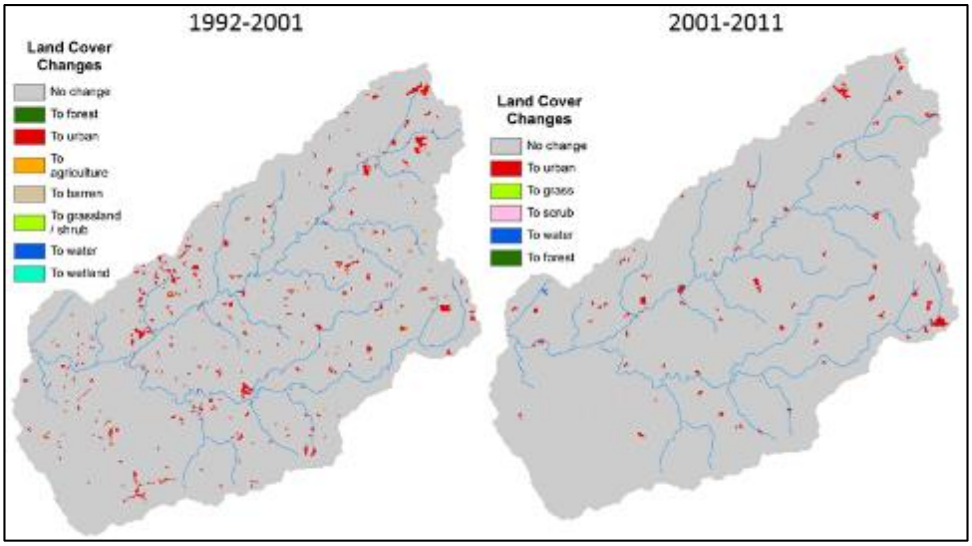

Figure 17 Peachtree Creek watershed land cover changes

Table 17 Peachtree Creek Watershed Changes 1992-2001 and 2001-2011

1992-2001 Land Cover Change	1992-2001 (hectares)	1992-2001 (%)	2001-2011 Land Cover Change	2001-2011 (hectares)	2001-2011 (%)
Forest to urban	434	1.9	Forest to urban	181	0.8
Forest to ag	13	0.1	Barren to urban	12	0.1
Forest to grassland/shrub	8	0.0	Forest to scrub	9	0.0
Ag to urban	6	0.0	Pasture to urban	4	0.0
Forest to open water	2	0.0	Wetland to urban	4	0.0
Urban to forest	2	0.0	Forest to water	3	0.0
Forest to wetland	1	0.0	Grass to urban	3	0.0
Ag to forest	1	0.0	Grass to scrub	1	0.0
Open water to urban	1	0.0	Forest to grass	1	0.0
Urban to wetland	1	0.0	Water to urban	1	0.0

3.1.7 Sope Creek Watershed

For the Sope Creek watershed, a large amount of the watershed was already urbanized by 1992 (Table 18, Figure 18). Land cover changes toward urbanization occurred more between 1992-2001 (Figure 18, Figure 19). The most dominant land cover change was forest-to-urban: approximately 6% of the watershed underwent urbanization from 1992-2001, and only 2% of the watershed underwent urbanization from 2001-2011 (Table 19). Urbanization appears to have taken place throughout the Sope Creek watershed, not just in certain locations (Figure 19).

Table 18 Sope Creek watershed land cover percentages

Land Cover	1992	2001	2011
Water	0.5	0.5	0.5
Urban	68.1	74.9	77.3
Barren	0.2	0.1	0.0
Forest	29.0	23.0	20.7
Shrubland	0.2	0.0	0.1
Grassland		0.2	0.2
Planted/Cultivated	1.4	0.7	0.6
Wetland	0.6	0.5	0.5

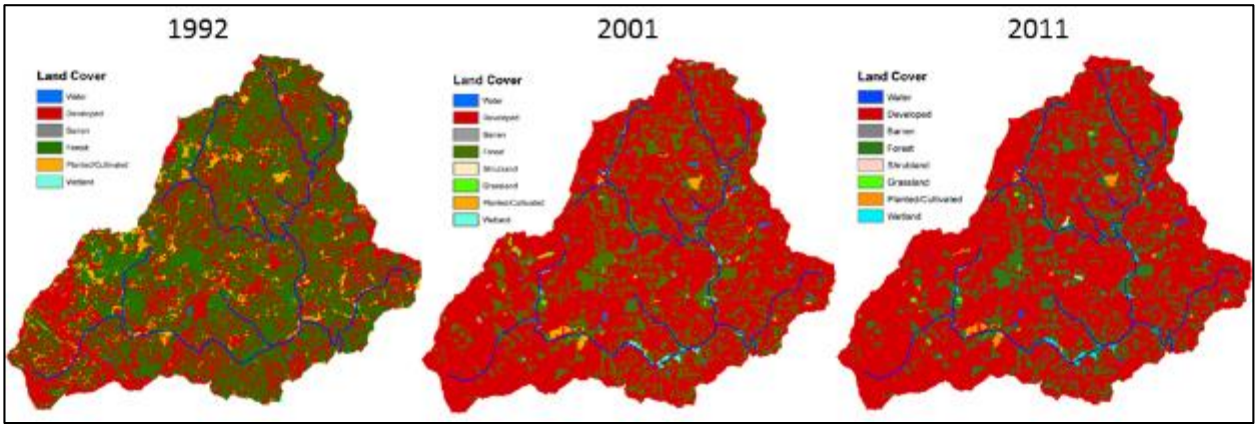

Figure 18 Sope Creek watershed land cover

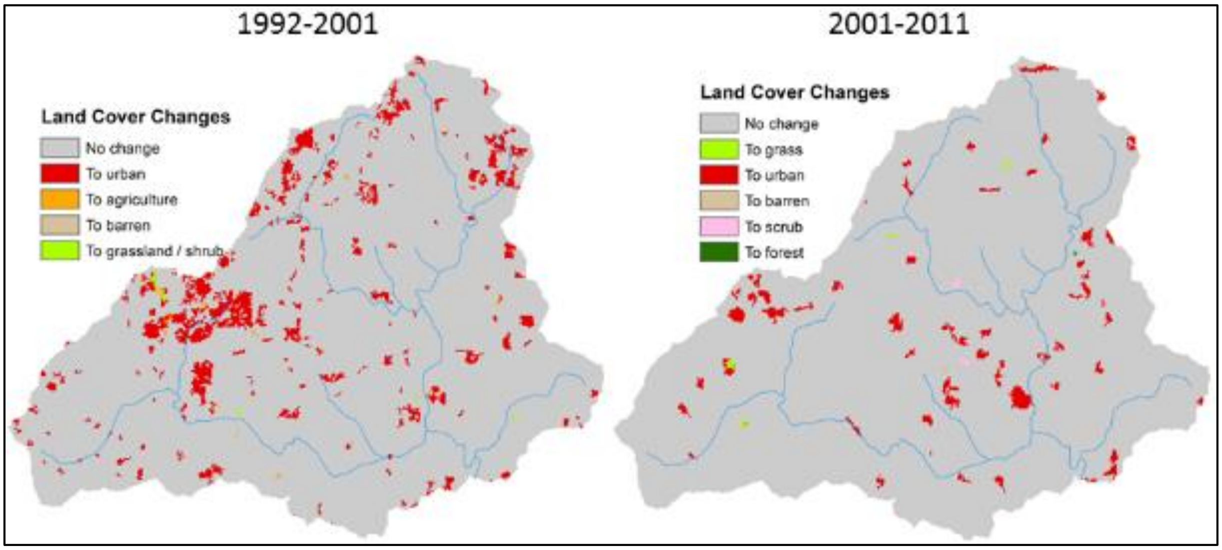

Figure 19 Sope Creek watershed land cover changes

Table 19 Sope Creek watershed changes 1992-2001 and 2001-2011

1992-2001 Land Cover Change	1992-2001 (hectares)	1992-2001 (%)	2001-2011 Land Cover Change	2001-2011 (hectares)	2001-2011 (%)
Forest to urban	482	6.1	Forest to urban	167	2.1
Forest to ag	12	0.2	Barren to urban	10	0.1
Ag to urban	11	0.1	Pasture to urban	8	0.1
Forest to grassland/shrub	7	0.1	Grass to urban	8	0.1
Forest to barren	2	0.0	Forest to grass	7	0.1
Open water to urban	1	0.0	Forest to scrub	7	0.1
Open water to grassland/shrub	1	0.0	Water to urban	1	0.0

No data	No data	No data	Forest to barren	1	0.0
No data	No data	No data	Barren to grass	1	0.0
No data	No data	No data	Scrub to forest	1	0.0
No data	No data	No data	Barren to urban	10	0.1
No data	No data	No data	Pasture to urban	8	0.1
No data	No data	No data	Grass to urban	8	0.1
No data	No data	No data	Forest to grass	7	0.1
No data	No data	No data	Forest to scrub	7	0.1
No data	No data	No data	Water to urban	1	0.0
No data	No data	No data	Forest to barren	1	0.0
No data	No data	No data	Barren to grass	1	0.0
No data	No data	No data	Scrub to forest	1	0.0

3.1.8 South River Watershed

By 1992, the South River watershed was already urbanized with about 58% urban and 37% forest; and by 2011, urban increased and forest decreased about the same amount – plus 10% for urban land cover and minus 10% for forest land cover (Table 19). In the South River watershed, a large amount of urbanization occurred before 1992 but not so much in the southern part of the watershed (Figure 20, Figure 21). The changes during 1992-2001 occurred more in the southern part of the watershed, and during 2001-2011 the changes occurred throughout the watershed (Figure 20). Forest-to-urban was the dominant land cover change with approximately 5% from 1992-2001 and approximately 3% from 2001-2011 (Table 21).

Table 20 South River watershed land cover percentages

Land Cover	1992	2001	2011
Water	0.4	0.5	0.4
Urban	58.2	62.7	67.2
Barren	0.3	0.5	0.3
Forest	36.6	30.7	26.6
Shrubland	1.0	0.4	0.9
Grassland		1.9	1.6
Planted/Cultivated	2.0	2.0	1.6
Wetland	1.4	1.4	1.3

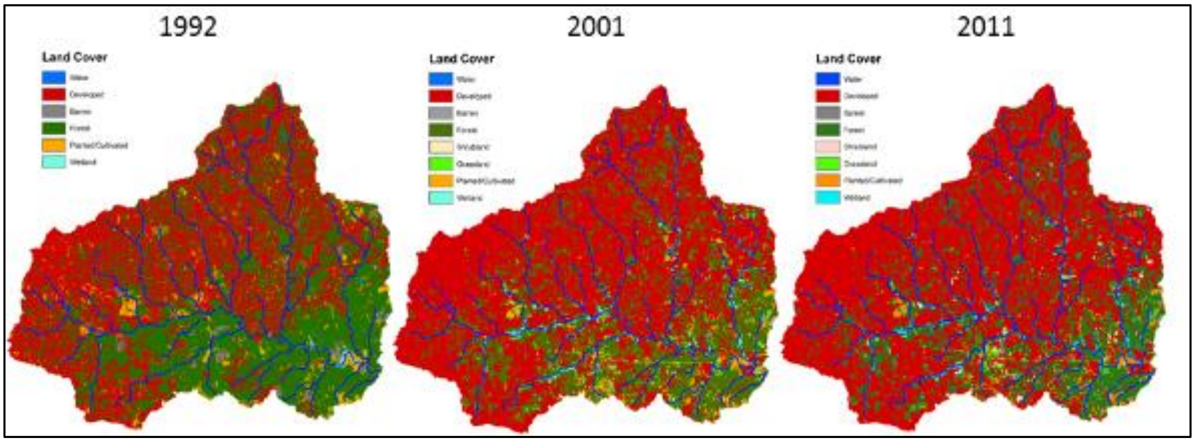

Figure 20 South River watershed land cover

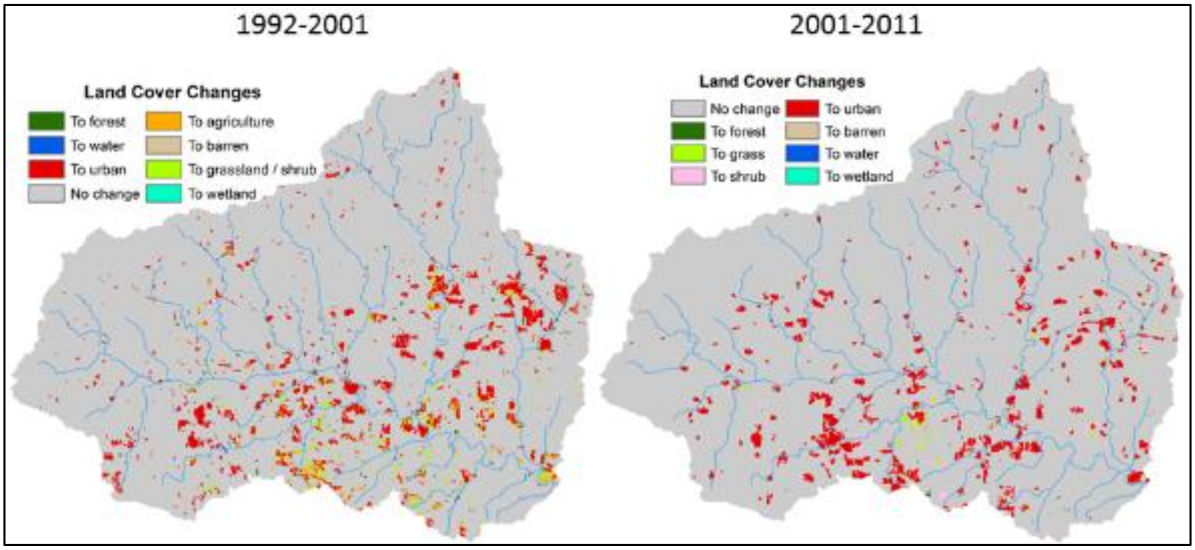

Figure 21 South River watershed land cover changes

Table 21 South River Watershed Changes 1992-2001 and 2001-2011

1992-2001 Land Cover Changes	**1992-2001 (hectares)**	**1992-2001 (%)**	**2001-2011 Land Cover Change**	**2001-2011 (hectares)**	**2001-2011 (%)**
Forest to urban	2220	4.7	Forest to urban	1513	3.2
Forest to grassland/shrub	432	0.9	Forest to scrub	296	0.6
Forest to ag	382	0.8	Grass to urban	254	0.5
Forest to barren	103	0.2	Pasture to urban	149	0.3
Ag to urban	64	0.1	Barren to urban	148	0.3
Ag to forest	43	0.1	Forest to grass	120	0.3
Urban to forest	34	0.1	Forest to barren	52	0.1

Forest to open water	15	0.0	Scrub to urban	42	0.1
Grassland/shrub to forest	9	0.0	Grass to scrub	22	0.0
Ag to open water	5	0.0	Pasture to scrub	18	0.0
Open water to urban	4	0.0	Scrub to forest	17	0.0
Urban to open water	3	0.0	Wetland to urban	16	0.0
Forest to wetland	2	0.0	Barren to grass	15	0.0
Grassland/shrub to urban	2	0.0	Pasture to grass	13	0.0
Open water to forest	2	0.0	Water to urban	9	0.0
Urban to grassland/shrub	1	0.0	Pasture to forest	7	0.0
Barren to open water	1	0.0	Grass to forest	5	0.0
Grassland/shrub to open water	1	0.0	Grass to barren	5	0.0
Grassland/shrub to barren	1	0.0	Water to forest	4	0.0
Open water to grassland/shrub	1	0.0	Barren to scrub	3	0.0
Urban to ag	1	0.0	Wetland to water	2	0.0
No data	No data	No data	Barren to forest	2	0.0
No data	No data	No data	Wetland to scrub	2	0.0
No data	No data	No data	Forest to water	1	0.0
No data	No data	No data	Scrub to grass	1	0.0

3.1.9 Suwanee Creek Watershed

For the Suwanee Creek watershed, drastic changes occurred from 1992-2001 through major development (Figure 22, Figure 23). Suwanee Creek experienced approximately double the urbanization from 1992-2011 than what was present in 1992: about 15% of the watershed changed from forest to urban from 1992-2001 and then approximately another 15% of the watershed become urbanized from 2001-2011 (Table 22). Most of the specific changes were forest-to-urban with approximately 15% of the watershed undergoing forest-to-urban land cover changes from 1992-2001 and then an additional 10% of the watershed undergoing forest-to-urban conversion from 2001-2011 (Table 23). Spatially, the changed parcels were spread around the entire watershed from 1992-2001, and from 2001-2011 the plots of land that changed to urban were spread across the watershed as well (Figure 23).

Table 22 Suwanee Creek watershed land cover percentages

Land Cover	**1992**	**2001**	**2011**
Water	0.3	0.4	0.3
Urban	29.3	45.2	60.9
Barren	2.0	2.2	0.4
Forest	57.2	40.1	29.1
Shrubland	1.9	0.5	0.8
Grassland		2.7	1.9
Planted/Cultivated	6.9	6.5	4.2
Wetland	2.5	2.5	2.4

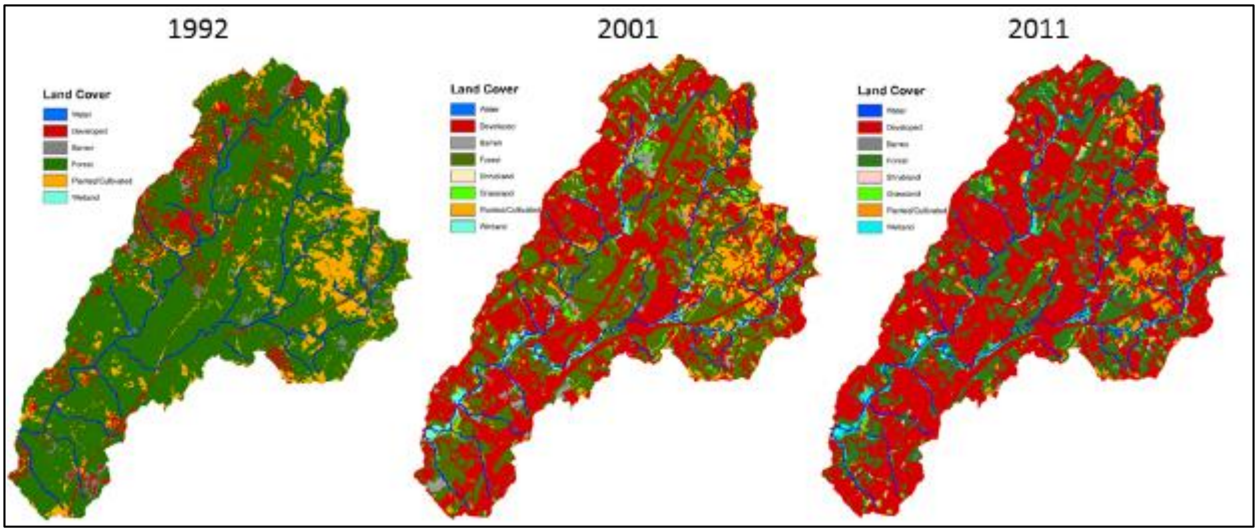

Figure 22 Suwanee Creek watershed land cover

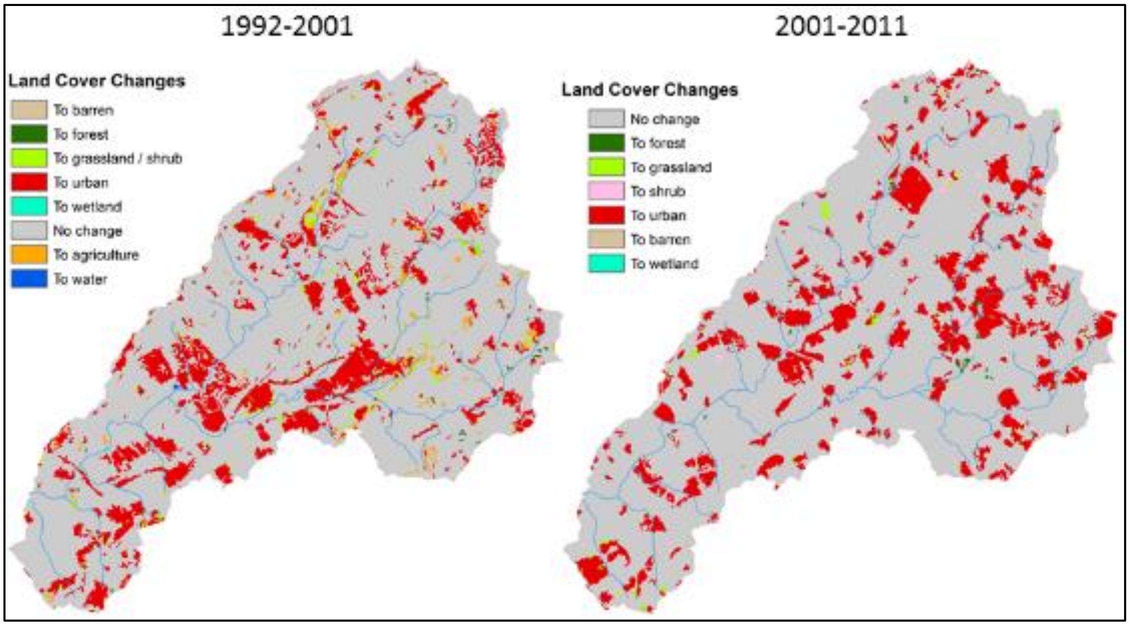

Figure 23 Suwanee Creek watershed land cover changes

Table 23 Suwanee Creek Watershed Changes 1992-2001 and 2001-2011

1992-2001 Land Cover Change	1992-2001 (hectares)	1992-2001 (%)	2001-2011 Land Cover Change	2001-2011 (hectares)	2001-2011 (%)
Forest to urban	1849	15.2	Forest to urban	1281	10.2
Forest to ag	194	1.6	Pasture to urban	273	2.2
Forest to grassland/shrub	137	1.1	Barren to urban	240	1.9
Forest to barren	57	0.5	Grass to urban	148	1.2
Ag to urban	23	0.2	Forest to scrub	66	0.5
Ag to forest	18	0.2	Forest to grass	48	0.4
Ag to barren	3	0.0	Wetland to urban	22	0.2
Forest to open water	3	0.0	Scrub to urban	19	0.2
Forest to wetland	1	0.0	Forest to barren	12	0.1
Urban to forest	1	0.0	Pasture to forest	10	0.1
Grassland/shrub to forest	1	0.0	Water to urban	10	0.1
Wetland to urban	1	0.0	Scrub to forest	10	0.1
Ag to wetland	1	0.0	Grass to forest	7	0.1
Ag to grassland/shrub	1	0.0	Pasture to grass	6	0.0
Urban to ag	1	0.0	Grass to scrub	3	0.0

No data	No data	No data	Barren to grass	2	0.0
No data	No data	No data	Pasture to barren	2	0.0
No data	No data	No data	Water to scrub	2	0.0
No data	No data	No data	Barren to scrub	2	0.0
No data	No data	No data	Pasture to scrub	1	0.0
No data	No data	No data	Forest to wetland	1	0.0
No data	No data	No data	Scrub to grass	1	0.0
No data	No data	No data	Grass to barren	1	0.0
No data	No data	No data	Barren to forest	1	0.0
No data	No data	No data	Wetland to forest	1	0.0
No data	No data	No data	Wetland to scrub	1	0.0

3.1.10 Sweetwater Creek Watershed

The Sweetwater Creek watershed was moderately urbanized from 1992-2011: 1992 it was approximately 29% urban, in 2001 it was approximately 34% urban, and by 2011 it was approximately 41% urban (Table 24). Sweetwater Creek watershed has been substantially urbanized especially in the downstream portion of the watershed, which is closer to the city of Atlanta (Figure 24, Figure 25). Forest-to-urban conversion was the most common land cover change from 1992-2001 with about 5% of the watershed changing, and from 2001-2011 with about 4.5% of the watershed changing (Table 25).

Table 24 Sweetwater Creek watershed land cover percentages

Land Cover	1992	2001	2011
Water	0.9	0.9	0.9
Urban	28.7	34.3	40.9
Barren	0.4	0.4	0.2
Forest	52.4	45.2	39.5
Shrubland	2.4	1.0	1.9
Grassland		3.0	3.0
Planted/Cultivated	11.3	11.0	9.5
Wetland	3.9	4.1	4.0

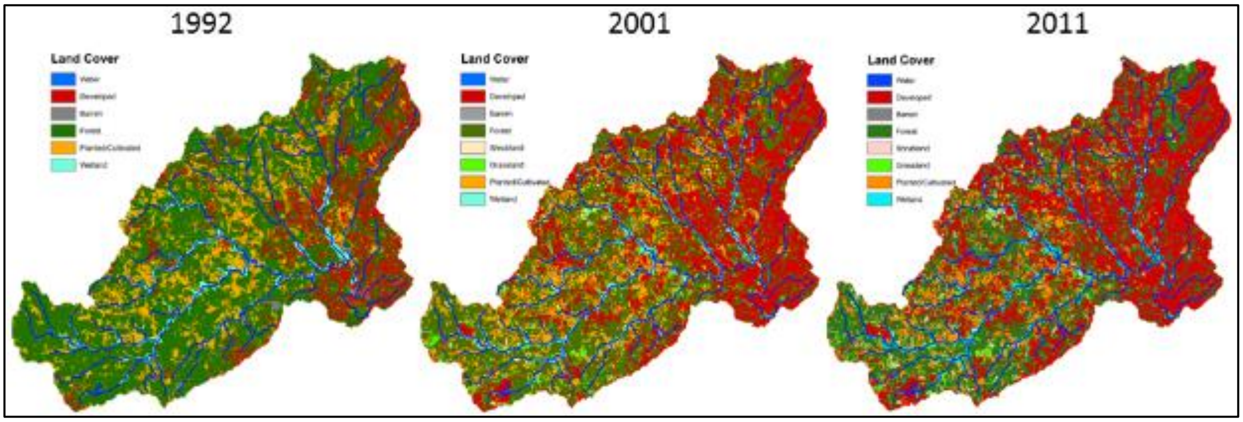

Figure 24 Sweetwater Creek watershed land cover

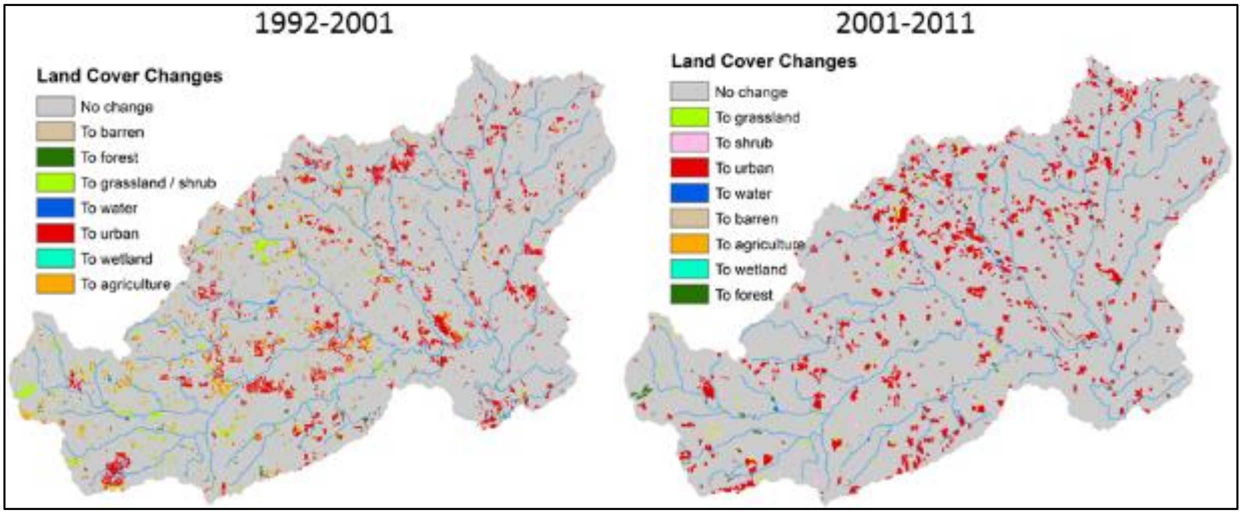

Figure 25 Sweetwater Creek watershed land cover changes

Table 25 Sweetwater Creek watershed changes 1992-2001 and 2001-2011

1992-2001 Land Cover Change	1992-2001 (hectares)	1992-2001 (%)	2001-2011 Land Cover Change	2001-2011 (hectares)	2001-2011 (%)
Forest to urban	3065	5.0	Forest to urban	2774	4.5
Forest to ag	1171	1.9	Pasture to urban	794	1.3
Forest to grassland/shrub	906	1.5	Forest to scrub	580	0.9
Ag to forest	128	0.2	Forest to grass	279	0.5
Forest to barren	114	0.2	Grass to urban	233	0.4
Ag to urban	64	0.1	Barren to urban	168	0.3
Urban to forest	48	0.1	Pasture to forest	65	0.1
Forest to open water	28	0.0	Scrub to urban	64	0.1

Ag to open water	13	0.0	Scrub to forest	61	0.1
Open water to forest	12	0.0	Grass to forest	57	0.1
Ag to grassland/shrub	9	0.0	Grass to scrub	43	0.1
Open water to urban	7	0.0	Forest to barren	43	0.1
Open water to wetland	7	0.0	Pasture to grass	39	0.1
Grassland/shrub to forest	6	0.0	Wetland to urban	35	0.1
Urban to open water	6	0.0	Pasture to scrub	31	0.1
Urban to wetland	6	0.0	Water to scrub	18	0.0
Open water to grassland/shrub	5	0.0	Water to urban	13	0.0
Forest to wetland	5	0.0	Wetland to water	12	0.0
Urban to ag	4	0.0	Water to forest	11	0.0
Open water to ag	3	0.0	Barren to grass	9	0.0
Ag to wetland	3	0.0	Scrub to grass	6	0.0
Grassland/shrub to open water	2	0.0	Forest to water	6	0.0
Ag to barren	1	0.0	Pasture to barren	5	0.0
Urban to grassland/shrub	1	0.0	Water to grass	4	0.0
Grassland/shrub to ag	1	0.0	Water to pasture	4	0.0
Grassland/shrub to wetland	1	0.0	Wetland to scrub	4	0.0
Open water to barren	1	0.0	Water to wetland	3	0.0
No data	No data	No data	Wetland to grass	3	0.0
No data	No data	No data	Forest to wetland	2	0.0
No data	No data	No data	Pasture to wetland	2	0.0
No data	No data	No data	Barren to scrub	2	0.0
No data	No data	No data	Water to barren	2	0.0
No data	No data	No data	Barren to water	1	0.0
No data	No data	No data	Grass to water	1	0.0
No data	No data	No data	Grass to wetland	1	0.0
No data	No data	No data	Wetland to forest	1	0.0
No data	No data	No data	Grass to barren	1	0.0

3.2 Study Area-wide Results

Precipitation values for the ten watersheds were similar across all watersheds, but a slight difference between the higher precipitation at the Etowah River versus the lower precipitation at Line Creek appears to follow order of latitude –Etowah River is most north and Line Creek is more south (Figure 26). Orographic lifting in the headlands was not captured in the estimate for the Etowah River watershed, so the rainfall amounts may be underestimated, but still the Etowah River has the highest runoff values compared to the lower values of the Flint River and Line Creek; this coincides with the average slopes of the watersheds (Figure 27, Table 26). The Flint River (upstream only) watershed has the highest runoff-rainfall ratio, and the Etowah River has the lowest (Figure 28). The Etowah River also has the highest baseflow values over 30 years while the Flint River and Line Creek have the lower baseflows (Figure 29). The BFIs for all streams are shown in relation to each other, and the box plots of the streams' BFIs are shown for the entire 30 years (Figure 30). The Etowah River, Big Creek, and South River watersheds have the highest BFI while Peachtree Creek and Flint River watersheds have the lowest BFI. The South River has the most consistent BFI ranges, and Sweetwater Creek has the highest and widest BFI range. Etowah River has a higher BFI as well. Line Creek and the Flint River have the highest amount of high flows (>95th percentile) per year, while the Etowah River and Sweetwater Creek have the most variability (Figure 32).

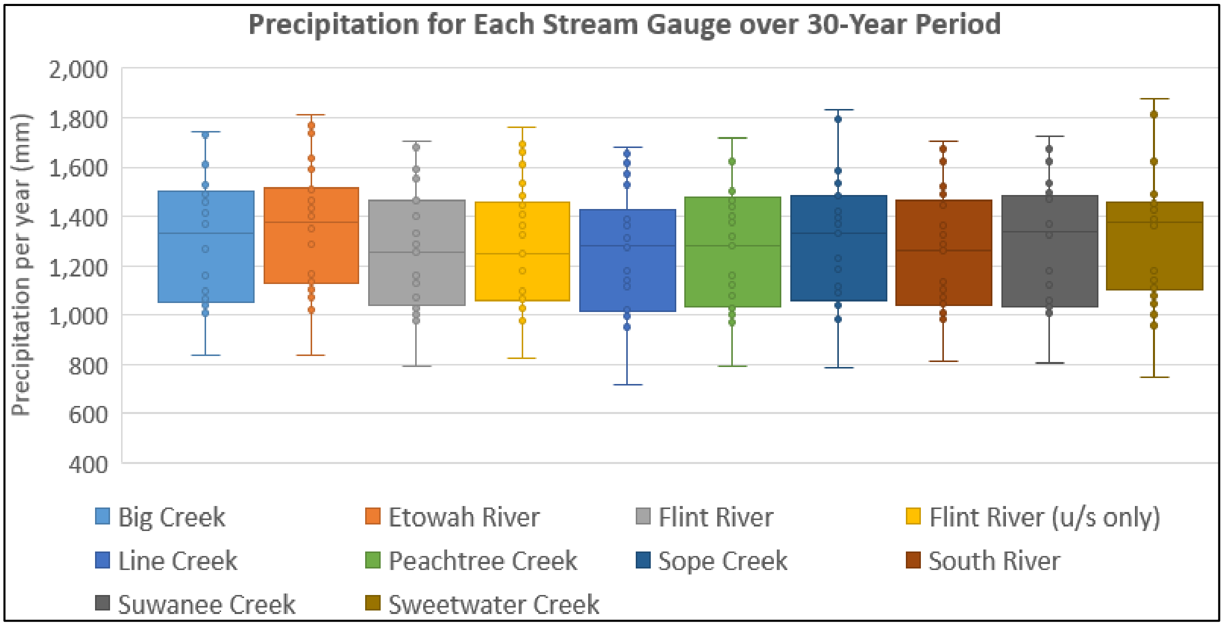

Figure 26 Precipitation at each stream gauge over 30 years

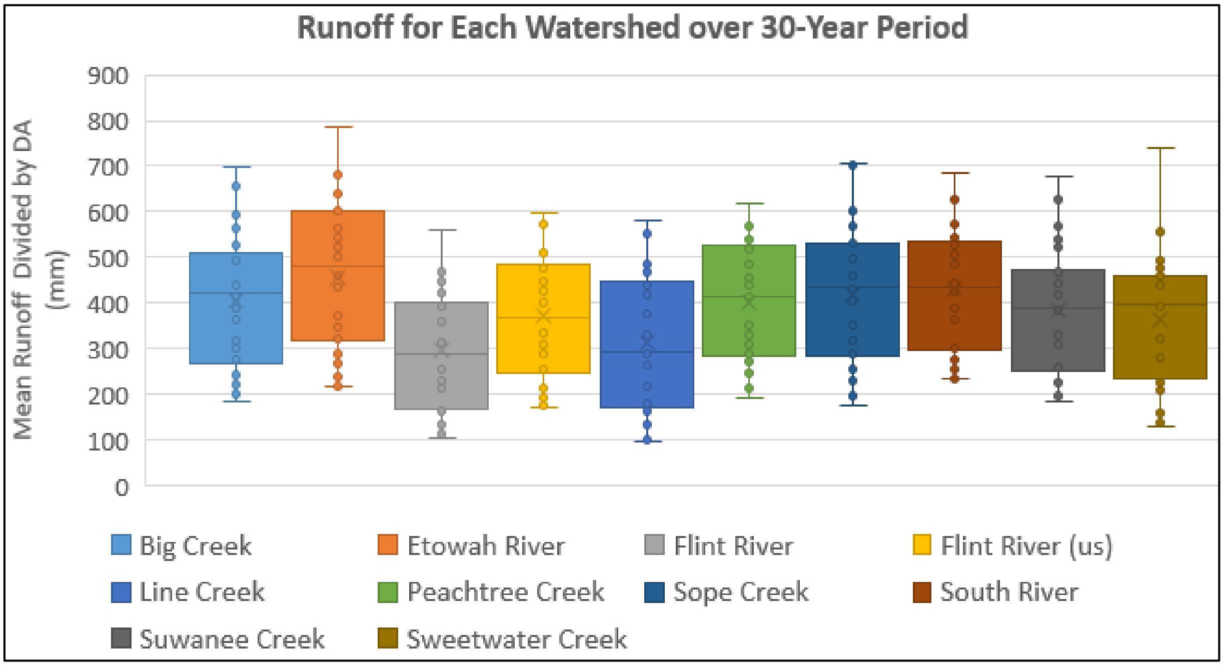

Figure 27 Runoff for each watershed over 30-year period

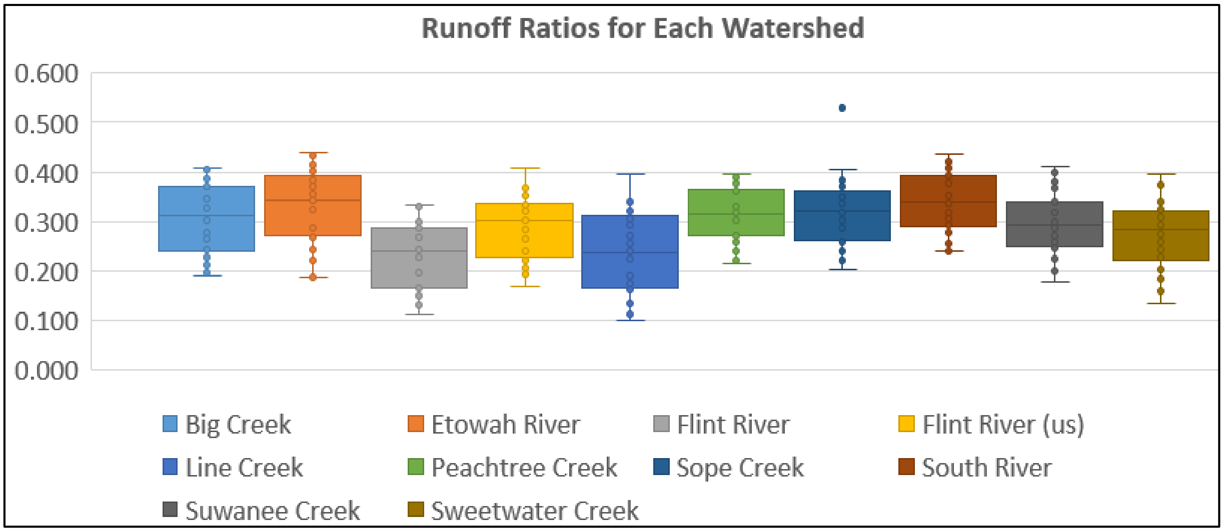

Figure 28 Runoff ratios for each watershed

Table 26 Watershed slope averages

WATERSHED	Average Slope (%)
Big Creek	7.21
Etowah River	14.82
Flint River	4.40
Flint River (u/s only)	5.00
Line Creek	5.00
Peachtree Creek	6.78
Sope Creek	7.03
South River	6.72
Suwanee Creek*	7.67
Sweetwater Creek	6.29

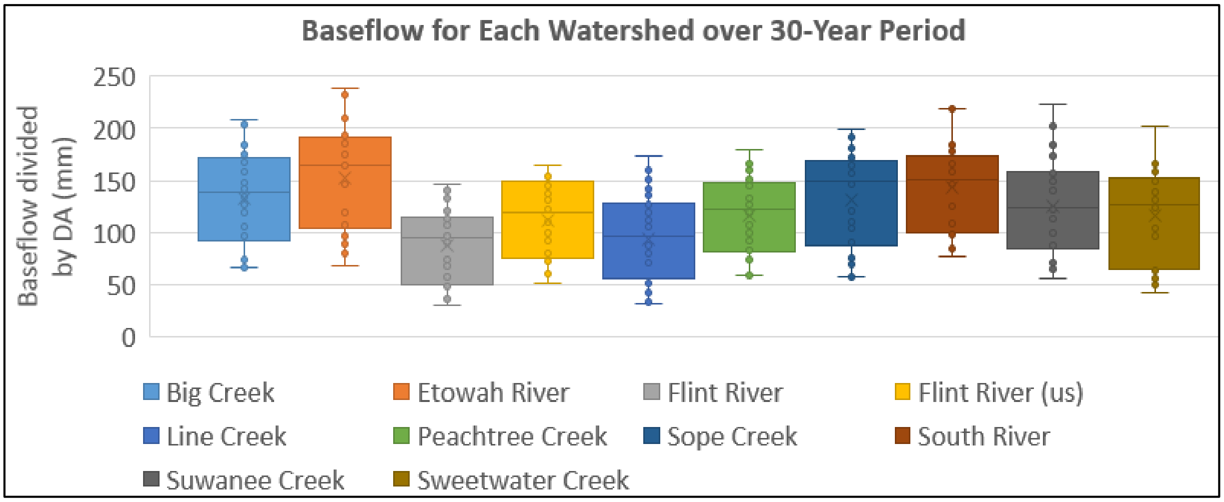

Figure 29 Baseflow for each watershed over 30-year period

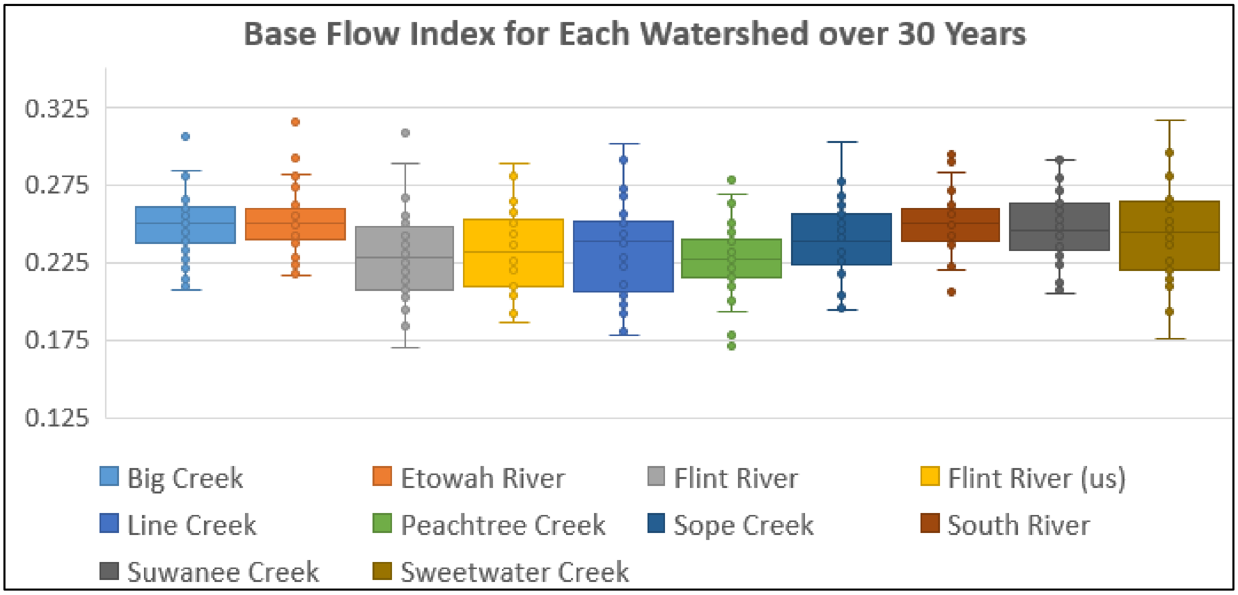

Figure 30 Baseflow indices for each watershed over 30 years

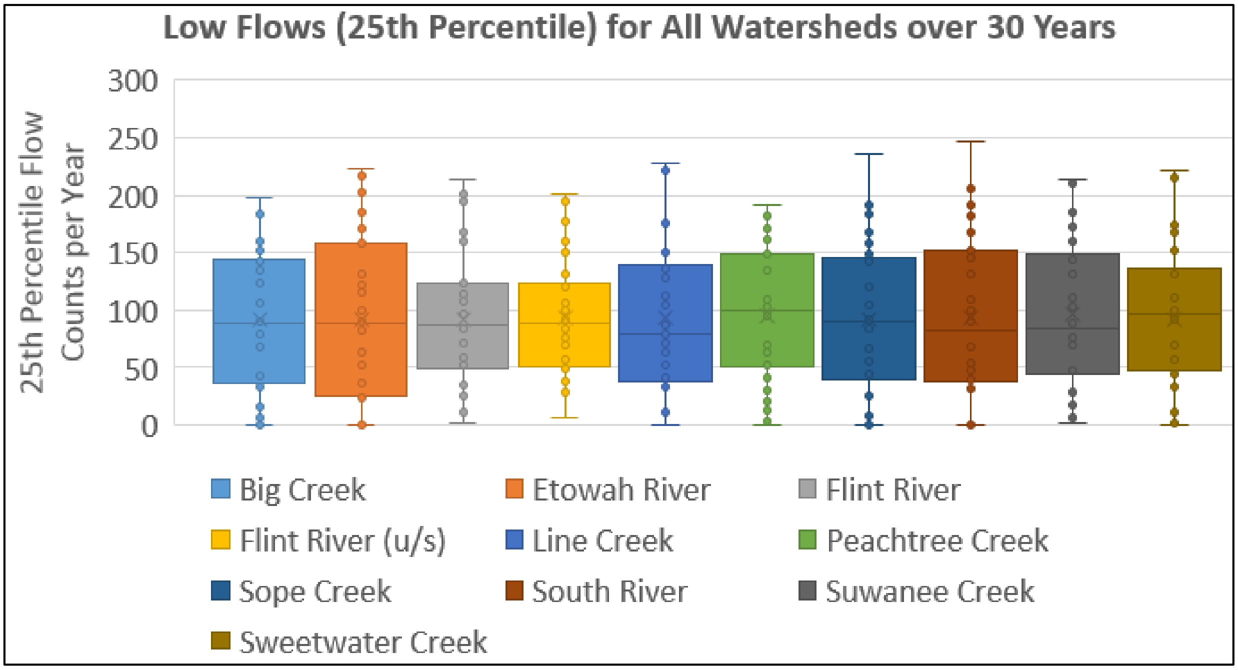

Figure 31 Low flows (25th percentile) for all watersheds over 30 years

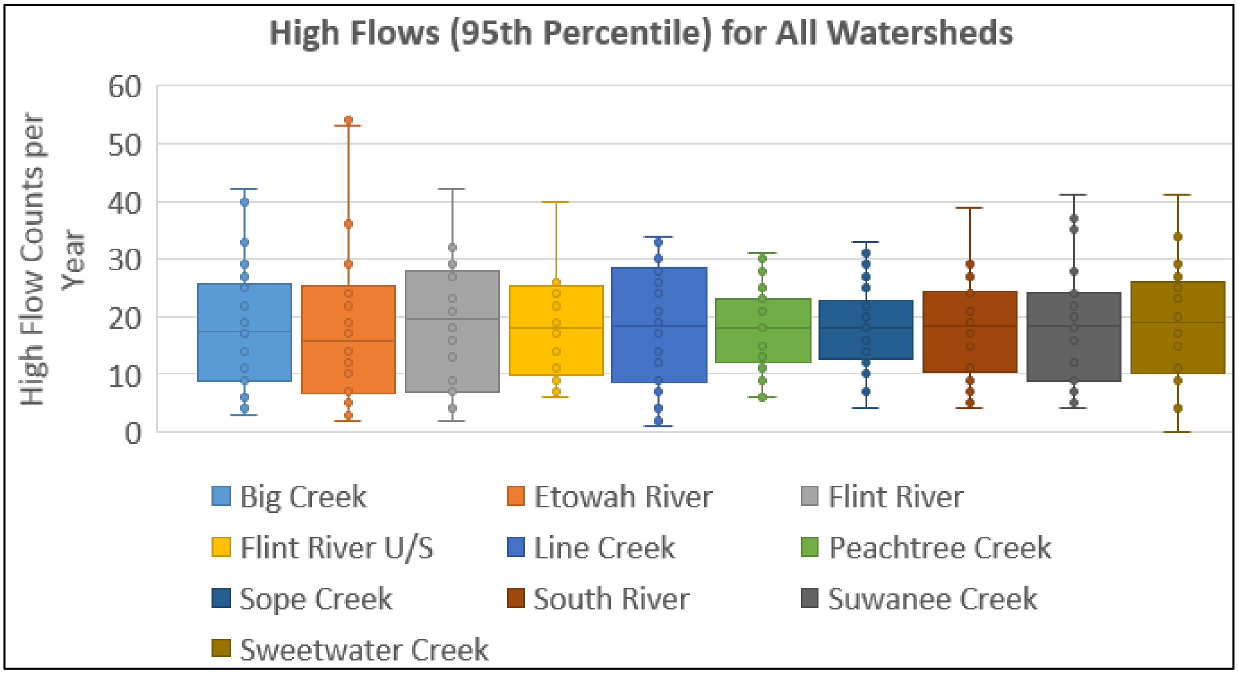

Figure 32 **High flows (95th percentile) for all watersheds over 30 years**

3.3 Interannual Variations in Streamflow

Each watershed's variables were calculated annually. The annual data was tested for trends. The precipitation-adjusted variables were only streamflow, runoff, and baseflow.

*3.3.1 Big Creek **

Big Creek watershed, streamflow and runoff were moderately correlated with precipitation, baseflow was slightly correlated, and naturally the runoff variable was the most correlated (Figure 33). High flows trend in Big Creek watershed were significant to 0.05 level and positive (Figure 34). Baseflow index and runoff ratio values of Big Creek ranged from 0.200 and 0.400, were not significant, but runoff ratio was slightly trending positive just not significant (Figure 35). Trends in the precipitation-adjusted streamflow and runoff variables (residuals) were significantly positive, and so was the count for high flows for Big Creek (Figure

36). High flows (>95th percentile of streamflow) have doubled increasing 100% from 1986-2015.

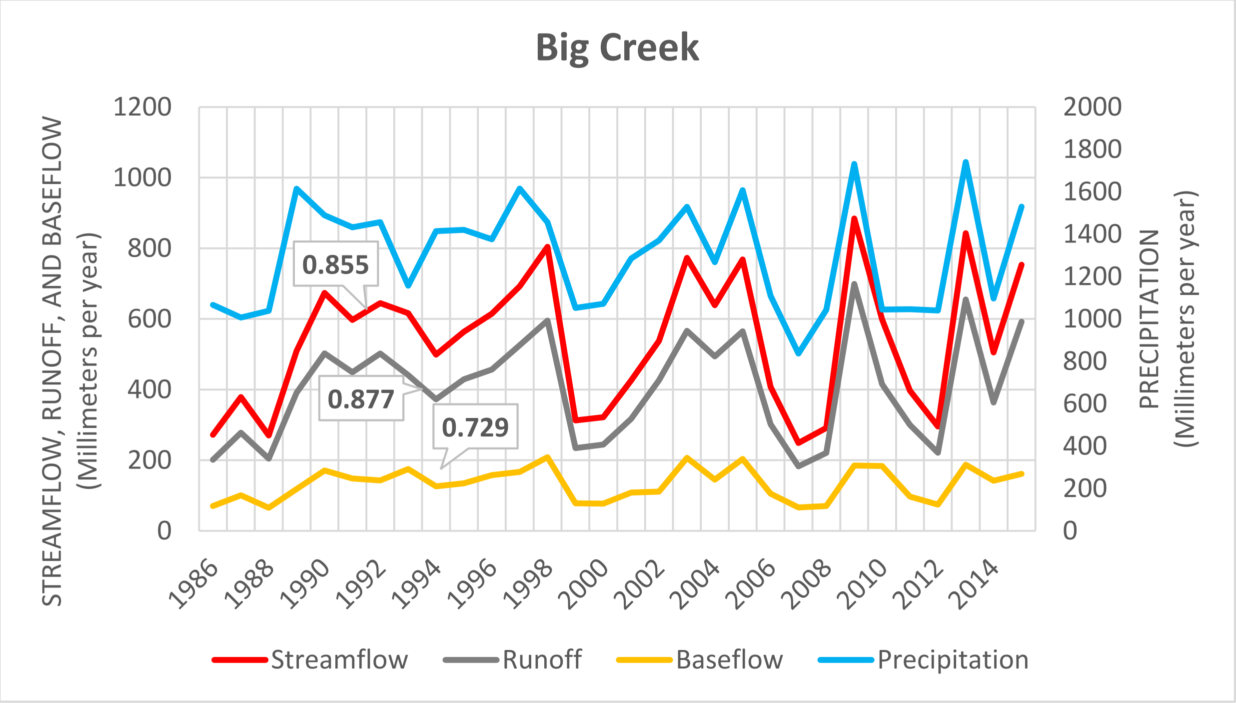

Figure 33 Big Creek streamflow variables with precipitation and their regression R values

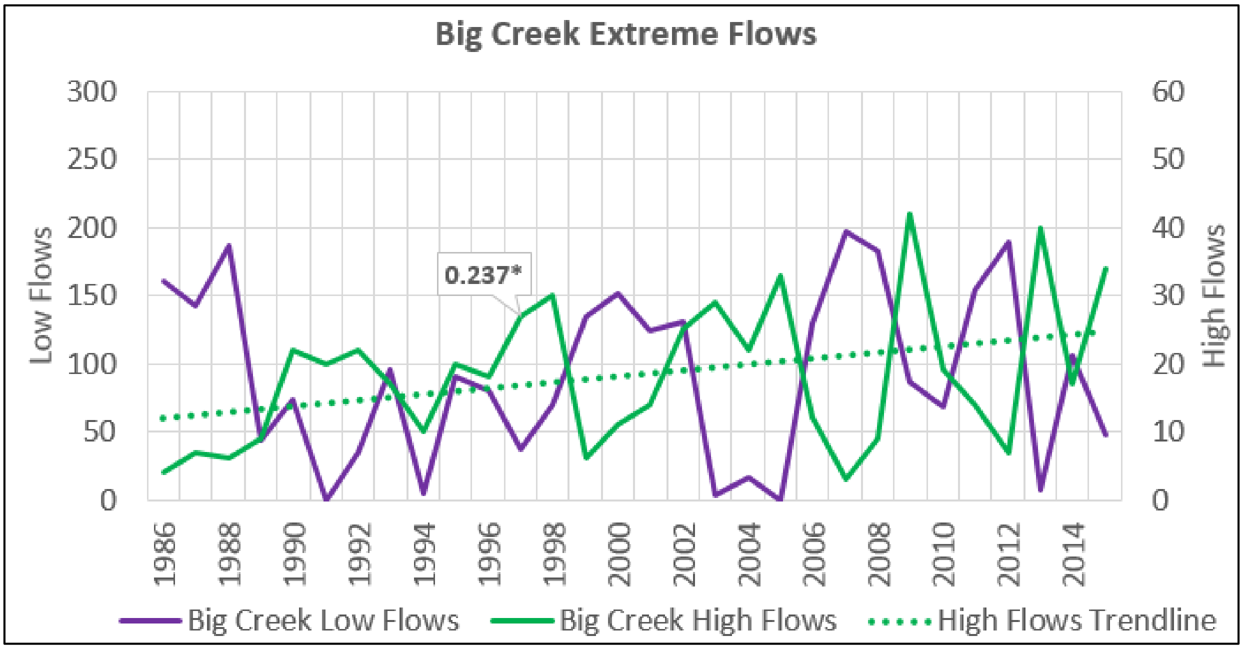

Figure 34 Big Creek extreme flows with coefficients of correlation

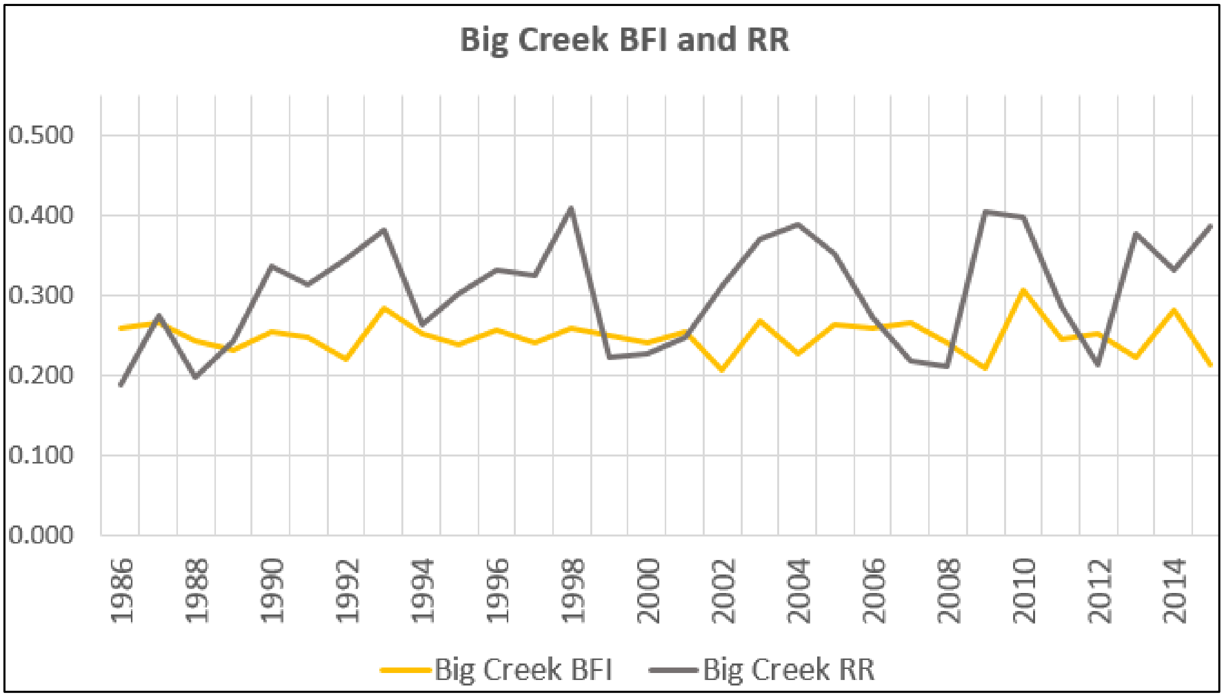

Figure 35 Big Creek BFI and RR

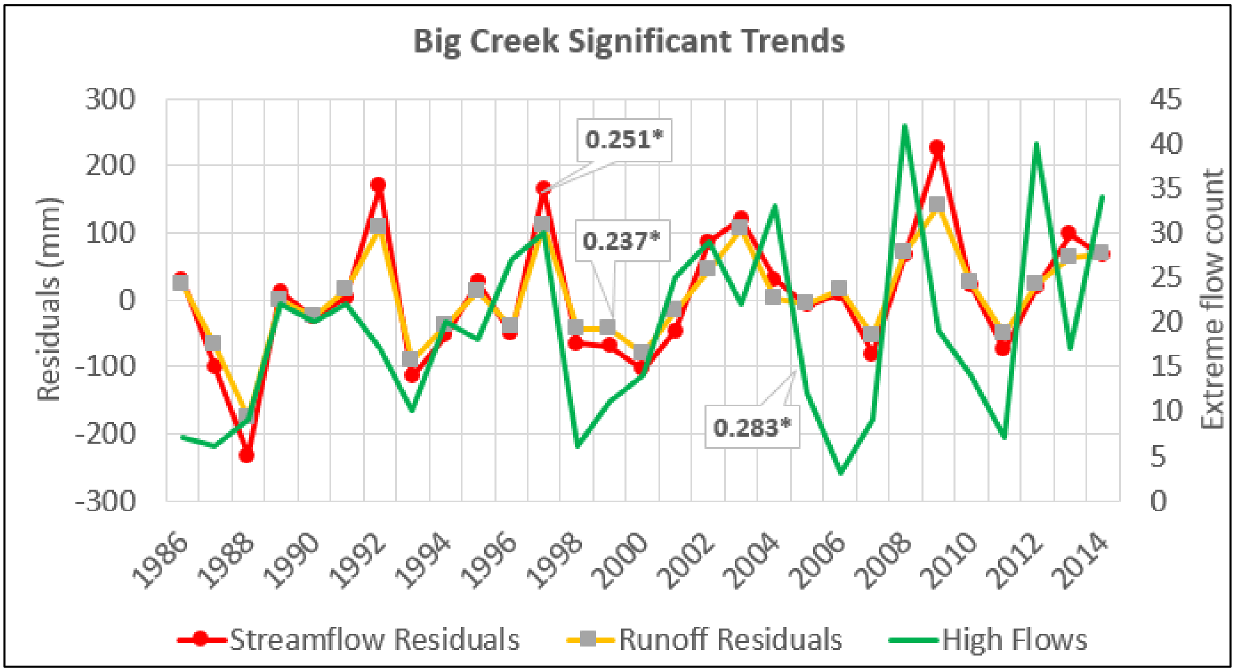

Figure 36 Big Creek significant residuals and extreme flow trends

3.3.2 Etowah River

In the Etowah River watershed, streamflow and runoff, moderately correlated with precipitation, but baseflow was barely slightly correlated (Figure 37). High flow and low flow trends in the watershed were not significant (Figure 38). Baseflow index and runoff ratio values ranged between 0.200 and 0.400, and only the runoff ratio trend was slightly leaning negative but non-significant (Figure 39).

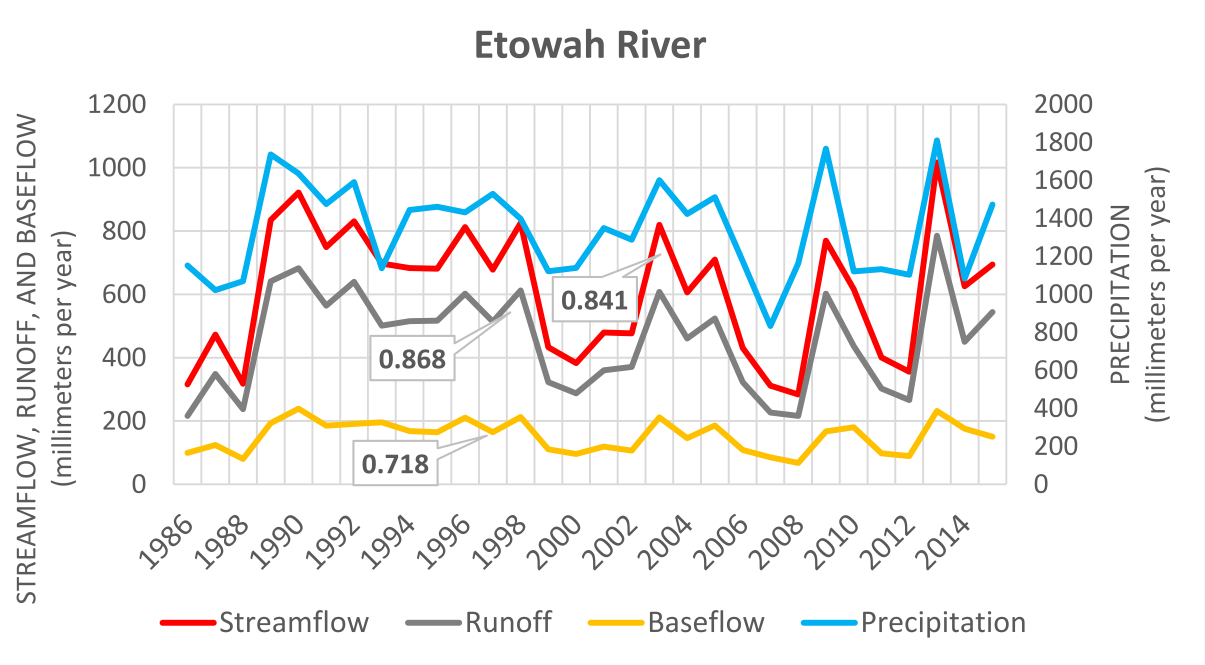

Figure 37 Etowah River streamflow variables and regression R values

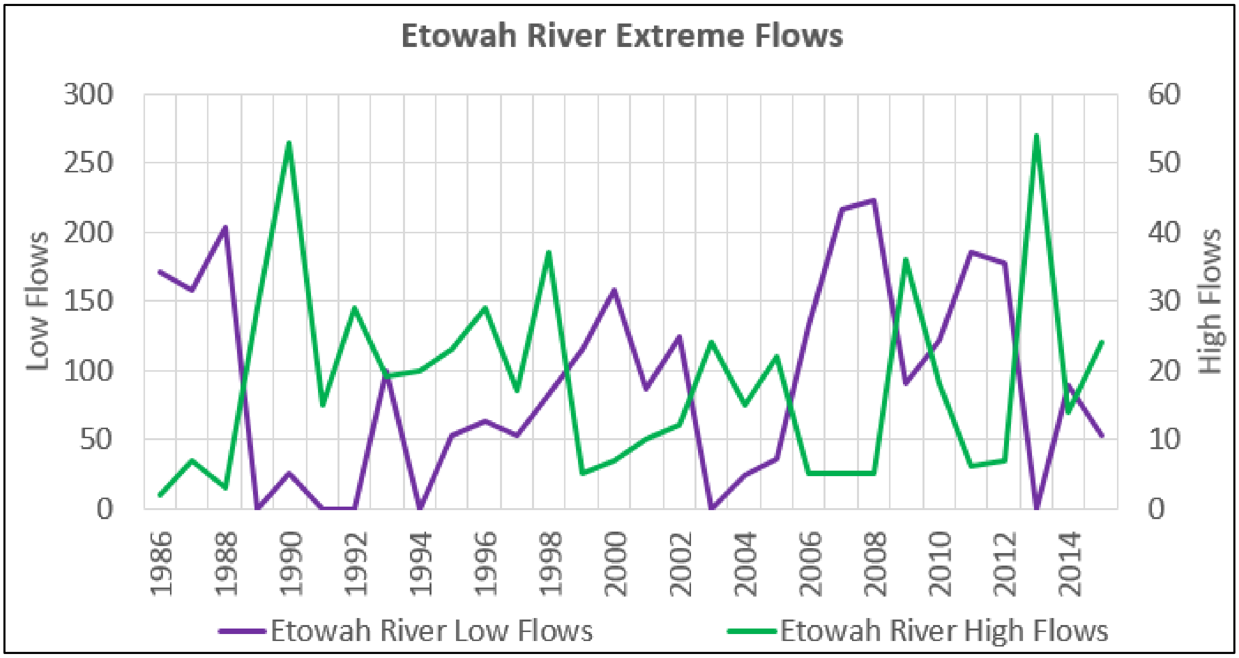

Figure 38 Etowah River extreme flows

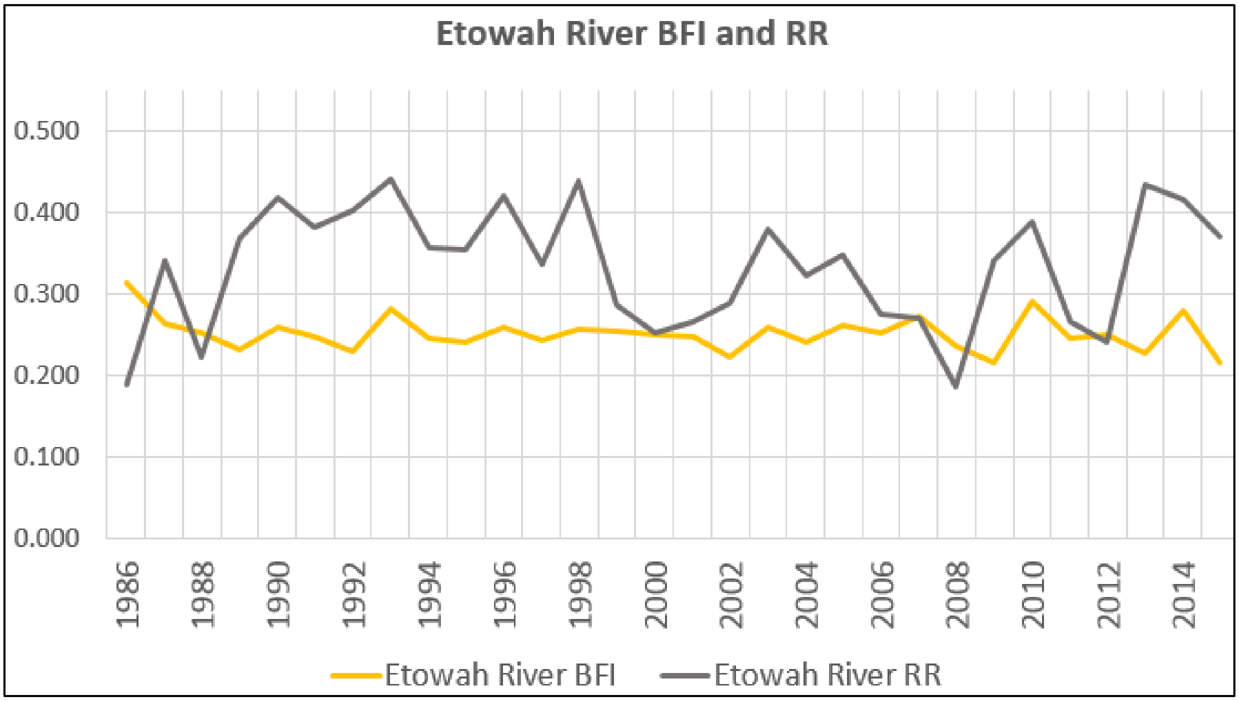

Figure 39 Etowah River BFI and RR

*3.3.3 Flint River **

In the Flint River, runoff was highly correlated with precipitation, streamflow was moderately correlated, and baseflow was barely slightly correlated (Figure 40). High flows and low flows trends in the watershed were not significant (Figure 41). Baseflow index and runoff ratio values ranged between 0.100 and 0.300, but trends were non-significant (Figure 42). Trends in the precipitation-adjusted streamflow and runoff variables (residuals) were significantly negative for the Flint River (Figure 43). Streamflow residuals from regression trended negative (α=0.05) with the Kendall's tau coefficient being -0.218 and the regression R value of 0.893. Runoff had the most negative trend, coefficient being -0.228 and R = 0.923.

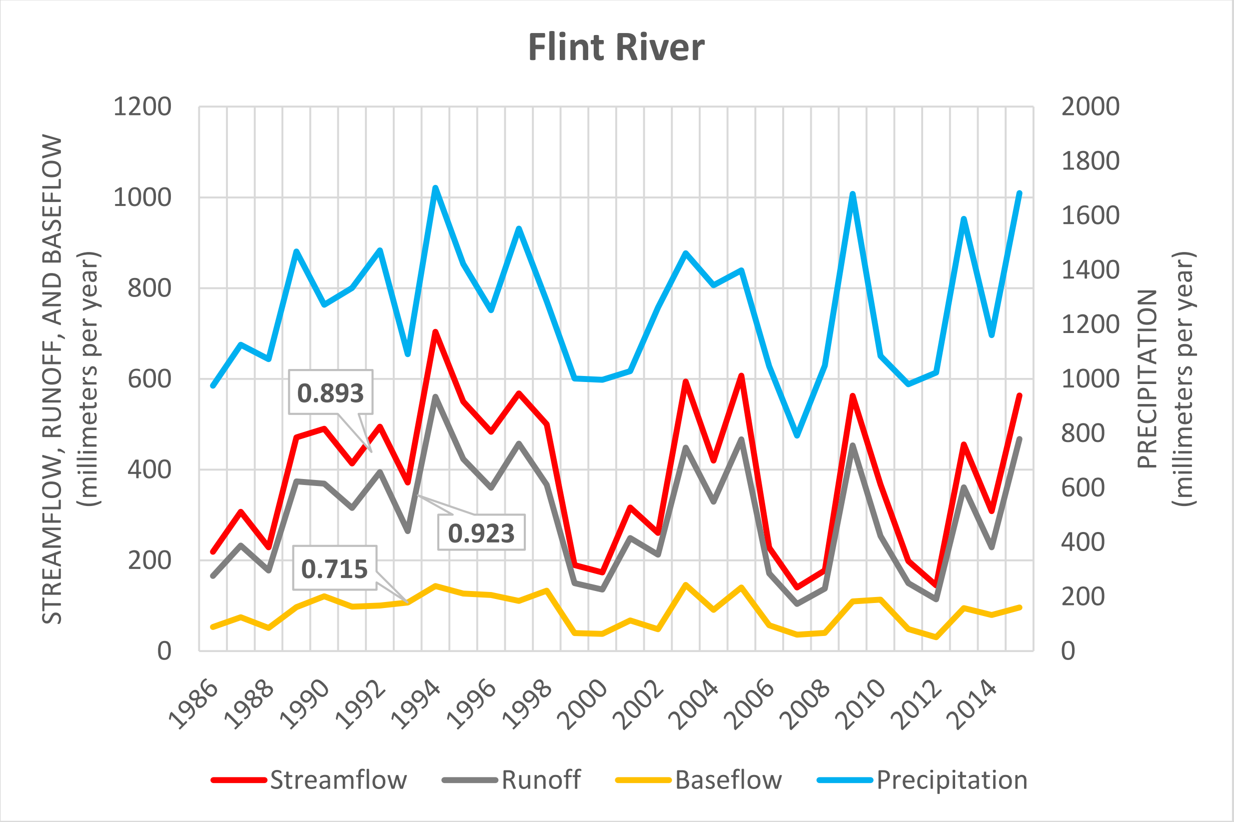

Figure 40 Flint River streamflow variables and regression R values

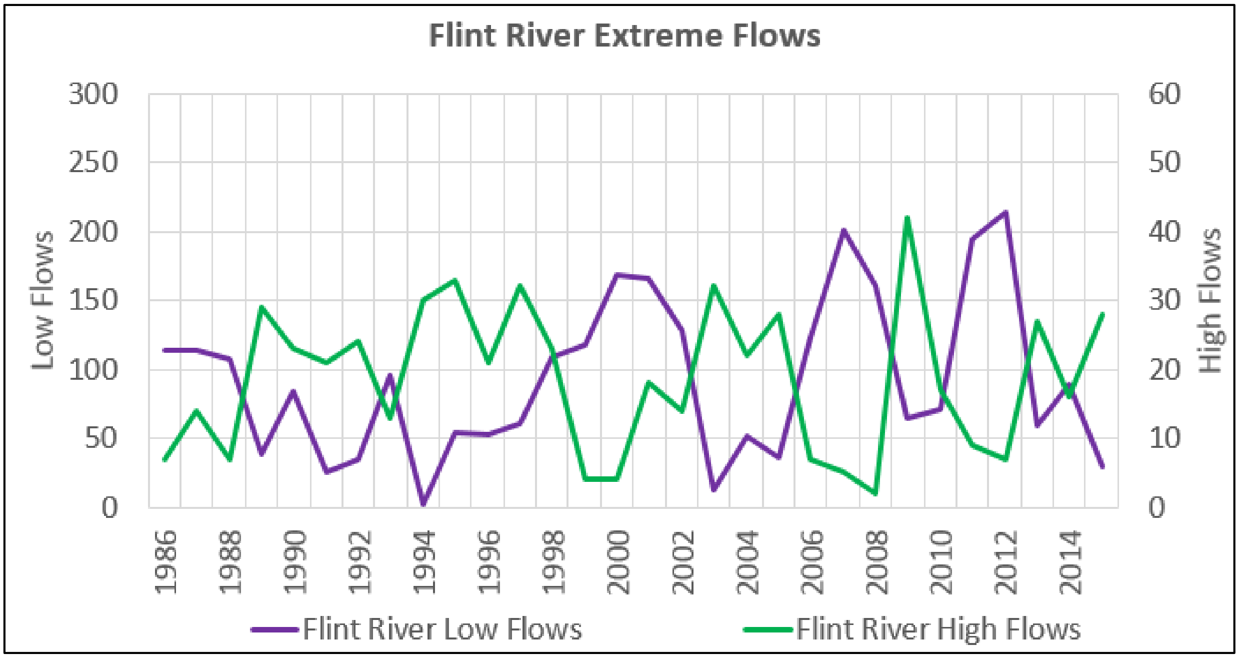

Figure 41 Flint River extreme flows

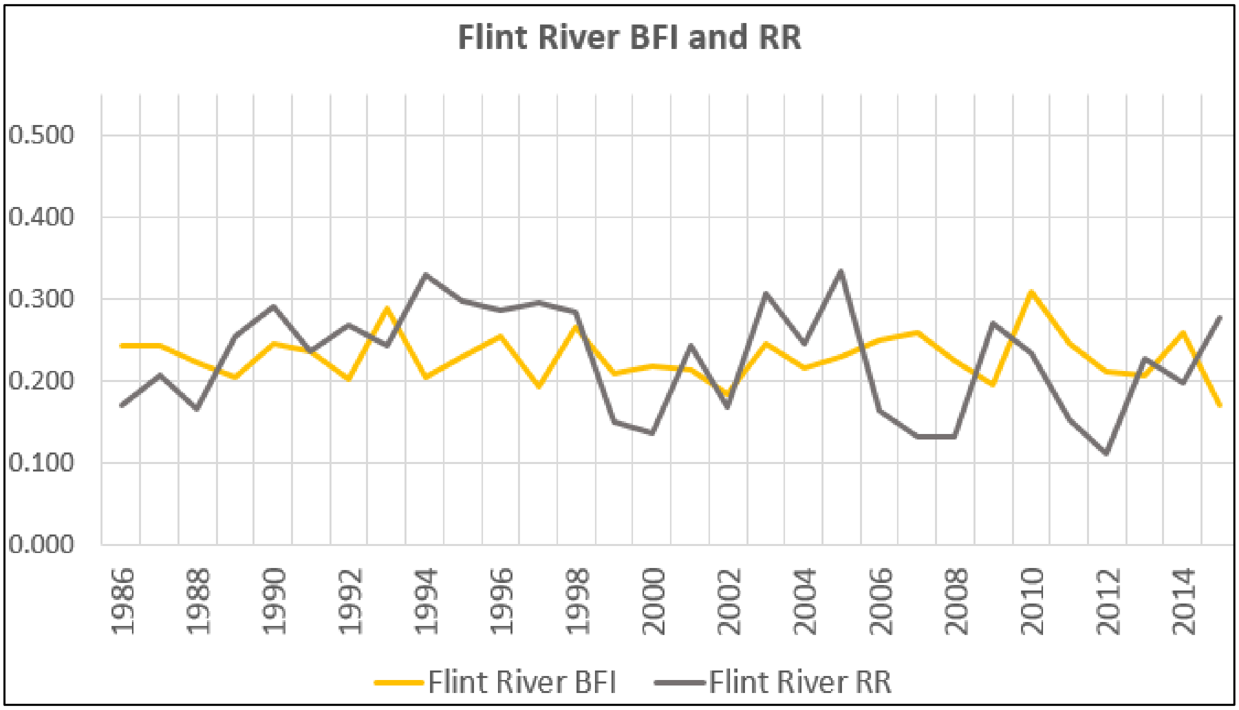

Figure 42 Flint River BFI and RR

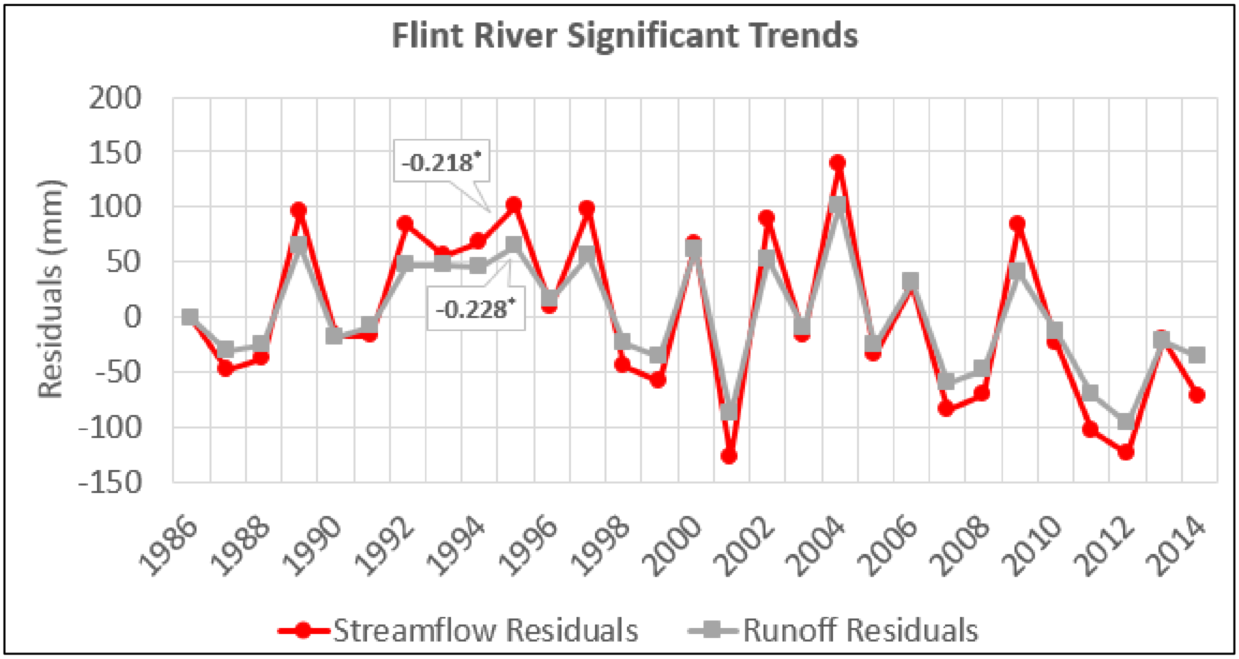

Figure 43 Flint River significant trends

3.3.4 Flint River (upstream)

Streamflow and runoff were highly correlated with precipitation, and baseflow was slightly correlated (Figure 44). High flows and low flows trends in the watershed were flat and non-significant (Figure 45). Baseflow index and runoff ratio values ranged between 0.200 and 0.400, but trends were non-significant (Figure 46).

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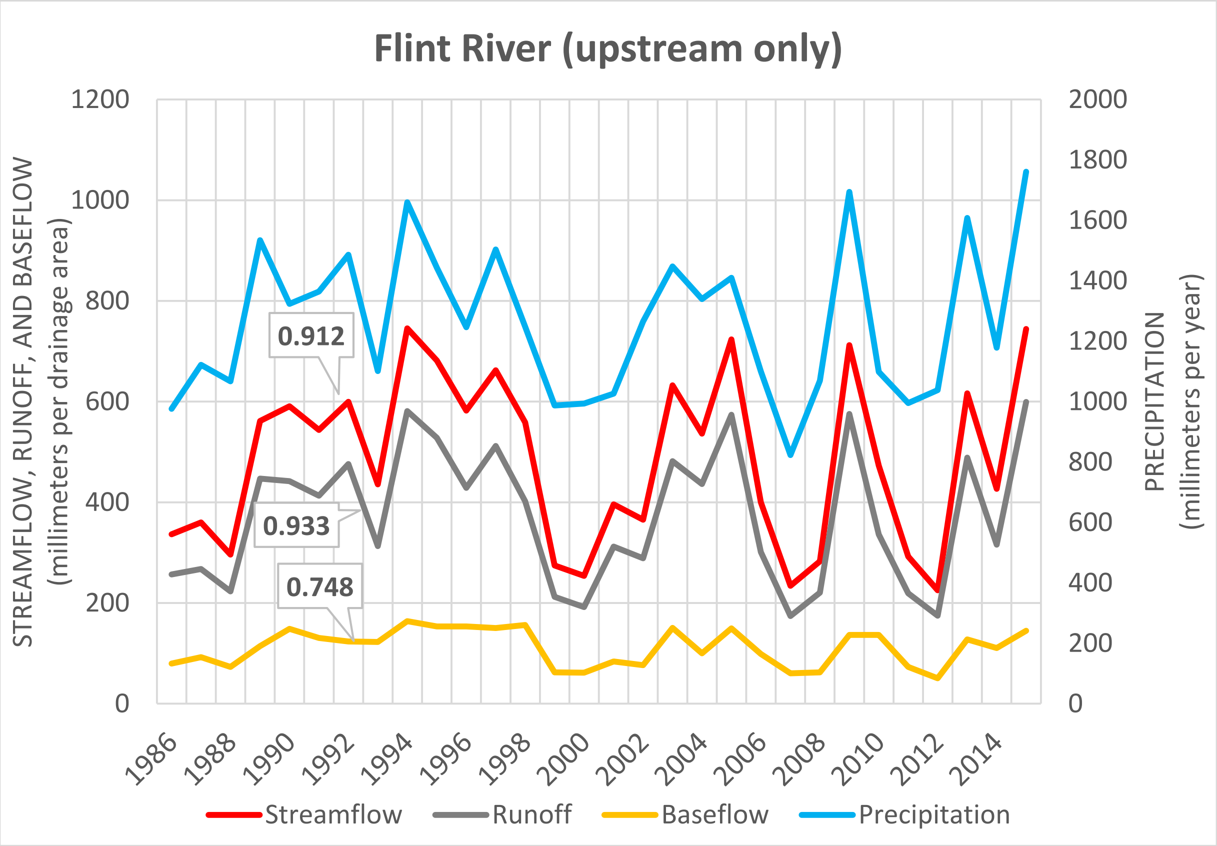

Figure 44 Flint River (upstream only) streamflow variables and regression R values

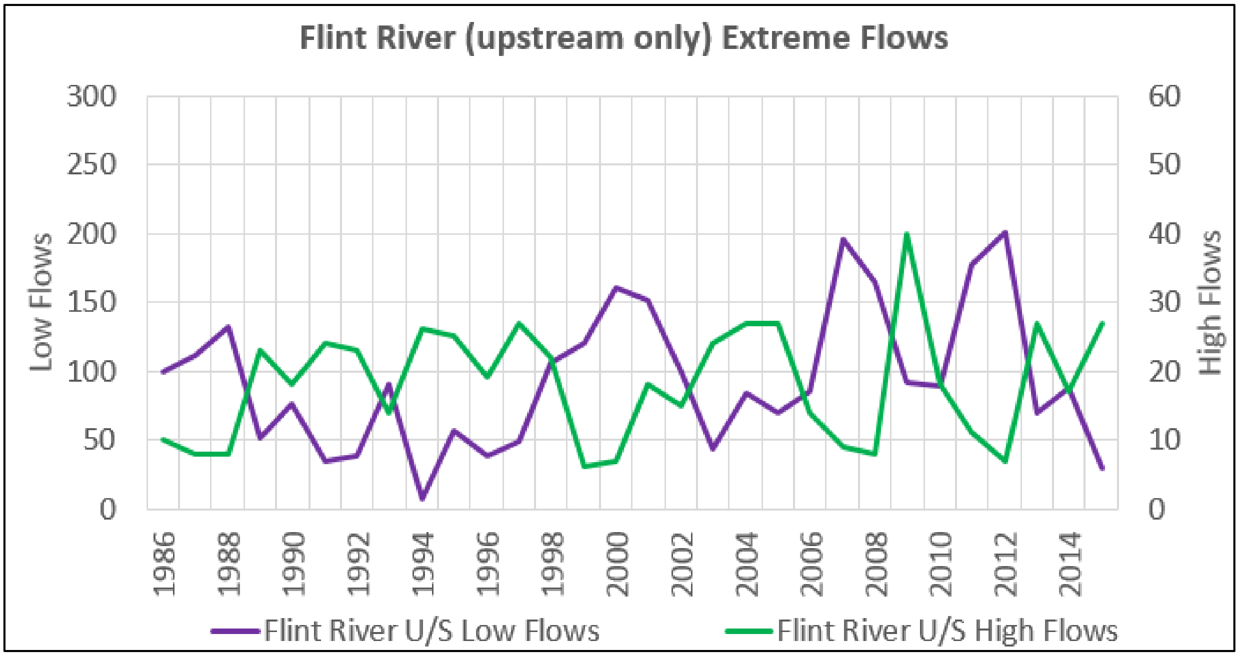

Figure 45 Flint River (upstream only) extreme flows

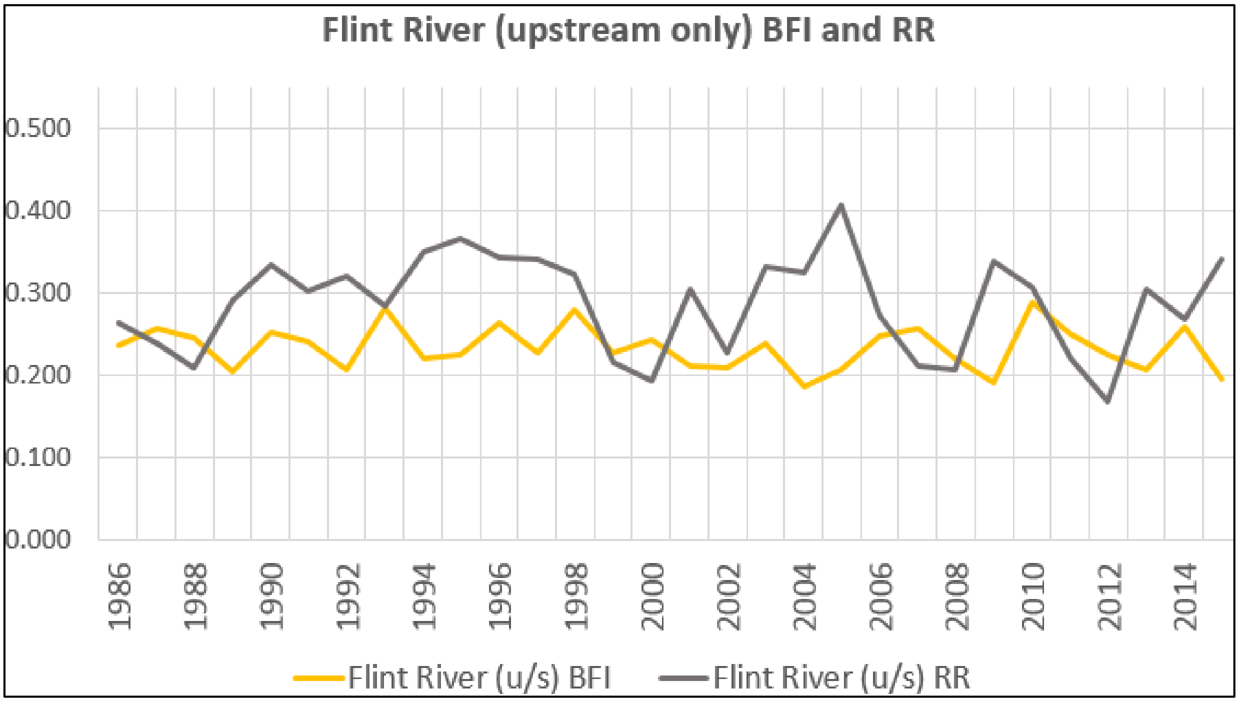

Figure 46 Flint River (upstream only) BFI and RR

3.3.5 Line Creek

In the Line Creek watershed, streamflow and runoff were moderately correlated with precipitation, but baseflow was slightly correlated (Figure 47). Extreme flows were both flat and non-significant (Figure 48). The BFI and RR trends were flat and non-significant (Figure 49).

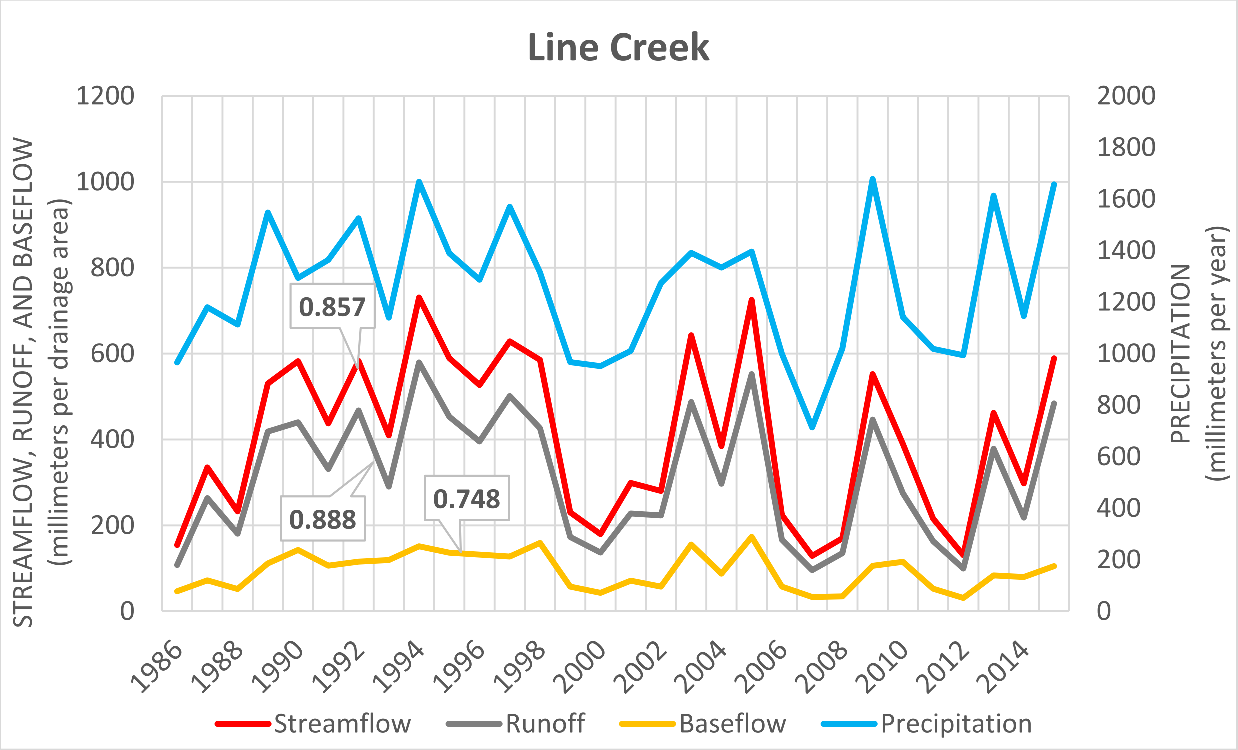

Figure 47 Line Creek streamflow variables and regression R values

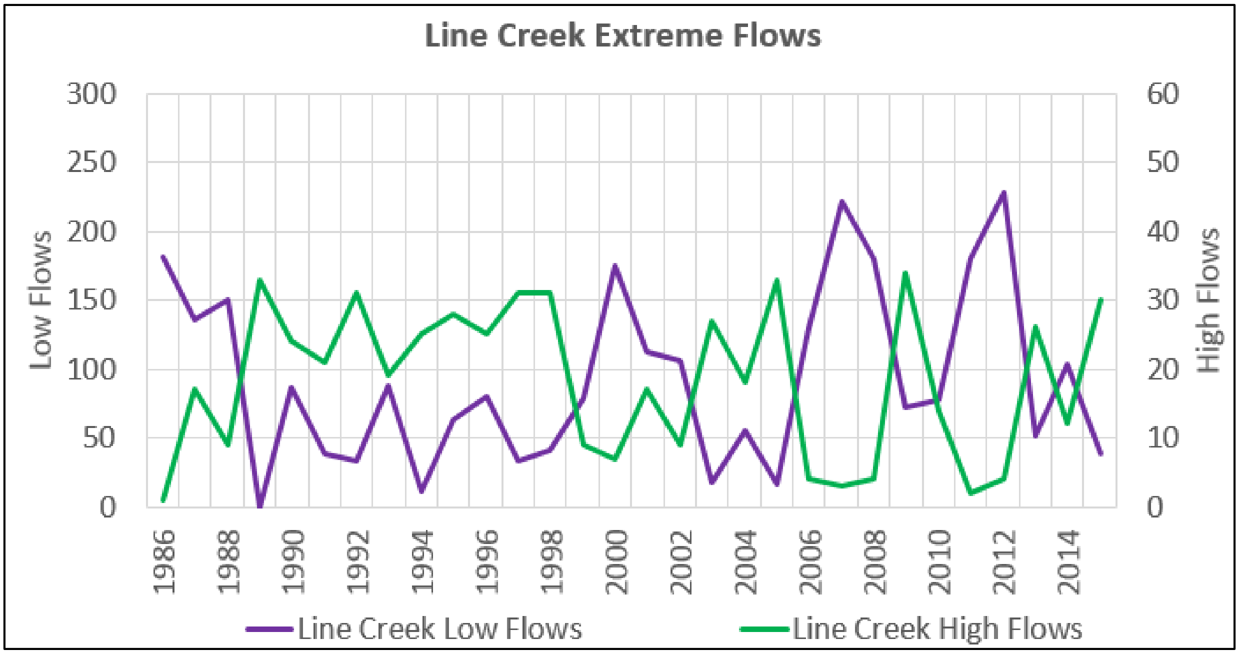

Figure 48 Line Creek extreme flows

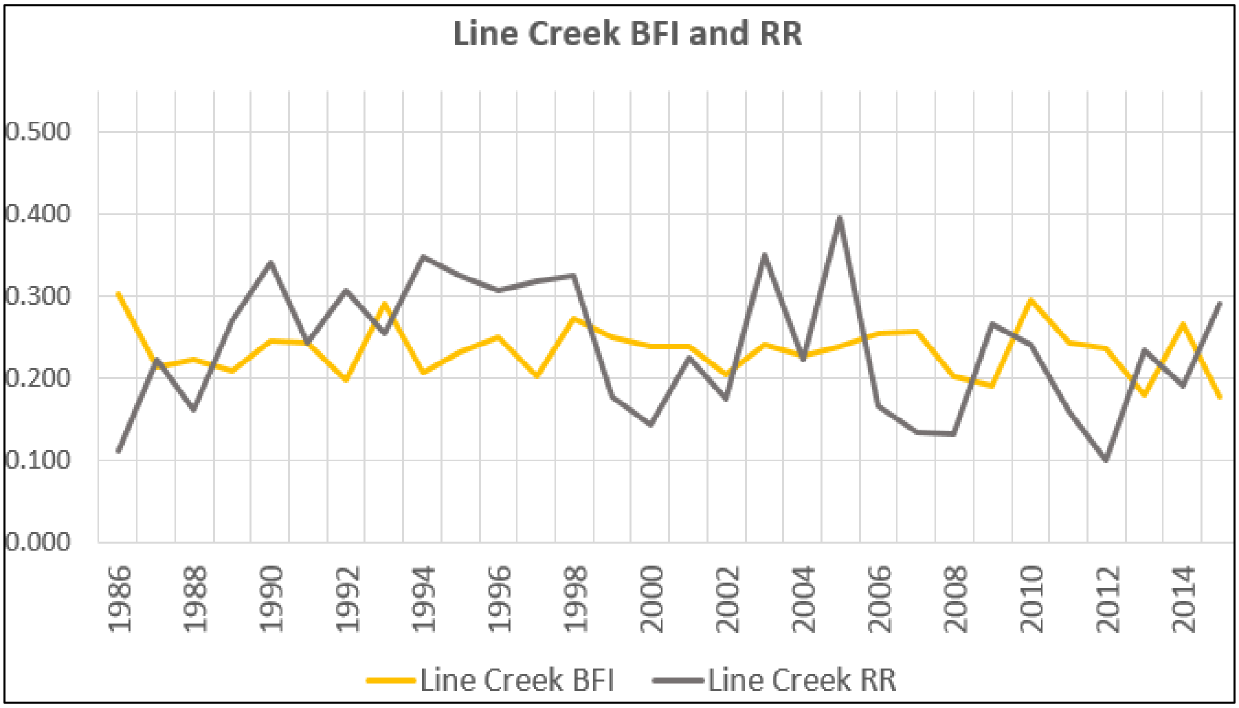

Figure 49 Line Creek BFI and RR

*3.3.6 Peachtree Creek **

In the Peachtree Creek watershed, streamflow and runoff were moderately correlated with precipitation, and baseflow was slightly correlated (Figure 50). Extreme flows were flat and non-significant (Figure 51). Baseflow index trends were non-significant, but runoff ratios were significantly negative (Figure 52). Trends in the precipitation-adjusted streamflow, runoff, and baseflow variables (residuals) were significantly negative for Peachtree Creek (Figure 53). Streamflow residuals from regression trended negative (α=0.05) with the Kendall's tau coefficient being -0.274; this was the most negative.

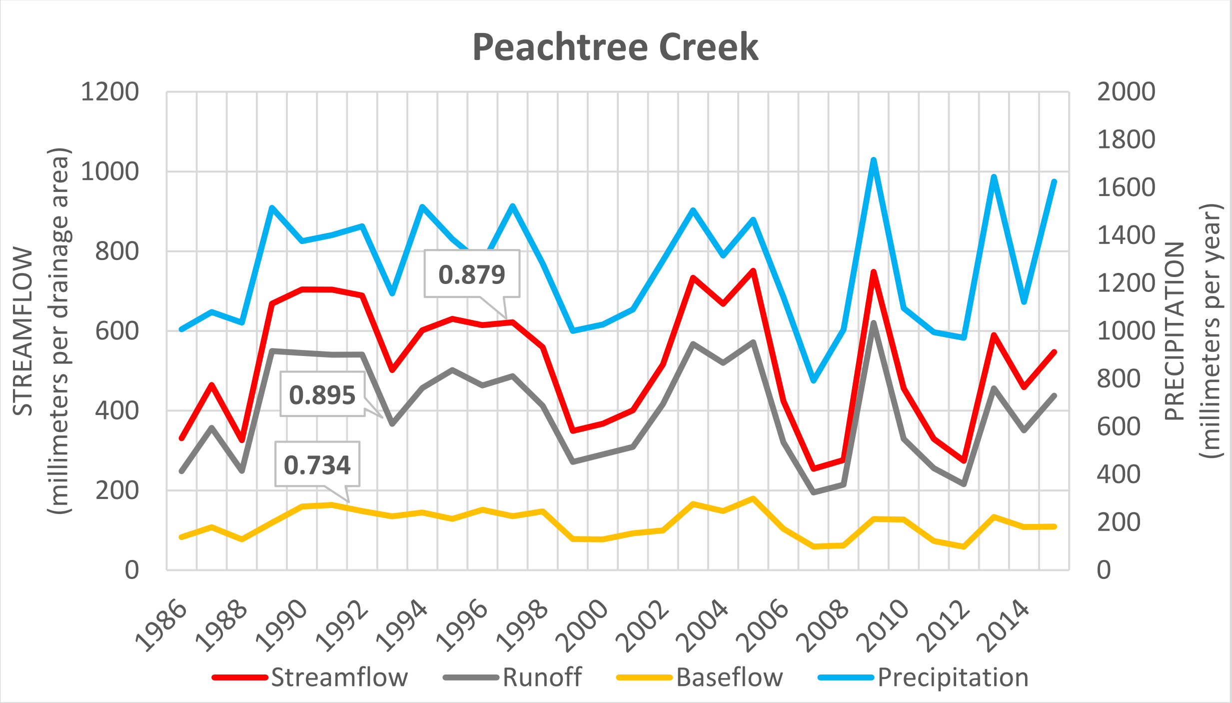

Figure 50 Peachtree Creek streamflow variables and regression R values

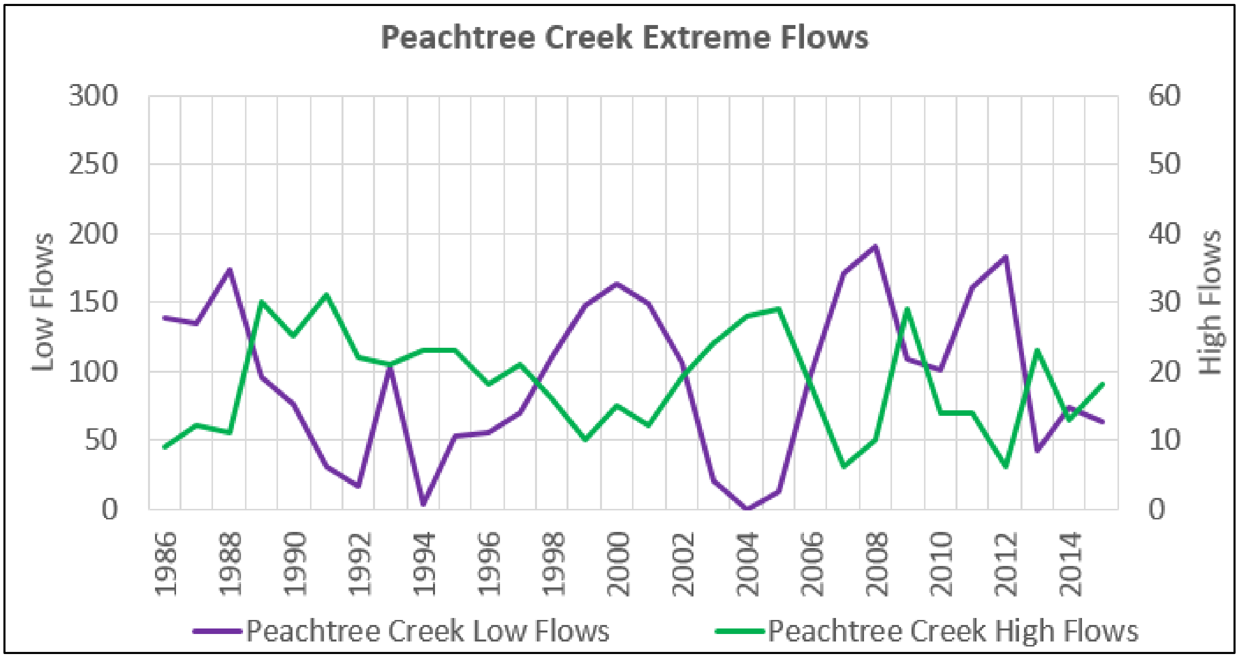

Figure 51 Peachtree Creek extreme flows

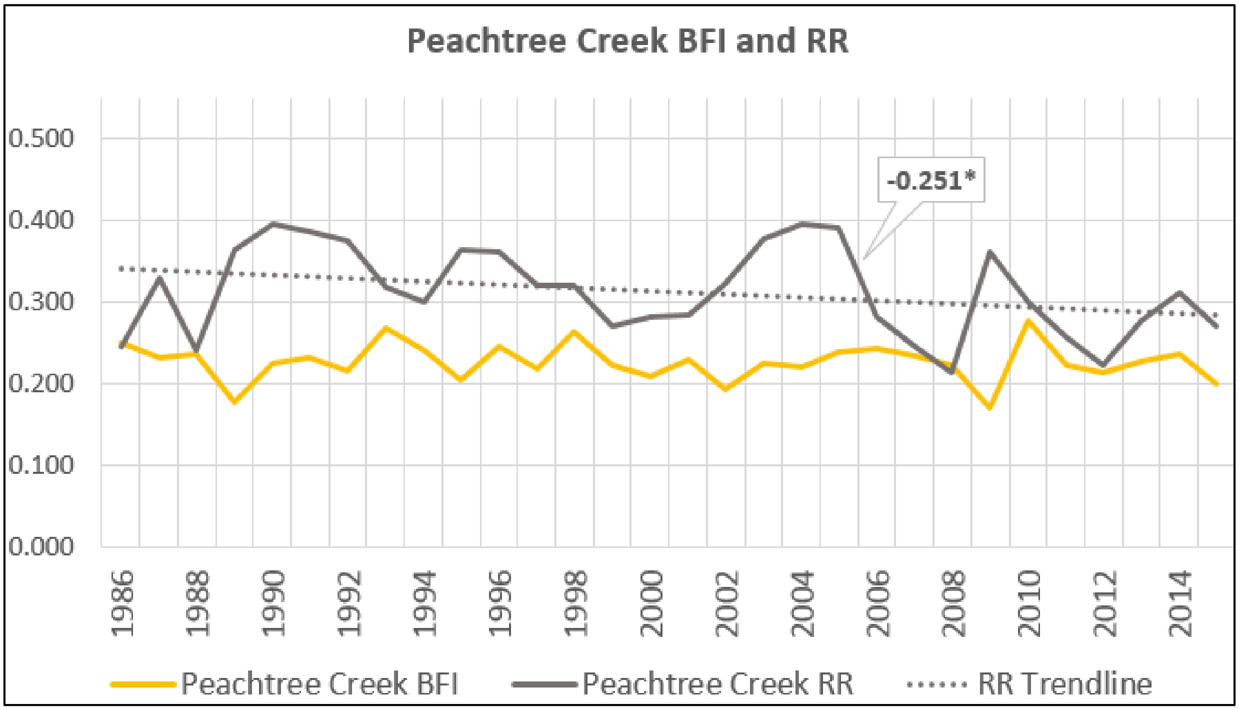

Figure 52 Peachtree Creek BFI and RR

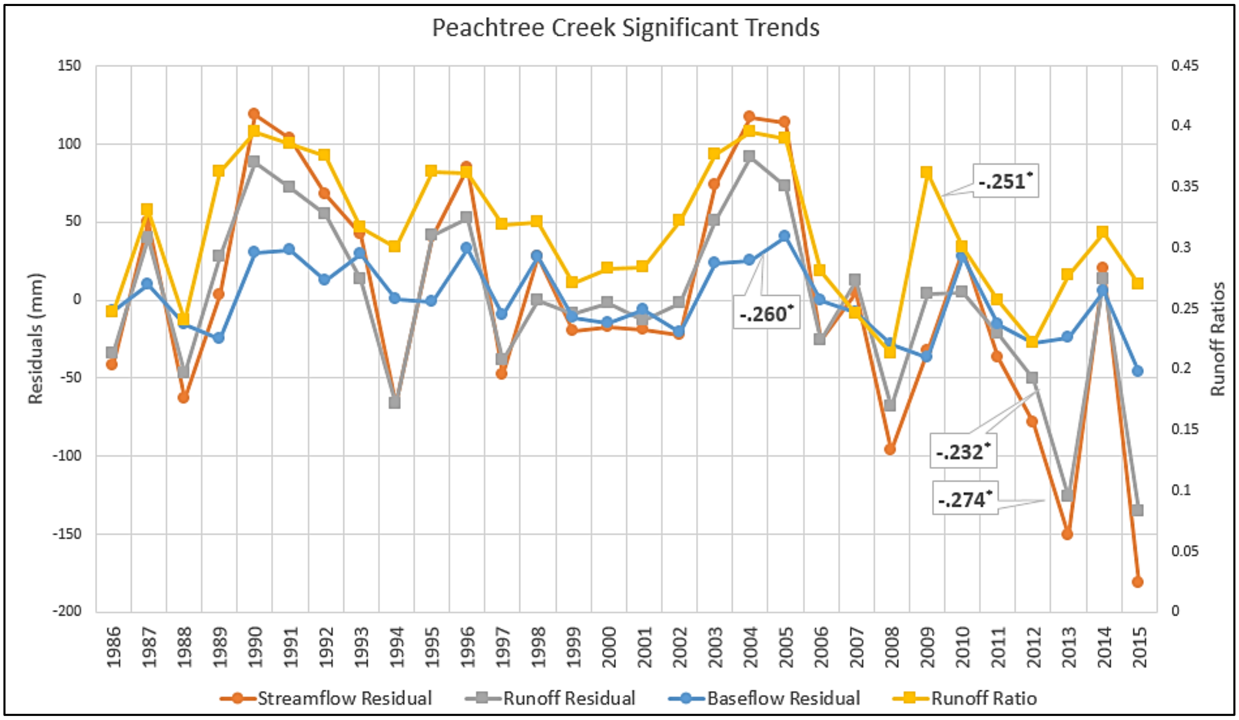

Figure 53 Peachtree Creek significant trends

3.3.7 Sope Creek

In the Sope Creek watershed, streamflow and runoff were moderately correlated with precipitation, and baseflow was slightly correlated (Figure 54). Extreme flows were flat and non-significant, but a positive low flows trend were almost statistically significant (Figure 55). Baseflow index and runoff ratio trends in Sope Creek watershed were flat and non-significant, but the runoff ratio in 2004 was very much higher than normal at more than 0.500 (Figure 56).

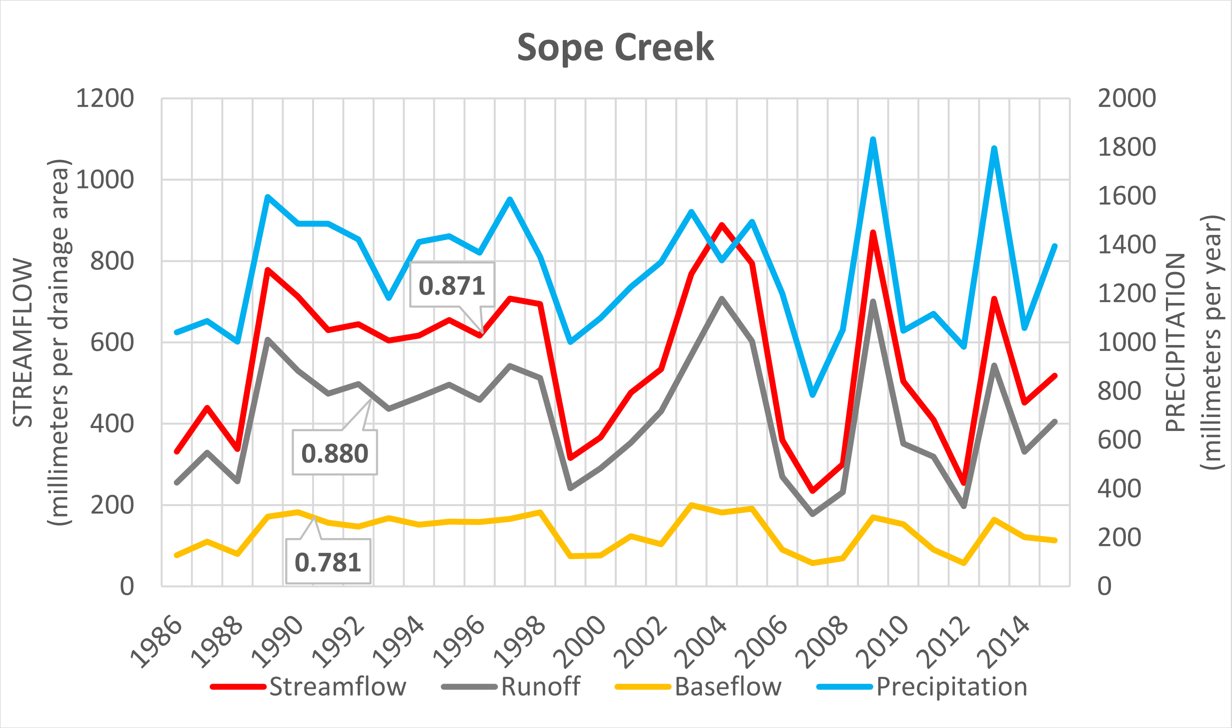

Figure 54 Sope Creek streamflow variables and regression R values

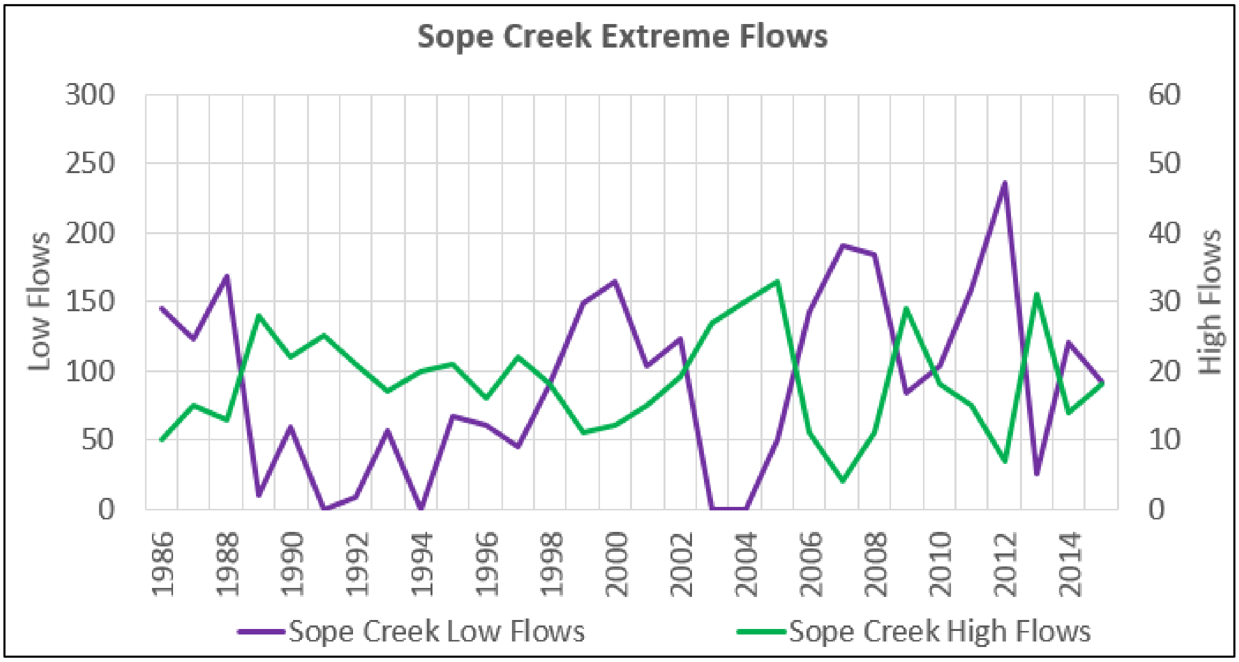

Figure 55 Sope Creek extreme flows

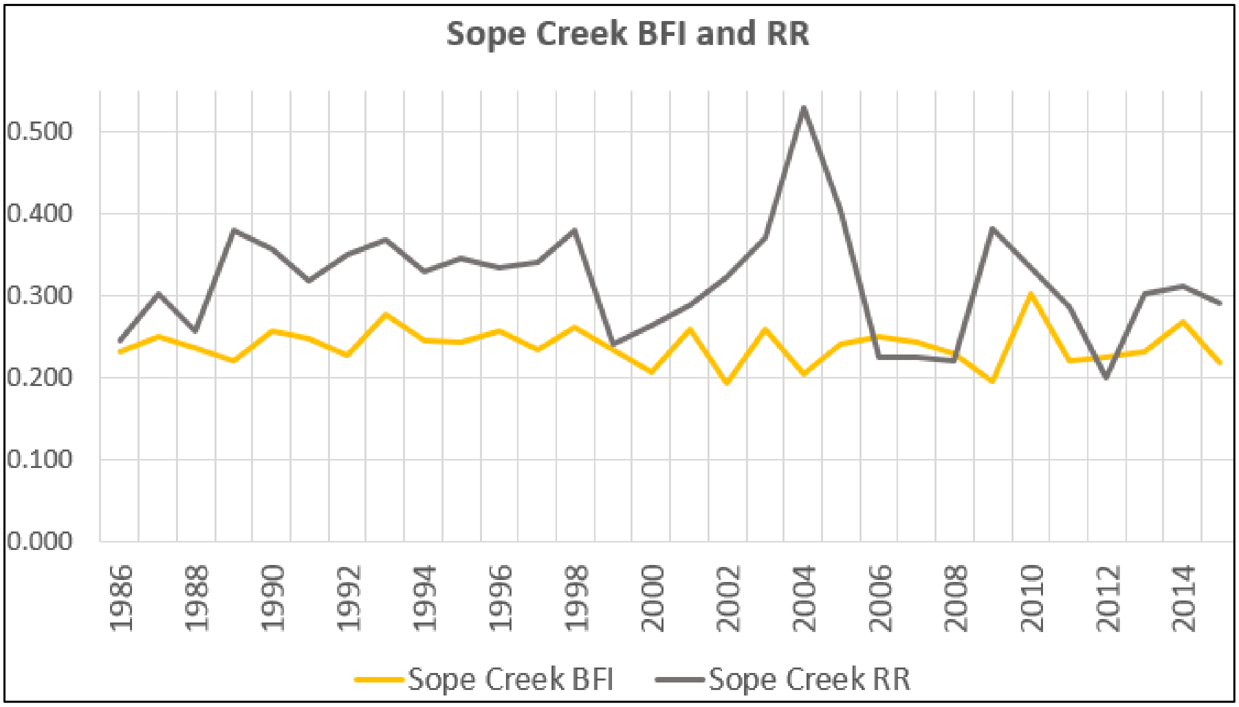

Figure 56 Sope Creek BFI and RR

3.3.8 South River

In the South River watershed, streamflow and runoff were moderately correlated with precipitation, and baseflow was slightly correlated (Figure 57).   Extreme flow trends were flat and non-significant, but the positive low flows trend was almost statistically significant (Figure 58). Baseflow index and runoff ratio trends were flat and non-significant (Figure 59).

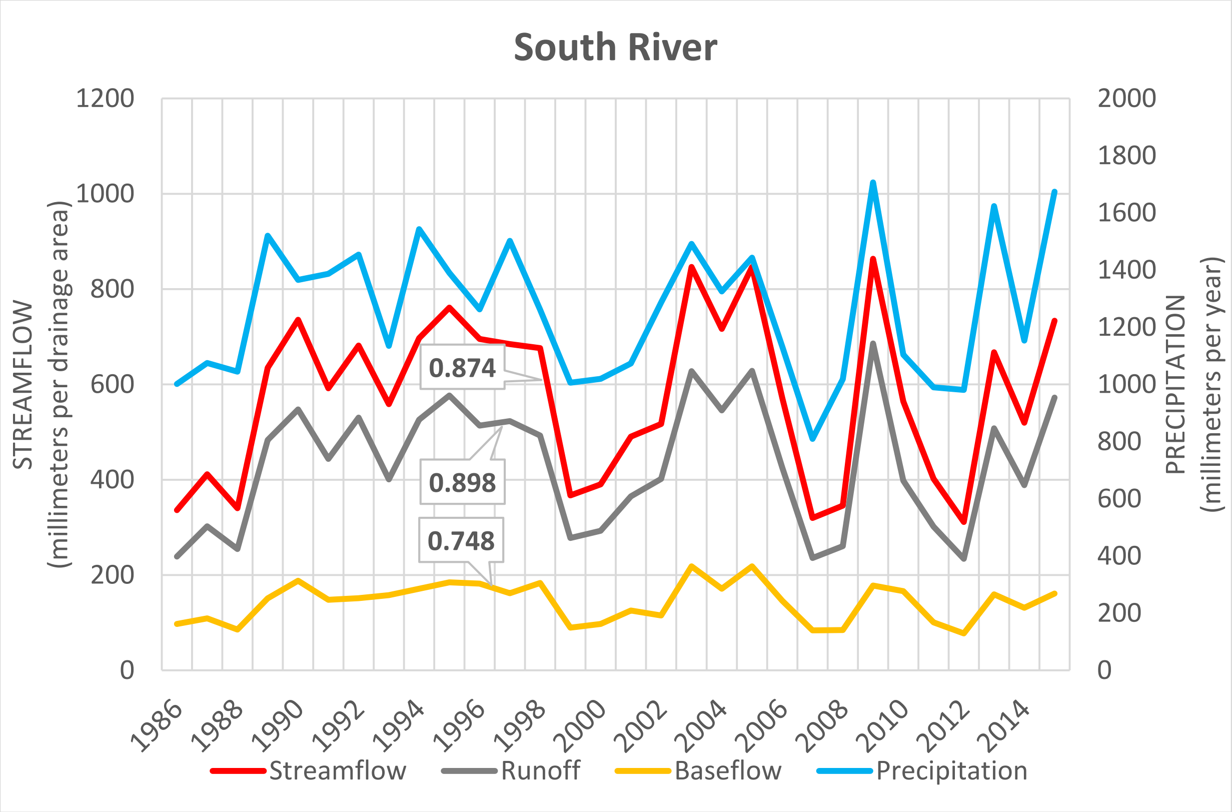

Figure 57 South River streamflow variables and regression R values

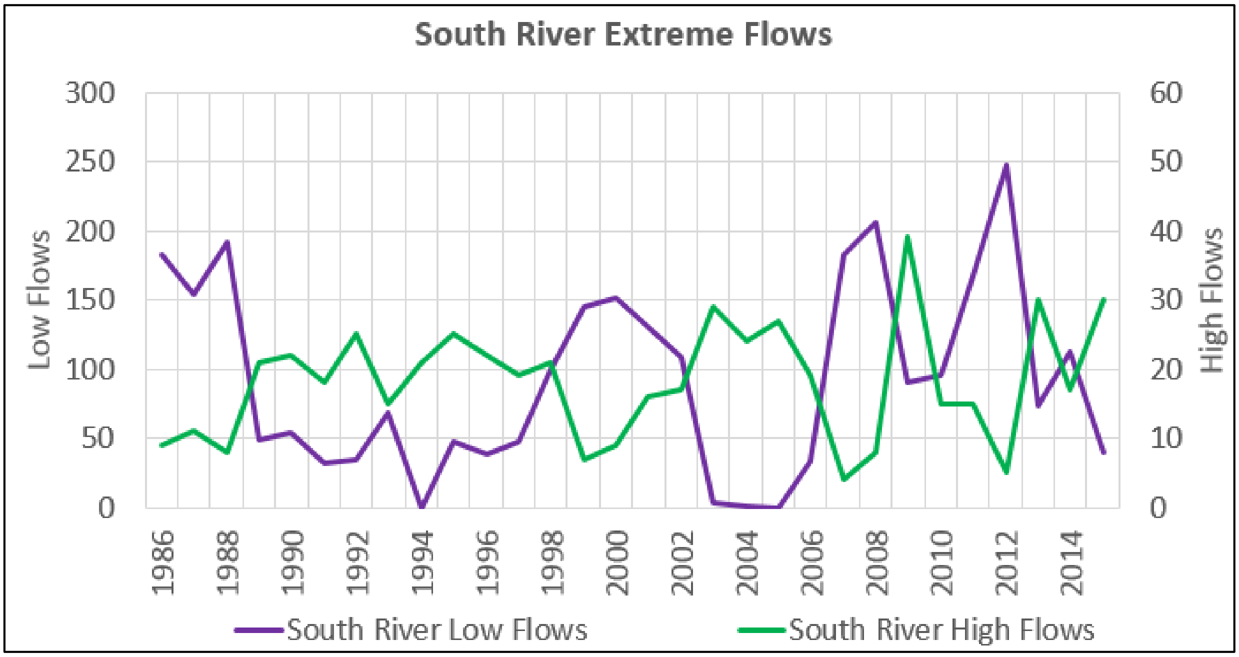

Figure 58 South River extreme flows

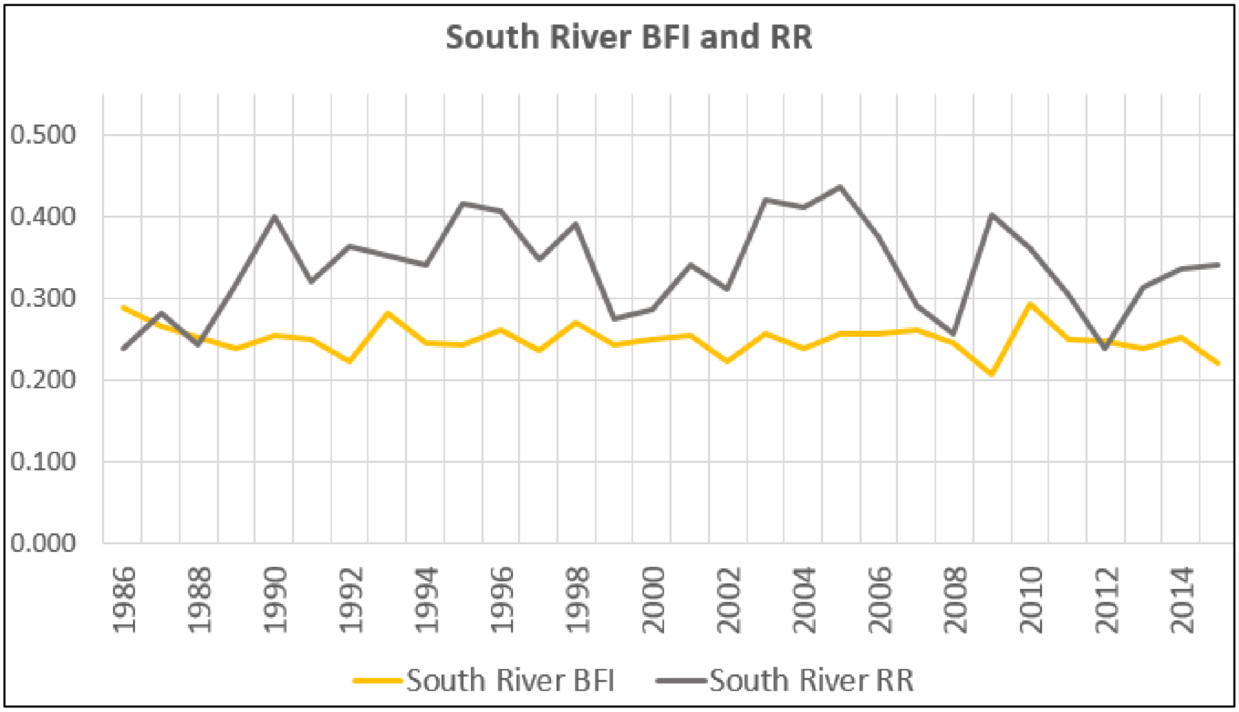

Figure 59 South River BFI and RR

*3.3.9 Suwanee Creek **

For the Suwanee Creek watershed, streamflow and runoff were moderately correlated with precipitation, but baseflow was hardly correlated with precipitation (Figure 60). High flow trends were significantly positive, but low flow trends were flat and non-significant (Figure 61). Suwanee Creek's runoff ratios trend was significantly positive, but the baseflow index trend was flat and non-significant (Figure 62). Trends in the precipitation-adjusted (residuals) streamflow, runoff residuals, runoff ratios, and high (>95th percentile) flows were all significantly positive (Figure 63). Streamflow and runoff residuals from regression trended positive.

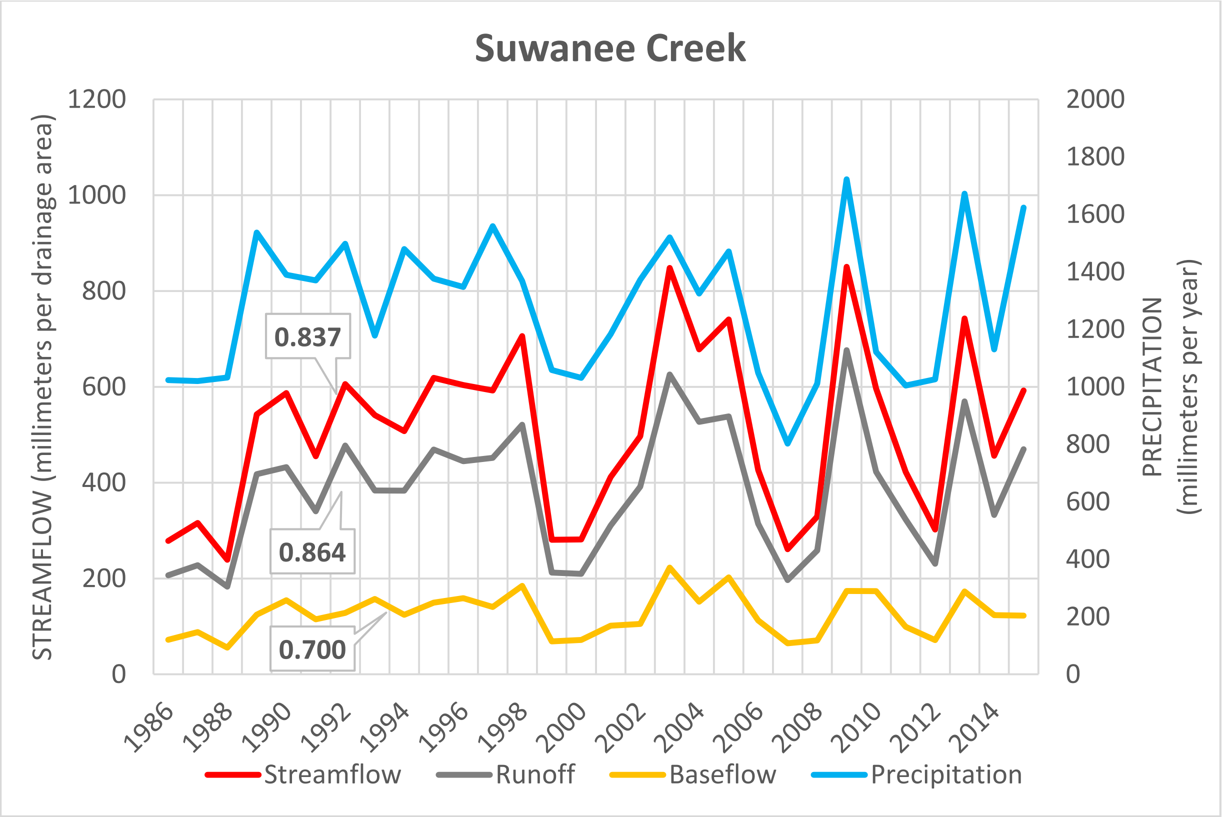

Figure 60 Suwanee Creek streamflow variables and regression R values

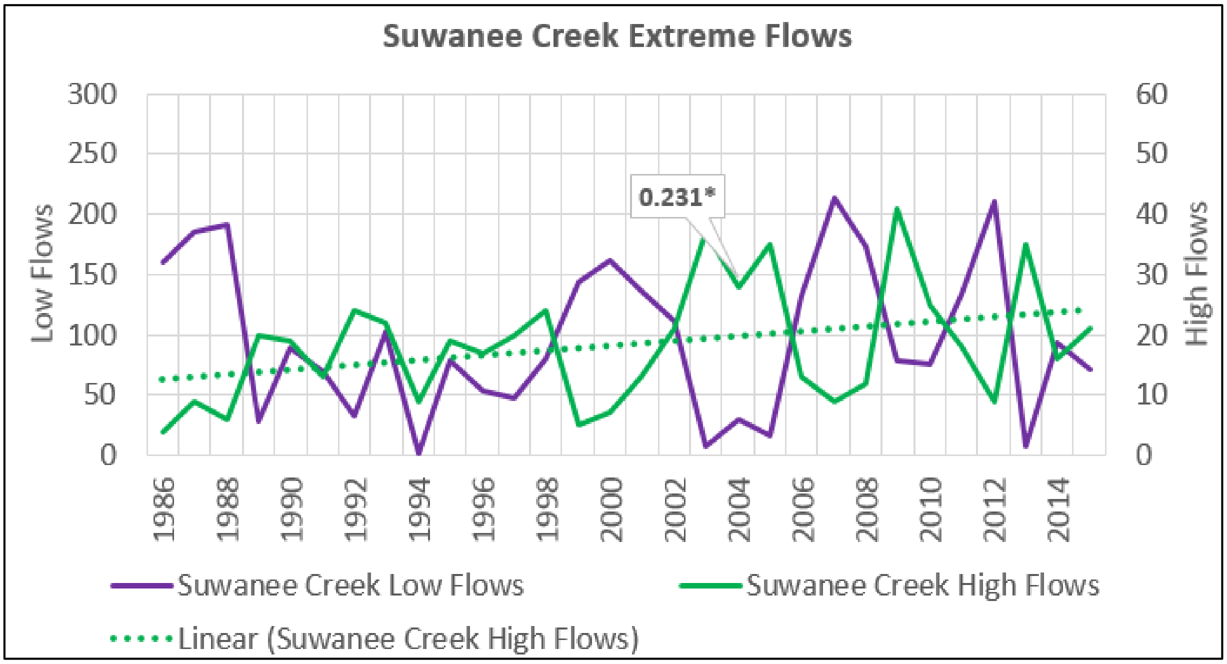

Figure 61 Suwanee Creek extreme flows

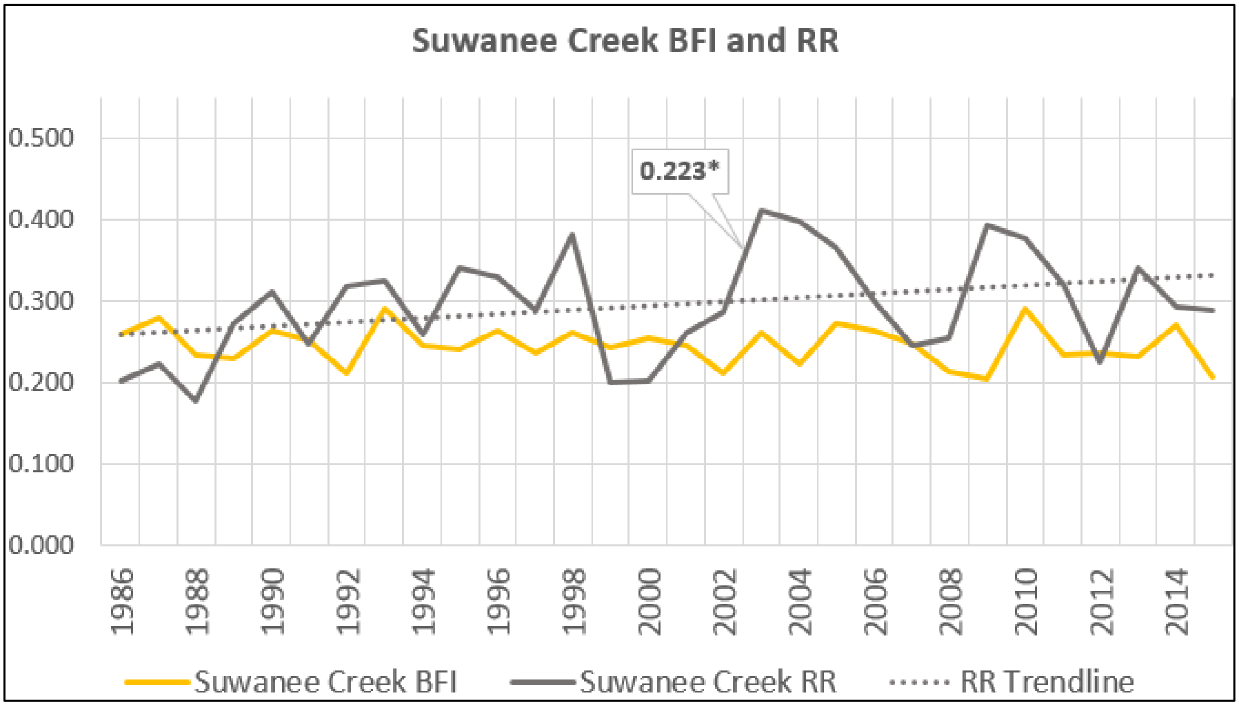

Figure 62 Suwanee Creek BFI and RR

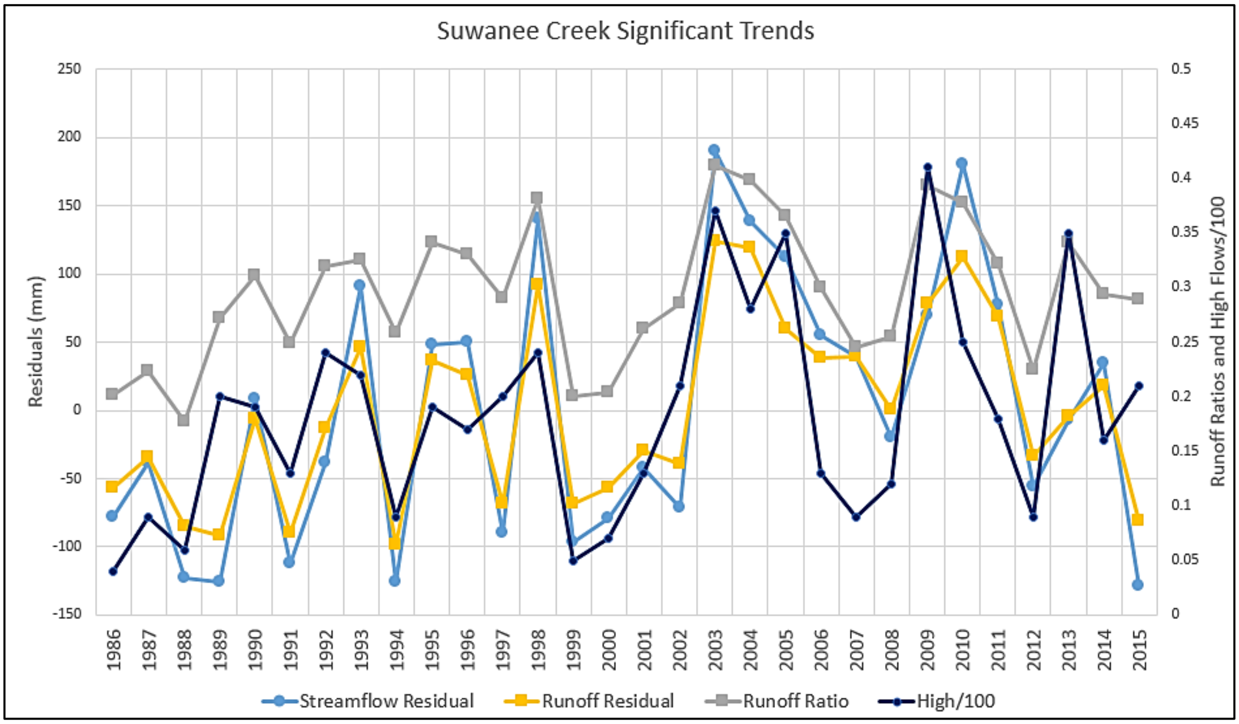

Figure 63 Suwanee Creek significant trends

3.3.10 Sweetwater Creek

In the Sweetwater Creek watershed, streamflow was moderately correlated, runoff highly correlated, and baseflow slightly correlated with precipitation (Figure 64). High and low flows trends were non-significant (Figure 65). Baseflow index and runoff ratio trends were flat and non-significant (Figure 66).

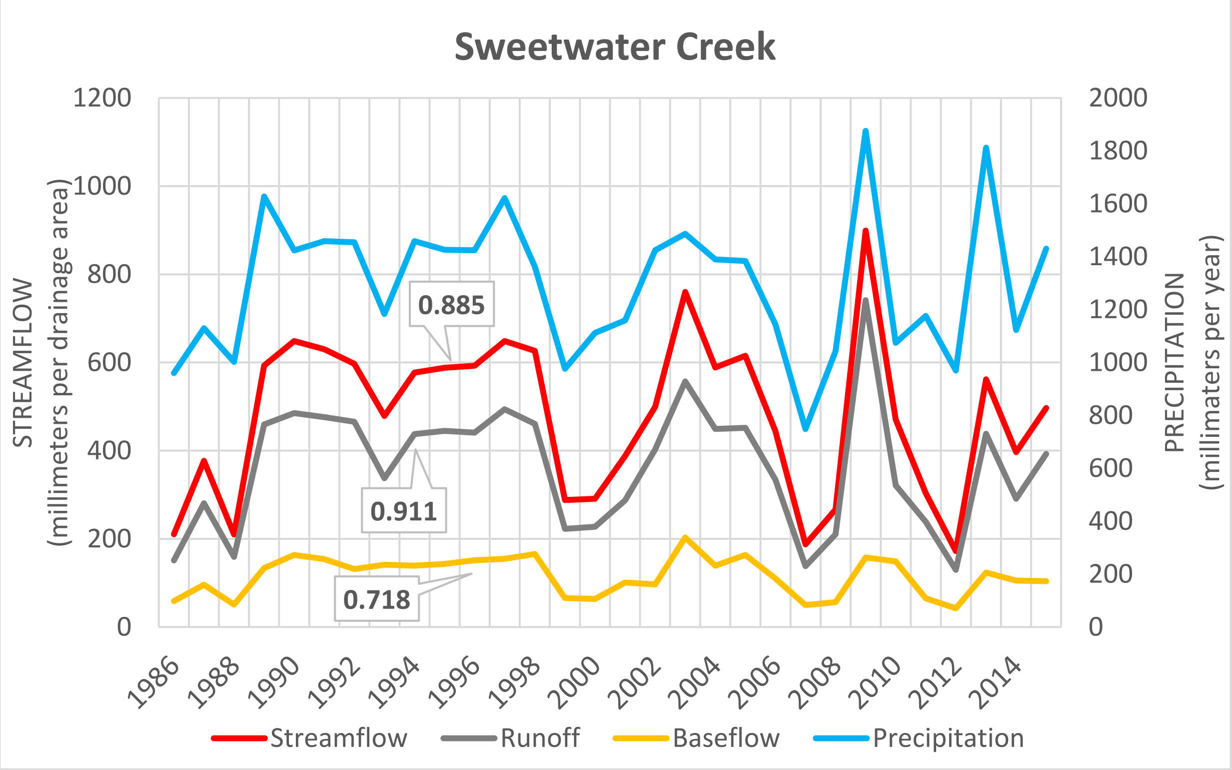

Figure 64 Sweetwater Creek streamflow variables and regression R values

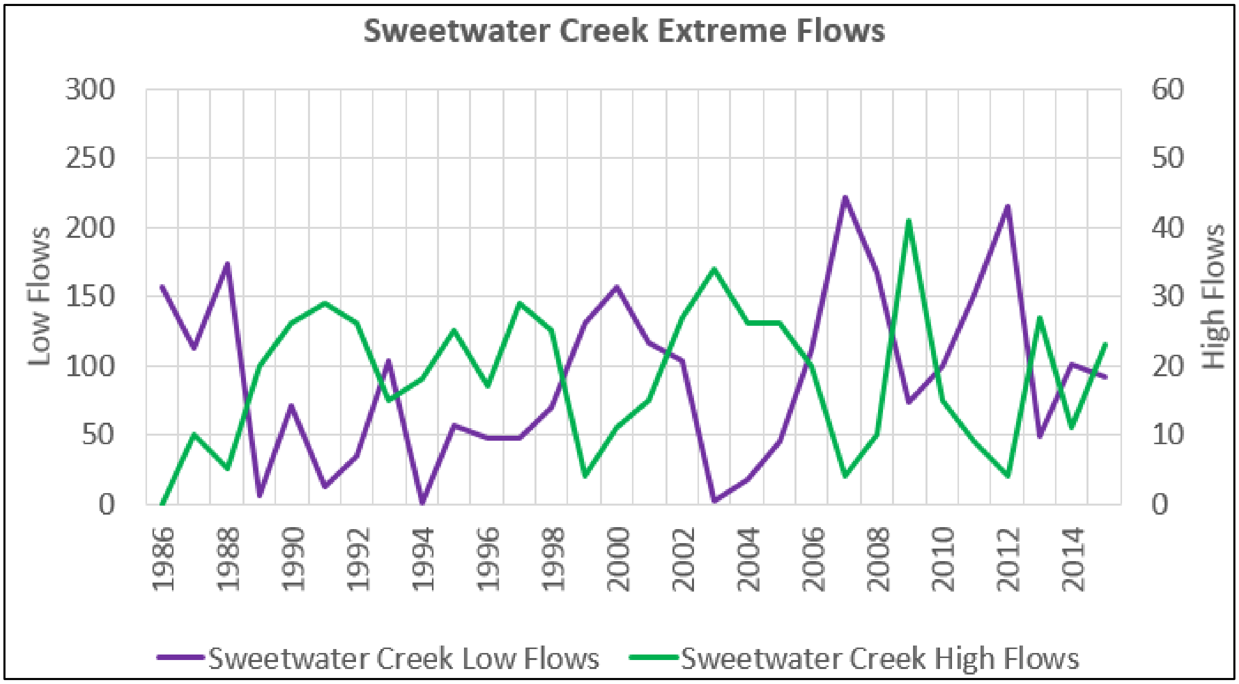

Figure 65 Sweetwater Creek extreme flows

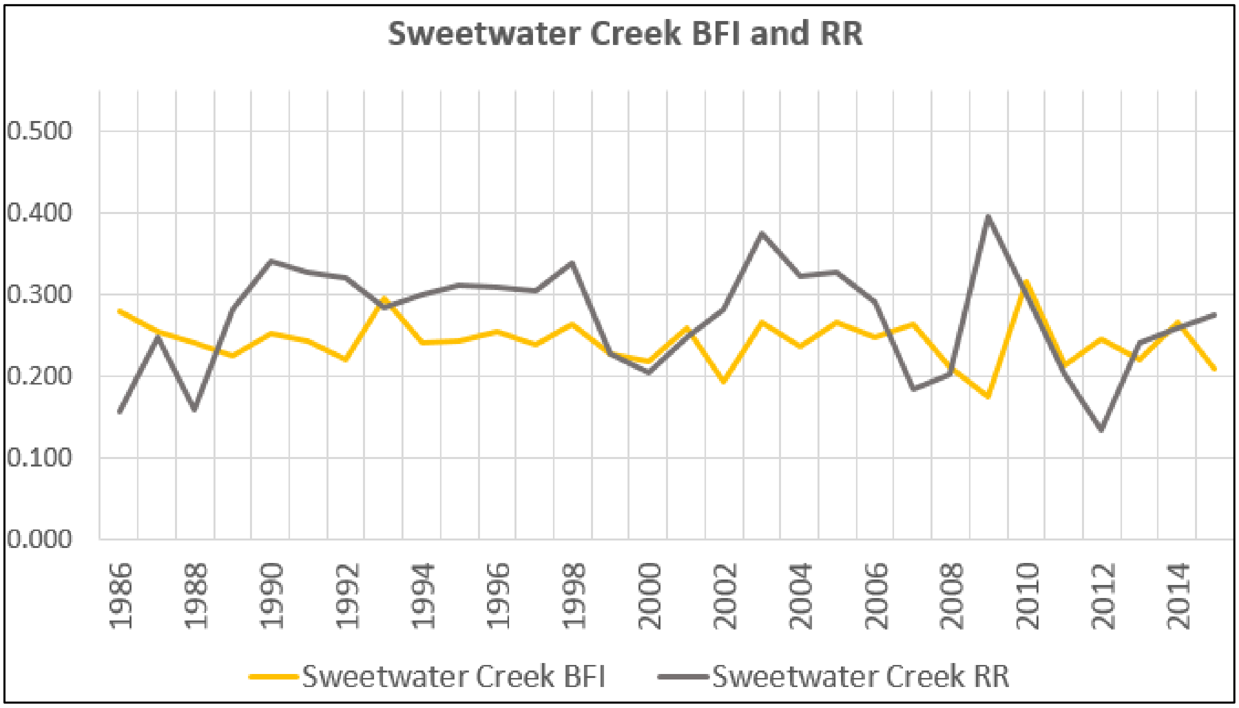

Figure 66 Sweetwater Creek BFI and RR

4 DISCUSSION

4.1 Increasing Flow in Big Creek and Suwanee Creek

The effects of urbanization in the Big Creek and Suwanee Creek watersheds caused significant increases to streamflow. Both streams had increases in streamflow over 30 years, and this supports one of the original findings about how urbanization via ICs can increase streamflow (Leopold, 1968; Paul & Meyer, 2001). It is not just ICs however; increases and peak flows are also due to the inadvertent connectedness of ICs and/or first-generation stormwater control devices especially if the engineered drainage is only mitigating volume of stormwater before reaching the stream (Fletcher, Andrieu, & Hamel, 2013; Meierdiercks et al., 2010). Both Big Creek and Suwanee Creek watersheds are considered peri-urban and were not built-up because they were rapidly urbanized (increased about 30%), and this is a condition that has been shown to be the most vulnerable to increased discharge (Derek B. Booth et al., 2016; Miller et al., 2014) At the very beginning of development before ICs or drainage networks are even installed, deforestation takes place and immediately reduces evapotranspiration (Giraldo, Jackson, & Van-Horne, 2015). This thereby increases streamflow in Big Creek and Suwanee Creek by 40%, and this supports that which has been observed locally (Schoonover et al., 2006). Other local observations in north metro-Atlanta have experience significant deforestation thereby affecting local water resources (Isik et al., 2013).

There was also an increase in high-flow days resulting from urbanization. Both Big Creek and Suwanee Creek experienced a strong positive trend in peak flows and a doubling of days when the main daily discharge exceeded the 95th percentile discharge over the entire 30 years. There multiple features in an urbanizing and an already urbanized watershed that can cause higher flows. In an urbanizing watershed like Big Creek and Suwanee Creek, where there are still significant parcels of agriculture and forest land, where data shows that then adding a large-scale storm drainage system can reduce the flood duration, but the frequency of flooding increases drastically (Miller et al., 2014). Since we did not capture duration of high flows, that is something left to be detected. High flows can also be indicative of combined sewer overflows since the watershed only experiences higher flows above 50% of the mean discharge (Braud et al., 2013). Urbanization impacts the beneficial functions of floodplains to a high degree, (Elosegi & Sabater, 2013; Franklin, Kupfer, Pezeshki, Gentry, & Smith, 2009) and those functions are the interconnected ecosystem services that a floodplain provides. According to FEMA, there have been multiple flooding events in the Big Creek watershed, and a new project to help decrease the flood heights of Big Creek.

4.2 Decreasing Flow in Peachtree Creek and Flint River

Peachtree Creek experienced a significant decrease of streamflow with an abrupt drop around 2006. Peachtree Creek's streamflow and runoff values were decreasing, but its high flows were not statistically significant. There was a major discontinuity in the residuals time series in 2006 (Figure 78).

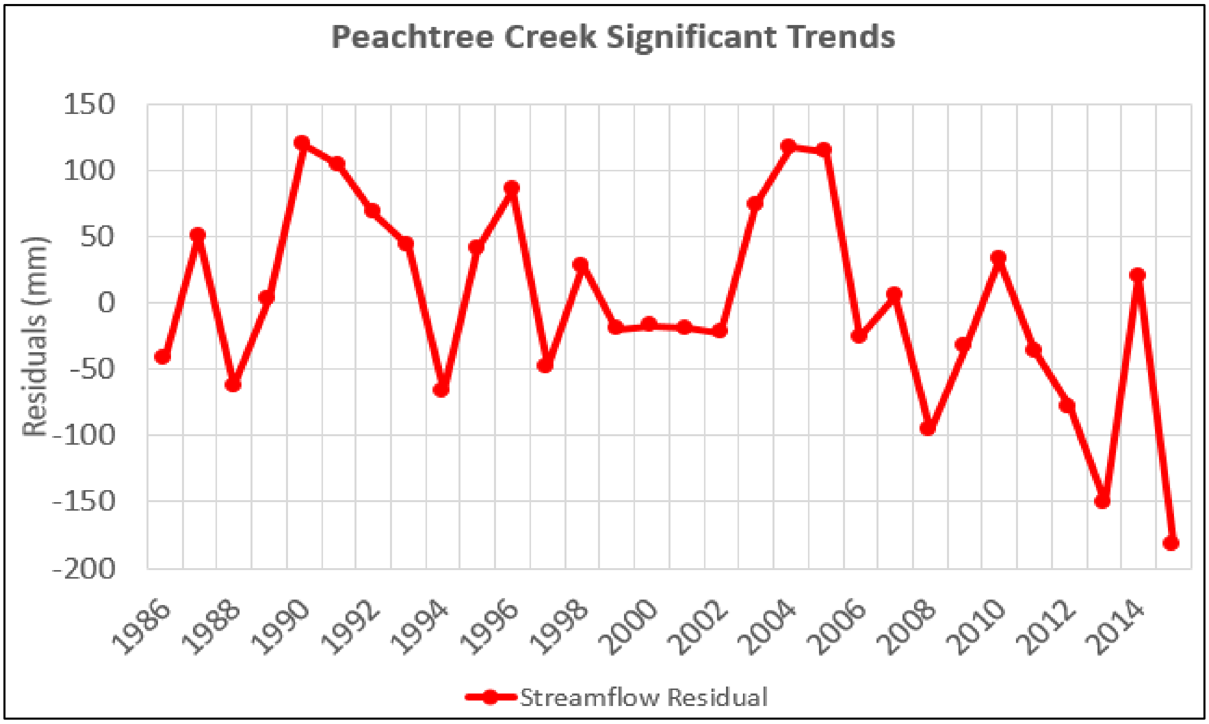

Figure 67 Abrupt change in Peachtree Creek streamflow

The decrease in streamflow for Peachtree Creek was speculatively due to a significant increase in water withdrawal that began in or around 2006. Since the precipitation signal was removed from streamflow by regression analysis, it is speculated that water was abruptly consumed or exported from the watershed. This could have been a change in the actual USGS gage. Combined sewer overflows are also suspected since high-intensity urban cities often have combined wastewater and storm sewer systems that, during heavy rainfall, CSOs occur along the sewer pipeline for extremely high flows, but during normal and dry weather all wastewater is sent treatment facilities (Braud et al., 2013). Additionally, subsurface wastewater pipelines are well-known to experience infiltration and inflow (I/I), and Peachtree Creek could be affected by older and weathered pipelines that need constant maintenance (Baur & Herz, 2002). The land cover in Peachtree Creek watershed was already 80% urban in 1992, so development and infrastructure are aging as well as becoming more complex underground.

Flint River also experienced a significant decrease of streamflow in a stair-stepped pattern. It appears that water in the Flint River is decreasing or exported every year. There must be something gradually affecting the lower portion of the watershed.

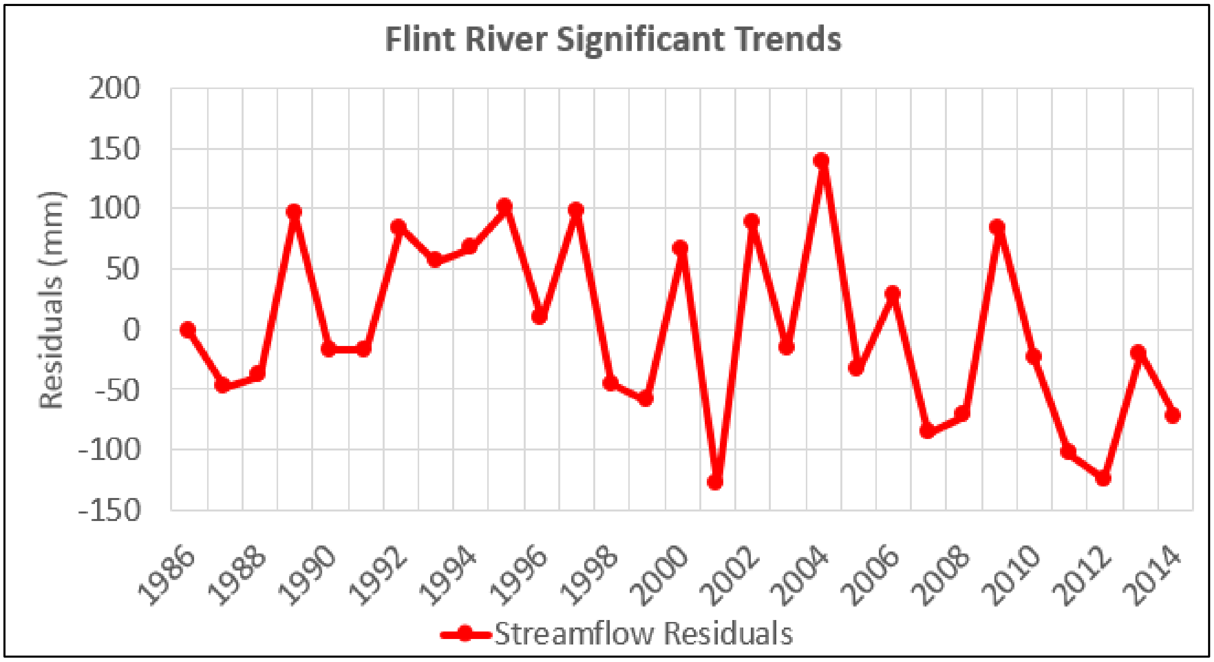

Figure 68 Gradual decreasing of water in the Flint River

Two major dams were constructed in the watershed based on land cover data showing the addition of upland open water reservoirs. Small watershed stormwater ponds do have some benefit in reducing flood frequencies (Wright, Smith, Villarini, & Baeck, 2012). However, during heavy rainfall, ponds fill and can act as ICs in hydrological models which would explain why high flows in the Flint River did not significantly decrease (Ignatius & Jones, 2014).

4.3 The Anomalous South River

Water transfers to the South River watershed may be the cause of the relatively large runoff ratio and baseflow for the river. The runoff ratio for South River has been the highest among neighboring watersheds even though its average slope is among the lowest. Etowah River has an average slope of around 14%; therefore, it has the highest runoff values which makes the runoff ratio among the highest. The South River receives about 36 million gallons of treated wastewater per day at an upstream in-city treatment facility, and it is among the highest in the vicinity even though all major river basins start around the northern metro Atlanta area (“NPDES Permitted Facilities,” 2016). This could only mean that it is receiving a significant amount of wastewater from other river basins, which are within approximately 3-5 miles from each other in the Atlanta area.

5 CONCLUSIONS

Forest land-cover on Earth is decreasing at a significant rate, and urban land has been expanding since 2000 and probably will expand much more considering population growth. As forest land cover is replaced by urban land cover, streams are being extensively impacted by a variety of impacts recognized throughout the world as urbanization as well as the actual deforestation. Metropolitan Atlanta / North Georgia’s forest land cover loss and urbanization has not yet been analyzed over a 30-year period with land-cover data spanning multiple decades and streamflow data for 30 years.

The research question was to study how streamflow changes in watersheds with varying degrees of urbanization. The primary methods were to obtain a full data set of precipitation in the region from 1986-2015, use that to adjust streamflow data and variables, and then statistically test for trends throughout the entire 30-year period. Land cover change analysis provided insight so that drastic changes in the streamflow could be validated with land cover changes in the watersheds.

Key results were found for four watersheds. Big Creek and Suwanee Creek experienced massive land cover change from forest to urban while at the same time, significant trends in streamflow showed an increase in a few variables, notably a doubling of high (>95th percentile of streamflow) flow days. Flint River and Peachtree Creek did not experience massive land cover changes, but instead their watersheds were impacted by features of the urban landscape: maintenance of a sewer system and the addition of two large lakes, respectively. Both Flint River and Peachtree Creek saw a significant decrease in streamflow as a result.

This study did not address several things that could be interesting future work. Duration of high and low flows for example would help in finding a better frequency of such flows since this only reported days. Finding support for decreased flood recession time with urbanization or to hypothesize why Peachtree Creek has perhaps seen an increase in flood recession time would be something for future studies as well (Miller et al., 2014; Rose & Peters, 2001). This may be of some interest since the Chattahoochee River flows through Atlanta, but it is regulated by the US Army Corps of Engineers upstream and purportedly for flood control. Actually a study finding flood recession time for all major creeks that enter the Chattahoochee River would be beneficial for the current body of research work. Measuring temperature and baseflow would only be of interest if baseflows were a major part of an urbanization study. Studying the impact of urbanization on regional streams is going to be a continued effort anyhow considering the impact seen in this study.

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