HYDROLOGICAL DROUGHT ANALYSIS FOR SEVEN NORTH GEORGIA WATERSHEDS (1970-2000)

Jessica L. Taylor
COLUMBUS STATE UNIVERSITY

HYDROLOGICAL DROUGHT ANALYSIS FOR SEVEN NORTH GEORGIA WATERSHEDS (1970-2000)

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BY
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January 2016
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A thesis submitted to the College of Letters and Sciences in partial fulfillment of the requirements for the degree of

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2016

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Abstract

Drought is a prolonged reduction in precipitation which may result in significant effects on local ecosystems, watersheds, and water sources, with the potential to have negative impacts on human populations. Normalized indexes can be used to characterize drought magnitudes and frequencies using historical data records on temperature, rainfall, snowpack, soil moisture, streamflow, and/or other water supply indicators. This study examined the applicability of two drought indices: Standardized Precipitation Index (SPI) and Streamflow Drought Index (SDI). The SPI and SDI estimate the magnitude of observed rainfall (SPI) and discharge (SDI) deviations from the long-term average.

In this study, SPI and SDI were used to determine droughts from 1970-2000 in 7 North Georgia catchments. Because other studies have shown the importance of time on index performance, SPI and SDI were calculated on data aggregated for 1, 3, 6, 9, 12, and 24 month intervals. The performance of the indices was evaluated using the strength of the relationship between SPI and observed discharge and between SPI and SDI using linear regression. The goodness of fit was measured by a statistic referred to as the coefficient of determination ($r^2$). The $r^2$ is the amount of variation in the dependent variable explained by the variation in the independent variable. Two-way Analysis of Variance (ANOVA) models were conducted to determine how watershed and temporal scale (independent variables) influenced the SPI-discharge and the SPI-SDI regression relationships. The dependent variable in these models was the coefficients of determination estimated using the linear regressions.

Hydrological drought severity was analyzed on an annual basis and revealed the following trends for SPI and SDI: 1) The timing of severe drought events varied slightly across watersheds; 2) the most extreme drought events occurred in 1978, 1981, 1986-1988, and 1999-2000; and 3) 1986-1988 events were similar in severity to the 1999-2000 drought events. Watersheds varied temporally in their hydrologic response to drought, which may be a function of localized recharge or anthropogenic factors. Based on $r^2$'s analysis, discharge and SPI had a more robust relationship with longer time steps (9 - 24 months); SPI and SDI relationships revealed an analogous pattern. Regions deficient in discharge data can use SPI as a viable alternative to SDI; whereas, SDI can
function as a proxy for SPI in catchments lacking precipitation data at timescales exceeding six months.

Keywords: Drought, Standardized Precipitation Index (SPI), Streamflow Drought Index (SDI), discharge, streamflow, Georgia
To my penguin...
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To Dr. Keller, Dr. Barineau, and Mr. Westbury, thanks for serving on my thesis committee. Without your assistance, I would have never been able to finish this endeavor. Dr. Keller was instrumental in conducting my statistical analysis.

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To my family and friends, I am grateful for all of the understanding and support.
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Introduction

One of the most subtle, yet devastating weather catastrophes is drought. Drought is the reduction in rainfall relative to normal conditions (Tannehill, 1947). Because drought intensity, duration, and frequency are stochastic in nature, there exists little consensus on a standard definition for what constitutes drought conditions (Tannehill, 1947; Wilhite and Glantz, 1985; Quiring et al., 2007). However, scholars concur on four common indicators of drought conditions: meteorological (e.g., reduction in average precipitation), agricultural (e.g., reduced soil moisture resulting in crop damage), socio-economic (e.g., shortages of drinking water), and hydrological (e.g., declining reservoir or river levels) (Byun and Wilhite, 1999; Wilhite and Buchanan-Smith, 2005; Nalbantis and Tsakiris, 2009). Drought, regardless of how it is assessed, can have profound effects on social, economic, and ecological systems (Dahm et al., 2003; Bernard et al., 2003).

The United States (US), despite its well-developed infrastructure for accessing and distributing water, has experienced severe droughts. In 1998, drought-related wild fires in Florida burned over 1920 square kilometers resulting in more than $500 million in damages. That same year Canada had the highest fire occurrence season in a quarter century, and Mexico suffered the worst drought in seventy years resulting disaster zone declarations (NOAA, 2013). Droughts during 1998-2002 and 2006-2009 in the Southeastern US caused severe crop damage, disrupted hydro-electric power generation, and resulted in water shortages. These events resulted in seven to ten billion dollars in drought damages during 1998 alone (Quiring et al., 2007; Pederson et al., 2012). Repeated water shortages in the headwaters of the Alabama-Coosa-Tallapoosa (ACT) and Apalachicola-Chattahoochee-Flint (ACF) river basins have placed Georgia in the middle of a tri-state water conflict (Chapman and Peck, 1997). This legal conflict over scarce water resources underscores the importance of having effective tools for identifying drought conditions so that coordinated and effective water resource management can be implemented to mitigate the socio-economic impacts of drought (Singh et al., 2015).

Because drought has such important socio-economic ramifications, there have been efforts to develop mathematical models, such as indices, for assessing drought (Wilhite et al., 2007). Generally these drought indices are designed to quantify intensity, duration, and/or spatial extent of precipitation deficits (Mishra and Singh, 2010). These indices have been used to assess drought
effects on lake levels, river discharge, and groundwater recharge (Vicente-Serrano et al., 2012b).

Normalized drought indices have been proposed to measure extreme weather events because they are inexpensive, can apply to various time scales, are relatively simple to calculate and understand, and require only one type of data (e.g., precipitation, Rimkus et al., 2013). These indices measure the magnitude and direction of the deviation from the norm of the long-term average (precipitation, discharge, or other water supply indicators). The Standardized Precipitation Index (SPI) was originally formulated to calculate meteorologic drought conditions using rainfall records (McKee et al., 1993); while, the Streamflow Drought Index (SDI) is a modified version of SPI that uses discharge data (Nalbantis, 2008). Because the SPI can be calculated across various time scales (e.g., 1 - 24 months), it has been used to assess drought effects on reservoir storage, stream flow, and irrigation (Giddings et al., 2005; Quiring et al., 2007).

These two indices differ in the types of droughts they assess most effectively. SPI is particularly valuable for identifying meteorological drought conditions, but does not factor in geologic characteristics of the study region (McKee et al., 1995). Mountainous topography can lead to seasonal drought variability through fluxes of rainfall and snowmelt (Vasiliades et al., 2011) and can, under certain circumstances, influence SPI-derived drought estimates. Conversely, SDI integrates more effectively the geologic characteristics that can confound studies of hydrological drought that use SPI, because SDI accounts for water table fluctuations that are controlled by rainfall, surface runoff, and subsurface flows. SDI has been broadly applied as illustrated by its use to delineate hydrological drought in the Athens, Greece Metropolitan Watershed (Nalbantis, 2008), Spanish Ebro River Basin (Vicente-Serrano et al., 2012), northwestern Iran (Tabari et al., 2013), and the European Neman River Basin (Rimkus et al., 2013). Given their practicality for use in real-world applications, it is surprising that so few studies (e.g., Nalbantis and Tsakiris, 2009 and Al-Faraj et al., 2014) directly compare the effectiveness of these two indices to delineate hydrological drought events. A comparison of SPI and SDI could be used to quantify regional historical hydrological drought formation, duration, and intensity or assess if these indices can act as proxies for basins lacking sufficient meteorological or hydrological data.

The purpose of this study was to evaluate the efficacy of the SPI and SDI for recording hydrologic drought. There were two specific goals of this research: 1) to determine how watershed (N=7) and temporal scale (1, 3, 6, 9, 12, and 24 month(s)) influence the relationship between
streamflows and SPI and 2) to assess how watershed and temporal scale affect the relationship between SPI and SDI. A comparison of SPI and SDI across seven North Georgia watersheds will provide a better understanding of the usefulness of both indices for quantifying hydrological drought.

Methods

Study Areas

The study area covers a 60,000 km$^2$ region that includes parts of Georgia, North Carolina, and South Carolina in the headwaters of the Alabama-Coosa-Tallapoosa (ACT) and Apalachicola-Chattahoochee-Flint (ACF) river basins (Fig. 1). These basins are critically important, because they are the source of drinking water for millions of people and the subject of ongoing disputes about water use allocations (Chapman and Peck, 1997). This region has abundant rainfall, with an annual average of 1000 to 2000 mm, typical of humid subtropical climatic regions (Konrad, 1997; Diem and Mote, 2005; Gotvald et al., 2009). The region is comprised of the Piedmont and Blue Ridge geologic provinces and is characterized by mountainous terrain underlain by igneous and metamorphic aquifers (Gotvald et al., 2009). To enhance the generality of this study, seven watersheds (Table 1) were selected because they showed similar geology (e.g. crystalline bedrock), watershed size (400–1000 km$^2$), and available hydrologic data (1970-2000) from the National Oceanic and Atmospheric Administration (NOAA) and US Geological Survey (USGS). Appendix A contains more detailed descriptions of each watershed.

Given limitations regarding the availability of long-term precipitation and discharge data, this study focused on watersheds having at least thirty years of discharge (USGS) and precipitation (NOAA - Global Historical Climatology Network – Daily or GHCND) data. Thirty years of data are recommended for SPI to calculate an accurate estimate of average climate conditions (McKee et al., 1993); however, 60 or more years would be necessary to account for the cyclical nature of droughts (Wu et al., 2005). Discharge and precipitation records from 1970 to 2000 were analyzed for this study because these data were readily available and records were relatively complete. The stations used as the source of the precipitation data were selected based on the following conditions: 1) located either within the stream’s watershed or 30 km buffer of the USGS station, 2) no data gap longer than three sequential months, and 3) a total of no more than 18 months of
missing data. Since SPI and SDI were assessed on monthly timescales, all daily rainfall and discharge were aggregated into cumulative monthly totals before analysis.

Figure 1. Study region depicting state boundaries, regional topography, seven study watersheds, USGS stream gauges (stars), and NOAA precipitation stations (open squares).
Table 1. Watershed name, site number, size, weather station name, and missing data for the seven watersheds used to calculate the SPI.

<table>
<thead>
<tr>
<th>Watershed Name</th>
<th>Site Number</th>
<th>Size (Sq Km)</th>
<th>Weather Station</th>
<th>Missing Data</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chattahoochee River</td>
<td>1</td>
<td>822</td>
<td>Cornelia</td>
<td>None</td>
</tr>
<tr>
<td>Chestatee River</td>
<td>2</td>
<td>393</td>
<td>Cleveland</td>
<td>None</td>
</tr>
<tr>
<td>Sweetwater Creek</td>
<td>3</td>
<td>616</td>
<td>Dallas</td>
<td>None</td>
</tr>
<tr>
<td>Coosawatte River</td>
<td>4</td>
<td>613</td>
<td>Ellijay</td>
<td>Weather: Nov 74, Dec 75, Aug 79, &amp; Feb 92</td>
</tr>
<tr>
<td>Chattooga River</td>
<td>5</td>
<td>537</td>
<td>Coweeta</td>
<td>Weather: Oct 00</td>
</tr>
<tr>
<td>Flint River</td>
<td>6</td>
<td>675</td>
<td>Atlanta Hartsfield</td>
<td>None</td>
</tr>
<tr>
<td>Middle Ocone River</td>
<td>7</td>
<td>1021</td>
<td>Gainesville</td>
<td>None</td>
</tr>
</tbody>
</table>

**SPI & SDI Analysis**

SPI calculates the difference between precipitation over a defined time period ($P_i$) and the period of record mean precipitation ($P_m$) scaled by the variation over the period of record (i.e. standard deviation $[SD_p]$) (McKee et al., 1995; Heim, 2002).

$$ \text{SPI} = \frac{P_i - P_m}{SD_p} $$

SPI is a dimensionless number where negative values indicate drought and positive values indicate wet periods (Bordi et al., 2001; Bonaccorso et al., 2003). This model assumes the underlying rainfall data are normally distributed (Panu and Sharma, 2002). Efforts should be made to use these models on complete data sets, because incomplete data sets may not represent a normal distribution (Mishra and Singh, 2010).

One of the goals for this study was to analyze USGS discharge records using a modified SPI analysis, referred here as the Streamflow Drought Index (SDI, developed by Nalbantis and Tsakiris, 2009). More recently, SDI has also been called the “Standardized Streamflow Index” or SSI (Vicente-Serrano et al., 2012a; 2012b; Tsakiris, et al., 2013). SDI could serve as an alternate
drought indicator because discharge data are readily available and contain more complete records than many of NOAA precipitation data. SDI was calculated as

$$SDI = \frac{Q_i - Q_m}{SD_Q}$$

where $Q_i$ is the discharge over a defined time period, $Q_m$ is the period of record mean discharge, and $SD_Q$ is the discharge’s standard deviation over the period of record.

SPI and SDI data were calculated using SPI gamma distribution software (http://drought.unl.edu/MonitoringTools/DownloadableSPIProgram.aspx) available through the National Drought Mitigation Center (NDMC). To investigate how time scale influences model behavior, both SPI and SDI drought indices were calculated on 1, 3, 6, 9, 12 and 24 month timescales. Missing data were converted to zero as suggested by the NDMC programming instructions (2016) since less than two percent of data was absent. A modified Mann-Kendall Test (Mann, 1945; Kendall, 1955; Hamed and Rao, 1998) was used to show that missing values do not affect long-term weather data analysis if less than seven percent of data is involved (e.x. Sen Roy and Balling, 2004; Zhang et al., 2011).

GIS Analysis

Site selection required three objectives to be met: 1) find a USGS stream gauge with discharge data, 2) develop a watershed for the USGS stream gauge, and 3) locate respective weather stations. First, an Excel file containing decimal degree coordinate locations of USGS streamflow gauges was converted to point shapefiles using the “Add XY Data” function. X was defined as longitude and Y as latitude. This same process was used to develop the weather station point layer. Once the streamflow point layers were imported into ArcMap, a 30 km buffer was created around the streamflow point layer using the “Buffer” Geoprocessing Tool. Study watersheds were created by merging a HUC12 basin layer and then reshaping the polygon to end at the streamflow gauge through visual analysis of a one meter DEM and surface flow lines. NOAA weather stations were then selected either within the 30 km buffer or study watershed boundary.
A series of descriptive maps were created to understand how land use, geology, ecoregions, and dam locations may have influenced each watershed. A 2001 raster land use file (USGS) was clipped to the individual study watershed features, where it was converted into a vector file. The attribute tables of each watershed’s land use was then exported into an Excel (Microsoft Corporation ® 2010) spreadsheet and the count of land use values was converted to percentages by dividing the count by the total number of pixel counts. Geology and ecoregion polygon layers were imported into ArcMap from external sources. These were then clipped to the individual watershed layers. Once clipped, a field was added to the attribute table to calculate area (in square meters) for each feature within the layer using the calculate geometry tool. The attribute tables of each watershed’s geology and ecoregions were then exported into an Excel spreadsheet and percentages were calculated by dividing the individual layer areas by the total study area. Dam layers were created by importing the Georgia National Inventory of Dams (NID) point layer into ArcMap and clipping it the study areas. Since the Chattooga River (Site #5) also spanned North and South Carolina (NC and SC), analysis of an aerial image was conducted to determine other dam locations. These were then verified by the Corp of Engineers of NC and SC NID database.

ArcMap10.1 (ERSI) was used to conduct all GIS analysis. No ArcMap extensions were used. Excel files, shapefiles, and raster layers were downloaded from the Internet (Table 11, Appendix D), and imported into ArcMap. Land use, geology, and dam location maps for each watershed are included in Appendix A.

Statistical Analysis

The performance of the indices was evaluated using the strength of the relationship between SPI and observed discharge and between SPI and SDI. The strength of these relationships was assessed using coefficients of determination derived from linear regression models (Sokal and Rohlf, 1995). Least-squares linear regression is a statistical technique used to quantify the slope and intercept for the linear relationship between independent (x) and dependent (y) variables. The goodness of fit is measured by a statistic referred to as the coefficient of determination (r^2). The r^2 is the amount of variation in the dependent variable explained by the variation in the independent variable (Sokal and Rohlf, 1995; Mittlböck and Heinzl, 2002; Morid et al., 2006). An r^2 of 1 indicates 100 % of the variance in y is explained by x. For this study, least-squared linear
regressions relating SPI (independent variable) to discharge (dependent variable) and SPI (independent variable) and SDI (dependent variable) were performed at each time scale (N = 6) and for each watershed (N = 7) combination (i.e., N = 42 total) using Microsoft Excel (ver. 2013). Due to the large number of regression models computed, the threshold probability for statistical significance was lowered to p = 0.001 (i.e., 0.05/42) using a Bonferroni correction (Sokal and Rohlf, 1995; Armstrong, 2014).

Two-way Analysis of Variance (ANOVA) models were used to determine how watershed and temporal scale (independent variables) influenced the SPI-discharge and the SPI-SDI regression relationships. The dependent variable in these models was the coefficient of determination estimated using the linear regressions. Two-way ANOVAs were selected for this analysis, because it could be used to assess both watershed and temporal scales simultaneously. The interaction term (site * time scale) was omitted due to a lack of replication. Tukey HSD was used because it corrects for the number of pairwise comparisons (Sokal and Rohlf, 1995). Both Two-way ANOVA statistical models and comparisons were performed in IBM SPSS Statistics software (ver. 21, IBM Corp., 2012).

Results and Discussion

Characteristics of the Study Area

Draining an average of 668 ± 203 km$^2$ (mean ± SD), the seven study watersheds are located in two Level III ecoregions (Griffith et al., 2001). These watersheds are located primarily within the Piedmont ecoregion with approximately one third of the area falling within the Blue Ridge ecoregion (Table 2). Only two rivers, Chattooga and Coosawattee, are located completely within the Blue Ridge ecoregion; while Sweetwater Creek, Flint River, and Middle Oconee Rivers occupy the Piedmont ecoregion. Ecoregions are defined by their biotic (e.g., vegetation and wildlife) and abiotic (e.g., geology, physiography, climate, soils, and land use) characteristics (Omernik, 1987; 1995). These characteristics can affect a watershed’s hydrology (Kokkoken et al., 2003). Dominated by gneiss, schist and granite, the Piedmont ecoregion is considered hillier than the mountainous Blue Ridge ecoregion (Griffith et al., 2001). The Blue Ridge ecoregion is a rugged terrain mix of igneous (mafic and ultramafic), metamorphic (low and high grade), and sedimentary (bouldery colluvium) geology (Griffith et al., 2001). Land uses (2001) in the study areas were predominately forested with less than 30% developed and agriculturally cultivated (Table 2).
Other land uses in the watersheds included wetlands and barren landscapes, but these uses composed less than 5% of the land area (Table 2). All watersheds had dendritic drainage systems normally associated with the hilly metamorphic and igneous terrain of the Appalachian Mountains (Chapman and Peck, 1997).

Table 2. Mean (\(\bar{x}\)) and standard deviation (SD) of percentages of watershed area by level III ecoregion and land use category (2001) for the seven study areas.

<table>
<thead>
<tr>
<th>Watershed Site Number</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>(\bar{x})</th>
<th>sd</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Ecoregion</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Piedmont [45]</td>
<td>72.4</td>
<td>69.6</td>
<td>100.0</td>
<td>0.0</td>
<td>0.0</td>
<td>100.0</td>
<td>100.0</td>
<td>63.1</td>
<td>45.0</td>
</tr>
<tr>
<td>Blue Ridge [66]</td>
<td>27.6</td>
<td>30.4</td>
<td>0.0</td>
<td>100.0</td>
<td>100.0</td>
<td>0.0</td>
<td>0.0</td>
<td>36.9</td>
<td>45.0</td>
</tr>
<tr>
<td><strong>Land Use</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Barren</td>
<td>0.3</td>
<td>0.5</td>
<td>0.5</td>
<td>0.1</td>
<td>0.1</td>
<td>0.5</td>
<td>1.1</td>
<td>0.4</td>
<td>0.3</td>
</tr>
<tr>
<td>Cultivated</td>
<td>12.7</td>
<td>9.5</td>
<td>11.4</td>
<td>5.1</td>
<td>1.9</td>
<td>13.4</td>
<td>25.0</td>
<td>11.3</td>
<td>7.4</td>
</tr>
<tr>
<td>Developed</td>
<td>8.6</td>
<td>7.3</td>
<td>33.9</td>
<td>6.6</td>
<td>3.7</td>
<td>34.9</td>
<td>16.5</td>
<td>15.9</td>
<td>13.2</td>
</tr>
<tr>
<td>Forested</td>
<td>77.8</td>
<td>82.3</td>
<td>49.2</td>
<td>87.9</td>
<td>94.0</td>
<td>42.4</td>
<td>53.5</td>
<td>69.6</td>
<td>20.7</td>
</tr>
<tr>
<td>Wet</td>
<td>0.6</td>
<td>0.4</td>
<td>5.0</td>
<td>0.3</td>
<td>0.2</td>
<td>8.8</td>
<td>3.8</td>
<td>2.7</td>
<td>3.3</td>
</tr>
</tbody>
</table>

Table 3 shows annual average basin rainfall varied 8 – 30% across the seven study catchments from 1970-2000. The Blue Ridge ecoregion typically experiences annual average precipitation over 2000 mm (Griffith et al., 2001). Located completely within the Blue Ridge ecoregion, the Coosawattee River (Site #4) and Chattooga River (Site #5) averaged similar annual precipitation. Site #5 also had the highest discharge of all of the watersheds, which may be connected with its land use and protection under the Wild and Scenic Rivers Act (Kent and Bayne, 2010; Smith and Moore, 2011). Ninety-four percent of the Chattooga River Watershed is comprised of forested land which is protected by three national forest districts: the Highlands District of the Nantahala National Forest (NC), the Andrew Pickens District of the Sumter National Forest (SC), and the Tallulah District of the Chattahoochee National Forest (GA) (Kent and Bayne, 2010).
Table 3. Mean annual precipitation ($\bar{P}_{12}$) and standard deviation (PSD) among study watersheds including the three highest ranking 12 month SPI values and their associated drought year (3).

<table>
<thead>
<tr>
<th>Site</th>
<th>$\bar{P}_{12}$ (mm)</th>
<th>PSD (mm)</th>
<th>1st (year)</th>
<th>2nd (year)</th>
<th>3rd (year)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1519</td>
<td>246</td>
<td>-2.33</td>
<td>-1.97</td>
<td>-1.69</td>
</tr>
<tr>
<td>2</td>
<td>1634</td>
<td>272</td>
<td>-1.96</td>
<td>-1.85</td>
<td>-1.39</td>
</tr>
<tr>
<td>3</td>
<td>1368</td>
<td>224</td>
<td>-2.17</td>
<td>-1.80</td>
<td>-1.67</td>
</tr>
<tr>
<td>4</td>
<td>1546</td>
<td>262</td>
<td>-2.28</td>
<td>-1.93</td>
<td>-1.50</td>
</tr>
<tr>
<td>5</td>
<td>1819</td>
<td>334</td>
<td>-1.98</td>
<td>-1.81</td>
<td>-1.76</td>
</tr>
<tr>
<td>6</td>
<td>1269</td>
<td>186</td>
<td>-2.18</td>
<td>-1.62</td>
<td>-1.36</td>
</tr>
<tr>
<td>7</td>
<td>1383</td>
<td>205</td>
<td>-2.12</td>
<td>-2.05</td>
<td>-1.84</td>
</tr>
</tbody>
</table>

The Flint River (Site #6) catchment was the driest basin conceivably due to the complex precipitation-recharge relationship (Kokkenen et al., 2003), historically low rainfall rates (Singh, 2015), water withdrawals (Ruhl, 2005; Pulido-Velazquez et al., 2008), or large scale dams (Chapman and Peck, 1997). Urban rainfall modification caused precipitation rates to vary in three contiguous watersheds studied within the Charlotte, North Carolina metropolitan area (Wright et al., 2013). Thirty-five percent of the Flint River basin is developed which may have led to storm formation downwind of the urban heat islands and lower rainfall rates within the watershed. Other studies (Kokkenen et al., 2003; Skoien et al., 2003; Zelelew and Alfredsen, 2014) have suggested that the location of rain and/or discharge gauges may affect hydrologic modeling results; Flint River’s weather station is located in top of the watershed while the discharge gauge is on the bottom. Furthermore, the Flint’s linear watershed shape could have affected accumulation totals. In North Carolina, the elongated shape of Little Sugar Creek watershed may have led to lower accumulation of rainfall due to basin shape and orientation in relation storm motion and formation to three broader watersheds (Wright et al., 2013). Groundwater recharge primarily maintains baseflows in the southern portions of Flint River within the Coastal Plain due to low rainfall rates especially in the summer months (Singh, 2015). Cropland irrigation could be furthermore decreasing the base flow in the Flint River (Torsk et al., 1996; Ruhl, 2005; Johnson, 2013), although this problem would be concentrated in the southern most portion of the Flint River.
watershed. Dams may have also contributed decreased streamflow by increasing evaporative losses; Site #6 has 52 water impoundments (Table 5 and Appendix A [dam location maps]).

Table 4. Mean annual stream discharge ($\bar{Q}_{12}$) and standard deviation (QSD) among watersheds including the three highest ranking 12 month SDIs and their associated drought year in parentheses.

<table>
<thead>
<tr>
<th>Site</th>
<th>$\bar{Q}_{12}$ (m$^3$/s)</th>
<th>QSD (m$^3$/s)</th>
<th>1st Highest</th>
<th>2nd Highest</th>
<th>3rd Highest</th>
</tr>
</thead>
</table>

Table 5. Total number of dams and their respective uses among watersheds.

<table>
<thead>
<tr>
<th>Dam Type</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>$\bar{x}$</th>
<th>sd</th>
</tr>
</thead>
<tbody>
<tr>
<td>Farm Pond</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>2</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Fishing</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Flood Control</td>
<td>13</td>
<td>0</td>
<td>1</td>
<td>15</td>
<td>0</td>
<td>0</td>
<td>13</td>
<td>6</td>
<td>7</td>
</tr>
<tr>
<td>Hydroelectric</td>
<td>2</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>Irrigation</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Recreation</td>
<td>30</td>
<td>15</td>
<td>45</td>
<td>23</td>
<td>0</td>
<td>48</td>
<td>18</td>
<td>26</td>
<td>17</td>
</tr>
<tr>
<td>Water Supply</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>5</td>
<td>2</td>
<td>2</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>Other</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>4</td>
<td>2</td>
<td>0</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>Total</td>
<td>47</td>
<td>15</td>
<td>47</td>
<td>40</td>
<td>9</td>
<td>54</td>
<td>35</td>
<td>35</td>
<td>17</td>
</tr>
</tbody>
</table>
Drought Extremes as Identified by SPI & SDI Analysis

SPI (Table 3) and SDI (Table 4) indicated extreme drought events occurred historically in all seven watersheds. According to the SPI, the most extreme calendar year meteorological and hydrological droughts occurred during the last 22 years of the study (1978, 1981, 1986-1988, 1999-2000). Similarly, the SDI’s highest drought severities occurred in last 19 years of the period of study (1981, 1986, 1999-2000). These results contrasted slightly from a 1943-1995 ACF and ACT River basins study (Chapman and Peck, 1997), which reported intense droughts from 1984-1988 based on USGS daily mean streamflow hydrographs. Barber and Stamey (2000) analyzed Georgia data from 1930-2000 and found surface water shortages similar in magnitude to the 1986 drought from 1998-2000. These authors also found that the 1980-82 water years resulted in the lowest stream levels since 1954. According to my analysis, this period experienced less severe drought than 1986, since the twelve month SDI and SPI results revealed more severe droughts across Georgia during 1986 in comparison to 1980-82 drought events (Tables 3 & 4). However, at a few sites the SPI (Chattahoochee and Middle Oconee Rivers) and SDI (Chattahoochee, Chattooga, and Middle Oconee Rivers) were consistent with findings of Barber and Stamey (2000).

SPI results varied only slightly across watersheds (Fig. 2a). The overall 12 month hydrological pattern indicated that droughts showed similar timing across the period of record with an intense drought at the end of the record. During these drought events, Georgia may be vulnerable to municipal, industrial, and recreational water shortages and other socio-economic impacts (Tsakiris et al., 2013). Bordi et al (2001) saw a decrease in wetness starting in the latter half of the 1970’s for Italy during a long term SPI study (1950-2000); local weather patterns or climate change may have been the cause (Bordi et al, 2001; Fisher et al., 2010). Another long term SPI study in China (Zhang et al., 2010) reported localized weather patterns and seasonal conditions caused SPI to vary across 42 Pearl River Basin catchments from 1960-2005. Less frequent or heavy rainfall events may have skewed SPI trends (Zhang et al., 2009; Fisher et al., 2010).

Normalized indices such as SPI and SDI assume normal probability distributions and thus, could be sensitive to data gaps. For example, missing data, commonly treated as zeroes, register in models as dry events where no precipitation occurred (Quiring et al., 2007; Mishra and Singh, 2010). From 1970-2000, all hydrologic streamflow records were complete for all study watersheds, so this problem was avoided in these SDI calculations. Two study sites were missing meteorological data, the Coosawattee River (4 months) and Chattooga River (1 month). The
Chattooga River (Site #5) was missing less than 1% of its weather station data (1/360 months = 0.3%). The Coosawattee River (Site #4) had about a 1% data deficiency (4/360 months = 1.1%), but none of the missing data from these months occurred within the same 12 month period.

![Graph A: SPI](image1)

![Graph B: SDI](image2)

Figure 2. Twelve month drought estimates for seven watersheds (a) SPI and (b) SDI. The dashed line indicates the threshold (0) between wet and dry conditions.

Other SPI studies have been challenged by data gaps. Lana et al. (2001) conducted an SPI study in Spain using 99 rain gauges (1961 to 1990). In this study rainfall gauges missing 2 or more months in a 12 month period were excluded. Sen Roy and Balling (2004) conducted a SPI study on 129 stations in India where 10.2% of data records were missing for all stations, but a variety of analyses indicated that the missing data had little effect on annual rainfall trends. Zhang et al. (2012) found similar results with monthly precipitation trends when they conducted a modified Mann-Kendall test and compared the use of the gap-fill method to replace missing precipitation values (1%) with the insertion of zeroes for 12 rain gauging stations. The gap-fill method consists
of replacing missing data values with statistically similar data from other gauging stations such as a nearby weather station (Zhang, 2011). Relative to these studies, the current study has relatively few data gaps which are unlikely to alter the study’s conclusions.

SDI scores varied moderately across watersheds (Fig. 2b), possibly due to localized river flow regimes (Tabari et al., 2013). SDI-estimated extreme droughts matched recorded water shortages for Georgia (Quiring et al., 2007). The overall 12 month hydrological record showed a drought near the end of the study period. Recent studies in Iran and Iraq indicated similar drying patterns from 1990-2009 (Tabari et al., 2013; Rimkus et al., 2013) which may have been due to climate change (Al-Faraj et al., 2014) or increased water demand from metropolitan areas or agriculture (Barber et al., 2000).

Table 6. Drought classification and corresponding event probabilities for 12 Month SPI and SDI for the seven watersheds studied.

<table>
<thead>
<tr>
<th>Drought Index value</th>
<th>Category</th>
<th>SPI Probability (%)</th>
<th>SDI Probability (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.00 or more</td>
<td>Extremely wet</td>
<td>0.4</td>
<td>0.0</td>
</tr>
<tr>
<td>1.50 to 1.99</td>
<td>Severely wet</td>
<td>2.1</td>
<td>1.3</td>
</tr>
<tr>
<td>1.00 to 1.49</td>
<td>Moderately wet</td>
<td>11.1</td>
<td>4.7</td>
</tr>
<tr>
<td>-0.99 to 0.99</td>
<td>Near normal</td>
<td>66.1</td>
<td>74.4</td>
</tr>
<tr>
<td>-1.49 to -1.00</td>
<td>Moderately dry</td>
<td>11.0</td>
<td>4.9</td>
</tr>
<tr>
<td>-1.99 to -1.50</td>
<td>Severely dry</td>
<td>6.3</td>
<td>7.7</td>
</tr>
<tr>
<td>-2 or less</td>
<td>Extremely dry</td>
<td>2.6</td>
<td>5.7</td>
</tr>
</tbody>
</table>

From 1970 to 2000, SPI and SDI displayed similar hydrological drought severities (Table 6) and overall timing (Fig. 2) in North Georgia. Quiring et al. (2007) found similar patterns in Texas. Fourteen Pinios River Basin watersheds in Greece (Vasiliades et al., 2011) found SPI identified historic hydrological droughts, but were highly variable across the watersheds both in severity and timing due to seasonality. Rimkus et al. (2013) reported similar results in the Neman River basins (Europe); seasonality caused fall droughts and spring flooding which were detected using both SPI and SDI. In the present study, drought events identified using the SPI tended to occur prior to SDI droughts (Fig. 2). The Blue River Basin in Oklahoma (Liu et al., 2012) found SPI’s meteorological components responded more quickly in identifying severe droughts than a hydrological drought.
index, Standardized Runoff Index. The Reconnaissance Drought Index (a meteorological drought index) proactively predicted water availability trends in the Diyala watershed spanning the Iraq and Iran border prior to SDI (a hydrological drought index) (Al-Faraj et al., 2014). Hydrological drought components tend to respond slower than meteorological components, which may be due to the complexity of the precipitation-runoff relationship (Quiring et al., 2007; Liu et al., 2012; Vicente-Serrano et al., 2014). Streamflow may be a better indicator for hydrological drought since it takes into account the multiple factors affecting regional river systems such as: water allocations and withdrawals (Pulido-Velazquez et al., 2008; Johnson, 2013), stream network structure (Skøien et al., 2003; Lopez-Moreno et al., 2013), infiltration rates, and topography (Hewlett and Hibbert, 1967; Kokkenen et al., 2003).

Factors Influencing the Relationship between SPI and Stream Discharge

To assess the SPI’s reliability as a drought indicator, the strength of the linear association (as measured by coefficient of determination or $r^2$) between SPI and measured discharge were analyzed (Fig. 3). SPI and discharge were linearly related with $r^2$ values averaging $0.48 \pm 0.19$ (\(\bar{x} \pm SD\)) across all basins and timescales. SPI versus streamflow $r^2$ values deviated from the average about 1 – 11 % across watersheds and 2 – 90 % among temporal scales (Table 7). The use of the $r^2$s in further statistical analyses was supported by the fact that 97% of all regressions were statistically significant (Table 7). The only exception was the 24 month time interval for the Flint River (Site #6, $r^2 = 0.345$, $p = 0.021$) which did not meet the Bonferroni adjusted alpha of $p < 0.001$.

Study site location had an important effect on the relationship between SPI and streamflow (Two-way ANOVA, $F = 3.268$, $p = 0.014$). Temporal factors (i.e. 1 to 24-month time scale) significantly influenced the SPI and discharge relationship (Two-way ANOVA, $F = 56.911$, $p < 0.0005$). According to a pairwise comparison, all watersheds were similar except for Site #6 (Flint) and #5 (Chattooga) (Fig. 4a, Tukey HSD, $p > 0.026$ for all). The $r^2$s values for 1, 3, and 6 month time scales were statistical similar (Fig. 4b, Tukey HSD, $p > 0.178$ for all), but $r^2$ values were lower than those measured at the comparable 9, 12, and 24 month time scales (Fig. 4b, Tukey HSD, $p > 0.998$ for all). The time period with the strongest linear associations between SPI and
discharge differed by catchment: Site 2, 3, and 6 at 9 months, Site 5 at 12 months, and Site 1, 4, and 7 at 24 months (Table 7).

Due to the time lag in the precipitation-surface runoff relationship, other hydrologic drought studies found SPI's timing varied in response to discharge between study watersheds (Quiring et al., 2007; Vasiliades et al., 2011; Wright et al., 2013). Temporal lags between precipitation and streamflow can be affected by anthropogenic actions such as surface and ground water withdrawals for agricultural, municipal, and industrial purposes (Giddings et al., 2005; Vicente-Serrano et al., 2014; Singh, 2015). From 1961 to 2007, 192 weather stations were analyzed with SPI to understand historical dry/wet patterns in Zhujiang River Basin (South China). These patterns were influenced by the spatial and temporal distribution of monsoons and periods of no rainfall along with urban land use and heat island effects (Fischer et al., 2010). A Northwest Pacific study (Abatzoglou et al., 2014) reported that the relationship between streamflow and SPI varied across 21 unregulated drainage basins both seasonally and spatially, with the most robust relationship between SPI and discharge occurred at 6 - 10 month timescales. Six Texas watersheds showed similar results; SPI best correlated with discharge and SDI at 6 and 9 month timescales (Quiring et al., 2007).
Figure 4. Boxplots showing coefficients of determination ($r^2$) for the linear regressions relating (a) SPI and stream discharge among study sites (N = 7); (b) SPI and stream discharge at various time scales (N = 6); (c) SPI and SDI among study sites (N = 7); and (d) SPI and SDI at various time scales (N = 6). Medians are represented by the dark horizontal line. Box ends represent 25th and 75th percentiles. Whiskers represent the 10th and 90th percentile. Gray circles represent outliers [> 1.5 * interquartile range (IQR)]; stars represent extreme outliers [> 3 * IQR]. Bars not sharing the same letters represent significant statistical difference (p ≤ 0.001) as indicated by Tukey HSD.
Table 7. Measure of fit of least-squares linear regressions ($r^2$) relating SPI to observed discharge (Q) and SDI on 1, 3, 6, 9, 12, and 24-month time scales (1970 to 2000). Bolded values mark $r^2$ values which did not meet the Bonferroni corrected significance threshold of $p < 0.001$.

<table>
<thead>
<tr>
<th>Site</th>
<th>1 Month</th>
<th>3 Month</th>
<th>6 Month</th>
<th>9 Month</th>
<th>12 Month</th>
<th>24 Month</th>
</tr>
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<tbody>
<tr>
<td>1</td>
<td>SPI v Q</td>
<td>0.27</td>
<td>0.33</td>
<td>0.36</td>
<td>0.63</td>
<td>0.75</td>
</tr>
<tr>
<td></td>
<td>SPI v SDI</td>
<td>0.39</td>
<td>0.51</td>
<td>0.61</td>
<td>0.69</td>
<td>0.77</td>
</tr>
<tr>
<td>2</td>
<td>SPI v Q</td>
<td>0.26</td>
<td>0.30</td>
<td>0.34</td>
<td>0.67</td>
<td>0.61</td>
</tr>
<tr>
<td></td>
<td>SPI v SDI</td>
<td>0.41</td>
<td>0.52</td>
<td>0.63</td>
<td>0.74</td>
<td>0.61</td>
</tr>
<tr>
<td>3</td>
<td>SPI v Q</td>
<td>0.28</td>
<td>0.29</td>
<td>0.31</td>
<td>0.72</td>
<td>0.70</td>
</tr>
<tr>
<td></td>
<td>SPI v SDI</td>
<td>0.53</td>
<td>0.56</td>
<td>0.67</td>
<td>0.74</td>
<td>0.70</td>
</tr>
<tr>
<td>4</td>
<td>SPI v Q</td>
<td>0.20</td>
<td>0.25</td>
<td>0.25</td>
<td>0.59</td>
<td>0.61</td>
</tr>
<tr>
<td></td>
<td>SPI v SDI</td>
<td>0.35</td>
<td>0.45</td>
<td>0.53</td>
<td>0.66</td>
<td>0.58</td>
</tr>
<tr>
<td>5</td>
<td>SPI v Q</td>
<td>0.26</td>
<td>0.35</td>
<td>0.41</td>
<td>0.70</td>
<td>0.80</td>
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<tr>
<td></td>
<td>SPI v SDI</td>
<td>0.37</td>
<td>0.53</td>
<td>0.63</td>
<td>0.78</td>
<td>0.81</td>
</tr>
<tr>
<td>6</td>
<td>SPI v Q</td>
<td>0.26</td>
<td>0.34</td>
<td>0.38</td>
<td>0.58</td>
<td>0.55</td>
</tr>
<tr>
<td></td>
<td>SPI v SDI</td>
<td>0.45</td>
<td>0.60</td>
<td>0.63</td>
<td>0.67</td>
<td>0.56</td>
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<tr>
<td>7</td>
<td>SPI v Q</td>
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<td>0.32</td>
<td>0.38</td>
<td>0.69</td>
<td>0.67</td>
</tr>
<tr>
<td></td>
<td>SPI v SDI</td>
<td>0.40</td>
<td>0.53</td>
<td>0.63</td>
<td>0.71</td>
<td>0.69</td>
</tr>
</tbody>
</table>

Factors Influencing the Relationship between SPI and SDI

To evaluate if SDI could be used as a substitute for SPI, it was critical to establish what factors influence their association. In this study, the measure of fit ($r^2$s) between SPI and SDI was influenced by location and timescale. SPI and SDI were linearly related with $r^2$ values averaging $0.60 \pm 0.13$ ($\bar{x} \pm SD$) across all basins and timescales. SPI and SDI $r^2$ values deviated from the average $0.4 - 11.3$ % across watersheds and $0.7 - 16.3$ % among temporal scales analyzed. All SPI and SDI regressions were statistically significant (Table 7) except the 24 month time interval for the Flint River (Site #6, $r^2 > 0.344$, $p > 0.021$).

Statistical analysis of spatial and temporal factors influencing the relationship between SPI and SDI revealed similar results to those reported for SPI and streamflow. Watershed location had no effect on the relationship between SPI and SDI (Fig. 4c, Two-way ANOVA, $F = 2.022$, $p = 0.094$). However, time scale significantly influenced the SPI and SDI (Fig. 4d, Two-way ANOVA, $F = 14.02$, $p < 0.0005$). The influence of time scale on the SPI and SDI relationship deviated slightly from its effect on the SPI and discharge patterns reported earlier. A one month interval had the
lowest fit for all timescales. One and three month intervals were statistically similar (Tukey HSD, 
p = 0.086) and generally lower than other periods. The 3 month time scale had intermediate fit 
values and was statistically indistinguishable from 1, 6, and 24 month time scales (Tukey HSD, p 
> 0.074 for all). Six month or greater time scales had the strongest SPI and SDI relationships and 
were statistically indistinguishable from one another (Tukey HSD, p > 0.249 for all).

Consistent with this study, Nalbantis and Tsakiris (2009) found high correlations between SPI 
and SDI for predicting extreme hydrological events at 3, 6, 9 and 12 month time scales in the 
Evinos River basin (Greece). Recent studies found robust relationships between SPI and other 
hydrological drought indices at 9 and 12 month time scales for 8 Aragon River watersheds 
(Vicente-Serrano and López-Moreno, 2005), a 24 month time scale for 22 southern Italy basins 
(Mendicino and Versace, 2006), and 3, 6, and 9 month time scales in the Diyala watershed between 
Iraq and Iran (Al-Faraj et al., 2014). In contrast, the Neman catchment spanning five countries 
(Lithuania, Belorussia, Russia, Poland, and Latvia) found SPI and SDI were poorly correlated, 
most likely due to the mountainous terrain creating winter snowfalls and high spring discharge 
(Rimkus et al., 2013).

Summary and Conclusions

In this study, historical hydrologic droughts from 1970-2000 were evaluated using SPI and 
SDI in seven North Georgia watersheds. Hydrological drought severity was analyzed on an annual 
basis and revealed the following trends for SPI and SDI: 1) all seven catchments experienced more 
dry events than wet events based on percent probability (Table 6); 2) SDI indicated eight percent 
more normal events than extreme events based on percent probability than SPI (Table 6); 3) the 
timing of severe drought events varied only slightly across watersheds; 4) the most extreme 
similar in severity to the 1999-2000 drought events.

Watersheds varied temporally in their hydrologic response to drought, which may be a function 
of localized recharge or anthropogenic factors. Based this analysis, discharge and SPI had a more 
robust relationship with longer time steps (9 - 24 months), while SPI and SDI revealed an 
analogous pattern. However, it should be noted that r^2 exceeded 0.5 at the 6 month timescale for 
SDI and SDI. According to Tukey HSD analysis, catch basins were statistically similar. Future
studies should be conducted to determine if SPI and SDI relationships vary temporally and spatially in other southern ecoregions such as in the coastal plain.

From a management standpoint, quantifying historical hydrologic drought can advance our understanding of drought dynamics and improve our response to these natural events. In Georgia, data availability is a key challenge limiting our capacity to conduct these analyses. Data gaps in existing gage records and an absence of gages in both USGS (discharge) and NOAA (precipitation) limited this study’s site selection. Future removal of stream and/or rainfall gages could limit our knowledge of drought, especially when 30 or more years is recommended for climate analysis. Accurate long-term and wide-range meteorological and streamflow monitoring networks are needed for water resource management especially for improved understanding of hydrological response patterns. Regions in Georgia’s Blue Ridge and Piedmont ecoregions that are deficient in discharge data can use SPI as a viable alternative to SDI. In addition, this study’s results indicate SDI can function as a proxy for SPI in catchments lacking precipitation data, particularly at longer time scales.

References


Chapman, M. J., & Peck, M. F. (1997). Ground-water resources of the middle Chattahoochee River basin in Georgia and Alabama, and upper Flint River basin in Georgia-Subarea 2 of the Apalachicola-Chattahoochee-Flint and Alabama-Coosa-Tallapoosa river basins (No. 96-492) USGS.


Appendices

APPENDIX A Watershed Descriptions
APPENDIX B Least-Squares Linear Regression SPI vs Q Figures
APPENDIX C Least-Squares Linear Regression SPI vs SDI Figures
APPENDIX D Metadata Sources
Appendix A Watershed Descriptions

All but one of the watershed study areas are located solely in Georgia: Chattahoochee River Near Cornelia, Chestatee River Near Dahlonega, Sweetwater Creek Near Austell, Coosawattee River Near Ellijay, Chattooga River Near Clayton, Flint River Near Griffin and Middle Oconee River Near Athens. The Chattooga River watershed near Clayton spans Georgia, South Carolina, and North Carolina. Georgia has naturally abundant water resources, however, the growth of the Atlanta metropolitan area has sparked many debates about future water availability of Georgia.

Georgia is a very dynamic geological state with four major geologic regions: the Valley and Ridge, Blue Ridge, Piedmont, and Coastal Plain. Most of the study sites were found within the Blue Ridge region. In northwest Georgia, the Valley and Ridge is comprised mainly of Paleozoic sedimentary rocks which were faulted and folded into northeast-southwest-trending valleys and ridges. In the northeast corner of Georgia, the Blue Ridge is comprised primarily of low-to-high-grade metamorphic rocks forming the North Georgia Mountains. The Piedmont is comprised of igneous and metamorphic rocks with lower elevations and less relief than the Blue Ridge. It is considered hilly and located in the middle of Georgia. The Fall Line marks the boundary between the Coastal Plain and Piedmont. Sedimentary rocks dating from Cretaceous to Cenozoic age are found within the Coastal Plain, which is located in the southern part of Georgia.

Ecoregions denote areas with comparable ecosystems characterized by abiotic and biotic factors such as geology, topography, vegetation, land use, and wildlife (Omernik, 1987; 1995; Griffith et al., 2001). Georgia encompasses six Level III ecoregions. The Southwestern Appalachians ecoregion is located in the northwestern corner of Georgia, where it abuts the Ridge and Valley. Faulted and folded shale, sandstone, limestone, dolomite, marble, and mudstone dominate these two ecoregions. Rugged high-gradient outcrops of Precambrian gneiss, schist, quartzite, slate, conglomerate, phyllite, metagraywacke, and other metamorphosed rocks comprise the Blue Ridge ecoregion in the northeastern corner of Georgia. The Piedmont is a transitional ecoregion between the northern mountainous forest dominated ecoregions and the low gradient mosaic of pastures, farmland, forests, and wetlands of the southern coastal plains.
Figure 5. Level III Ecoregions in Georgia.
Figure 6. Level IV Ecoregions with watershed.
Table 8. The watershed land use percentages as of 2001 were primarily composed of forest and farming landscapes. The remaining topography was a mix of developed space, riparian environments, and barren land.

<table>
<thead>
<tr>
<th>Land Use Type</th>
<th>Watershed Site Number</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1</td>
</tr>
<tr>
<td>Barren Land</td>
<td>0.29</td>
</tr>
<tr>
<td>Cultivated Crops</td>
<td>0.01</td>
</tr>
<tr>
<td>Deciduous Forest</td>
<td>58.76</td>
</tr>
<tr>
<td>Developed, High Intensity</td>
<td>0.10</td>
</tr>
<tr>
<td>Developed, Low Intensity</td>
<td>1.08</td>
</tr>
<tr>
<td>Developed, Medium Intensity</td>
<td>0.35</td>
</tr>
<tr>
<td>Developed, Open Space</td>
<td>7.05</td>
</tr>
<tr>
<td>Emergent Herbaceous Wetlands</td>
<td>0.00</td>
</tr>
<tr>
<td>Hay/Pasture</td>
<td>12.67</td>
</tr>
<tr>
<td>Herbaceous</td>
<td>4.51</td>
</tr>
<tr>
<td>Mixed Forest</td>
<td>3.99</td>
</tr>
<tr>
<td>Open Water</td>
<td>0.47</td>
</tr>
<tr>
<td>Shrub/Scrub</td>
<td>0.69</td>
</tr>
<tr>
<td>Woody Wetlands</td>
<td>0.15</td>
</tr>
</tbody>
</table>
Table 9. Geologic zones vary by watershed with a mix of igneous, metamorphic, and sedimentary rocks.

<table>
<thead>
<tr>
<th>Geologic Unit</th>
<th>Watershed Site Number</th>
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<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>( \bar{x} )</th>
<th>( \sigma )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Basal Lower Cambrian Clastic Rocks</td>
<td>3.7</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.53</td>
<td>1.40</td>
</tr>
<tr>
<td>Catacalastic rocks</td>
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<td>0.0</td>
<td>0.0</td>
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<td>0.0</td>
<td>0.87</td>
<td>1.69</td>
</tr>
<tr>
<td>Felsic Orthogneiss (Granite/Gneiss)</td>
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<td>0.0</td>
<td>31.3</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>4.47</td>
<td>11.82</td>
</tr>
<tr>
<td>Felsic Paragneiss/Schist</td>
<td>0.9</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>16.5</td>
<td>50.1</td>
<td>0.0</td>
<td>9.64</td>
<td>18.86</td>
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<td>Lower Paleozoic</td>
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<td>13.1</td>
<td>0.0</td>
<td>0.0</td>
<td>21.1</td>
<td>0.0</td>
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<td>8.41</td>
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<td>Lower Paleozoic granitic rocks</td>
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<td>24.9</td>
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<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>9.33</td>
<td>13.48</td>
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<td>16.3</td>
<td>26.3</td>
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<td>0.0</td>
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<td>0.0</td>
<td>0.0</td>
<td>7.54</td>
<td>10.52</td>
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<td>Middle Paleozoic granitic rocks</td>
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<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>4.1</td>
<td>4.6</td>
<td>0.0</td>
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<td>Migmatite</td>
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<td>0.0</td>
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<td>24.2</td>
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<td>14.80</td>
<td>29.88</td>
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<td>Orthogneiss</td>
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<td>0.0</td>
<td>0.0</td>
<td>14.8</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>2.12</td>
<td>5.60</td>
</tr>
<tr>
<td>Paragneiss and schist</td>
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<td>10.6</td>
<td>9.0</td>
<td>0.0</td>
<td>62.6</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>16.81</td>
<td>23.78</td>
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<tr>
<td>Ultramafic rocks</td>
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<td>0.0</td>
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<td>1.5</td>
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<td>0.0</td>
<td>0.0</td>
<td>0.22</td>
<td>0.58</td>
</tr>
<tr>
<td>Z sedimentary rocks</td>
<td>33.2</td>
<td>48.2</td>
<td>1.7</td>
<td>86.9</td>
<td>19.4</td>
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<td>0.0</td>
<td>0.0</td>
<td>27.08</td>
<td>32.24</td>
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Table 10. Mountainous ecoregions (Piedmont [45] and Blue Ridge [66] dominate the watersheds.

<table>
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<th>Ecoregion Level IV</th>
<th>Watershed Site Number</th>
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<td></td>
<td>1</td>
</tr>
<tr>
<td>8.3.4 45a Southern Inner Piedmont</td>
<td>72.4</td>
</tr>
<tr>
<td>8.3.4 45b Southern Outer Piedmont</td>
<td>0.0</td>
</tr>
<tr>
<td>8.4.4 66d Southern Crystalline Ridges &amp; Mountains</td>
<td>27.6</td>
</tr>
<tr>
<td>8.4.4 66g Southern Metasedimentary Mountains</td>
<td>0.0</td>
</tr>
<tr>
<td>8.4.4 66j Broad Basins</td>
<td>0.0</td>
</tr>
</tbody>
</table>
Chattahoochee River Watershed near Cornelia, Georgia (Watershed Site #1)

This river is a prominent water resource of Georgia and a key player in the Apalachicola-Chattahoochee-Flint River (ACF) Basin water wars. The Chattahoochee River is the largest of all the rivers inside the ACF Basin. Concerns over local fishing and salt water intrusion from the Gulf have placed restrictions on how much water can be withheld from Apalachicola Bay. Atlanta also uses this river as its primary water source. Approximately 430 miles in length, the Chattahoochee River stretches from the Blue Ridge Mountains near Brasstown Bald South to become a tributary of the Apalachicola River immediately north of the Georgia-Florida state boundaries, draining a total area of 8,770 square miles.

Headwaters of this significant waterway were included in this study. This drainage area is 822 square kilometers (318 square miles) and includes portions of Habersham, White, Union, and Towns Counties. The location of the USGS gauging station (#02331600) at latitude 34°32'26.6"N, longitude 83°37'21.99"W (Fig. 7) is referenced to North American Datum of 1983, and lies within Habersham County, GA, Hydrologic Unit 03130001, on the downstream side of the bridge on Duncan Bridge Road (GA 384), 1.0 mile downstream from Soque River, 6.0 miles northwest of Cornelia, and at mile 401.4. The USGS discharge data period of record is from August 1957 to present.

Cornelia is the respective NOAA weather station. It is located at 34°30'58.783" N, longitude 83°32'1.428" W. Its period of record spans from May 1919 to present.

Figure 7. USGS Gauge #02331600 for the
Figure 8. Chestatee and Chattahoochee watershed land use during 2001 (top) and geology (bottom).
Chestatee River Watershed near Dahlonega, Georgia (Watershed Site #2)

The Chestatee River flows 51 miles to become a major tributary of the Chattahoochee River, joining it at Lake Lanier. It flows through the Blue Ridge geologic region and is part of the Dahlonega gold belt, which was the main target region for gold exploration during the 1829 Georgia Gold Rush. The city of Dahlonega uses the Chestatee River for tubing, whitewater rafting, kayaking, and fishing.

The headwaters of this waterway were included in this study. The drainage area is 393 square kilometers (152 square miles) and includes portions of Lumpkin and White Counties. The location of the USGS gauging station (#02333500) at latitude 34°31'41" N, longitude 83°56'23" W (Fig. 11) are referenced to North American Datum of 1983, and lies within Lumpkin County, GA, Hydrologic Unit 03130001, on the left bank 250 feet upstream from Bearden Bridge on GA 52, 2.0 miles downstream from Ballplay Creek, 2.5 miles east of Dahlonega, and 3.5 miles upstream from Yahoola Creek. The USGS discharge data period of record is from July 1929 to present.

Sweetwater Creek Watershed near Austell, Georgia (Watershed Site #3)

This stream is the largest stream in Cobb County, Georgia. Sweetwater Creek State Park is named after this stream and is the site of an abandoned mill. New Manchester Manufacturing Company used the local waterway to construct fabric products, but in 1864, General William...
Sherman had the mill burned to ground during the American Civil War. Its ruins stand today as a tourist attraction. Sweetwater Creek is a 303(d) listed stream for fecal coliform.

Figure 11. Local mill ruins near Sweetwater Creek. Photo taken by author.

Headwaters of this waterway were included in this study. The Drainage area is 616 square kilometers (238 square miles) and includes portions of Carroll, Paulding, Cobb, and Douglas Counties. The location of the USGS gauging station (#02337000) at latitude 33°46'35.4", longitude 84°36'56.2" (Fig. 14) is referenced to North American Datum of 1927, and lies within Douglas County, GA, Hydrologic Unit 03130002, near the right bank 100.0 feet upstream from the bridge on Interstate 20, 400.0 feet upstream from Blair Bridge, 3.0 miles southeast of Austell, and 5.5 miles upstream from its confluence with the Chattahoochee River. The USGS discharge data period of record is from May 1904 to present.

Dallas 7 NE is the respective NOAA weather station. It is located at 33°58'59.391" N, longitude 84°45'7.35" W. Its period of record spans from February 1947 to present.
During 2001, the Sweetwater River watershed was moderately developed. Land uses were primarily deciduous forest, evergreen forest, developed open space, developed low intensity, and pasture lands. Developed land only totaled 33.93%. Agricultural land totaled 11.38%. Undeveloped land totaled 53.76%.

The Sweetwater Creek watershed is located in the Blue Ridge geologic region of Georgia. Lower Paleozoic granitic rocks, felsic orthogneiss, and mafic paragneiss are the main geological units. Paragneiss, schist, and preCambrian metasedimentary rocks compose the remaining geology of the Sweetwater watershed.
Figure 14. Sweetwater watershed land use during 2001 (top) and geology (bottom).
Figure 15. Dam locations and totals within the Sweetwater watershed.

Coosawattee River Watershed near Ellijay, Georgia (Watershed Site #4)

The Coosawattee River used to be utilized for whitewater rafting prior to the construction of Carter’s Lake. It starts north of Ellijay at the confluence of the Ellijay and Cartecay Rivers. The Coosawattee River flows through the Blue Ridge geologic region. Fishing, canoeing, and kayaking are common on this river. James Dickey’s novel *Deliverance* was partially inspired from canoeing this river along with Chattooga and Chattahoochee Rivers.

The headwaters of this waterway were included in this study. The drainage area is 613 square kilometers (237 square miles) and includes portions of Fannin, Gilmer, Pickens, and Dawson Counties. The location of the USGS gauging station (#02380500) at latitude 34°40'30" N, longitude 84°30'31" W (Fig. 17) is referenced to North American Datum of 1927, and is located within Gilmer County, GA, Hydrologic Unit 03150102, on the right bank 0.5 miles downstream from State Highway 5, 2.0 miles southwest of Ellijay, and 2.2 miles downstream from the
confluence of the Cartecay and Ellijay Rivers. The USGS discharge data period of record is from October 1938 to present.

Ellijay (GHCND: USC00093115) is the respective NOAA weather station. It is located at 34° 40' 59.9874" N and longitude 84° 28' 59.9874" W. Its period of record spans from June 1937 to January 2014.

During 2001, the Coosawattee River watershed was largely undeveloped. Land uses were primarily deciduous forests. Developed land only totaled 6.56%. Agricultural land totaled 5.12%. Undeveloped land totaled 88.48%.

The Coosawattee watershed is located in the Blue Ridge geologic region of Georgia. PreCambrian metasedimentary rocks are the main geological units. Lower Paleozoic rocks compose the remaining geology of the Coosawattee watershed.

Figure 16. USGS Gauge #02380500 location in stream channel (left) and general location (right) for the Coosawattee River (USGS, 2000).
Figure 17. Coosawattee watershed land use during 2001 (top) and geology (bottom).
Chattooga River Watershed near Clayton, Georgia (Watershed Site #5)

This river is recognized as a national wild and scenic river. It flows through the Blue Ridge geologic region and three states, starting in North Carolina, then flowing into South Carolina, and ending in Georgia. The Chattooga River flows 57 miles to become the main tributary of the Tugaloo River in Georgia. Commercially, the Chattooga is used for rafting and was featured in the book and film Deliverance. Also, it intersects the Ellicott Rock Wilderness.

Headwaters of this waterway were included in this study. The drainage area is 536 square kilometers (207 square miles) and includes portions of Rabun (Georgia), Jackson (North Carolina), and Oconee (South Carolina) Counties. The location of the USGS gauging station (#02398000) at latitude 34°48'50" N, longitude 83°18'22" W (Fig. 20) is referenced to North American Datum of 1927, and is located within Oconee County, SC, Hydrologic Unit 03060102, on the left bank 150 feet downstream from the bridge on US 76, 2.8 miles upstream from Stekoa Creek, 9.0 miles downstream from its confluence with Warwoman Creek, 9.0 miles upstream from its confluence
with Tallulah River, and 7.0 miles southeast of Clayton, Georgia. Its USGS discharge data period of record is from October 1939 to present.

Coweeta Experiment Station (GHCND: USC00312102) is the respective NOAA weather station. It is located at 35° 4' 9.984" N and longitude 83° 26' 49.992" W. Its period of record spans from December 1942 to present.

During 2001, the Chattooga River watershed was largely undeveloped. Land uses were primarily deciduous forest and evergreen forest. Developed land only totaled 3.69 %. Agricultural land totaled 1.91 %. Undeveloped land totaled 94.40 %.

The Chattooga watershed is located in the Blue Ridge geologic region of North Carolina, South Carolina, and Georgia. Paragneiss, schist, and metasedimentary rocks are the main geological units. Cataclastic, ultramafic, and orthogneiss rocks compose the remaining geology of the Chattooga watershed.

Figure 19. USGS Gauge #0239800 for the Chattooga River (USGS, 2000).
Figure 20. Chattooga watershed land use during 2001 (top) and geology (bottom).
Flint River Watershed near Griffin, Georgia (Watershed Site #6)

The Flint River is the second largest waterway in the ACF River Basin. The Flint River provides a drinking water source for much of western Georgia. Flowing approximately 344 miles in length, the Flint River stretches from the upper Piedmont (South of Atlanta) to become a tributary of the Chattahoochee River in the Gulf Coastal Plain near the southwestern Georgia state boundary.

The headwaters of this significant waterway were included in this study. Its drainage area is 703 square kilometers (272 square miles) and includes portions of Pike, Spalding, Fayette, Clayton, Henry, and Fulton Counties. The location of the USGS gauging station (#02344500) at latitude 33°14’39”, longitude 84°25’45” (Fig. 23) is referenced to North American Datum of 1983, and lies within Spalding County, GA, Hydrologic Unit 03130005, at the downstream side of a bridge pier on GA 16, 1.5 miles downstream from Shoal Creek, 5.5 miles upstream from Line...
Creek, 10.0 miles west of Griffin, and at river mile 304.4. USGS discharge data period of record is from March 1937 to present.

Atlanta Hartsfield International Airport is the respective NOAA weather station. It is located at 33°38'0" N, longitude 84°27'0" W. Its period of record spans from January 1930 to present.

During 2001, the Flint River watershed was fairly developed. Land uses were primarily deciduous forest, evergreen forest, pasture lands, developed low intensity, and developed open space. Developed land only totaled 34.93 %. Agricultural land totaled 13.35 %. Undeveloped land totaled 51.71 %.

The upper Flint River watershed is located in the Piedmont geologic region of Georgia. Migmatite is the main geological unit. Middle Paleozoic granitic and felsic paragneiss/schist compose the remaining geology of the Flint watershed.

Figure 22. USGS Gauge #02344500 for the Flint River (USGS, 2000).
Figure 23. Flint watershed land use during 2001 (top) and geology (bottom).
Figure 24. Dam locations and totals within the Flint watershed.

**Middle Oconee River Watershed near Athens, Georgia (Watershed Site #7)**

The Middle Oconee River starts in Hall County, Georgia and flows through the Piedmont geologic region. The Middle Oconee River is a drinking water source for Athens, Georgia. Whitewater rafting and fishing are common on this river. Fecal coliform, nitrogen, and sediment are listed on the 303(d) Georgia Impairment List as pollutants of concern for the Middle Oconee River.

The headwaters of this waterway were included in this study. Its drainage area is 1021 square kilometers (394 square miles) and includes portions of Hall, Gwinnett, Barrow, Jackson, Clarke, and Oconee Counties. The location of the USGS gauging station (#02217500) at latitude 33°56'48" N, longitude 83°25'22" W (Fig. 26) is referenced to North American Datum of 1983, and lies within Clarke County, GA, Hydrologic Unit 03070101, on the left bank 0.5 miles upstream
from US 78 and US 29 Business, 2.0 miles west of Athens, and 5.0 miles upstream from Barber Creek. The USGS discharge data period of record is from October 1901 to present.

Gainesville (GHCND: USC00093621) is the respective NOAA weather station. It is located at 34° 17' 59.9994" N and longitude 83° 50' 59.9994" W. Its period of record spans from October 1891 to present.

During 2001, the Middle Oconee River watershed was moderately developed. Land uses were primarily deciduous forest and pasture lands. Developed land only totaled 16.54%. Agricultural land totaled 25.05%. Undeveloped land totaled 58.41%.

The Middle Oconee watershed is located in the Piedmont geologic region of Georgia. Lower Paleozoic paragneiss, schist, migmatite rocks are the main geological units. Granitic and cataclastic rocks compose the remaining geology of the Middle Oconee watershed.

Figure 25. USGS Gauge #02217500 for the Middle Oconee River (USGS, 2000).
Figure 26. Middle Oconee watershed land use during 2001 (top) and geology (bottom).
Figure 27. Dam locations and totals within the Middle Oconee watershed.

References


Figure 28. Least-squares linear regression of the SPI in relation to discharge rates on (A) 1 & (B) 3 month time scale for the Chattahoochee River Watershed (1970 to 2000).
Figure 29. Least-squares linear regression of the SPI in relation to discharge rates on (A) 6 & (B) 9 month time scale for the Chattahoochee River Watershed (1970 to 2000).
Figure 30. Least-squares linear regression of the SPI in relation to discharge rates on (A) 12 & (B) 24 month time scale for the Chattahoochee River Watershed (1970 to 2000).
Figure 31. Least-squares linear regression of the SPI in relation to discharge rates on (A) 1 & (B) 3 month time scale for the Chestatee River Watershed (1970 to 2000).
Figure 32. Least-squares linear regression of the SPI in relation to discharge rates on (A) 6 & (B) 9 month time scale for the Chestatee River Watershed (1970 to 2000).
Figure 33. Least-squares linear regression of the SPI in relation to discharge rates on (A) 12 & (B) 24 month time scale for the Chestatee River Watershed (1970 to 2000).
Figure 34. Least-squares linear regression of the SPI in relation to discharge rates on (A) 1 & (B) 3 month time scale for the Sweetwater Creek Watershed (1970 to 2000).
Figure 35. Least-squares linear regression of the SPI in relation to discharge rates on (A) 6 & (B) 9 month time scale for the Sweetwater Creek Watershed (1970 to 2000).
Figure 36. Least-squares linear regression of the SPI in relation to discharge rates on (A) 12 & (B) 24 month time scale for the Sweetwater Creek Watershed (1970 to 2000).
Figure 37. Least-squares linear regression of the SPI in relation to discharge rates on (A) 1 & (B) 3 month time scale for the Coosawattee River Watershed (1970 to 2000).
Figure 38. Least-squares linear regression of the SPI in relation to discharge rates on (A) 6 & (B) 9 month time scale for the Coosawattee River Watershed (1970 to 2000).
Figure 39. Least-squares linear regression of the SPI in relation to discharge rates on (A) 12 & (B) 24 month time scale for the Coosawattee River Watershed (1970 to 2000).
Figure 40. Least-squares linear regression of the SPI in relation to discharge rates on (A) 1 & (B) 3 month time scale for the Chattooga River Watershed (1970 to 2000).
Figure 41. Least-squares linear regression of the SPI in relation to discharge rates on (A) 6 & (B) 9 month time scale for the Chattooga River Watershed (1970 to 2000).
Figure 42. Least-squares linear regression of the SPI in relation to discharge rates on (A) 12 & (B) 24 month time scale for the Chattooga River Watershed (1970 to 2000).
Figure 43. Least-squares linear regression of the SPI in relation to discharge rates on (A) 1 & (B) 3 month time scale for the Flint River Watershed (1970 to 2000).
Figure 44. Least-squares linear regression of the SPI in relation to discharge rates on (A) 6 & (B) 9 month time scale for the Flint River Watershed (1970 to 2000).
Figure 45. Least-squares linear regression of the SPI in relation to discharge rates on (A) 12 & (B) 24 month time scale for the Flint River Watershed (1970 to 2000).
Figure 46. Least-squares linear regression of the SPI in relation to discharge rates on (A) 1 & (B) 3 month time scale for the Middle Oconee River Watershed (1970 to 2000).
Figure 47. Least-squares linear regression of the monthly SPI in relation to discharge rates on (A) 6 & (B) 9 month time scale for the Middle Oconee River Watershed (1970 to 2000).
Figure 48. Least-squares linear regression of the SPI in relation to discharge rates on (A) 12 & (B) 24 month time scale for the Middle Oconee River Watershed (1970 to 2000).
Figure 49. Least-squares linear regression of the SPI in relation to the SDI on (A) 1 & (B) 3 month time scale for the Chattahoochee River Watershed (1970 to 2000).
Figure 50. Least-squares linear regression of the SPI in relation to the SDI on (A) 6 & (B) 9 month time scale for the Chattahoochee River Watershed (1970 to 2000).
Figure 51. Least-squares linear regression of the SPI in relation to the SDI on (A) 12 (B) 24 month time scale for the Chattahoochee River Watershed (1970 to 2000).
Figure 52. Least-squares linear regression of the SPI in relation to the SDI on (A) 1 & (B) 3 month time scale for the Chestatee River Watershed (1970 to 2000).
Figure 53. Least-squares linear regression of the SPI in relation to the SDI on (A) 6 & (B) 9 month time scale for the Chestatee River Watershed (1970 to 2000).
Figure 54. Least-squares linear regression of the SPI in relation to the SDI on (A) 12 & (B) 24 month time scale for the Chestatee River Watershed (1970 to 2000).
Figure 55. Least-squares linear regression of the SPI in relation to the SDI on (A) 1 & (B) 3 month time scale for the Sweetwater Creek Watershed (1970 to 2000).
Figure 56. Least-squares linear regression of the SPI in relation to the SDI on (A) 6 & (B) 9 month time scale for the Sweetwater Creek Watershed (1970 to 2000).

\[
y = 0.8179x + 0.0005 \\
r^2 = 0.6699 \\
p<0.0000
\]

\[
y = 0.8153x - 0.0098 \\
r^2 = 0.7389 \\
p<0.0000
\]
Figure 57. Least-squares linear regression of the SPI in relation to the SDI on (A) 12 & (B) 24 month time scale for the Sweetwater Creek Watershed (1970 to 2000).
Figure 58. Least-squares linear regression of the SPI in relation to the SDI on (A) 1 & (B) 3 month time scale for the Coosawattee River Watershed (1970 to 2000).
Figure 59. Least-squares linear regression of the SPI in relation to the SDI on (A) 6 & (B) 9 month time scale for the Coosawattee River Watershed (1970 to 2000).
Figure 60. Least-squares linear regression of the SPI in relation to the SDI on (A) 12 & (B) 24 month time scale for the Coosawattee River Watershed (1970 to 2000).
Figure 61. Least-squares linear regression of the SPI in relation to the SDI on (A) 1 & (B) 3 month time scale for the Chattooga River Watershed (1970 to 2000).
Figure 62. Least-squares linear regression of the SPI in relation to the SDI on (A) 6 & (B) 9 month time scale for the Chattooga River Watershed (1970 to 2000).
Figure 63. Least-squares linear regression of the SPI in relation to the SDI on (A) 12 & (B) 24 month time scale for the Chattooga River Watershed (1970 to 2000).
Figure 64. Least-squares linear regression of the SPI in relation to the SDI on (A) 1 & (B) 3 month time scale for the Flint River Watershed (1970 to 2000).
Figure 65. Least-squares linear regression of the SPI in relation to the SDI on (A) 6 & (B) 9 month time scale for the Flint River Watershed (1970 to 2000).

\[ y = 0.7932x - 0.0017 \]
\[ r^2 = 0.6289 \]
\[ p<0.0000 \]

\[ y = 0.8122x - 0.0242 \]
\[ r^2 = 0.6691 \]
\[ p<0.0000 \]
Figure 66. Least-squares linear regression of the SPI in relation to the SDI on (A) 12 & (B) 24 month time scale for the Flint River Watershed (1970 to 2000).
Figure 67. Least-squares linear regression of the SPI in relation to the SDI on (A) 1 & (B) 3 month time scale for the Middle Oconee River Watershed (1970 to 2000).

(A) 
\[ y = 0.6305x - 0.0042 \]
\[ r^2 = 0.3991 \]
\[ p<0.0000 \]

(B) 
\[ y = 0.7276x - 0.0002 \]
\[ r^2 = 0.5300 \]
\[ p<0.0000 \]
Figure 68. Least-squares linear regression of the SPI in relation to the SDI on (A) 6 & (B) 9 month time scale for the Middle Oconee River Watershed (1970 to 2000).
Figure 69. Least-squares linear regression of the SPI in relation to the SDI on (A) 12 & (B) 24 month time scale for the Middle Oconee River Watershed (1970 to 2000).
## Appendix D Metadata Sources

Table 11. Summary of weather, streamflow, and ArcGIS Metadata.

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