THE SPATIOTEMPORAL VARIABILITY OF FLASHINESS ACROSS NORTH GEORGIA

by

LINDSEY M. NIXON

(Under the Direction of J. Marshall Shepherd)

ABSTRACT

The North Georgia region experiences frequent instances of flash flooding due to the effects that urbanization have on precipitation enhancement. Historically, flash flooding has occurred within the metropolitan Atlanta area, and it is expected to increase as the climate continues to change. This research focuses on the use of stream gauge data provided by the United States Geological Survey to calculate the variable flashiness $ft^3mi^{-2}s^{-2}$. Alongside the calculation of flashiness, the spatiotemporal distribution will be statistically tested to determine relationships between the magnitude of flashiness, the percentage of urban imperviousness, and the degree of hill slope at each stream gauge. The utilization of ArcGIS Pro will provide analysis techniques, as well as visualizations. Additionally, the seasonality of flashiness will be investigated to understand the periodic flash flood risk of this region.

INDEX WORDS: Flashiness, Flash Flooding, Urban Flooding, Stream Gauges

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CHAPTER 1

INTRODUCTION

The Atlanta metropolitan region has been defined as the most populated urban area in the Southeastern United States (Dixon & Mote 2003). As of 2010, the urbanized portion of metropolitan Atlanta contained an area of 6850.519 square kilometers, however, as development continues to increase as will this value (U.S.C.B. 1994). The expansive metropolitan region is composed of 11 counties, including Cherokee, Clayton, Cobb, Dekalb, Douglas, Fayette, Forsyth, Fulton, Gwinnett, Henry, Rockdale. However, the impact of urbanization outstretching into suburban regions is closely connected to the increase of impervious surfaces from development. The study area of this research focuses on both the urbanized metropolitan area, as well as the surrounding counties that make up the northern portion of the state of Georgia.

The process known as “flash flooding” is defined by the National Weather Service as being “a flood which occurs within 6 hours or less of the causative event” (Dobur, 2006). Additionally, flash flooding determined by streamflow is expressed as the “discharge rising from base flow to exceeding bank-full in fewer than 6 hours” (Teale et al. 2016). This atmospheric process has been heavily researched across the Contiguous United States (CONUS), however, there has been minimal focus on the spatial distribution of flash flooding across the North Georgia region. The risk of flash flooding is increasing within cities, due to their “propensity to alter convective activity,” and ultimately change precipitation characteristics (Rose et al. 2008; Diem & Mote 2005). As impervious materials continue to overlay current permeable land types, counties surrounding the metropolitan areas will require continued analysis on their future likelihood of experiencing flash flooding. The influence of urbanization on flooding can be completed by analyzing locations, reviewing their past atmospheric processes, determining the expected influence of climate change, and finding the rate of industrial development (Bentley et al. 2010).

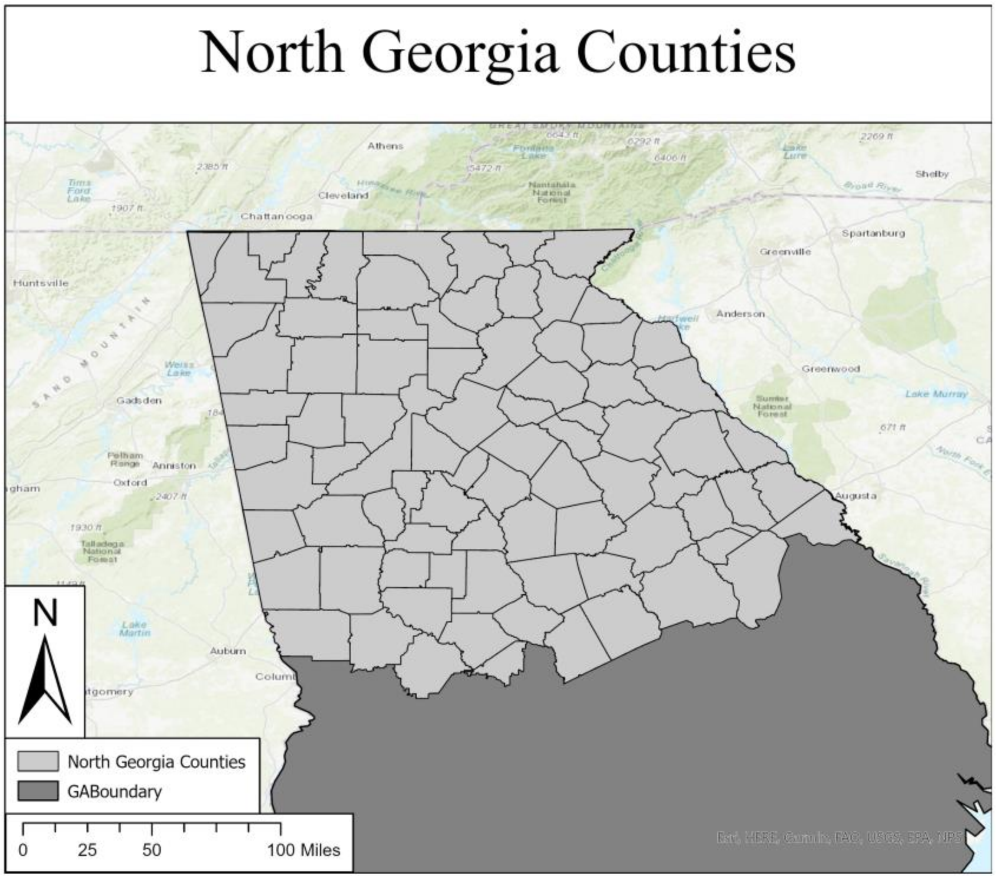

Figure 1. The 83 counties located in the northern half of the state of Georgia.

The risks associated with flash flooding are directly tied to the severity of the flooding within the area and can be expressed by a term known as the "flashiness index" (Saharia et al. 2017). The term “flashiness” was originally introduced by Poff et al. (1997), and defined by “how quickly flow changes from one magnitude to another” within rivers. Sahara et al. (2017) emphasizes the need for improvement in understanding “flash flooding…for assessing vulnerabilities and developing flood mitigation strategies”. The calculated term uses components of stream gauge collected data to produce an index that determines the severity of the flash flood; the index is dependent on the "rate of rise of the hydrography during flooding conditions" (Saharia et al., 2017). Flashiness with units of $ft^3mi^{-2}s^{-2}$ is calculated using four variables: peak discharge [Dp] measured in cubic feet per second, action stage discharge [Da] measured in cubic feet per second, basin area [A] measured in square miles, and flood rising time [T] measured in seconds.

$$\varphi = \frac{D_p - D_a}{A\ T}$$

Equation 1. Formula for calculating flashiness.

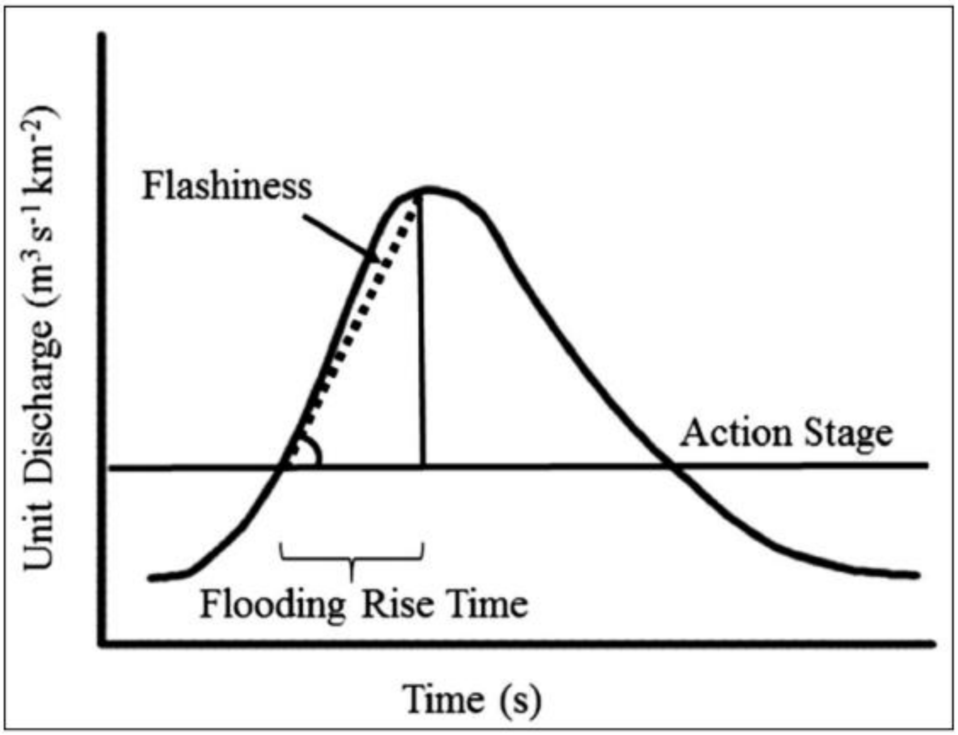

Figure 2. Graphical representation of the definition of flashiness (Saharia et al. 2017)

The usage of stream gauges provides additional information that aids in validating the models used to mitigate flash flooding incidents. The National Weather Service utilizes both the precipitation forecasts with known Quantitative Precipitation Estimates (QPE) and the stream gauge conditions to create rapid alerts of flooding conditions. It is critical to understand the land type where the stream gauges are located, including the "size of the drainage basin, the topography of the basin, and the amount of urban use within the basin" (Doswell et al. 1996). Finally, this research will study the patterns of flashiness in and around the Atlanta metropolitan region of North Georgia over the years of 2013-2021. Specifically, the following questions will be answered:

1.1 Research Questions

- How is flashiness distributed spatially across the urban metropolitan cluster and its surrounding North Georgia counties?
- Is there a statistically significant signal in flashiness as a function of urbanization and hill slope topography?
- Is there a signature of increased flashiness values during warm season precipitation events compared to cold season precipitation events, indicating that flashiness is a function of seasonality?

1.2 Research Hypotheses

- The spatiotemporal distributions of flashiness will have distinct hotspots in regions of urbanization and associated defined hill slopes.
- Flashiness will have maximums during the summer and fall seasons.

The following sections of this thesis describe the literature that previously has been studied on this topic, the research design and methodology, the results, and the conclusions made from this project. Each section aims at elucidating the research questions provided and determining the acceptance or rejection of the two hypotheses. Visuals were produced to show the results of each research question in a map format of the study area. Additionally, tables and plots were developed to express the results of the statistical analysis.

CHAPTER 2

LITERATURE REVIEW

2.1 Review of Flash Flooding

Meteorological events resulting in flash flooding have been previously researched to elucidate the causes of heavy precipitation events and their relationship to other hydrologic components (Dobur et al. 2006). Flash flooding and heavy precipitation events have been analyzed focusing on the broad scale of the Contiguous United States (CONUS) (Khajehei et al. 2020). Additionally, flash flooding clusters have been previously identified in the southeastern Appalachian region. The Appalachian region includes north Georgia and the largest population center of the southeastern United States, Atlanta, Georgia, therefore increasing the significance in understanding flooding across the north Georgia region (Khajehei et al. 2020). These clusters are commonly characterized by their frequency, magnitude, duration, and severity (Khajehei et al. 2020). It has been concluded that when the rainfall rate is the heaviest for an extended period of time the largest amount of precipitation occurs (Schumacher 2017).

Studies focused on the United States have determined that flooding events, specifically flash flooding events, have resulted in the highest number of casualties and injuries among populations (Ashley & Ashley 2008). Previous research has concluded that "tropical cyclones were the most common producers of heavy rainfall across the southeastern United States" (Schumacher & Johnson 2003; Shepherd et al. 2007). However, tropical cyclones are not the only producer of intense rainfall within these urban regions. It has been found that atmospheric events that primarily produce "extreme precipitation in the southeastern United States include cut-off lows, tropical cyclones, frontal and damming systems, warm season convection, and atmospheric rivers" (McLeod et al. 2017). Atmospheric rivers "continually form, move, and evolve with storms in the midlatitudes" and commonly draw "tropical water vapor and heat" in the mid-latitudes (Ralph and Dettinger 2011). Elevated rainfall totals have been found "in the east and northeast suburbs" of Atlanta, located downwind during the warm season rainfall climatology (Mote et al. 2007; McLeod et al. 2017; McLeod & Shepherd 2022). Debbage and Shepherd (2019) found that urbanized environments are more vulnerable to flooding due to runoff and the quantity of precipitation events due to urban rainfall enhancements. Future precipitation has been shown to increase due the climate changing (Yang et al. 2016; Khajehei et al. 2020; Alipour et al. 2020). Significant growth of urban regions is expected to continue to increase precipitation due to land use changes and anthropogenic influence (Liu and Nuyogi 2019).

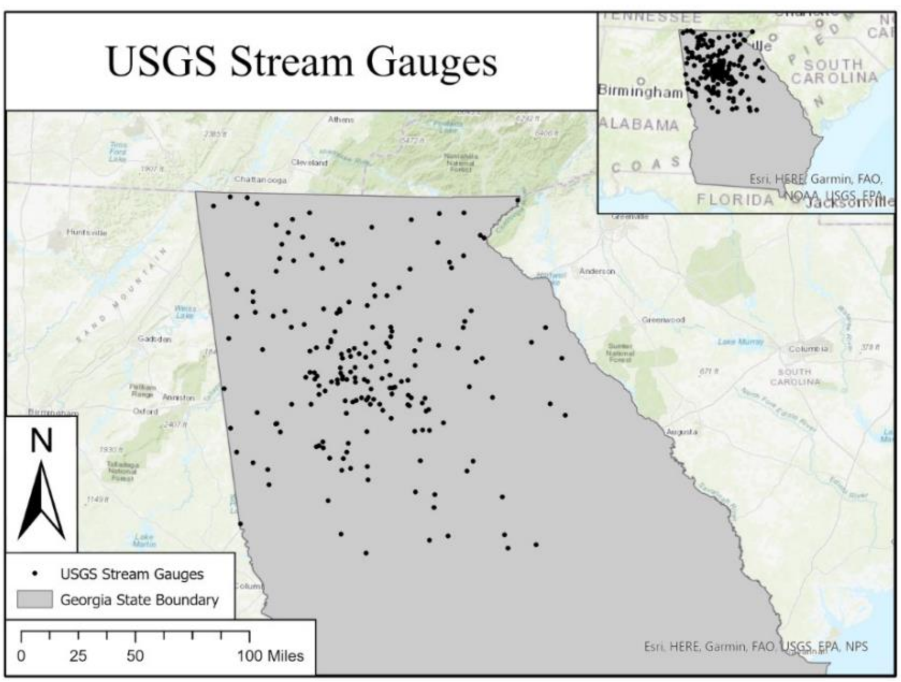

Figure 3. United States Geological Survey (USGS) stream gauge stations located in the norther portion of Georgia.

2.1.1 Stream Gauge Usage for Flood Determination

The United States Geological Survey (USGS) collects streamflow measurements for areas across North Georgia. According to USGS, "flood events are…when streamflow exceeds the defined action stage" at a gauge (Khajehei et al. 2020). Previous flash flood studies acknowledge the difficulty of determining the risk of an area lacking a stream gauge, therefore, areas that do not have a local gauge have an increased chance of being under-represented in flash flood risk analysis (Schroeder et al. 2016). By combining the data provided by both rain gauges and radar, precipitation measurement accuracy is increased, as well as the response time during a flash flooding event (Ochoa-Rodriquez et al. 2019). Additionally, it has been determined that gauged measurements are the most useful in areas that have mountainous terrains (Volkmann et al. 2010).

2.2 Influence of Urbanization and Impervious Surface Expansion

Research has shown that the urban landscape influences the increase of precipitation in urbanized city centers along with convergence and aerosol presence (Bentley et al. 2010; Debbage & Shepherd 2015; Oke 1982). Urban environments provide the conditions favorable for thunderstorm formation due to the heat and convergence present (Bentley et al. 2010). The urban heat islands are formed by "enhanced anthropogenic heat emissions, reduced evaporative cooling, increased surface roughness, and lower surface albedos" (Oke 1982). Alongside the UHI, cities experience enhancement in thunderstorms due to the "thunderstorm winds interacting with the urban heat island circulations" (Bentley et al. 2010). There are greater risks associated with flash flooding within urbanized regions due to the elevated population within the flood zone, as well as the modifications made to the surface materials that "largely govern rainfall-runoff processes" (Debbage & Shepherd 2019). The introduction of land use changes "have the potential to initiate and enhance precipitation," which provides more opportunities for flash flooding events (Diem & Mote 2005. McLeod et al. (2017) suggested continued research of "extreme rainfall within the context of urban landscapes since flooding is increasingly a physical and socio-economic hazard." Due to the advancements in urbanization, it has been estimated that these basins will be "more prone to intense rainfall with reduced infiltration" because of the lack of vegetation (Khajehei et al. 2020). The increase of precipitation within urbanized regions is influenced by the "surface roughness and elevated atmospheric aerosol concentrations" (Rosenfeld et al. 2008; Ntelekos et al. 2009). Consequently, urbanized watersheds have recently had "research investigating the critical temporal and spatial resolutions of rainfall fields for urban flood response" (Yang et al. 2016). Additionally, the continued addition of "increase in the fraction of impervious surfaces…lead to an increase in flood peaks and decrease in lag time between maximum rainfall rate and peak discharge" (Yang et al. 2016).

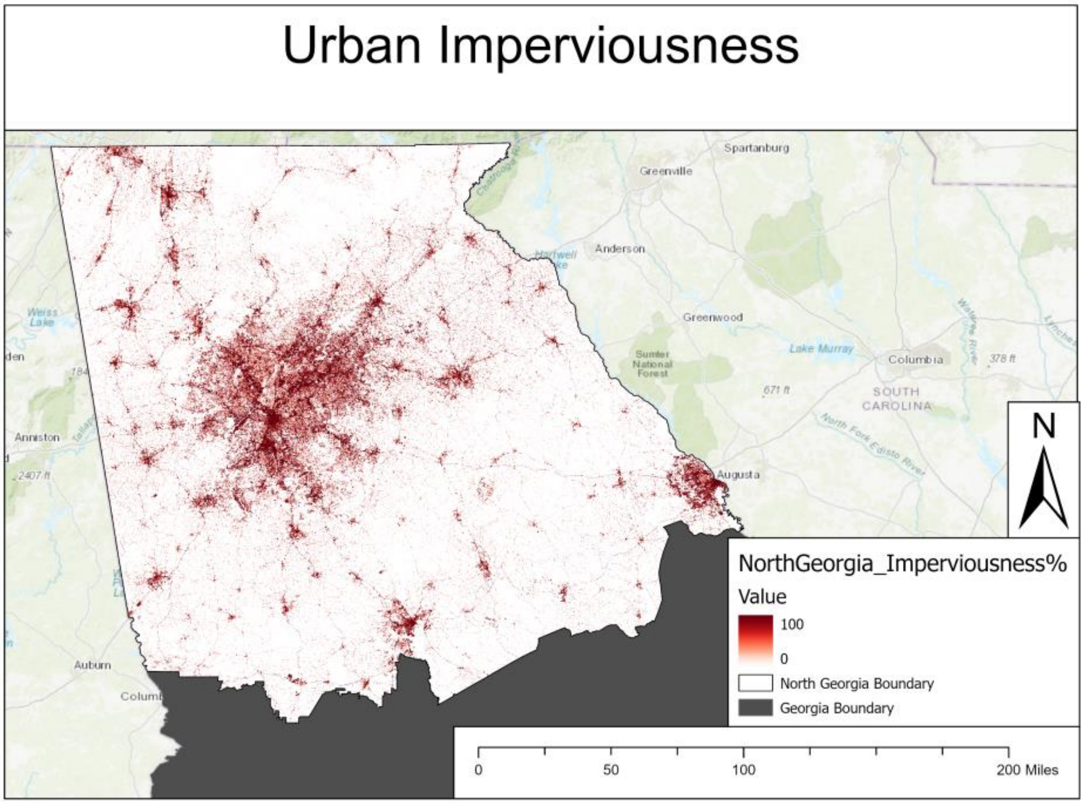

Figure 4. Percentage of Urban Imperviousness in 2019 presented across North Georgia. National Land Cover Database (NLCD) 2019.

2.3 History of Flash Flooding in Urbanized Regions

Metropolitan Atlanta has historically experienced flash flooding; Shepherd et al. (2011) discussed the atmospheric conditions that led to the "disastrous Atlanta flood of 2009." This event was characterized by the "United States Geological Survey measuring the largest flow ever recorded on Sweetwater Creek near Austell," (Shepherd et al. 2011). The heavy precipitation was caused by a weak cut-off low that was "stalled over the southern Plains and lower Mississippi Valley" (Shepherd et al. 2011). This flooding event has been characterized as catastrophic due to the continuous 500 mm rainfall that covered North Georgia (Schroeder et al. 2016). As rapid urbanization continues globally, the issue of flash flooding becomes a "global natural hazard" (Schroeder et al. 2016). However, the instances of flash flooding are not limited to the city of Atlanta, Georgia, providing the need for continued research.

2.4 Influence of Hillslopes and Topographic Variations on Flooding

The association between both slope and topography is significant in understanding the flood risk within a specific region. Previous studies have found that "areas at low elevation are more prone to flooding than areas at high elevations because runoff is directed…at the base of slopes" (Rafiei-Sardooi et al. 2021). In addition to localized lower elevations increasing the flooding of an area, regions that exist in zones with low slope gradients have a "high susceptibility to flooding" (Fernandez and Lutz 2010). Research completed by Kim et al. (2016) found that the region with the lowest slope, measuring at 1.29 degrees, experienced the highest number of floods when compared to those existing at higher slopes. Dalu et al. (2018) found that regions of low gradient slopes have increased vulnerability to flooding when compared to high gradient slopes. The details of the topography provide useful information for flood planning and improvements in flood analysis techniques. The increase in slow runoff in addition to the land type pose a threat to individuals in the low slope zones. The decrease of green spaces leads to a decrease in infiltration at the surface in situations where runoff is decreasing in velocity.

2.5 Influence of Seasons on Atmospheric Processes and Flooding

Atmospheric processes are commonly grouped into seasonal categories to determine the seasonality of these events for both forecasting and mitigation improvements. Prior studies have focused on the seasonality of heavy precipitation and flash flooding events in the southeastern United States. Different "flood generating events may be dominant during different seasons, produce precipitation with distinctly different duration and intensity characteristics" of varying magnitudes (Lecce 2000). Previous research has found that the southeastern United States experiences increases in precipitation measured by both magnitude and frequency during the summer and fall months (Mallakpour & Villarini 2017). Knutson and Tuleya (2004) discuss the projected increases within climate models of tropical cyclone generated precipitation across the southeastern United States. Climate model projections provide information on the modifications of current precipitation events that are associated with a changing climate (Knutson and Tuleya 2004). The continued research of seasonality of flash flooding events is necessary to develop proper mitigation strategies for flood events. Lecce (2000) recognized the significance of understanding the seasonality of both the magnitude and frequency of these meteorological precipitation producing events that result in floods.

Across the southeastern United States flooding commonly impacts communities during all seasons, with maximums in the summer and fall seasons (Lecce 2000). Ultimately, it is important to determine the spatial distribution of these floods within each season to better prepare and mitigate for flash flooding events. Heavy precipitation events, specifically flash flooding events, are expected to increase as climate change continues to worsen (Alipour et al. 2020).

CHAPTER 3

RESEARCH DESIGN

This thesis aims at understanding the spatial variability and seasonal variability of flashiness across the metropolitan region of Atlanta and the surrounding counties. Additionally, the research is focused on determining the influence of both imperviousness and hillslope on flashiness within the study area.

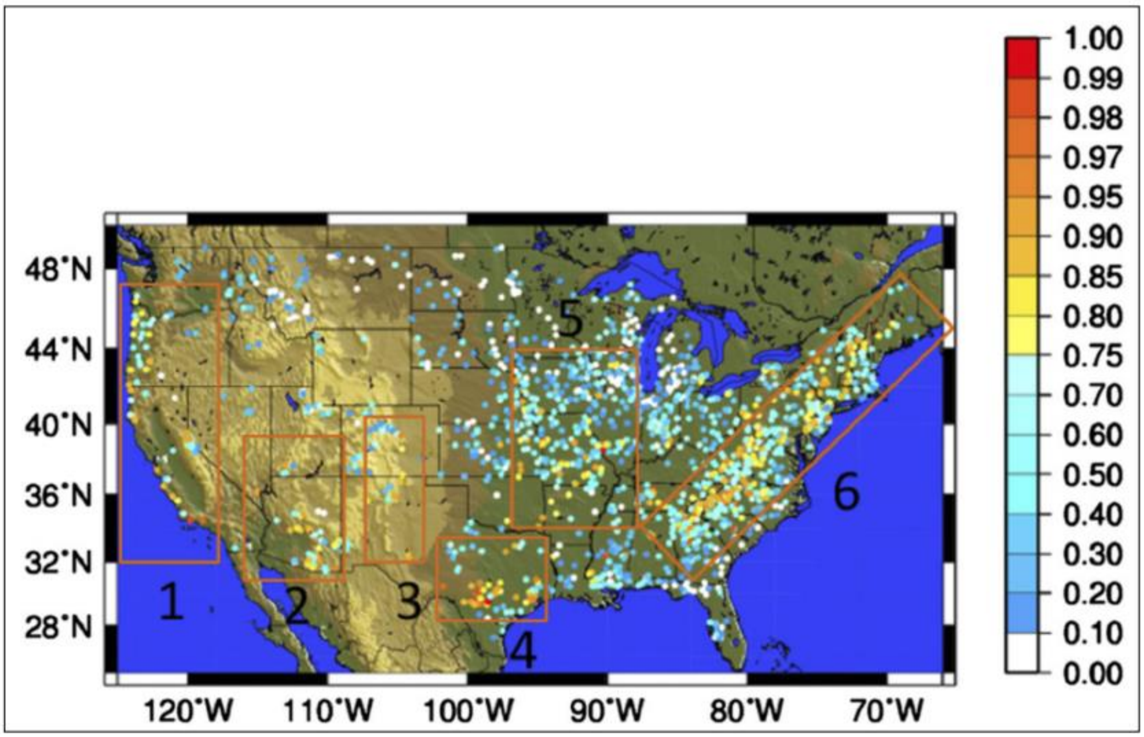

Figure 5. Distribution of flashiness across the Continental United States from the study conducted by Saharia et al. 2017.

3.1 Research Objectives

Previous studies have focused on the variability and the severity of flash flooding across the continental United States through use of the flashiness index, however, there are few studies that concentrate on the Atlanta metropolitan area. This research will focus on the spatial distribution of flashiness across North Georgia to understand the areas of highest risk due to their impervious surface percentages and the hill slope of the topography. The study will also determine if flashiness is a function of seasonality to further understand the patterns of flash flooding severity in Atlanta. The increase in impervious surface coverage and urban expansion within cities is drawing attention due to the seasonal and temporal changes in the patterns from climate change and anthropogenic causes (Ye et al. 2017). Through analyzation of flashiness across the study area, this research determined the spatial variation in flood severity surrounding the metropolitan region of Atlanta, Georgia. Additionally, the relationship of both hillslope and urbanization on flashiness was determined by usage of statistical test and analyzation of magnitudes. The research questions below were investigated throughout this thesis.

Research Question 1: How is flashiness distributed spatially across the urban metropolitan cluster and its surrounding North Georgia counties?

Research Question 2: Is there a statistically significant signal in flashiness as a function of urbanization and hill slope topography?

Research Question 3: Is there a signature of increased flashiness values during warm season precipitation events compared to cold season precipitation events, indicating that flashiness is a function of seasonality?

The foundation of this research focuses on the recently altered flashiness formula by Saharia et al. (2017). This formula, although similar to R-B Index determines flashiness values at each recorded observation using real-time collected data, while Baker et al. (2004) utilizes mean daily streamflow data for the final calculation. Therefore, the formula developed by Saharia et al. (2017) allows for a finer temporal resolution of data for the calculation, which is necessary for determining instances of flash flooding which occur on a 6-hour or less time frame.

CHAPTER 4

METHODS

4.1 Data

The primary data that was used for this research project was sourced from the United States Geological Survey National Water Information System. The streamflow discharge daily data was collected at fifteen-minute increments for each stream gauge. This frequency of data collection results in approximately 1,440 records of observational data for each day of the calendar year. This research focuses on the years of 2013-2021. This period of time was chosen as a continuation of the flash flooding following the research completed by Dober (2006) and based upon data availability of the USGS stream gauge data for North Georgia. Urban Imperviousness data was sourced from the United States Geological Survey National Land Cover Database for the most recently collected year of 2019. Lastly, Digital Elevation Data was collected from the United States Geological Survey Database. All data within ArcGIS Pro was projected to the NAD 1927 Georgia Statewide Albers (US Feet) to ensure accuracy in spatial calculations, area and distance.

In order to ensure that each dataset includes a significant number of observations for analysis all stream gauge stations must include 93% of records for the total period of 2013-2021. This percentage of data ensures that the observational data includes roughly 48.5 complete weeks of data for the 52-week calendar year. Through the reduction of datasets both inconclusive readings and processing errors resulting in null values were removed from each station. Following this data processing, 108 stream gauge stations were included in the final analysis process.

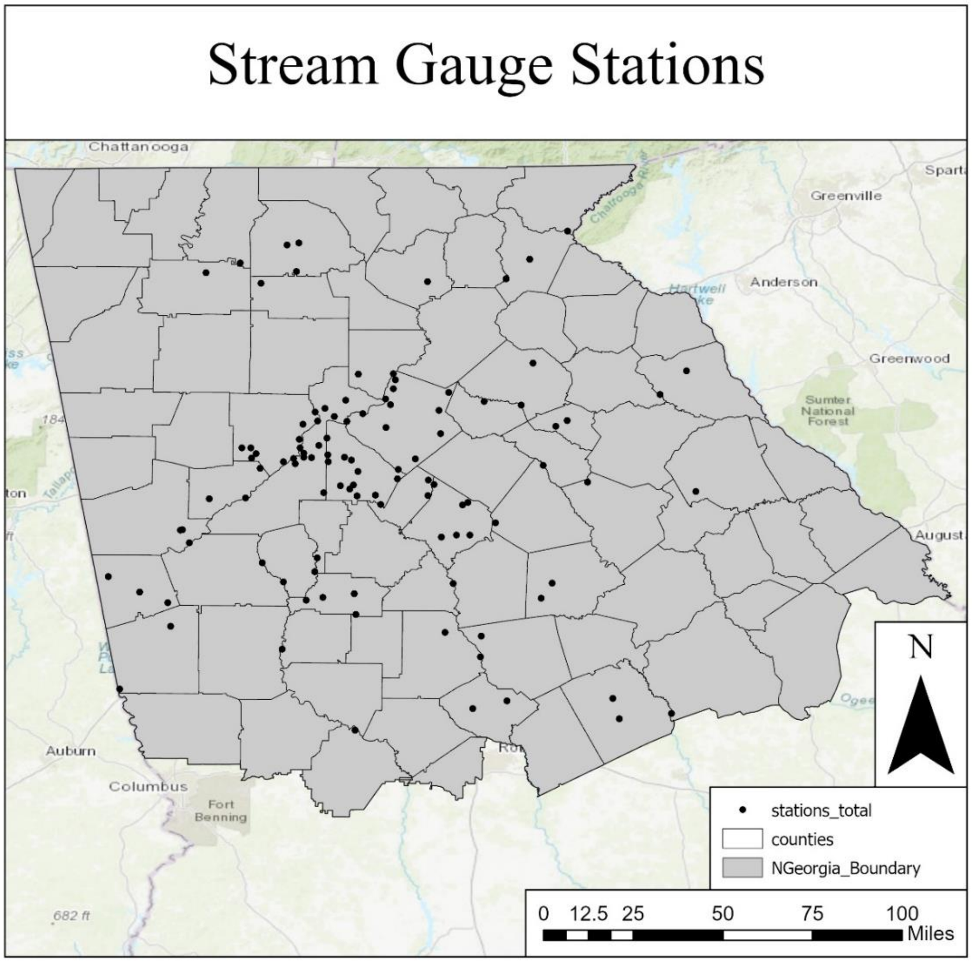

Figure 6. 108 United States Geological Survey Stream Gauge Stations included in this research study. These stations included 93% of observational data during the period of 2013-2021.

4.2 Tools for Data Management and Analysis

The software R was utilized by use of written code to obtain stream gauge data directly from the United States Geological Survey National Water Information System. This software allows for the datasets to be imported and updated as data continuously is approved by using code written by the user. For each step of the programming process of this thesis, I wrote the code necessary to import the data, process the variables, and successfully extract the necessary years of data. Additionally, R was used for the calculation the "flashiness" for each station included in the study. This calculation was completed by use of code I wrote within the R Studio interface. The formula used for this calculation was directly sourced from Saharia et al. (2017), however, there was additional programming that needed to be completed prior to the final calculation. This flashiness calculation code allows the determination of the magnitude of flashiness at every recorded observation time. This results in a flashiness value recorded every 15 minutes. The ESRI product, ArcGIS Pro, was used to produce visualizations of maps and conduct spatial analysis across the study area. Additionally, ArcGIS Pro was used to conduct a hot spot analysis of the flashiness indices across the study area. This process was completed to determine the statistically significant highest and lowest values of flashiness. The hill slope calculations were completed by using the software ArcGIS Pro calculate the slope of the digital elevation data for each stream gauge location.

4.3 Methods: Research Question 1

The results of Saharia et al. determined "high values of flashiness from Georgia" along the Appalachian Mountains, however, there were minimal results within published research on how flashiness spatially presents across the urban center of North Georgia (Saharia et al. 2017). The research conducted by Saharia et al. produced bounding boxes that represented hot spots of flash floods, which contained the northern half of the state of Georgia. The calculated flashiness values from the software R for each of the stream gauges determine the spatial distribution of flashiness across North Georgia. The majority of stream gauges within this study fall within the spatial boundary of the metropolitan region of Atlanta. Following the calculation of flashiness, the resulting values are visualized spatially across the study area by points representing their value of flashiness. The flashiness values are plotted utilizing ArcGIS Pro, providing one value for each stream gauge location in the study area.

4.4 Methods: Research Question 2

To determine results for this question there are two characteristics of the landscape that will be tested to determine significance during this study: hill slope and urbanization. In order to calculate the imperviousness, the National Land Cover Database Urban Imperviousness for the study area was classified with values ranging from 1-100% of imperviousness. The regions that do not include urbanized land type will be removed from the processing. Additionally, the percentage of imperviousness by county will be represented within ArcGIS Pro using a county polygon shapefile. The imperviousness raster file will be processed to a polygon, projected to the NAD 1927 Georgia Statewide Albers (US Feet), and then clipped from the county polygon shapefile. Following this step, the percentage of area covered by imperviousness will be calculated through the calculate geometry tool within the attribute table of ArcGIS Pro. The final step of this analysis includes the use of the calculate field tool within the attribute table, where the total county area had the imperviousness area removed, divided by the total area, and multiplied by 100 to create the final percentages.

The flashiness indices that were previously calculated for the first research question were utilized to determine spatial clustering of hillslope and flashiness values. The specific hot spot analysis tool, Getis-Ord Gi*, produces a statistic for each feature that is being analyzed. The calculation produces both z-scores and p-values to conclude high or low clusters with statistically significant findings. A Mann-Whitney U Test was completed to determine if flashiness is affected by land type. This process was completed by utilizing both urban and rural data, and placing a 20 km buffer around all stations to ensure they are not influenced by surrounding imperviousness. The specified distance of 20 kilometers for the buffer was determined by using an intersection analysis, which provided information of the distance rural sites were from impervious land.

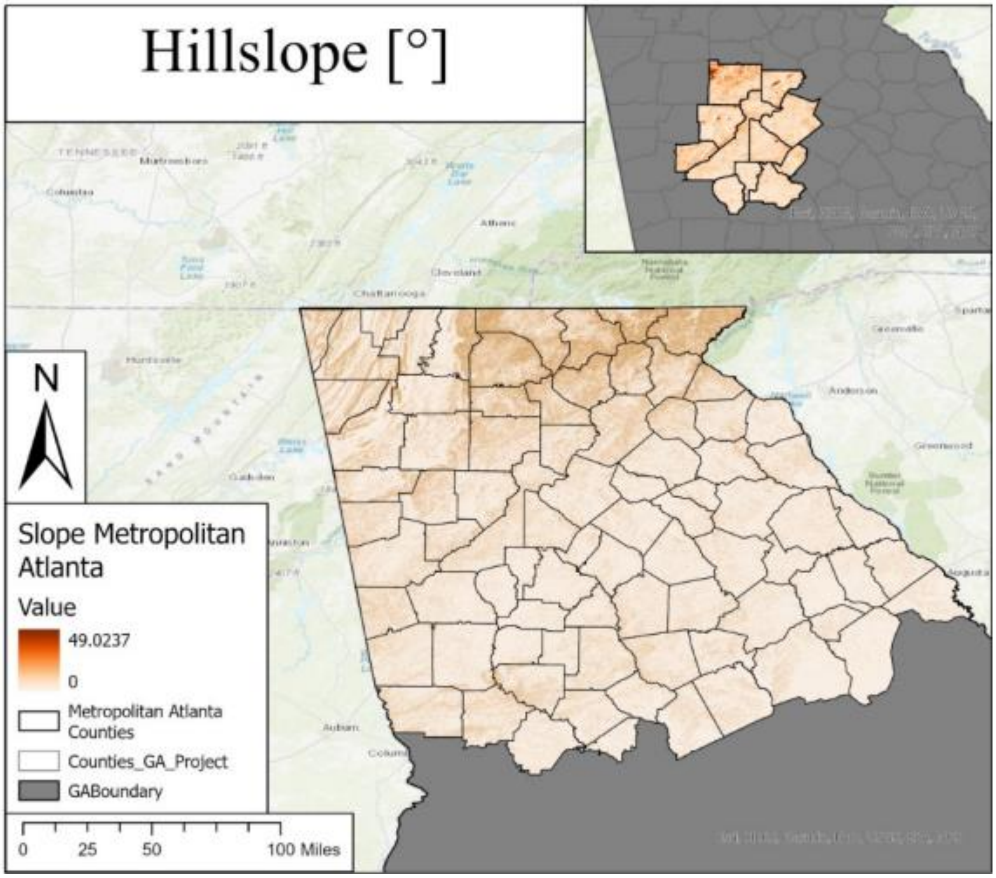

Figure 7. Hillslopes across North Georgia in Degrees. (USGS DEM).

4.5 Methods: Research Question 3

As previously mentioned, the flash flooding in the southeastern United States historically has occurred during the summer and fall seasons. Wright et al. (2012) determined that the "rainfall and flood climatology across the southeastern United States is the result of a mixture of tropical cyclones, winter and springtime extratropical systems, and warm-season thunderstorm systems". For this research question, the calculated flashiness indices from the earlier analysis will be subdivided by the results into the meteorological classifications of seasons. Following the calculation of flashiness for the 2013-2021 period, the data was categorized by their respective seasons within ArcGIS Pro. The seasonal classifications will be determined by using climatological season groupings of DJF, MAM, JJA, and SON. By creating subgroups of the data, I was able to determine if flashiness shows periodic fluctuations, and is therefore, a function of seasonality. The research included the usage of hot spot analyses utilizing Arc GIS Pro produced by ESRI. This method has been previous used by researchers to determine statistical significance for areas of local flash flooding hot spots and cold spots (Khajehei et al. 2020). Following the hot spot analysis results, areas of like-values that are deemed significant were represented as concentrated hot spots or cool spots, depending on their magnitude. The hot spot analysis tool requires specific values of flashiness to conceptualize spatial relationships. The fixed-distance setting was utilized for the hot spot analysis with a specific distance based upon the nearest neighbor test. This test is chosen within ArcGIS Pro when using the hot spot analysis tool to ensure a proper number of neighbors are within a specific distance to calculate the spatial hot spots and cold spots. The calculated values of flashiness were displayed on a map of north Georgia produced in ArcGIS Pro.

CHAPTER 5

RESULTS

5.1 Flashiness: Total Study Period

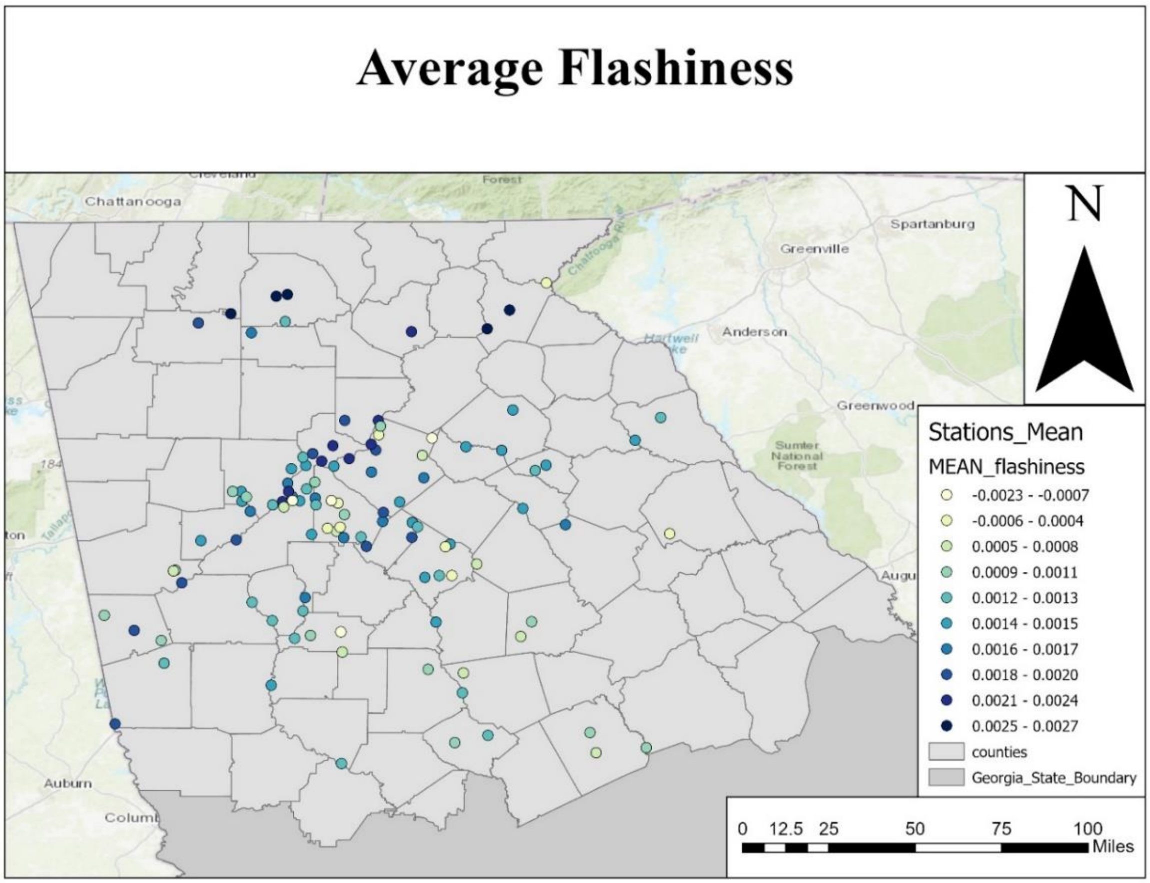

Figure 8. The average flashiness calculated for each stream gauge station including all data from 2013-2021.

The mean flashiness calculation shown above in Figure 8 represents the total average for each station over the period of analysis of 2013-2021. There are flashiness patterns spatially across the study area, specifically represented through higher values within the northern region and across the metropolitan cluster and lower values to the south and eastern regions. Although there are higher total averages for each station in the more northern stream gauge stations, it is important to highlight the large cluster of larger means at urban stations across both Fulton and Dekalb counties. While a positive flashiness represents a specific stream gauge that experiences a peak in the water level above the action stage, which indicates a risk for flooding, a negative flashiness represents an area that water is below the action stage.

Out of the 108 stream gauge stations present in this analysis, 102 experienced positive flashiness values and 6 experienced negative flashiness values. This result shows that 94.4% of stations experienced a positive average value of flashiness, which indicates that they had conditions where the water was above the action stage at the gauge location. However, additional

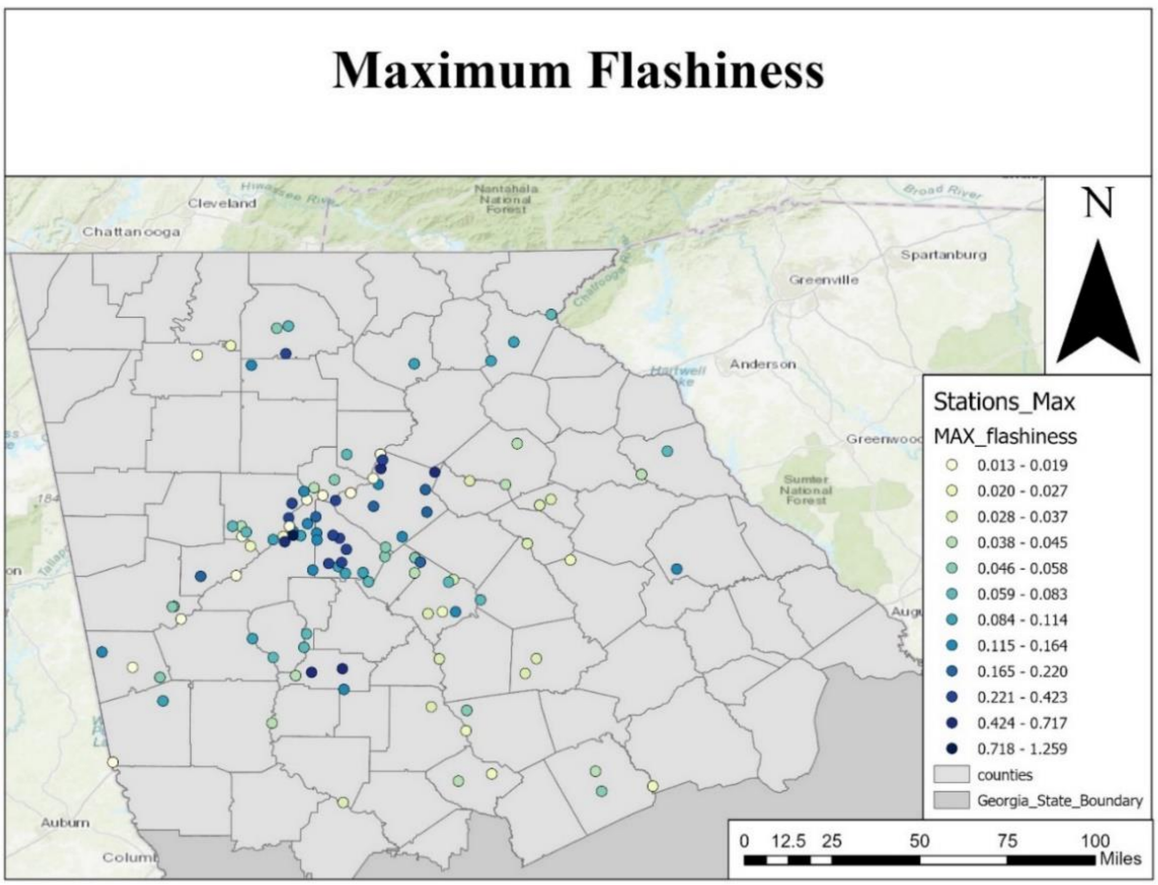

Figure 9. The maximum flashiness calculated for all stream gauge stations across the study area from 2013-2021.

analysis is needed to understand the spatial variability of maximum values at each the station for flooding risk.

Figure 9 shows the maximum values of flashiness for each stream gauge location over the years 2013-2021. Through visual analysis the metropolitan region has a cluster of maximum values across Fulton, Cobb, Dekalb, and Gwinnet counties. As the counties increase in distance from the urban core their flashiness values decrease when moving in the southern direction.

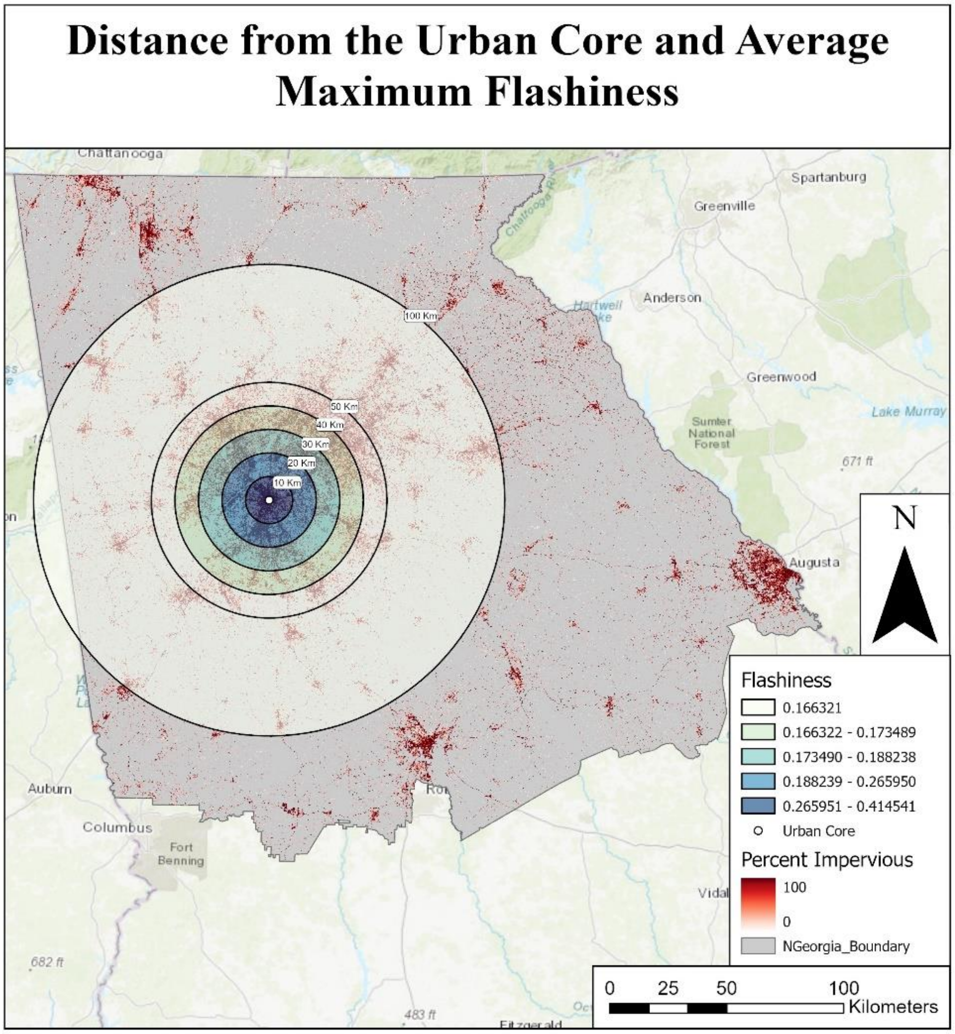

Figure 10. The average maximum flashiness values for 2013-2021 dependent on distance from the urban core. The figure visualizes the increasing distance from the urban core shown in contrast with urban imperviousness. Each distance is measured from the urban core as follows: 0-10km, 0-20km, 0-30km, 0-40km, 0-50km, and 0-100km.

The significance of analyzing the maximum values in addition to the averages is to understand the stations who have the greatest amount of flashiness, which indicates that there is a risk of flooding over a short time frame. The lowest maximum value of flashiness is measuring at 0.013 $ft^3mi^{-2}s^{-2}$ while the highest maximum value of flashiness is 1.259 $ft^3mi^{-2}s^{-2}$.

However, there is significance in understanding the level of maximum flashiness on an incremental scale as distance increases from the urban core. An additional figure has been developed to allow a more detailed visual of how flashiness varies spatially from the urban core. Shown in Figure 10 are the average totals of maximum flashiness within each buffer based upon the donut method geomasking technique. This method ensures that each value falls within the minimum and maximum distance for each buffer zone.

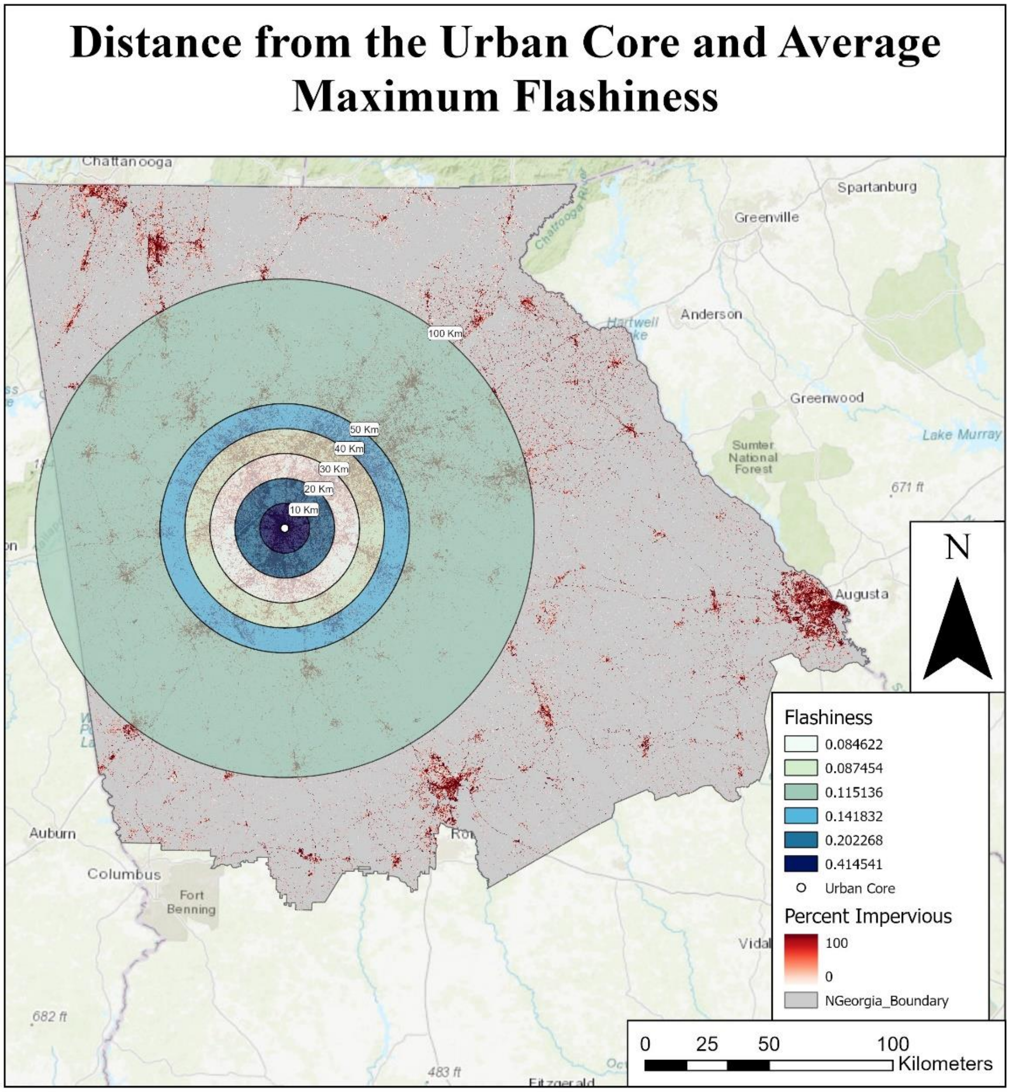

Figure 11: The average maximum flashiness values for 2013-2021 dependent on distance from the urban core. The figure visualizes the increasing distance from the urban core shown in contrast with urban imperviousness. Each distance is measured from the smallest boundary of the buffer zone to the maximum boundary as follows: 0-10km, 10-20km, 30-40km, 40-50km, 50-100km.

Additionally, Figure 11 shows the maximum flashiness by distance from the urban core on an incremental increase of 0-10km, 10-20km, 20-30km, 30-40km, 40-50km, and 50-100km. By using this method, the influence of the urban core on flashiness values is magnified visually as both the 0-10 kilometer and 10-20 km zones experience the greatest magnitude of flashiness out of all buffer zones moving outward from the urban core. The urban core is the location where the highest amount of imperviousness exists and the location of the metropolitan county clusters. As the distance of the buffer zones increase to 20-30 kilometers from the urban core, the average maximum flashiness drops to the lowest recorded average. This decrease in flashiness at the 20-30 km distance is outside of the boundaries of the city of Atlanta, however, this region is still within the boundary of the metropolitan county limits.

In review of both the average flashiness and the maximum flashiness for the period of 2013-2021 there are significant indicators that show clustering of high flashiness values across the metropolitan region, while also demonstrating the decrease in flashiness as distance from the urban core increases. These characteristics lead to the further analysis of the influence of imperviousness, urbanization, and defined hillslopes on the value of flashiness and the risk of regions to experiencing flash flooding.

Represented in Figure 12 is a box and whisker plot which represents the distribution of values within each buffer zone for the average maximum flashiness values. There is the greatest range of distribution across the 0-10km zone and the second greatest range of distribution across the 10-20 km zones. The highest median value exists within the 0-10km buffer zone. The patterns shown within the box-and-whisker support the results of the visual map represented in Figure 10.

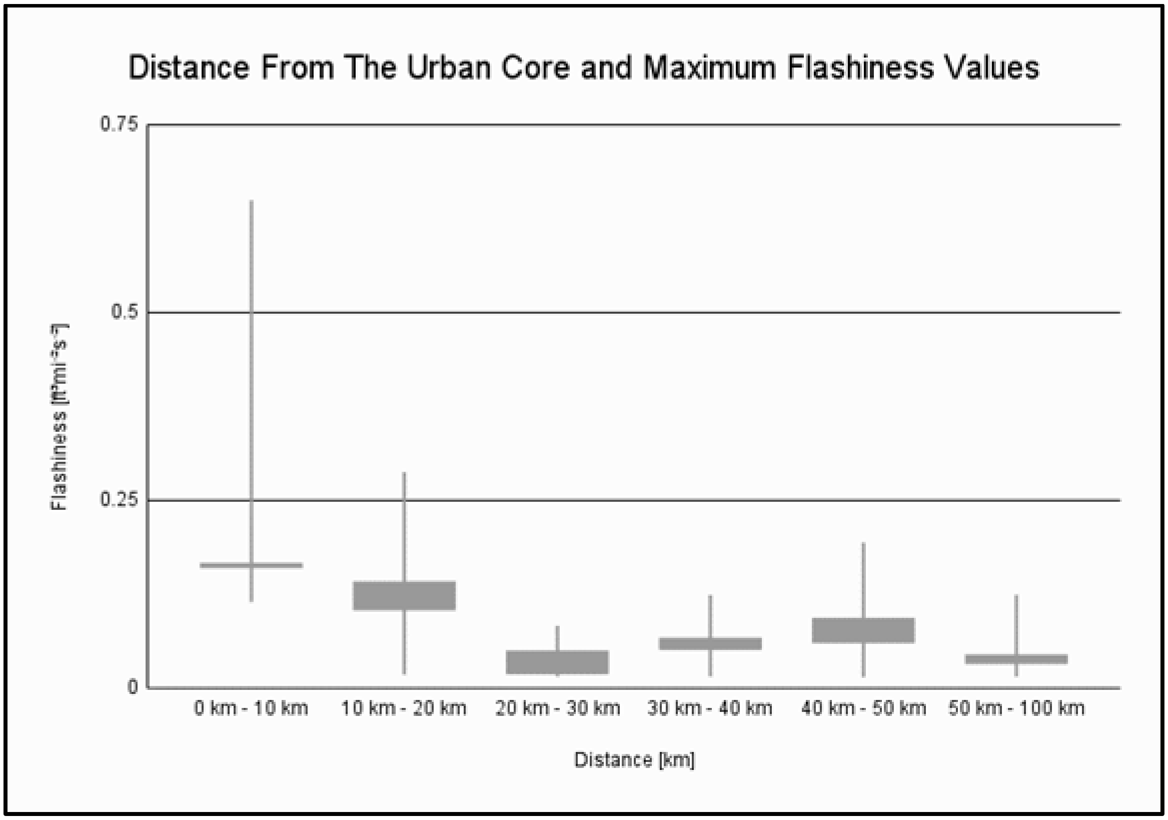

Figure 12: The average maximum flashiness measured from the urban core represented through a box-and-whisker plot.

5.2 Surface Imperviousness

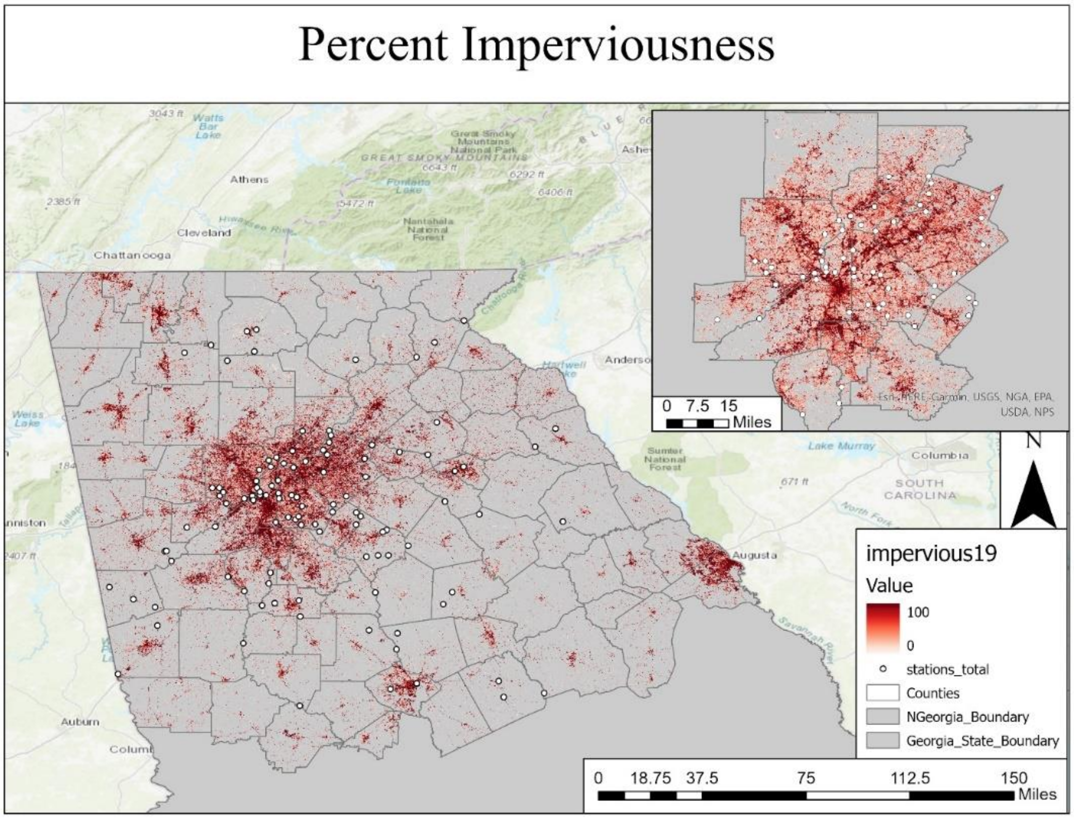

Figure 13. Percentage imperviousness across the study area. The upper right hand displays the percentage of imperviousness within the 11 metropolitan counties at a larger scale.

The percentage of imperviousness and the locations of all 108 stream gauges within the study area is shown in Figure 13. This thesis aims at understanding the influence of imperviousness on flashiness. By layering the counties boundaries on top of the percentage of imperviousness in 2019, the variation of urbanized land by county is more clearly visualized. The urban core is pictured in the upper right corner of Figure 13, the cluster of eleven counties that compose the metropolitan region of Atlanta, Georgia.

Figure 14 presents the percent imperviousness by county, with varying totals across the study area shown through intensity of a monochromatic color. The highest percentage of imperviousness exists in Cobb, Dekalb, and Gwinnet counties with a range of 64-72%. The lowest value of imperviousness across the study area measures at 3.94% and is spatially located to the south the metropolitan center of the study area. Although these values do not show the change from the beginning of data collection in 2013 to the end of data collection at 2021, the percentages represent the overall urbanization that is present across the counties of study in 2019. More specifically, these imperviousness values in 2019 develop the foundation of data for future studies as the influence of imperviousness on flash flooding continues to be researched.

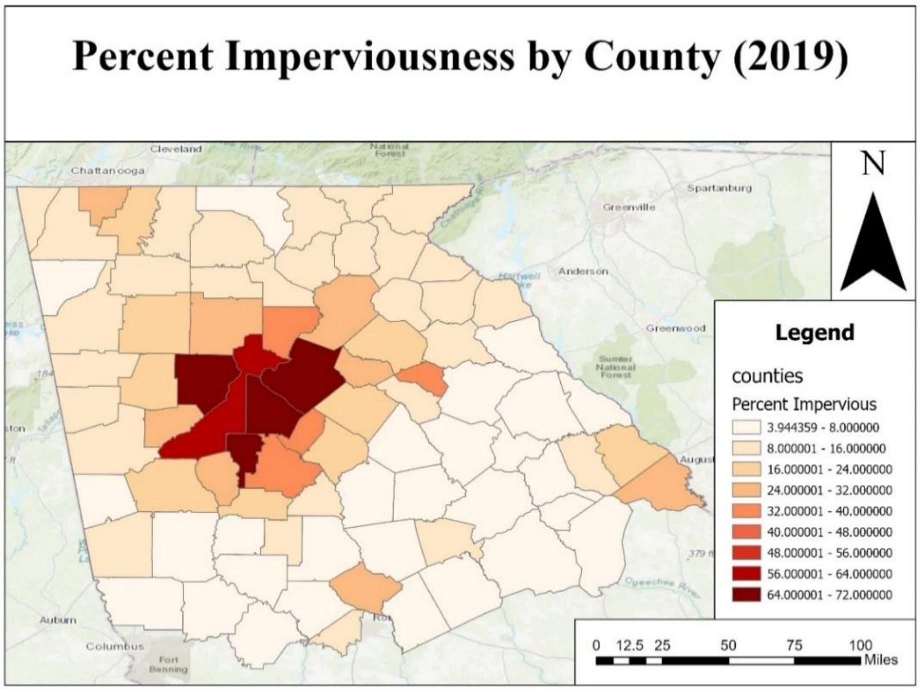

Figure 14. The percentage of imperviousness within each county calculated within ArcGIS Pro. NLCD Urban Imperviousness.

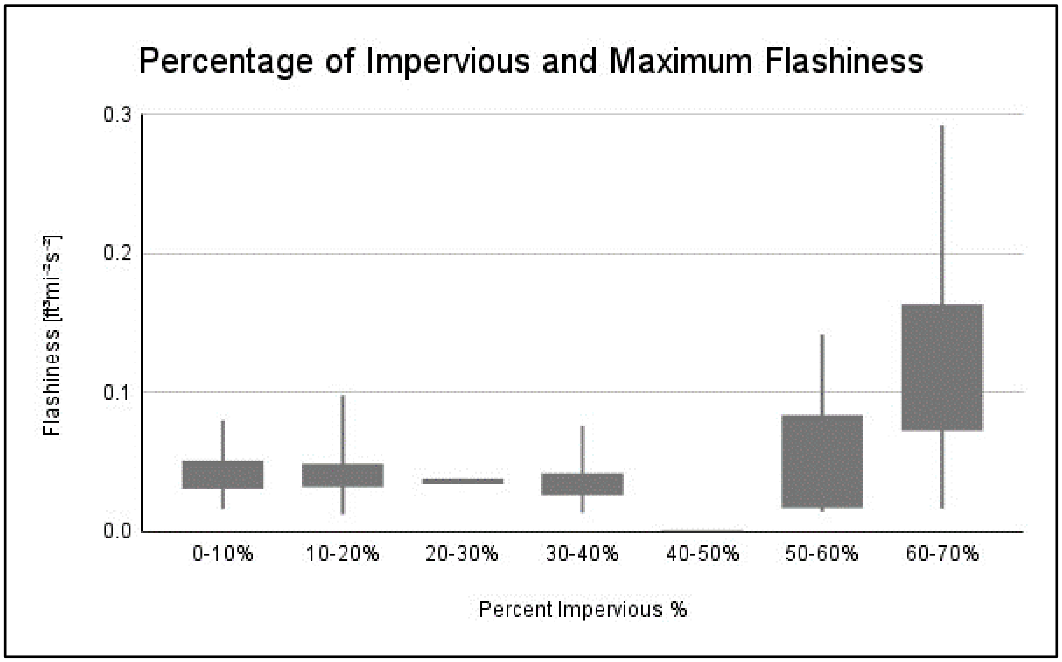

Figure 15. A box-and-whisker plot representing the statistical distribution of flashiness depending on percentage of imperviousness within each county.

The statistical distribution of maximum flashiness based upon the percentage of imperviousness is displayed in a box-and-whisker plot in Figure 15. The largest distribution of maximum flashiness is within the 60-70% imperviousness category. Additionally, the highest median value of maximum flashiness is within the highest category of imperviousness. There were not stations located within a county with 40-50% imperviousness, which resulted in an empty section of the box-and-whisker plot.

5.3 Hillslope of North Georgia

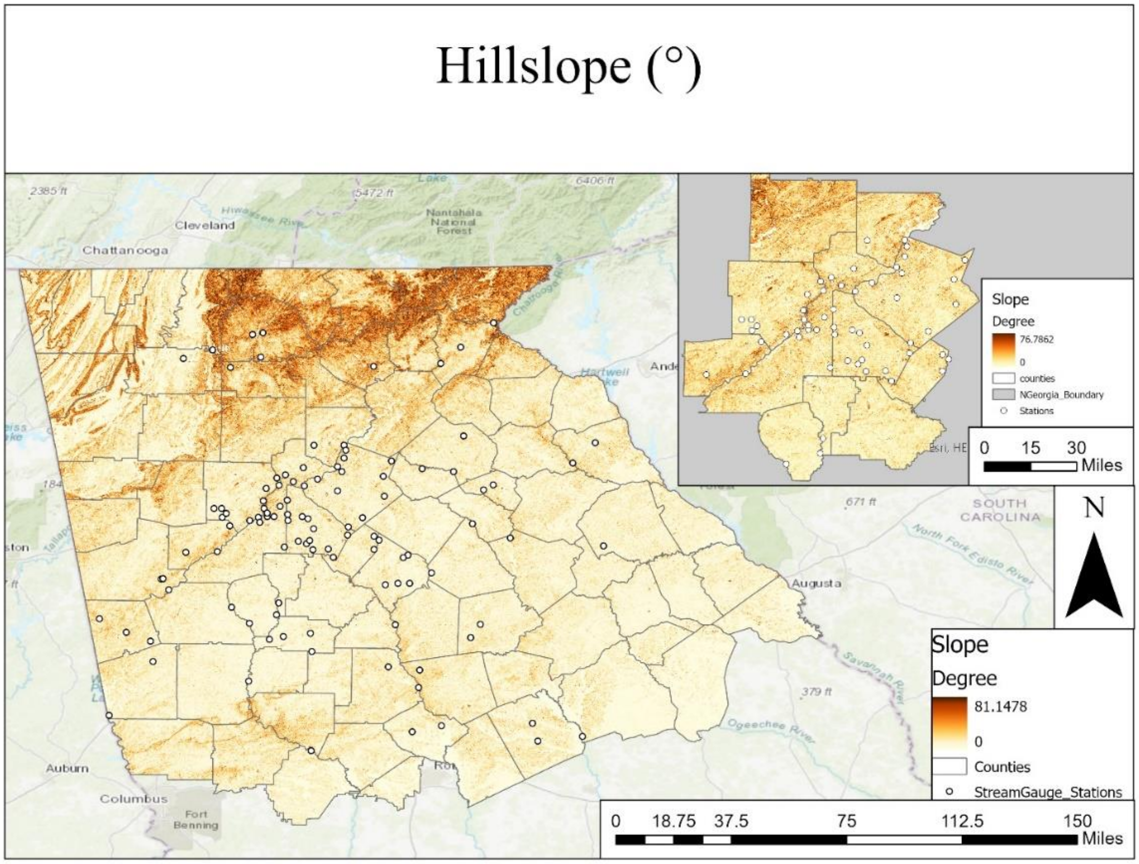

Figure 16. The degree of hillslope across the study area. United States Geological Survey Digital Elevation Data converted to Hill Slope.

Alongside imperviousness, the influence of hillslope requires further analysis to determine the significance of degrees of slope on flashiness, and therefore, risk of flooding. In Figure 16, the stations are clustered across the center of the study area. This distribution is a result of data availability during the full study period of 2013-2021. However, there are stream gauges located in both the northern region of the study area where hillslope is greater, as well as the southern region where the hillslope is less to show the influence of the transition of hillslope on stream gauge determined flashiness. It is important to consider the diverse land types and hillslope measurements when finding the catalyst of flash flooding in a specific region like

Metropolitan Atlanta. The lowest areas of hillslope maintain a slope of 0.00 degrees while the steepest hillslope, which is located in the northern portion of Georgia, measures at 81.15 degrees. Figure 17 shows the specific slope for each station, which is represented through the variation in color of the station. This color scale is the same as the raster hillslope behind the stations, however, including the value within each point aids in the visual interpretation of the slope.

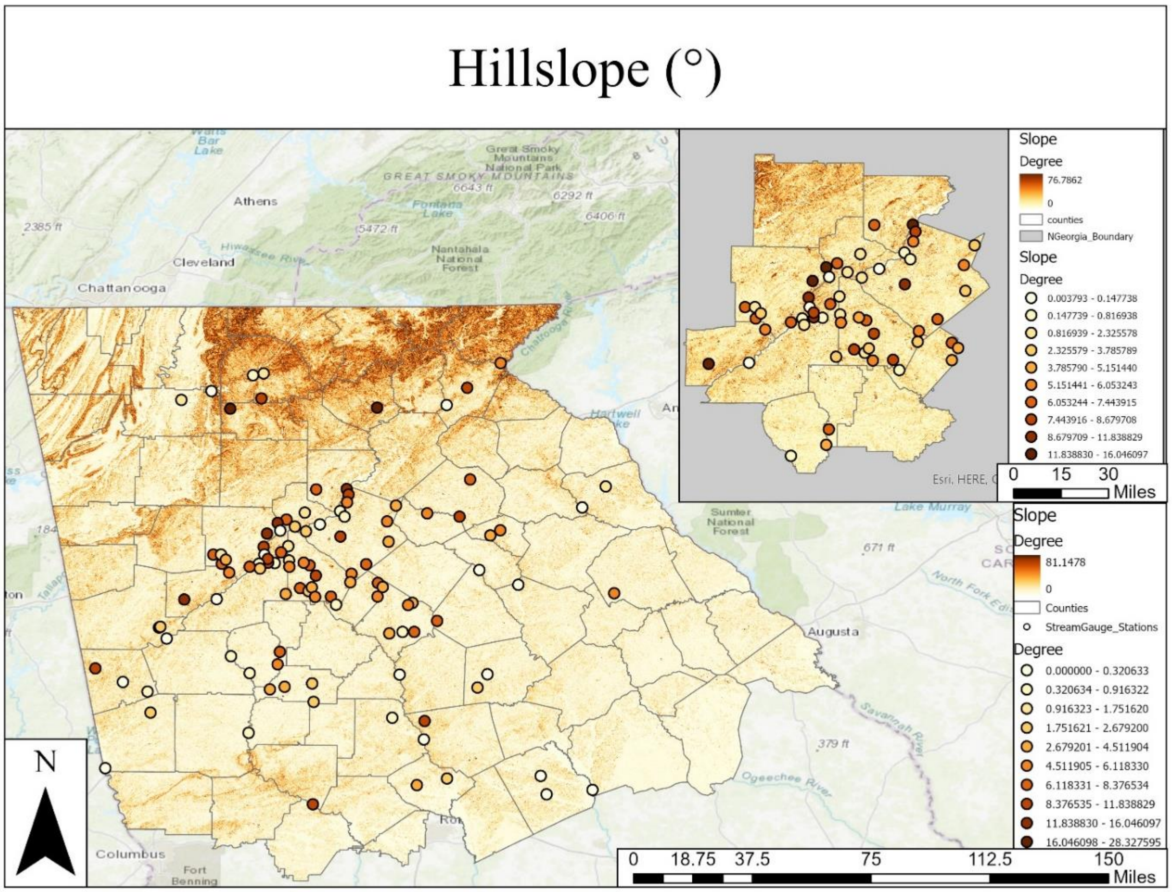

Figure 17. The degree of hillslope presented at each stream gauge station included in the study. (USGS)

5.4 Seasonality of Flashiness

In order to determine the seasonality of the flashiness across the north Georgia area, the yearly station data from 2013 to 2021 was split into meteorological season categories. This organization of data allows for understanding about both warm season and cold season patterns, as well as the flashiness patterns of the transitional periods between them. The climatological season classifications are DJF, MAM, JJA, and SON. The further analysis of both the maximum flashiness and the average flashiness during each season for every station provides results regarding the seasonality of flashiness within the study area.

5.4.1 Winter:

Displayed in the Figure 18 is the average flashiness for each station over the period of 2013 to 2021. This average includes all data for each station over the 9 complete years of data collected by the United States Geological Survey. These averages were calculated by determining the mean value for the years 2013-2021 for each station. While the lowest average values are -0.002 $ft^3mi^{-2}s^{-2}$ the highest values within the winter season are 0.006 $ft^3mi^{-2}s^{-2}$. There is a noticeable signature of higher values around the center and across the Blue Ridge Mountains of North Georgia. The average mean value for all 108 stations for the winter season is 0.002 $ft^3mi^{-2}s^{-2}$. Through visual analysis, this average value appears to be clustered around the Metropolitan area.

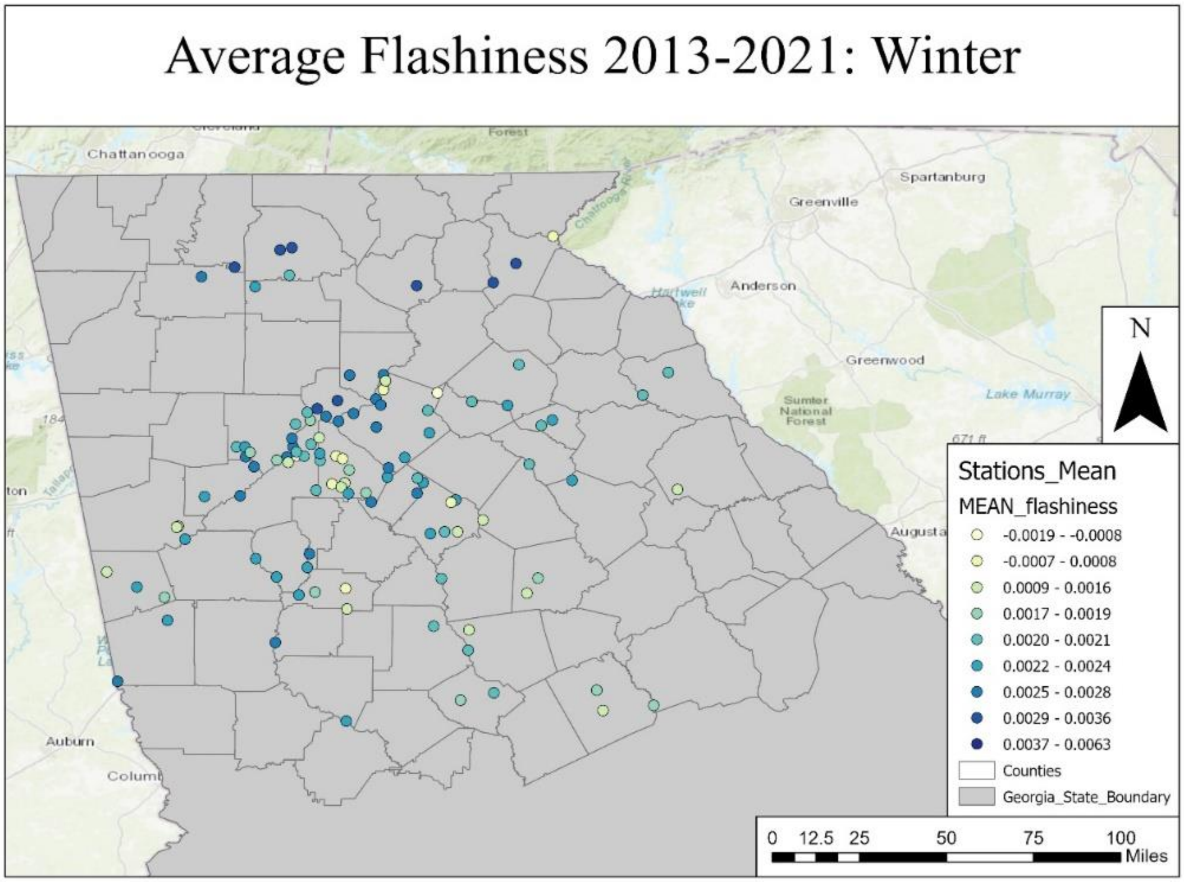

Figure 18. The average flashiness calculated at each station for December, January, and February observations from 2013-2021. (USGS)

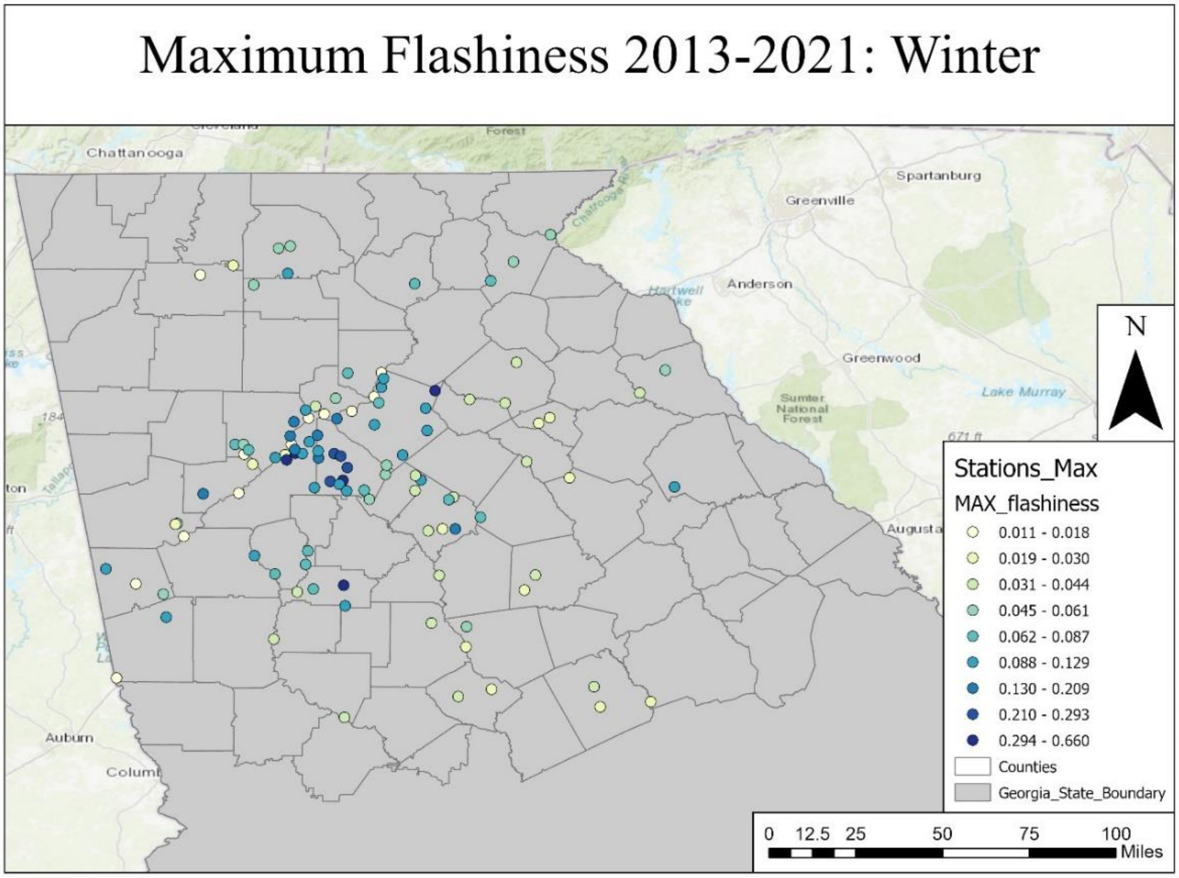

Figure 19. The maximum flashiness calculated at each station for December, January, and February observations from 2013-2021. (USGS)

Figure 19 represents the maximum values of flashiness for each station during the winter months of the 2013-2021 study period. The increased flashiness values from the average flashiness to the maximum indicates potential flood risk due to the rapid response to heavy rainfall. Although these maximums are not associated with a specific weather event resulting in precipitation, they indicate a situation where the rivers increased quickly in relation to the basin area. The lowest maximum value that was reached during the winter season from 2013-2021 is 0.011 $ft^3mi^{-2}s^{-2}$ and the highest maximum value that was reached is 0.660 $ft^3mi^{-2}s^{-2}$. The average maximum flashiness value for the winter season is 0.091 $ft^3mi^{-2}s^{-2}$.

The spatial distribution of flashiness averages and maximum values indicate a cluster of increased values in the center of the metropolitan region of Atlanta. In order to confirm the possibility of hot spots, the ArcGIS Pro Hot Spot Analysis Spatial Statistics tool was used to visualize the clustering while including statistical significance. Presented in Figure 19 are the results of the Hot Spot Analysis for the average flashiness for each station. This analysis was conducted using a fixed-distance technique where the distance band was set to 10 kilometers. The 10 km distance was chosen to ensure that each station has neighboring stations within the required distance to accurately determine the hot and cold spots that are deemed statistically significant. During the winter season, the average flashiness values indicated hot spots at five stations across the study area, and two hot spots were location within the Metropolitan Atlanta boundary. The two significant hot spots within the winter season were determined at 95% confidence and 90% confidence. However, there were 9 stations within the urban metropolitan center in Figure 17 that were calculated as cold spots. These stations ranged from 90% to 99% confidence in their cold spot significance.

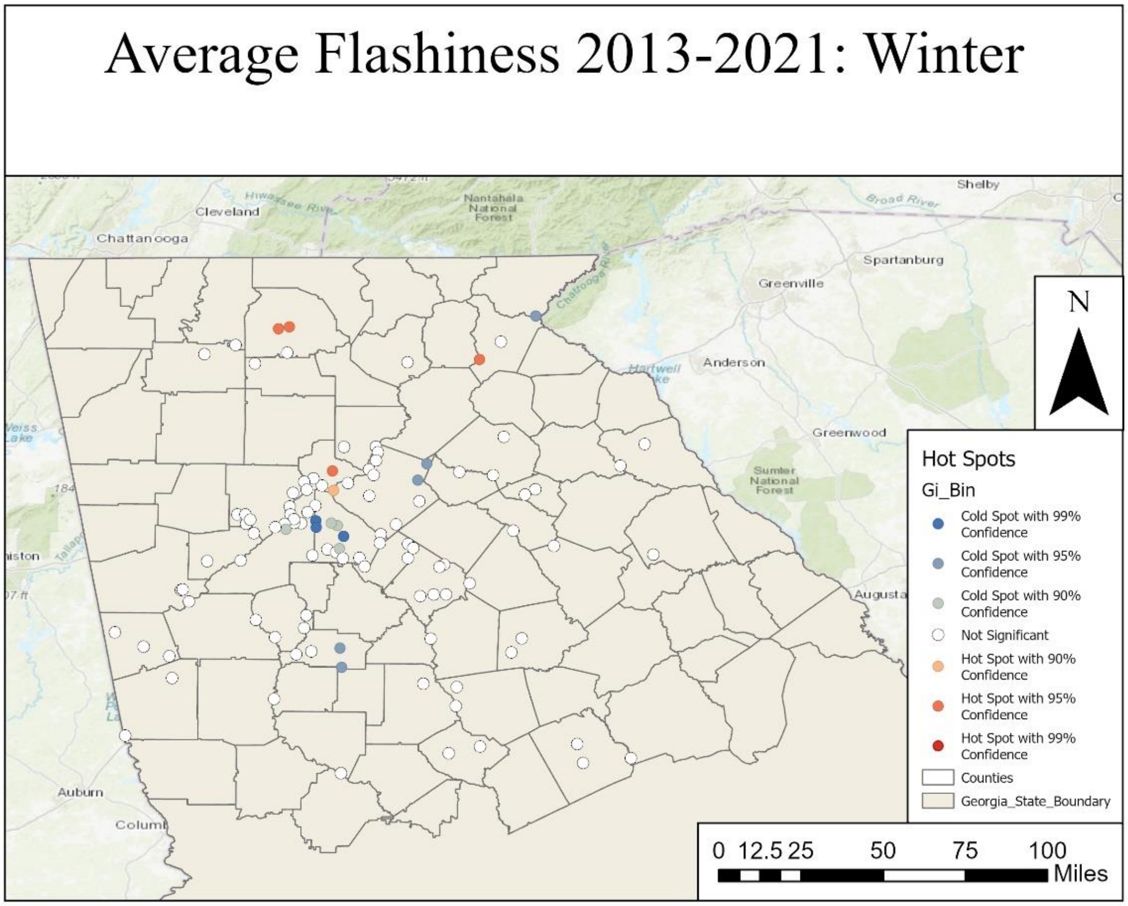

Figure 20. The Hot Spot Analysis (Getis-Ord Gi* Statistic) results for the average flashiness during the winter seasons of 2013-2021. This statistic compares the local values to those of the overall total.

The analysis of winter season maximum hot spots is continued and visually represented in Figure 21. The visual of hot spots within Figure 21 presents the clustering of high values within the urban center. This is critical in understanding that although the average values might present hot spots across the study area, the maximum values are located within the urban metropolitan region. This region is not only the most populated and frequented, but is the area that is covered by the highest percentage of impervious surfaces. The average impervious coverage is 64% covered for the counties where the hot spots have been recognized. These hotspots within Fulton, Dekalb, and Gwinnet counties are recognized at varying levels of confidence ranging from 90%-99%. However, in comparison to the maximum flashiness for the total 2013-2021 yearly values, there are 10 hotspots that are calculated with 99% confidence.

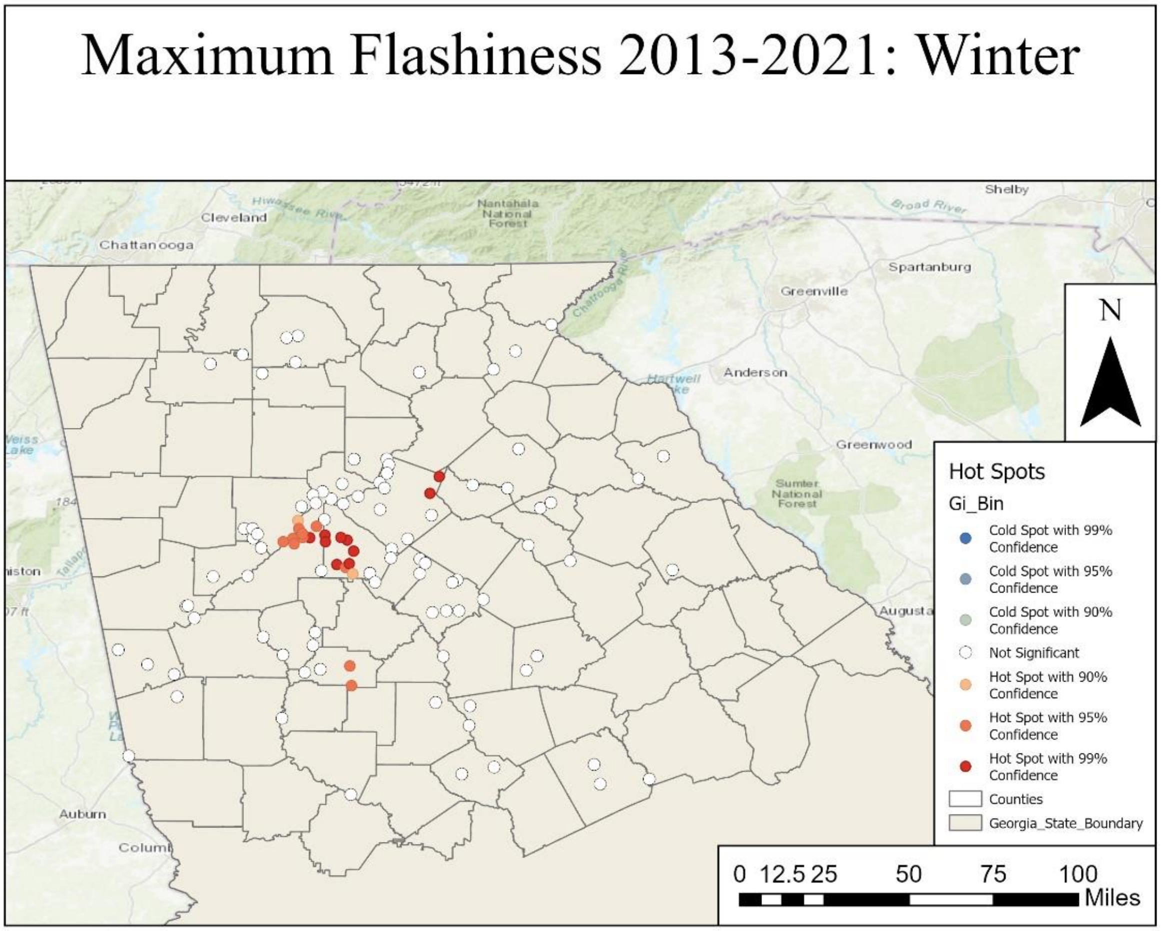

Figure 21. The Hot Spot Analysis (Getis-Ord Gi* Statistic) results for the maximum flashiness during the winter seasons of 2013-2021. This statistic compares the local values to those of the overall total.

5.4.2 Spring:

Transitioning to the spring season, the average flashiness is presented in Figure 22. The urban center has a variety of flashiness values ranging from the calculated lowest value to the highest value of the dataset. This season does not show the flashiness urban signature clearly, but there are similar patterns to the winter season through higher flashiness values across the northern Fulton County and Cobb County border. The minimum average flashiness value is recorded at -0.002 $ft^3mi^{-2}s^{-2}$ and the maximum value is 0.005 $ft^3mi^{-2}s^{-2}$. The mean average value of flashiness for the spring season is measured at 0.002 $ft^3mi^{-2}s^{-2}$.

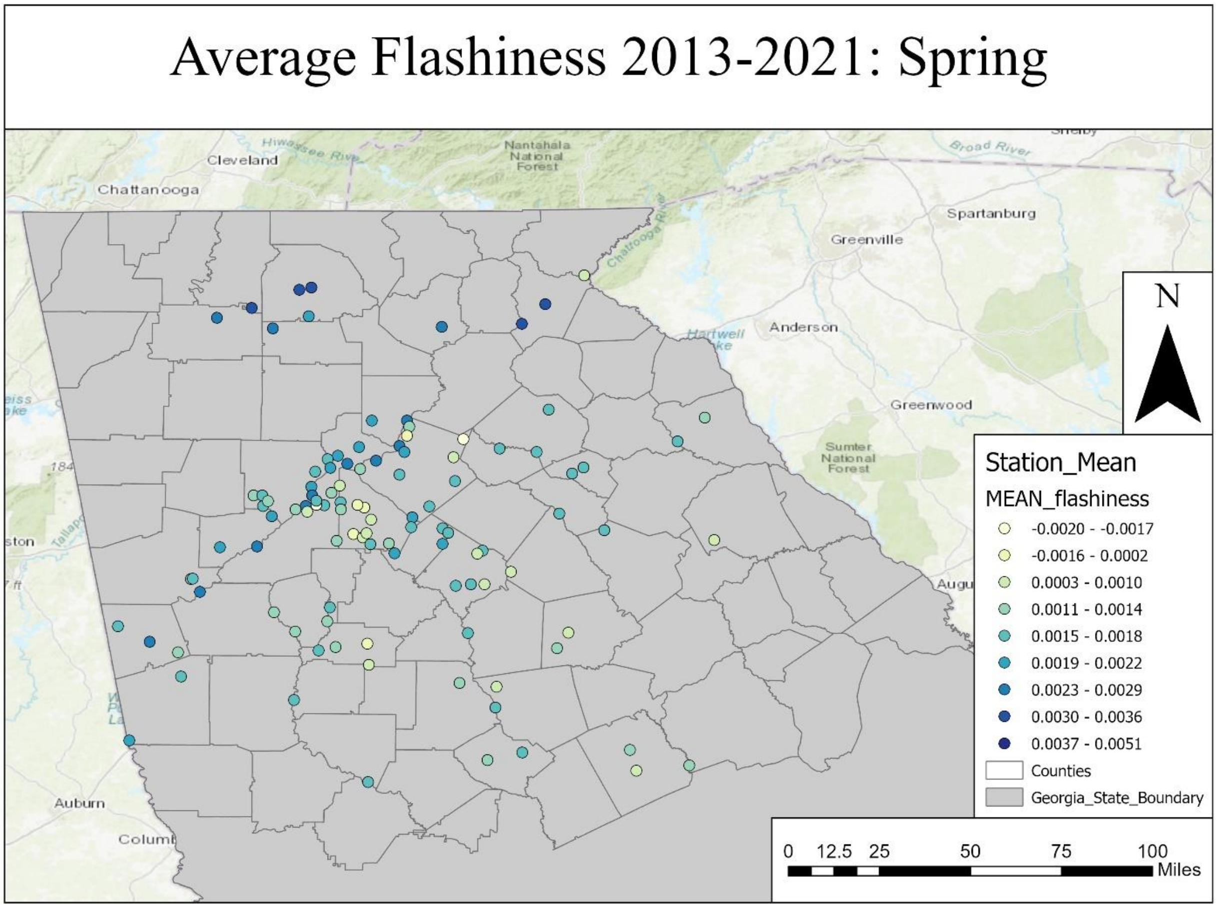

Figure 22. The average flashiness calculated at each station for March, April, May observations from 2013-2021. (USGS)

In comparison to the average flashiness, the maximum flashiness spatial distribution in Figure 23 indicates a stronger signature of increased flashiness across the center of the metropolitan region. The minimum maximum flashiness for the spring is calculated at 0.011 $ft^3mi^{-2}s^{-2}$ and the highest maximum value is determined to be 0.566 $ft^3mi^{-2}s^{-2}$. The average maximum value for the spring season is calculated to be 0.097 $ft^3mi^{-2}s^{-2}$, which is 0.006 $ft^3mi^{-2}s^{-2}$ higher than the winter maximum flashiness average.

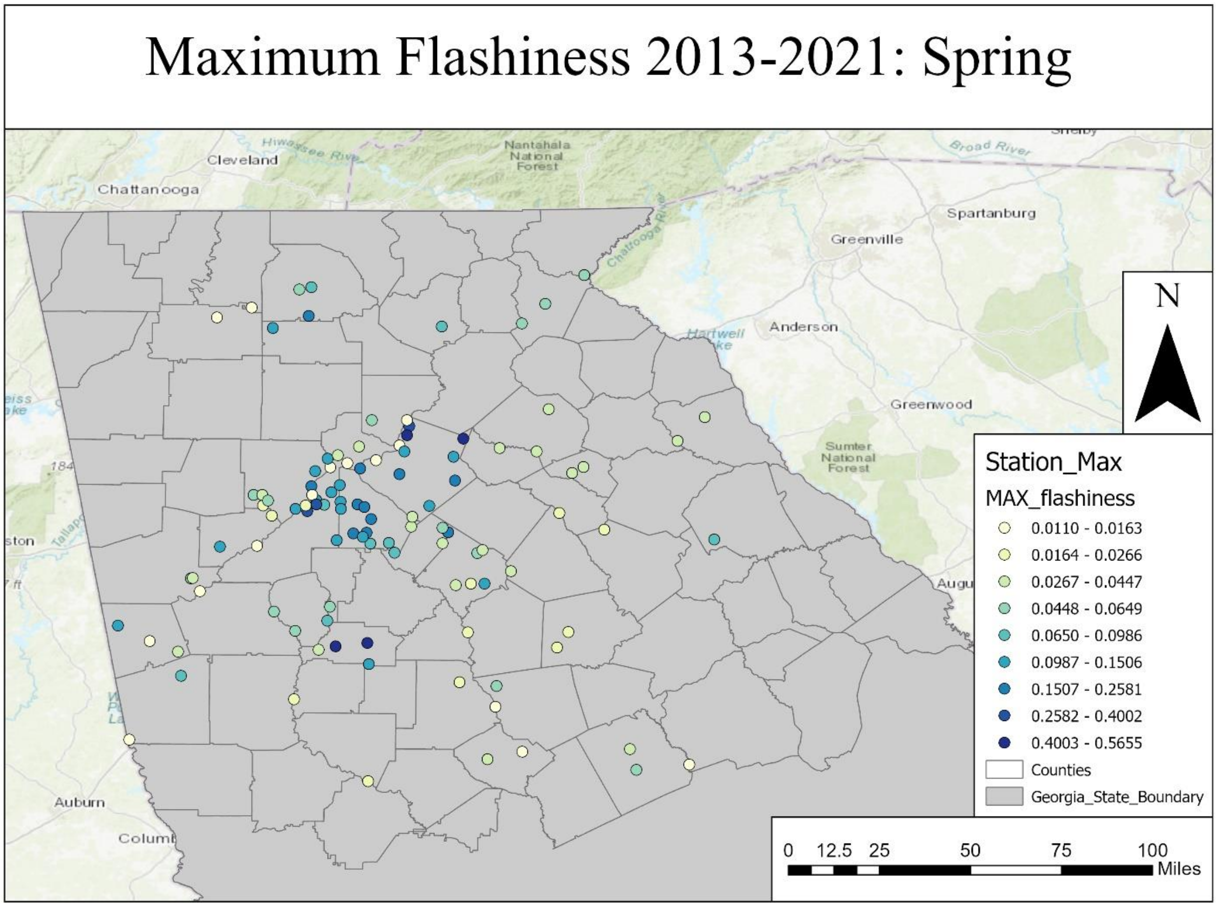

Figure 23. The maximum flashiness calculated at each station for March, April, May observations from 2013-2021. (USGS)

The spring season does not show a hot spot signature for average flashiness at the center metropolitan center where Fulton County is located. The results of the hot spot analysis for the average flashiness for springtime shows a cold spot signature within Dekalb County and Gwinnet County, although there are hot spots with 99% confidence located within Gilmer County. There are 9 cold spots recorded across the metropolitan counties ranging from 90% to 99% confidence. These results are similar to the pattern that were shown visually on Figure 22, which shows the average flashiness values for springtime.

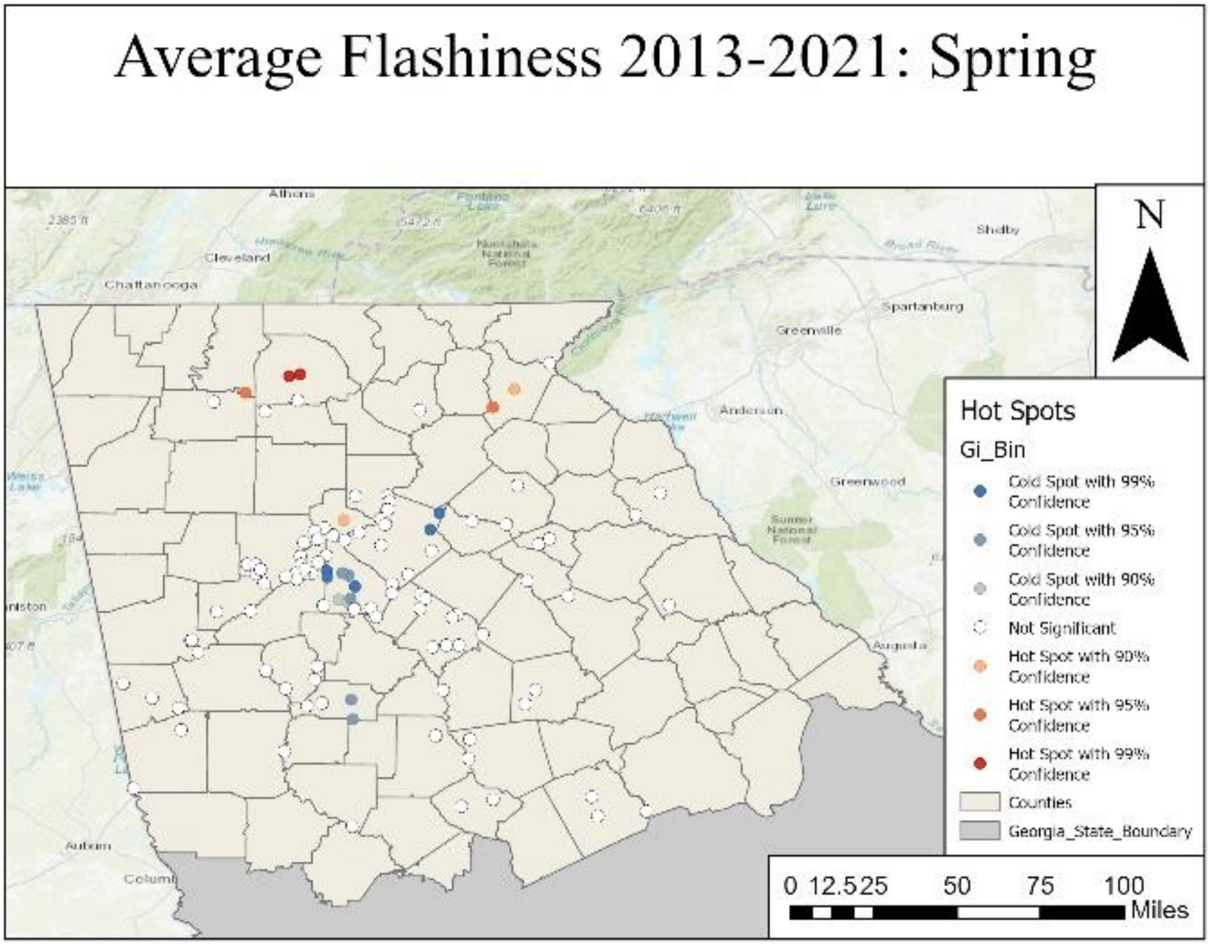

Figure 24. The Hot Spot Analysis (Getis-Ord Gi* Statistic) results for the average flashiness during the spring seasons of 2013-2021. This statistic compares the local values to those of the overall total.

In review of the hotspot analysis for the maximum flashiness in Figure 25, for springtime, there are hotspot signatures ranging from 90% to 99% confidence across the metropolitan area. There are 10 stations that are located inside of the metropolitan cluster, however, there are an additional 4 stations that are determined to be a hot spot at 99% confidence to the south in Spalding County. These results indicate a continued maximum flashiness hot spot signature within the urbanized region, and suggest that regions outside of the urban core have insignificant flashiness values when compared to their neighboring stations.

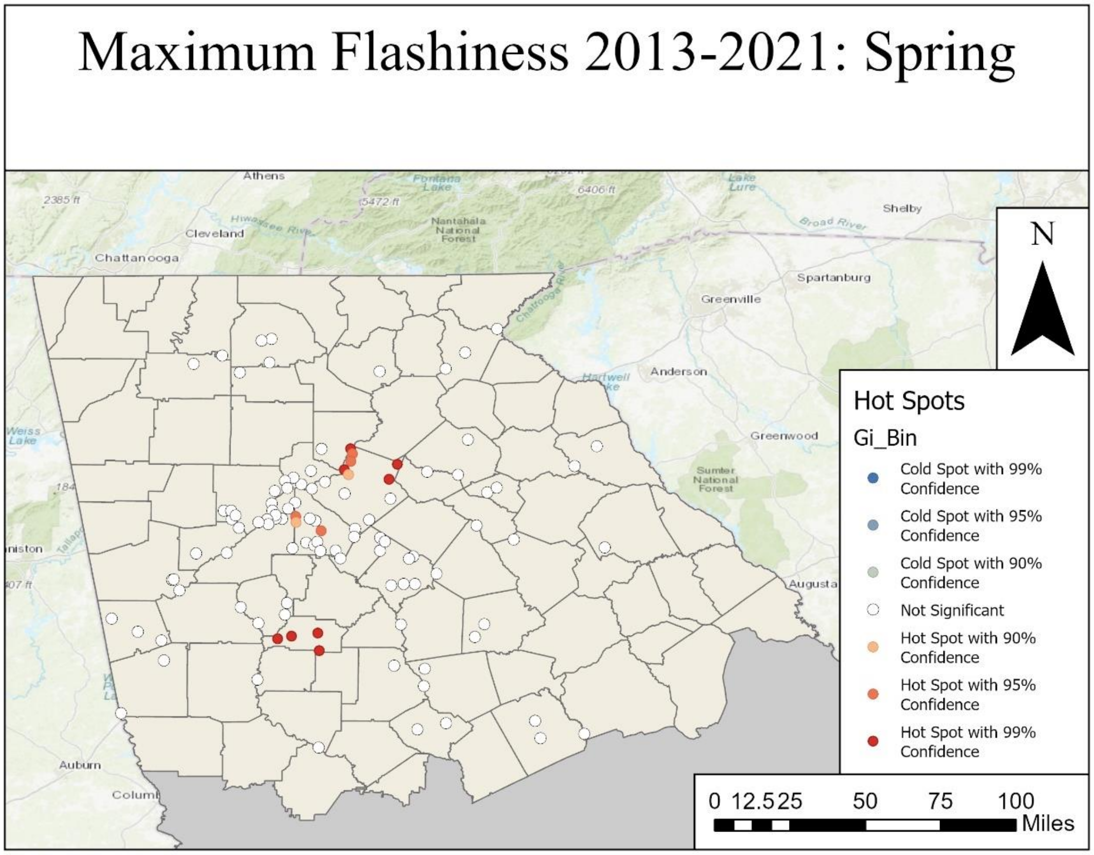

Figure 25. The Hot Spot Analysis (Getis-Ord Gi* Statistic) results for the maximum flashiness during the spring seasons of 2013-2021. This statistic compares the local values to those of the overall total.

5.4.3 Summer:

Presented in Figure 26 are the average flashiness values at each station for the summer season. The minimum average value within the summer season is recorded as -0.003 $ft^3mi^{-2}s^{-2}$ and the maximum average value is 0.004$ft^3mi^{-2}s^{-2}$. During the June, July, and August period the mean average flashiness for all stations 0.008 $ft^3mi^{-2}s^{-2}$. This value is lower than both the winter and spring seasons, however, this is most likely due to the smaller minimum and maximum average values. Consistent with the winter and spring seasons, higher flashiness values are spatially distributed along the Blue Ridge Mountains of North Georgia, specifically in Gilmer

County. There is a similar pattern of increased flashiness values along the Fulton County and Cobb County border stretching to the western side of Gwinnett County.

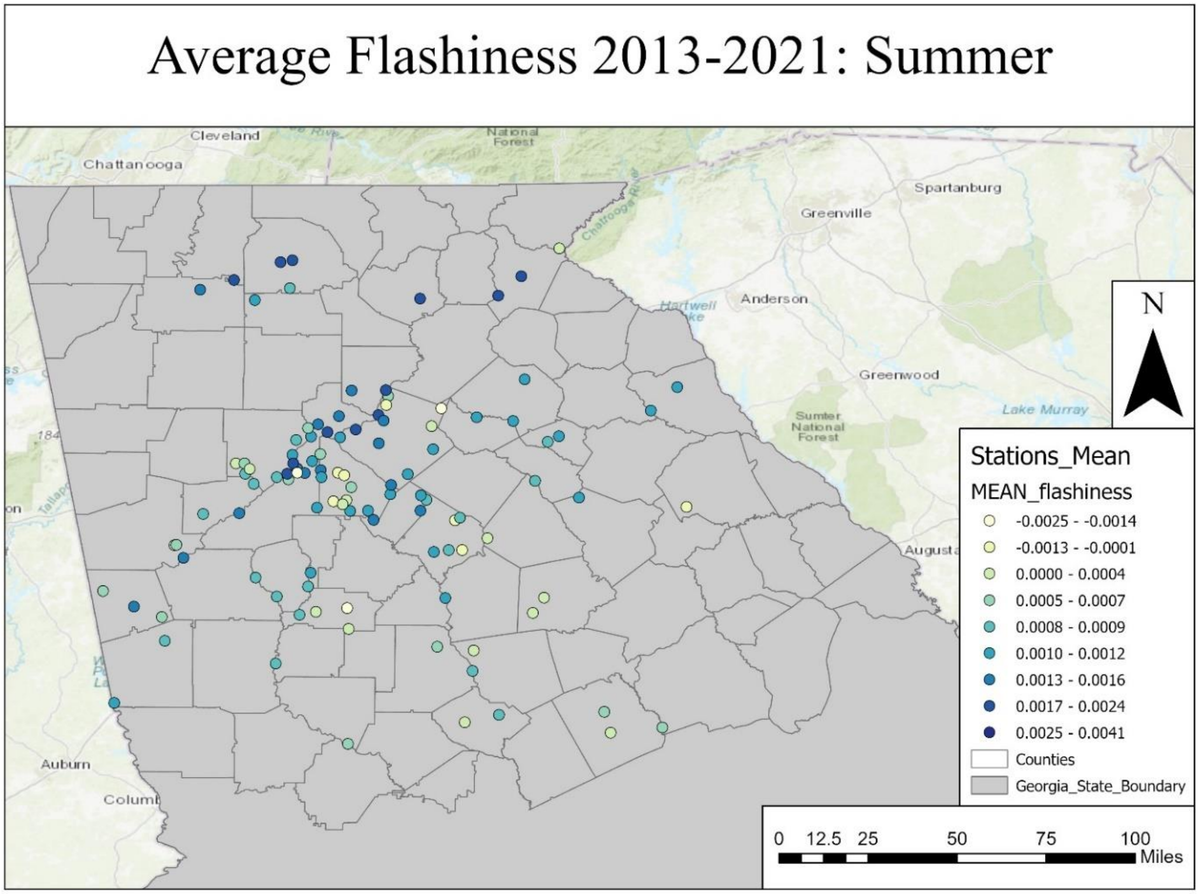

Figure 26. The average flashiness calculated at each station for June, July, and August observations from 2013-2021. (USGS)

Displayed in Figure 27 are the maximum flashiness values for the summer season. There are a range of low to high values of maximum flashiness at the stations within the metropolitan county cluster. Comparing the summer season maximum values to both the winter and spring maximums, the stations within Gordon, Gilmer, Lumpkin, and Habersham counties are lower than those located at the urban center. The lowest maximum value is 0.004 $ft^3mi^{-2}s^{-2}$and the highest maximum value is 0.717 $ft^3mi^{-2}s^{-2}$. The average maximum value for flashiness during the summer season is calculated at 0.080 $ft^3mi^{-2}s^{-2}$.

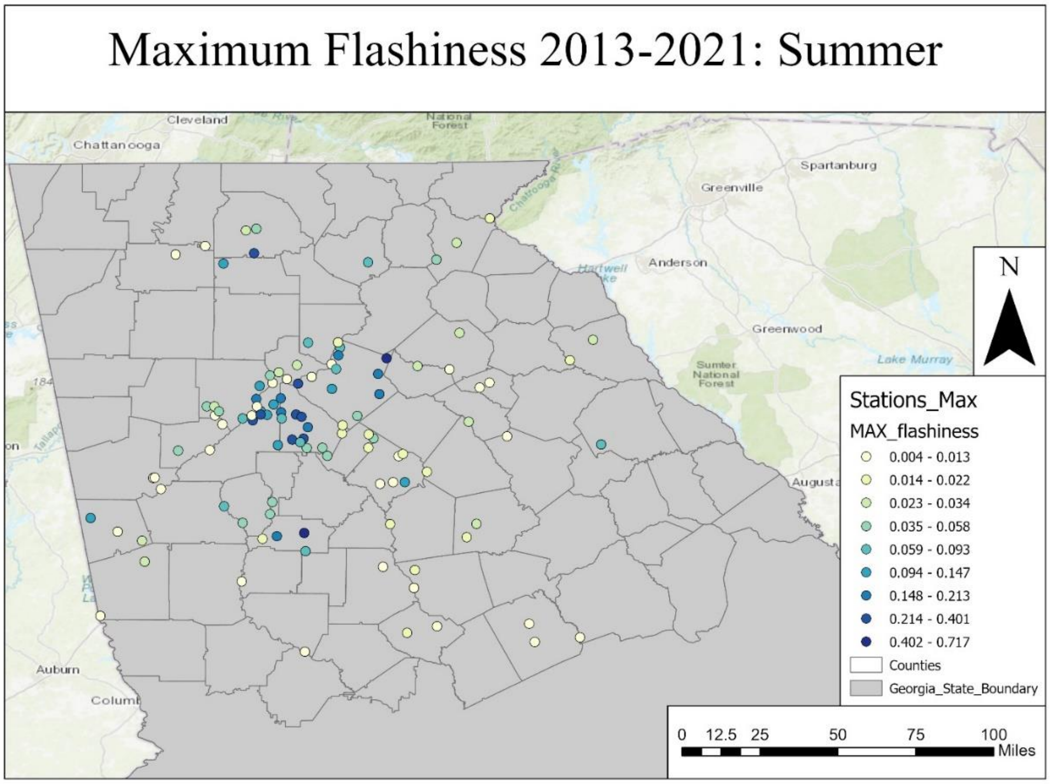

Figure 27. The maximum flashiness calculated at each station for June, July, and August observations from 2013-2021. (USGS)

The hot spot analysis for the average flashiness for the summer in Figure 28 captures both hot spots and cold spots within the study area. There are 2 recorded hot spots within Fulton County, while the other 4 are located within Gilmer and Habersham counties. Although Gilmer and Habersham are less impervious, ranging from 8% to 16% coverage, they are located in more mountainous terrain, with an increased hillslope at the station and north of the stations. There are 3 recorded cold spots within the metropolitan Atlanta cluster of counties, and these stations are within Dekalb county.

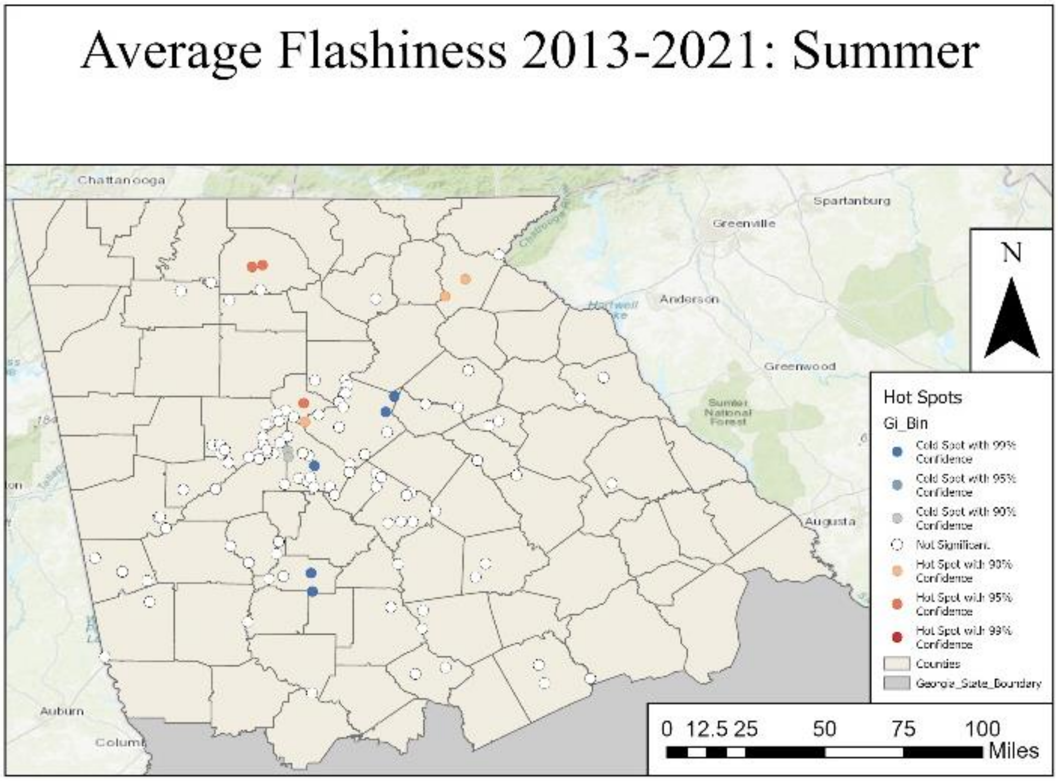

Figure 28. The Hot Spot Analysis (Getis-Ord Gi* Statistic) results for the average flashiness during the summer seasons of 2013-2021. This statistic compares the local values to those of the overall total.

In comparison to the average flashiness for the summer season, the maximum flashiness for June, July, and August in Figure 29 indicates all hot spots within the statistical analysis. Visualized below are the 19 hot spots ranging from 90% to 99% confidence. Out of the 19 stations with a hot spot signature, 12 of the stations are within either Fulton County or Dekalb County. These two counties are highly impervious and have surfaces ranging from 46% to 72% urbanized coverage. Additionally, Gwinnett County has 2 stations that are considered hot spots at the 99% confidence interval.

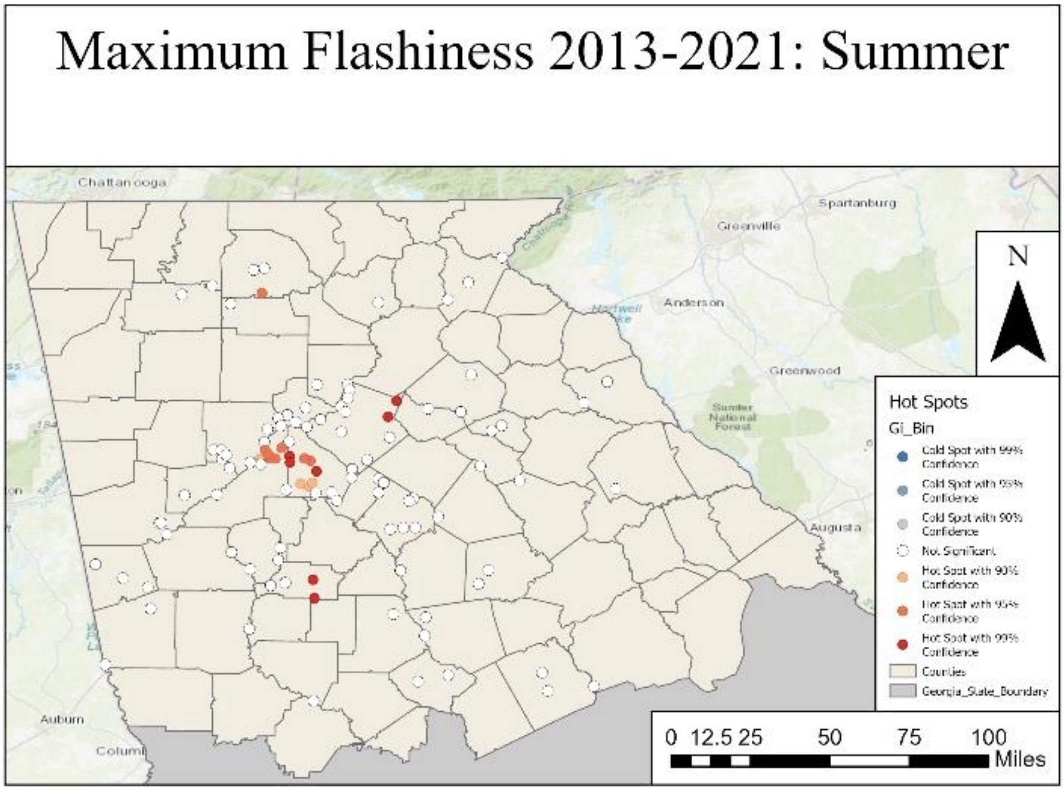

Figure 29. The Hot Spot Analysis (Getis-Ord Gi* Statistic) results for the maximum flashiness during the summer seasons of 2013-2021. This statistic compares the local values to those of the overall total.

5.4.4 Fall:

During the fall season, the months of September, October, and November, the spatial pattern of average flashiness values resembles that of the winter, spring, and summer seasons. The minimum average flashiness value for the fall is -0.003 $ft^3mi^{-2}s^{-2}$ and the maximum average flashiness is 0.004 $ft^3mi^{-2}s^{-2}$. The average mean flashiness for all 108 stations for the fall season is 0.007 $ft^3mi^{-2}s^{-2}$.

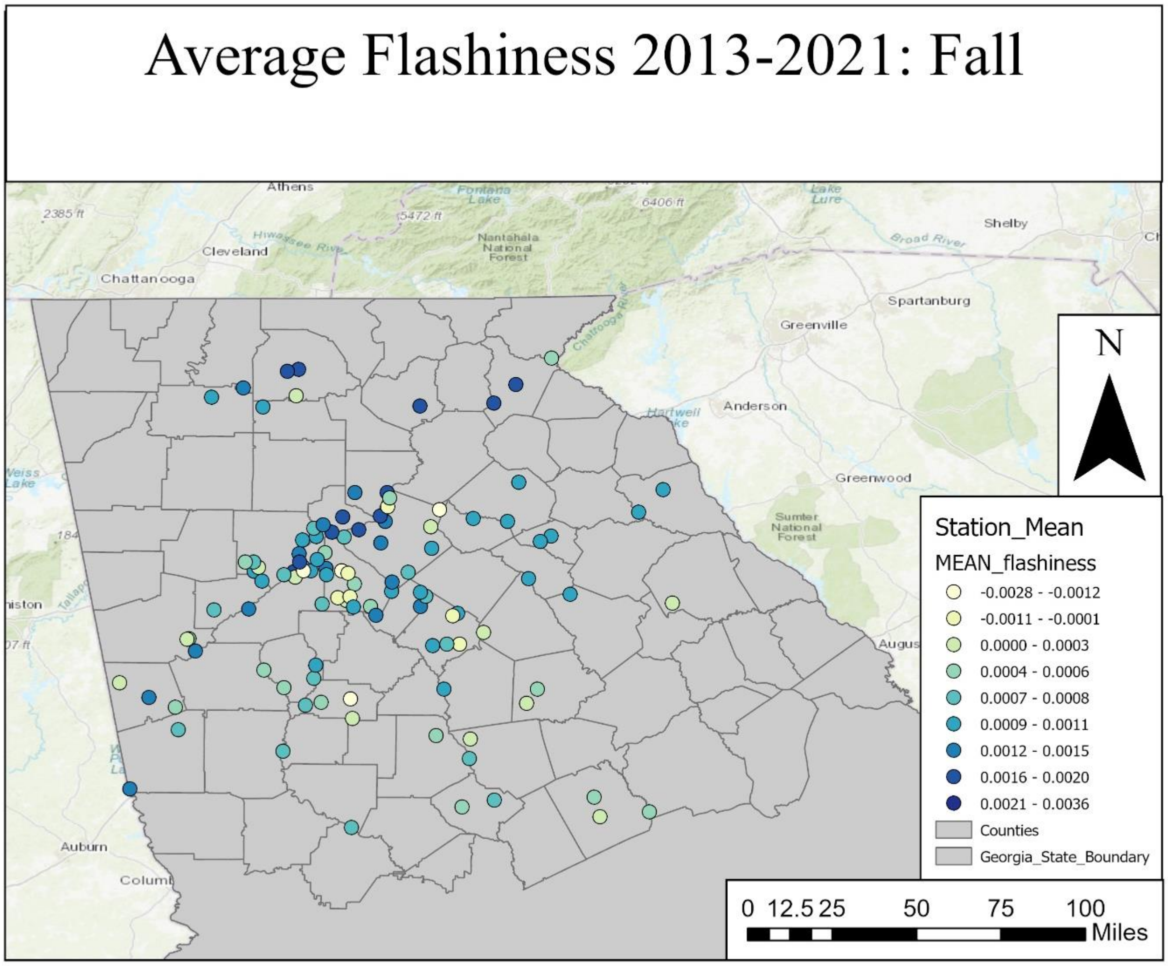

Figure 30. The average flashiness calculated at each station for September, October, and November observations from 2013-2021. (USGS)

The maximum flashiness for the fall season recorded the highest maximum out of all seasons. The recorded maximum value for the fall out of all 108 stations is 1.259 $ft^3mi^{-2}s^{-2}$and the minimum maximum value is 0.004 $ft^3mi^{-2}s^{-2}$. The average maximum flashiness for all stations for fall is 0.101 $ft^3mi^{-2}s^{-2}$. Additionally, this is the highest recorded average maximum out of all seasons and when compared to the total average maximum.

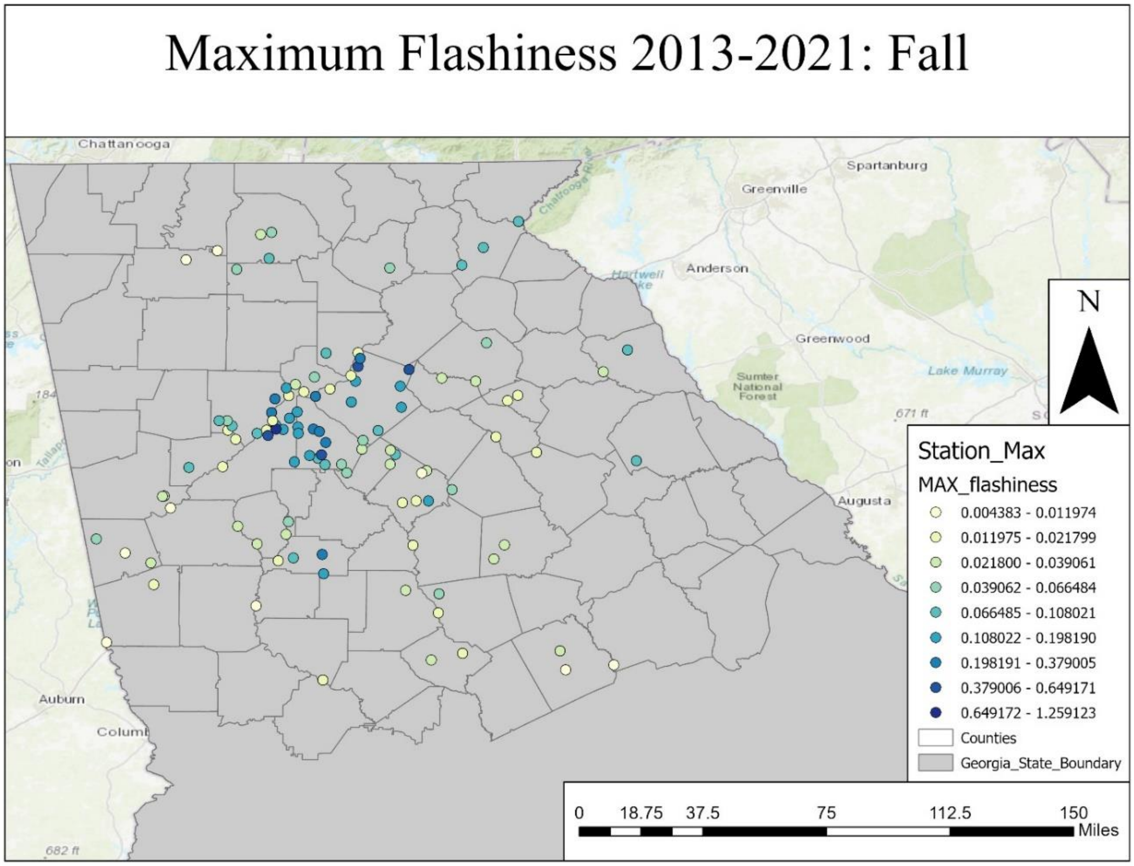

Figure 31. The maximum flashiness calculated at each station for September, October, and November observations from 2013-2021. (USGS)

In review of the hot spot analysis for the average flashiness values for the fall season, there is a continued pattern of hot spots and cold spots. The spatial distribution of these average flashiness hot spot and cold spot clusters is similar to that of the summer season in spatial distribution, with 3 hot spots existing within Fulton County. Additionally, the 3 stations presenting hot spots within the North Georgia mountainous region are located within Gilmer County and Habersham County.

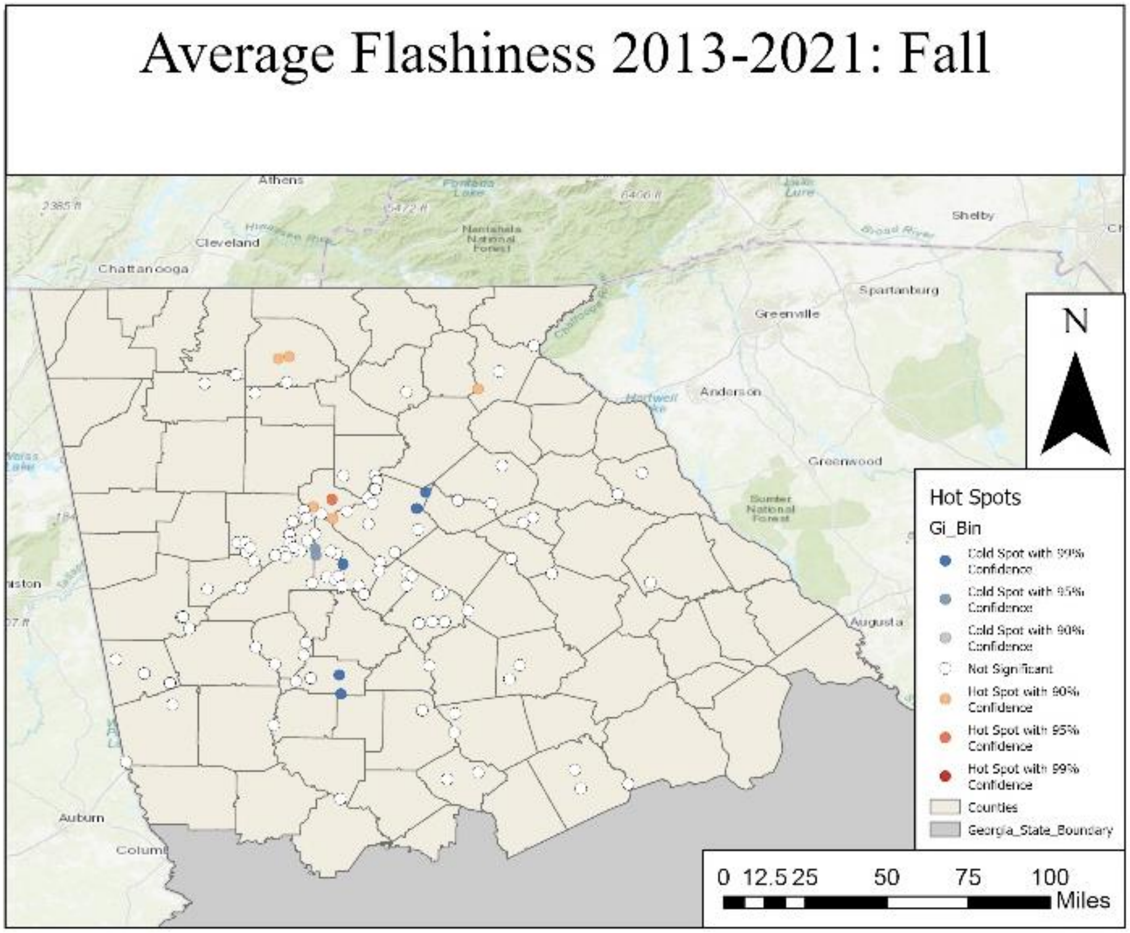

Figure 32. The Hot Spot Analysis (Getis-Ord Gi* Statistic) results for the average flashiness during the fall seasons of 2013-2021. This statistic compares the local values to those of the overall total.

Figure 33 presents solely hot spots for the maximum flashiness within the fall season. Out of the 16 stations that are determined to be hot spots, the 12 stations that have 99% confidence are located within Cobb, Fulton, and Dekalb counties. The additional 4 stations that are recorded with 95% confidence are within Dekalb and Gwinnett Counties. The maximum flashiness within the fall season holds the highest percentage of confidence of the hot spots with all at or above 95% statistical significance.

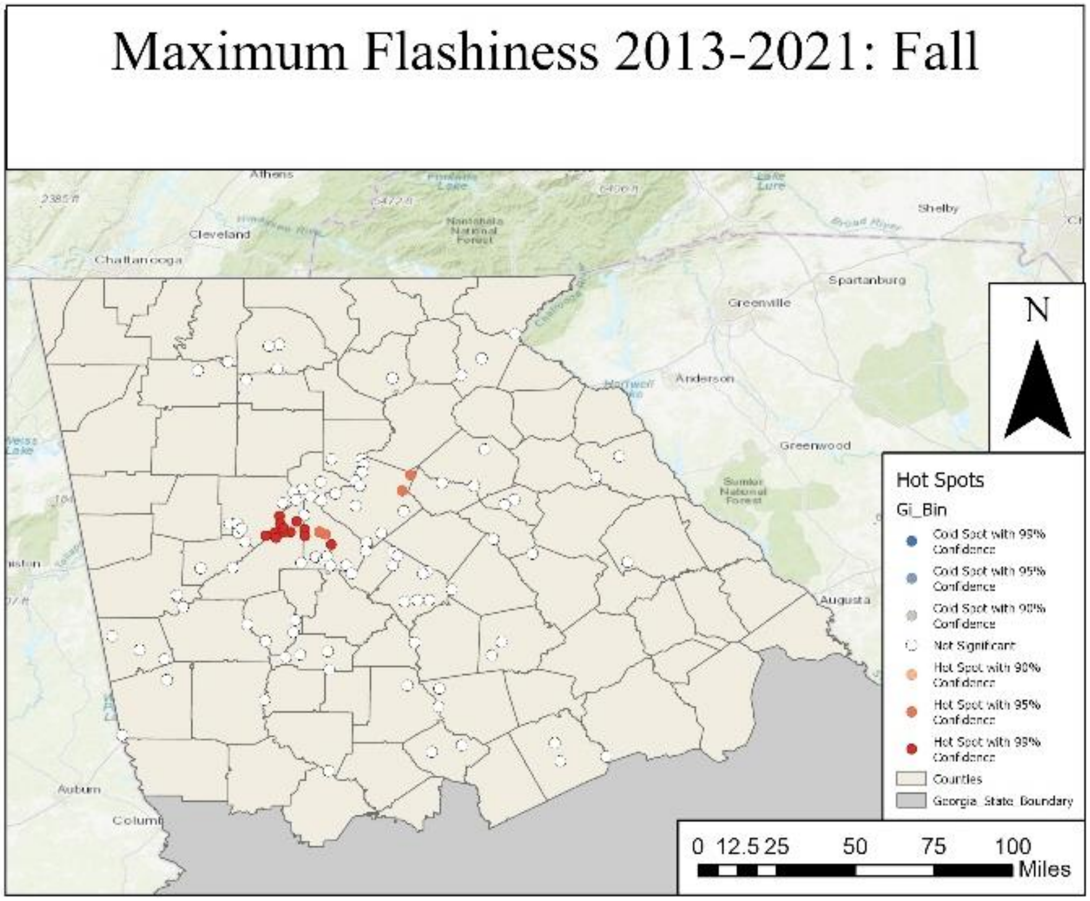

Figure 33. The Hot Spot Analysis (Getis-Ord Gi* Statistic) results for the maximum flashiness during the fall seasons of 2013-2021. This statistic compares the local values to those of the overall total.

In review of the maximum flashiness distribution across all seasons and the results from each hot spot analysis, there are noticeable maximums within both the summer and fall seasons. These seasonal patterns can be connected to the expected meteorological causes of precipitation associated with the two seasons, summer and fall. During the summer, warm season convection commonly produces precipitating events such as thunderstorms across the southeastern United States (Bentley, Ashley and Stallins 2010). Additionally, Bentley et al. (2010) concluded that the convective thunderstorms that develop across the southeastern United States could produce urban flooding events. These findings align with the results of the increased magnitude of maximum flashiness values within the summer season.

The greatest maximum flashiness values were found during the fall season, which is commonly when the southeastern United States is impacted by tropical cyclone produced precipitation (Powell and Keim 2015). As climate change continues to alter the frequency, magnitude, and duration of hurricanes, it is necessary

5.5 Statistical Analysis Utilizing Mann-Whitney U Test

In order to determine the detailed significance of both hillslope and imperviousness on the stream gauge stations a Mann-Whitney U Test was performed. This test was chosen due to the results of a Shapiro-Wilk Normality Test resulting that both the urban stations located on impervious surfaces and the rural stations located on pervious surfaces contained non-normally distributed data. The Shapiro-Wilk Normality test results are shown in Table 1. This test is based upon two hypotheses, the null hypothesis (H_0) and the alternative hypothesis (H_1).

H_0: The sample comes from a normal distribution.

H_1: The sample does not come from a normal distribution.

5.5.1 Shapiro-Wilk Test on Maximum Flashiness on Urban and Rural Stations

The p-values for both the urban and the rural stations are below the required p-value= 0.05, which tells that the value is not normally distributed. This confirms the need to accept the alternative hypothesis and to use a non-normally distributed test, such as the Mann-Whitney U Test.

Table 1. Shapiro-Wilk Normality Test Urban vs Rural Surface Maximum Flashiness

Shapiro-Wilk Normality Test	**Data:**	**W**	**p-value**
Urban (Impervious)	maximum flashiness	0.637	6.13E-13
Rural (Pervious)	maximum flashiness	0.572	1.43E-07

5.5.2 Mann-Whitney Test on Maximum Flashiness on Urban and Rural Stations

The Mann-Whitney U Test is based upon the acceptance of either the null or alternative hypothesis. This test was based upon an alternative hypothesis that the urban stations have a greater maximum flashiness median value than the rural stations maximum flashiness median value. The two hypotheses are as stated, the null hypothesis (H_0) and the alternative hypothesis (H_1).

H_0: The urban maximum flashiness and the rural maximum flashiness have the same median.

H_1: The urban maximum flashiness median is greater than the rural maximum flashiness median.

The results of the Mann-Whitney test are shown in Table 2. The p-value is measured at 0.0652, which tells us we can reject the null hypothesis and accept the alternative hypothesis at the 90th percentile.

Table 2. Mann-Whitney U Test: Urban and Rural Locations Results

Mann-Whitney U Test:	**Data:**	**W**	**p-value**
Urban and Rural	maximum flashiness	1277	6.52E-02

5.5.3 Shapiro-Wilk Test on Maximum Flashiness on Hillslope

Shown in Table 3 are the results of the Shapiro-Wilk Normality Test for the maximum flashiness values at the low-slope stations compared to the high-slope stations. The p-values for both the low-slope and high-slope are below the required p-value= 0.05 to reject the null hypothesis, which tells that the value is not normally distributed. This confirms the need to accept the alternative hypothesis and to use a non-normally distributed test, such as the Mann-Whitney U Test. This test is based upon two hypotheses, the null hypothesis (H_0) and the alternative hypothesis (H_1).

H_0: The sample comes from a normal distribution.

H_1: The sample does not come from a normal distribution.

Table 3. Shapiro-Wilk Normality Test Low Slope vs High Slope Maximum Flashiness

Shapiro-Wilk Normality Test	**Data:**	**W**	**p-value**
Low Slope (≤ 5°)	maximum flashiness	0.617	1.01E-09
High Slope (> 5°)	maximum flashiness	0.591	7.08E-12

5.5.4 Mann-Whitney U Test: Low-Slope and High-Slope

The Mann-Whitney U Test results in Table 4 shows whether or not to reject or accept the null hypothesis. The two hypotheses are as stated, the null hypothesis (H_0) and the alternative hypothesis (H_1).

H_0: The low-slope maximum flashiness and the high-slope maximum flashiness have the same median.

H_1: The low-slope maximum flashiness median is greater than the high-slope maximum flashiness median.

The statistical test shows us that the null hypothesis can be rejected due to p-value which is lower than p-value=0.05. This means that the alternative hypothesis can be accepted at the 95th percentile.

Table 4. Mann-Whitney U Test: Low Slope and High Slope Results

Mann-Whitney U Test:	**Data:**	**W**	**p-value**
Low-Slope and High-Slope	maximum flashiness	1967	3.92E-04

When reviewing the both the Shapiro-Wilk Test and the Mann-Whitney U Test, there is evidence that the land surface material is influential of the flashiness at a specific stream gauge station. The results of the Mann-Whitney U Test provide information that stations located within urban environments, upon imperviousness, are connected to a higher maximum flashiness value at the 90th percentile. Additionally, the influence of hillslope upon the value of flashiness was tested through both a Shapiro-Wilk Test and a Mann-Whitney U Test. The results of the Mann-Whitney U Test indicate that stream gauge stations located at low-slopes experience a greater maximum flashiness than stations located at high-slope at the 95^{th} percentile. Ultimately, the statistical analysis of both imperviousness and hill-slope support the findings of increased maximum flashiness within metropolitan Atlanta due to both its slope and imperviousness.

CHAPTER 6

CONCLUSION

The analysis of the spatiotemporal variability was conducted through flashiness calculations, surface inspection, hillslope determination, and statistically significant hot spot investigations across the North Georgia region. This study included nine full years of data beginning in 2013 and ending in 2021. The research reviewed the calculation of flashiness for the total years within the study, in addition to each season individually. As climate change continues to occur globally, urbanization enhances, and the weather patterns change, the determination of flash flooding events needs to be reviewed from multiple lenses. The value of flashiness provides the relationship between the stream flow to the river basin and the time of increase of stream flow. Although this method is not a replacement for satellite data, radar methods, and surface precipitation observation data for flash flooding analysis, it does provide indications of patterns in flooding across a region.

The utilization of stream gauges in flash flooding instances provides data to calculate the flood risk for a specific region based upon their flooding rise time and the basin area. The usage of the formula by Saharia et al. 2017 provides incremental data based upon the time between each observation at the gauge. The determination of flood risk in a community is supported by the National Academies Flood Risk Assessment (2019), which describes the four main components: flood hazard, flood exposure, flood vulnerability, and flood performance. The usage of the flashiness calculation provides information on the flood hazard, and with the additional information about population and local policy for mitigation reports, flashiness could provide timely information regarding local risk to flooding. The burial of streams within urbanized regions, by “high concentrations of impervious surfaces,” change the natural drainage system within cities (National Academies 2019).

The analysis of both the total flashiness and the seasonal variability of flashiness indicates hot spot signatures within the urbanized center of the metropolitan Atlanta area. These hotspots were consistent among the maximum flashiness at each station for all seasons and the total period of 2013-2021. However, the average flashiness showed increased hotspots within the summer and fall seasons. Additionally, the maximum values of flashiness were highest within the summer and fall season, with the largest flashiness value existing in the fall season. These high maximum flashiness values indicate that although these events might not occur as frequently, their magnitudes result in increased risk to those located in these regions. The density of the Georgia population within the metropolitan area due to both residents, commuters, and travelers provide a need to understand the signature of flash flooding events within the city.

The research conducted by Debbage and Shepherd (2019) determined that “the urban environment of Atlanta played a notable role in governing the location and quantity of precipitation and runoff that ultimately produced the record-breaking 2009 flood.” The urbanized surfaces prevent proper infiltration of runoff, which leads to increased runoff and flooding within significant heavy precipitation events. The increase of convective precipitation events during the summer and fall seasons in Atlanta, as well as the start of hurricane season, provide flooding opportunities within the city and surrounding areas. As the urban sprawl of metropolitan increases, the influence of urban flooding events on at-risk communities has the potential to increase directly. The future of stream gauge flood related analysis requires the increase in gauges in under-represented areas around the city. While the metropolitan cluster of counties around Atlanta has a significant number of gauges, the counties directly outside of the city are lacking in observational records which alters the results of flooding research across the urban sprawl. The continued research focused on the urban influence of flooding is necessary to mitigate and prepare for the changes associated with increased imperviousness within the region.

The results of this thesis determine the need for increased stream gauge stations within underrepresented counties to better determine flash flood severity as urbanization continues to affect rural areas. Additionally, the visual of the spatial distribution of current stream gauge stations benefits emergency management agencies as they aim to improve flooding mitigation within their specific sector of the state. There were increased maximum flashiness values found within the summer and fall seasons, indicating that counties need to prepare mitigation strategies to combat potential flash flooding events specifically during these seasons. The implementation of physical mitigation strategies to combat flooding and to reduce the effects of flash flooding within urban regions would greatly benefit these communities. This research provides both visual and numerical data to push communities and local emergency management agencies to request the addition of stream gauges within their counties to improve flash flood severity understanding as the climate continues to change. Globally, cities have begun introducing green roofs to work as a mitigation element within regions that frequently are affected by flash flooding events by reducing stormwater runoff (Mora-Melià et al. 2018; Ferreira et al. 2021). By knowing the locations that experience the maximum flashiness from this research project, urban planners, engineers, and emergency management agencies can better request and develop green roof and other mitigation strategies to reduce the harmful effects of flooding.

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