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Katelyn Boisvert April 1, 2020

The Impact of Urbanization on Environmental Systems and Applications to Urban Sustainability

A Case Study of the Atlanta Metro Region, Georgia

by

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An abstract of
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Abstract

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Urban sustainability is increasingly becoming a critical topic in policy decisions and city planning, as well as in personal choices of where people move, and understanding the relationship between environmental factors and urban impacts is an important dynamic. This thesis assesses the impact of urbanization on environmental systems for the Atlanta Metro Region in Georgia during the years 2000 to 2019. Urbanization is described using GIS methods to present data on population spread and urban density. The study analyzes thunderstorm occurrence, duration and intensity using METAR data from ASOS stations at urban and rural locations to understand meteorologic impacts. Analysis of impervious surface cover and basin discharge profiles at urban and rural USGS stream gage sites reflect effects on the hydrologic system and describe stream impacts and flood risk. Results show that the rate of urban spread in Atlanta is declining; but both urban and rural areas are increasing in density, which creates greater impervious surface area as residential spaces shift to commercial and industrial land uses. Increased impervious surface cover contributes to urban heat island effects and urban-initiated thunderstorm development. Although a significant difference was not found between thunderstorm occurrence at urban versus rural stations, results did show a significant increase in thunderstorm duration in urban locations. Results further show that impervious surface area positively correlates with average stream discharge, with the highest values at urban sites, which translates to increased occurrence and regularity of flooding events for the urban watershed. Observed data and trends were used to inform a definition of urban sustainability that serves as the perspective for evaluating sustainable practices being employed in Atlanta and presenting alternatives to consider. As our population continues to expand into cities, we must manage municipalities with the mindset that development and growth can be independent from environmental degradation. This study sought to present accessible methodologies and connect some of the science behind urban environmental impacts with sustainability solutions in an approachable manner, with the goal to provide all stakeholders with needed information for understanding the issues, evaluating areas of greatest concern, and identifying strategies that apply to their region.

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More generally, I would like to thank the Environmental Sciences Department for supporting the Honors Program, and faculty including Michael Page for instruction on GIS components used in this thesis, and Dr. Eri Saikawa who has been very supportive and inspired me to view the field of environmental sciences through a wider lens. I would also like to thank Taylor Spicer from the Office of Sustainability Initiatives who was my first point-of-contact with sustainability at Emory and played a pivotal role in my decision to pursue this field as my career choice. Lastly, I would like to thank my family and friends who encouraged me throughout this process and showed their positive support for all of my endeavors.

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Abbreviations

ARC	Atlanta Regional Commission
ASOS	Automated Surface Observing System
EPA	Environmental Protection Agency
GIS	Geographic Information Systems
METAR	Meteorological Aerodrome Reports
MSA	Metropolitan Statistical Area
NCEI	National Centers for Environmental Information
NOAA	National Oceanic and Atmospheric Administration
UHI	Urban Heat Island
USGS	United States Geological Survey

INTRODUCTION

Georgia’s population has been increasing rapidly in recent years, and Atlanta is now the largest metropolitan area in the Southeast (Kundell and Myszewski 2017, “Urban Sprawl”). Atlanta has served as a hub of transportation dating back to the city’s origin, and much of its growth can be attributed to the convergence of railroad lines in the city, which established the area as an important center of commerce (Ambrose 2019, “Counties, Cities & Neighborhoods-Atlanta”). Atlanta’s economy later shifted from its dependency on the railroads to a focus on a developing business culture in the city (Ambrose 2019, “Counties, Cities & Neighborhoods-Atlanta”). This shift spurred another explosive growth of the city, which continues to this day. According to Census data, population density is increasing within the city, with increases of 24% documented between the years 2000 to 2010 (Kundell and Myszewski 2017, “Urban Sprawl”). These increases are promoting the expansion of urban areas throughout the Atlanta metro region.

The United Nations Human Settlements Programme (UN-Habitat) estimates that 70% of the world’s population will be living in urban areas by 2050, and much of this urban infrastructure is yet to be built (United Nations 2016, “Science of Cities Tool”). The U.S. Census Bureau defines an area as urban when a census tract contains a population density of greater than 500 people per square mile (USDA 2019, “What is Rural”). Shifts towards a more urban lifestyle and increases in urbanization of rural regions are expected trends for the coming years. As a result, urban planning and sustainability will increasingly become topics of importance, especially when considering policy decisions and regional development.

The expansion of urban areas in Atlanta has not only changed the appearance of the city’s skyline or the inner-workings of the city’s economy, but it has also vastly changed the local environment. From diminished air quality to loss of greenspace and stressed water resources, urbanization poses many concerns for the environment (Quattrochi 2013, 86-108; and National Geographic 2020, “Urban Threats”). This study will present an overview of urbanization trends in the Atlanta metro region and the resulting impacts on environmental systems, the understanding of which will be critical to support a growing urban population and assure sustainability of the region.

Environmental Systems

As cities expand and new areas undergo urbanization, the landscape changes from open vegetated areas to highly dense areas composed of streets, parking lots, and buildings. This change results in the formation of Urban Heat Islands (UHI), which are defined by the U.S. Environmental Protection Agency (EPA) as areas where the average surface temperature is higher than comparative rural areas (EPA 2019, “Learn About Heat Islands”). According to the EPA, annual mean air temperature in large cities can be 1-3°C higher than in rural counterparts during the day, or as much as 12°C higher during calm, clear nights (EPA 2019, “Heat Islands”).

Numerous occurrences in urban environments contribute to the UHI effect, and include such factors as anthropogenic heat from the burning of fuel, transportation, and other industrial processes, as well as changes in the albedos in urban environments (Quattrochi 2013, 86-108; Shahmohamadi et. al. 2011, 1-9). The albedo of a surface is a measure of the amount of solar radiation that is reflected off of it. The Earth’s average albedo is 30%, and light-colored surfaces like snow and ice have albedos significantly higher than this average value. In comparison, surfaces that are found in urban environments, such as the asphalt used for streets and parking lots or the shingles on roofs, can have albedos as low as 5% (Hulley 2012, 79-98). Without the benefit of trees and other vegetation that provide shade, urban surfaces are exposed to direct sunlight, the majority of which is absorbed by these surfaces and re-emitted as infrared radiation that increases surface temperatures during the day. As these surfaces cool at night, they release heat into the environment that results in increased nighttime temperatures for urban areas (Hulley 2012, 79-98; Mohajerani, Bakaric, and Jeffrey-Bailey 2017, 522-538).

Trends of increasing temperatures can be observed in major cities across the United States, and the UHI effect has been well documented in the literature (Stone and Rodgers 2001, 186-198; Quattrochi 2013, 86-108; NASA Earth Observatory 2006, “Urban Heat Island”; Dixon and Mote 2001, 1273-1284; and Riebeek 2006, 1-4). This impact is demonstrated for Atlanta, Georgia in Figure 1. The graph presents the annual average temperatures in Atlanta compared to the surrounding North Georgia region, and was created using climate data from the National Centers for Environmental Information at the National Oceanic and Atmospheric Administration (NOAA) (NOAA, “Climate Data Online”). Data from the climate station located at the Hartsfield-Jackson International Airport reflects the annual average temperatures for the city of Atlanta. Data from seven climate stations summarizing temperature conditions for the entire

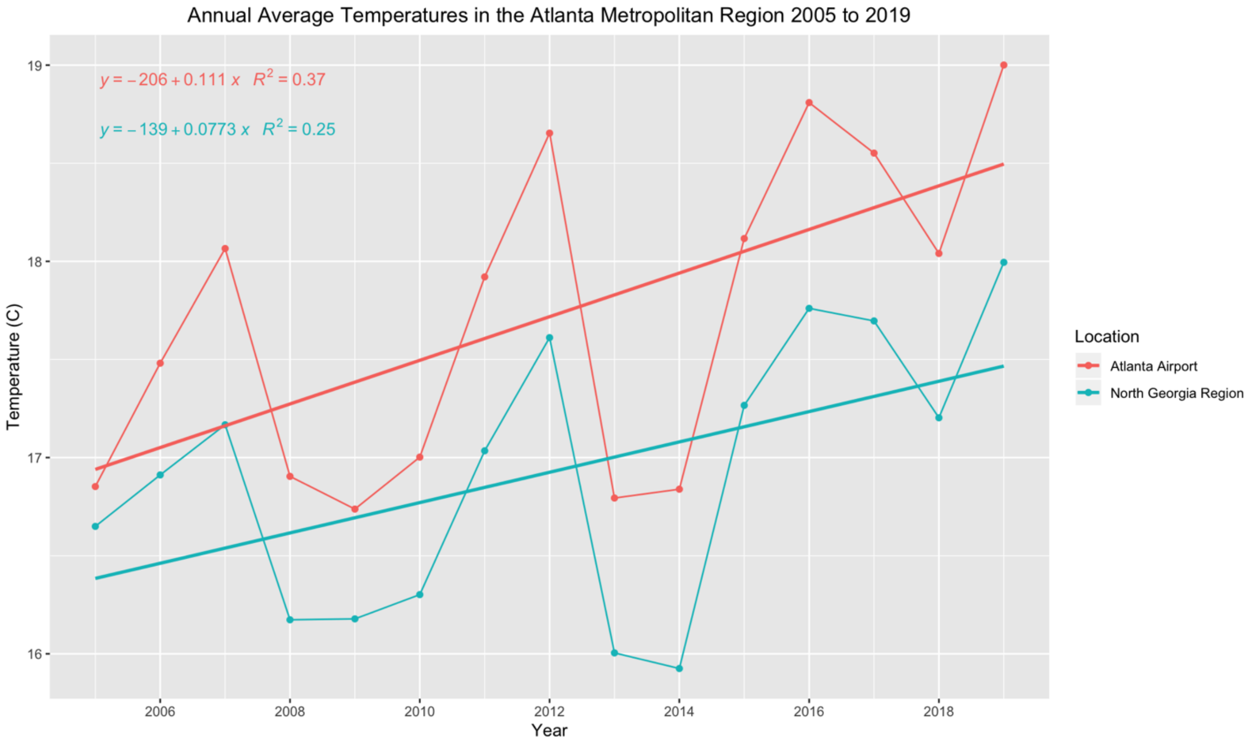


FIGURE 1. *Trends of Annual Average Temperature for Atlanta Compared to Northern Georgia*. Created by Katelyn Boisvert using source date (NOAA, “Climate Data Online”).

North Georgia region included three sites that are considered urban and four in more rural locations. As can be seen in this graph, temperatures at the Atlanta station are warmer than temperatures for the greater region, and temperatures are on the rise over the course of 2005 to 2019. Important to note is that temperatures for Atlanta are increasing at a faster rate of 0.11°C per year, as compared to 0.08°C per year for Northern Georgia. The faster rate suggests that the increasing temperatures in this urban area are due to more than observed climate change alone. Considering the increasing frequency and/or intensity of heat waves, the UHI effect has major implications for health-related concerns in cities, in which residents may experience respiratory distress and organ failure from heat stroke, as well as cardio-respiratory illness due to trapped harmful ozone (Kleerekoper 2012, 30-38).

The abnormal increase in surface and air temperatures within urban areas can result in consequences for the meteorological conditions of these regions, and may influence factors such as precipitation and thunderstorm occurrence. Thunderstorms form in areas where there is adequate moisture, unstable air, and a lifting mechanism. Since warmer air is less dense than cooler air, if it is lifted it will continue to rise as long as it stays warmer than the surrounding air. This rising motion is responsible for the formation of clouds and thunderstorms when the conditions are right (NOAA, “Severe Weather 101”). Warmer temperatures associated with the UHI effect provide the potential for unstable air, and buildings in urban areas alter air flow patterns; these result in convergence and the potential for air to rise, which lead to cloud formation and increased precipitation in these areas (Riebeek 2006, 1-4). Increased precipitation can potentially have major impacts for streamflow and flood risk in urban areas, especially when combined with the influence of impervious surfaces.

One of the most visible and easily quantifiable impacts of urbanization on environmental systems is the shift from natural areas of filtration to impervious surfaces. As rural areas shift to urban, or residential areas shift to alternate land uses such as commercial and industrial, the number of areas available for natural filtration decreases. Impervious surfaces, such as roads, roofs and parking lots, do not allow water to pass through their materials to reach groundwater aquifers below the surface. Instead of re-charging local aquifers through infiltration, water can accumulate on the surface contributing to flash floods, and increased water flow along the surface can increase runoff into streams. The increased occurrence of runoff modifies natural streamflow patterns and carries pollutants from agriculture, manufacturing and other industrial processes into waterways (Arnold and Gibbons 1996, 243-258). As is described in Figure 2,

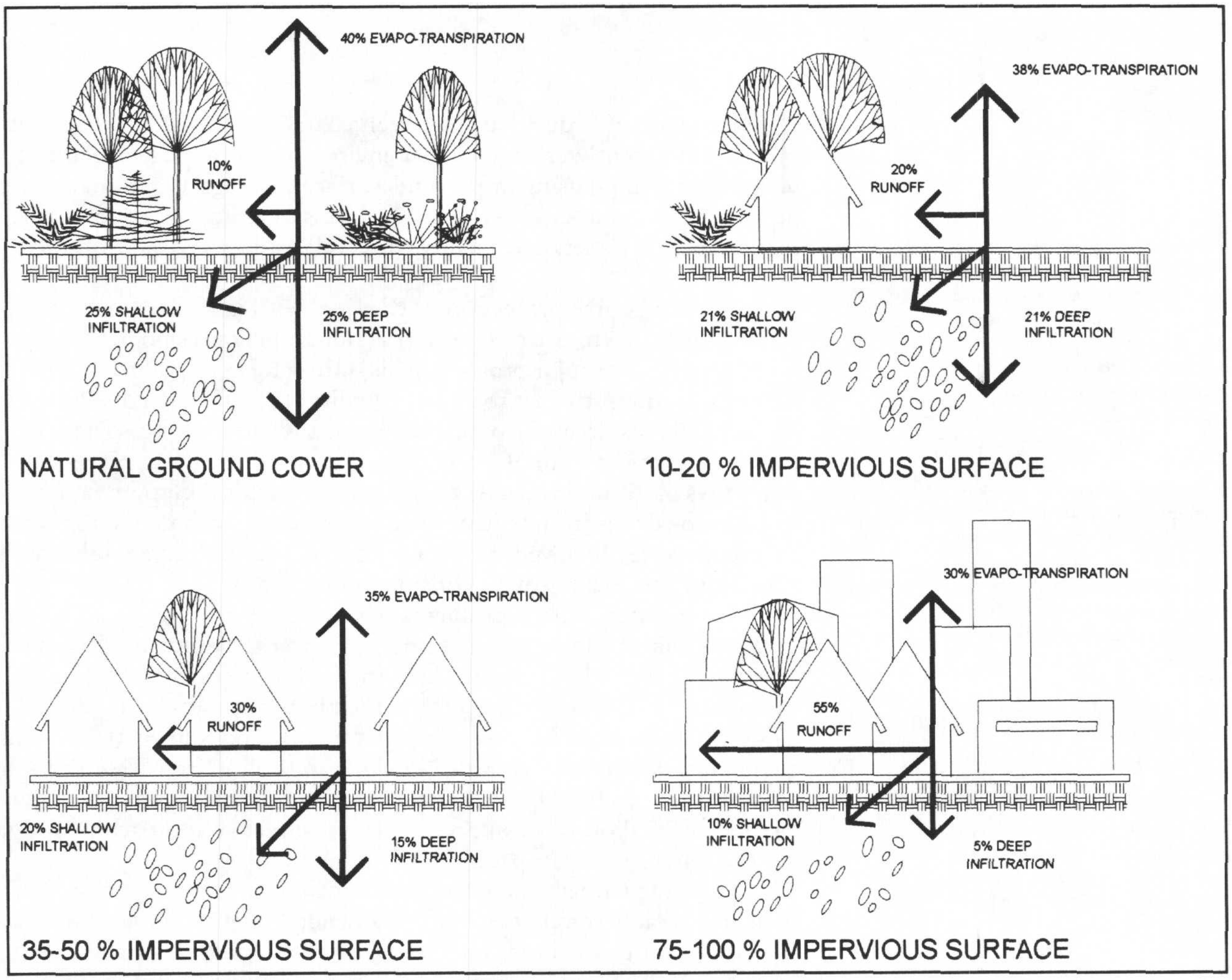


FIGURE 2. *Changes in Water Flow from Increased Impervious Surface with Urbanization*. (Arnold and Gibbons 1996, 244; Image source: EPA Report #840-B-92-002, 1993).

under natural ground cover conditions, 10% of water is runoff and there is 50% infiltration; while in highly urbanized areas, over 50% of rain becomes surface runoff, with infiltration limited to 15% (Arnold and Gibbons 1996, 244).

In addition to impervious surface impacts on water flow, population growth in urban areas increases the demand for water, leading to potential water shortages. In Atlanta specifically, the Tri-State Water Wars between Georgia, Alabama and Florida showcase the importance of water management strategies in regard to developing urban areas (Atlanta Regional Commission 2018, “Tri-State Water Wars”).

CHAPTER 1

Urban Spread and Density in Atlanta, Georgia from 2000-2016

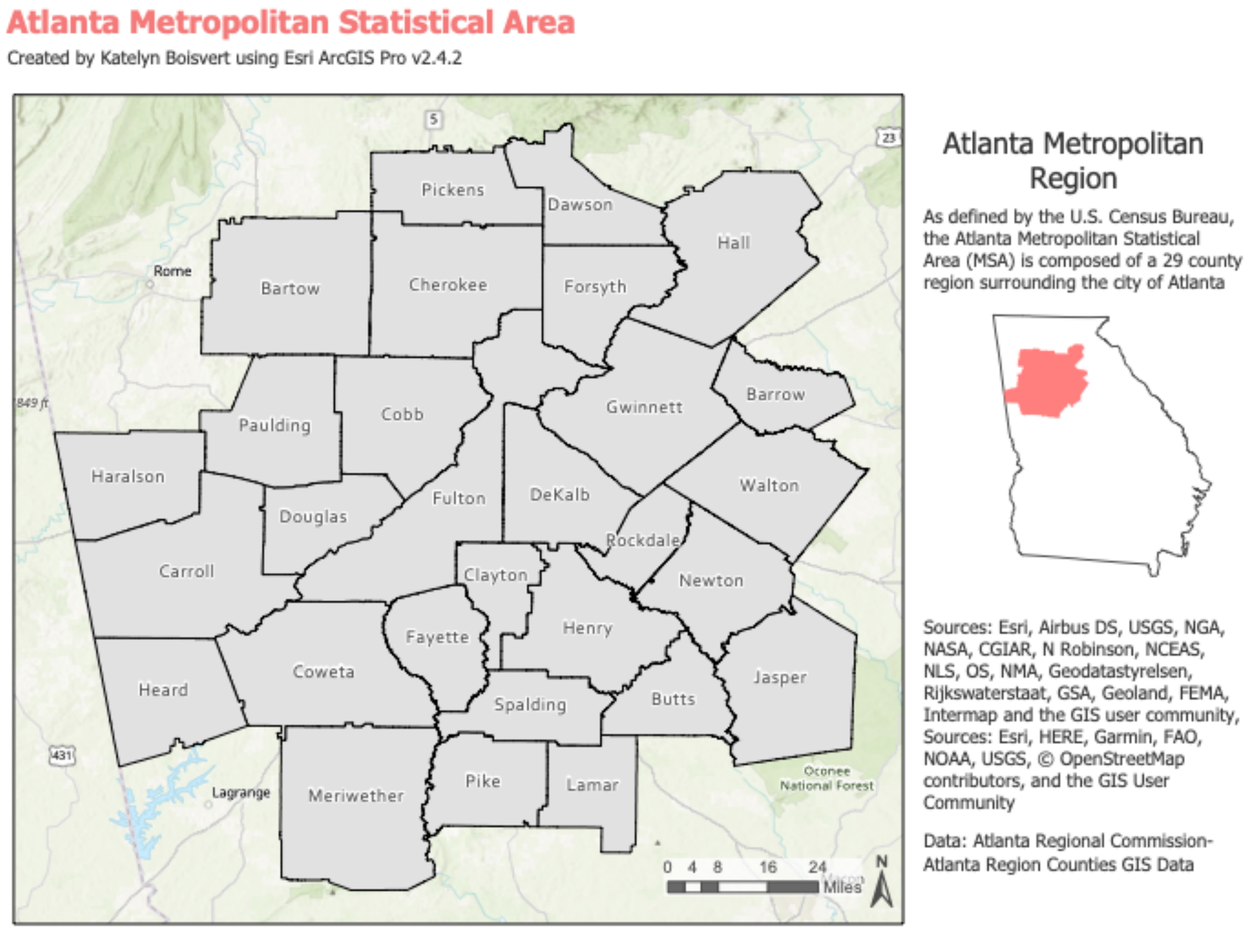
The objective of this chapter is to quantify changes in the urbanization of Atlanta in recent years. Approaches to sustainability action for the region would differ depending on whether there are shifts from rural to urban areas or increases in impervious surfaces, as these account for the greatest changes in environmental impacts resulting from urbanization. In order to determine the relationship between these factors, the quantity of both urban spread and density changes will be evaluated using GIS methodology.

Data and Methods

Mapping was completed using ArcGIS Pro version 2.4.2. Data used in this study consisted of both vector and raster data and was analyzed using a collection of toolboxes and extensions offered by the advanced license provided by Emory University. A complete list of tools and methods used in this analysis can be found in Appendix A.

Map Scale and Spatial Reference

The Atlanta Metropolitan Statistical Area (MSA) was chosen for this analysis in order to compare urban and rural areas within in a similar geographic region with known links in social and economic factors. To be classified as an MSA by the U.S. Census Bureau, an area must contain an urban core of at least 50,000 inhabitants, and the surrounding areas must be linked by common economic and social factors (U.S. Census Bureau 2018, “About”). The Atlanta MSA is a 29-county region surrounding the city of Atlanta, as depicted in Figure 1.1 (Metro Atlanta Chamber, “29-County Metropolitan Statistical Area”).


Atlanta Metropolitan Statistical Area

Created by Katelyn Boisvert using Esri ArcGIS Pro v2.4.2

Atlanta Metropolitan Region

As defined by the U.S. Census Bureau, the Atlanta Metropolitan Statistical Area (MSA) is composed of a 29 county region surrounding the city of Atlanta

Sources: Esri, Airbus DS, USGS, NGA, NASA, CGIAR, N Robinson, NCEAS, NLS, OS, NMA, Geodatastyrelsen, Rijkswaterstaat, GSA, Geoland, FEMA, Intermap and the GIS user community, Sources: Esri, HERE, Garmin, FAO, NOAA, USGS, © OpenStreetMap contributors, and the GIS User Community

Data: Atlanta Regional Commission-Atlanta Region Counties GIS Data

FIGURE 1.1. *Map of Counties in the Atlanta Metropolitan Statistical Area.*

Analysis of population changes within the Atlanta MSA was conducted at the census tract level, which allowed for differentiating overall trends in rural and urban areas without limiting data by using too small of an area for analysis.

Throughout the years explored in this study, census tract boundaries for some tracts shifted as population grew, which could have resulted in an issue when comparing population data across years with differing boundaries. Population density within each census tract was instead used, which allowed for comparison across census tracts even when boundaries shifted.

All data used in this study was projected using the North American Datum (NAD) 1983 State Plane Georgia East FIPS 1001 (US Feet) projection. Projecting data was the first step for all following methodologies.

Data Acquisition

Data required for this study included population data at the census tract level and land cover data for the 29 counties in the Atlanta MSA. Population data was acquired from the Atlanta Regional Commission (ARC), which creates datasets to demonstrate population change across Georgia. Acquired ARC datasets included: a population change dataset for the years 2000-2008 [containing Census 2000 data, and 2008 data from the ACS]; and a population change dataset for the years 2010-2016 [containing Census 2010 data, and 2016 data from the ACS].

The ARC utilized Census 2000 and Census 2010 data obtained from the U.S. Census Bureau. Population data for 2008 and 2016 was developed by the Research & Analytics Group of the ARC using the 5-year estimates from the American Community Survey (ACS) conducted by the U.S. Census Bureau. Since the data for 2008 and 2016 represents an estimate of population, it is not as accurate as measurements for the years 2000 and 2010, which should be considered when comparing population data across those years.

Land use data was also acquired from the ARC. The years that land use data (LandPro) was offered was limited to the years 1999-2012. This restricted density analysis to the years 2000-2010 even though population data was acquired up through 2016. As a result, urban spread was evaluated for the years 2000-2016, and density was evaluated for the years 2000-2010.

LandPro shapefiles for the years 1999, 2008 and 2010 were downloaded from the ArcGIS mapping hub. The 1999 shapefile does not contain all counties in the current Atlanta MSA but does encompass the majority of urban areas for this time. These counties were excluded for the purposes of analyzing density impacts for the year 2000 and included for analysis post-2000.

Urban Spread

A graduated color map of population density was produced using ArcGIS Pro following methodology outlined in Appendix A. Data was displayed using a custom interval according to the U.S. Census Bureau definition of urban areas, which states the following criteria: to be defined as urban, a census tract must contain a population density of greater than 500 people per square mile; census tracts with population densities between 500 to 1000 people per square mile are defined as urban areas; and census tracts with populations greater than 1000 people per square mile are defined as urban cores (USDA 2019, "What is Rural"). The scale values chosen for this map were based on the U.S. Census definition for the distinction between urban and rural sites, and the values for the remaining classes were chosen using a rounded geometric interval. Table 1.1 describes the values used in this interval and the definition of each corresponding class.

TABLE 1.1. Manual Interval Approach for Population Mapping

Interval Class Value	Census Tract Definition
≤ 500	Rural
≤ 1000	Urban Area
≤ 3000	Low Density Urban Core
≤ 9000	Medium Density Urban Core
≤ 40000	High Density Urban Core

Urban Density

The land use data downloaded from the ARC divides areas into more land use types than are used in the density analysis. In order to properly analyze data, each land use type provided in the LandPro data was reclassified into one of four categories: low-density residential, high-density residential, commercial, and industrial. Values were reclassified according to the land use based on percent of impervious surfaces and degree of environmental impacts. Table 1.2

describes which land use types provided in the LandPro data were included in each of the four categories. Greenspaces were removed from all analysis as these areas are expected to have little to no impervious surface resulting in a density of zero, and these land use descriptions are also included in the table.

Based on literature review (Tilley and Slonecker 2006, 1–34; USDA, "Hydrology Training Series"), residential areas were defined as the least dense with minimal impervious surfaces and environmental impacts. Low density residential areas, such as single-family homes on large land lots, were further separated from high density residential uses, such as apartment buildings and single-family homes on small land lots, as these contain a higher percentage of impervious surface. Commercial facilities were classified as medium density areas due to impervious surface percentage from buildings and parking lots, and the potential for environmental damage. Industrial facilities were classified as the densest due to high impervious surface percentage, and the potential for extreme environmental damage from runoff and other pollutants. The corresponding density for each land use type is included in Table 1.2.

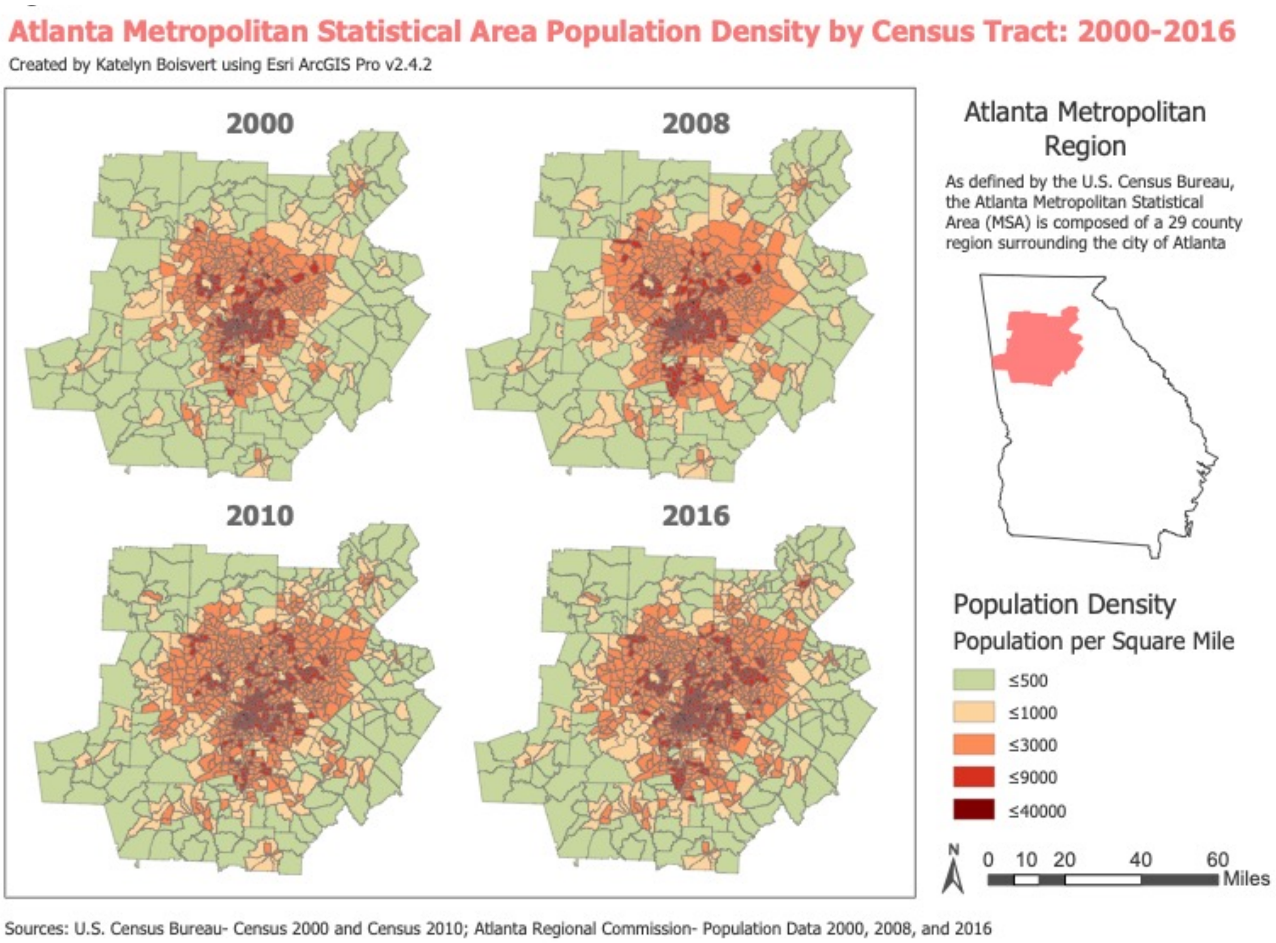
These reclassified land use maps were overlaid with the population density data to create maps of urban density, following ArcGIS methodologies outlined in Appendix A.

TABLE 1.2. Land Use Data Classification for Density Analysis

Land Use Class	Density Description	LandPro Data Types
Greenspace	-	Park Lands; Forest; Wetlands; Crops; Orchard; Rivers; Reservoirs
Low-Density Residential	Low Density	Low Residential; Mobile Homes
High-Density Residential	Low Density	Multifamily; Medium Residential; High Residential
Commercial	Medium Density	Parks; Golf Courses; Cemetaries; Commercial; Intensive Institutional; Extensive Institutional; Other Agriculture; Other Urban
Industrial	High Density	Industrial; Industrial/Commercial Complexes; Exposed Rock; Quarries; Transportation, Communication and Utilities; Highways

Results

Maps were created to explore and quantify both urban spread and urban density. Figure 1.2 displays the population density maps for the years 2000 to 2016. These maps show an increase in population density throughout many census tracts, and an overall increase in the number of urban census tracts.



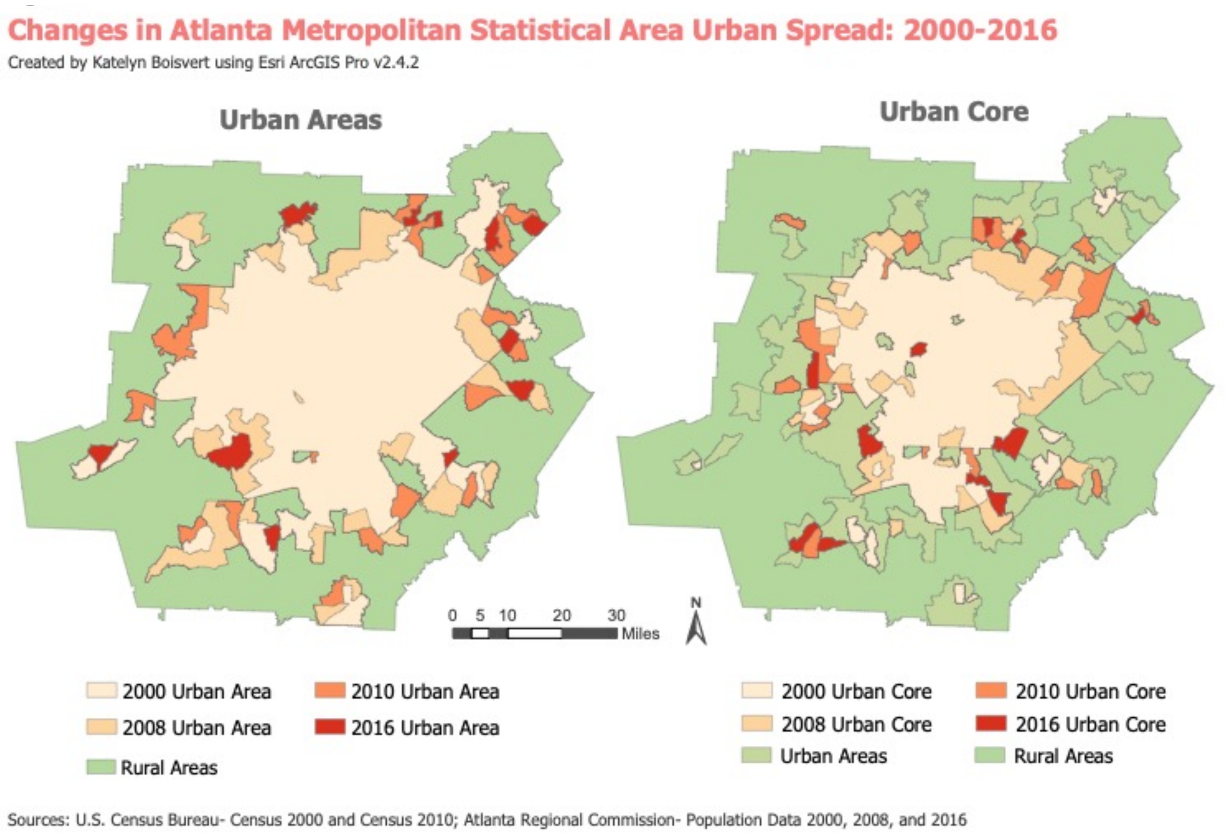
Atlanta Metropolitan Statistical Area Population Density by Census Tract: 2000-2016

Created by Katelyn Boisvert using Esri ArcGIS Pro v2.4.2

Sources: U.S. Census Bureau- Census 2000 and Census 2010; Atlanta Regional Commission- Population Data 2000, 2008, and 2016

FIGURE 1.2. *Map of Calculated Population Density in the Atlanta Metropolitan Region, 2000-2016.*

Figure 1.3 focuses on the development of urban areas and urban cores. As the years progress towards 2016, there is decrease in the rate that census tracts become urban areas or urban cores as compared to previous years.



Changes in Atlanta Metropolitan Statistical Area Urban Spread: 2000-2016

Created by Katelyn Boisvert using Esri ArcGIS Pro v2.4.2

Urban Areas

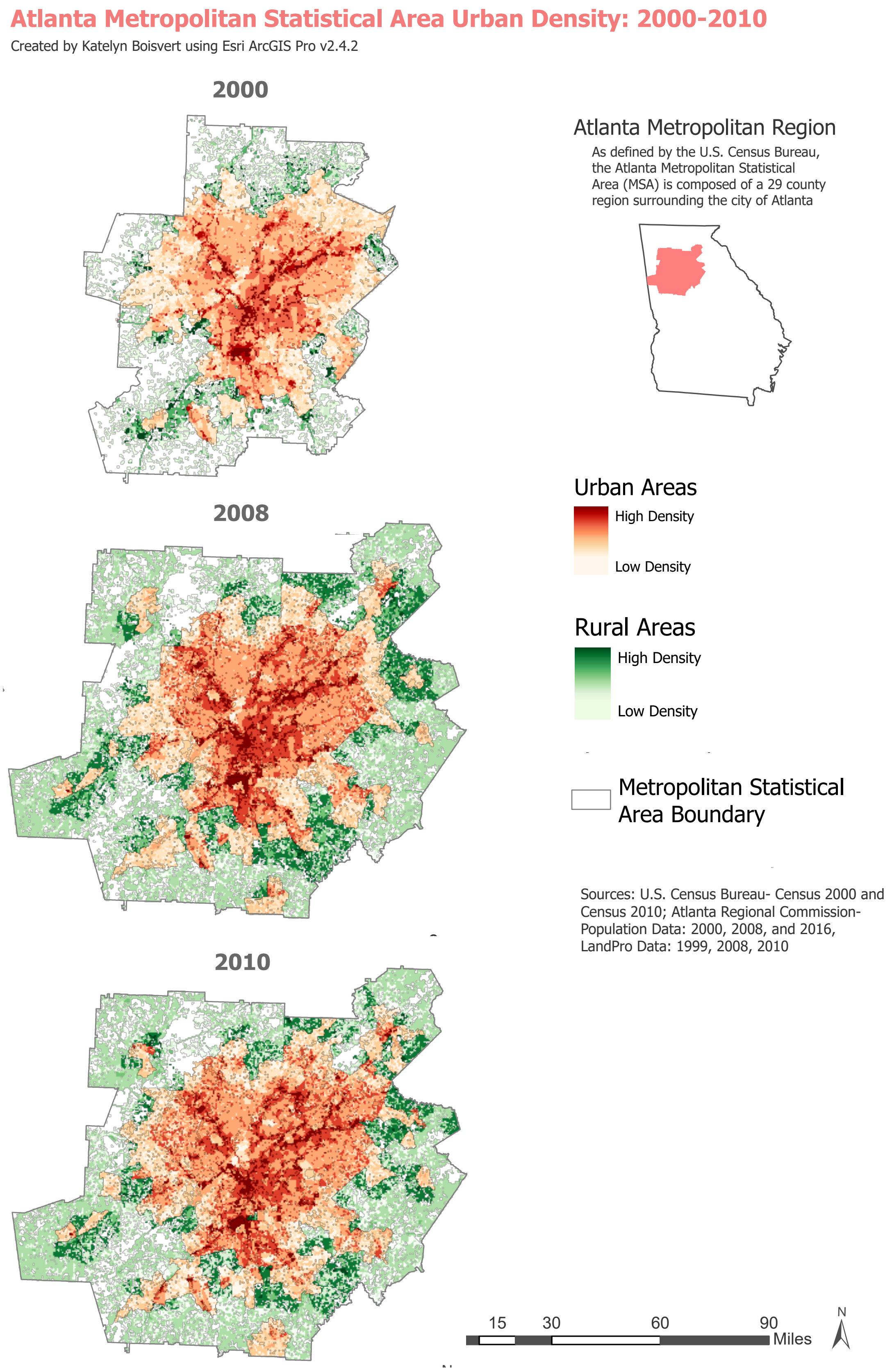
Urban Core

Sources: U.S. Census Bureau- Census 2000 and Census 2010; Atlanta Regional Commission- Population Data 2000, 2008, and 2016

FIGURE 1.3. *Map of Calculated Urban Spread in the Atlanta Metropolitan Region, 2000-2016.*

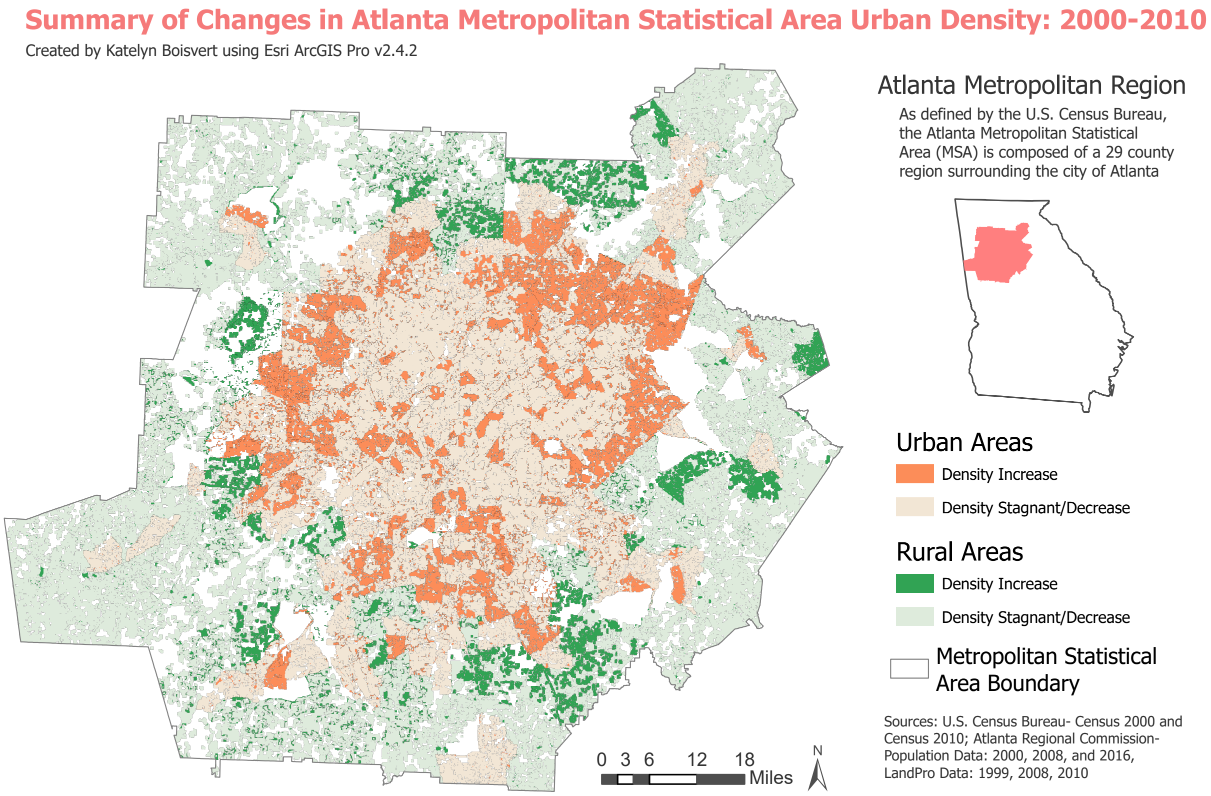
Figure 1.4 displays the changes in urban density over the years 2000 to 2010. These maps show a gradient of low- to high-density population for both rural and urban areas. An increase in high density areas for both urban and rural regions of the city are observed over time.

Figure 1.5 summarizes the data to display the areas that have experienced an increase in density compared to those that have experienced a density decrease or remained stagnant. Even within the central urban core, which has been an urban area for many years, there are observed increases in density, showing that these urban areas are still changing and growing.



Sources: U.S. Census Bureau- Census 2000 and Census 2010; Atlanta Regional Commission- Population Data: 2000, 2008, and 2016, LandPro Data: 1999, 2008, 2010

FIGURE 1.4. *Map of Calculated Urban Density in the Atlanta Metropolitan Region, 2000-2010.*



Summary of Changes in Atlanta Metropolitan Statistical Area Urban Density: 2000-2010

Created by Katelyn Boisvert using Esri ArcGIS Pro v2.4.2

Atlanta Metropolitan Region

As defined by the U.S. Census Bureau, the Atlanta Metropolitan Statistical Area (MSA) is composed of a 29 county region surrounding the city of Atlanta

Sources: U.S. Census Bureau- Census 2000 and Census 2010; Atlanta Regional Commission- Population Data: 2000, 2008, and 2016, LandPro Data: 1999, 2008, 2010

FIGURE 1.5. *Summary of Urban Density Changes in the Atlanta Metropolitan Region, 2000-2010.*

Discussion

The results of this chapter show that the urbanization of Atlanta is a continually changing process, even in recent years. While results show that urban spread is still increasing to new census tracts, the rate of change in this variable is not as significant as it was in the history of Atlanta’s urban sprawl (Kundell and Myszewski 2017, “Urban Sprawl”). More of the change is now occurring in the density of these areas, with results demonstrating that even areas of the city that have been an urban core since 2000 continue to increase in density.

This pattern reveals shifts from lower density land uses, such as residential areas, to higher density uses including commercial or industrial areas, which results in a greater percentage of impervious surfaces and an increase in impacts such as pollution on local environmental issues. Based on these results, sustainability solutions for commercial and industrial areas should be a priority for addressing risks posed from urbanization. Strategies such as permeable pavement and improved water management and runoff from industrial facilities are key examples of approaches that could be considered for this region.

It is likely with the changes observed in density between the years 2000 to 2010 that similar increases in density can be expected for the years 2010 to 2020. However, trends cannot be confirmed due to the lack of data for these years. Determination of more recent trends in density change would be an important next step in order to assess the best course of action for sustainability approaches.

Additional analysis would be helpful to determine specifics of the changing profile of urbanization in Atlanta. For example, is the density of residential areas increasing? Are there trends in people moving out of single-family homes and into apartment buildings? This type of trend would showcase a need for prioritizing sustainable building practices, as previously residential areas are converted into higher-density regions such as apartment buildings.

Conclusions

This study sought to quantify the urbanization of Atlanta, Georgia in order to inform approaches to sustainability regarding environmental impacts that are associated with the urbanization process. Results found that the rate of the spread of urban areas has declined in recent years, but that urban areas are experiencing increases in density. Increased density can lead to the greater potential for environmental impacts as a result of land use in these areas.

This study serves as a basis for conducting quantitative analysis of urbanization changes in Atlanta, and further analysis could be completed following similar methodologies to more accurately characterize the changing urban profile of Atlanta and best inform future policy and sustainability decisions.

CHAPTER 2

Meteorologic Effects of Urbanization

The objective addressed in this chapter is the analysis of the changes in meteorological conditions resulting from urbanization, specifically focusing on thunderstorm occurrence, duration and intensity. Since changes in meteorological conditions have further impacts on water availability and quality, flooding, and other risks related to the sustainability of a region, it is important to understand the interaction of these systems in urban areas.

Previous studies on meteorological impacts in urban areas have presented focused approaches to evaluating the causation of thunderstorms in relation to urban areas. Studies often assess weather effects to demonstrate increased precipitation over urban centers, and more recently studies have shown that in addition to impacting precipitation levels, urban areas have the potential to result in thunderstorm formation directly. (Dixon and Mote 2003, 1273-1284; Bentley, Ashley, and Stallins 2009, 1589-1594; Shem and Shepherd 2009, 172-189; Bornstein and Lin 2000, 507-516).

To evaluate the formation of urban-initiated thunderstorms, many studies utilize radar imagery to examine the formation of a particular thunderstorm and assess changes in its composition and/or structure resulting from its interface with urban areas (Bentley, Ashley, and Stallins 2009, 1589-1594; Niyogi et al 2011, 1129-1144; Ashley, Bentley, and Stallins 2012, 481-498; Haberlie, Ashley, and Pingel 2015, 663-675; Shem and Shepherd 2009, 172-189). This study instead sought to evaluate a different methodology using available METAR weather data that could allow for comparison of a greater number of thunderstorm occurrences, and more importantly could provide accessible methodology for both scientists and non-scientists alike, which would benefit a wider range of stakeholders including city planners and local government who may utilize this information when considering urban sustainability impacts and decision-making.

Data and Methods

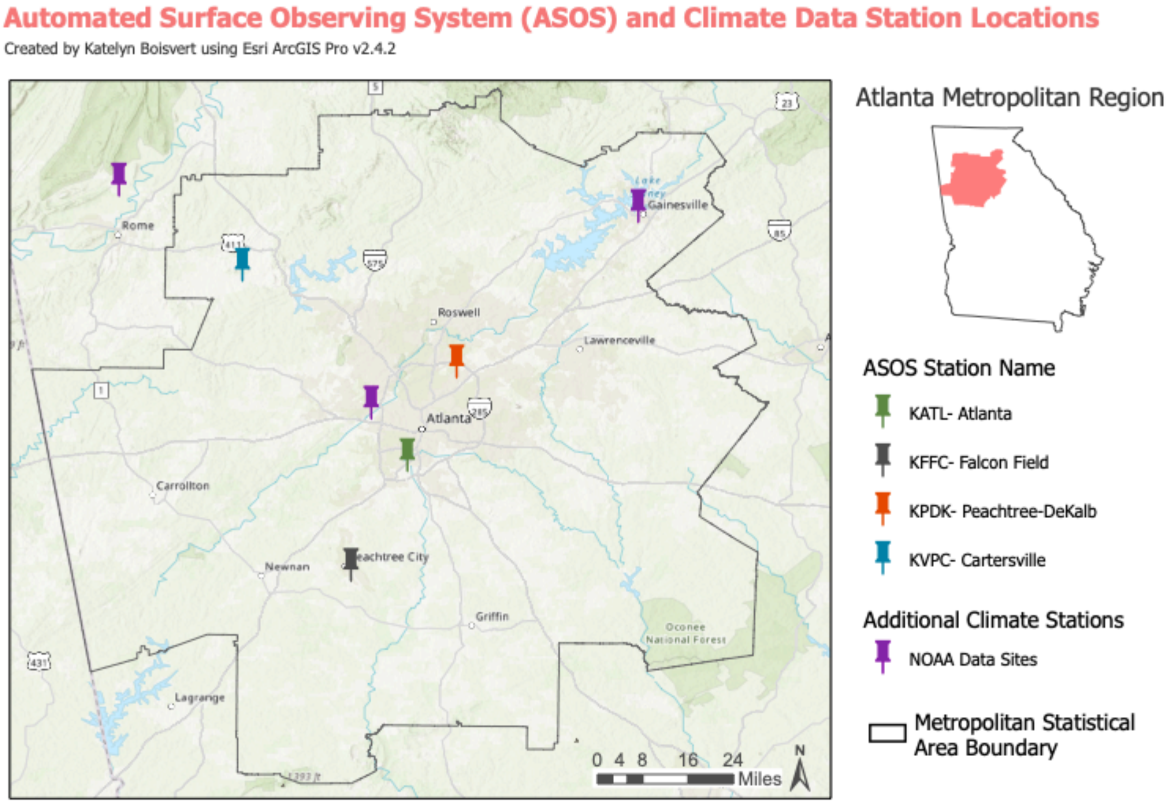
All analysis was completed using R software and explored data at four locations in both urban and rural areas of the Metro Atlanta region for a span of 15 years including 2005 to 2019.

Data Acquisition

There was currently no database that contains all thunderstorm occurrences for the Atlanta Metro Region, so the first step in this study was to create a database utilizing METAR weather data collected at stations throughout Atlanta. Automated Surface Observing System (ASOS) 5-minute observation data was downloaded from the NOAA National Centers for Environmental Information (NCEI) website. Four sites representing the Atlanta metro area were selected: KATL (Atlanta: Hartsfield-Jackson, Fulton, GA); KPDK (Atlanta: Dekalb-Peachtree, Dekalb, GA); KFFC (Atlanta: Falcon Field, Fayette, GA); and KVPC (Cartersville, Bartow, GA). These four sites (identified in Figure 2.1) were categorized as urban or rural based on the urbanization analysis completed in Chapter 1, with KATL and KPDK identified as urban stations, and KFFC and KVPC identified as rural.

The ASOS raw data was downloaded from the NOAA website in text file format (NOAA, “ASOS”). Each file contained the data for one month for one of the four stations chosen for analysis. Data was downloaded for all months for the years 2005 to 2019. This sequence was completed to acquire data for all four sites in the study.

Daily climate data was also downloaded from the NOAA NCEI website for a total of seven climate stations located throughout North Georgia (NOAA, “Climate Data Online”). In addition to the four ASOS sites previously identified, climate observations were recorded at sites in Rome, GA and Gainesville, GA (identified as rural), and at the Atlanta-Fulton Airport (identified as urban). This data included maximum, minimum and average daily temperature, as well as total daily precipitation. The daily climate data was used along with the ASOS files to allow comparison of the climatic conditions between sites in the Atlanta urban area to the larger North Georgia region.



Sources: Esri, Airbus DS, USGS, NGA, NASA, CGIAR, N Robinson, NCEAS, NLS, OS, NMA, Geodatastyrelsen, Rijkswaterstaat, GSA, Geoland, FEMA, Intermap and the GIS user community, Sources: Esri, HERE, Garmin, FAO, NOAA, USGS, © OpenStreetMap contributors, and the GIS User Community

FIGURE 2.1. *Site Locations for METAR Weather Data and NOAA Climate Data Collection in the North Georgia Region.*

Data Cleaning and Processing

Using R (R Project for Statistical Computing), a coding methodology was developed to identify patterns in the ASOS data and isolate for variables of interest. Data files were subset from the 5-minute ASOS data for each month over the past fifteen years (2005-2019) to retrieve only entries where a thunderstorm occurrence observation was recorded. R code was used to remove the following variables from the rows identified as having a thunderstorm occurrence:

station identifier, date and time recorded, thunderstorm intensity, wind speed, temperature, and dew point. Out of all 34,352 thunderstorm occurrence observations recorded, a total of 4,262 individual thunderstorms were identified across the four stations over the course of the 15-year study. Table 2.1 displays the breakdown of the number of thunderstorms at each station, and the number of data points examined in order to arrive at these values.

TABLE 2.1. Thunderstorms in Atlanta Metro Region 2005 to 2019: Data Processing Using R

Station	Number of Thunderstorms	Number of Thunderstorm Observations	Number of Data Points Collected
Atlanta	1250	14,203	~1,576,800 *
Peachtree	879	7225	~1,576,800 *
Falcon Field	1081	6473	~1,576,800 *
Cartersville	1052	6451	~1,576,800 *
Overall	4262	34,352	~6,307,200 *

* Based on standard 5-minute interval METAR data collection from Automated Surface Observing System (ASOS)

Data was summarized to obtain one row of data corresponding to each individual thunderstorm occurrence. The end of a storm was identified if more than 5 minutes of observation time had passed without a thunderstorm being reported. This was coded in R based on the time variable recorded in the ASOS data. Data for each identified thunderstorm event was summarized to complete the following: calculate the storm duration; categorize storm intensity; and calculate the average the wind speed, temperature, and dew point. This process was repeated for each month, and data was first compiled for each year, and then overall for the 15-year course. Data was processed following the same methods for each of the four stations.

The ASOS data does not contain information about the amount of precipitation received during thunderstorms, so this information was obtained from the daily climate data. In R, the date of each previously identified thunderstorm occurrence was used to select only the data that corresponded to a storm occurrence. Data was added to original ASOS tables for further analysis.

Results

Analysis of Temperature Anomalies

In order to identify potential urban-initiated thunderstorms, the NOAA NCEI climate data was used to calculate temperature anomalies between the temperature observed at the time of the thunderstorm and the temperatures recorded at the NCEI climate stations. The rural area temperature anomaly was calculated by averaging the daily average temperatures at the three rural climate stations, and subtracting this value from the reported temperature during thunderstorm occurrences at the urban sites. Overall temperature anomaly was calculated by averaging the daily average temperature across all seven climate stations in North Georgia, and subtracting this value from the reported temperature during thunderstorm occurrences at the urban sites.

Smaller datasets were subset from these to select only rows with a temperature anomaly of greater than 1°C, 2°C and 3°C. Correlations between thunderstorm duration and the number of storms per month were evaluated against the temperature anomaly variable in these three datasets to identify trends between higher average daily temperatures and thunderstorm occurrences. However, these were not found to be significant and were not analyzed further in the results. Table 2.2 summarizes this information.

TABLE 2.2. Temperature Anomaly Correlations

Rural Temperature Anomaly		Regional Temperature Anomaly	
Temperature Anomaly	Correlation Value	Temperature Anomaly	Correlation Value
1℃	-0.0879	1℃	-0.0927
2℃	-0.0745	2℃	-0.1246
3℃	-0.1113	3℃	-0.1469

Thunderstorm Duration

Thunderstorm duration was evaluated using results for the duration variable that was calculated during the data cleaning process. The distribution of thunderstorm duration values was graphed for each ASOS station using a density plot (Figure 2.2). Mean duration values for all locations are represented by dashed lines. Results demonstrate that the two rural ASOS sites had fairly similar thunderstorms durations, which are notably shorter in duration than the two urban areas. Also, the Atlanta ASOS station representing the most urbanized of the four areas has the longest duration thunderstorms on average and demonstrates the most variability in its range.

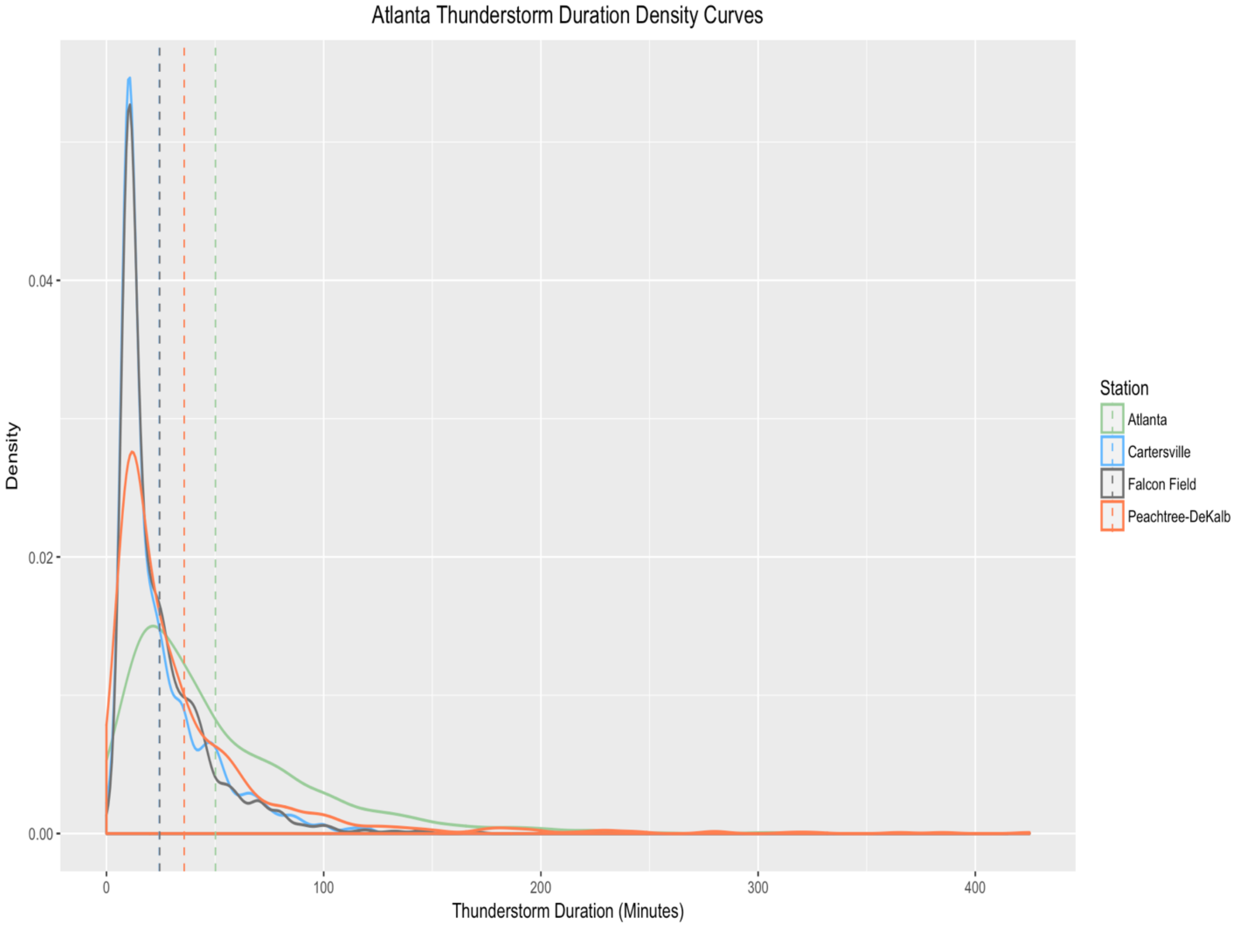


FIGURE 2.2. *Thunderstorm Duration Density Curves and Average Durations at ASOS Stations.*

Pairwise comparison using t-tests with a pooled standard deviation was used to evaluate differences in thunderstorm duration between sites to a set alpha of 0.01. Due to the large sample size considered (n > 100 for all four sites), it was assumed that the data assessed met the conditions to perform this test. Results demonstrated a statistically significant difference between the average thunderstorm duration at the Atlanta Airport ASOS site compared to the other three locations, and between the Peachtree-DeKalb Airport site and the two rural locations, as shown by values in Table 2.3.

TABLE 2.3. P-Value Matrix for Thunderstorm Duration

	Atlanta	Cartersville	Falcon Field
Cartersville	< 2e-16 *	-	-
Falcon Field	< 2e-16 *	0.89	-
Peachtree-DeKalb	< 2e-16 *	5.4e-13 *	7.8e-13 *

In a Pairwise Comparison using T-Tests with a Pooled Standard Deviation, (*) results were significant to well below the set alpha of 0.01

Thunderstorm Number

Since differences in the number of thunderstorms at each ASOS station could be attributed to a variety of factors and not isolated to urbanization influences alone, the number of thunderstorms occurring at each station could not be compared directly. Instead, the proportion of thunderstorm occurrences was calculated using R. The total number of thunderstorms that occurred in a given month over the course of the 15-year study period were summed, and the proportion for that month out of the total number of storms that occurred in the 15-year period at each station was calculated.

Figure 2.3 displays the monthly proportion of thunderstorms at each ASOS station. The general seasonality of thunderstorm occurrences can be seen, with higher proportions of thunderstorms occurring during the summer months. There were no other trends observed in this data indicating that the number of thunderstorms was not particularly influenced by urban versus rural locations. Pairwise comparison using t-tests with a pooled standard deviation confirmed that differences between the monthly proportions of thunderstorms at each station (alpha 0.01) were not found to be statistically significant (Table 2.4).

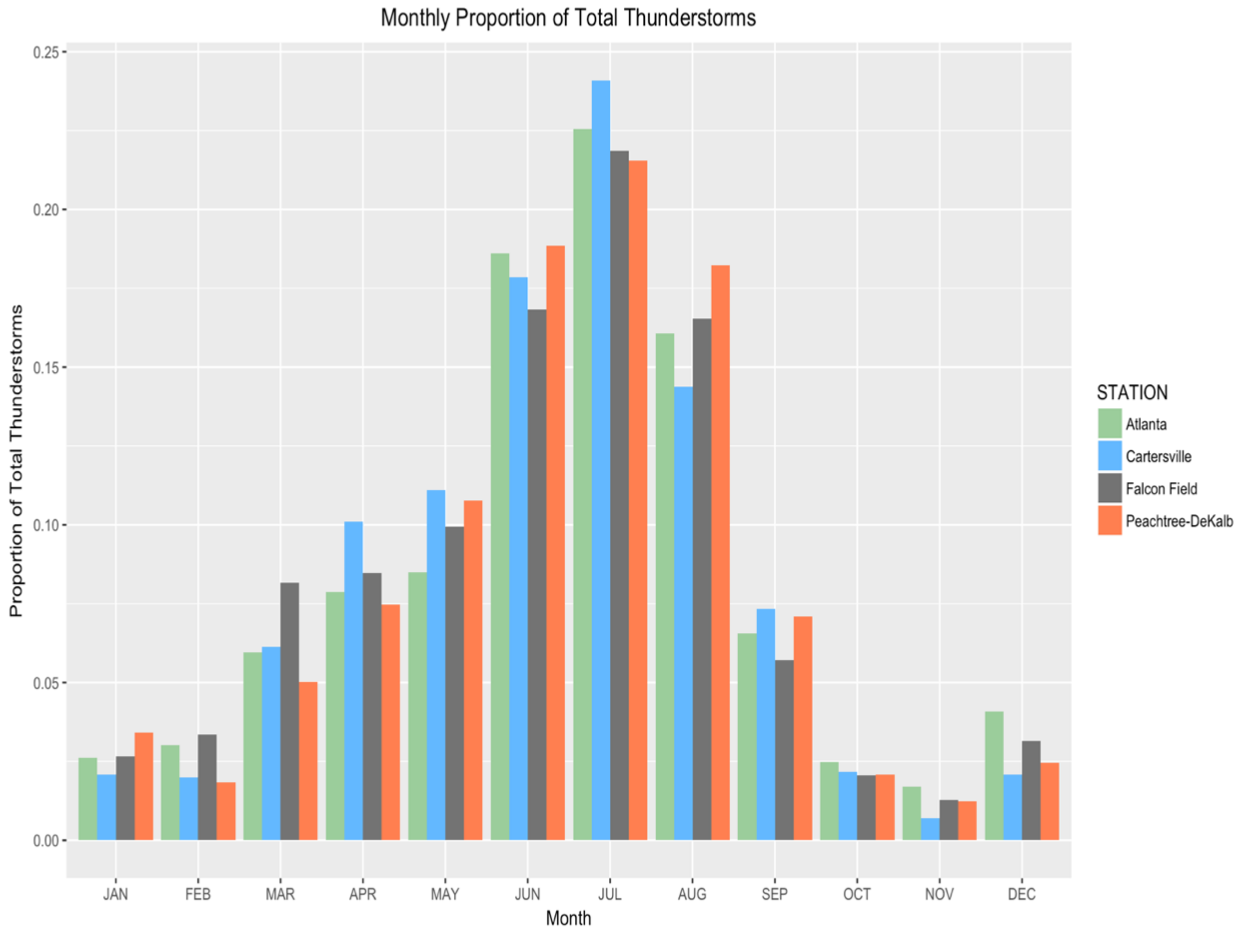


FIGURE 2.3. *Monthly Proportion of Total Thunderstorms Occurring at ASOS Stations.*

TABLE 2.4. P-Value Matrix for Number of Thunderstorms

	Atlanta	Cartersville	Falcon Field
Cartersville	0.489	-	-
Falcon Field	0.366	0.639	-
Peachtree-DeKalb	0.078	0.325	0.366

In a Pairwise Comparison using T-Tests with a Pooled Standard Deviation, no results were significant using a set alpha of 0.01

Thunderstorm Intensity

Thunderstorm intensity was also evaluated using results for the intensity variable that was calculated during the data cleaning process. Thunderstorms were categorized as either a light thunderstorm (corresponding to a METAR reading of “-TS”) a normal thunderstorm (corresponding to a METAR reading of “TS”), or a heavy thunderstorm (corresponding to a METER reading of “+TS”). Pie charts were created to present the data as the percentage proportion of each intensity of thunderstorm for all four ASOS stations, as shown in Figure 2.4. Results do not vary dramatically, but there is a slight increase in the occurrence of heavy thunderstorms for the rural sites as compared to the urban sites.

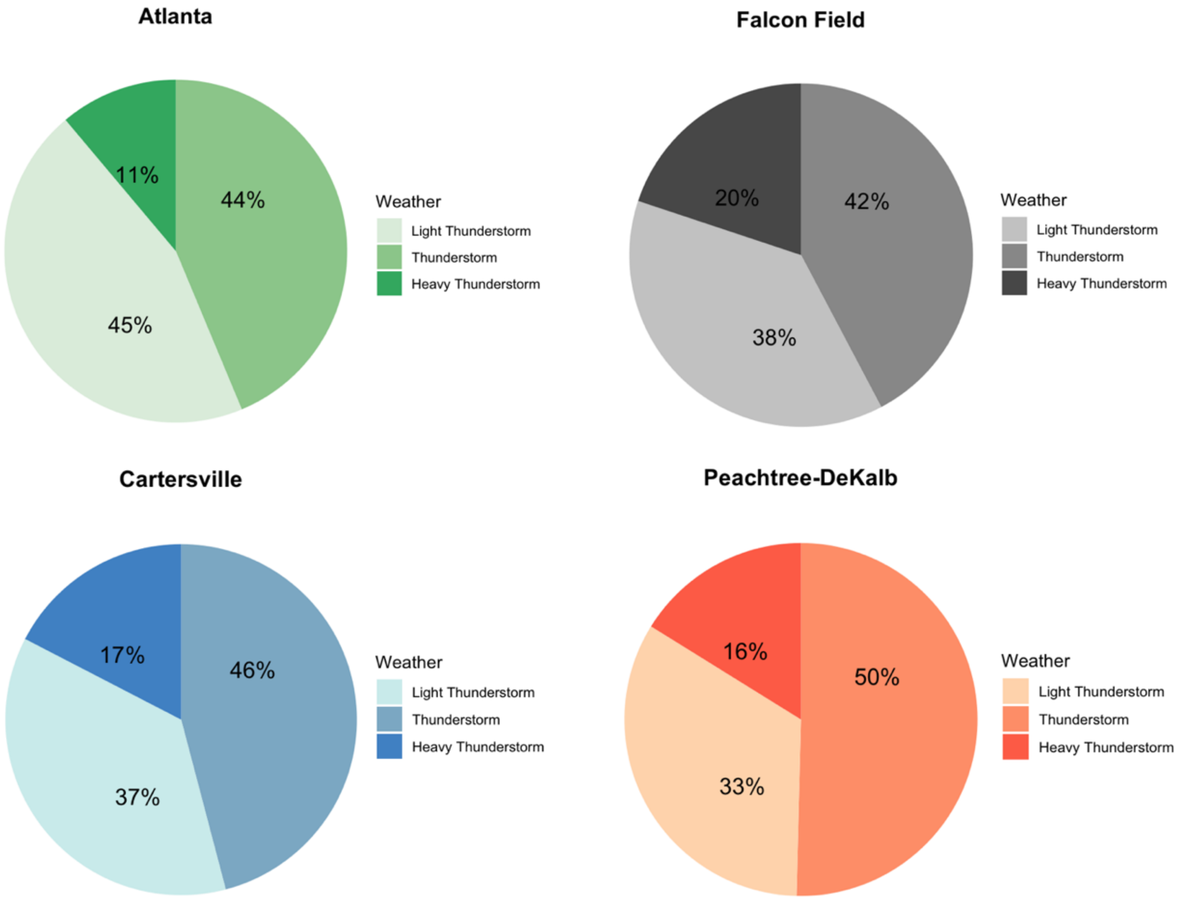


FIGURE 2.4. *Comparative Proportions of Thunderstorm Intensities at ASOS Stations.*

Discussion

While the results of this study did not find a significant difference in the number of thunderstorms at urban stations as compared to rural stations, it is well documented in the literature that cities, and in particular Atlanta, have been shown to create conditions for enhanced precipitation and thunderstorm formation. (Bornstein and Lin 2000, 507-516; Dixon and Mote 2003, 1273-1284; Shem and Shepherd 2009, 172-189; Ashley, Bentley, and Stallins 2012, 481-498; Bentley, Ashley, and Stallins 2009, 1589-1594). There are several reasons that this trend may not have been observed in this study, namely that the stations were too close together to identify differences in thunderstorm formation without more specific information on where these thunderstorms originated from and their patterns of travel. It is likely that a thunderstorm could be initiated in one of the urban areas and then proceed to move into a rural area, thereby equally impacting both stations even though that thunderstorm was a direct result of urban center influences, and this was supported by this study's findings in the thunderstorms proportion analysis. This also shows that rural areas surrounding urban centers are also at risk to increased thunderstorms, even if they are not responsible for causing the thunderstorm's formation. Examining radar data is most beneficial for determining thunderstorm initiation, and other approaches to obtaining more descriptive data without the necessity of radar use should continue to be considered for future work. Other factors that could influence thunderstorm occurrence include moisture content, topography of the region, and general climatological differences. These additional influences could explain some of the noted differences between the total number of thunderstorms at each station, even though the proportions of thunderstorms each month do not show significant differences.

This study demonstrates a significant impact of urban regions on meteorological systems as evidenced by the increase in average storm duration for these areas. As the literature previously reviewed also indicates, cities have the potential to create conditions necessary for precipitation and thunderstorm formation. This facilitating influence, paired with the findings of this study that show thunderstorm duration is on average longer in urban areas, significantly increases the risk to urban centers. The urban stations also showed a slight decrease in the proportion of heavy thunderstorms as compared to rural stations, which could lower threat from high intensity rains, winds and hail, but the significantly higher duration of storms poses a major threat for flooding, and especially flash flooding. The National Weather Service states that flash floods are often due to slow-moving thunderstorms, such as the storms identified by this study in Atlanta's urban areas; flash floods are the top weather-related cause of death in the United States, and also pose concerns for infrastructure and water quality (NOAA, "Flash Floods").

Conclusions

This study demonstrates that rural areas surrounding urban centers, such as the Atlanta Metro Region urban core, are at similar risk of increased thunderstorm occurrence as the city. This stresses the importance of considering sustainability initiatives to address the risks from thunderstorms not only for urban centers, but also for the areas immediately surrounding them.

This study further presents a strong link between the degree of urbanization within the Atlanta Metro Region and the average duration of thunderstorms in these areas, which highlights the concerns for community issues including flood risk, infrastructure damage, and water quality matters.

More studies should be conducted that seek to understand exactly how cities cause and sustain thunderstorms in order to best inform sustainability decisions, and further explore variables like duration and others to achieve a full picture of the meteorological effects of urbanization.

CHAPTER 3

Hydrologic Effects of Urbanization

When considering the impacts of urban areas on the environment, the negative effects of impervious surfaces—including streamflow changes and water pollution potential, as well as decreases in areas of natural filtration—come to the forefront of discussion and will be topics of concern for the purposes of this study. The objective addressed in this chapter is to analyze the changes in streamflow patterns in three river basins in the Atlanta metro region, resulting from increased impervious surface coverage occurring with urbanization. Land use data will be utilized to evaluate impervious surface percentages, and the knowledge of these interactions and risks posed could be applied toward sustainability planning and decision making.

With the rise of urbanization, many studies have been conducted to examine the impact of impervious surfaces on streams. Studies have generally demonstrated that the increases in impervious surfaces associated with increases in urbanization can have major impacts for the local waterways, in terms of streamflow, water quality, erosion, and health of stream organisms. (Ladson, Walsh, and Fletcher 2005, 23-33). Other studies have focused on a single watershed and examined the specific changes occurring as a result of increases in impervious surfaces in that region. (Huang et. al. 2007, 2075-2085; Du et. al. 2015, 1457-1471; Jennings and Jarnagin 2002, 471-489). In Atlanta, it has been shown that urbanization has severely impacted both streamflow and water quality within urban watersheds, demonstrating a variety of concerns including altered peak and low flow rates, and contaminants and sediment-related materials (Peters 2009, 2860-2878; Ferguson and Suckling 1990, 313-322).

Rather than evaluating effects on a single watershed over a long duration of time to capture changes in urbanization, this study chose to compare three river basins—including their rivers and tributaries— across the Atlanta metro region over the course of the past 15 years (2005 to 2019) in order to identify recent impacts on urban watersheds, and to compare the effects of urbanization processes throughout the metro region.

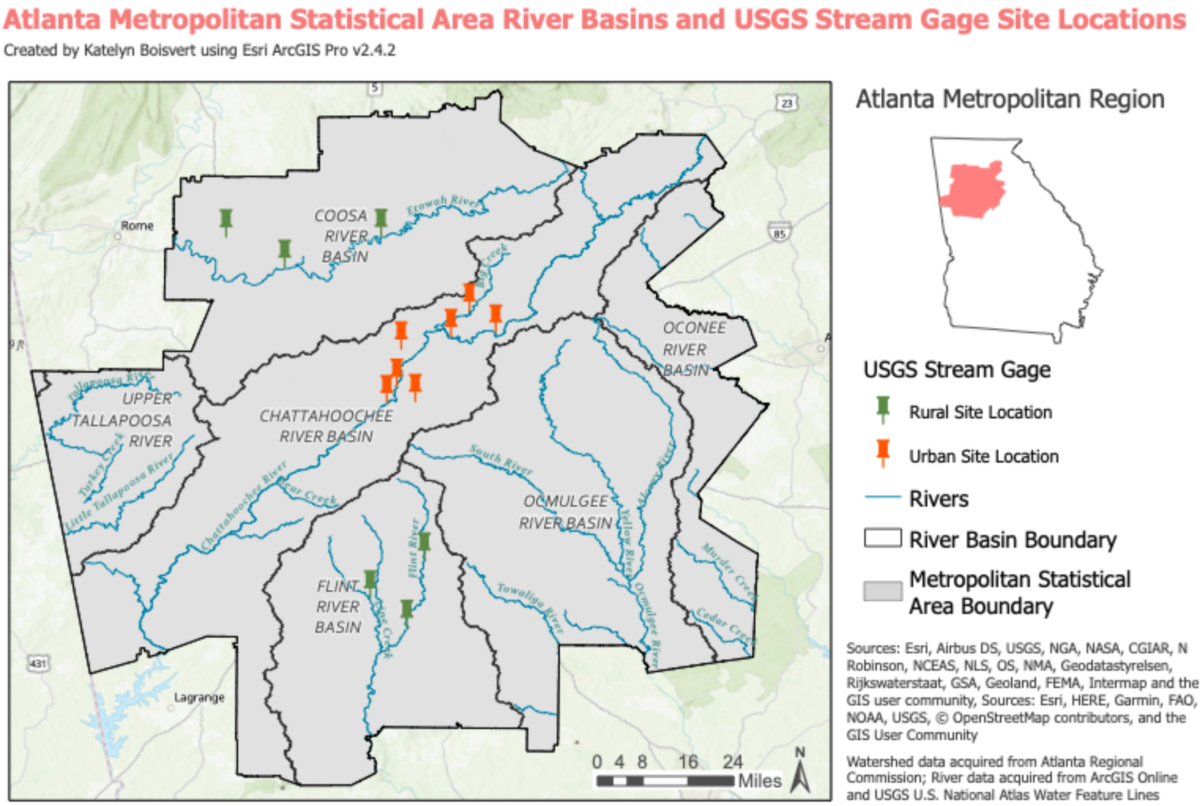
Data and Methods

All analysis was completed using R software and explored data for three water basins representing both urban and rural areas within the Metro Atlanta region for a span of 15 years including 2005 to 2019.

Data Acquisition

Streamflow data was acquired from stream gage sites operated by the United States Geological Survey (USGS) and downloaded from the USGS National Water Information System website. Data was downloaded for a total of 14 sites throughout the Atlanta Metropolitan Region as presented in Figure 3.1. Sites were chosen based on the following parameters: location within the study area; proximity to one of the NOAA NCEI climate stations used for meterologic studies in Chapter 2; and containing a full discharge data record for the years 2005 to 2019. Discharge data provides a measure of stream flow, detailing the volume of water moving in the stream in a set amount of time, as recorded at the stream gage stations.

Each of the stream gage sites was classified as urban or rural based on the urbanization analysis completed in Chapter 1. Sites within the Coosa and Flint River Basins were identified as rural areas, and sites within the Chattahoochee River Basin were identified as urban. Site identification information including the stream gage number, location, and drainage area for each site were collected from the USGS National Water Information System Web Interface and are displayed in Table 3.1. In addition, flood stage levels were acquired from the National Weather Service for each of the USGS stream gage sites. These levels denote the height at the gaging station that determines when the stream is considered to be flooded, which corresponds to when the water levels reach above this value.



Sources: Esri, Airbus DS, USGS, NGA, NASA, CGIAR, N Robinson, NCEAS, NLS, OS, NMA, Geodatastyrelsen, Rijkswaterstaat, GSA, Geoland, FEMA, Intermap and the GIS user community, Sources: Esri, HERE, Garmin, FAO, NOAA, USGS, © OpenStreetMap contributors, and the GIS User Community

Watershed data acquired from Atlanta Regional Commission; River data acquired from ArcGIS Online and USGS U.S. National Atlas Water Feature Lines

FIGURE 3.1. *Map of the Atlanta Drainage Basin Systems; and Locations of USGS Stream Gages Used in this Study.*

TABLE 3.1. Stream Gage Stations

		USGS Data			NWS Data	
Basin	USGS #	Stream Name	Location	Drainage Area (sq.mi)	NWS Code	Flood Stage
Coosa	02392000	Etowah River	Near Canton, GA	613	CNNG1	16
	02394000	Etowah River	At Allatoona Dam	1122	ETWG1	9
	02395000	Etowah River	Near Kingston, GA	1634	KGTG1	20
	02395120	Two Run Creek	Near Kingston, GA	33.1	KTRG1	8
Flint	02344350	Flint River	Near Lovejoy, GA	127	LOVG1	12
	02344500	Flint River	Near Griffin, GA	272	GRFG1	12
	02344700	Line Creek	Near Senoia, GA	101	LING1	10
Chattahoocee	02335000	Chattahoocee River	Near Norcross, GA	1170	NCRG1	12
	02335450	Chattahoocee River	Above Roswell, GA	1220	RWLG1	9
	02335700	Big Creek	Near Alpharetta, GA	72	APHG1	7
	02335870	Sope Creek	Near Marietta, GA	30.7	MARG1	12
	02336000	Chattahoocee River	At Atlanta, GA	1450	VING1	14
	02336300	Peachtree Creek	At Atlanta, GA	86.8	AANG1	17
	02336490	Chattahoocee River	At GA 280, Atlanta	1590	CHAG1	24

Historical daily data was downloaded for each site as a csv file for the years 2005 to 2019. All data available on discharge and gage height was included in these downloads. However, each stream gage station contained a different variable record, with sites containing some combination of the following variables: maximum discharge, minimum discharge, average discharge, maximum gage height, minimum gage height, or average gage height. All sites contained an average daily discharge value, so this was the primary measurement used in analysis of data.

Since the USGS data does not contain reliable values for precipitation, these values were calculated using the climate data previously downloaded from the NOAA NCEI website for analysis in Chapter 2. Each of the seven climate stations were assigned to one of the three river basins being studied based on their location. The precipitation values at each climate station within a basin were averaged to determine a precipitation value for that specific basin, and this precipitation value was used for all stream gage stations located within that basin.

Impervious Surface Analysis

A review of prior studies reveals that impervious surface coefficients are often developed by completing a geospatial analysis of a particular area to evaluate percentage of impervious cover by land type for that particular region. (Tilley and Slonecker 2007, 1-34; OEHHA 2008, "Impervious Surface Coefficients"; Roy and Shuster 2009, 198-209; Arnold and Gibbons 1996, 243-258) Unfortunately, such values for Georgia were not publicly available and calculation of these values was beyond the scope of this paper. For the purpose of this study, the impact of impervious surface area was estimated using a proxy method. Runoff was calculated utilizing a coefficient value based on land use in order to determine the percentage of precipitation that runs off impervious surface. These coefficient values were based on factors, such as residential versus business designated areas, that align well with the land use types contained in LandPro data for the Atlanta region (used in Chapter 1 analysis). Table 3.2 shows the classification of each land use code in the LandPro data, along with the corresponding runoff coefficient value. The average coefficient was calculated for each subwatershed within the three basins being studied, using the ArcGIS zonal statistics function, based on the relative areas of each land use type. These values were added to the datasets for each stream gage station.

TABLE 3.2. Impervious Surface Runoff Coefficients *

Runoff Category	Runoff Coefficient	Land Use Types
Greenspace	0.05	Park Lands; Forest; Wetlands; Crops; Orchard; Rivers; Reservoirs
Parks and Cemetaries	0.15	Parks; Golf Courses; Cemetaries
Agriculture	0.2	Agriculture
Suburban	0.3	Low Residential; Mobile Homes
Single Family Residential	0.45	Medium Residential; High Residential
Multi-Unit Residential	0.6	Multifamily
Industrial	0.65	Industrial; Industrial/Commercial Complexes; Exposed Rock; Quarries
Commercial	0.7	Commercial; Intensive Institutional; Extensive Institutional; Other Urban
Streets	0.75	Transportation, Communication and Utilities; Highways

* Table created using source information (USDA. Hydrology Training Series, Module)

Results

Basin Discharge Profiles

Stream gage data was normalized by the drainage basin area to compare discharge values between the basins, representing both their rivers and tributaries. The discharge values for each stream gage station were divided by that station's drainage area as reported by the USGS Water Web Interface. Next, an average base flow was calculated for each station; this value represents the stream flow between storm events. To determine this value, streamflow data on days with no recorded precipitation were subset, and the averages of these flows were calculated to describe each station.

To evaluate each basin, stream gage stations were sorted by river and tributaries. The average monthly discharge was then calculated for the major river in each basin, as well as for the tributaries contributing to those rivers. Figure 3.2 shows the discharge profile for the three basins over the 15-year study period, with the calculated base flow represented by a dashed line.

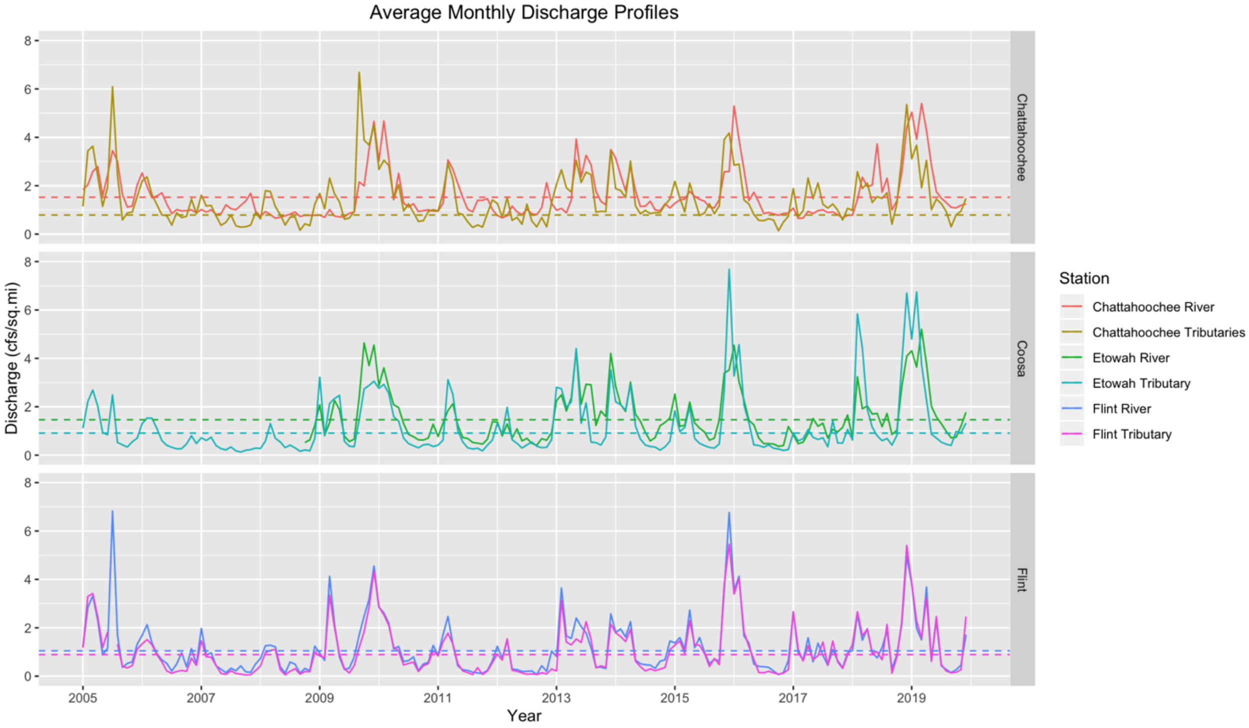


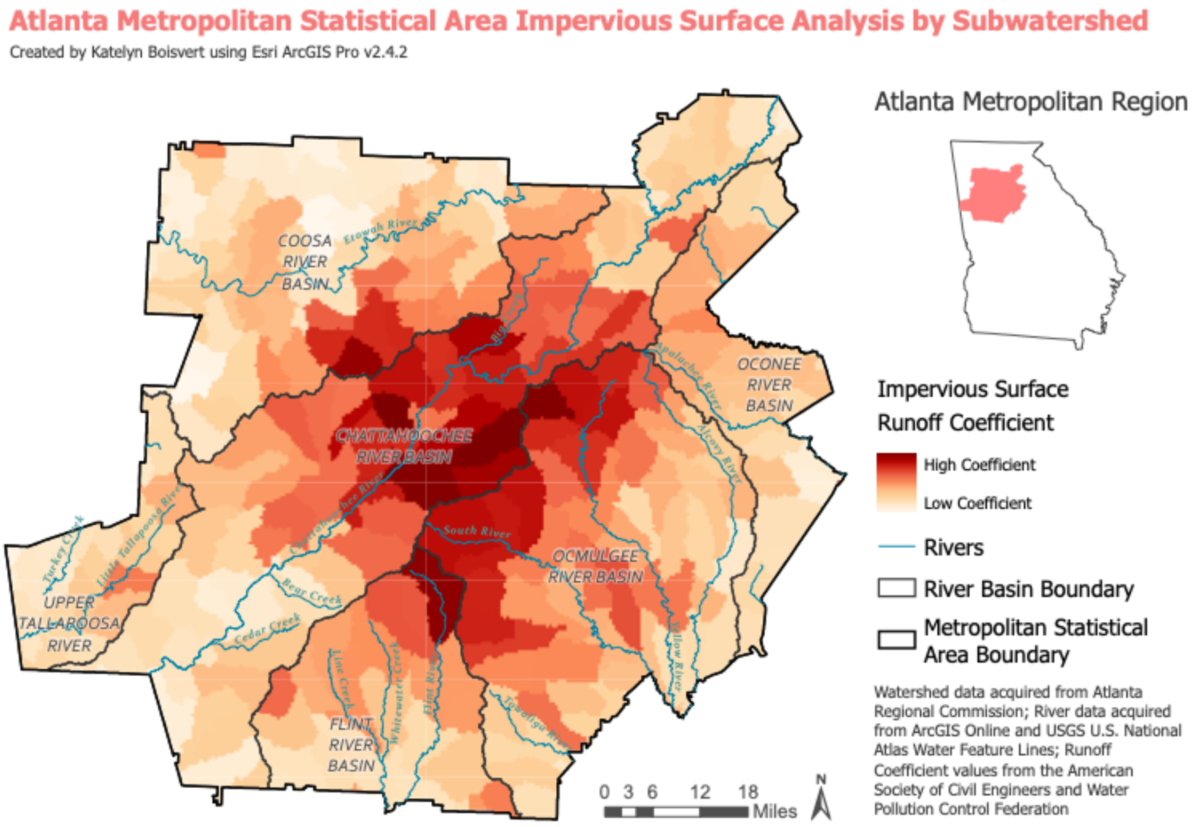
FIGURE 3.2. *Average Monthly Discharges and Base Flow Values for the Major Rivers and Tributaries in Each of the Three Study Basins.*

Results shows that the river stream gage locations and the tributary locations experience similar discharge patterns as a result of rainfall events over time. This is most clear for the Flint River Basin, which has very similar discharge amplitudes and timing, as well as similar base flow rates. The Chattahoochee River Basin, however, demonstrates differences in discharge response between the river and tributary values, with the most erratic timing of the three basins and some noted variations in amplitude. Discharge values are more frequently above the base flow rates for the Chattahoochee basin tributaries. The Coosa River Basin displays some differences between the river and tributary values, but timing is more consistent than the Chattahoochee. Similarities in seasonality can be seen across all three basins, showing consistent wet and dry seasons in Georgia.

Impervious Surface Cover and Stream Impacts

The impervious surface comparisons calculated from the runoff coefficient values for each land use type were used to create a map displaying the differences between subwatersheds in the Atlanta metro region. Darker values correspond to higher runoff coefficient value, and thus a higher percentage of runoff as a result of impervious surface.

Results presented in Figure 3.3 show high impervious surface percentages in the urban core of Atlanta, mostly located within the Chattahoochee River Basin. The Coosa River Basin has very low impervious surface cover overall, and the areas of highest impervious cover in this basin are not directly along the stream channel. In the Flint River Basin, there is also low impervious cover, but it is notable that the high impervious cover occurs at the headwaters of the Flint River.


Atlanta Metropolitan Statistical Area Impervious Surface Analysis by Subwatershed

Created by Katelyn Boisvert using Esri ArcGIS Pro v2.4.2

Watershed data acquired from Atlanta Regional Commission; River data acquired from ArcGIS Online and USGS U.S. National Atlas Water Feature Lines; Runoff Coefficient values from the American Society of Civil Engineers and Water Pollution Control Federation

FIGURE 3.3. *Map of the Atlanta Drainage Basin Systems Showing the Runoff Coefficient Values Calculated for Each Subwatershed.*

The runoff coefficient for each station was determined by taking the value from the impervious surface analysis map based on the subwatershed the gaging station is located in. The average discharge was calculated for each gaging station location and plotted against these runoff coefficient values to determine the relationship between impervious cover and stream discharge. Figure 3.4 displays a positive correlation between the runoff coefficient value and average discharge. The correlation coefficient between these variables was found to be 0.66.

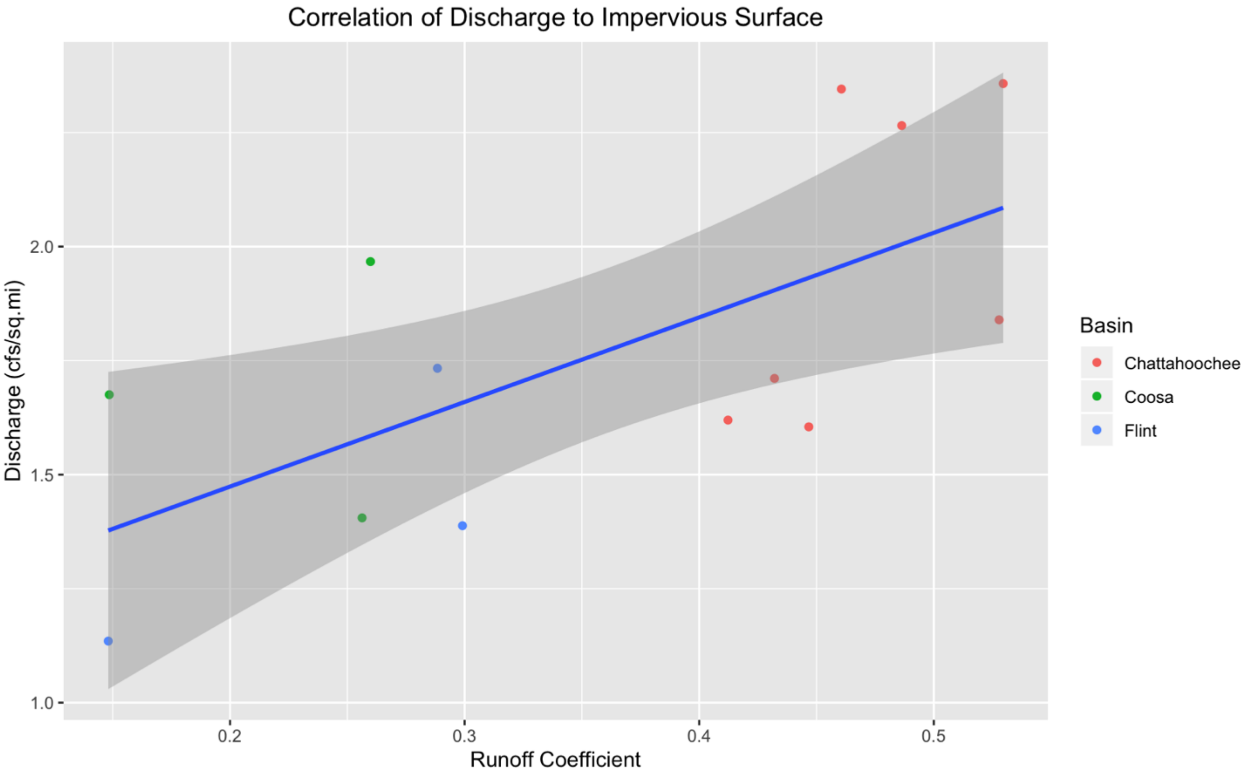


FIGURE 3.4. *Relationship Between Runoff Coefficient Values and Average Discharge at Gaging Stations.*

Flood Events

The number of days for which the recorded gage height surpassed the flood stage, as determined by the National Weather Service, was calculated in R for each stream gage site. These values were summed for all stream gage sites along the rivers in each of the three basins, as well as for the respective tributaries. Figure 3.5 shows this data organized to represent yearly sums of flooding events for the 15-year study from 2005 to 2019.

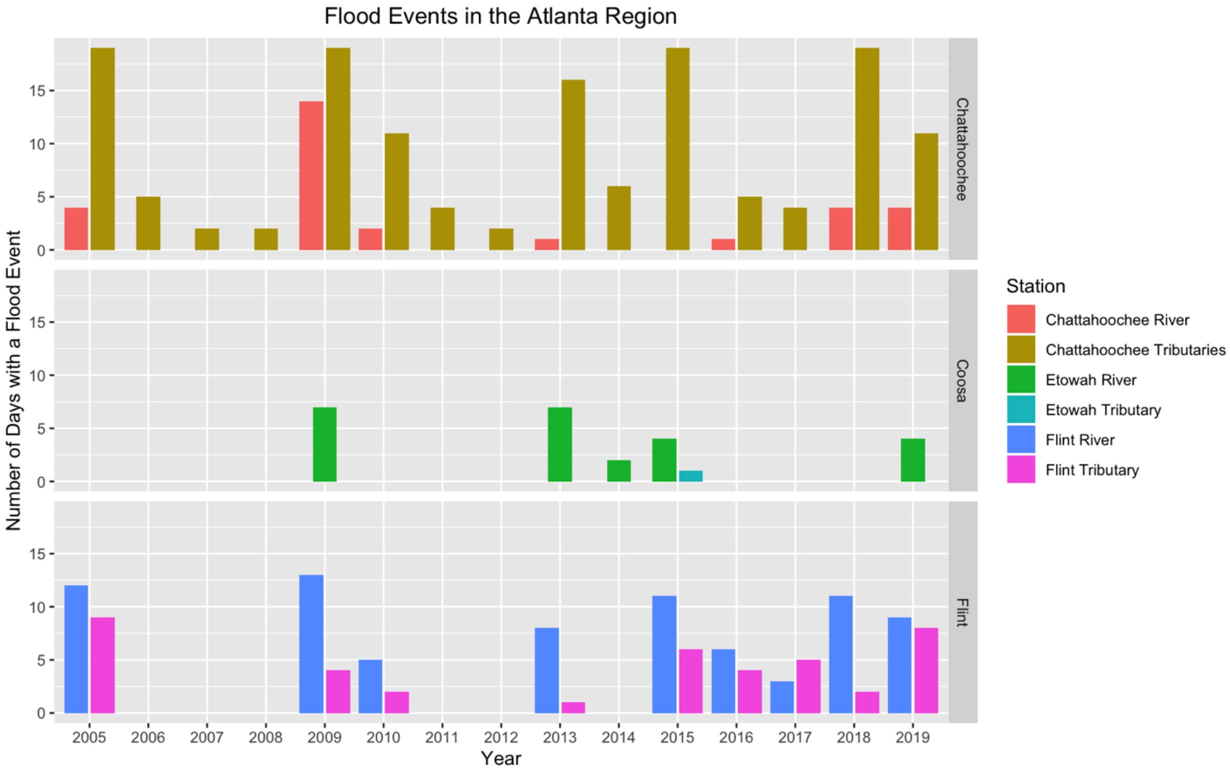


FIGURE 3.5. *Number of Flood Events in Three River Basins in the Atlanta Metro Region.*

Results demonstrate that the Chattahoochee River Basin experiences the highest number of flood events per year, with consistent flooding across the study period. Tributaries in the Chattahoochee basin flooded every year of the study, and the river flooded nearly 50% of the years with increased frequency over the past five years (2015-2019). The Coosa River Basin experiences infrequent flood events with the lowest number overall, and these occur mainly for the river; no other trends in flooding were observed for this basin, which is in an area identified as rural in this study. The Flint River Basin experiences a high number of flooding events, although still less as compared to the Chattahoochee. When flooding does occur for this basin, it presents in both the river and its tributaries. Of particular note, is that the Flint basin has consistently demonstrated flooding for the past five years in a row, as compared to previous years in the study (2005-2014) when flooding was not a consistent annual occurrence.

Discussion

Previous literature has shown that documented changes in the urbanization of regions, such as Atlanta, create devastating impacts on the local waterways covering a diverse range of issues from erosion and water quality, to effects on fish and wildlife, to flooding and economic loss (Hammer 1972, 1530-1540; Wenger 2008, 1250-1264; Peter 2009, 2860-2878; Ladson, Walsh and Fletcher 2005, 23-33). This study demonstrated the impact of urban regions on hydrologic systems as evidenced by the positive correlation between impervious surface cover and stream discharge, as well as a rise in flooding effects for more urbanized areas.

The Chattahoochee River Basin region is the most urbanized of the three Atlanta metro region river basins studied here, corresponding to increased density as noted in Chapter 1 results and high impervious surface percentage as reported in this chapter. It may be suggested that the Flint River Basin, although categorized as a rural area overall for this study's comparisons, has experienced change over recent years moving toward being more urbanized. The Coosa River Basin is the most rural of the areas studied. Exploring a longer time period would have allowed for observation of the gradual development of urban areas, and shown how the impacts on the Chattahoochee River and surrounding tributaries evolved over that course. This study, however, was effective to demonstrate hydrologic impacts on the Atlanta metro areas.

Results in this hydrologic systems review demonstrated that with increased urbanization comes a disruption in patterns of discharge into streams and an increased risk for flooding. In the discharge profiles examined, the amplitude differences and more erratic timing of the discharge response in the Chattahoochee River Basin between the river and its tributaries is likely due to urbanization impacts, as the positive correlation between impervious surface cover and discharge supports. The Chattahoochee River also contains a series of dams, which could influence the patterns of discharge for the Chattahoochee River as compared to the tributaries. However, within the tributaries in the Chattahoochee River Basin, the discharge is frequently above the expected base flow value showing changes in the discharge profile amplitude and timing. It is possible that the tributaries receive proportionally higher discharge for the same amount of rainfall or that the scale of discharge to drainage area for these highly urbanized locations is no longer a one-to-one ratio as suggested in a study by Galster et. al. (2006, 713-716). This is likely due to the fact that not only does total runoff increase, but so does the rate at which water is transported into the stream relative to the size of the discharge area. The Coosa River Basin displays a different streamflow pattern than the Chattahoochee, with the timing of the discharge flows relatively consistent and only the tributary discharge slightly higher than the river. One possible explanation could be that there is an operational dam on the Etowah River, which could be affecting the discharge rates if streamflow is controlled by the dam.

This study also demonstrated that runoff coefficients combined with land use data is an effective means to evaluate impervious surface percentages. The outcome of the analysis using these methods was fairly consistent with expected outcomes according to previous studies that utilize remote sensing methods to develop coefficients specific to an area. Using runoff coefficients could provide a means to make a quicker assessment of the impact of changes in land use in a region.

The potential for flooding is one of the greatest concerns of a high percentage of impervious surface cover. The results of this study show that the highly urbanized Chattahoochee River Basin experiences the greatest number of flood days as compared to the two rural stations, and that flooding is a significant risk with annual events noted for the course of the 15-year study. Conversely, the most rural station of the Coosa River Basin, which demonstrates the lowest runoff coefficient value of all areas studied, experiences very few flood events. Per this study's mapping results, the Flint River Basin is most urbanized at its headwaters, and as this site is located on the boundary of the urban and rural regions, urbanization is likely to be spreading faster in these areas. This may account for the increases in flooding consistency over the past five years as reported in this chapter's results.

As urban areas continue to spread and increase in density, converting natural filtration areas to impervious surfaces, the impacts on hydrologic systems will only increase. When paired with increases in thunderstorm potential and duration, the number of flood events in urban watersheds like the Chattahoochee and in diversifying watersheds like Flint, would be expected to increase posing major risks for those living in these areas and for the environment. Efforts to reduce the impact of ever-expanding urbanization on these hydrologic factors will become increasingly important to address.

Conclusions

This study demonstrates that runoff coefficients combined with land use data is an effective means to evaluate impervious surface cover percentages. Using runoff coefficients for such analysis could provide a methodology for simpler and faster evaluation of impervious surfaces and related impacts on streams making it more accessible for use by a wider range of stakeholders.

This study demonstrates a relationship between the amount of impervious surface cover occurring with urbanization of land use and altered streamflow patterns, including increased average discharge. Such changes translated to the increased occurrence and regularity of flooding events in the more urbanized areas of the Atlanta Metro Region.

CHAPTER 4

Applications to Urban Sustainability

The results of this study highlight some of the environmental challenges created by the urbanization of regions. The rise in population density and consolidation of city centers, as well as the expansion of urban sprawl to ever increasing sizes, have contributed to an increase in impervious surface cover. This, along with reduced green space and anthropogenic factors, results in increased temperatures from the Urban Heat Island effect (UHI), which in turn creates the perfect conditions for development of rain clouds and thunderstorms. Increased precipitation from longer duration thunderstorms in urban areas results in greater runoff secondary to impervious surfaces, which has the potential to create flooding and lead to erosion, water quality reduction, and other stream effects. The interconnectedness of these impacts suggests how urbanization can lead to cascading effects that impart significant challenges and consequences for city centers and its inhabitants.

These impacts are major drawbacks of urban areas when considered through this lens. However, cities offer many potential benefits, especially when they are managed in sustainable ways. The high population density within urban areas promotes shared transportation methods, such as public transportation and ride-sharing, and for those that still commute, the distance from workplaces to homes is much shorter for those living in the city than in the suburbs, reducing energy costs and air pollution associated with transportation (Sanderson, Walston and Robinson 2018, 412-426). In addition, high density can provide efficiencies in resource use including water, resulting in cities using on average less water per capita than more rural areas (Mahjabin et. al. 2018, “Large Cities”). Similar efficiencies exist for energy and waste production (Sanderson, Walston and Robinson 2018, 412-426). Outside of a strictly environmental perspective, cities also often have larger economies and offer a better diversity and larger number of jobs. They are areas that promote education and family planning, and in many cases lead to a decline in population growth as compared to rural areas (Sanderson, Walston and Robinson 2018, 412-426). This makes cities places that have the potential to offer benefits both to environmental sustainability as well as social sustainability.

Sustainability is a concept that can take many forms, adjusting in its focus and practices depending on the scope and nature of the participants. At its base, sustainability is the ability of a system to endure for future generations. In the context of a university, like Emory University in Atlanta, sustainability refers to recycling and composting efforts, or programs to reduce water or energy use. In the context of businesses, much of the focus is on reducing the company's carbon footprint or switching to renewable energy. Although these topics are also important aspects of sustainability in a city, they are not at the heart of urban sustainability, which addresses the inherent ability of the city itself to support life and growth into the future. Recycling and reducing carbon footprints play a role in ensuring this occurs, but without a city that is designed to be sustainable, recycling and reducing carbon use alone are not enough to preserve the city when considering factors such as the urban heat island effect and flooding. Urban sustainability describes the incorporation of sustainability principles into the design and planning of urban spaces, with the goal being to provide a livable area that supports growth for years to come.

The UN Environment Programme establishes three goals to address climate change: decarbonize, detoxify, and decouple (Andersen 2019, "Our Planet"). The first two address switching from fossil fuels to renewables and changing how we manage our waste. These are the aspects of sustainability often discussed in businesses and at institutions. The last one, decouple, addresses the need to separate economic growth from environmental degradation. While this is not as obviously connected, this approach describes well the goal of urban sustainability. As we build new infrastructure and grow and expand into new areas, we must do so with knowledge of environmental impacts and in such a way that it is not a choice between either new infrastructure or environmental protection, but that instead both are being addressed in a sustainable way. Following this approach would allow the environmental drawbacks of cities to lessen, and the benefits would become an important step toward ensuring sustainability on a global scale.

There are different ways that urban sustainability can be applied to the environmental challenges discussed in this study. Strategies can be taken to reduce the extent of the urban heat island effect or to mitigate impacts on streams as a result of increases in impervious surface cover, and increased population density in city areas can be managed in unique ways to maximize the efficiencies of this system and create viable communities for the future.

Reducing Urban Heat Island Potential

As discussed in the introduction, the Urban Heat Island (UHI) effect is a direct result of the design of cities due to the materials used for roofs and pavements, the removal of greenspace areas, and the addition of sources of anthropogenic heat. The UHI in turn has major implications for the meteorological conditions in urban areas, as well as for the surrounding rural region. While the increase in thunderstorm duration shown in this study is not something that can be directly managed by city planners and building designers, it does demonstrate the need to understand and address the underlying factors that contribute to UHI, which present implications for urban economies as well as its residents. It is important to consider the many tangible strategies and solutions available to address this issue, and to continue working to expand innovations and creative applications.

Albedo and Building Materials

When considering the UHI, the greatest heating effect for the city is created by the darkest surfaces that radiate more heat into the surrounding air than vegetation or lighter surfaces. One of the largest strategies to reduce the UHI is the replacement of traditional building materials, such as asphalt used for roads and roof shingles, with others that have lighter or more reflective surfaces (Hulley 2012, 79-98). Pearce (2018, "Urban Heat") reports that "fresh asphalt reflects only 4 percent of sunlight compared to as much as 25 percent for natural grassland and up to 90 percent for a white surface such as fresh snow." Often called "cool pavements" there are a number of different ways this strategy could be implemented. Cities may completely switch to a new building material, such as using concrete instead of asphalt, or simply paint over asphalt with a lighter color—a strategy that was recently used for roads in Los Angeles, California as reported by Pearce (2018, "Urban Heat"). Another study explored different coloring options for asphalt and how they might increase albedo as compared to traditional asphalt colors, while still providing other benefits associated with using asphalt as a material, such as reducing road noise (Synnefa et. al. 2011, 38-44).

A study by Oleson et. al. (2010, 1-7) found that if this lighter color approach would be applied to roofs in large cities around the world, the UHI would decrease by one-third and maximum daily temperatures would decrease by 0.6°C. Other researchers suggest even greater reductions could be achieved through urban adaptations, with temperatures decreased from 1.5°C to 1.8°C in warm, sunny regions (Georgescu et. al. 2014, 2909-2914). Strategies such as these that seek to raise the albedo of city surfaces have a significant impact on reducing the UHI effect, and such innovations do not require extensive design changes nor alter functionality for a city and its residents.

Vegetation

The process of urbanization is accompanied over time by the conversion of vegetation to hardscape in the form of buildings and pavement. The removal of vegetation in urban areas reduces its beneficial cooling effects that result from evaporation and transpiration processes, as well as reduces shade that could otherwise have diminished the amount of solar radiation directly reaching low albedo surfaces such as pavement (Kleerokoper et. al. 2012, 30-38). Changes in urban planning and building design to ensure that greenspaces and areas of vegetation are dispersed throughout the city can play a significant role in reducing UHI effects.

According to the EPA, the amount of solar energy that passes through a tree canopy is only 10-30% of the solar energy that hits the top of the canopy (Hulley 2012, 79-98). In this way, a tree dramatically reduces the amount of solar energy that reaches the Earth's surface, and thus reduces the amount of solar energy that can be absorbed by city surfaces such as pavement. Kleerokoper et. al. (2012, 30-38) describe several strategies involving vegetation that can be implemented in cities at help reduce UHI effects. One example is increasing ground vegetation through the creation of urban parks that offer a dense, centralized greenspace that has the added benefit of providing a recreational area. Planting in street medians disperses numerous trees effectively throughout the city. A structural strategy to introduce more vegetation into cities is the construction of green roofs and building facades.

Green roofs apply the same principles for cooling and shade to the surfaces of buildings, in a similar way as do park and street trees. As pointed out by the San Francisco Planning Department (2017, "Better Roofs"), rooftops account for up to 30% of the city's land area, and so "living roofs are one of a number of sustainable design approaches that take advantage of underutilized rooftop space." In 2017, San Francisco became the first city in the U.S. to legislate that living roofs be included on most new construction. An earlier endeavor in San Francisco, the

Green Roof Bus Shelter Demonstration Project, provided over two acres of green space by using 2,000 bus shelters throughout the city and helped to raise awareness about green roofs and urban sustainability initiatives in general by bringing green roofs “down to street level” (450 Architects 2008, “Green Roof Bus Shelter”).

While green roofs are a slightly more intensive approach than changes in building materials or shifts to higher albedo colors, green roofs offer multiple benefits beyond simply reducing UHI. In addition to increasing shade and evapotranspiration rates, green roofs provide other benefits, such as improvements to real estate value and better stormwater management (San Francisco Planning Dept. 2017, “Better Roofs”). One concern with the white roof coloring strategy is the potential need for increased heating during winter months, which is not a concern for green roofs that provide cooling mechanisms during the summer and keep buildings warmer during the winter (Pearce 2018, “Urban Heat”). Additionally, green roofs can maximize the benefits of other sustainability strategies, such as solar panels, which perform best in cooler temperatures (Snow 2016, “Green Roofs Take Root”).

Green roof installations use a combination of native, low maintenance and low water-use plants, taking into consideration the climate conditions of the region and water conservation needs (San Francisco Planning Dept. 2017, “Better Roofs”; Velazquez 2009, “Tour Metro Atlanta”). The Greenroofs Projects Database (Velazquez 2009, “Tour Metro Atlanta”) provides photos and descriptions of green roof and wall installations by location; it describes the following examples for the Atlanta Metro Region. An example of a green roof is at the Northpark Town Center, which serves as an office complex featuring garden-like terraces and a two-acre park on its roof; and a green building façade is located at the W Hotel in Midtown Atlanta. Educational and recreational opportunities, as well as locations for growing food and nurturing pollinators, are additional perks of green infrastructure that extend beyond UHI cooling and stormwater management (Williams 2017, “Green Roofs at Emory”). Emory University in Atlanta features several green roof installations on its campus.

Anthropogenic Heat

While addressing albedo and vegetative cover are the two more common and larger impact solutions, more research is beginning to address the role of anthropogenic heat sources. Anthropogenic heat can originate from the burning of fuel, transportation, and other industrial processes (Shahomandi 2011, 1-9). One benefit offered by urban areas is the incentive for increased public transit options, which can play a role in altering the amount of anthropogenic heat sources in a city in addition to having economic benefits and convenience for residents. Cities have often been designed with more of a focus on car travel rather than other means of transport, although this seems to be changing in recent years. Public transportation, such as buses, subways and light rail, offers an opportunity to decrease car travel, as does ride-share programs. Cities that are designed to be walkable and prioritize bike lanes and safe pedestrian areas offer important opportunities to further reduce sources of anthropogenic heat, and also have the secondary benefit of improving air quality (Project Drawdown 2020, “Walkable Cities”).

One such example is Portland, Oregon, which is described by city planner Jeff Speck as a city that prioritizes alternative transportation options. He states that instead of focusing on expanding highways in the city, Portland has invested in public transit and bike infrastructure that has translated to significant decreases in driving time for residents (Speck 2013, “Walkable City” Excerpt). Beyond the benefits this holds for reducing anthropogenic heat sources and carbon emissions, this approach has also been shown to save people money; these savings in turn are likely to be spent supporting local businesses, rather than being spent on driving costs (Speck 2013, “Walkable City” Excerpt).

Outside of Portland, some major cities, such as New York, San Francisco and Boston, are also ranked highly—with walk scores in the 80s—for their walkability by Walk Score, a company that uses an algorithm to determine the average distance one needs to walk from their home to access typical daily errands (Walk Score 2020, "Cities"). Atlanta, Georgia is described by Walk Score as a car-dependent city with some public transportation but not many bike lanes, and is ranked the 22nd most walkable large city in the US with a walk score of 48 (Walk Score 2020, "Cities"). This could be an area of improvement for Atlanta to reduce anthropogenic heat sources in the city and enhance urban sustainability.

Mitigating Stream Impacts Resulting from Impervious Surface Cover

While reducing the extent of a city's UHI may be beneficial in reducing the occurrence of urban-initiated thunderstorms, this category of thunderstorms represents only the additional risk beyond normal weather events in urban areas. As shown in this study, thunderstorms and large rainfall events in urban areas create situations of accumulated surface water and increased runoff as a result of greater impervious surface cover that prevents precipitation from infiltrating groundwater, which poses concerns for increased flooding and reduced stream health. Intervention strategies in urban areas are often focused on using structural barriers like levees and drainage canals to manage water flow, or attempting to minimize the impacts of a flood after they occur (Serre, Barroca, and Diab 2010, 299-309). A more proactive and presumed effective strategy would be to acknowledge the direct link between impervious surfaces and runoff volume, and instead work to mitigate these impacts. In order to fully prepare an urban area to sustain the combined effects of UHI and urban flooding, innovative strategies should be implemented to better manage stormwater and also ensure stream health and quality.

Permeable Pavement

The largest factor causing increased runoff in urban areas is impervious surfaces. Materials like solid concrete and asphalt do not allow water to pass through into the soil and groundwater reservoirs, which is the natural process when rainfall hits areas of greenspace. The resulting problem is that water flows off these impermeable surfaces and directly into nearby streams. The outcome is a drastic increase in stream levels during storm events, and a reduction in the base level of the river when there is no rain because of a lack of groundwater to replenish the stream. Impervious surfaces also worsen erosion of streambeds because of greater runoff volume, and increase the number of pollutants entering streams as they are carried along with the water from urban areas (Ladson, Walsh, and Fletcher 2005, 23-33; Peters 2009, 2860-2878; Ferguson and Suckling 1990, 313-322).

One of the strategies for reducing runoff impacts is to replace impervious surfaces with alternative materials and construction designs that are instead permeable to water. An Ohio Department of Transportation training workshop presented this topic and provided solutions, identifying alternatives including porous asphalt, pervious concrete, permeable pavers, grid pavements and plastic grids, along with other permeable materials (Hein and Schaus 2018, “Permeable Pavements Workshop”). They also described how such choices would help to increase infiltration, reduce stormwater volume and peak flows, reduce stormwater pollutant load, and decrease downstream erosion.

In 2015, Atlanta began one of the largest permeable pavement projects in the U.S. to address neighborhood flooding that contaminated residents’ yards and homes (Shamma 2015, “Atlanta is Home”). Several areas replaced asphalt roads with individual permeable pavers. Emory University in Atlanta has applied this same technology to parking lots on campus and at other associated facilities (Williams 2013, “Permeable Parking Lot”; Emory News Center 2019, “Woodruff Health Sciences Center”). This strategy allows water to flow into groundwater reserves, and as an engineer with Emory Campus Services reported it provides “a filtering effect for pollutants, oil and dirt—but more importantly, it minimizes runoff impact that can cause flooding and stream bank erosion” (Williams 2013, “Permeable Parking Lot”).

The Atlanta Permeable Pavement Project estimated that installing pavers cost at least 20 percent more than using asphalt, plus additional costs for underlayment preparations (Shamma 2015, “Atlanta is Home”). Although these costs may seem prohibitive, the approach yields positive results and other US cities are adopting the strategy. A study by Liu, Chen and Peng (2014, 6-14) found that replacing even half of the impervious surfaces in an urban area with permeable pavement could reduce runoff by around 46% and peak flows, that are often responsible for flood occurrences, by as much as 38%.

Greenspace and Green Infrastructure

In addition to helping reduce UHI effects, adding areas of greenspace or green infrastructure in an urban region can improve water flow and quality. To re-state from previous discussion, greenspace areas allow water infiltration into groundwater where it recharges the aquifer for use, and reduces surface water runoff from precipitation and larger storm systems. Greenspace also allows for the natural materials of soil and rocks to filter some pollutants from stormwater as they percolate through the ground. In addition, some of the water is retained by the plants for growth or is transpired by the plant back into the atmosphere. Similarly, green roofs will catch rainwater before it has a chance to runoff into the stormwater system, as it would have from a traditional impervious surface roof. In some regions of the US, it has been observed that water retained by plants for growth or transpiration can account for 50-60% of the rainfall that falls on a green roof (Jarrett 2016, “Green Roofs”).

The resulting benefits of greenspace and green infrastructure to urban centers include minimizing flood risk, decreasing streambank erosion, and reducing harmful pollutants and sediment buildup in waterways. In turn, I suggest that urban areas could experience more effective management of several issues: stream water quality; fish, plant and animal life; human health risk; and economic costs related to flooding. It has been shown that jointly integrating multiple of the approaches discussed in this section resulted in the greatest reduction in runoff volume and peak flows as each strategy has particular strengths in improving water flow and stream health (Liu, Chen and Peng 2014, 6-14). As many of these strategies are difficult or costly to retrofit, it is important to account for environmental impacts and consider all approaches prior to converting greenspace areas to impervious surface cover.

Strategies for Maximizing Efficiency of Urban Density Increases

As previously mentioned, increasing density of urban areas offers some benefits, namely the increased efficiency of resource use including energy and water. However, under current common models of city development, increasing density also means increasing impervious surfaces, which can have major impacts for UHI and flooding as presented in this study. The strategies outlined in this chapter so far offer ways to lessen this impact while maintaining a similar trajectory for urban development; however, there are other examples and types of community structures that may offer even more viable options for urban sustainability.

In this study, areas with high impervious surface, such as commercial zones and apartment buildings, were rated as environmentally worse than other areas, such as single-family homes. This is due to the fact that many of the environmental challenges cities face are a direct result of the increase in impervious surface cover associated with apartment buildings and commercial areas. Conversely, single family homes present different environmental challenges because a decrease in their impervious surface, comes with an increase in overall volume of land that is taken away from forests and other natural ecosystems and shifted to human living (Manjoo 2020, “Let’s Stop Fetishizing). Consolidation within city areas can open surrounding lands back up for reforestation efforts. As seen with Atlanta, the first method of city growth was sprawl. New neighborhoods began to expand as residential areas replaced forests. Only in recent years did that sprawl begin to decrease and instead move towards densification. If the issues with UHI and impervious surfaces are not addressed, densification will trade one problem for another.

One style of community that encapsulates the strategies presented in this paper, and builds upon the strengths of an increasing urban population, is mixed-use development. As defined by the Washington State Municipal Research and Services Center, mixed-use development contains “a complementary mix of uses such as residential, retail, commercial, employment, civic and entertainment uses in close proximity - sometimes in the same building” (MRSC of Washington, “Mixed Use”). This structure helps to limit the increase in impervious surfaces associated with numerous roads connecting residential and commercial areas, or large parking lots that often accompany major commercial buildings. When combined with strategies, such as permeable pavements, these communities offer an ideal set-up for stormwater management practices. In addition, these communities support walkability and can be easily outfitted with public transportation options because major residential and commercial sectors are within close proximity.

A great example of mixed-use construction is the Emory Point community near Emory University’s campus in Atlanta (Moricle 2013, “Shops at Emory Point”). Opened in 2012, Emory Point offers apartment housing within walking distance of campus, and features restaurants, stores and other retailers all within the same overall footprint of land. Interspersed with greenspace and trees, Emory Point showcases a blend between city living and environmental protection. Another mixed-use development is in the planning stages for Midtown Atlanta (Keenan 2020, “Fresh Renderings”). The proposed site will include residences along with restaurants and shops, provide parking within the structure, and incorporates green infrastructure into the design plan.

Summary

As our population continues to expand and move into cities, we must manage these municipalities with the mindset that development and growth of cities can be independent from environmental degradation that is typically associated. This study reviewed many scientific studies that are being completed to understand the specifics behind urban heat islands and the development of urban-initiated thunderstorms or to document the impacts of stormwater runoff and pollutants on stream health. While these studies are critical to informing urban decision making, many are still being written to communicate strictly with other scientists instead of city planners, policymakers and other important stakeholders. In order to create a modern definition of what it means to be a sustainable city, city planners and designers as well as governing agents need to be able to understand the scientific reasoning behind urban changes and environmental impacts, evaluate areas of greatest concern, and identify solutions that apply to their region.

This study sought to connect some of the science behind urban environmental impacts with sustainability solutions in an approachable manner. However, there are other issues outside of the scope of this project that are important parts of the conversation and should be included in urban planning considerations, namely climate change and concerns of gentrification. Climate change will exacerbate already existent problems in cities, especially UHI, and poses numerous social and economic risks. For many cities that are looking toward environmental improvement, gentrification, property values, and cultural shifts are serious concerns. While not a matter of environmental sustainability that is being addressed in this paper, urban development that favors or is geared toward a higher-income class clash with principles of social sustainability and creates disproportionate opportunities. As modeled by the U.N. Sustainable Development Goals, social and environmental sustainability should be considered jointly when solving urban challenges, as well as the over-arching role of climate change.

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APPENDIX A

ArcGIS Methodology

A variety of ArcGIS extensions and toolsets were used in the creation of the maps presented in this study (see Table A.1). The methodology utilized for creation of the maps is presented below, with procedures for each map described individually.

TABLE A.1. ArcGIS Pro Extensions and Toolboxes Used for Data Analysis and Mapping

Extension or Toolbox	Toolset(s)
Analysis	Extract
Conversion	To Geodatabase; To Raster
Data Management	Projections and Transformations; Layers and Table Views; Generalization; Fields
Spatial Analyst	Map Algebra; Raster Reclassify; Extraction; Statistical

Urban Spread Analysis- Figure 1.2

Shapefiles downloaded from the ARC were imported into ArcGIS Pro and separate feature classes were created for each of the four years—2000, 2008, 2010 and 2016. These new feature classes were created using the Feature Class to Feature Class tool to select for the following variables: census tract identifier; county name; population for corresponding year; and square miles. Variable names differed by dataset, but the correct name corresponding to each of these variables was determined from the key on the ARC website.

Once separate feature classes were extracted, a graduated color map was created for each feature class. The population variable was used as the field of interest, and the map was normalized using the square miles field to be able to compare across census tracts. The custom interval scale described previously was used to determine the five categories used in mapping. Population maps were colored to show differences between urban and rural areas, as well as differences in urban population—green to correspond to rural areas, and orange to urban.

Change in Urban Spread- Figure 1.3

Urban spread was evaluated both by changes in overall urban areas, as well as changes in urban cores. In order to complete this analysis, new feature classes were created for each year to separate urban areas versus urban cores. A new field was added to each population feature class for population density. This field was calculated by dividing the population within each census tract by the total area of the tract in square miles. The Select By Attribute function was used to select for areas with a population density between 500 to 1000 people per square mile for urban areas, and greater than 1000 people per square mile for urban cores utilizing this new variable for the selection expression.

Once feature classes for urban areas and urban cores had been created for each of the years, the Dissolve function was used to remove the census tract boundaries from the map and display only the extent of each of these areas. Each feature class was colored in a shade of orange to distinguish the year it corresponded to. Feature classes were displayed on a single map in order to identify changes in urban spread by urban area and by urban core.

Urban Density- Figure 1.4

Density analysis was completed separately for urban and rural areas. To begin, new feature classes were created for the population datasets using the Select By Attribute feature to create a feature class for urban and a feature class for rural areas for each year. Each of these new feature classes was converted into a raster using the Polygon to Raster tool using the calculated population density variable as the value field.

In order to complete analysis of urban and rural density, both population and land use data was reclassified according to the following scales. The reclassification process simplifies data that falls within a given range of values to a single numeric value. In this study, high density values were reclassified to higher numeric values.

For population data, rasters were reclassified based on population density. A four-class scale was used for urban areas following the convention set forth in the previous urban spread analysis, with the exception that the fourth and fifth class from that analysis was merged into one class for this analysis. A two-class scale was used for rural areas, which was determined using a geometric interval. Table A.2 shows the reclassification scales for urban and rural areas and the corresponding density description for each class.

TABLE A.2. Population Data Raster Reclassification Scales for Density Analysis

	Urban				Rural		
Reclassification	Start Value	End Value	Density Description	Reclassification	Start Value	End Value	Density Description
1	500	999	Low Density	1	0	274	Low Density
2	1000	2999	Medium Density	2	275	500	High Density
3	3000	8999	High Density				
4	9000	40000	Dense Core				

LandPro data shapefiles downloaded from the ARC were imported into ArcGIS Pro. Each file was converted to a raster using the Polygon to Raster function. These rasters were then reclassified following the established guidelines for classification of land use types. Table A.3 shows the reclassification values for each of these classes.

TABLE A.3. Land Use Data Raster Reclassification Scales

Reclassification	Land Use Class
NODATA	Greenspace
1	Low-Density Residential
2	High-Density Residential
3	Commercial
4	Industrial

The reclassified land use rasters contained data for both urban and rural areas. Since analysis for urban and rural was completed separately, the Extract By Mask function was used to select urban areas and rural areas from the land use rasters using the previously created population rasters. Once all data files were reclassified the Raster Calculator function was used to compute overall density. This function applies a given formula to the values within a raster to compute a new value which is displayed in a new raster shapefile. The formula used for this analysis was: Land Use * Population Density. This formula was applied to both urban and rural datasets for each of the three years analyzed. An orange color scale was used to show density in urban areas, and a green color scale to show density in rural areas.

Since this data is using both census tract and land use data the resolution of the resultant outcome of this analysis was higher than needed. The Focal statistics function was used to run a 3x3 majority function over the rasters produced to determine overall patterns of change. This function determines the majority value within a 3x3 rectangle and displays that corresponding pixel value within the whole 3x3 cell area, generalizing the data to show majority trends.

Changes in Urban Density- Figure 1.5

Areas that have experienced a change in density between 2000 to 2010 were also determined. The Raster Calculator was used to find the difference between raster values. Raster values for the year 2000 were subtracted from the 2008 values, and raster values for the year 2008 were subtracted from the 2010 values to create resultant rasters showing density change.

These rasters were reclassified to separate positive values, showing an increase in density, from areas with a negative or zero value, showing a decrease in density or stagnancy. This analysis was completed for both rural and urban rasters and a map was created to display these resultant areas.