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Comparative Analysis of Inter-Basin Transfers, Leakage, and Precipitation as Inflows within the Urban Hydrologic Cycle

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Comparative Analysis of Inter-Basin Transfers, Leakage, and Precipitation as Inflows within the Urban Hydrologic Cycle

by

Sarah Lowe

Under the Direction of Luke A. Pangle, PhD

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

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ABSTRACT

Water budgets are useful frameworks for urban planning, water management, and water conservation efforts—particularly as urban populations continue to grow. This research quantifies and compares magnitudes and temporal dynamics of precipitation, inter-basin transfers (IBTs), and leakage of potable water as inflows within the South River Watershed (SRW), an urbanized watershed located near Atlanta, GA USA. Monthly and annual precipitation totals derived from local gauge networks and from the PRISM model showed good agreement, with a long-term spatial average of 1407 mm for the watershed. Annually, precipitation was the dominant inflow into the watershed at 88%, the net IBT of potable water was 165 mm, or 10% of inflows, while leakage was 30 mm or 2%. Dividing leakage volume by whole-watershed area belies the reality that those inflows are very localized. Over land areas where the leakage can conceivably occur, it may represent 48-96% of total inflow.

INDEX WORDS: Urban hydrology, Inter-basin transfers, Precipitation, Water budget, Leakage

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DEDICATION

I would like to dedicate this body of work to those who helped me along the way. I would like to thank my parents, John and Lisa, for their endless support throughout my academic career. I would like to thank my good friend Dinah Carlton for the advice and for always being on my team. Finally, I would like to thank Anthony Mathis, for supporting me as I navigated this process.

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I would like to acknowledge the efforts put forth by other individuals to bring this body of work together. Firstly, I would like to thank my committee chair, Dr. Luke Pangle for his endless patience and guidance in researching various aspects of precipitation, inter-basin transfers, leakage, and water budgets. I would like to thank committee member Dr. Sarah Ledford for her support, and encouragement in both academic and mental challenges during my time at Georgia State University. Finally, I would like to acknowledge Dr. Jeremy Diem for his expertise in the development of this methodology. Without these individuals this thesis would not be what it is today.

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INTRODUCTION

Rising populations strain water supply and infrastructure resulting in urban water scarcity (Dinar 1998; Tavernia et al., 2013; Li et al., 2014; McDonald et al., 2014; Opalinski et al., 2019; Pincetl et al., 2019). Population growth has concentrated human demand for potable water resulting in alteration of hydrologic processes within urbanized regions. Urban population growth within the United States increased by 12% for the period 2000 to 2010, with more than 82% of the overall population living within these urban areas (Census Bureau 2022). Previous studies confirm that as populations in metropolitan regions continue to grow, the total municipal water demand increases in parallel (Falkenmark and Widstrand 1992; Postel et al., 1996; McDonald et al., 2011a; 2011b).

Municipal water utilized by urban dwellers often exceeds the supply available from local surface and ground water bodies. When this occurs, cities may look elsewhere to supplement the water deficit. When the potable water delivered to consumers is extracted from an aquifer or surface-water body that exists outside the topographic boundaries of that watershed, it is referred to as an inter-basin transfer (IBT) of water (Schroeder et al., 2011; ORSANC 2014; Zhuang 2016; Dickson and Dzombak 2017). Examples of this can be seen globally, from the largest man-made water distribution infrastructure from water abundant southern China to water deficient northern China (Li et al., 2016), to smaller transfers in Australia, to the complex movement of water within the U.S. (Snaddon 1999). Inter-basin transfers may result in significant alterations to hydrologic processes in both the donor and recipient watersheds (Cole et al., 2011; Zhuang 2016; Purvis and Dinar 2020). Within recipient basins, the precise hydrological impacts depend on how the IBT is distributed. For example, an IBT of water routed to the residents within the recipient watershed through infrastructure would make its way into the sanitary-sewer system. Following treatment at a wastewater treatment facility, this water distribution would primarily influence flow within the waterbody that receives the treated water (e.g., as shown in Diem et al., 2017).

Researchers have found that leakage from man-made water infrastructure (Lerner 1990, Lerner and Barrett 1996; Lerner 2002; EPA 2015; Hevesi and Johnson 2016; Cao et al., 2019; Yang et al., 2020), irrigation (Taylor et. al., 2013; Hevesi and Johnson 2016), and other landscape applications integrates portions of the IBT into the hydrologic cycle of watersheds upstream of the wastewater treatment plant as well. Results indicate a wide variation in infrastructure leakage from city to city, with works by (Lerner 1986; Lerner 1990) reporting leakage values ranging from 10-50% of piped flows for cities like Lima, Peru and Hong Kong, China. Within the United States, Baskar et al. (2012) found that water supply pipe leakage and irrigation accounted for 14% of the overall watershed inflows for the city of Baltimore Maryland. The hydrological relevance of these leakages of potable water is likely to vary depending on the local precipitation regime of any particular metropolitan area.

Urban irrigation can have profound impacts on the hydrologic environment, with work from Hevesi and Johnson (2016) finding that applied irrigation can account for 56% of the total recharge in semi-arid environments. While Kokkonen et al. (2018) similarly found that urban irrigation within two Vancouver B.C. neighborhoods accounted for 56% of the annual water input. This same study found irrigation offset evaporation losses brought on by land cover changes, and instead followed an upwards trend of evaporative loss up to a threshold—after which excess became runoff. Both leakage and irrigation may cause alterations to groundwater recharge (Lerner, 1986; Lerner 1990; EPA 2015; Lerner 2002), evapotranspiration (Vahmani and Hogue 2015; Litvak et al., 2017; Kokkonen et al., 2018) and streamflow magnitude (Debbage and Shepherd 2018). Considering these alternative distributions of potable water, it is relevant to consider IBTs alongside precipitation as a mechanism of water inflow into the urban hydrologic cycle. To the extent possible, it is also important to distinguish the hydrological impacts of unintentional leakages versus intentional outdoor applications, as the options for managing these two modes of distribution are markedly different.

Although IBTs are widespread among U.S. metropolitan areas (Dickson and Dzombak 2017), their magnitudes are often poorly constrained or completely unknown. Similarly, average rates of potable water leakage are reported for many U.S. metropolitan areas (EPA 2015), though additional analysis is required to translate leakage rates to actual volumes, and to contextualize the importance of these volumes within the water budget for the entire watershed. Such analyses are rarely reported. **This research involves a case study of one watershed within a major metropolitan region, with the goal of quantifying and contextualizing IBTs and leakage as components of the overall water balance.**

1.1 Urban Water Budgets:

A water budget is an expression of the principle of conservation of mass applied to stocks and flows of water within a watershed (e.g., Grimmond et al., 1986). Water budget equations include quantitative variables representing inflows and outflows of water through a specified land area over a determined period. These budgets consider volumes or stores of water within the subsurface, surface, and atmosphere of a catchment (Welty 2009). Urban budgets are more complex than those representing natural watersheds (Graham 1976). Spatial heterogeneity created through land cover conversions and additional inputs from urban infrastructure introduces components within water budgets that are not found in natural environments.

Urbanized water budgets include infrastructure components such as piped stormwater, potable water, and wastewater for either inflows or outflows depending on site specific conditions. These components differ from natural water budgets that only utilize precipitation and groundwater flow as inflow components, and runoff, groundwater outflow, and evapotranspiration as outflows.

The conceptual representation of the water budget and its constituent terms is relatively uniform among studies that examine watersheds absent major human disturbances, whereas water budgets for urban watersheds may vary dramatically depending on the array of alternative flow processes that are recognized or can be reasonably quantified. Equation 1 provides an example of the former case including precipitation, evaporation, transpiration, and discharge from streams and rivers.

$$\Delta S = P - E - T - Q \qquad (1)$$

This differs from Equations 2 and 3, presented by Bhaskar et al. (2012) and Mitchell et al. (2003), respectively. Equation 2 captures more of the complexities involved within urbanized landscapes, attempting to quantify I&I, reservoir withdrawals, and lawn irrigation. These components were determined along with precipitation, evapotranspiration, water supply pipe leakage, and streamflow.

$$\Delta S = P + I + L - ET - Q - W - I\&I \qquad (2)$$

The equation from Mitchell et al. (2003) includes similar components quantifying, precipitation, imported water, but specifies components like actual evapotranspiration, stormwater runoff, and wastewater discharges.

$$\Delta S = (P + I) - (E_a + R_s + R_w) \qquad (3)$$

These water budget equations are expected to vary among urban environments due to the presence or absence of specific flow processes, or the availability of data that may enable quantification of specific flows. Increasingly detailed conceptualizations of the urban water budget and enhanced quantification of components is an important goal in urban hydrology and watershed management, especially for the hypothetical and retrospective analysis of different water management mechanisms (e.g., as discussed by Mitchell 2006 and Bach et al. 2014).

1.2 Precipitation:

Precipitation as a component inflow within an urban water budget is a critical part of studying catchment water balances. Estimations and magnitudes of these precipitation values vary throughout the U.S.—particularly in urbanized regions. Urbanized regions have been found to have higher temperatures due to reduced cooling during afternoon and nighttime hours (Oke 1987; Gallo and Owen 1999), increased surface roughness (Changnon 1981), and increased wind speeds (Balling et al., 1987)—all of which are factors that have been found to alter precipitation.

Occurrences of higher surface temperatures in urban versus rural environments is known as the urban heat island effect (UHI). In cases with UHI, heat generation from various urban sources enhances turbulent transport of water vapor into the upper atmosphere and subsequent precipitation amounts. This results in spatial variation of precipitation estimations, particularly during localized convective storms. This alteration of surface temperatures has been well documented in previous works by (Bornstein and LeRoy 1990; Bornstein and Lin 2000; Baik et al., 2001; Dixon and Mote 2003; Shepard and Burian 2003; Shepard 2005; Diem 2008; Dou et al., 2014; Niyogi et al., 2017; McLeod et al., 2017) all of which have provided evidence that urban environments can alter or induce precipitation.

Urban water budgets need accurate data to create representative flows within watersheds which requires high resolution precipitation estimates. Analyzing spatial and temporal variability of precipitation in urbanized regions has been a notable source of error in studying hydrologic processes (Niemczynowicz 1988). Studies estimating precipitation have utilized methodologies such as rain gauges, pluviographs (Lanza and Stagi 2009), and radar to quantify precipitation using microwave pulses and response times (Winchell et al., 1998; Jefferson 2019). Previous research has also utilized modeling programs that take input variables, such as vegetation characteristics, land cover/ usage, atmospheric conditions, and surface roughness (Shepard et al., 2010).

No standard method of estimating precipitation has been determined for urban environments (Karl and Knight 1988) and each methodology has advantages, but all have associated error. For example, the tipping bucket rain gauge has been found to underestimate or under-catch the amount of precipitation (Sevruk 1994; Sevruk and Zahlavova 1996), and radar has biases introduced within the data processing component that must be addressed through bias adjustment (Steiner et al.,1999). Acknowledging errors associated with these prominent methodologies is necessary because accurate quantification of precipitation estimates can influence the overall water budget.

1.3 Municipal Water:

Urban water budgets utilize components that do not appear within natural environments, particularly the component inflow of municipal water. Municipal water is defined within this study as the water for public use or domestic purposes (USGS 2021). In 2015 the U.S. had a total water usage of 322,000 billion gallons per day with the three largest categories of use being thermoelectric power, irrigation, and public water supply (Dieter et al., 2018). With over half the global population living within metropolitan areas, (United Nations 2014) understanding trends of current and future municipal water use is relevant for accurate quantification of inter basin transfers and other water balance components.

Urban water scarcity has been a growing concern in many metropolitan regions (Dinar 1998; Tavernia et al., 2013; McDonald et al., 2014; Li et al., 2014; Pincetl et al., 2019; Opalinski et al., 2020). To mitigate these water deficits many cites utilize man-made infrastructure to bring in water from an outside watershed, often in the form of IBTs. Inventories of IBTs in the U.S. have been primarily conducted by two different studies Petsch (1985) and Dickson et al. (2017) which established a total of 2,161 IBTs but do not quantify volumes transferred. Although IBTs are often measured and quantified by the water-management agencies involved in their implementation, their impacts on specific flows within the urban water budget are rarely resolved.

Influences of IBTs can be seen both within the recipient watershed and the donor watershed (Gupta et al., 2008; Schroeder and Woodcock 2011; Zhuang 2016). Impacts on the donor watershed include decreased runoff volumes, in-stream flows, lowering of the water table, degradation of aquatic ecosystems, and even soil salinity (Schroeder and Woodcock 2011; Zhuang 2016). These negative impacts exhibited by the donor watershed give IBTs the reputation as a controversial water management practice when used to supplement water shortages. Recipient basins experience hydrologic alterations from IBTs in a different way. Examples of this would be when observing water brought into the recipient watershed via the pipe system. Infrastructure degrades overtime leading to potential leakages into the groundwater that can range anywhere from 2-5% (Mitchell et al., 2003) to 20-50% (Lerner 1986). This leakage from pipes or sewer infrastructure can be contributed to size, materials used within construction, and age of infrastructure (US EPA 2002). This leakage from infrastructure has been found to contribute to groundwater recharge in urban areas, as well as contributing to the treated outflows from the sanitary sewer system (Lerner 1986; Barrett et al., 1999; Lerner 1990; Lerner 2002; Welty 2009; Passarello et al., 2012; US EPA 2015). Leakage from infrastructure, irrigation, and outdoor water use all influence aspects of the water budget—this is seen as what is thought to be secure inflows percolate into other aspects of the hydrologic cycle. Inter-basin transfers represent important inflows and outflows from urban watersheds and quantifying the redistribution of water is crucial for urban water management and water conservation efforts.

1.4 Transboundary Water Disputes:

Watershed boundaries often do not coincide with physical country or state boundaries. Political contentions over water rights and resources have been increasing as the demand for water supply intensifies and IBTs become more widespread. An example of this is seen within the Apalachicola-Chattahoochee-Flint (ACF) basin and the Alabama-Coosa-Tallapoosa (ACT) basin that supplies water to the states of Georgia, Florida, and Alabama. Alabama and Florida filed a lawsuit against the state of Georgia to ban the US Army Corps of Engineers (USACE) from reallocating water from Lake Lanier for water supply in northern Georgia (Missimer et al. 2014). This legal battle continued for several years, as the state of Florida claimed that the over consumption of water from the ACF basin was leading to the destruction of the oyster industry (*Florida v. Georgia*, 2019). The case was ruled in favor of the State of Georgia stating that Florida had failed to prove to the court that Georgia's water consumption was unreasonable and the cause of the declining oyster population (Sherman 2021). Often there are political, economic, and environmental factors that play a role in water allocation that must be considered. Water disputes are growing in number as urban water scarcity increases with shifting populations and climate change (Duan et al., 2019). As these issues arise, it is important to gain a better understanding of the movement and magnitude of water resources on both urbanized regions as well as their donor or natural counterparts.

1.5 Research Objectives:

Inter-basin transfers of water are widespread within the U.S. and the associated volumes of water transferred are likely to increase as the country's population continues to grow and migrate towards metropolitan areas. Though well-documented, most IBTs are poorly quantified, due to the lack of correspondence between jurisdictional boundaries of different water management authorities and the physical boundaries of actual watersheds. Minimal information is available regarding the comparative magnitudes of IBTs, precipitation, and leakage as inflows within urban watersheds at daily to annual time scales. To address these knowledge gaps, this research focuses on the following objectives: **(1) quantify the IBT of water from the Chattahoochee River, within the Apalachicola-Chattahoochee-Flint River basin (ACF), to the South River watershed (SRW) within DeKalb County and the broader Altamaha-Oconee-Ocmulgee basin (AOO), (2) to quantify whole-watershed precipitation using a distributed network of rain gauges and an inter-comparison of interpolation and averaging schemes, and (3) to examine the comparative magnitudes and temporal dynamics of IBTs and leakage versus natural precipitation as inflows within the water budget for the SRW and a selection of its tributary basins.**

2 STUDY REGION

The SRW is located within the metropolitan region of Atlanta, Georgia (Figure 1), which lies within the Piedmont physiographic province in the southeastern United States. The Piedmont province is characterized by low rolling hills and northeast-southwest trending ridgelines ranging in elevation from 200-350 meters above sea-level (Heath 1984). Predominant geology of this area is late Precambrian to Permian aged highly deformed metamorphic crystalline rock with intrusive igneous bodies (Miller 1990; Golley 2004). The climate of the Georgia Piedmont is defined as humid sub-tropical distinguished by the hot, humid summers and mild winters (Belda et al. 2014). Annual precipitation (1951-1980) ranges from 122 to 203 cm, with minimal seasonal variation across the region (Miller 1990). The first-order streams comprising the headwaters of the SRW begin at the eastern sub-continental divide of North America. The upper portion of the SRW is the delineated study area with a watershed outlet defined at the UGSG gauge [02204070] on Klondike Rd. The upper SRW drains an area of roughly 478 square kilometers and is positioned within the AOO basin. However, residents of the SRW obtain their potable water via an IBT from the ACF basin, a large portion of which is treated and pumped back into the AOO basin. That transfer represents the single largest IBT of water from the ACF, and therefore has relevance to the long-standing legal disputes between GA, AL, and FL regarding allocations of water from the ACF (Missimer et al., 2014).

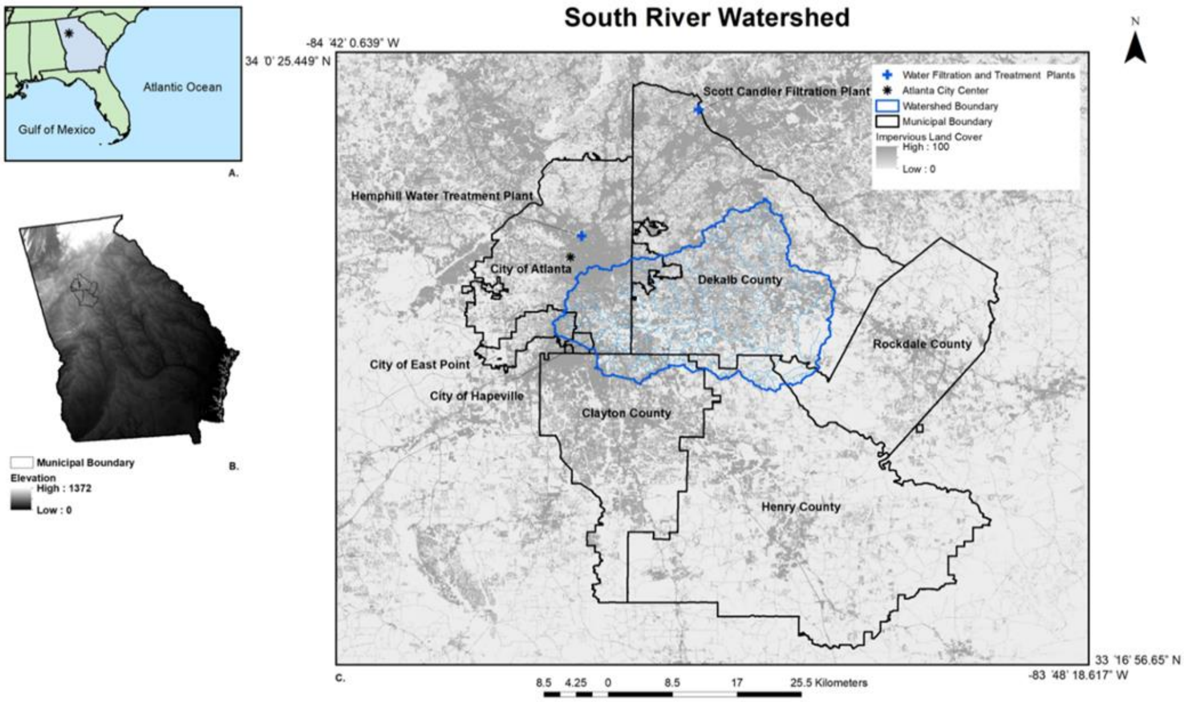

Figure 1: (A) Map showing the location of the study area in relation to the state of Georgia and the southeastern United States. (B) Digital elevation model of Georgia with black outlines indicating the boundaries of city and county jurisdictional areas that partially overlap with the boundaries of the South River Watershed. (C) Map of the South River Watershed including the Hemphill Filtration Plant, the Scott Candler Filtration Plant, and the aforementioned jurisdictional boundaries. Gray shading shows the % impervious land cover.

Numerous precipitation gauges operate within and around the SRW (Figure 2) and the seven counties whose boundaries partially overlap with the SRW have municipal water use records available via open records request. Water audits and water efficiency reports created by the Georgia Environmental Protection Division (EPD) are also available to aid in quantifying municipal water use (Georgia EPD 2022). Given that the SRW is geologically and climatologically representative of the Piedmont region, and given the abundance of available data, the SRW is an ideal location to analyze and compare complex inflows within an urbanized watershed.

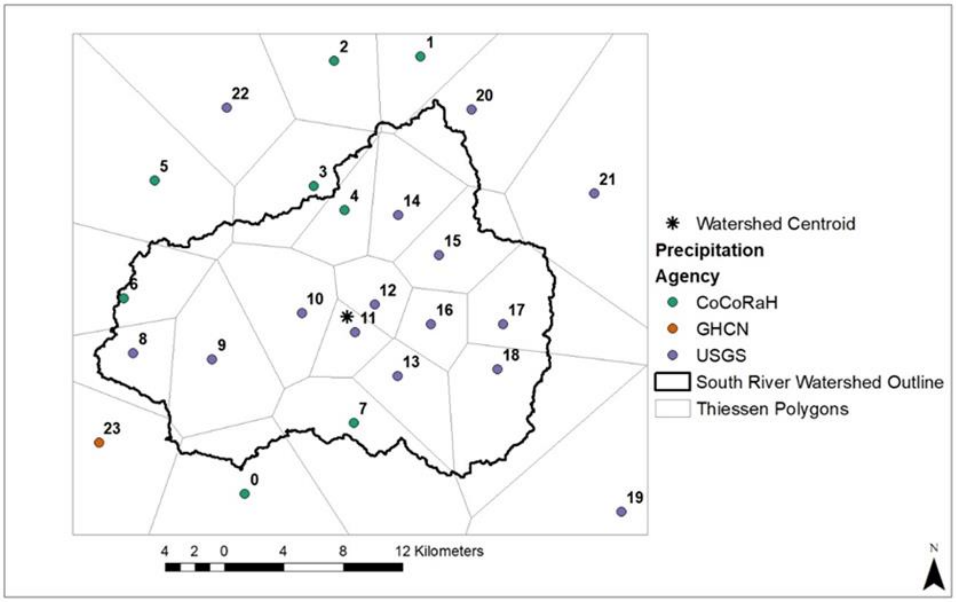

Figure 2: Precipitation station distribution including the Thiessen polygons and centroid used for the watershed-wide precipitation totals.

3 METHODOLOGY

3.1 Quantifying Precipitation:

Daily precipitation data for 2018-2020 were obtained for 24 rain gauges located within the SRW or within 10 kilometers of the watershed boundary (Figure 2). Data from 6-inch-diameter tipping bucket gauges were obtained from the Hartsfield-Jackson Airport and from the United States Geological Survey (USGS) (Table 1). Other data were obtained from the Community Collaborative Rain, Hail and Snow Network (CoCoRaH), which uses butyrate plastic 4-inch-diameter rain gauges with openings the height of 14 inches (Official CoCoRaHS gauge 2021).

We used data from only those gauges that had less than 10% missing data. Missing data within the USGS and CoCoRaH gages were filled using averages from the three nearest stations.

If multiple stations used for calculating the average values were missing data for the observed time-series, then the missing data were filled using the airport [the Global Historical Climatology Network daily (GHCNd)] gauge value for that missing time series. Data from CoCoRaH was intended to be recorded daily, but the 2018-2020 dataset held multiple instances of grouped daily totals. These multi-day totals were disaggregated into daily totals based on proportions calculated from rainfall data collected at the airport [the Global Historical Climatology Network daily (GHCNd)]. Manual data collection for CoCoRaH gauges is recorded daily in the morning and represents the previous 24-hours of rainfall (COCORAHS 2021).

To account for this the daily totals of precipitation were assigned to the date prior to the date of collection and recording. There is some potential for error here, as any rainfall that occurs on the current day prior to collection by the worker will be incorrectly added to the rainfall total for the previous day. We ultimately intend to compare piped water flows, and potable water leakage, to precipitation at monthly to annual time scales, rather than daily. Hence, the possibility of this error type is reduced and relevant only for the morning hours of the first day of each month prior to the current day recording of rainfall depth. Using the USGS tipping bucket gauges, we calculated specifically the total rainfall accumulation from midnight until 7:00 am on the first day of each month during 2018 to 2020. We found that the precipitation totals during these morning hours of the first day of each month were less than 1% of the total rainfall depth for the preceding month in 28 out of the 35 months analyzed. Only one occurrence of rainfall in the early hours of 1/1/2019 accounted for more than 1% of the total rainfall depth for the preceding month but did not account for more than 3% of the previous month’s total rainfall. Based on these observations we reason that influence of this error source on monthly and annual rainfall totals is negligible.

With no indication of spatial autocorrelation, a term used to describe the tendency for nearby areas to exhibit similar values of a particular variable (Haining 2001), and a calculated Moran's I value of 0.072, it was determined that a comprehensive value for the entire watershed would be sufficient. Moran's I is a statistic that measures the 'spread' of a variable over a particular area, a value close to zero represents a random dispersion with no clusters. Watershed-scale precipitation totals derived from the 24 gauges were estimated using Thiessen polygon approach, centroid-based (or inverse-distance weighting) approach, as well as the arithmetic average. The Thiessen polygon approach is a common methodology for distributing precipitation point estimates over a specified area, by creating polygons centered around the precipitation station so that one station is within each polygon. The area of each polygon is the weighting value used in the calculation of weighted mean precipitation totals for the entire SRW (Thiessen, A.H. 1911). The centroid-based approach uses the inverse of distances from the gauges to the SRW centroid as weighting values (Figure 2). The weighted mean precipitation totals calculated by each approach were computed on monthly and annual time scale.

Table 1: Precipitation Gage Information

Map ID:	Station ID:	Agency:	Percent Data Available:
0	GA-CN-8	CoCoRaHS	98%
1	GA-DK-1	CoCoRaHS	95%
2	GA-DK-2	CoCoRaHS	100%
3	GA-DK-33	CoCoRaHS	100%
4	GA-DK-49	CoCoRaHS	98%
5	GA-FT-24	CoCoRaHS	100%
6	GA-FT-37	CoCoRaHS	99%
7	GA-HY-7	CoCoRaHS	95%
8	USGS02203603	USGS	92%
9	USGS02203655	USGS	99%
10	USGS02203831	USGS	99%
11	USGS02203863	USGS	99%
12	USGS02203873	USGS	98%
13	USGS02203900	USGS	99%
14	USGS02203950	USGS	99%
15	USGS02203957	USGS	100%
16	USGS02203960	USGS	99%
17	USGS02204010	USGS	96%
18	USGS02204037	USGS	90%
19	USGS02204130	USGS	100%
20	USGS02207130	USGS	98%
21	USGS02207160	USGS	99%
22	USGS02336120	USGS	99%
23	USW00013874	GHCNd	100%

Previous studies (e.g., Opalinski et al. 2019; Bhaskar et al., 2012; Mango et al., 2017) have utilized gridded precipitation estimates from the Parameter-elevation Regressions on Independent Slopes Model (PRISM) for their research. PRISM is a climate analytical model that utilizes point data, digital elevation models (DEM), and other spatial data to create gridded estimates of "event-based" climate phenomenon (Daly et al., 1993; Daly et al., 1997; Daly et al., 2008). Within this study, PRISM data is compared and analyzed against the gauge-based data from the USGS, CoCoRaH and GHCNd. Daily 4-k resolution data were acquired for the initial time series 2018-2020 from the PRISM Climate Group (Figure 3).

Through a simple linear regression model, the relationship between the PRISM data and the gauge-based data was evaluated. A strong correlation is found between the PRISM data values and the gauge-based values over the observed study period, as the linear regression model displayed a slope value of 0.966 and an R^2 value of 0.959 (Figure 4). As both the slope of the linear regression model and the associated R^2 value were close to 1, then it is appropriate to assume that there is minimal variation between the regression model and the PRISM and gage values. From the assessment of the PRISM and gage relationship, it was determined that the PRISM data can be utilized for a longer timer period of analysis with what should be comparable results to that of the gauge data. Utilizing the PRISM data allows for a more extensive period of analysis for comparing and assessing inflows within the SRW, that could not be achieved with gauge-based precipitation data alone.

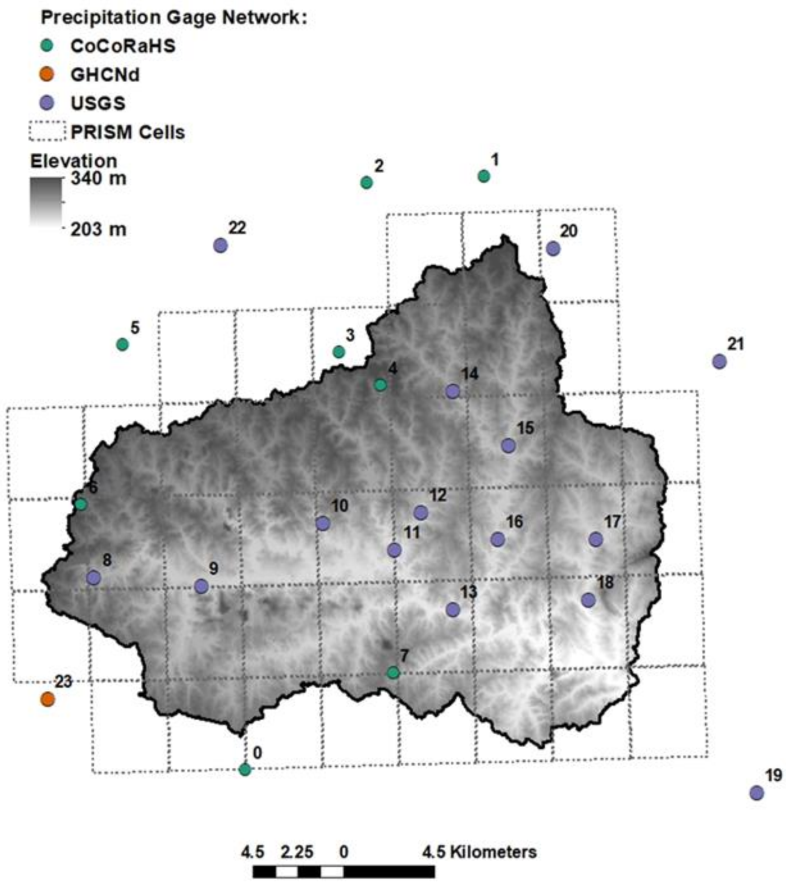

Figure 3: Precipitation gage distribution overlain by the PRISM cells used for long-term precipitation comparison.

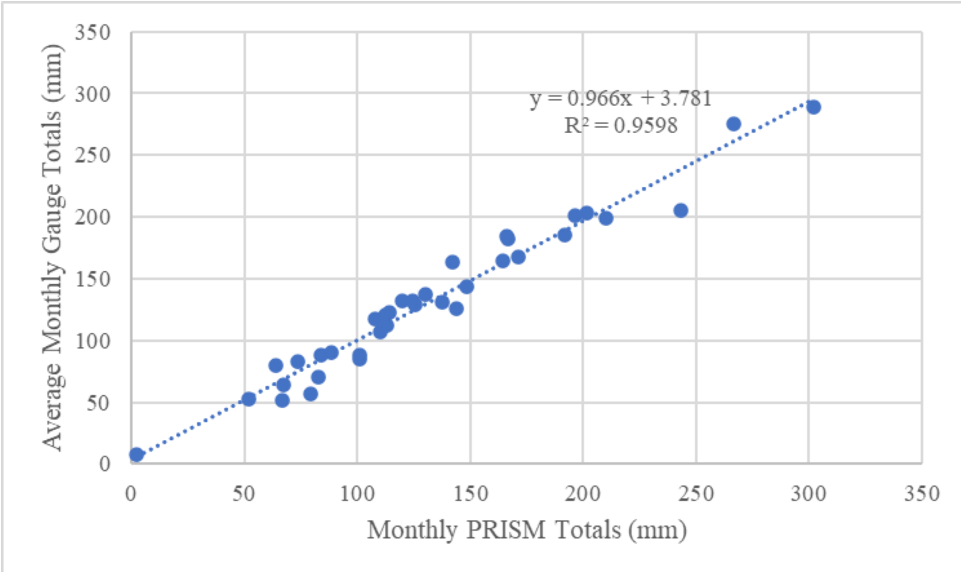

Figure 4: Linear Regression model to observe the relationship between the monthly gauge totals and the monthly totals generated by PRISM for the period 2018-2020. R-squared value and linear equations displayed on graph.

3.2 Quantifying Municipal Water:

3.2.1 Conceptualizing the Inter-Basin Transfer:

Framing an IBT in a similar manner to that of a water budget facilitates in understanding the complexity of quantifying these transfers. Volumes of water brought into the basin to distribute to users (I_{R1}) makes up the primary inflow within Equation 4. Portions of this conceptualized budget are reported or have estimated values denoted with the subscript (R) and unknown components are denoted with the subscript (NR). Potential leakage (L_{R2}), irrigation (Irr_{NR}), and combined sewer overflow events (CSO_{NR}) all contribute portions of water into the broader hydrologic system of the AOO basin but quantifying them is difficult as municipalities often do not specifically measure these flows.

$$IBT = I_{R1} - L_{R2} - Irr_{NR} - CSO_{NR} - Q_{NR} \quad (4)$$

Contextualizing the SRW's IBT, the portion of water brought in from ACF to users within the AOO is treated and pumped back into the ACF basin through the 3-Rivers Tunnel (Q_{NR}) (Figure 5). Although water from this IBT is primarily transferred back to the ACF basin, there are portions of this transfer that remain within the AOO basin. Outflows from the Pole Bridge and Snapfinger Creek Wastewater Treatment Facilities are reported values that discharge their treated waters into the South River instead of being transferred back into the ACF basin. Water distributed from the Hemphill Water Treatment Plant to the East Area of the City of Atlanta is directed to the Custer Avenue Combined Sewer Control Facility where flows are either sent to the Intrenchment Creek Facility for water treatment or directly to the South River during certain precipitation events. Portions of the transferred municipal water are also applied for lawn irrigation by users within the AOO, which may integrate portions of the transferred water into the broader hydrologic system, alongside leakage from infrastructure. Quantifying this transfer of water may seem like a straightforward process but determining the flows that utilize the transferred water is difficult as not all the water is transferred through the 3-Rivers Tunnel back into the ACF basin.

Municipal water distributed to users within the SRW represents the largest IBT of water from the ACF basin into the AOO basin. A representative conceptual model of the transfer of water between these basins is illustrated within Figure 5. Arrows within Figure 5 represent component flows that potentially contribute to the net IBT. Green arrows show flows into or out of a natural water source, blue arrows represent flows of distributed water to users within the basin, and red arrows represent wastewater flows. Quantification of municipal water volumes associated with the IBT to users within the SRW is within the described methodology below.

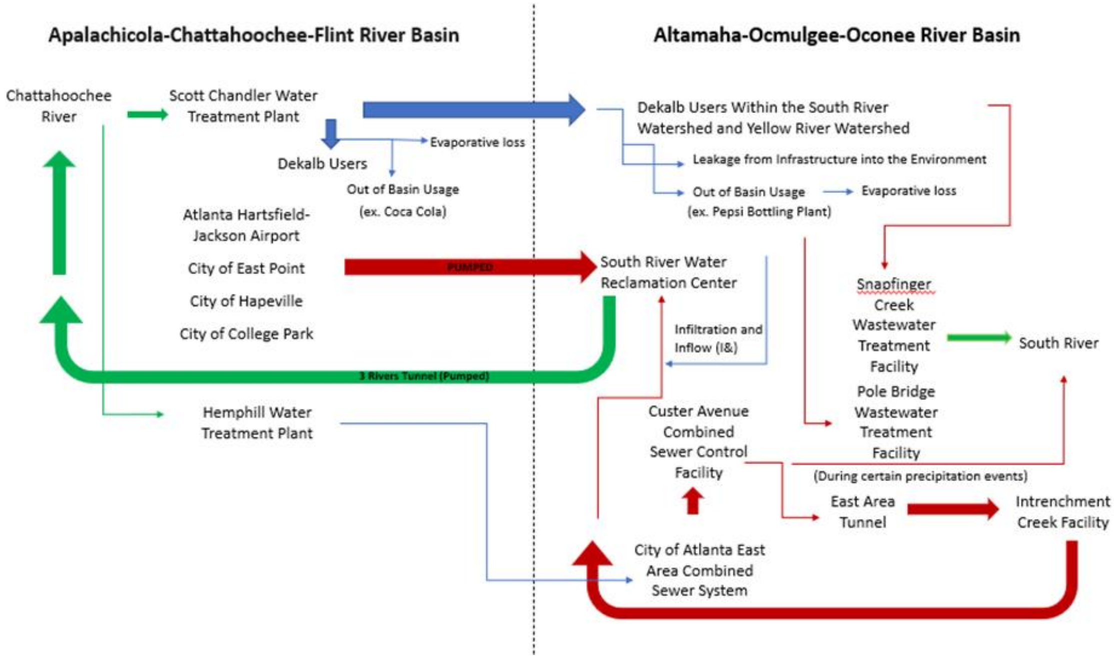

Figure 5: Transport of water from the Apalachicola-Chattahoochee-Flint River basin to the Altamaha-Ocmulgee-Oconee River basin. Green arrows represent flows coming to or from a natural source. The red arrows represent wastewater, and the blue arrows represent the treated water distributed to users within the basin.

3.2.2 Data Collection:

Multiple water management jurisdictions convey water to users within the SRW (Figure 6). Quantification of water conveyed from each jurisdiction was conducted to calculate a comprehensive value for the entire SRW. Annual audits of water use, water efficiency, and water loss were collected from the Georgia Department of Natural Resources Environmental Protection Division (EPD) for the period 2011-2018. Audits are created on an annual basis through the Water Stewardship Act of 2010 which aimed to develop goals and progress toward improving water supply efficiency (EPD 2021). Software to complete these audits are from the American Water Works Association, utilizing Volumes 5 and 6 for Georgia municipalities (EPD 2022). From these audits we were able to extract estimates of the total water distributed to end users (in million gallons per year) within the jurisdictional areas, Dekalb, Clayton, Henry, Rockdale, and Fulton counties, and the cities of Hapeville, Atlanta, and East Point. Distributed annual volumes of water for each jurisdiction were measured and reported as the amount of water leaving the respective treatment facility. Missing 2011 water audit values for the City of Hapeville were filled with 2012 water audit data values.

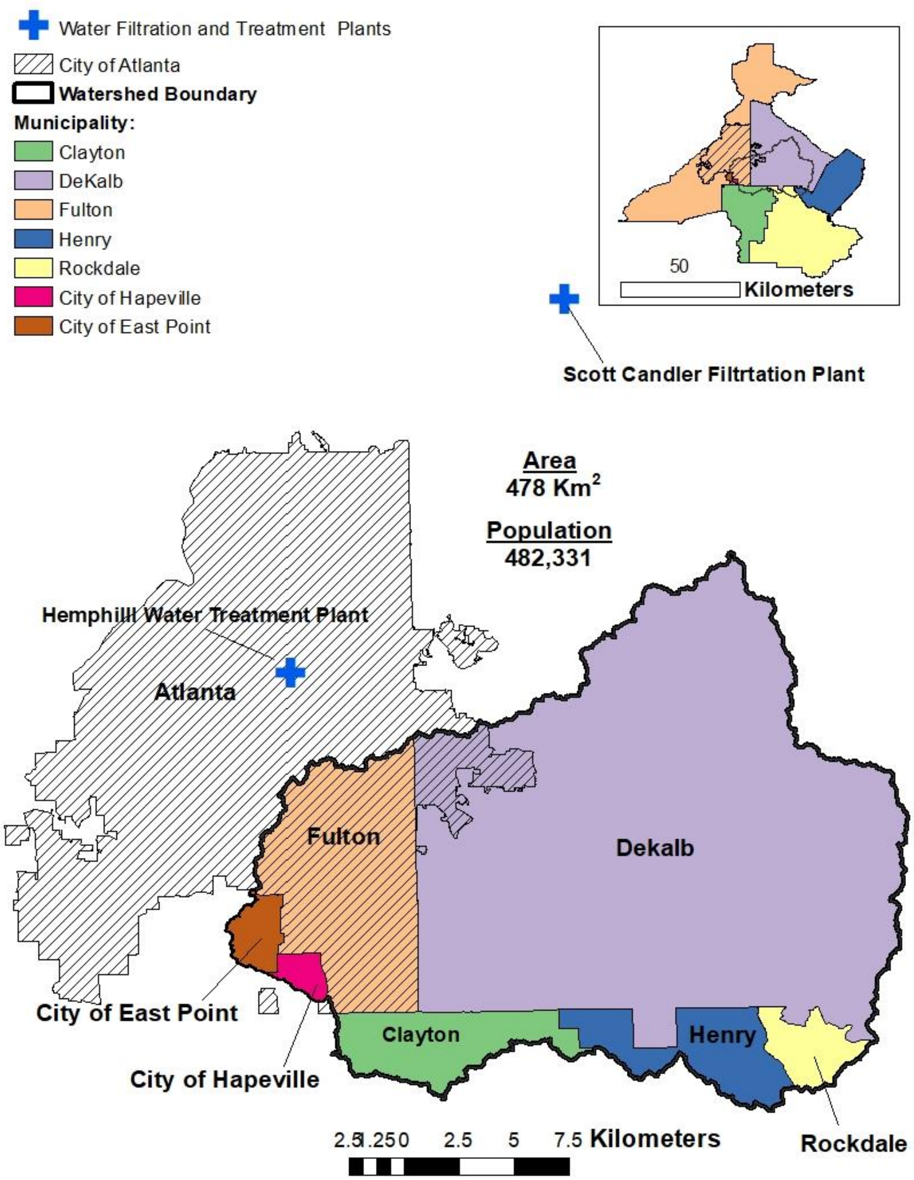

Figure 6: Jurisdictions that make up the South River watershed along with the Hemphill Water Treatment Plant and the Scott Candler Water Filtration Facility which conveys water to users with their respective regions. Population value derived from 2019 NLDC data set.

3.2.3 Spatial Weighting:

With varying jurisdictional, watershed, and census block groups boundaries it was necessary to develop a methodology that represented the watershed area alone. Dasymetric mapping is a geospatial technique that utilizes ancillary information to redistribute numerical data over a specified spatial area to represent the underlying statistical surface (Wright 1936; Mennis 2003; Petrov 2012). This dasymetric technique was utilized to distribute the volume of water estimated by the Georgia EPD water audits to each jurisdictional area within the SRW through areal weighting of the census block group population data. This methodology was inspired by, though distinct from, that presented by Debbage and Sheppard (2018), where census block group population data was taken and spatially allocated to flood plain area using National Land Cover Data. This methodology was altered for the purpose of this research to determine the percentage of population within the SRW out of the population of the entire jurisdiction through areal weighting of land area. These percentages or proportional values will be utilized in conjunction with the Georgia EPD water audit values to estimate the water use across the spatial area of the SRW.

Seven different water management jurisdictions overlap with the boundary of the SRW (Figure 6). To distribute the annual water audit data provided by the Georgia EPD to the spatial area of the SRW, population data was acquired from the Census Bureau’s American Community Survey for the period 2010-2019, with no data representing the calendar year 2016. Population data from the Census Bureau are provided as collated total population values for every census block group. The population density (D_j) within each jurisdiction was then calculated as the sum of population totals from each census block group (P_j) divided by the sum of areas represented by each census block group within the jurisdiction (A_j) (Equation 5). The total population within the jurisdiction was calculated as the product of that density and total area.

$$D_j = \frac{P_j}{A_j} \qquad (5)$$

The shapefile representing census block groups within each jurisdiction was then clipped with the shapefile representing the SRW boundary. This created a clipped area where the census block group within each jurisdiction overlapped with the SRW. New population densities and totals were calculated for each of the clipped partial-jurisdictional areas that lie within the SRW (P_{j+SRW}). The new population totals (for the portion of the jurisdiction lying within the SRW) was divided by the total population within the whole jurisdictional area (P_j). These proportions were used as spatial allocation factors: they were multiplied by the total water volume distributed to users within the jurisdiction per year ($W_{j,q}$), as presented in the water audit reports, to calculate the water distributed within the portion of the jurisdiction that also resides within the SRW (Equation 6) (EPD 2021).

$$W_{j+SRW,q} = \frac{P_{j+SRW}}{P_j} \times W_{j,q} \qquad (6)$$

3.2.4 Temporal Scaling:

Each of the contributing jurisdictions receives potable water from a different filtration facility. However, we were only able to obtain estimates of potable water conveyance from the Scott Candler filtration plant, which serves the DeKalb County jurisdiction. For the purpose of quantifying the temporal dynamics of potable water distribution to users in the other jurisdictions, we assume that the temporal patterns recorded at the Scott Candler filtration facility are representative throughout. We developed temporal allocation factors that are described below.

Daily outflow data from the Scott Candler Filtration Plants was obtained through Open Record Requests to Dekalb County for the period 2011-2020. Measured outflow data from the plant was reported by the McCrometer Insertion Magnetic Meter - Model 395L that has an associated accuracy of ±0.5% (John Patterson, personal communication, March 31, 2022). The Scott Candler outflow values were aggregated to a monthly scale by creating monthly allocation factors. These factors were calculated by taking the total water use for the month ($W_{SC,m}$) and dividing it by the annual total water use that included that month ($W_{SC,q}$) (Equation 7).

$$\theta_m = \frac{W_{SC,m}}{W_{SC,q}} \qquad (7)$$

$$W_{j+SRW,m} = \theta_m \times W_{j+SRW,q} \qquad (8)$$

These allocation factors (θ_m) were multiplied by the annual water audit values, collected from the Georgia EPD that were spatially allocated to the SRW through the areal weighting dasymetric technique using the census block group population data ($W_{j+SRW,q}$) to create monthly water use estimates ($W_{j+SRW,m}$) (Equation 8). The resulting value represents the volume of water distributed to users within each jurisdiction within the SRW, in units of cubic meters per month. The sum of $W_{j+SRW,m}$ for all jurisdictions *j* represents total potable water distribution to users within the SRW each month. Those monthly totals were then summed to yield an annual total.

3.2.5 Water Audit vs Zip-Code Billing Data:

Initial efforts within this research focused on obtaining zip-code based billing data from each water management department to gain data with a higher resolution than that of the available data within the Georgia EPD water audits. These values were only successfully obtained for the City of Atlanta. Due to the limited data availability from the other jurisdictions, the zip-code water billing data obtained from the City of Atlanta Department of Watershed Management is used for comparison with that of the Georgia EPD water audit data (Figure 7).

Evaluating the deviation between the two data sets is relevant as the zip-code based data has a finer resolution of data, reported as monthly water use totals per user account, versus the Georgia EPD water audits that report annual water use totals for the entire jurisdiction. Observing the created linear regression model (Figure 8), the relationship between the City of Atlanta zip-code based water use data and the Georgia EPD water use data was evaluated to find a moderate correlation. The coefficient of determination value suggests that there is variation in the data from the fitted regression trendline, or significant deviation from the mean value. Although this deviation is present within the data sets, due to the limited data availability from jurisdictional water providers, the Georgia EPD water audit data was used for determining water conveyed to users within the SRW.

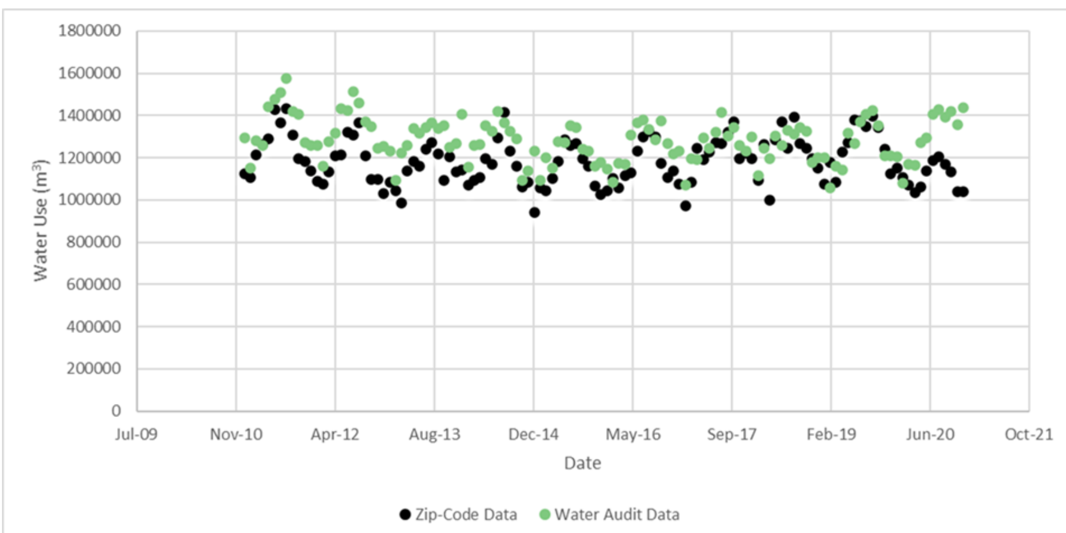

Figure 7: City of Atlanta zip-code based water use data comparison against the water use data provided by the Georgia EPD for the period 2011-2020.

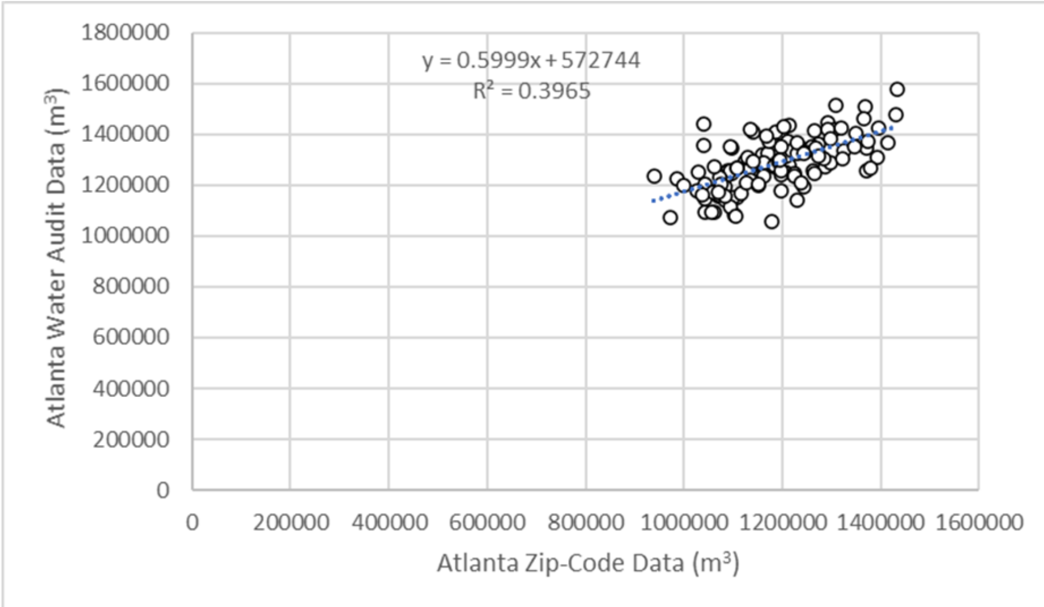

Figure 8: Liner Regression model to observe the relationship between the City of Atlanta zip-code based water use data and the water use data provided by the Georgia EPD.

3.3 Quantifying Leakage:

Assumed leakage from the municipal supply system was determined from the Georgia EPD's Water Efficiency and Water Loss Audits. The water audits provide an estimated leakage or 'real loss' value for each municipality, for each year's water audit. Leakage values were determined by first calculating a proportional real loss value (R_{LV}). This was done by taking the Georgia EPD's provided real losses (R_{L}) and dividing them by the total water supplied to the entire jurisdiction ($W_{S,EPD}$) (Equation 9). After each real loss value (RLV) was calculated it was multiplied by each municipality's individual municipal water use within the SRW ($W_{j+SRW,q}$). This created a comprehensive leakage value for the portion of the SRW that overlapped with the jurisdictional area (L_{j+SRW}) (Equation 10). Data was aggregated to the monthly time scale and all jurisdictional areas eventually summed for a comprehensive leakage value throughout the SRW. This methodology does assume a constant leakage throughout the entire portion of the jurisdiction within the SRW, when leakage into the subsurface would only occur around compromised pipe infrastructure.

$$\frac{R_L}{W_{S,EPD}} = R_{LV} \qquad (9)$$

$$R_{LV} \times W_{j+SRW,q} = L_{j+SRW} \qquad (10)$$

3.3.1 Estimating Leakage on Different Spatial Scales:

Two alternative approaches were used to calculate the leakage as an area-normalized depth, which may more realistically contextualize its hydrological significance. Lacking spatial information about the pipe system that conveys potable water, the first alternative approach utilized a shapefile that included length and diameter estimates for all pipes within the sanitary sewer system. The total length of sanitary sewer pipes was multiplied by the average outside diameter (OD) of the pipes (the average OD was 9 inches), yielding an estimate of the vertically projected area of the pipe system. This spatial data was available only for DeKalb County, not the other jurisdictions within the SRW. The vertically projected pipe area was then divided by the area of Dekalb County overlapping the SRW. That ratio of pipe area to land area was multiplied by the entire area of the SRW, including the other six jurisdictional areas for which maps of the pipe system were not available. The determined area was then utilized in dividing the estimated volume of leakage for the SRW to obtain an area-normalized depth.

The second alternative approach used to calculate leakage as an area-normalized depth using an obtained roadway shapefile obtained from the Georgia GIS Clearinghouse. This file was then reduced to the size of the SRW, and a total length of roadway was determined. The total length of roads within the SRW was then multiplied by a determined roadway average width taken from (AASHTO 2001). This calculation yielded a roadway area that was then used to determine leakage for a more contextualized value.

4 RESULTS

4.1 Precipitation:

Precipitation estimates calculated through the Thiessen polygon approach, centroid-based (or inverse-distance weighting) approach, and the arithmetic average were relatively similar (Figure 9, Table 2). An average of all three methodologies was used to estimate precipitation for the entire spatial area of the SRW for the study period 2018-2020. The average-monthly precipitation was 132 mm ± 61 (uncertainty bounds are one standard deviation, SD). Total-annual precipitation during 2018, 2019, and 2020 was 1680, 1264, and 1804 mm, respectively Table 2). The annual precipitation during 2019 is similar to the 30-year average (1986-2015) of 1240 mm recorded at the Panola Mountain Research Watershed (Aulenbach & Peters 2018), which lies within the broader SRW. Total-annual precipitation during 2018 and 2010 was 416 and 540 mm greater than this long-term average.

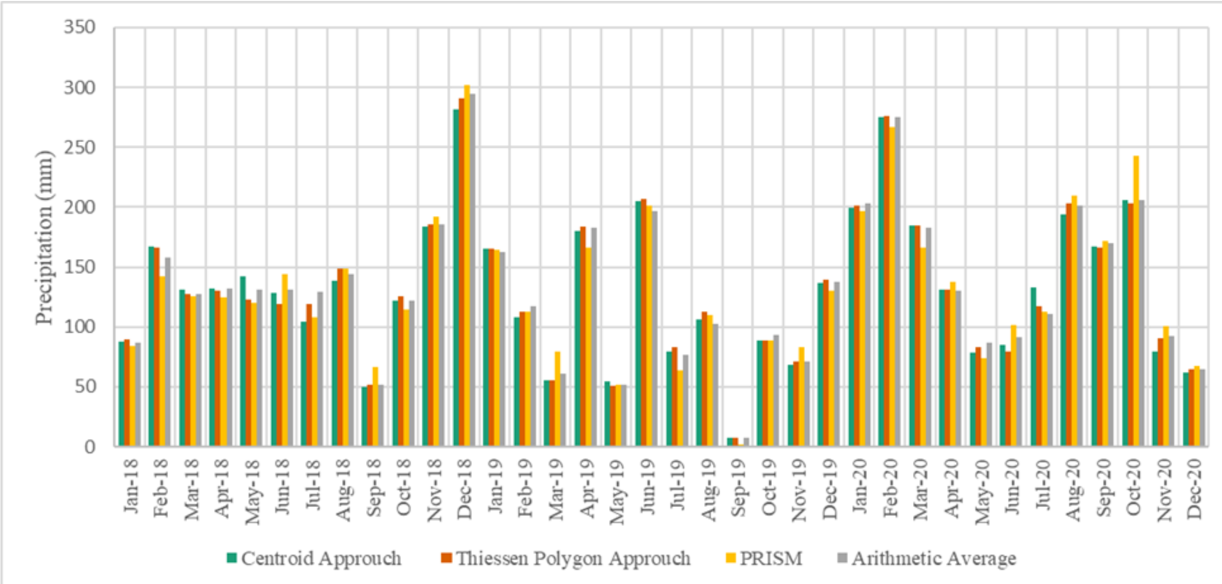

Figure 9: Precipitation estimates calculated via the Thiessen polygon approach, centroid based approach, arithmetic average, and as generated by PRISM.

Table 2: Annual Precipitation Totals by Methodology (mm)

	Centroid Approach	Thiessen Polygon Approach	Arithmetic Average	Average of Methodologies	PRSIM
2018	1669	1677	1694	1680± 13 *SD*	1671
2019	1254	1277	1260	1264± 12*SD*	1255
2020	1797	1800	1815	1804± 10 *SD*	1847

**Note: SD= Standard Deviation*

4.2 Municipal Water:

Figures 10 and 11 illustrate that users within Dekalb County and the City of Atlanta constitute the largest demand for municipal water among the jurisdictions overlapped by the SRW. On average, users within those jurisdictions receive area-normalized depths of 95 mm ± 7.3 SD and 60 mm ± 1.6 SD per year, respectively. While Clayton County, Henry County, Rockdale County, and the cities of Hapeville and East Point exhibited average-area normalized depths roughly two orders of magnitude less, ranging from 0.156 mm ± 0.008 SD to 4.161 mm ± 0.122 SD per year. DeKalb County and the City of Atlanta make up for 50% and 40% of the total population of users within the SRW, while the remaining five jurisdictions make up for the last 10% of the population.

There is minimal seasonal variation in the area-normalized depth of water conveyed to users within the SRW (Figures 10 and 12). During the three warmest months of the year (June, July, and August) the average area-normalized depth of water was 12 mm per month. While during the three coldest months of the year (December, January, and February) the average area-normalized depth was 10 mm per month. This comparison is slightly skewed as the month of February has less days than the other observed months, and to account for that an average area-normalized depth was determined on a daily scale for both three-month periods. The warmest months exhibited an average area normalized depth of 0.39 mm/ day, while the coldest months exhibited a similar rate at 0.35 mm/ day.

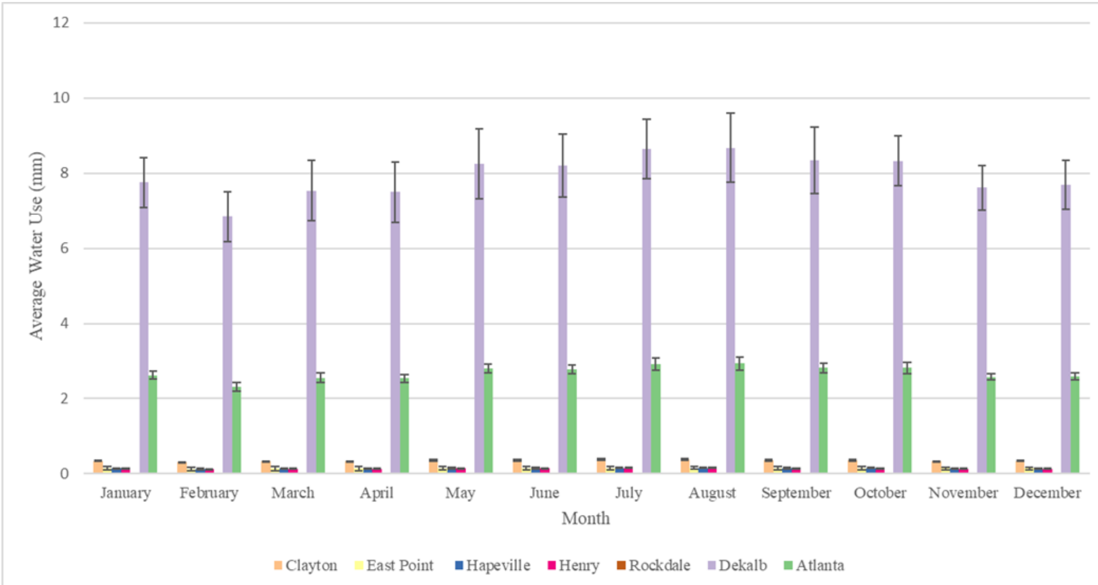

Figure 10: Average monthly water use for each contributing jurisdiction to the South River watershed for the time series 2011-2020. Water use is reported as an area normalized depth in millimeters by dividing by the total area of the SRW. Error bars represent ± 1

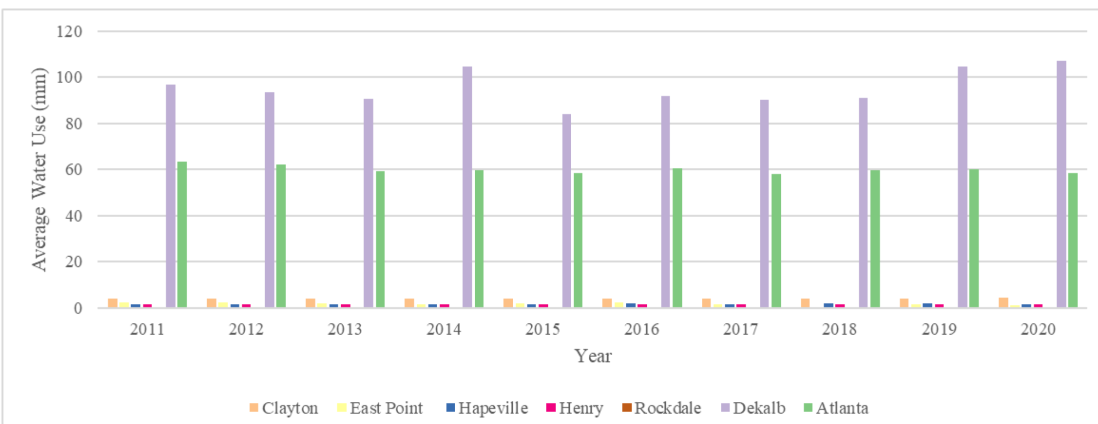

Figure 11: Average annual water use by consumers within the South River watershed for the time series 2011-2020. Values were determined through summation of the seven contributing jurisdictions and reported as an area normalized depth.

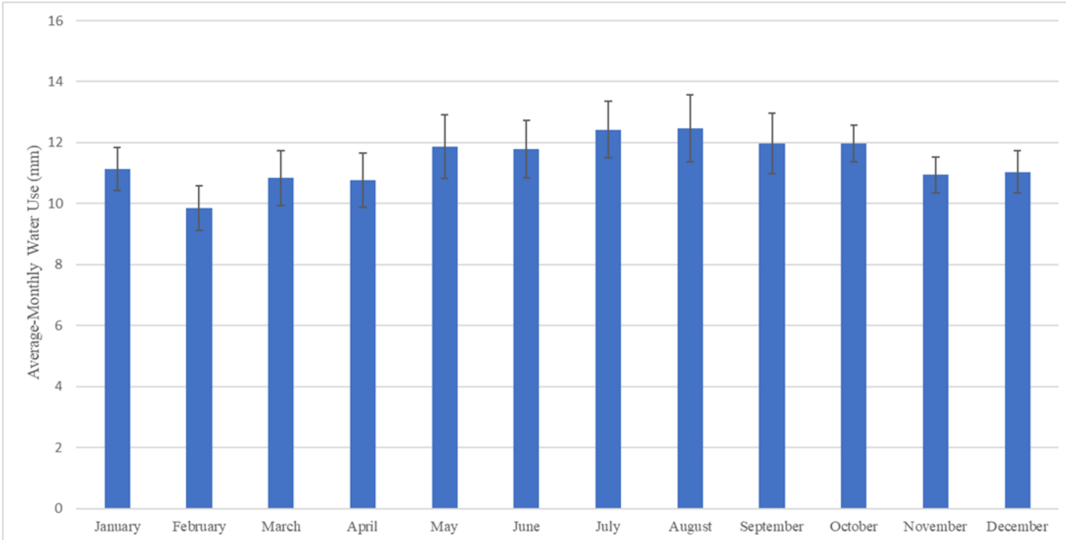

Figure 12: Average monthly water use by consumers within the South River watershed for the time series 2011-2020. Values were determined through summation of the seven contributing jurisdictions and reported as an area normalized depth. Error bars represent ± 1.

Total municipal water brought into the SRW was calculated through the summation of the seven contributing jurisdictions. For the entire observed time series (2011-2020) the estimated water distributed to users within the SRW on an annual basis was, on average, 165 mm ± 7.6 SD. Calendar year 2015 displayed the lowest level of total water distributed to users at 151.66 mm ± 7.6 SD, while 2014, 2019, and 2020 exhibited the highest level of water distributed, ranging from 173.22 mm ± 7.6 SD to 174.43 mm ± 7.6 SD (Figure 13).

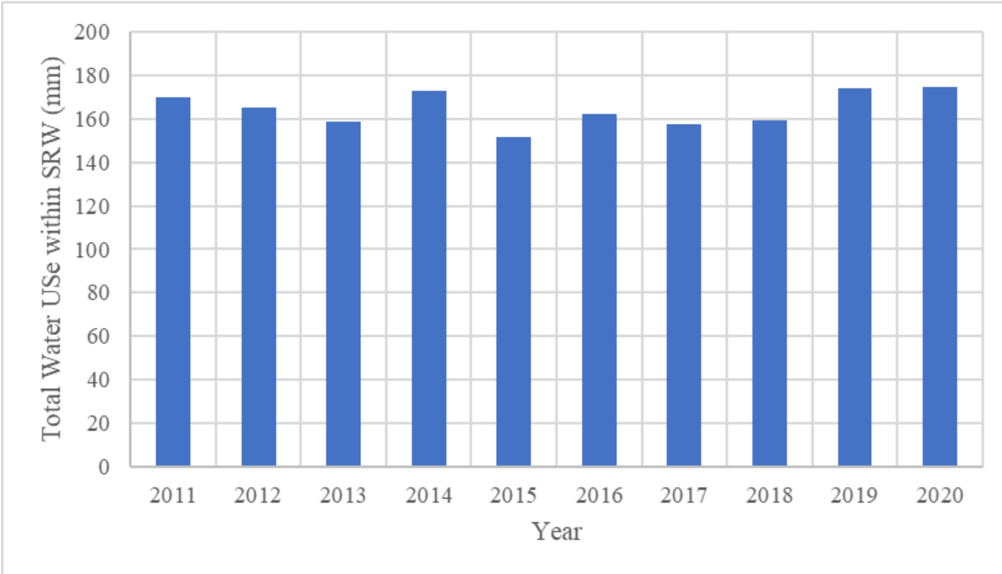

Figure 13: Total annual water usage for the South River watershed determined through the summation of the seven contributing jurisdictions for the years 2011-2020.

4.3 Leakage:

Estimated leakage from pipe infrastructure varied widely on an annual and monthly basis within the SRW (Figures 14 and 15). Average annual leakage throughout the SRW was calculated as 31.15 mm with a minimum value observed within the calendar year 2016 of 17.51 ± 8.80 SD. Maximum leakage during this time series was during the calendar year 2019 of 45.39 ± 8.80 SD. Leakage estimates are calculated using the ‘real losses’ provided by the Georgia EPD, which showed a large variation of potential leakage percentages, and did not seem to follow any particular trend.

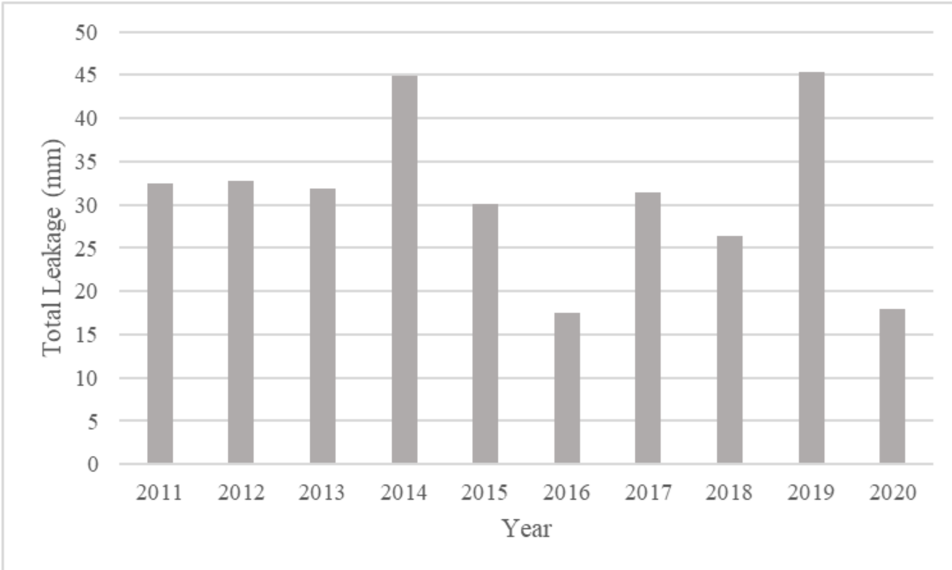

Figure 14: Total annual leakage for the South River watershed for the time series 2011-2020. Calculated from the seven contributing water jurisdictions and reported as an area normalized depth.

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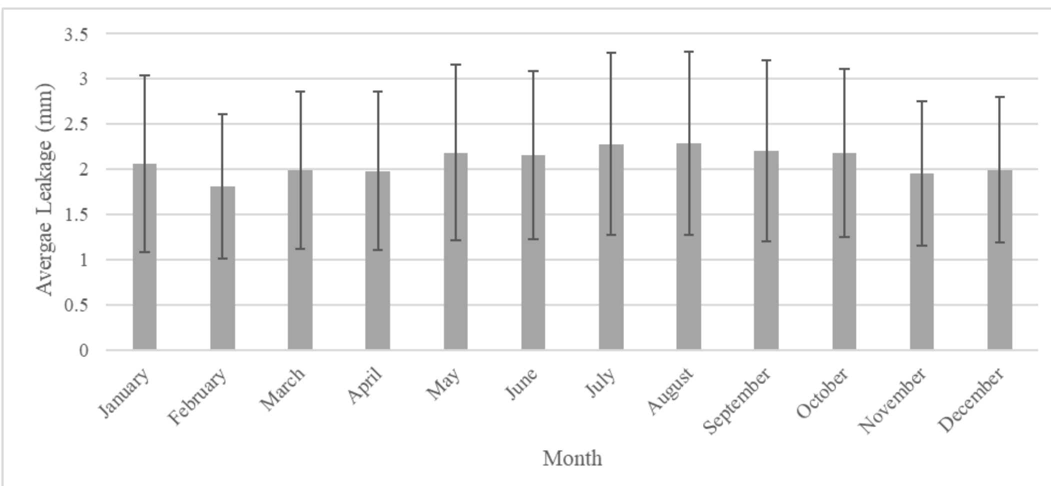

Figure 15: Average-monthly leakage of municipal water within the South River watershed (n = 10 years). Monthly totals include all seven contributing jurisdictions. Error bars represent ± 1 standard deviation around the mean.

Quantified volumes of inflows and estimated leakage rates were determined for the SRW for the 10-year period (2011-2020). Long term PRISM values yielded an average annual precipitation value of 1407 mm (± 317 SD). Average annual municipal water distributed to users within the SRW, representative of the IBT from the ACF basin to the AOO basin, was determined to be a value of 165 mm (± 8 SD). The associated leakage from the municipal supply system was estimated as an average annual value of 30 mm (± 9 SD). Comparative analysis of these components found that roughly 88% of the total inflow of water to the SRW was from precipitation, while municipal water only accounted for 10%, and leakage into the subsurface as an estimated 2% (Figure 16). When observing the fitted linear relationship between the PRISM precipitation data to the estimated municipal water conveyed to users within the SRW, there was minimal correlation shown between the two sets of values. The trend line equation was $(y = -0.0079x + 175.9)$ with and R2 value of 0.1106—suggesting little correlation.

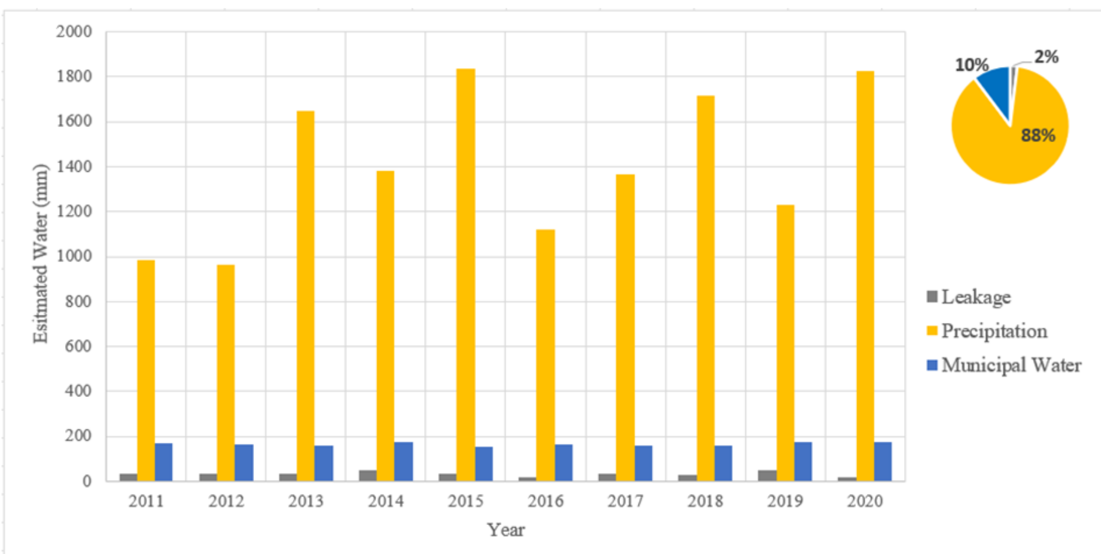

Figure 16: Comparative analysis of inflows into the South River watershed for the time series 2011-2020. Values are reported as area-normalized depth calculated by dividing each volume by the entire area of the SRW.

When divided by the entire area of the SRW to obtain an area-normalized depth, the IBT of municipal water and associated leakage into the landscape are relatively small in comparison to precipitation. In particular, leakage might seem like an almost negligible inflow term within the water budget for the SRW. Of course, the leakage does not occur across the entire watershed area, it only occurs where the pipes are buried. When normalizing the leakage flow by the vertically-projected area of the sewer pipes (as described in methodology section 3.3) produced an average-annual leakage of 32733 mm ± 1507 SD (Figure 17)—a significant increase in the area-normalized depth than when the flow is divided by the entire area of the SRW (Figure 16).

Alternatively, leakage was also calculated based on roadway area (as described in methodology section 3.3) the location of most municipal supply lines. Produced results are considerably greater than if of flows were divided by the entire watershed area, exhibiting an average area-normalized depth of 1282 mm ± 60 SD. Comparison of the vertically projected roadway area leakage with precipitation shows that on this scale, leakage is on par with the depth of precipitation that falls within the watershed (Figure 18). Depth of area-normalized leakage surpasses precipitation in of the four years out of the total ten-year study period (Figure 18).

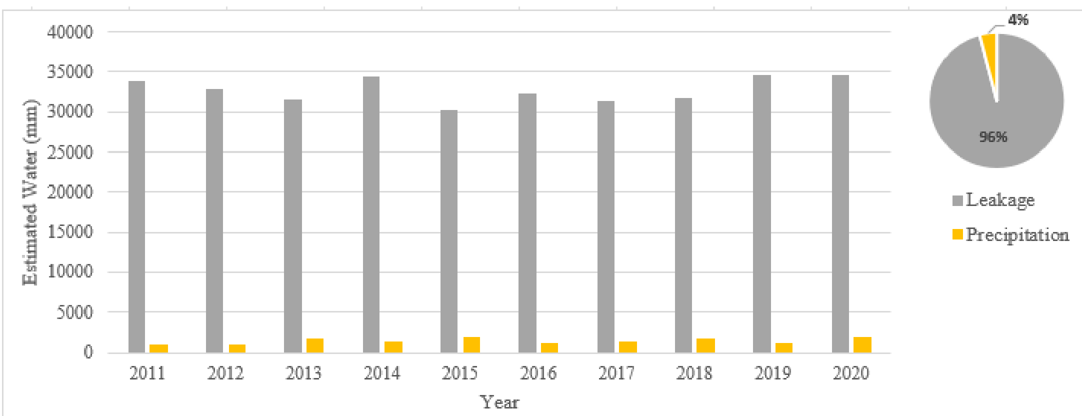

Figure 17: Comparative analysis of inflows into the South River watershed for the time series 2011-2020. Values are reported as area-normalized depth. Precipitation volume was divided by the entire area of the SRW over which it falls. In this figure, the leakage

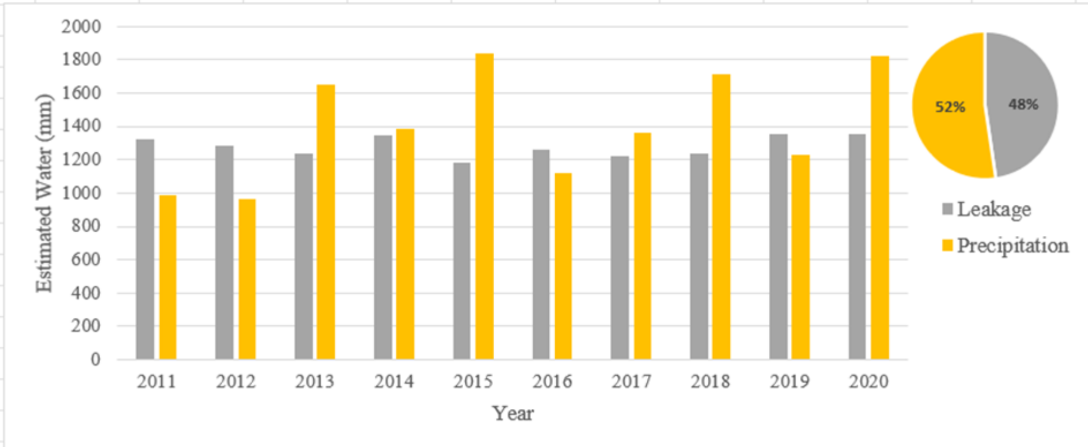

Figure 18: Comparative analysis of precipitation and leakage within the South River watershed for the time series 2011-2020. Precipitation volume was divided by the entire area of the SRW over which it falls. In this figure, the leakage volumes were divided by t the projected-vertical area of road surfaces within the SRW—that area being more realistically representative of the surface areas over which this inflow may occur.

5 DISCUSSION

Water budgets are useful frameworks for water management in urban and suburban watersheds [e.g., Mitchell et al., 2001; Mitchell et al., 2003; Mitchell 2006; Mitchell et al., 2008; particularly as continued population growth and water consumption within major metropolitan areas increases. Accurate conceptualization and quantification of inflows within urban and suburban watersheds is of foremost importance in water budget analysis. This research illustrates some of the inherent complexities of the task, which requires understanding of both the political-jurisdictional and physical environment.

5.1 Spatially Averaged Precipitation within Urban/Suburban Southeastern Watersheds:

Constructed infrastructure within urban watersheds can influence precipitation dynamics (Freitag and Nyiogi 2018) by altering wind patterns and turbulent heat transport from land to atmosphere. In the Piedmont physiographic province of the southeastern U.S., additional spatial variability in rainfall accumulation may result due to localized convective storms. Despite these alterations, at monthly and annual time series, no systematic spatial patterns in precipitation were observed at the watershed spatial scale with a Moran's I value of 0.072. As a measure of spatial autocorrelation, or how alike values are across a specified area, a Moran' s I value near zero, represents a random distribution or no correlation among values. Results are similar to those of (Zhang et al., 2018) who reported Moran's I values ranging from 0.003 to 0.292 for a 132-km^2 catchment in Southwest England. Authors from that study emphasized the importance of not only the variation of rainfall values, but also the spatial distribution across the study area particularly for 'complex precipitation events' (Zhang et al., 2018).

Across 100-km^2 spatial scales within the southeastern Piedmont, our results support the conclusion that the arithmetic average of discrete precipitation measurements is sufficient to calculate monthly and annual totals of precipitation. The calculated totals are not markedly different than those derived from interpolation schemes that assume an underlying correlation structure. Our results provide further empirical validation of the utility of PRISM precipitation estimates for this region.

Results reflect values reported within work by (Daly et al., 2017) which found that in comparing ground-based rain gauge derived values to that of PRISM derived values at the ~ 4 km spatial scale within the Coweeta basin, located in western North Carolina, that there was a less than 5% difference between mean annual gridded values for the period 1950-1958. General trends across the watershed were reflected within both the PRISM derived gridded values and the ground-based rain gauge values with a southeast-northwestern trend in precipitation and similar minimum and maximums. Spatial trends were not observed within either the PRISM-derived precipitation estimates, or the ground-based precipitation estimates for the SRW.

Work by (Prat and Nelson 2014) found similar results across the continuous U.S., on a daily, seasonal, and annual temporal resolution, where PRISM-derived precipitation estimates, and ground-based GHCN-D derived precipitation estimates were compared and used as a baseline against remotely sensed precipitation estimates from 2002-2012. The PRISM derived precipitation estimates do utilize observations from GHCN-D, but also the National Weather Service Cooperative Observer Program (COOP), Weather Bureau Army Navy (WBAN) stations, USGS, USDA NRCS Snow Telemetry (SNOTEL), USDA Forest Service, and other climate tracking agencies (Daly et al., 2008). Daily precipitation rates for the ground-based GHCN-D derived values and PRISM derived precipitation values were 2.47 and 2.42-mm day^{-1} respectively. Only a 2-3% difference in average rain rate was observed, regardless of season, and on an annual temporal scale 4%, suggesting a good agreement between the ground-based

GHCN-D precipitation values and the estimated PRISM derived precipitation values (Prat and Nelson 2014). While most comparative studies have reported low error values between ground-based rain gauge estimations and PRISM derived precipitation estimates, some like (Zhang et al., 2018) have found that the 4 km resolution PRISM gridded estimates could overpredict by as much as 30% when compared to annual precipitation derived from the Florida Automated Weather Network (FAWN) over the years 2011-2015. Data from the FAWN station network was added to the PRISM analysis in October 2015 (Daly et al., 2013), near the end of the study period. That coupled with the FAWN network having a spatial density of one station for every 5000 km^2, or 34 ground-based gauges, may account for this larger discrepancy between the FAWN network precipitation estimates and the PRISM derived precipitation estimates. Within this study, a denser gauge network was available for estimating areal-averaged precipitation on a smaller spatial scale which allowed for a more accurate depiction of ground-based precipitation estimation within the SRW. Estimated PRISM derived precipitation estimates did not vary significantly from the ground-based precipitation estimates—a finding consistent with most research utilizing PRISM derived data within hydrology.

Works by (Bornstein and Lin 2000; Dixon and Mote 2003; Shepard et al., 2003; Diem and Mote 2005; Diem 2008) have found that precipitation and surface temperatures around the Atlanta metropolitan region has experienced alteration due to urban influences. This research did not find any spatial distribution pattern within the ground-based precipitation data and instead determined that a spatial average would be sufficient for short term comparison to the PRISM derived precipitation data and use within the conceptualized water budget. In work from Hewlett and Hibbert (1967), the more topologically complex terrain of the Coweeta basin, located within the Blue Ridge physiographic province, was reported as having mean-annual precipitation of

1829 mm. They did not critically examine spatial variability, although Daly et al. (2017) found a strong dependence of mean annual precipitation totals on elevation within the Coweeta Basin. The watershed is located on the leeward side of a mountain range with elevations ranging from 675 to 1592 m from the northeast to the southwestern ridgeline with associated mean annual precipitation of 1500 mm to 2400 mm (Daly et al., 2017). In localities with complex topographical changes, it may be argued that a mean annual precipitation value may not be representative of the whole watershed, but work by Volkmann et al. (2010) found that in a semi-arid 91-km^2 catchment located near Tucson Arizona, a sparse but optimized rain gauge network produced an adequate rainfall estimate for the catchment versus the denser network thought to be needed. Elevations within the SRW only range from 203m to 339m— a 136m elevation change versus the 917m elevation change observed within the Coweeta basin. At the observed spatial scale, the SRW was not considered a steep locality, and the resulting average annual precipitation values are representative of the overall watershed inflow within this conceptualized water budget.

5.2 Inter-Basin Transfers Represent Complex Net Fluxes:

To compensate for growing populations many cities have turned to outside sources to mitigate the difference in needed water supply. With cities like Los Angeles obtaining over 90% of their water from IBT's (Ashoori et al. 2015) it is appropriate to address them alongside other components of urban water budgets to connect and contextualize these flows to the broader hydrologic cycle. Quantification and tracking of water resources within a water budget framework holds value for future water management authorities and regulatory policies.
What may be simplified to a singular inflow within a conceptualized water budget, IBTs are representative of complex net fluxes and multiple constituent flows. The SRW exemplifies this

complexity as seven different jurisdictions contribute approximately 165 mm of water to users annually. Quantifying jurisdictional volumes distributed to users proved challenging as water management authorities vary greatly in their data monitoring and recording practices that are often dictated by political boundaries rather than physical watershed boundaries. Intricacy of these transfers are exemplified further within Figure 5, which illustrates that wastewater from the Atlanta Hartsfield-Jackson Airport and the cities of East Point, Hapeville, and College Park is pumped into the AOO basin, treated at the South River Reclamation Center, before being pumped back into the ACF basin. This transfer of water should in theory be a closed loop, but pipe leakage from aging infrastructure may potentially leak into the subsurface of the broader hydrologic system a phenomenon documented in works by (e.g., Lerner 1986; Lerner 1990; Barrett et al., 1999; Lerner 2002).

In the SRW, the volume of leaked potable water ultimately represents a relatively small inflow in the overall water budget—a qualitative result that may reasonably transfer to other American metropolitan areas with similar climate. When estimated over the entire watershed area, the volume of water leaking from the man-made infrastructure only accounts for 2% of the total inflows. This inflow was lesser than reported by (Bhaskar and Wely 2012) which determined the sum of supply pipe leakage to be roughly 11-20 mm per month or 14% of the total watershed inflows for the city of Baltimore Maryland. These area-normalized depths are calculated by dividing the volume of leakage by the entire watershed area, as is conventionally done when converting streamflow volume to an area-normalized depth. The latter calculation is logical because the entire watershed area receives precipitation and can convey some portion of that precipitation to the stream or river. However, the leakage of potable water does not occur over the entire watershed area. It occurs only where there are pipes. Dividing the volume of leakage by the entire watershed area yields a small area-normalized depth in this case that potentially belies the relevance of this flow process.

We attempted to characterize the localized hydrological impact of potable-water leakage by computing two alternative estimates of the area-normalized depth—each invoking an assumed, approximate area over which the leakage actually happens. When assuming the leakage occurs only over roadway areas, the localized water depth accounts for 48% of all inflow over that area (Figure 19). When estimated based on the vertically projected area of sanitary-sewer pipes (a proxy for the unknown vertically projected area of potable-water pipes), leakage accounted for 96% of the inflows over that area (Figure 18). Considering the former estimate conservatively low, these results imply that areas where leakage is occurring are receiving almost double the volume of water as the remainder of the watershed area.

The multitude of engineered supply lines and drainage networks not only have the potential to introduce additional water into the sub-surface, but they also create dynamic flow pathways of macro-pores surrounding the pipped infrastructure known as 'urban karst' (Kaushal and Belt 2012). These preferential pathways of high hydraulic conductivity material surrounding the piped infrastructure, such as gravel or coarse-grained sand, act as megapores for water to easily move through the sub-surface creating connectivity within the upper portion of urban headwaters (Meriano et al., 2011; Sharp et al., 2013; Bonneau et al., 2017). Pathways created around the piped infrastructure alters the way groundwater contributes to streamflow. This occurs by creating new discharge points versus the 'natural' discharge point that would occur without human infrastructure (Bonneau et al., 2017). Leakage may involve latent, chronic seeps that contribute water and solutes to these preferential pathways, potentially modulating the temporal dynamics and chemistry of urban baseflow. Leakage also occurs as episodic, catastrophic events that may cause sinkholes and substantial overland flow until the leak is repaired. Especially in the latter case, leakage can essentially be conceived as an episodic expansion of the infrastructure-mediated channel network (Kaushal and Belt, 2012). More research is necessary to accurately quantify how leakage of pressurized potable water can locally impact the hydrology, solute chemistry, and morphology of urban streams.

6 CONCLUSION

Political-jurisdictional and physical environmental boundaries rarely align within urbanized settings. This research demonstrates the complexity of quantifying conceptualized inflows within an urban-suburban water budget framework. Precipitation was quantified through three interpolation schemes and compared to long-term annual PRISM data. Results demonstrate that for the studied Piedmont watershed, that an annual average would be sufficient for the 100 km^2 spatial scale due to the relatively consistent elevation across the study area. Inter-basin transfers have been inventoried for the U.S., but few studies have looked at the volumes of water transferred and the potential impacts that may have on the recipient watershed. Within this research the transfer of water from the ACF basin to the South River watershed within DeKalb County and the broader AOO basin was quantified as an area-normalized 95 mm ±7.3 SD. This transfer represents over 58% of the total watershed's municipal inflows while the city of Atlanta makes up the other major component, at 36%. Quantifying this transfer and the other contributing jurisdictions municipal volumes was challenging as water management authorities vary greatly in their monitoring and data recording practices— which is primarily defined by political boundaries versus watershed boundaries.

Aging infrastructure has the potential to impact the broader hydrologic cycle through leakage, a conceptualized inflow investigated within this research. Analyzed over the entire watershed are, leakage is a relatively small inflow, but when area-normalized to a more realistic vertically projected area leakage can account for more than 96% of the total inflows. This leakage can impact the broader hydrologic system of the localized urban environment, but also the greater downstream tributaries. Results reported within this study hold significance to water managements authorities and future water management policies. Population growth and concentrated movement towards urban centers has impacted the way water flows within cities and understanding these changes in urban environments is necessary as climate change continues to alter the world around us.

REFERENCES

American Association of State Highway and Transportation Officials. (2001). *AASHTO Green: A Policy on Geometric Design of Highways and Streets*. http://archive.org/details/gov.law.aashto.green.2001

Ashoori, N., Dzombak, D. A., & Small, M. J. (2017). Identifying water price and population criteria for meeting future urban water demand targets. *Journal of Hydrology*, *555*, 547–556. https://doi.org/10.1016/j.jhydrol.2017.10.047

Aulenbach, B. T., & Peters, N. E. (2018). Quantifying Climate-Related Interactions in Shallow and Deep Storage and Evapotranspiration in a Forested, Seasonally Water-Limited Watershed in the Southeastern United States. *Water Resources Research*, *54*(4), 3037–3061. https://doi.org/10.1002/2017WR020964

Bach, P.M., Rauch, W., Mikkelsen, P.S., McCarthy, D.T., and Deletic, A. (2014). A critical review of integrated urban water modeling--Urban drainage and beyond, *Environmental Modeling and Software*, *54*, p. 88-107.

Baik, J.-J., Kim, Y.-H., & Chun, H.-Y. (2001). Dry and Moist Convection Forced by an Urban Heat Island. Journal of Applied Meteorology, 40(8), 1462–1475. https://doi.org/10.1175/1520-0450(2001)040<1462:damcfb>2.0.co;2

Balling, R. C., & Cerveny, R. S. (1987). Long-Term Associations between Wind Speeds and the Urban Heat Island of Phoenix, Arizona. *Journal of Climate and Applied Meteorology*, *26*(6), 712–716.

Barrett, M. H., Hiscock, K. M., Pedley, S., Lerner, D. N., Tellam, J. H., & French, M. J. (1999). Marker species for identifying urban groundwater recharge sources: A review and case study in Nottingham, UK. *Water Research*, *33*(14), 3083–3097. https://doi.org/10.1016/S0043-1354(99)00021-4

Belda, M., Holtanová, E., Halenka, T., & Kalvová, J. (2014). Climate classification revisited: from Köppen to Trewartha. Climate research, 59(1), 1-13.

Bhaskar, A. S., & Welty, C. (2012). Water Balances along an Urban-to-Rural Gradient of Metropolitan Baltimore, 2001-2009 [Article]. Environmental & Engineering Geoscience, 18(1), 37-50. https://doi.org/10.2113/gseegeosci.18.1.37

Bonneau, J., Fletcher, T. D., Costelloe, J. F., & Burns, M. J. (2017). Stormwater infiltration and the ‘urban karst’ – A review. *Journal of Hydrology*, *552*, 141–150. https://doi.org/10.1016/j.jhydrol.2017.06.043

Bornstein, R. and M. LeRoy. 1990. Urban barrier effects on convective and frontal thunderstorms. Extended Abstracts, Fourth Conf. on Mesoscale Processes, Boulder, CO, Amer. Meteor. Soc., 120–121

Bornstein, R., & Lin, Q. (2000). Urban heat islands and summertime convective thunderstorms in Atlanta: Three case studies. *Atmospheric Environment*, *34*(3), 507–516. https://doi.org/10.1016/S1352-2310(99)00374-X

Bureau, U. S. C. (2022, July 8). Urban Areas Facts. The United States Census Bureau. https://www.census.gov/programs-surveys/geography/guidance/geo-areas/urban-rural/ua-facts.html.

Bureau, U.S. C. (n.d.). State of US Population and Death Statistics| 2021 State of the Union Facts. USAFacts. Retrieved January 3, 2022, from https://usafacts.org/state-of-the-union/population/

Cao, Y. S., Tang, J. G., Henze, M., Yang, X. P., Gan, Y. P., Li, J., Kroiss, H., van Loosdrecht, M. C. M., Zhang, Y., & Daigger, G. T. (2019). The leakage of sewer systems and the impact on the 'black and odorous water bodies' and WWTPs in China. Water Science and Technology, 79(2), 334–341. https://doi.org/10.2166/wst.2019.051

COCORAHS: The Community Collaborative Rain, Hail and Snow Network. (n.d.). COCORAHS: The Community Collaborative Rain, Hail and Snow Network. Retrieved September 28, 2021, from https://media.cocorahs.org/docs/CoCoRaHSBrochure15FINAL.pdf

CoCoRaHS Data Quality Control. (2021). CoCoRaHS - Community Collaborative Rain, Hail & Snow Network. https://www.cocorahs.org/content.aspx?page=aboutqc

Cole, D. "Scott," & Carver, W. (2011, April 11). INTERBASIN TRANSFERS OF WATER. *Proceedings of the 2011 Georgia Water Resources Conference*. 2011 Georgia Water Resources Conference, University of Georgia. https://www.gwri.gatech.edu/sites/default/files/files/docs/2011/3.5.4Cole.pdf

Changnon, S. A. (1981). Impacts of Urban Modified Precipitation Conditions. In Metromex: A Review and Summary (pp. 153–177). American Meteorological Society. https://doi.org/10.1007/978-1-935704-29-4_8

Daly, C., Neilson, R. P., & Philips, D. L. (1993). *A Statistical-Topographic Model for Mapping Climatological Precipitaion over Mountainous Terrian*. *33*, 19.

Daly, C., G. Taylor, and W. Gibson. 1997. The PRISM approach to mapping precipitation and temperature. 10th AMS Conf. on Applied Climatology, Reno, NV, 10-12.

Daly, C., Halbleib, M., Smith, J. I., Gibson, W. P., Doggett, M. K., Taylor, G. H., Curtis, J., & Pasteris, P. P. (2008). Physiographically sensitive mapping of climatological temperature and precipitation across the conterminous United States. *International Journal of Climatology*, *28*(15), 2031–2064. https://doi.org/10.1002/joc.1688

Daly, C., 2013. *Descriptions of PRISM spatial climate datasets for the conterminous United States* [online]. PRISM Doc. Available from: http://www.prism.oregonstate.edu/documents/PRISM_datasets_aug2013.pdf

Daly, C., Slater, M. E., Roberti, J. A., Laseter, S. H., & Swift, L. W. (2017). High-resolution precipitation mapping in a mountainous watershed: Ground truth for evaluating uncertainty in a national precipitation dataset: HIGH-RESOLUTION PRECIPITATION MAPPING IN A MOUNTAINOUS WATERSHED. *International Journal of Climatology*, *37*, 124–137. https://doi.org/10.1002/joc.4986

Debbage, N., & Shepherd, J. M. (2018). The Influence of Urban Development Patterns on Streamflow Characteristics in the Charlanta Megaregion [Article]. Water Resources Research, 54(5), 3728-3747. https://doi.org/10.1029/2017wr021594

Dekalb County. (2019). Watershed Management. Watershed Management | DeKalb County, GA. https://www.dekalbcountyga.gov/watershed-management/watershed-management.

Dickson, K. E., & Dzombak, D. A. (2017). Inventory of Interbasin Transfers in the United States. Journal of the American Water Resources Association, 53(5), 1121-1132. https://doi.org/10.1111/1752-1688.12561

Diem, J.E., Hill, T.C., and Milligan, R.A., 2017, Diverse multi-decadal changes in streamflow within a rapidly urbanizing region, *Journal of Hydrology*, *556*, p. 61-71.

Diem, J.E. 2008. Detecting summer rainfall enhancement within metropolitan Atlanta, Georgia USA. International Journal of Climatology 28:129–133.

Diem, J. E., & Mote, T. L. (2005). Interepochal Changes in Summer Precipitation in the Southeastern United States: Evidence of Possible Urban Effects near Atlanta, Georgia. *Journal of Applied Meteorology (1988-2005)*, *44*(5), 717–730.

Dinar, A., 1998. Water policy reforms: Information needs and implementation obstacles. Water Policy, 1(4): 367–382.

Dieter, C.A., Maupin, M.A., Caldwell, R.R., Harris, M.A., Ivahnenko, T.I., Lovelace, J.K., Barber, N.L., and Linsey, K.S., 2018, Estimated use of water in the United States in 2015: U.S. Geological Survey Circular 1441, 65 p., https://doi.org/10.3133/cir1441.

Dixon, P. G., & Mote, T. L. (2003). Patterns and Causes of Atlanta's Urban Heat Island–Initiated Precipitation. *Journal of Appplied Meterorology*, *42*. https://doi.org/10.1175/1520-0450(2003)042%3C1273:PACOAU%3E2.0.CO;2

Dou, J., Wang, Y., Bornstein, R., & Miao, S. (2014). Observed Spatial Characteristics of Beijing Urban Climate Impacts on Summer Thunderstorms in: Journal of Applied Meteorology and Climatology Volume 54 Issue 1 (2015). *JOURNAL OF APPLIED METEOROLOGY AND CLIMATOLOGY*, *54*. https://doi.org/10.1175/JAMC-D-13-0355.1

Duan, K., Caldwell, P. V., Sun, G., McNulty, S. G., Zhang, Y., Shuster, E., … Bolstad, P. V. (2019). Understanding the role of regional water connectivity in mitigating climate change impacts on surface water supply stress in the United States. Journal of Hydrology, 570, 80–95. https://doi.org/10.1016/j.jhydrol.2019.01.011

Falkenmark, M., & Widstrand, C. (1992). Population and Water Resources: A Delicate Balance. 47(3).

Florida v. Georgia, 142 U.S. Supreme Court (2019)

Freitag, B. M., Nair, U. S., & Niyogi, D. (2018). Urban Modification of Convection and Rainfall in Complex Terrain. *Geophysical Research Letters*, *45*(5), 2507–2515. https://doi.org/10.1002/2017GL076834

Gallo, K. P., & Owen, T. W. (1999). Satellite-Based Adjustments for the Urban Heat Island Temperature Bias. Journal of Applied Meteorology, 38(6), 806–813. https://doi.org/10.1175/1520-0450(1999)038<0806:SBAFTU>2.0.CO;2

Golley, F. B. (2004). Piedmont Geographic Region. In New Georgia Encyclopedia. Retrieved Jul 26, 2017, from https://www.georgiaencyclopedia.org/articles/geography-environment/piedmont-geographic-region/

Graham, G.S., 1976. Urban water resources modelling, M.Eng.Sc. thesis, Monash University, Australia.

Grimmond, C. S. B., Oke, T. R., & Steyn, D. G. (1986). Urban Water Balance: 1. A Model for Daily Totals. Water Resources Research, 22(10), 1397-1403. https://doi.org/https://doi.org/10.1029/WR022i010p01397

Gupta, J., & van der Zaag, P. (2008). Interbasin water transfers and integrated water resources management: Where engineering, science and politics interlock. Physics and Chemistry of the Earth, Parts A/B/C, 33(1), 28-40. https://doi.org/https://doi.org/10.1016/j.pce.2007.04.003

Heath, R. C., 1984, Groundwater Regions of the United States: U.S. Geological Survey Water Supply Paper 2242, 78 p.

Hevesi, J. A., & Johnson, T. D. (2016). Estimating spatially and temporally varying recharge and runoff from precipitation and urban irrigation in the Los Angeles Basin, California. In Estimating spatially and temporally varying recharge and runoff from precipitation and urban irrigation in the Los Angeles Basin, California (USGS Numbered Series No. 2016–

5068; Scientific Investigations Report, Vols. 2016–5068, p. 208). U.S. Geological Survey. https://doi.org/10.3133/sir20165068

Haining, R. P. (2001). Spatial Autocorrelation. In N. J. Smelser & P. B. Baltes (Eds.), International Encyclopedia of the Social & Behavioral Sciences (pp. 14763–14768). Pergamon. https://doi.org/10.1016/B0-08-043076-7/02511-0

Hewlett, J., & Hibbert, A. (1967). Factors Affecting the Response of Small Watersheds to Precipitation in Humid Areas. *Forest Hydrology*, 275–290.

Jefferson, A. (2019, February 6). *Measuring precipitation: Radar and satellite-based measurements*. https://all-geo.org/jefferson/measuring-precipitation-radar-and-satellite-based-measurements/

Karl, T. R., & Knight, R. W. (1998). Secular Trends of Precipitation Amount, Frequency, and Intensity in the United States. *Bulletin of the American Meteorological Society*, *79*(2), 231–242. https://doi.org/10.1175/1520-0477(1998)079<0231:STOPAF>2.0.CO;2

Kaushal, S. S., & Belt, K. T. (2012). The urban watershed continuum: Evolving spatial and temporal dimensions. *Urban Ecosystems*, *15*(2), 409–435. https://doi.org/10.1007/s11252-012-0226-7

Kokkonen, T.V., Grimmond, C.S.B., Christen, A., Oke, T.R., and Jarvi, L., 2018, Changes to the water balance over a century of urban development in two neighborhoods: Vancouver, Canada, *Water Resources Research*, *54,* p. 6625-6642.

Lanza, L. G., & Stagi, L. (2009). High resolution performance of catching type rain gauges from the laboratory phase of the WMO Field Intercomparison of Rain Intensity Gauges. *Atmospheric Research*, *94*(4), 555–563. https://doi.org/10.1016/j.atmosres.2009.04.012

Lerner, D. N. (2002). Identifying and quantifying urban recharge: a review [Article]. Hydrogeology Journal, 10(1), 143-152. https://doi.org/10.1007/s10040-001-0177-1

Lerner, D. N., & Barrett, M. H. (1996). Urban Groundwater Issues In The United Kingdom. Hydrogeology Journal, 4(1), 80–89. https://doi.org/10.1007/s100400050096

Lerner D. N. (1990) Groundwater recharge in urban areas. Atmos Environ 24B(1):29–33

Lerner, D. N. (1986). Leaking Pipes Recharge Ground Water. 24(5), 654–662. https://doi.org/10.1111/j.1745-6584.1986.tb03714.x

Li, Y., Xiong, W., Zhang, W., Wang, C., & Wang, P. (2016). Life cycle assessment of water supply alternatives in water-receiving areas of the South-to-North Water Diversion Project in China. *Water Research*, *89*, 9–19. https://doi.org/10.1016/j.watres.2015.11.030

Li, W., A. Sankarasubramanian, R.S. Ranjithan, and E.D. Brill, 2014. Improved Regional Water Management Utilizing Climate Forecasts: An Interbasin Transfer Model with a Risk Management Framework. Water Resources Research 50(8):6810-6827. https://doi.org/10.1002/2013WR015248.

Litvak, E., Manago, K. F., Hogue, T. S., & Pataki, D. E. (2017). Evapotranspiration of urban landscapes in Los Angeles, California at the municipal scale. Water Resources Research, 53(5), 4236–4252. https://doi.org/10.1002/2016WR020254

Manago, K. F., & Hogue, T. S. (2017). URBAN STREAMFLOW RESPONSE TO IMPORTED WATER AND WATER CONSERVATION POLICIES IN LOS ANGELES, CALIFORNIA [Article]. Journal of the American Water Resources Association, 53(3), 626-640. https://doi.org/10.1111/1752-1688.12515

McDonald, R. I., Weber, K., Padowski, J., Florke, M., Schneider, C., Green, P. A., Gleeson, T., Eckman, S., Lehner, B., Balk, D., Boucher, T., Grill, G., & Montgomery, M. (2014). Water on an urban planet: Urbanization and the reach of urban water infrastructure

[Article]. Global Environmental Change-Human and Policy Dimensions, 27, 96-105. https://doi.org/10.1016/j.gloenvcha.2014.04.022

McDonald, R. I., Green, P., Balk, D., Fekete, B. M., Revenga, C., Todd, M., & Montgomery, M. (2011a). Urban growth, climate change, and freshwater availability. Proceedings of the National Academy of Sciences, 108(15), 6312–6317. https://doi.org/10.1073/pnas.1011615108

McDonald, R. I., Douglas, I., Revenga, C., Hale, R., Grimm, N., Grönwall, J., & Fekete, B. (2011b). Global Urban Growth and the Geography of Water Availability, Quality, and Delivery. AMBIO, 40(5), 437–446. https://doi.org/10.1007/s13280-011-0152-6

McLeod, J., Shepherd, M., & Konrad, C. E. (2017). Spatio-temporal rainfall patterns around Atlanta, Georgia and possible relationships to urban land cover. Urban Climate, 21, 27-42. https://doi.org/https://doi.org/10.1016/j.uclim.2017.03.004

Meriano, M., Howard, K. W. F., & Eyles, N. (2011). The role of midsummer urban aquifer recharge in stormflow generation using isotopic and chemical hydrograph separation techniques. *Journal of Hydrology*, *396*(1), 82–93. https://doi.org/10.1016/j.jhydrol.2010.10.041

Miller, J. A. (1990). HA 730-G Regional summary text. https://pubs.usgs.gov/ha/ha730/ch_g/G-text1.html.

Mennis, J. (2003). Generating Surface Models of Population Using Dasymetric Mapping. *Professional Geographer*, *55*(1), 31–42. Information Science & Technology Abstracts (ISTA).

Mitchell, V. G., H. A. Cleugh, C. S. B. Grimmond, and J. Xu (2008), Linking urban water balance and energy balance models to analyse urban design options, Hydrol. Process., 22(16), 2891-2900, doi:doi:10.1002/hyp.6868.

Mitchell, V. G. (2006), Applying integrated urban water management concepts: A review of Australian experience, *Environmental Management*, *37*(5), 589-605, doi:10.1007/s00267-004-0252-1.

Mitchell, V. G., T. A. McMahon, and R. G. Mein (2003), Components of the total water balance of an urban catchment, Environmental Management, 32(6), 735-746, doi:10.1007/s00267-003-2062-2.

Mitchell, V. G., R. G. Mein, and T. A. McMahon (2001), Modelling the urban water cycle, Environmental Modelling & Software, 16(7), 615-629, doi:https://doi.org/10.1016/S1364-8152(01)00029-9.

Missimer, T. M., Danser, P. A., Amy, G., & Pankratz, T. (2014). Water crisis: the metropolitan Atlanta, Georgia, regional water supply conflict. Water Policy, 16(4), 669–689. https://doi.org/10.2166/wp.2014.131

Nations, U. (2014, July 10). *More than half of world's population now living in urban areas, UN survey finds*. UN News Global Perspective Human Stories. https://news.un.org/en/story/2014/07/472752-more-half-worlds-population-now-living-urban-areas-un-survey-finds

Niemczynowicz, J. (1988). The rainfall movement — A valuable complement to short-term rainfall data. Journal of Hydrology, 104(1), 311-326. https://doi.org/https://doi.org/10.1016/0022-1694(88)90172-2

Niyogi, D., Lei, M., Kishtawal, C., Schmid, P., & Shepherd, M. (2017). Urbanization Impacts on the Summer Heavy Rainfall Climatology over the Eastern United States. Earth Interactions, 21(5), 1–17. https://doi.org/10.1175/ei-d-15-0045.1

NOAA. (n.d.). AHPS Precipitation Analysis. National Weather Service. Retrieved January 4, 2022, from https://water.weather.gov/precip/download.php

Official CoCoRaHS gauge. (2021). Weather Your Way: The Official Dealer for CoCoRaHs. https://weatheryourway.com/products/official-cocorahs-gauge

Oke, T. R. (1987). Boundary Layer Climates. 2d ed. Routledge, 435 pp.

Opalinski, N. F., Bhaskar, A. S., & Manning, D. T. (2019). Spatial and Seasonal Response of Municipal Water Use to Weather across the Contiguous U.S. JAWRA Journal of the American Water Resources Association, 56(1), 68–81. https://doi.org/10.1111/1752-1688.12801

ORSANCO (Ohio River Valley Water Sanitation Commission), 2014. Interbasin Transfers of the Ohio River Basin. http://www.orsanco.org/images/stories/files/miscPublications/Interbasin%20Transfers%20Report%20Jun15.pdf, accessed May 1.

Passarello, M. C., Sharp, J. M., JR, & Pierce, S. A. (2012). Estimating Urban-Induced Artificial Recharge: A Case Study for Austin, TX. *Environmental and Engineering Geoscience*, *18*(1), 25–36. https://doi.org/10.2113/gseegeosci.18.1.25

Postel, S. L., Daily, G. C., & Ehrlich, P. R. (1996). Human Appropriation of Renewable Fresh Water. Science, New Series, 271(5250), 785–788.

Petsch, H.E., 1985. Inventory of Interbasin Transfers of Water in the Western Conterminous United States. U.S. Geological Survey Open-File Report 85-166. http://pubs.usgs.gov/of/1985/0166/ report.pdf.

Prat, O. P., & Nelson, B. R. (2014). Characteristics of annual, seasonal, and diurnal precipitation in the Southeastern United States derived from long-term remotely sensed data. *Atmospheric Research*, *144*, 4–20. https://doi.org/10.1016/j.atmosres.2013.07.022

Petrov, A. (2012). One Hundred Years of Dasymetric Mapping: Back to the Origin. *The Cartographic Journal*, *49*(3), 256–264. https://doi.org/10.1179/1743277412Y.0000000001

Pincetl, S., Porse, E., Mika, K. B., Litvak, E., Manago, K. F., Hogue, T. S., Gillespie, T., Pataki, D. E., & Gold, M. (2019). Adapting Urban Water Systems to Manage Scarcity in the 21st Century: The Case of Los Angeles [Article]. Environmental Management, 63(3), 293-308. https://doi.org/10.1007/s00267-018-1118-2

PRISM Climate Group at Oregon State University. (n.d.). Retrieved February 3, 2022, from https://prism.oregonstate.edu/normals/

Purvis, L., & Dinar, A. (2020). Are intra- and inter-basin water transfers a sustainable policy intervention for addressing water scarcity? *Water Security*, *9*, 100058. https://doi.org/10.1016/j.wasec.2019.100058

Schroeder, L.A. and K.A. Woodcock, 2011. Turbid Waters: The Interaction between Interbasin Transfers and the Clean Water Act. Nevada Lawyer, January 2011.

Sevruk, B., & Zahlavova, L. (1994). Classification system of precipitation gauge site exposure: Evaluation and application. *International Journal of Climatology*, *14*(6), 681–689. https://doi.org/10.1002/joc.3370140607

Sevruk, B. (1996). Adjustment of tipping-bucket precipitation gauge measurements. Atmospheric Research, 42(1-4), 237–246. https://doi.org/10.1016/0169-8095(95)00066-6

Snaddon, C. D. (1999). *A Global overview of inter-basin water transfer schemes, with an appraisal of their ecological, socio-economic and socio-political implications, and recommendations for their management*. Water Research Commission.

Sherman, M. (2021, April 1). ABC news. https://abcnews.go.com/Business/wireStory/supreme-court-georgia-win-water-war-florida-76810945.

Sharp, J. M., Krothe, J. N., Mather, J. D., Gracia-Fresca, B., & Stewart, C. A. (2003). Effects of urbanization on groundwater systems. *Earth science in the city: A reader*, 257-278. doi:10.1029/SP056p0257.

Shepherd, J. M., & Burian, S. J. (2003). Detection of Urban-Induced Rainfall Anomalies in a Major Coastal City. Earth Interactions, 7(4), 1–17. https://doi.org/10.1175/1087-3562(2003)007<0001:DOUIRA>2.0.CO;2

Shepherd, J.M., 2005: A review of current investigations of urban-induced rainfall and recommendations for the future. Earth Interactions. Vol. 9. No. 12, 1–27.

Steiner, M., Smith, J. A., Burges, S. J., Alonso, C. V., & Darden, R. W. (1999). Effect of bias adjustment and rain gauge data quality control on radar rainfall estimation. *Water Resources Research*, *35*(8), 2487–2503. https://doi.org/10.1029/1999WR900142

Tavernia, B.G., M.D. Nelson, P. Caldwell, and G. Sun, 2013. Water Stress Projections for the Northeastern and Midwestern United States in 2060: Anthropogenic and Ecological Consequences. Journal of the American Water Resources Association 49(4):938- 952. https://doi.org/10.1111/jawr.12075.

Taylor, R. G., Scanlon, B., Döll, P., Rodell, M., van Beek, R., Wada, Y., Longuevergne, L., Leblanc, M., Famiglietti, J. S., Edmunds, M., Konikow, L., Green, T. R., Chen, J., Taniguchi, M., Bierkens, M. F. P., MacDonald, A., Fan, Y., Maxwell, R. M., Yechieli, Y., … Treidel, H. (2013). Ground water and climate change. Nature Climate Change, 3(4), 322–329. https://doi.org/10.1038/nclimate1744

Thiessen, A. H. (1911). PRECIPITATION AVERAGES FOR LARGE AREAS. Monthly Weather Review, 39(7), 1082–1089. https://doi.org/10.1175/1520-0493(1911)39<1082b:PAFLA>2.0.CO;2

US EPA. (2002). *Deteriorating Buried Infrastructure Management Challenges and Strategies* (p. 37). https://www.epa.gov/sites/default/files/2015-09/documents/2007_09_04_disinfection_tcr_whitepaper_tcr_infrastructure.pdf

US EPA, (2015, December 31). Urbanization—Hydrology [Data and Tools]. https://www.epa.gov/caddis-vol2/caddis-volume-2-sources-stressors-responses-urbanization-hydrology

Vahmani, P., & Hogue, T. S. (2015). Urban irrigation effects on WRF-UCM summertime forecast skill over the Los Angeles metropolitan area. Journal of Geophysical Research: Atmospheres, 120(19), 9869–9881. https://doi.org/10.1002/2015JD023239

Volkmann, Till, Lyon, S., Gupta, H., & Troch, P. (2010). Multicriteria design of rain gauge networks for flash flood prediction in semiarid catchments with complex terrain. *WATER RESOURCES RESEARCH*, *46*.

Water Efficiency and Water Loss Audits. (n.d.). Environmental Protection Division. Retrieved January 12, 2022, from https://epd.georgia.gov/watershed-protection-branch/water-efficiency-and-water-loss-audits

WATER AUDITS AND WATER LOSS CONTROL FOR PUBLIC WATER SYSTEMS. (n.d.). United States Environmental Protection Agency. https://www.epa.gov/sites/default/files/2015-04/documents/epa816f13002.pdf

Water-Use Terminology | U.S. Geological Survey. (n.d.). Retrieved June 29, 2022, from https://www.usgs.gov/mission-areas/water-resources/science/water-use-terminology

Welty, C. (2009). The Urban Water Budget. Springer, Boston, MA, 17–28. https://doi.org/10.1007/978-0-387-84891-4_2

Winchell, M., Gupta, H. V., & Sorooshian, S. (1998). On the simulation of infiltration- and saturation-excess runoff using radar-based rainfall estimates: Effects of algorithm uncertainty and pixel aggregation. *Water Resources Research*, *34*(10), 2655–2670. https://doi.org/10.1029/98WR02009

Wright, J. K. (1936). A Method of Mapping Densities of Population: With Cape Cod as an Example. *Geographical Review*, *26*(1), 103–110. JSTOR. https://doi.org/10.2307/209467

Yang, L., Feng, Q., Yin, Z., Deo, R. C., Wen, X., Si, J., & Liu, W. (2020). Regional hydrology heterogeneity and the response to climate and land surface changes in arid alpine basin, northwest China. CATENA, 187, 104345. https://doi.org/10.1016/j.catena.2019.104345

Zhang, J., Han, D., Song, Y., & Dai, Q. (2018). Study on the effect of rainfall spatial variability on runoff modelling. *Journal of Hydroinformatics*, *20*(3), 577–587. https://doi.org/10.2166/hydro.2018.129

Zhang, M., Leon, C. de, & Migliaccio, K. (2018). Evaluation and comparison of interpolated gauge rainfall data and gridded rainfall data in Florida, USA. *Hydrological Sciences Journal*, *63*(4), 561–582. https://doi.org/10.1080/02626667.2018.1444767

Zhuang, W. (2016). Eco-environmental impact of inter-basin water transfer projects: a review [Review]. Environmental Science and Pollution Research, 23(13), 12867-12879. https://doi.org/10.1007/s11356-016-6854-3