

Water supply, waste assimilation, and low-flow issues facing the Southeast Piedmont Interstate-85 urban archipelago

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Abstract

Rapidly growing cities along the Interstate-85 corridor from Atlanta, GA, to Raleigh, NC, rely on small rivers for water supply and waste assimilation. These rivers share commonalities including water supply stress during droughts, seasonally low flows for wastewater dilution, increasing drought and precipitation extremes, downstream eutrophication issues, and high regional aquatic diversity. Further challenges include rapid growth; sprawl that exacerbates water quality and infrastructure issues; water infrastructure that spans numerous counties and municipalities; and large numbers of septic systems. Holistic multi-jurisdiction cooperative water resource planning along with policy and infrastructure modifications is necessary to adapt to population growth and climate. We propose six actions to improve water infrastructure resilience: increase water-use efficiency by municipal, industrial, agricultural, and thermoelectric power sectors; adopt indirect potable reuse or closed loop systems; allow for water sharing during droughts but regulate inter-basin transfers to protect aquatic ecosystems; increase nutrient recovery and reduce discharges of carbon and nutrients in effluents; employ green infrastructure and better stormwater management to reduce nonpoint pollutant loadings and mitigate urban heat island effects; and apply the CRIDA framework to incorporate climate and hydrologic uncertainty into water planning.

KEYWORDS

climate variability/change, urban areas, water resources management, water supply

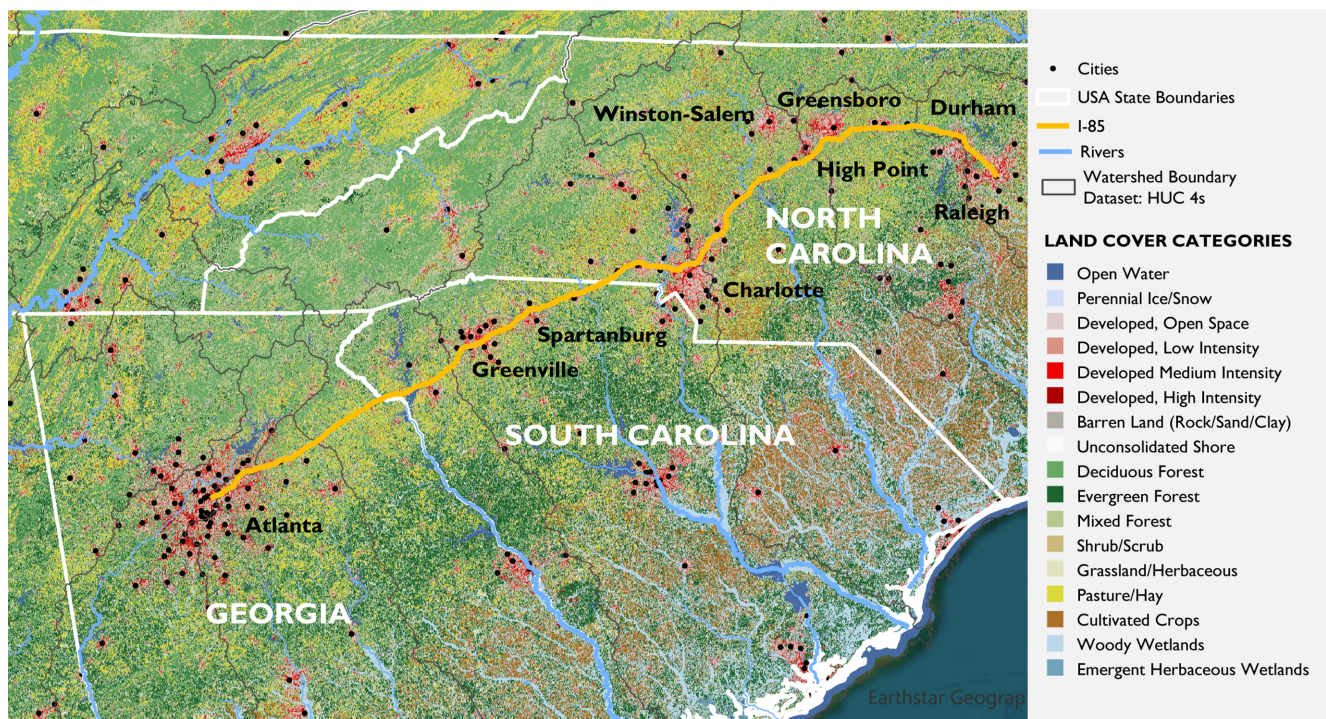
Research Impact Statement

Holistic policy and technological adaptations are necessary to address water supply, waste assimilation, and climate issues challenging water management in the Atlanta to Raleigh urban archipelago.

1 | INTRODUCTION

Urban growth creates challenges for water supply and waste assimilation, necessitating technological and policy innovations to stretch limited natural resources over larger populations. The 21st century is the first urban century in the Earth's history, with 55% of the world's population living in urban areas in 2018, and projections suggesting that 60% will live in urban spaces by 2030 (United Nations, 2020). In the United States, 86% of the population currently lives in metropolitan areas, and this fraction is increasing (Census 2020) as a result of both population growth and migration to urban areas. Urbanization alters land cover, local and regional climate, biodiversity, and biogeochemical cycling, particularly of water, carbon, and nutrients. Before the advent of modern transportation technologies, large cities usually developed only on natural ports or large rivers, as the trade upon which cities depended required the ability to handle shipping (Fujita & Mori, 1996; Krugman, 1996). The adjacency of rivers and large bodies of water provided the additional benefit of water supply and waste assimilation. The development of railroads, modern highways, and large airports fostered the growth of cities in locations without large rivers, but as these cities grow, they must overcome limitations of both water supply and waste assimilation capacity.

The string of cities growing along I-85 between Atlanta, GA, and Raleigh-Durham, NC, (Figure 1) exemplifies many of the challenges posed by automobile-supported urbanization and suburbanization (Jakle, 1990). The growth of the cities is characterized by rapid, low-density urbanization, fueled by migration from northern states, rural areas, and other countries. This has been one of the most rapidly growing regions of the country (Brown et al., 2005), and cities in the corridor have some of the highest sprawl indices and lowest compactness metrics of major American cities (Hamidi & Ewing, 2014). Terando et al. (2014) predicted that by 2060, an interconnected megalopolis will have formed along the I-85 corridor. The growth of this megalopolis is predicted to degrade aquatic and terrestrial habitat, harm wildlife populations (Terando et al., 2014; Van Metre et al., 2019), and warm the regional climate by intensifying urban heat island effects, which are altering the regional climate synergistically with global climate change (Shepherd et al., 2013). Shepherd et al. (2013) called this corridor an “urban archipelago,”



Landcover Data: IMG - NLCD CONUS Land Cover (MRLC 2016)

FIGURE 1 The metropolitan areas and incorporated cities along I-85 (yellow line) showing their position relative to HUC 4-digit watersheds draining the Piedmont and Appalachian highlands.

hypothesizing that the linear system of urbanized spaces exerts an influence on the hydroclimatic system that is greater than any individual city or urban heat island.

The cities of the archipelago are similar in terms of growth, biogeographic setting, and water resource constraints. They are connected not only by the I-85 travel corridor but also by a common set of challenges: water quality, water supply, waste assimilation, urban growth, regional biodiversity, and climate change. All of these cities occur high in their watersheds (Figure 1) and are thus supported by relatively small rivers (Table 1). They are also geologically similar and are located on low-productivity crystalline rock aquifers ill-suited to augment surface water supplies for metropolitan areas, although localized groundwater usage occurs (e.g., many suburban homes use wells for water supply and some urban homeowners drill wells to water lawns to avoid paying tiered water conservation rates; Montginoul et al., 2005). Per-capita water availability (the total average river flow available to each water supply system divided by its served population) indicates that two of these cities (Greensboro and High Point in the Triad) face absolute scarcity, and all but two of these metropolitan cities (Charlotte and Winston-Salem) suffer from water supply scarcity or stress according to United Nations thresholds (Table 2). Meanwhile, populations of these cities are growing by 0.75%–2.1% per year, with a weighted average of 1.5% and a total current population of about 10 million (Table 2). Income inequality and racial segregation are high in this region (Othering and Belonging Institute, 2020; US Census Bureau, 2022), and it is important to acknowledge that the burden of scarcity is felt unevenly among the population (Rodríguez-Labajos & Martínez-Alier, 2015). Without changes to water infrastructure and water consumption habits, cities within the archipelago will be unable to sustain growth while providing equitable access to reliable water supplies and protecting aquatic resources for downstream users.

Higher elevations of the Appalachian Mountains and foothills interact with atmospheric moisture flows from the Gulf of Mexico and the Atlantic Ocean to boost precipitation in watersheds supplying the archipelago. Consequently, the basins supplying the region are relatively wet, with annual precipitation ranging from 1120 to 1850 mm/year, and high water yield, typically 400–800 mm (Younger et al., 2020). Still, high summer evapotranspiration and low aquifer productivity (Georgia Board of Natural Resources, 2001) tend to produce very low baseflows in late summer and autumn (e.g., Ledford et al., 2020; Price et al., 2011; Figure 2), creating seasonal constraints for water supply and waste and heat assimilation.

TABLE 1 Drainage areas, flows, per-capita water availability, and UN water stress levels for each city or regional water authority along the Atlanta–Raleigh urban archipelago. UN water stress levels are as follows: absolute scarcity <370 gpd, scarcity <713 gpd, water stress <1215 gpd, and no stress at >1215 gpd.

City or metro area, principal supply	Most relevant gage	Gage #	Pop.	Relevant DA (mi ²)	Qave cfs	Q90 cfs	Per-capita supply (gpd)	Condition (UN)
ATL, main source— Chattahoochee R (supplies 72% of 5.5 M population)	Chattahoochee @ ATL	02336000	3,960,000	1450	2418	995	395	Scarcity
Greenville	None	NA	530,000					No stress
Spartanburg, S. and N. Pacolet Rivers	Pacolet R nr Fingerville, SC	02155500	306,850	212	328.1	99	691	Scarcity
Charlotte, Catawba R.	Catawba R @ Rock Hill	02146000	1,100,000	3050	4055	916	2382	No stress
Piedmont Triad Total			1,600,000	1986	2735.5	964.7	1105	Stress
Winston Salem, Yadkin R	Yadkin R @ Enon	02115360	238,500	1694	2397	923	6495	No stress
Greensboro, Reedy Fork	Reedy Fk nr Gibbsonville	02094500	287,000	105	77	5.21	173	Abs. Scarcity
High Point, W Fk Deep River	W. Fk. Deep R Nr High Pt.	02098500	109,000	62	60.8	10.2	360	Abs. Scarcity
Randleman Regional Reservoir	Deep R Nr. Randleman	02099500		125	200.7	26.3		
Durham, Flat River & Little River			275,123	266.9	188	2.12	442	Scarcity
Flat River	Flat R @ Dam Nr Bahama	02086500		168	122	0.02		
Little River	Little R @ Faintosh, NC	0208524975		98.9	66	2.1		
Raleigh, Neuse R.	Neuse R nr Falls, NC	02087183	450,000	711	589.5	72.9	847	Stress

TABLE 2 Water supply status for individual metropolitan areas along I-85 Piedmont Megapolitan Corridor.

City, pop., growth rate	Total average use and per-capita water use	Supply quality concerns	Downstream flow concerns
Atlanta, 5.5M, Metro N. Ga Water Planning Dist. 1.6%/year ^a	Total 97–106 gpd (2017). 30% reduction from 150 gpd in 2000 Domestic 52–57 gpd 19% outdoor use (single families)	Eutrophication of Lakes Allatoona and Lanier, driven mostly by P from return flows, urban runoff, and poultry farms Sedimentation of stream and river intakes	Florida has sued ATL in Federal Court seeking to reduce ATL water withdrawals and free more streamflow for Apalachicola Bay. Litigation began in 1990s and continues today
Greenville, Approx. 525,534 in Greenville Water service area. 1.23%/year ^b	About 100gpd total		Greenville imports much of its water from the Savannah River basin, and thus augments flows in its local receiving rivers
Spartanburg, 38,732 city, 327,997 county (2020) 1.45%/year last 10years	142 gpd (total, 100gpd for domestic use)		
Charlotte 1.1 million Mecklenburg County. 1.86% growth rate last 8 years.	74gpd	Water Quality in Lake Norman and Mountain Island Lake is reported to be very good based on an index heavily weighted toward fecal coliforms. However, the potential threat of coal ash ponds adjacent to these sources is concerning	Competing uses exist in on Lake Norman: drinking water supply, irrigation, and two Duke Energy power facilities (one coal and one nuclear) Large demand within the basin strain water resources. Large presence of power generation in this basin High sedimentation rates documented downstream in Lake Wateree, but reports hypothesize primarily due to two specific creeks—Rocky Creek and Cedar Creek
Piedmont Triad of Winston-Salem, Greensboro, and High Point, 1.6M (2010), 0.75%/year	141 gpd (Forsyth Co.) 135 gpd (Guilford Co.)		Each city has its own water supply, but there is also a regional reservoir and substantial cross-basin sharing. Without regional water sharing, Greensboro and High Point could not function
Winston-Salem, 238,500 (2016)	See above		Yadkin River drains to three reservoirs downstream and eventually to the Pee Dee River and Waccamaw Neck Estuary in South Carolina
Greensboro, 287,000 (2016)	See above		Haw River drains to Cape Fear estuary near Wilmington, NC
High Point, 109,000 (2016)	See above		Deep River drains to Cape Fear estuary near Wilmington NC
Durham, 275,423 (2017), 1.8%/year (2010–2016) ^c	92 gpd total 50 gpd domestic	Lake Michie considered moderate susceptibility concern to contamination. Little River higher concern from runoff, animal operations, and permitted discharges	
Raleigh 470,000 2.1%/year	104gpd ^d	Fall Lake Reservoir suffers from eutrophication and resulting algae blooms. Significant changes in technology and nutrient credit development and trading necessary to achieve water quality goals for the reservoir	Neuse River Basin—estuarine eutrophication problem. Large numbers of CAFOs on lower river. Several large fish kills following tropical storms

Note: Unless otherwise noted, water usage data from USGS water use data (Dieter & Maupin, 2017). Population numbers from 2020 census.

^aMetro North Georgia Water Planning District, 2017. Water Resource Management Plan, June 2017, 276p.

^bGreenville Water, 2016, Annual Comprehensive Financial Report. 93p.

^c<https://durhamnc.gov/DocumentCenter/View/12971/City-of-Durham-Population-Growth-2010-2016?bld=>.

^dWaldroup et al. (2013). 2013 City of Raleigh Water Resources Assessment and Plan.

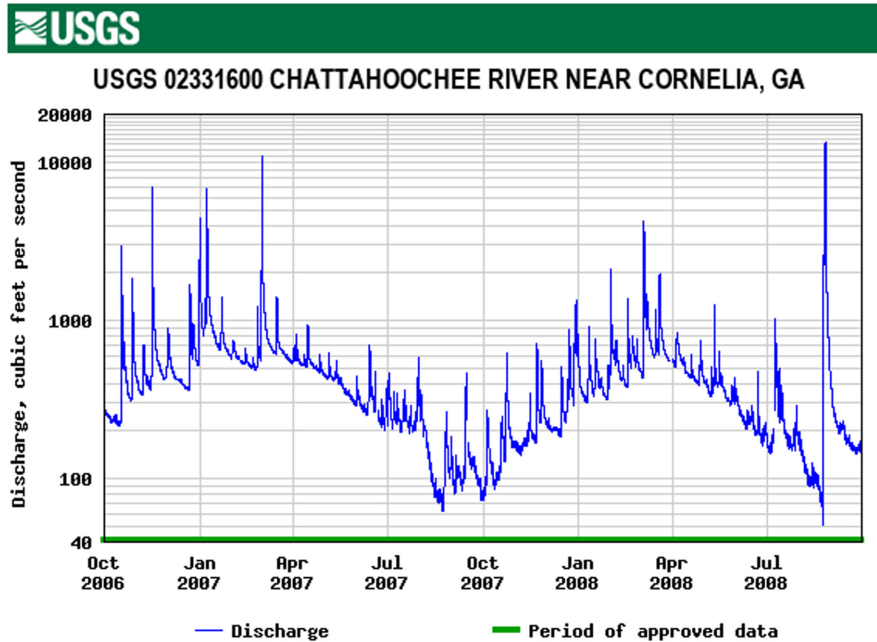


FIGURE 2 Two years of USGS flow data for the unregulated Chattahoochee River (USGS gage 02331600) just upstream of Lake Lanier, the primary water supply reservoir for the Atlanta metropolitan region. Baseflow varies seasonally, with higher baseflow during the winter–spring period following winter recharge and lower baseflow during the late summer–fall period as water tables fall due to high evapotranspiration rates. During dry years, flows fall to as little as 50 cfs in the river supplying a metropolitan area of 5 million people.

The I-85 megalopolis is located within a region of high natural biodiversity, especially of freshwater species. Lack of past glaciation has allowed for greater speciation than elsewhere in the temperate world, and the complex topography has created high habitat diversity. Consequently, the region is a global biodiversity hotspot for fish, mussels, snails, amphibians, and plants, with high species endemism (Collen et al., 2014; Elkins et al., 2019). Because the Appalachian Mountains and the Southeast Piedmont are largely forested (Liu et al., 2021), streams supplying the I-85 corridor are generally low in pollutants, except where elevated by agricultural practices (Jackson et al., 2017, 2022), urban runoff, treated wastewater, or untreated wastewater (sewer leaks, combined sewer overflows [CSOs], and failing septic systems). Communities of color and low-income communities suffer disproportionately from overflows and pollutant releases in Atlanta, and likely in the rest of corridor (Deme, 2021).

Here, we evaluate the water supply and waste assimilation issues of the I-85 urban archipelago and consider how these cities could create more sustainable water futures. We begin by reviewing regional climate and streamflow trends, the recent history of drought management issues and policies, population and water use trends, upstream and downstream water quality concerns, and documented research and monitoring needs. We then identify key policy considerations for supporting sustainable water futures for the growing but water-constrained cities in the archipelago.

2 | CLIMATE AND STREAMFLOW TRENDS

The complex mix of climate variability, population, and water management is likely to increase water stress along the I-85 corridor. Water stress is defined by Wada et al. (2014) as exceeding a threshold (40%) of available basin water withdrawn. Global distributions of precipitation per person (PPP, Haupt et al., 2018; Shepherd et al., 2020) illustrate that parts of the Southeast United States have PPP values similar to highly water stressed regions of the world including parts of India, Africa, and China. Areas of water supply stress are rare in the eastern United States and are concentrated in the I-85 corridor (Averyt et al., 2013). Low PPP likely indicates that precipitation alone cannot sustain the current population without increased water use efficiency or augmented supply in the future.

The dynamic intersection of future water demand and supply in this urban corridor will depend on population growth, global climate change effects on river flows and water quality, and the effects of urbanization and local climate change on urban stream hydrology and water quality (Shepherd et al., 2016). Effects of a changing hydroclimate will be layered upon existing drought management issues. Periodic, severe droughts are normal climate occurrences in the Southeast United States as illustrated by the time series of the Palmer Drought Severity Index (Figure 3). As cities have grown, each occurrence of such droughts has required cities to take steps to decrease per-capita demand and extend supplies.

Southeast Palmer Drought Severity Index (PDSI)

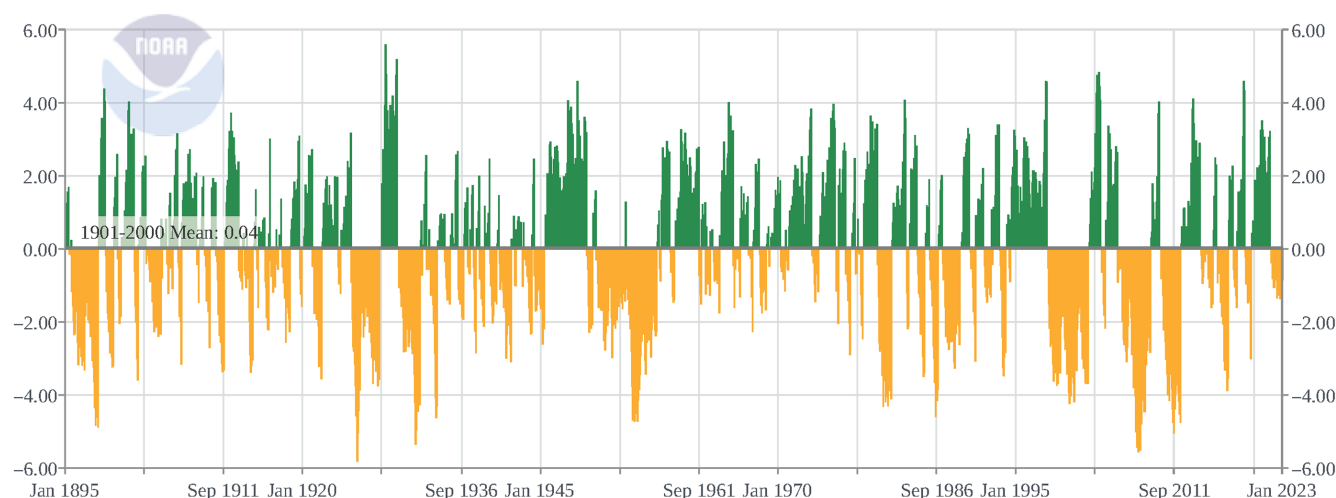


FIGURE 3 NOAA Palmer Drought Severity Index from 1895 to 2019 for the Southeast Region. Green periods are wet and orange periods are dry relative to the long-term mean. Magnitude of deviations from zero reflects the severity of wetness/dryness (NOAA, 2020). Severe and extended droughts are common for the region, and drought severity and frequency are highly variable over the last 125 years.

The National Climate Assessment (NCA, 2018) warns that “changes in the frequency and intensity of climate extremes relative to the 20th century and deteriorating water infrastructure are contributing to declining community and ecosystem resilience.” The Southeast United States exhibits a drying trend in precipitation in recent decades, with expectations for reductions in spring and summer precipitation and large increases in fall precipitation, both enhancing the strong seasonality of river flows in the region. Episodic weather extremes, including heavy rain events, tropical cyclones, and severe droughts, will complicate water resource, agriculture, and infrastructure planning. Chang et al. (2016) note that climate models project that average intensity of precipitation events will be amplified at the rate of 6%–7% per degree Celsius rise. Li et al. (2012) demonstrated that anthropogenic climate change has modified the North Atlantic subtropical high and increased summer rainfall variability in the Southeast. Long-term regional climate observations indicate extreme events, including heavy rainfall and severe droughts, are becoming more common (Burt et al., 2018; Oishi et al., 2018).

Recent analyses of streamflow records across the Southeast reveal evidence of widespread and significant declines in the magnitude of low flows across the region (Stephens & Bledsoe, 2020). Furthermore, trend slopes quantified across varying time periods indicated a faster rate of decline in low-flow magnitude over recent decades compared to the last century. Continued development in these basins will increase peak flows and alter water budgets (Li et al., 2020). While many factors can interact to influence low-flow trends, negative trends across the region were identified in records regardless of flow regulation and degree of human interference, indicating climate change is an important factor to consider in all water resource planning.

Changes in land use and land cover have influenced flow in the archipelago. Depending on how urban water systems have been engineered, urbanization has been shown to increase or decrease base flows (Bhaskar et al., 2016; Ledford et al., 2020). However, the frequency and severity of periods of low flow in urban centers along the Charlotte–Atlanta corridor are positively correlated with the extent of urban development and influenced by the spatial distribution of development (Debbage & Shepherd, 2018). In the surrounding rural areas, the decline of Piedmont farming precipitated by the depression in 1930 has resulted in extensive afforestation (Ellenburg et al., 2016; Trimble et al., 1987), which has been shown to decrease annual water yield (Andréassian, 2004; Bosch & Hewlett, 1982). Increasing conifer composition of forests can also reduce water yield (Younger et al., 2020). Human activities can further alter water budgets and contribute to low flow declines through consumptive water usage (irrigation and power plant cooling), evapotranspiration from man-made reservoirs, and inter-basin water transfers.

Current trends in low-flow magnitudes highlight how nonstationary hydrologic behavior across the region can affect water resources planning and management. For instance, if regulatory pollutant loading rates are based on stationary estimates of dilution flows, then in-stream pollutant concentrations will increase as flows decline, and water withdrawal rates established to maintain minimum environmental flows will not reflect water availability during more extreme low-flow conditions. During low-flow periods, streams become warmer, water velocities decrease, and both situations exacerbate effluent dilution issues and create low dissolved oxygen conditions harmful to fish and aquatic life. Fisk kills are common during such periods. Extreme low flows can fall below intake levels for water supply systems and cooling systems for thermoelectric power plants. Research is needed to identify and understand the causal mechanisms behind trends in low flows and water budgets. Recent experience with climate-related shifts in water supply reliability indicates that water planning needs to account for the uncertainty created by these potential climate- and land-use-driven changes in river flows (Fowler et al., 2022). The Climate Risk Informed Decision

Analysis (CRIDA) framework has been developed to help water supply planners incorporate hydrologic change and uncertainty into system management (UNESCO, 2018).

3 | PAST DROUGHT CRISES

Increasing populations are exacerbating drought issues. For water supply managers, droughts are defined by water supply shortages that occur when available water is insufficient to meet demand at regular prices. Water supply droughts become more frequent and severe as human population increases. Such droughts can be managed by reducing demand or increasing supplies. Increasing prices to reduce demand creates equity issues and unintended consequences such as private well-drilling (Montginoul et al., 2005).

Multiple water supply droughts in the region over the last 20 years have altered per-capita water consumption and perceptions of water supply reliability and raised fundamental questions about water supply infrastructure and policy. Prior to the 1980s, droughts were generally not considered to be a water supply problem in the region because metropolitan water demand was not yet large enough to stress available supplies. Before the recent spate of droughts, water use in the megalopolis was quite high, approximately 568 L per capita per day (lpcd) or 150 gallons per capita per day (gpcd; Table 2), nearly double the 2015 national average of 310 lpcd (82 gpcd; Dieter & Maupin, 2017). Droughts motivated state and municipal efforts to increase water efficiency through increasing public education, implementing tiered conservation pricing, requiring water efficiency retrofit, and auditing water uses, among others. Consequently, per-capita water usage dropped dramatically in most of these cities (Table 2, next section). Drought events also motivated exploration of new reservoir construction and inter-basin transfers (Georgia Water Council, 2008; Water Allocation Study Team, 2008). Each city in the region has taken different routes to water use efficiency, reflecting differences in their water supply stress and drought history.

In the last 50 years, metropolitan Atlanta has moved from being water rich to water scarce. In 1956, the United States Army Corps of Engineers completed Buford Dam on the Chattahoochee River, forming Lake Lanier upstream of Atlanta and creating a sense of water security for the Atlanta metropolitan area. Atlanta augments its Chattahoochee River/Lake Lanier water supplies through additional withdrawals from the Etowah and the upper reaches of the Altamaha, Coosa, and Flint Basins (Table 2). Nevertheless, severe regional droughts of 1980–1981 and 1986–1988 showed that summer water demand of the growing metropolitan region could deplete available storage during such conditions (Chaisson, 2012). After the 1980 drought, the governors of Georgia, Alabama, and Florida, the three states through which the Chattahoochee river flows, signed a memorandum of agreement to create a water management plan for the basin, including a drought management plan (ACT/ACF, 1995). Following the 1986 drought, the USACE and the States of Georgia, Alabama, and Florida established a Drought Management Committee to facilitate communication and coordinate responses during droughts. In 1990, Georgia Governor Joe Frank Harris proposed a regional network of reservoirs to “drought-proof” the modern economic engine of Georgia (ACT/ACF, 1995). However, because lake evaporation in the region is about 72% greater than the evapotranspiration of the prior forested areas, reservoir construction necessarily means less water flowing downstream (Zhao & Gao, 2019). Predictably, Alabama and Florida, to which the Chattahoochee River flows, opposed the construction of additional reservoirs to supply Atlanta, a sign of the interstate tension and distrust that would end with Florida leaving the tristate water management compact in 2003. Consequently, the responsibility for interstate water management among these states moved to federal courts.

Drought crises can motivate government action. Droughts of 1999–2000 and 2007–2008 galvanized Atlanta's need to increase water efficiency and drought resilience. In 2008, Lake Lanier levels dropped 7.4 m below the full pool level, a historical record. Drought management actions included lawn watering restrictions, car washing bans, implementation of industrial and institutional water efficiency plans, drought awareness campaigns, and proposed legislation mandating retrofitting of water-efficient toilets and spigots at the time of home sale. Following the 1999 drought, Georgia initiated a Statewide Water Planning process. The 16-county Metro North Georgia Water Planning District was created to facilitate water planning and management across all local governmental jurisdictions within the Atlanta metropolitan area. Through policy changes including conservation pricing, public education, and independent efficiency efforts by businesses and institutions, per-capita water consumption dropped 33% as discussed above (Table 2). In 2015, in response to lobbying from the landscaping industry, the State of Georgia instituted a rule requiring municipalities wishing to enact stricter restrictions on outdoor water use than the state to seek a variance from the Georgia Environmental Protection Division (n.d.) effectively making it more difficult for municipalities to respond to droughts (Georgia Administrative Code, n.d., Ga. Comp. R. & Regs. 391-3-30-.08). Drought experiences also spurred interest and action in creating additional regional reservoirs (Georgia Water Council, 2008), several of which have come on line since.

Upstate South Carolina experienced one of its worst multi-year droughts from 1998 to 2002 (Walker et al., 2008), during which reservoir levels dropped so low that some municipalities had only a few months of water remaining (Badr et al., 2004). South Carolina had been one of the first states in the region to establish a drought response program, the South Carolina Drought Response Act of 1985 (Altman & Lackstrom, 2018; Walker et al., 2008). The 1998–2002 drought, however, revealed that water shortages were a real threat in the state. In 2000, the original act was amended to implement the guidelines elaborated in the 1998 South Carolina Water Plan, and the 2004 South Carolina Water Plan recommended regulating withdrawals and introduced a strategy for sharing water across districts.

Charlotte and Greenville are the least water-stressed cities in the corridor (Table 2), but increasing water demands due to population growth and climate change could exhaust safe yield for Charlotte's reservoirs (HDR, 2014). The drought of 1998–2002 is among the longest and most severe droughts recorded in the area, and it resulted in mandatory water conservation and record low reservoir levels and stream flows (Weaver, 2005). Charlotte's water supply was maintained during the drought by strategically adjusting reservoir release schedules to store water during the winter and timing releases based on the needs of downstream water users (Weaver, 2005). As a result of the 1998–2002 drought and the relicensing of hydroelectric dams on the Catawba River, the Catawba-Wateree Drought Management Advisory Group was formed, creating a partnership among industry, local, federal, and state agencies to ensure adequate water supply for communities along the river. As a participating member, Charlotte implemented the “Low Inflow Protocol” (LIP) developed by the group. The LIP defines multiple stages of drought that trigger various management strategies for maintaining adequate water supply during times of drought such as voluntary conservation measures and strategic reservoir release operations. Since the 1998–2002 drought, additional severe droughts have occurred, and per-capita water use in Charlotte has declined (Table 2). However, population growth, climate change, and downstream water demands will require additional efficiency measures to achieve sustainable water management.

The individual Piedmont Triad cities (Greensboro, High Point, and Winston-Salem) differ substantially in available per-capita water supply (Table 2), and have developed systems to effectively share water during shortages. The Triad has limited surface and groundwater supplies; therefore, short periods of time with below-average rainfall can push the region into severe drought (Whisnant & Holman, 2010), as occurred in 2002–2004 and 2006–2007. In 2002, the Yadkin River experienced exceptionally low flows that compromised drinking water supplies and hydroelectric power production for communities along the river. Droughts have been managed through water-use restrictions, strong conservation messages in the community, conservation pricing, and vital interconnects and water sharing among the region's water supply systems. Greensboro has the smallest per-capita water supply and storage, and the city relies on water purchases from adjacent water systems during severe droughts. By 2060, water supply demand in Greensboro will likely exceed 80% of capacity (Ford & Stober, 2013; Larkins et al., 2018). Greensboro already falls into the UN absolute scarcity classification (Table 2), and its ability to supply water to its residents depends on regional cooperation, which may be compromised by recurring and more intense droughts coupled with continued population growth.

During the drought of 2007–2008 in the southeast United States, Raleigh's water supply reservoir dropped to a record low of nearly 3 m below full pool level, prompting the city to introduce a range of water restrictions. These included a ban on car washing except at certified facilities, prohibition on filling of new swimming pools, and prohibition on serving drinking water in restaurants unless requested by the customer (Manuel, 2008). It also prompted a fierce debate among city council members on whether the city should raise water connection fees, institute water capacity impact fees, or even put a moratorium on growth (Manuel, 2008). While none of those measures were implemented, the city has steadily improved water efficiency, somewhat offsetting increased water demand due to population growth. Nevertheless, in 2013, the city forecasted a water supply shortfall in non-drought periods by 2030 and noted that the increased efficiency had hardened demand and reduced the capacity for conservation during drought periods (Waldroup et al., 2013). To meet increased demand, Raleigh has pursued a multi-pronged approach to expand its water supply, including a long-proposed reservoir on the Little River that has faced environmental permitting hurdles. In 2019, however, the US Army Corps of Engineers approved a reallocation of Falls Lake to allow Raleigh to access much of the volume previously designated as water quality storage, which is expected to yield an additional 22 MGD in water supply. The city argued that this will not compromise water quality in the Neuse River downstream, as 87% of its water is returned to the river even in drought periods (Waldroup et al., 2013). Regional water sharing agreements have eliminated the need for the Little River reservoir for the foreseeable future.

4 | INCREASING POPULATIONS AND WATER USE EFFICIENCY

Population growth along this corridor is high, approximately 1.5% per year (Table 2), suggesting increasing water stress for already supply-stressed cities. However, many of these cities have shown significant progress in improving water efficiency over the last two decades. In several well-documented cases, per-capita water use has declined faster than population has grown.

Greenville Water expects total demand to remain flat, or even decrease slightly, due to improvements in water efficiency (Greenville Water, 2016). It attributes much of the decrease in per-capita water demand to more efficient fixtures and appliances and “increased conservation.” Greenville Water expects per-capita residential consumption to continue to drop until it levels out at about 170 lpcd (45 gpcd). Similarly, total water use in Greensboro and Durham remained flat from 1995 to 2014 despite population growth, but in these two cases, it was economic shifts, specifically the decline in water-using industries, that flattened the demand curve (Hester & Larson, 2016).

Domestic per-capita water usage still varies substantially across these cities, reflecting different economic conditions and water management policies. In Raleigh, total water demand increased as the population increased until the drought of 2010, at which point the implementation of conservation pricing caused both per capita and total water demand to decrease substantially (Hester & Larson, 2016). By 2014, total demand had dropped to 1997 levels. Average water consumption in the Metro North Georgia Water Planning District has dropped from 568 to 379 lpcd (150–100 gpcd) in the last 20 years. Between 2002 and 2011, the Charlotte region reduced usage from 428 to 322 lpcd (113 to 85 gpd), and its master plan sets a goal of reducing it to 265 lpcd (70 gpcd; HDR, 2014).

Observed improvements in domestic water efficiency have been the result of a broad set of strategies and programs, mostly initiated after critical drought conditions discussed above, the relative importance of which has varied among the cities but has included: replacement of low-efficiency water appliances (toilets, washing machines, and dishwashers) with low-flow and higher efficiency models, behavior modification through water efficiency educational efforts, implementation of tiered conservation pricing, and voluntary water audits of commercial and institutional water users. Many institutional and commercial users redesigned operations to increase efficiency, such as changing HVAC systems to looped systems rather than single-pass through systems. The lifespans of dishwashers and washing machines are not long, in the range of 9–13 years (Consumer Reports, 2019), and newer appliances are generally much more water-efficient than older appliances. Toilets have long functional lives, so widespread reduction in water used for flushing can only be achieved by rebate programs or by requiring that all toilets must be low-flow toilets at the time of sale of the property. Between 2008 and 2019, a toilet rebate program in metro Atlanta incentivized replacement of 145,000 inefficient toilets. Large improvements in water efficiency have been possible through education, technological innovation, efficiency incentivization, and conservation pricing.

5 | WATER QUALITY AND AQUATIC ECOSYSTEMS

Population increases in the archipelago come with increased loadings of nutrients and carbon to water reclamation facilities. These increasing effluent loadings from water reclamation facilities (WRFs), coupled with other nonpoint nutrient and sediment loading from agricultural and residential lands, will strain river assimilative capacity and potentially compromise water quality and freshwater habitat. Aging onsite wastewater systems and leaking sewer lines contribute substantially to water quality degradation (Divers et al., 2013; Kaushal & Belt, 2012), but the magnitude of these loadings is uncertain. In the United States, national census data on sanitation have not been collected since 1990 (Dig Deep and US Water Alliance, 2019), and many jurisdictions do not have adequate information about the density and condition of onsite wastewater treatment systems, such as septic systems. Onsite wastewater treatment systems are typically managed by individual landowners after they are installed, and municipal intervention by public health officials only occurs when system failure presents a known risk to the community (Swann, 2001).

Excess amounts of the nutrients nitrogen (N) and phosphorus (P) negatively impact rivers, lakes, and coastal zones in the United States, including the southeast (USEPA, 2020). Nutrients generated within cities affect both urban streams and downstream water bodies. The 2020 National Rivers and Streams Assessment (NRSA) found that 80% of rivers in the Southern Appalachian region (which includes the Piedmont physiographic province and most of the I-85 archipelago) had P concentrations associated with a “Poor” rating and 45% of rivers had N concentrations associated with a “poor” rating. Coastal Plain rivers likewise had relatively high percentages of rivers with poor ratings due to P (39%) and N (32%; USEPA, 2020). The most recent National Lakes Assessment (NLA) showed poor ratings for high percentages of lakes (>4 ha) in the Southern Appalachian and Coastal Plain ecoregions, respectively, due to P (34%, 55%) and N (83%, 44%), and poor condition due to dissolved oxygen (D.O.) concentration in 8% of lakes in both ecoregions (USEPA, 2022a). Smaller lakes (>1 ha) have high percentages of poor ratings due to P (77%, 38%), N (89%, 35%), D.O. (15%, 5%), atrazine (a commonly used pesticide) detection (32%, 9%), and microcystin (a toxin produced by algae) detection (10%, 25%) in Southern Appalachian and Coast Plain regions, respectively, indicating the need for much greater control of nutrients and other pollutants. The most recent National Coastal Condition Assessment Report (NCCA) indicates that eutrophication is particularly widespread in Southeast estuaries. Less than 20% of Southeast estuaries sampled were considered in good (vs. fair or poor) condition due to elevated phosphorus concentrations and algal biomass compared to 33% nationally (USEPA, 2021). Much of the comparative data in the NRSA, NLA, and NCCA indicate increasing nutrient pollution and decreasing water quality through time (USEPA, 2020, 2021). Harmful algal blooms and increased algal productivity have caused problems for city water sources (e.g., Lake Allatoona on the Etowah River, Raleigh-Falls Lake on the Neuse river—Lake Jordan on the Cape Fear—Haw, etc.), sometimes requiring installation of aerators to mitigate low dissolved oxygen problems. However, aeration is an expensive treatment for symptoms, not causes, of nutrient impairment. North Carolina DWR has created an online map of harmful algal blooms that clearly indicates the breadth of this problem (NCDWR, 2022).

Urban WRFs are a significant point source of nutrients, typically accounting for 10%–20% of nutrient loadings in and downstream of urban areas. Nutrient and carbon loadings increase almost linearly with population growth and are not responsive to the same efficiencies that can be applied to water use. Human waste also impacts water bodies as a nonpoint nutrient source via the large number of septic systems in the I-85 urban archipelago, which are generally poorly mapped and often poorly maintained. Despite the challenges of increased loading from septic and sewer, the greatest reductions in stream water nutrient concentrations (1982–2012) have occurred in urban watersheds, indicating the success of targeted reduction strategies (Stets et al., 2020). Over the period 1992–2012, significant reductions in N and P occurred in most urban watersheds, contrasting with agricultural watersheds where about half of watersheds showed increases and half showed decreases. Reducing nutrient loadings from agricultural setting is more cost-effective than increasing removal in WRFs, so increasing the adoption of agricultural best management practices should be part of watershed-level nutrient loading reduction. Successes in reducing nutrient loadings from urban centers have come from treatment upgrades to WRFs and also better stormwater management (Stets et al., 2020). Municipalities along the I-85 corridor have opportunities to reduce nutrient loadings by incentivizing agricultural BMPs in the same basins, by improving

nutrient processing in urban streams through application of green infrastructure and better stormwater management, and by increasing nutrient removal in WRFs. To improve water quality within and downstream of cities, and improve the quality of life for urban residents, water supply, waste water treatment, stormwater management, and nonpoint pollution control should be managed holistically through a “one water” framework (US Water Alliance, 2016).

With the implementation of the Infrastructure Investment and Jobs Act (IIJA) underway, there is a generational opportunity to make progress toward greater water resilience and water quality improvements through infrastructure investments that benefit water quality and system resilience, thereby improving equitable access and helping to alleviate environmental justice concerns. Significant funding is available for upgrading and expanding conventional WRF and stormwater infrastructure, as well as natural infrastructure such as wetlands, riparian buffers, urban river parkways, and greenspaces. In addition to improving water quality, combining natural infrastructure with conventional systems can provide a broad array of co-benefits including improved air quality, better health outcomes through recreation, flood risk reduction, and moderation of extreme heat (Jackson et al., 2014; Meerow & Newell, 2017; Simperler et al., 2020). Building water resilience through IIJA and other investments will, however, require a strategic approach to do the right projects, the right way (ASCE, 2022). Doing so will require policy changes and breaking down silos across management programs. Most jurisdictions in the region have yet to intentionally attempt to align and integrate water management across utilities, public works, floodplain administration, parks and recreation, and natural area programs to realize the vision of one water. Improved maintenance and asset management of conventional and natural water infrastructure will also be essential for achieving sustainable improvements in water quality and system resilience.

Urban watersheds in Metropolitan Atlanta are also compromised by combined sewer systems (CSOs). While Atlanta was the only city in the archipelago that built a combined sewer system (serving the city limits as defined in 1910), its overflows have repeatedly degraded water quality in the Chattahoochee River and reduced assimilative capacity for downstream municipalities. Flooding events associated with CSOs have threatened the health and safety of the residents of Atlanta, and have been most prevalent in non-White and impoverished communities (Johnson Gaither, 2019). Recently, Atlanta greatly reduced its combined sewer overflow problems by (1) separating storm and sanitary sewers over about 27% of the combined network, and (2) building 18.5 miles of 30-foot diameter CSO storage tunnels under the city at an approximate cost of \$3B (EPA Office of Inspector General, 2018). The tunnels store a large proportion of CSO flows during storms, so they can be treated between storms. However, the city has yet to mitigate the effects of all combined systems, and some regions of the city, such as the Entrenchment Creek, South River, and Proctor Creek Watersheds, still regularly experience CSO-associated flooding and water quality problems geographically coincident with low-income non-White neighborhoods (Deme, 2021; Entrenchment Creek One Water Management Task Force, 2020; Johnson Gaither, 2019).

WRF effluent and urban runoff are not the biggest sources of excess nutrients in these aquatic systems, and the other sources set the assimilative template against which point source effluent standards are set. Major nonpoint sources of excess nutrients are fertilizers applied to both agricultural lands and residential yards, manure from poultry and hog farms, and direct livestock access to streams. Even low-density rural landscapes in this region suffer from high in-stream nutrient and sediment concentrations as well as high summer water temperatures (Jackson et al., 2017, 2022; Webster et al., 2019).

Although N and P are the leading sources of water pollution in the United States, effective management of these point and nonpoint source pollutants has been elusive. In 1998, the U.S. EPA tasked states with developing nutrient criteria for different water bodies (Rivers and Streams, Lakes and Reservoirs, Coastal and Estuarine Waters and Wetlands). Water quality criteria are used in assessment, wastewater permitting, and setting restoration targets (e.g., TMDLs), so numeric nutrient criteria would improve management. According to the most recent database of state numeric nutrient criteria, Georgia and South Carolina have limited N and P criteria for a subset of lakes and none for streams or coastal waters. North Carolina has no adopted numeric N and P criteria for any water (USEPA, 2022b). Without criteria to set water quality targets, it has been challenging for many states to implement and evaluate nutrient control strategies. Voluntary actions embodied in nutrient action plans or nutrient-sensitive water assignments (NC) have met with only limited success because of under-implementation.

Projections of future climate change indicate that harmful algal blooms will become more frequent if nutrient inputs are not controlled because many of the types of algae that form harmful blooms grow best at high-water temperatures (Huisman et al., 2018). Furthermore, the assimilative capacity of rivers (for nutrients or other pollutants) is reduced by higher water temperatures. Warmer water holds less dissolved oxygen due to gas solubility, and warmer water speeds algal growth as well as decomposition and associated oxygen consumption. These factors interact to result in low nighttime dissolved oxygen that reduces the capacity to assimilate pollutants.

6 | RESEARCH AND MONITORING NEEDS

As the I-85 urban archipelago grows and its metropolitan areas merge, the region will need to weigh the costs and benefits of alternative strategies to improve water supply resilience including greater efficiency, reuse, and new storage infrastructure. Increasing reservoir storage has been a primary policy option in Georgia, with several new regional reservoirs constructed in the last 25 years (including the Dog River, Hard Labor Creek, Richland Creek, and Bear Creek reservoirs). However, additional reservoir storage necessarily increases evapotranspiration, thus

reducing average flow downstream (approximately 17.5 L/s/km² of reservoir). Reservoirs eliminate flowing water habitat that is required for many native aquatic species, block movement of migratory fish species, fragment and isolate populations of non-migratory species, and also degrade downstream aquatic habitat by altering flow patterns. Reservoirs also increase the emissions of the greenhouse gas methane because of the slow anaerobic decomposition of organic matter (Bevelhimer et al., 2016). Finally, reservoirs are expensive and difficult to site and permit, and they eventually fill with sediment (e.g., Palmieri et al., 2001). Given these limitations, alternative approaches need to be considered in concert with increasing reservoir capacity to support sustainable water resource development.

Economic and behavior studies need to be performed to examine the relative efficacy of alternate water efficiency policies including (a) the reduction in water use due to conservation pricing, (b) the effect of conservation pricing on the installation of private wells, (c) identification of factors affecting lawn-watering behavior, (d) the optimum per-capita water use that can be achieved, and (e) reduction of water use by reducing system water pressures. These studies need to identify drawbacks of each strategy, such as whether reducing system pressures below 30 psi causes backflow issues. The public likes high water pressure, but high pressures increase system leakage.

Continuous analysis of streamflow and water quality data will be necessary to guide adaptive use policies. Water supply planning has been based on historical flow data collected by the USGS, but climate change and land use change can alter water budgets and hydrographs and render analyses conducted with historical flow data obsolete. Cities and states will need to monitor and assess flow trends as affected by climate and land use change. As waste assimilation issues become as critical as water supply issues, basin-level nutrient budgets will be needed to set nutrient reduction targets and prioritize areas for nutrient reduction. Nutrient budgets will also be needed to identify and target water quality offset policies.

Regardless of water use efficiency, increasing population growth in the I-85 archipelago will increase loading of recalcitrant waste products like pharmaceuticals, microplastics, personal care products, and PFAS. Monitoring and research will be needed on the transport and fate of these chemicals and the efficacy of alternative wastewater treatment systems for mineralizing or sequestering such chemicals, as well as attention to the populations affected. A recent report on drinking water contamination in the United States indicates that there were correlations between unsafe drinking water and non-White race, low income, and non-English-speaking households that include violations across the I-85 urban archipelago (Fedinick et al., 2019). Therefore, contaminant issues should be particularly addressed in economically and culturally vulnerable communities.

7 | BUILDING A SUSTAINABLE WATER FUTURE

Water managers in these cities recognize they will have to adapt their infrastructure and policies for assuring both water quantity and quality in the face of continued population growth and climate change. The region naturally experiences extreme climate events including heavy rainfall events (e.g., ATL 2009 event), hard freezes, and severe droughts, all of which place heavy strains on water supply and waste treatment systems and all of which are expected to become more frequent under climate change. Atlanta, Charlotte, and the Piedmont Triad have developed strategic plans with explicit focus on resilience strategies (Charlotte Water, n.d.; MNGWPD, 2015; Piedmont Triad Regional Council, 2018) to improve their ability to maintain water and wastewater services during extreme climate events and to protect water quality under increased loading, reduced low flows, and higher summer temperatures. Charlotte also engages in comprehensive watershed management planning for the entire Catawba-Wataree River systems through the Catawba-Wataree Water Management Group consisting of cities, counties, and electrical utilities throughout the basin (Catawba Wataree Water Management Group, 2014). Going forward, water resource planning and management must incorporate projections and uncertainties of future climate, streamflow, population, and water use trends, as well as inter-annual variability, using frameworks like CRIDA that have been developed for this purpose.

Multiple uncertainties associated with population growth, water use, and climate change interact to create a complex water future for cities in the archipelago. Improvements in water efficiency cannot be continued indefinitely. They become more difficult, and eventually greater efficiency becomes undesirable. For instance, in the range of 114–132 lpcd (30–35 gpcd), conventional gravitational sewage conveyance systems may flow too slowly, depending on topography, and strong sewer gases may accelerate pipe degradation, as observed in Germany (Chandavarkar, 2009).

Once efficiency has been maximized, water needs associated with additional population growth can only be met by policies supporting water reuse. As cities in the I-85 archipelago approach this point, they will need to develop systems for direct or indirect potable reuse (IPR; Hopson & Fowler, 2022), or closing the loop, that is, treating wastewater to drinking water standards. Some utilities have already built the infrastructure to support this. For example, Georgia's Clayton County Water Authority, which serves parts of southeast Atlanta, conventionally treats its wastewater, provides tertiary polishing through constructed wetlands, then discharges to small lakes from which it draws its water supply. While the effluent spends a short period of time in the natural aquatic environment and receives inputs of new water from the hydrologic system, this system is largely a closed loop for which new water is required only to meet evaporative demand and groundwater losses during each cycle. Similar systems are in place along Lake Lanier, which is the principal water supply for Atlanta. Several Atlanta suburbs draw water directly from the lake and release their treated wastewater back into the reservoir. These IPR loops on Lake Lanier mean that Atlanta's

water supply is composed mostly of new river water but also of reclaimed water that has been returned to the lake. Meanwhile, the lake is also serving as a major summer recreational amenity for Atlanta and North Georgia, with thousands of boaters and swimmers using the lake every summer day.

Inter-basin transfers are politically unpopular, but are currently a significant part of metropolitan plumbing in this region. The Triad cities of North Carolina employ extensive water sharing infrastructure that moves water across river boundaries as needed during droughts. Charlotte and the other water supplies within the Catawba-Watauga basin have created a flexible collaborative framework for sharing water across systems during periods of water supply stress. While the Chattahoochee River is Atlanta's principal water supply, the city also draws water from the Etowah River and the Ocmulgee basin, and these withdrawn waters are sometimes discharged into different basins.

Hydrologic connections become more complicated when water sharing among adjacent counties in the Atlanta metropolitan area is considered. Interbasin transfers create fears that large cities like Atlanta will import water from distant rivers that would otherwise support beneficial uses in the river of origin. As former Augusta Mayor Bob Young once wrote while lobbying for legislation to ban inter-basin transfers, "It is unjust for communities that practice good planning to have their natural resources diverted to subsidize the lack of planning in other communities." The Georgia statute (O.C.G.A 12-5-584) that created the MNGWPD specifically prohibited new inter-basin transfers to the District, partly to allay fears that the planning behemoth would seek further water imports. In the future, however, maintaining and increasing inter-basin transfers are likely pragmatic necessities. During droughts of spatially variable intensity (Figure 4), inter-basin transfers can increase drought resiliency and provide water to more stressed communities. However, predictions of the effects of inter-basin transfers indicate they can severely negatively impact the diversity of species in the basins in which they occur (Grant et al., 2012). State laws should specifically regulate and provide for monitoring of inter-basin transfers to protect aquatic ecosystems and avoid resource allocation inequities (Water Allocation Study Team, 2008). Water planners and policy makers need to consider both positive benefits and negative repercussions associated with inter-basin transfers. Questions to consider when evaluating inter-basin transfers include:

1. What are the relative costs and benefits to the transmitting and receiving basins?
2. Do all affected governmental jurisdictions approve of the transfers?
3. How will the water transfer affect water quality, aquatic ecology, and species of conservation concern in the affected systems?
4. Is there a monitoring/policy feedback loop by which policies can be adjusted based on new data or information on costs and benefits?

Increased water efficiency does not reduce carbon and nutrient loading to WRFs. As city populations increase, carbon and nutrient discharges to wastewater systems will increase commensurately. Consequently, correspondingly higher levels of nutrient removal in WRFs will be necessary to maintain downstream water quality. Waste assimilation will become as serious a water resource issue as water supply. In addition to recovering water, nutrient recovery in wastewater will need to be adopted to reduce downstream transport of nutrients as well as make sources of nutrients for fertilizer, particularly P, locally accessible and affordable. The F. Wayne Hill Water Resources Center, a WRF in Gwinnett County, GA, recovers P from wastewater, producing significant amounts of P-rich fertilizer and reducing downstream export of

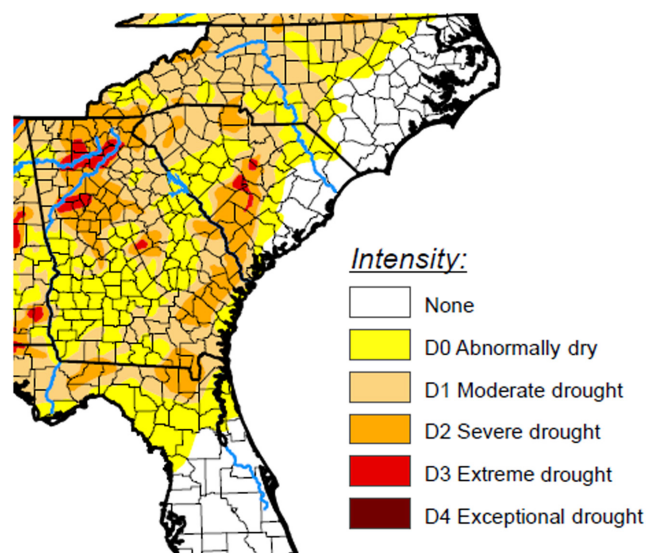


FIGURE 4 Southeast drought monitor for October 1, 2019, from the U.S. Drought Monitor produced by Brian Fuchs, The National Drought Mitigation Center at University of Nebraska–Lincoln. On this date, drought conditions along the I-85 archipelago varied over four drought conditions, from D0 to D3, sometimes with a two-step difference among adjacent counties. Inter-basin water sharing can increase drought resilience across supply systems.

P (Gwinnett County, 2022). This recovery meets the dual needs of acquiring a critical growth-limiting nutrient with projected global scarcity (Cordell et al., 2011) and reducing negative ecological impacts downstream.

As incremental nutrient removal costs increase, states and municipalities may need to consider water quality offset policies whereby city residents pay to improve other aspects of aquatic ecosystem function to offset the effects of increased nutrient loadings. Such offset activities could include riparian forest restoration, homeowner outreach and education regarding fertilizer application, fencing cattle out of streams, facilitating better agricultural nutrient management, reducing sediment runoff from unpaved roads, and fish passage improvement. Although not addressed in this paper, it must be acknowledged that water quality and assimilative capacity in urban streams are largely dictated by stormwater management. Urban stormwater and stream management set the water quality and nutrient cycling template into which WRF plant effluent is introduced. Improving water quality within and downstream of cities will require integrated management of point and nonpoint pollution and will have to consider the water quality affecting activities of agriculture and urban residents.

Finally, the climate and streamflows that set the baseline for water supply and quality are changing, and water planning and policies must account for both trends in climate and streamflow and uncertainty in those trends. We can expect greater extremes in the climate and streamflows with larger and more intensive precipitation events and droughts of greater severity. Water planners should use uncertainty frameworks like CRIDA to maintain and operate resilient supply and waste assimilation systems.

AUTHOR CONTRIBUTIONS

C. Rhett Jackson: Conceptualization; data curation; supervision; visualization; writing – original draft; writing – review and editing. **Seth Wenger:** Conceptualization; writing – original draft; writing – review and editing. **Brian P. Bledsoe:** Conceptualization; resources; writing – review and editing. **J. Marshall Shepherd:** Conceptualization; writing – original draft. **Krista A. Capps:** Conceptualization; investigation; writing – original draft. **Amy D. Rosemond:** Conceptualization; investigation; writing – original draft. **Michael J Paul:** Writing – original draft; writing – review and editing. **Meredith Welch-Devine:** Conceptualization; writing – original draft; writing – review and editing. **Ke Li:** Conceptualization; visualization; writing – original draft. **Tim Stephens:** Conceptualization; investigation; writing – original draft. **Todd C. Rasmussen:** Conceptualization; writing – original draft.

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CONFLICT OF INTEREST STATEMENT

We have no conflicts of interest.

DATA AVAILABILITY STATEMENT

No new data were collected for this analysis. All data are public and referenced in the manuscript.

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