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RESEARCH ARTICLE

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Intra-annual variability of urban effects on streamflow

Jeremy E. Diem[1] | Luke A. Pangle[1] | Richard A. Milligan[1] | Ellis A. Adams[2]

[1]Department of Geosciences, Georgia State University, Atlanta, Georgia, USA

[2]Keough School of Global Affairs, University of Notre Dame, Notre Dame, Indiana, USA

Correspondence
Jeremy E. Diem, Department of Geosciences, Georgia State University, 38 Peachtree Center Ave, Suite 730, Atlanta, GA 30303, USA.
Email: jdiem@gsu.edu

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Abstract

While considerable research has established the impacts of urbanization on streamflow, there has been little emphasis on how intra-annual variations in streamflow can deepen the understanding of hydrological processes in urban watersheds. This study fills this critical research gap by examining, at the monthly scale, correlations between land-cover and streamflow, differences in streamflow metrics between urban and rural watersheds, and the potential for the inflow and infiltration (I&I) of extraneous water into sewers to reduce streamflow. We use data from 90 watersheds in the Atlanta, GA region over the 2013–2019 period to accomplish our objectives. Similar to other urban areas in temperate climates, Atlanta has a soil-water surplus in winter and a soil-water deficit in summer. Our results show urban watersheds have less streamflow seasonality than do rural watersheds. Compared to rural watersheds, urban watersheds have a much larger frequency of high-flow days during July–October. This is caused by increased impervious cover decreasing the importance of antecedent soil moisture in producing runoff. Urban watersheds have lower baseflows than rural watersheds during December–April but have baseflows equal to or larger than baseflows in rural watersheds during July–October. Intra-annual variations in effluent data from wastewater treatment plants provide evidence that I&I is a major cause of the relatively low baseflows during December–April. The relatively high baseflows in urban watersheds during July–October are likely caused by reduced evapotranspiration and the inflow of municipal water. The above seasonal aspects of urban effects on streamflow should be applicable to most urban watersheds with temperate climates.

KEYWORDS
baseflow, inflow and infiltration, seasonality, streamflow, urban hydrology, wastewater

1 | INTRODUCTION

Urbanization is a global phenomenon that can dramatically alter existing hydrological processes of watersheds. Urbanization changes watersheds by increasing the coverage of impervious surfaces, thereby increasing runoff (Aulenbach, Landers, Musser, & Painter, 2017; Booth & Jackson, 1997; Paul & Meyer, 2001). Through mechanical disruption, urban soils can be greatly modified (Herrmann, Schifman, & Shuster, 2018); however, it is debatable whether urban soils have less infiltration capacity compared to undisturbed soils (Herrmann, Shuster, & Garmestani, 2017; Yang & Zhang, 2011). Urbanization, through the removal of vegetation, reduces ET in temperate regions (Dow & DeWalle, 2000), especially in the summer (Bhaskar & Welty, 2012). In addition, increased summer rainfall has been found over urban areas resulting from the urban heat island effect and increased convergence (Shepherd, 2005).

Urbanization also can introduce new processes associated with municipal water and wastewater. Losses from pressurized supply pipes is a global problem (Abd Rahman, Muhammad, & Wan Mohtar, 2018), and in the United States, for example, leakage rates between 20% and 25% are common for municipal systems (Lerner, 2002). Water loss also occurs from sewer pipes (i.e., wastewater exfiltration), but this process only occurs in pipes above the groundwater table (Rutsch et al., 2008). The leaking water from both systems noted above can recharge groundwater (Garcia-Fresca & Sharp Jr., 2005). Recharge also can be caused by excessive landscape irrigation (Grimmond & Oke, 1999; Hibbs & Sharp, 2012). In humid regions, there also can be a substantial amount of extraneous water (i.e., clean water) entering sewer systems through inflow and infiltration (I&I) (Dirckx, Fenu, Wambecq, Kroll, & Weemaes, 2019). Inflow is rainwater and surface water that is routed into a sewer system through direct connections (e.g., downspouts, yard drains, sump pumps, etc.), while infiltration is groundwater seeping into the sewer pipes via cracks, leaky joints, and through aging manholes (Pawlowski, Rhea, Shuster, & Barden, 2014). It is not uncommon for clean water to constitute at least 30% annually of the total water volume entering a WWTP (Bareš, Stránský, & Sýkora, 2012; Rödel, Günthert, & Brüggemann, 2017).

It is widely known that urban watersheds have intensified peak streamflow and increased streamflow flashiness, but urban impacts on baseflow are varied. The more urbanized the watershed, the more imperviousness and storm sewers, and the higher the frequency and magnitude of high flows (Booth & Jackson, 1997; Brown et al., 2009). As a result, urban streams tend to have more frequent and intense flooding than rural streams (Konrad, 2003; Paul & Meyer, 2001). Associated with high flows is flashiness, which is the rate of change of streamflow (Baker, Richards, Loftus, & Kramer, 2004). The flashiest watersheds in the contiguous United States are usually located in urban areas (Smith & Smith, 2015). It is also common for hydrological studies to note that baseflow—the portion of streamflow occurring between precipitation events and presumably resulting largely from groundwater discharge—decreases with the urbanization of a watershed (Hubbart & Zell, 2013). Typical causes of the lower baseflow are decreased infiltration of storm water and the occurrence of I&I (Bhaskar, Beesley, et al., 2016; Schwartz & Smith, 2014). However, other processes in urban areas, such as leakage from water-supply pipes, lawn irrigation, managed infiltration of stormwater (e.g., detention basins), and leaking/overflowing sewer systems, also could enhance baseflows (Bhaskar, Beesley, et al., 2016; Eng, Wolock, & Carlisle, 2013; Price, 2011; Schwartz & Smith, 2014). The overall effect of the altered flows in urban watershed is ecologically degraded urban streams, characterized by elevated concentrations of contaminants and nutrients and altered channel morphology (Walsh, Roy, Feminella, Cottingham, & Groffman, 2005).

Despite sometimes dramatic seasonal differences in hydrological processes, there has been little emphasis on how intra-annual variations in streamflow can deepen the understanding of hydrological processes in urban watersheds. The few urban-hydrology studies with obvious intra-annual components typically focus on differences between seasons with respect to a single process, often ET (e.g., Bhaskar, Hogan, & Archfield, 2016; Boggs & Sun, 2011; Meierdiercks, Smith, Baeck, & Miller, 2010). One particular process that needs more focus is I&I, which has received relatively little attention by the hydrological research community even though I&I can contribute to significant environmental and public-health problems, such as sanitary sewer overflows (SSOs) (Cahoon & Hanke, 2017).

Guided by the aforementioned gaps in the literature, our overarching research question is as follows: How do intra-annual differences in streamflow metrics between urban and rural watersheds elucidate urban impacts on hydrological processes? The major objectives are to examine–at the monthly scale–correlations between land cover and streamflow, differences in streamflow between urban and rural watersheds, and the potential for I&I, which is mostly an urban-watershed process, to impact streamflow. By using a large number of watersheds and focusing on the monthly scale, rather than a more traditional approach such as using a small number of paired watersheds to examine hydrologic differences at the annual scale, we reveal season-specific information about hydrological processes in urban watersheds.

2 | STUDY REGION

The chosen study region, the Atlanta–Sandy Springs–Gainesville combined statistical area in the southeastern United States, is an ideal locale for examining the intra-annual variability of urban effects on streamflow (Figure 1). The topography, soils, and climate are relatively uniform across the region, and the region has an abundance of stream gauges. Nearly the entire region exists within a single physiographic province, the Piedmont province, which is characterized by rolling hills underlain by metamorphic and igneous rocks (Miller, 1990). There is little variation in soil orders across the region: Ultisols is the dominant soil order and Udults are the only suborder for Ultisols (Natural Resources Conservation Service, 2020). The entire region has a humid-subtropical climate (Cfa), which is characterized by hot, humid summers and no seasonal differences in precipitation (Trewartha & Horn, 1980). Cfa climates are prevalent across the globe (Beck et al., 2018), and, along with much of the non-arid portion of the middle latitudes, Cfa climates typically have a soil-water surplus during winter and a soil-water deficit during summer (Abatzoglou, Dobrowski, Parks, & Hegewisch, 2018). Therefore, the common climate of the Atlanta region makes the findings from this study relevant to urban areas in many countries. The Atlanta region had 90 suitable stream gauges with data for the entire study period, 2013–2019. This time period was selected because it straddles the 2016 national land-cover database, which is the most recent database. Details about the stream-gauge data and the land-cover database are provided in Section 3.

3 | DATA AND METHODS

3.1 | Land-cover and population data

High-resolution, gridded land-cover and imperviousness data for 2016 were obtained from the Multi-Resolution Land Characteristics Consortium. The two datasets were the National Land Cover Database (NLCD) land-cover product and the NLCD imperviousness product.

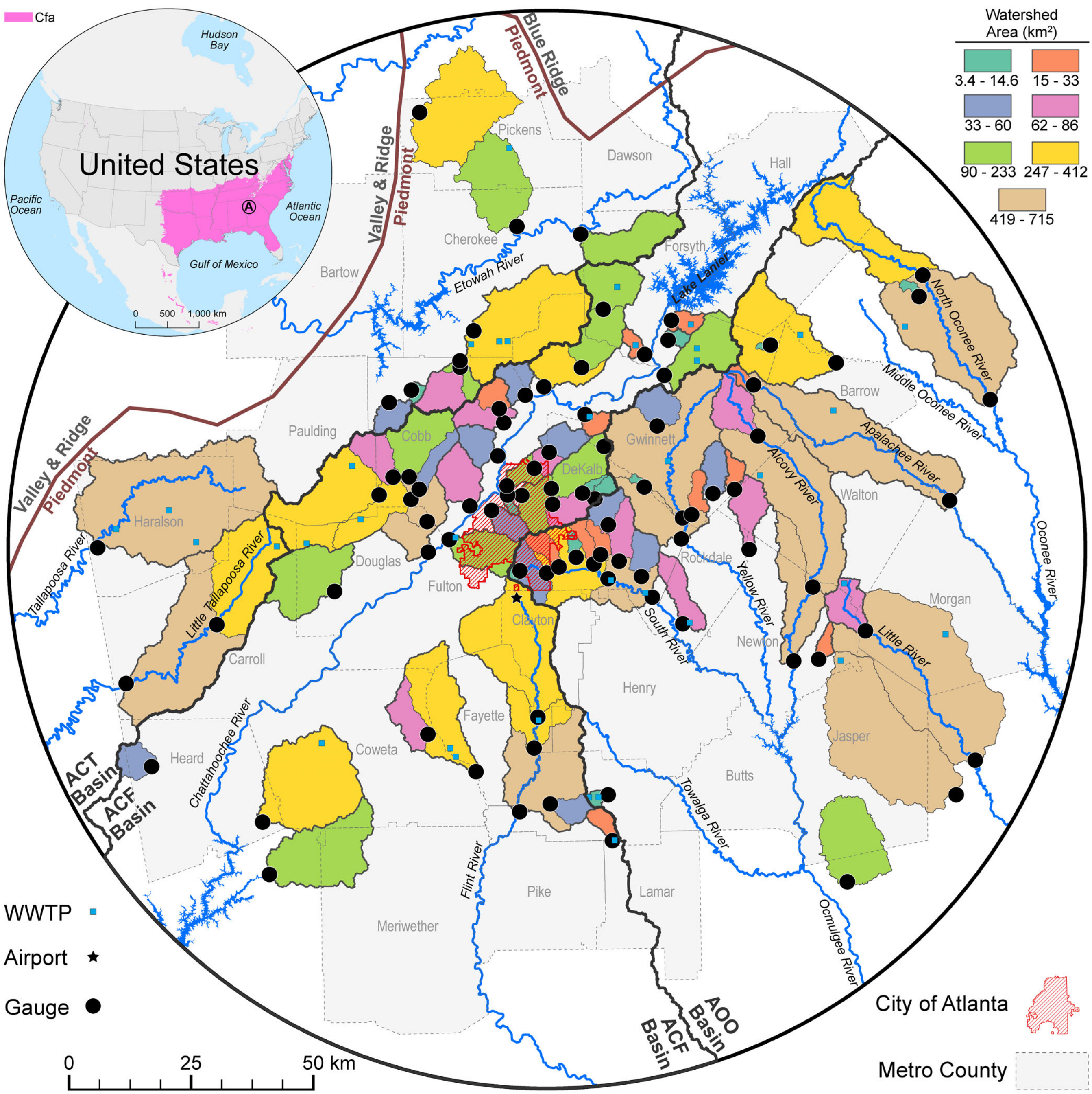

FIGURE 1 Locations of the 90 gauged watersheds within and proximate to the Atlanta metropolitan area. Shown within the watersheds are locations of the 36 wastewater treatment plants (WWTPs) used in this study. The study region includes three major river basins: Alabama-Coosa-Tallapoosa (ACT), Apalachicola-Chattahoochee-Flint (ACF), Altamaha-Ocmulgee-Oconee (AOO). The inset map shows the locations of Atlanta (a) within the Cfa climate type, which covers most of the southeastern United States

Both datasets had a spatial resolution of 30 m. The land-cover product had 15 classes for the Atlanta region, and the imperviousness product had for each grid cell the percentage of developed surface that was impervious surfaces.

Population data were obtained from the U.S. Census Bureau's American Community Survey 2013–2017 5-year estimates. Population totals at the block-group level were converted to density values, and weighted means (based on area of a block group within a watershed) were used to estimates the population densities within the watersheds.

3.2 | Precipitation and temperature data

Gridded monthly precipitation and temperature data from 1990 to 2019 were obtained from the PRISM (Parameter-elevation

Regressions on Independent Slopes Model) Climate Group. These data were provided at a 4-km resolution. Precipitation and temperature values for the watersheds were weighted means of grid-cell values, with the weights derived from the areas of the grid cells within the watersheds.

Daily precipitation totals and mean temperatures were obtained for Hartsfield-Jackson Atlanta International Airport for 1990–2019. These data were part of the GHCN (Global Historical Climate Network)-Daily database of the National Oceanic and Atmospheric Administration.

3.3 | Streamflow data and metrics

Daily mean streamflow from 2013 to 2019 were acquired from the United States Geological Survey (USGS) for 90 gauges. None of the gauges were immediately downstream of dams (i.e., if there were any visible dams, they were at least 10 km upstream), and the watersheds for all gauges were entirely within the Piedmont province while also being less than 800 km^2 and with a mean slope less than 16%. The entire streamflow dataset for the 90 gauges was missing only 0.07% of daily values. Only 21 of the gauges were missing values, and the percentage of missing values for those gauges ranged from 0.04% to 3.64%. Linear interpolation involving neighbouring days was used to replace one to 3 days in a row with missing values. Predicted values from linear regression equations were used to replace missing values involving four or more days in a row; the independent variables were daily values from a gauge with a time series that had the strongest correlation with the time series of the gauge having the missing values. The serially complete daily streamflow values were normalized by watershed area to produce discharge values in millimetres.

The following seven streamflow metrics were calculated at the monthly scale: maximum daily flow (Q_{max}), mean daily flow (Q_{mean}), median daily flow (Q_{med}), minimum daily flow (Q_{min}), high-flow frequency (i.e., the frequency of days above the 90th percentile of flows), low-flow frequency (i.e., the frequency of days below the 10th percentile of flows), and flashiness index (FI). Q_{max} (Q_{min}) is the mean of the daily maximum (minimum) flows observed within each month across the 7 years (i.e., the mean of seven values) (Poff, Bledsoe, & Cuhaciyan, 2006; Smakhtin, 2001). Since daily streamflow records have positively skewed distributions, median flow can be treated as a conservative upper bound for low flows (Smakhtin, 2001). Both Q_{med} and Q_{min} have been classified as baseflow metrics (Elliott, Spigel, Jowett, Shankar, & Ibbitt, 2010; Hamel, Daly, & Fletcher, 2015). Q_{mean} should be much more similar to the high-flow variable, Q_{max}, than the low-flow variables (i.e., baseflow metrics), Q_{med} and Q_{min}. Flashiness was calculated with the Richards-Baker Flashiness Index (Baker et al., 2004):

$$FI = \frac{\sum_{i=1}^{n} |q_i - q_{i-1}|}{\sum_{i=1}^{n} q_i}, \tag{1}$$

where q is daily flow, i denotes the day, and n is the number of days. The index is high for flashy hydrographs.

3.4 | Estimating intra-annual variations in soil water

Estimates of monthly soil-water balances and soil moisture for the Atlanta region were produced for two time periods, 1990–2019 and 2013–2019. Soil-water balances were generated using the University of Delaware's WebWIMP program, which uses a modified Thornthwaite procedure (Willmott, Rowe, & Mintz, 1985). The balances were created for the climatological period, 1990–2019, and the study period, 2013–2019. Monthly values of soil moisture at 4-km resolution from 2003 to 2019 were obtained from the TerraClimate dataset; the values were produced from a one-dimensional modified Thornthwaite-Mather climatic water-balance model (Abatzoglou et al., 2018).

3.5 | Correlations between land cover and streamflow

Correlations between the seven streamflow metrics and four land-cover variables were calculated for each month. On average, approximately 95% of a watershed was forest, pasture/hay, or developed land. Therefore, the land-cover variables were (a) a combination of the three forest classes, (b) pasture/hay, (c) combined open-space and low-intensity developed land, and (d) combined medium-intensity and high-intensity developed land. Correlations were assessed using Pearson product–moment correlation tests ($\alpha = 0.01$; one tailed).

3.6 | Comparisons of urban and rural watersheds

Watersheds were placed into two groups of urban watersheds and two groups of rural watersheds, and differences in watershed characteristics and streamflow were assessed. Gauges/watersheds with streamflow substantially augmented by WWTP effluent were not included in any of the four watershed groups. The two groups of urban watersheds were (a) the top 10 watersheds in terms of proportional coverage by open- and low-intensity developed land and (b) the top 10 watersheds in terms of proportional coverage by medium- and high-intensity developed land. The two groups of rural watersheds were (a) the top 10 watersheds in terms of proportional coverage by forest and (b) the top 10 watersheds in terms of proportional coverage by pasture/hay. Mann–Whitney U tests were used to determine significant ($\alpha = 0.01$; one-tailed) differences between urban and rural watersheds (i.e., the 20 urban watersheds were compared to the 20 rural watersheds) with respect to watershed size, land-cover, population density, monthly temperature, monthly precipitation, slope, and monthly values of the seven streamflow metrics.

3.7 | Intra-annual variability of I&I and its impacts on streamflow

The region-wide intra-annual variability of I&I was assessed through an examination of monthly WWTP effluent from 2013 to 2019. I&I is the primary cause of intra-annual variations in WWTP effluent (Dirckx et al., 2019; Weiß, Brombach, & Haller, 2002); therefore, WWTP effluent was used a proxy for I&I in this study. Monthly effluent was acquired for the 48 WWTPs that discharged into any of the 90 watersheds. These data were extracted from the U.S. Environmental Protection Agency's ICIS-NPDES Permit Limit and Discharge Monitoring Report Data Sets. There were 36 WWTPs that had more than 80% of months with data, and these data were retained for further analysis. Mann–Whitney *U* tests ($\alpha = 0.05$; one tailed) were used for each month at each WWTP to determine if that month had significantly higher effluent than the other months.

The minimum-effluent method was used to assess the intra-annual variability of I&I impacts on streamflow within the South River Watershed (SRW). The selected sewershed was the Snapfinger sewershed (Figure 2). The first step in the minimum-effluent method involved estimating the base sanitary flow, which is the effluent discharge during a dry weather period (U.S. EPA, 2014). Over the 2013–2019 period, the month with the minimum effluent from the Snapfinger WWTP was identified, and the antecedent and coincident atmospheric conditions along with soil-moisture estimates were assessed to verify that minimum soil water likely coincided with the minimum effluent. The 84 monthly I&I totals at the Snapfinger WWTP were estimated by subtracting the minimum effluent value from each monthly effluent value. Geospatial sewer-line data for the Snapfinger sewershed were obtained from DeKalb County, and monthly I&I totals were allocated among the three watersheds based on the proportion of the gravity-sewer lines within each watershed. Therefore, it was assumed that sewer-line density was the dominant control over I&I and that other factors affecting I&I, such as sewer age, had negligible spatial variations within the sewershed.

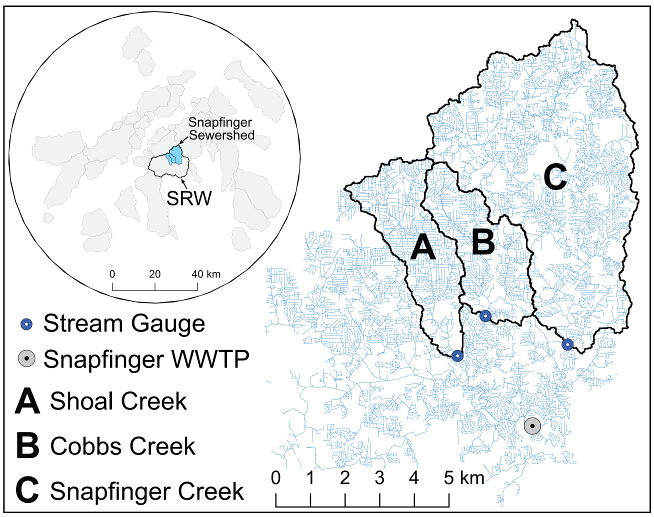

FIGURE 2 Location of the Snapfinger sewershed and its wastewater treatment plant as well as locations of the three gauged watersheds entirely within both the sewershed and the South River watershed (SRW). The blue lines are gravity sewers within the Snapfinger sewershed. Information about the three gauged watersheds is in Table 2

The monthly I&I totals were converted to daily values thereby enabling an assessment of I&I impacts on streamflow in the three watersheds. Since the effluent data was at the relatively coarse monthly scale, it had to be assumed that there was no variation in daily values within a month. The monthly I&I estimates (in m^3) for each watershed were divided by the area of the watershed to eventually produce I&I estimates in millimetres. The monthly I&I estimates (in mm) were converted to daily I&I estimates (i.e., monthly total divided by number of days in month), and those daily I&I estimates were added to the daily streamflow values to produce I&I-adjusted daily streamflow values. Monthly Q_{max}, Q_{mean}, Q_{med}, and Q_{min} were then calculated with the I&I-adjusted streamflow values. Those five metrics derived from adjusted streamflow were compared with the five metrics derived from unadjusted streamflow as well as with the five metrics for the 20 rural watersheds.

4 | RESULTS

4.1 | Intra-annual variability in soil water

The Atlanta region, with its Cfa climate, has substantial seasonal variations in amount of soil water (Figure 3). There is a water-surplus season from December to April and a water-deficit season from July to September/October. The 2013–2019 period had roughly similar soil-water balances to those for the most recent climatological period (Figure 3(a,b)), with the main difference between the extension of the deficit season into October. For the 2013–2019 period, the amount of soil moisture during the water-surplus season was 70% larger than the amount during the water-deficit season (Figure 3(c)).

4.2 | Correlations between land cover and monthly flow metrics

Q_{max} and FI were significantly positively correlated with developed land and significantly negatively correlated with rural land (i.e., pasture/hay and forest) in all months, while Q_{mean} had significant correlations in all months except for March (Figure 4(a,b,g)). Q_{max} and FI had the most positive correlations with medium- and high-intensity developed land and the most negative correlations with forest land. Correlations with Q_{mean} were strongest during June–October; there were positive correlations with developed land and negative correlation with rural land.

Correlations between the low-flow metrics (i.e., Q_{med} and Q_{min}) and the land-cover variables mostly reversed in sign from winter to summer (Figure 4(c,d)). Correlations between rural land and both low-flow metrics were significantly positive for January–April. Outside of

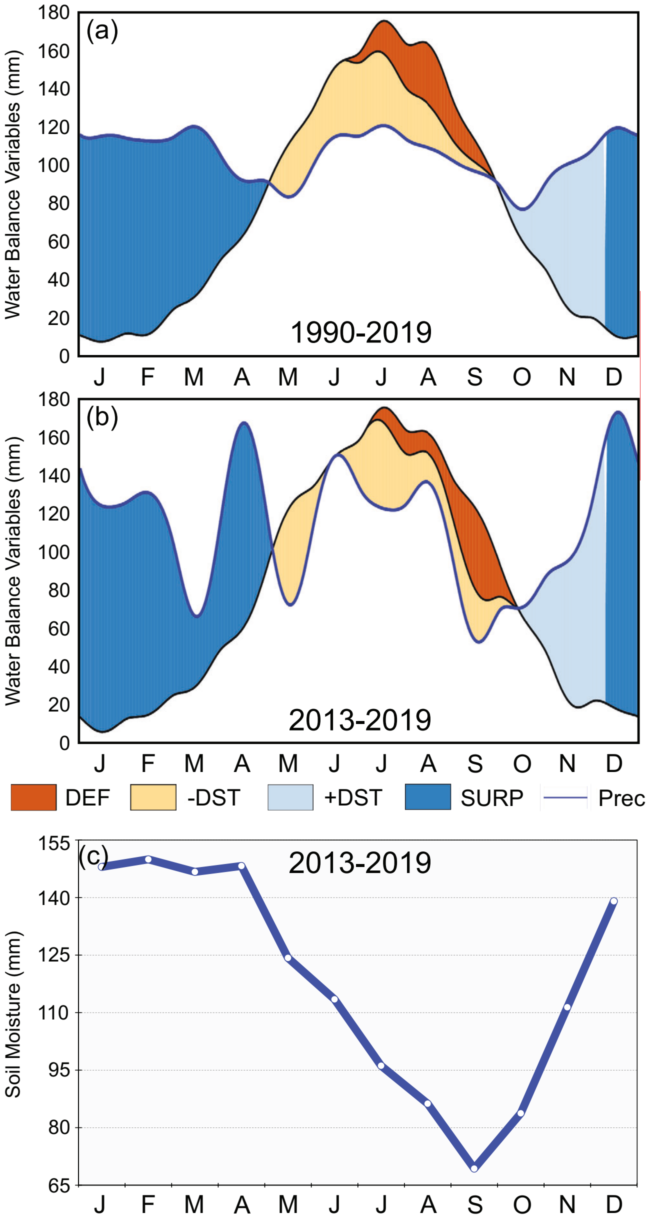

FIGURE 3 Approximate monthly soil-water balances for Atlanta, GA for (a) 1990–2019 and (b) 2013–2019. DEF is the deficit or unmet atmospheric demand for moisture. DST is the estimated change in soil moisture from the end of the previous month to the end of the current month. SURP is surplus (i.e., surface runoff plus percolation below the plant root zone). Prec is the monthly total precipitation. The balances were generated by the University of Delaware's WebWIMP program. (c) Estimates of monthly soil moisture for 2013–2019 from TerraClimate (Abatzoglou et al., 2018)

those months, the only other significant correlation between rural land and a low-flow metric occurred in August. Correlations between developed land and both low-flow metrics were significantly negative during February–April, with the most negative correlations involved medium- and high-intensity developed land. The only significant positive correlations between the low-flow metrics and developed land involved Q_{med} and open-space and low-intensity developed during July–September.

There was a strong seasonality to correlations between land cover and high-flows frequency, while there were mostly negligible correlations between land cover and low-flows frequency (Figure 4(e, f)). During December–April, high-flows frequency was significantly positively correlated with rural land, while during May–October the correlations were significantly negative (Figure 4(e)). Developed land had the opposite significant correlations for those groups of months. Few of the correlations involving low-flows frequency were significant, and there was no consistent seasonal pattern to the correlations (Figure 4(f)).

4.3 | Differences among urban and rural watershed groups

4.3.1 | Watershed characteristics

The urban watersheds, located in the centre of the study region, differed greatly from the rural watersheds, located on the periphery of the study region, with respect to size, land cover, and population density (Figure 5(a) and Table 1). There were no significant differences in temperature and slope between the urban and rural watersheds (Figure 5(b) and Table 1), and significant differences in precipitation existed only for September (Figure 5(c)). The least developed watersheds were in the Rural A group, and these watersheds were nearly 70% forested, had only 2% impervious cover, and had fewer than 50 persons k/m^2. The other group of rural watersheds, Rural B, had less forest, more pasture/hay, more developed land, and twice the population density than the Rural A group. Of the two urban groups, Urban A was the less developed category, but it was still much more developed than the rural watersheds. Urban A watersheds had less than half the forest cover of the rural watersheds, had virtually no pasture/hay, were nearly 80% developed, were over 20% impervious cover, and had a high population density that was similar to that of the more developed urban watersheds (i.e., Urban B). Urban B watersheds had little forest cover (~10%), virtually no pasture/hay, were nearly 90% developed, were over 40% impervious cover, and had the aforementioned high population density. In addition, the urban watersheds were approximately 10 times smaller than the rural watersheds.

4.3.2 | Streamflow metrics

There were significant differences for every month between urban and rural watersheds for Q_{max}, FI, and frequencies of high-flow days, with urban watersheds having much larger Q_{max} and FI values than rural watersheds throughout the year and high-flow days for urban watersheds being more evenly distributed throughout the year (Figure 5(d,f,j)). Urban B watersheds consistently had the largest Q_{max} and FI values among the four watershed groups (Figure 5(d,j)). Throughout the year, Q_{max} and FI values were at least 70% and 80%

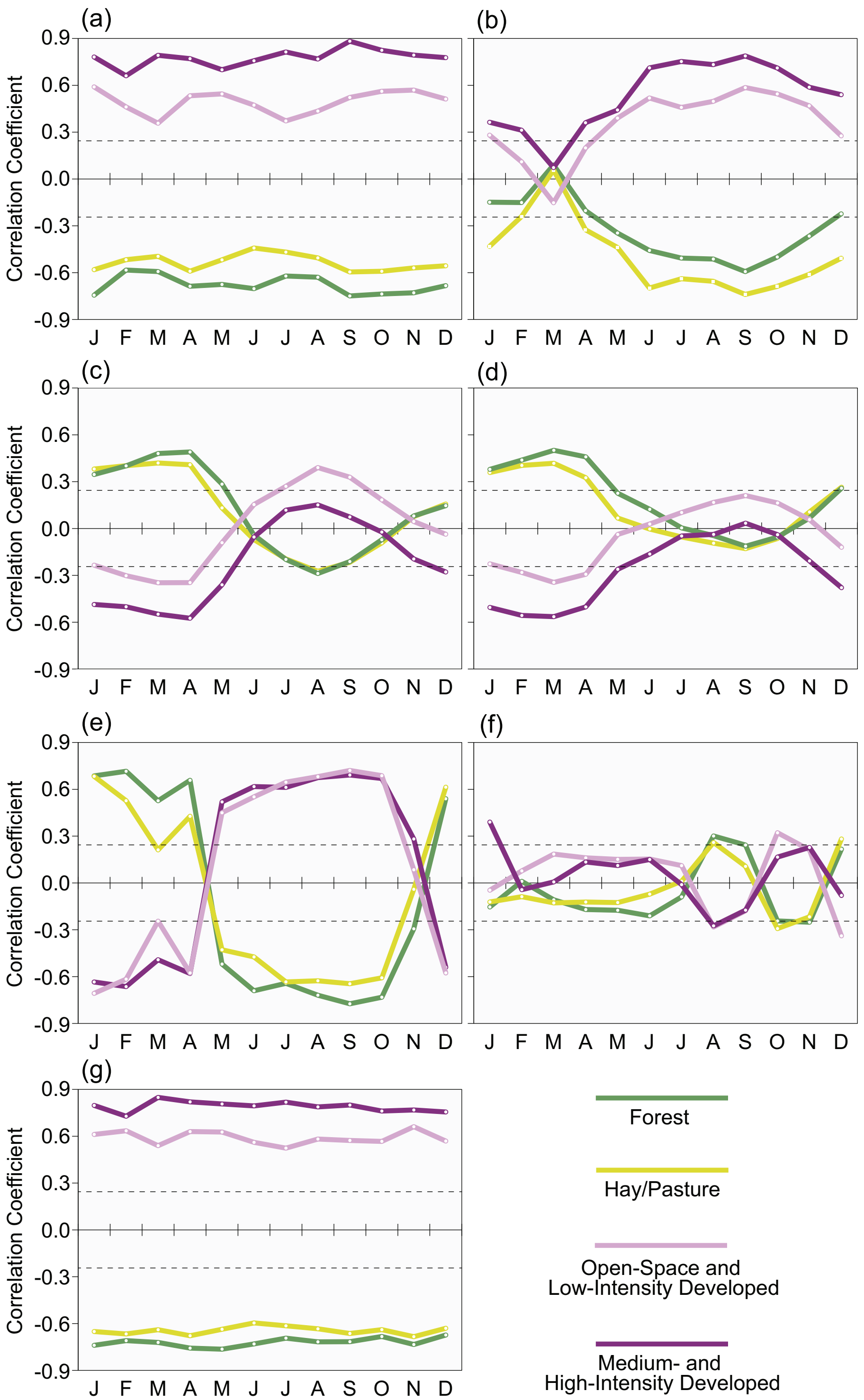

FIGURE 4 Correlations between land-cover variables and mean monthly values of (a) Q_{max}, (b) Q_{mean}, (c) Q_{med}, (d) Q_{min}, (e) frequency of high-flow days, (f) frequency of low-flow days, and (g) flashiness. Correlations above the upper dashed line or below the lower dashed line are significant ($\alpha = 0.01$; one-tailed)

larger, respectively, than values for rural watersheds. Differences in Q_{max} peaked during August–October: urban watersheds had Q_{max} values over four times larger than those for rural watersheds. Compared to rural watersheds, urban watersheds had significantly fewer numbers of high-flow days (i.e., the top 10% of days in terms of flow) during December–April but significantly more high-flow days during May–November (Figure 5(h)). The urban–rural disparity peaked during August–October, when urban watersheds had over three times as many high-flow days.

In contrast to Q_{max} and FI, urban watersheds only had higher Q_{mean} compared to rural watersheds during late spring through autumn (Figure 5(e)). Q_{mean} can be scaled to total stream discharge. During May–December, discharge from urban watersheds was >50% larger than discharge from rural watersheds. Within that period, the difference was maximized during August and September, when urban watersheds had double the discharge of rural watersheds.

Urban watersheds only had lower Q_{med} and Q_{min} flows than rural watersheds during December–April, and low-flow days for all

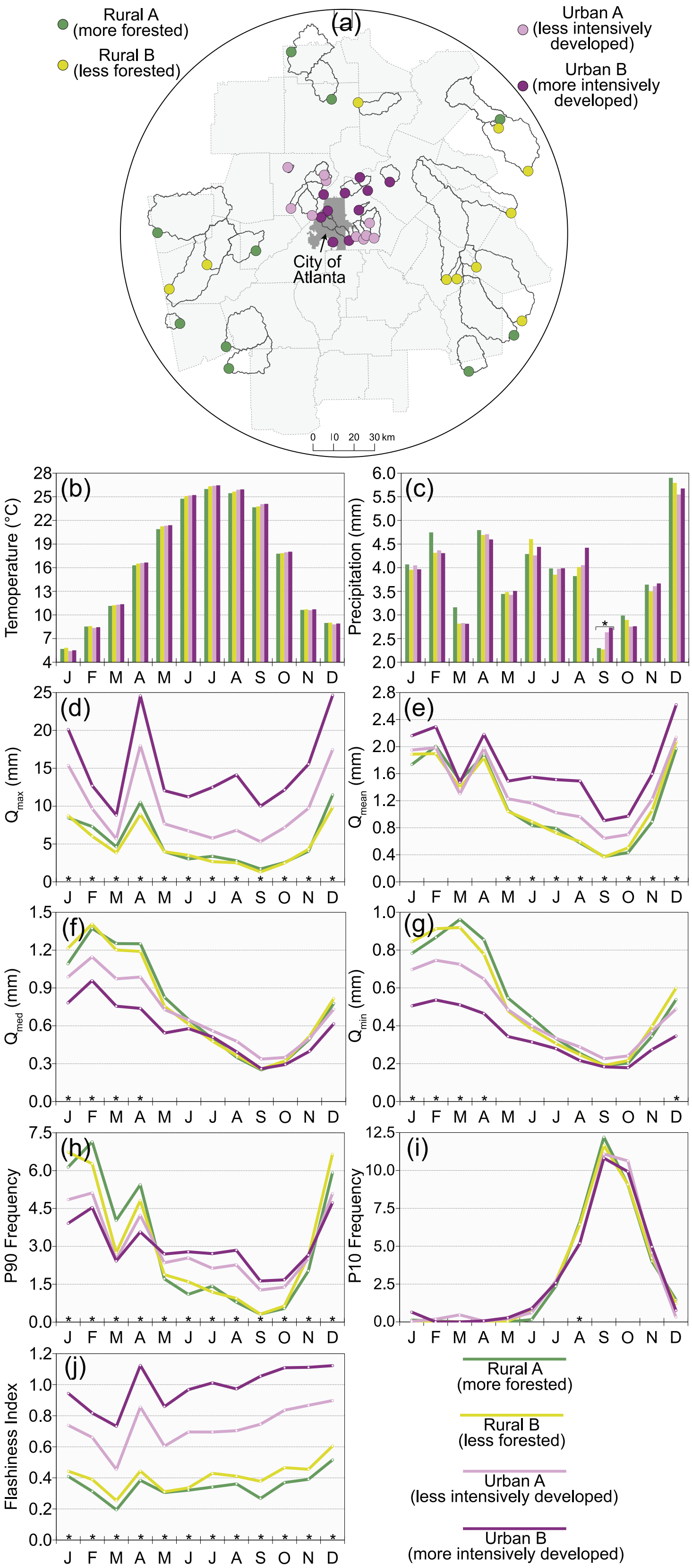

FIGURE 5 (a) Locations of the four groups of watersheds derived from land-cover characteristics, and intra-annual variations in (b) temperature, (c) precipitation, (d) Q_{max}, (e) Q_{mean}, (f) Q_{med}, (g) Q_{min}, (h) frequency of high-flow days (P90) per 30 days, (i) frequency of low-flow days (P10) per 30 days, and (j) flashiness. Asterisks denote significant ($\alpha = 0.01$; one-tailed) differences between urban and rural watersheds

watershed groups were almost entirely limited to July–November (Figure 5(f,g,i)). There were significant differences in Q_{med} and Q_{min} between urban and rural watersheds during January–April and December–April, respectively (Figure 5(f,g)). During January–April, Q_{med} values for urban watersheds were 27% smaller than the values for rural watersheds. During December–April, urban watersheds had

TABLE 1 Mean size, slope, land-cover, imperviousness, and population densities of the four groups of watersheds

Watershed group	Area (km^2)	Slope (%)	F (%)	P&H (%)	OS&LI (%)	MI&HI (%)	I (%)	PD (ppl. K/m^2)
Rural A (more forested)	292	9.8	67	13	8	1	2	47
Rural B (less forested)	359	6.5	50	26	13	2	3	112
Urban A (less developed)	41	7.2	21	1	64	13	21	1248
Urban B (more developed)	26	6.5	11	1	48	39	41	1171

Note: There were significant ($\alpha = 0.01$; one-tailed) differences between the urban and rural watersheds for all variables except slope.
Abbreviations: F, forest; I, imperviousness; MI&HI, medium-intensity and high-intensity developed; OS&LI, open-space and low-intensity developed; P&H, pasture/hay; PD, population density.

TABLE 2 Sewer characteristics of the three watersheds in the South River watershed used for the analysis of inflow and infiltration (I&I)

Gauge/watershed	USGS ID	Name	Area (km^2)	Sewers (km)	Allocation factor
A	02203863	Shoal Creek	22.4	203	0.114
B	02203873	Cobbs Creek	20.6	172	0.097
C	02203960	Snapfinger Creek	85.3	637	0.359

Note: The locations of the three gauges and watersheds are shown in Figure 3. The three watersheds are located in the Snapfinger sewershed, which has 1770 km of sewer lines. Shown in the table are the USGS identification numbers of the gauges, the name of the gauges/watersheds, the area of the watersheds, the total length of gravity mains in each watershed, and the factors used to allocate the sewershed I&I total to each watershed.

Q_{min} values 30% smaller than those for rural watersheds. There were no significant differences in Q_{med} and Q_{min} between urban and rural watersheds during May–November. Urban A watersheds did have the largest Q_{med} and Q_{min} values among the four watershed groups during July–October. The only significant difference between urban and rural watersheds in numbers of low-flow days (i.e., the bottom 10% of days in terms of flow) was in August, where urban watersheds had lower frequencies than rural watersheds (Figure 5(i)).

4.4 | Intra-annual variation in I&I

4.4.1 | I&I across the Atlanta region

WWTP effluent had a strong seasonal component, with flows during winter and early spring much larger than flows during summer and early autumn (Figure 6). Flows during December–April were 12% higher than flows during July–October. January and February had the largest flows, and nearly half the WWTPs had significantly larger flows in February compared to the other months. September and October had the smallest flows, and nearly half the WWTPs had significantly smaller flows in October compared to the other months. Therefore, I&I was prevalent across the region and peaked in magnitude during winter and early spring.

4.4.2 | I&I impacts on streamflow in the SRW

We were fortunate to have over the 2013–2019 period a month, October 2016, that presumably had negligible I&I and was thus an appropriate month to assign base sanitary flow (Figure 7(b–d)). This

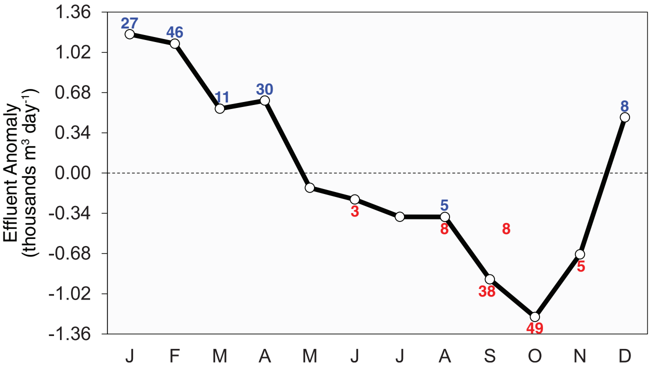

FIGURE 6 Mean monthly effluent from 2013 to 2019 for 36 wastewater treatment plants (WWTPs) within the 90 watersheds. Numbers for each month are the percentages of WWTPs with significantly ($\alpha = 0.05$; one-tailed) higher (blue) discharge and lower (red) discharge for that month compared to the rest of the months

month had the lowest effluent of the 84 months (Figure 7(b)). It was exceptionally warm and dry and was preceded by period of warm and dry conditions (Figure 7(c)). As a result, October 2016 was likely the month with the least soil moisture over the 7 years for the Atlanta region (Figure 7(d)).

I&I contributed substantially to the total effluent from the Snapfinger WWTP and was presumably the main control of the intra-annual variations in effluent (Figure 7(e)). As noted earlier in the paper, the causal relationship between I&I and WWTP effluent has been found in previous studies (Dirckx et al., 2019; Weiß et al., 2002). Based on the minimum-effluent method for estimating I&I, approximately 25% of water treated at the facility was I&I. Mean monthly I&I was approximately twice as large during the soil-water surplus period than during the soil-water deficit period. February was the maximum

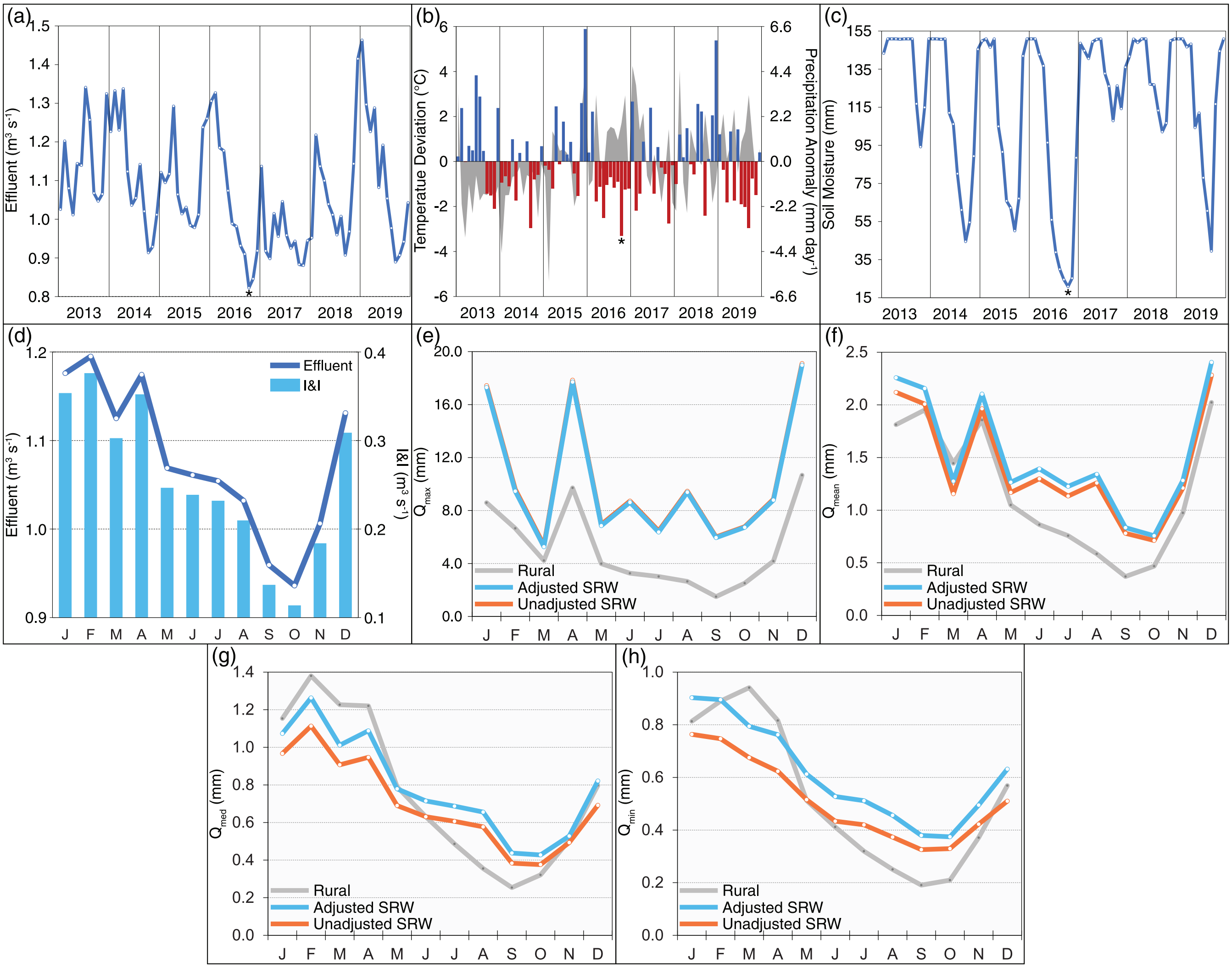

FIGURE 7 (a) Monthly effluent from 2013 to 2019 for the Snapfinger wastewater treatment plant, with the asterisk denoting the minimum value during October 2016. (b) Monthly temperature deviations (i.e., monthly temperature minus mean temperature for that month) as grey areas and monthly precipitation anomalies (i.e., mean daily precipitation total for a month minus the mean daily precipitation total for all months) as blue bars (positive anomalies) and red bars (negative anomalies) from 2013 to 2019 at Atlanta Hartsfield-Jackson International airport. The asterisk denotes October 2016. (c) Monthly soil-moisture estimates for the Atlanta region from 2013 to 2019. The asterisk marks the minimum value during October 2016. (d) Mean monthly effluent and estimated inflow and infiltration (I&I). Mean monthly values for the three SRW gauges without any I&I adjustments, the three SRW gauges with I&I adjustments, and the 20 rural gauges for (e) Q_{max}, (f) Q_{mean}, (g) Q_{med}, and (h) Q_{min}

I&I month and October was the minimum I&I month; there was over three times as much I&I in February than in October.

I&I reduced streamflow in general and was responsible for much of the low-flow reduction during winter and spring (Figure 7(f–i)). All three watersheds examined were in the Urban A group; therefore, the impact on flow statistics for those watersheds should be representative for that watershed group (i.e., less intensively developed urban watersheds). With I&I water added back into the watersheds, there was a negligible impact on Q_{max} (Figure 7(f)), but Q_{mean}, Q_{med}, and Q_{min} did increase by 7%, 14%, and 20%, respectively (Figure 7(g–i)). Assuming the I&I-impacted watersheds would have had similar Q_{med} and Q_{min} values from December–April as the rural watersheds (i.e., the 20 watersheds in the Rural A and B groups) if development had not occurred, then the I&I adjustments made to streamflow during that period account for most of the difference in Q_{med} and Q_{min} between the rural watersheds and the I&I-impacted watersheds. In addition, the anomalously high July–October low flows in the watersheds would have been even more different than natural conditions had I&I not occurred.

5 | DISCUSSION

A major difference between urban watersheds and rural watersheds shown in this study is the decreased seasonality of multiple streamflow metrics for urban watersheds. Compared to rural watersheds, urban watersheds have smaller differences in values of streamflow metrics between the soil-water surplus season

(December–April) and the soil-water deficit season (July–October). This contrast between urban and rural watersheds can be seen clearly for maximum daily streamflow, mean streamflow, median streamflow, minimum streamflow, and the frequency of high-flow days (Figure 5). Those results confirm findings of decreased seasonality in high-flow days (Diem, Hill, & Milligan, 2018) and baseflow (Bhaskar, Hogan, & Archfield, 2016) for watersheds that have undergone urbanization. In the remaining paragraphs in this section, we explain how urban effects on hydrological processes cause the reduced seasonality of streamflow.

Urban watersheds have higher maximum flows and total stream discharge, which is heavily impacted by high flows, than rural watersheds throughout the year, with the disparity peaking during the soil-water deficit season. Also during the soil-water deficit season is a much larger frequency of high-flow days in urban watersheds compared to rural watersheds. This seasonal aspect of urban effects on high flows is not exclusive to the Atlanta region; for example, the largest urban impacts on high flows in the United Kingdom have been observed in the summer (Prosdocimi, Kjeldsen, & Miller, 2015). Urban watersheds in this study have approximately 30% impervious cover, compared to 3% for rural watersheds (Table 1). Therefore, the increased impervious cover of urban watersheds decreases the importance of antecedent soil moisture—which reduces soil drainage—to produce runoff (Manago & Hogue, 2017; Miller & Hess, 2017).

During the soil-water surplus season, urban watersheds have much smaller baseflows than rural watersheds, and I&I is an important contributor to the smaller baseflows. Soil moisture is highest during December–April (Figure 3), thereby maximining I&I and resulting in smaller baseflows in urban watersheds (Figure 7(g,h)). Results from studies in western Europe confirm the peak in I&I during winter and early spring (Braud et al., 2013; Dirckx et al., 2019; Rodel et al., 2017; Weiß et al., 2002). The intra-annual variation in WWTP effluent throughout the Atlanta area (Figure 6), as well as the detailed analysis of WWTP effluent in the SRW (Figure 7(a–d)), provides strong evidence for I&I as a major cause of reduced baseflows in winter and spring.

During the soil-water deficit season, reduced ET in urban watersheds helps to keep baseflow in urban watersheds equal to or larger than baseflow in rural watersheds. It has been well-established that in non-arid climates, ET rates of urban watersheds, which have considerably less vegetation than rural watersheds, have much lower ET rates than rural watersheds during the summer (Bhaskar & Welty, 2012; Boggs & Sun, 2011; Dow & DeWalle, 2000). Urban watersheds in this study have approximately one-quarter the forest cover of rural watersheds (Table 1).

Also during the soil-water deficit season, there should be groundwater recharge in urban watersheds that enhances baseflows compared to baseflows in rural watersheds. A majority of the urban watersheds in this study are in DeKalb County and the City of Atlanta (Figures 1 and 5(a)), and those two municipalities have roughly 20% of distributed water entering watersheds via leaks (Chattahoochee Riverkeeper, 2019). Water use and thus leakage from pipes should be maximized during the summer in the Atlanta region: outdoor water use–primarily through landscape irrigation–causes monthly water use during July–September to be approximately 40% higher than monthly water use during December–March in cities in the southeastern United States (Opalinski, Bhaskar, & Manning, 2020). In addition to increased water leakage during this season, groundwater also should be recharged by excessive irrigation water and net exfiltration from sewers (Passarello, Sharp, & Pierce, 2012).

6 | CONCLUSIONS

Through an examination of intra-annual variations in streamflow from a large number of diverse watersheds in the Atlanta region, this study has shown that season-specific components are needed in the conceptual model of urban effects on streamflow in temperate regions. The two most relevant seasons are the soil-water surplus season and the soil-water deficit season. Those two seasons for the Atlanta region during 2013–2019 were December–April and July–October, respectively. Urban watershed only have reduced baseflow during the soil-water surplus season, and a likely major cause of the reduced baseflow is I&I. During the soil-water deficit season, baseflows may actually be higher in less-developed urban watersheds compared to rural watersheds, and reduced ET combined with municipal-water leaks and outside water use (e.g., irrigation) are the likely causes of the enhanced baseflows. Also during that season, increased development increases the likelihood of high-flow days. Those days for rural watersheds are typically limited to the soil-water surplus season, when soil drainage is minimized. Atlanta, with its temperate climate and associated large differences in soil moisture between winter and summer is representative of many locales in the middle latitudes; therefore, findings in this paper should be highly transferable geographically.

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DATA AVAILABILITY STATEMENT

Data sharing is not applicable to this article as no new data were created or analyzed in this study.

ORCID

Jeremy E. Diem https://orcid.org/0000-0003-1949-5245

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