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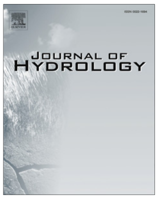

Research papers

Diverse multi-decadal changes in streamflow within a rapidly urbanizing region

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A R T I C L E I N F O

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A B S T R A C T

The impact of urbanization on streamflow depends on a variety of factors (e.g., climate, initial land cover, inter-basin transfers, water withdrawals, wastewater effluent, etc.). The purpose of this study is to examine trends in streamflow from 1986 to 2015 in a range of watersheds within the rapidly urbanizing Atlanta, GA metropolitan area. This study compares eight watersheds over three decades, while minimizing the influence of inter-annual precipitation variability. Population and land-cover data were used to analyze changes over approximately twenty years within the watersheds. Precipitation totals for the watersheds were estimated using precipitation totals at nearby weather stations. Multiple streamflow variables, such as annual streamflow, frequencies of high-flow days (HFDs), flashiness, and precipitation-adjusted streamflow, for the eight streams were calculated using daily streamflow data. Variables were tested for significant trends from 1986 to 2015 and significant differences between 1986–2000 and 2001–2015. Flashiness increased for all streams without municipal water withdrawals, and the four watersheds with the largest increase in developed land had significant increases in flashiness. Significant positive trends in precipitation-adjusted mean annual streamflow and HFDs occurred for the two watersheds (Big Creek and Suwanee Creek) that experienced the largest increases in development, and these were the only watersheds that went from majority forest land in 1986 to majority developed land in 2015. With a disproportionate increase in HFD occurrence during summer, Big Creek and Suwannee Creek also had a reduction in intra-annual variability of HFD occurrence. Watersheds that were already substantially developed at the beginning of the period and did not have wastewater discharge had declining streamflow. The most urbanized watershed (Peachtree Creek) had a significant decrease in streamflow, and a possible cause of the decrease was increasing groundwater infiltration into sewers. The impacts of urbanization on streamflow within the metropolitan area have undoubtedly been felt by a wide of range of communities.

1. Introduction

Urban development within watersheds can cause major changes to streamflow. Urbanization results in the creation of severely compacted and impervious surfaces, changes in consumptive use of water, inter-basin water transfers, and the presence of water-supply, sewage, and stormwater infrastructure (DeWalle et al., 2000; Emerson et al., 2005; Claessens et al., 2006; Goff and Gentry, 2006; Cuo et al., 2008; Bhaskar et al., 2016). When urbanization occurs in forested areas the impacts on hydrology are magnified; compared to agriculture-to-urban changes, forest-to-urban changes cause dramatic decreases in evapotranspiration (Dow and DeWalle, 2000; Brown et al., 2009).

One of the dominant impacts of urbanization is increased peak flows and stream flashiness. The frequency of high flows is positively correlated with the degree of urbanization of a watershed, especially those in warm, humid climates (Poff et al., 2006; Brown et al., 2009; Steuer et al., 2010). Multiple studies have found increasing peak-flow volumes and increasing frequencies of high flows over time as watersheds become more urbanized (Jennings and Jarnagin, 2002; Konrad and Booth, 2005; White and Greer, 2006; Beighley and Moglen, 2002; Rosburg et al., 2017). Stream flashiness is positively correlated with urbanization in non-arid regions (McMahon et al., 2003; Poff et al., 2006), and flashiness increases over time for streams in urbanizing watersheds (Dow, 2007). The increased flashiness is reflected in a storm recession constant for urban streams that is up to double that of other streams (Rose and Peters, 2001). The introduction and expansion of storm drainage systems is a major contributor to increased flashiness (Miller et al., 2014).

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Previous research has shown a weak impact of urbanization on mean annual streamflow. Increased impervious surfaces should increase storm runoff and thus streamflow, but infiltration reduction can lead to reduced dry-period flows (Cuo et al., 2008). Nevertheless, leaks are present in water-distribution systems and may provide recharge to shallow aquifers or augmented flows in surface waters (Meyer, 2002). Wastewater pipes in a watershed can both increase and decrease streamflow: sewer leaks, which occur when the pipes are above the water table, increases groundwater discharge to streams, while sewer infiltration, which occurs when pipes are below the water table, reduces groundwater discharge to streams (Meyer, 2002; Bhaskar et al., 2016). Infiltration and inflow (I&I), which combines the aforementioned groundwater infiltration with stormwater inflow into wastewater pipes, can greatly reduce subsurface water storage in urbanized watersheds (Bhaskar et al., 2015). In addition, flow in wastewater pipes may be supplemented by captured streams and springs (Broadhead et al., 2013). Spatially extensive water supply and wastewater treatment systems of urbanizing areas often rely upon inter-basin transfers, diminishing streamflow in one basin and augmenting another (Zhuang, 2016), but also altering groundwater hydraulics in combination with I&I (Schwartz and Smith, 2014)

In addition to streamflow-altering infrastructure, precipitation variations also can mask expected increasing trends in mean annual streamflow resulting from urbanization. Annual precipitation and mean annual streamflow are often highly correlated; for example, annual precipitation totals explain 44% of the variance in streamflow in urbanizing watersheds in the Houston, Texas area (Rogers and DeFee, 2005). Runoff ratios (i.e., streamflow divided by precipitation), a commonly used precipitation-adjustment metric, also have been shown to be significantly positively correlated with precipitation (Hubbart and Zell, 2013); therefore, runoff ratios do not remove the precipitation effect.

Greater insight into the effects of urbanization on streamflow could be produced if a study compared watersheds over multiple decades, while minimizing the influence of inter-annual precipitation variability. Having both multi-decadal data and a robust number of watersheds in a region enhances an investigation of environmental causes of streamflow changes (Dow, 2007). Therefore, the purpose of this study is to examine trends in precipitation-adjusted streamflow from 1986 to 2015 in a range of watersheds within an urbanizing metropolitan area.

2. Study region

The selected study region is the Atlanta, Georgia metropolitan area in the Piedmont physiographic province in the eastern United States (Fig. 1). Atlanta has been one of the fastest growing areas in the United States over the past several decades: the population of the metropolitan area (i.e., 29 counties) increased from 2.2 million persons in 1980 to 5.3 million persons in 2010 (U.S. Census Bureau, 1996, 2017). Urban effects on streamflow in the Piedmont have been found in multiple studies (Brun and Band, 2000; Rose and Peters, 2001; Jennings and Jarnagin, 2002; Brandes et al., 2005; Konrad and Booth, 2005; Brown et al., 2009; Hopkins et al., 2015b). Comparison studies show that urbanization impacts streamflow in the Piedmont more than in other regions, especially those regions without natural forest cover (Brown et al., 2009; Hopkins et al., 2015b). The eight streams used in this study are Big Creek, Flint River, Line Creek, Peachtree Creek, Sope Creek, South River, Suwanee Creek, and Sweetwater Creek (Table 1).

Metropolitan Atlanta is situated on the eastern sub-continental divide of North America and spans three major river basins; the hydrologic and hydraulic impacts of Atlanta's urbanization affect the Apalachicola-Chattahoochee-Flint (ACF), the Alabama-Coosa-Tallapoosa (ACT), and the Altamaha-Ocmulgee-Oconee (AOO) river basins (Fig. 1). Seven of the eight watersheds examined in this study are in the ACF basin; the South River watershed is in the AOO basin. Approximately 73% of the water supply in the 15-county Metropolitan North Georgia Water Planning District is sourced from the Chattahoochee River basin (e.g., Lake Lanier in Fig. 1) (Metropolitan North Georgia Water Planning District, 2009). For example, the water users in the entire drainage area of the upper South River drainage considered in this study are provided with water sourced from the Chattahoochee basin. Legal conflicts between Georgia, Florida, and Alabama over flows in the ACF and ACT impacted by metro Atlanta water use have persisted for over 25 years, and as such these inter-basin transfers of water are pertinent to ongoing transboundary water resource disputes (Borden, 2014). Urban flooding is a persistent problem in the watersheds of the Atlanta metropolitan area, and growth in exposure to flooding has been directly linked with population growth and spatially correlated with concentrations of urban development (Ferguson and Ashley, 2017).

3. Material and methods

3.1. Population and land cover

Population, housing, and land-cover data were analyzed to determine changes over approximately twenty years within the eight watersheds as well as the relative differences in ages of sewers. Gridded population density data for 1990 and 2010 at 100-m and 60-m resolution, respectively, were obtained from the United States Geological Survey (USGS) (Falcone, 2016). National Land Cover Databases (NLCD) from 1992, 2001, and 2011 were acquired from the Multi-Resolution Land Characteristics (MRLC) consortium (Vogelmann et al., 2001; Homer et al., 2015; Xian et al., 2011). Each database had a spatial resolution of 30 m. A land-cover database with 21 classes was available for 1992, while for 2001 and 2011 there were 16-class land-cover databases along with percent developed impervious databases available. The NLCD 1992/2001 Change Retrofit Product (Fry et al., 2009) allowed proper comparison between 1992 and 2001 by combining the land-cover classes into six general classes (agriculture, barren, developed, forest, grass/shrubland, water, and wetland). Estimates of percent imperviousness for the eight watersheds in 1992 were calculated by dividing the percent developed land in 1992 by the mean of the 2001 and 2011 ratios of developed land to developed impervious land. Finally, the mean year of structure completion, which was used as a proxy for age of sewers, was extracted from American Community Survey 2011–2015 block-group data, provided by the U.S. Census Bureau.

3.2. Precipitation

Precipitation time series from 1986 to 2015 for the eight watersheds were created using precipitation totals at nearby weather stations (Fig. 1 and Table 2). Monthly precipitation data for 12 stations were extracted from the Global Historical Climatology Network database of the National Oceanic and Atmospheric Administration. If multiple rain gauges were associated with a station during a month, then the median total from those stations was used for that station. Griffin and Winder had 67 and 5 months, respectively, with missing rainfall totals, and those missing values were replaced with mean totals from the closest of the remaining stations. An inverse-distance weighting scheme was used to estimate watershed precipitation totals from the gauge-based totals; the weights are shown in Table 2. At least four stations were used to estimate monthly precipitation at a watershed, since the pooling

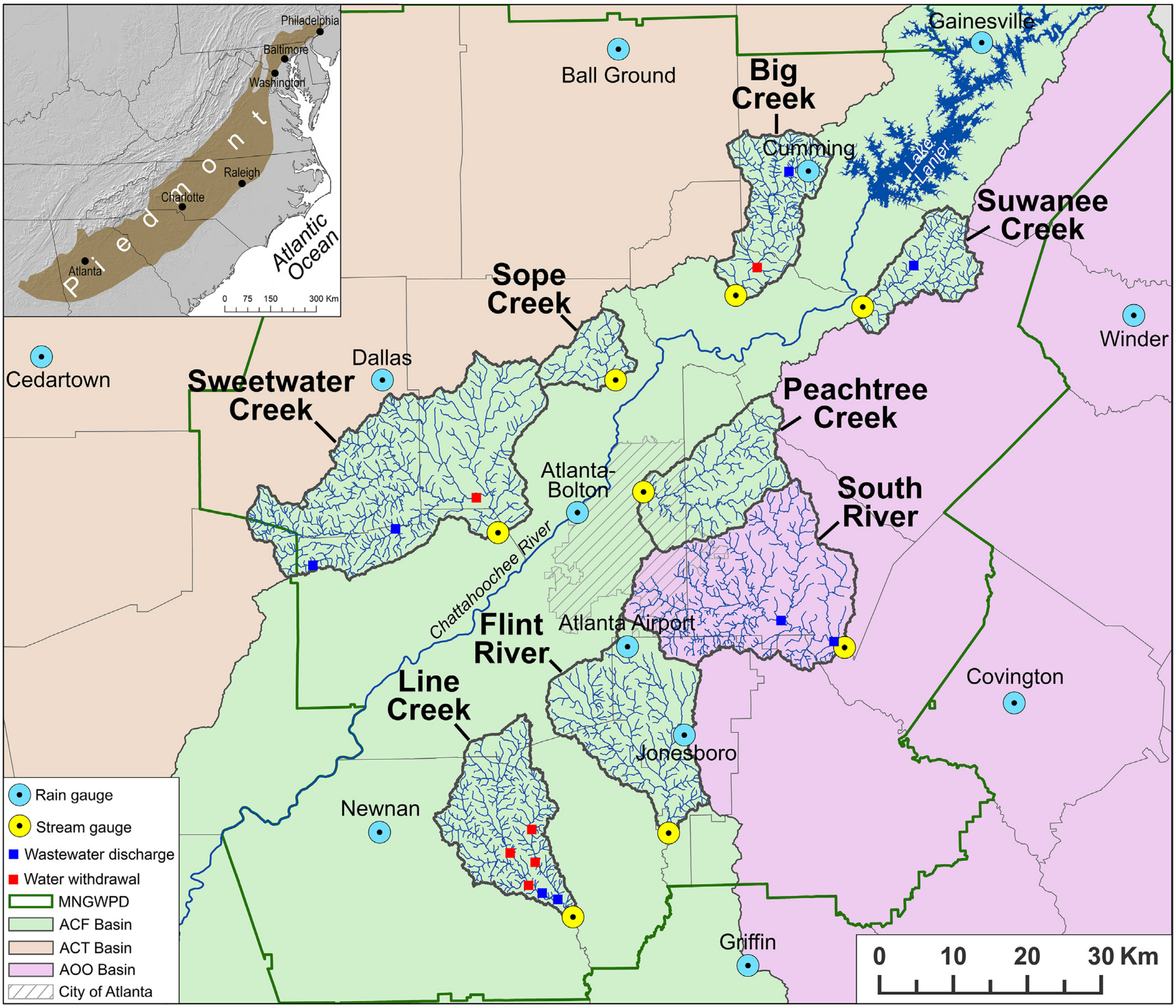

Fig. 1. Locations of the eight watersheds within the Atlanta metropolitan area. MNGWPD is the Metropolitan North Georgia Water Planning District. ACT, ACF, and AOO are the Alabama-Coosa-Tallapoosa, Apalachicola-Chattahoochee-Flint, and the Altamaha-Ocmulgee-Oconee river basins, respectively. The shaded-relief map shows the locations of large cities in the piedmont physiographic province of the eastern United States.

Table 1
Characteristics of the eight streams/watersheds used in the study. Stream abbreviations, which are used in the figures are provided in parentheses. ID is the USGS gauge identification number. Gauge Start is the starting month/year of stream gauge data. Area is the drainage area of the watershed. Structure Year is the mean year of structure completion date. Pop. Dens. 1990 is 1990 population density (persons km^{-2}). Pop. Dens. 2010 is the 2010 population density (persons km^{-2}). Pop. Dens. Increase is the percent increase in population density from 1990 to 2010. Dev. 1992 is the percent of watershed developed in 1992. Dev. 2011is the percent of watershed developed in 2011. Imp. 1992 is the percent of watershed with impervious cover in 1992. Imp. 2011 is the percent of watershed with impervious cover in 2011.

Stream/Watershed	ID	Gauge Start	Area (km^2)	Structure Year	Pop. Dens. 1990	Pop. Dens. 2010	Pop. Dens. Increase (%)	Dev. 1992 (%)	Dev. 2011 (%)	Imp. 1992 (%)	Imp. 2011 (%)
Big creek (BC)	2335700	05/1960	189	1998	111	529	377	28	55	8	17
Flint river (FR)	2344350	05/1985	330	1981	484	673	39	50	64	19	25
Line creek (LC)	2344700	09/1964	259	1993	111	259	133	22	34	6	9
Peachtree creek (PC)	2336300	06/1958	222	1973	1214	1644	35	80	83	31	32
Sope creek (SOC)	2335870	10/1984	79	1979	785	904	15	68	77	18	21
South river (SR)	2204070	10/1983	476	1973	829	928	12	58	67	18	21
Suwanee creek (SUC)	2334885	10/1984	125	1995	129	476	269	29	61	9	21
Sweetwater creek (SWC)	2337000	05/1904	615	1988	222	432	95	29	41	7	10

Table 2
Weights of monthly precipitation totals from rain gauges for each watershed. Refer to Table 1 for the watershed abbreviations.

Station	BC	FR	LC	PC	SOC	SR	SUC	SWC
Atlanta (Airport)	–	0.338	0.223	0.219	–	0.274	0.094	–
Atlanta (Bolton)	0.086	–	–	0.289	0.356	0.197	0.106	0.278
Ball ground	0.143	–	–	–	0.181	–	–	–
Cedartown	–	–	–	–	–	–	–	0.121
Covington	–	–	–	0.111	–	0.130	0.102	–
Cumming	0.614	–	–	0.128	0.195	0.088	0.296	–
Dallas	0.074	–	–	–	0.267	–	–	0.470
Gainesville	–	–	–	–	–	–	0.193	–
Griffin	–	0.091	0.167	–	–	–	–	–
Jonesboro	–	0.483	0.239	0.161	–	0.232	–	–
Newnan	–	0.088	0.372	–	–	–	–	0.131
Winder	0.083	–	–	0.092	–	0.079	0.210	–

of data from multiple stations helps minimize the impacts of station-specific discontinuities (Easterling and Peterson, 1995).

3.3. Soil-water budget

A soil-water budget was used to determine when water surplus and water deficit typically occur, thereby enabling a better understanding of intra-annual variations in streamflow. An initial budget corresponding to a 0.5° grid cell centered on 34.0° N and 84.5° W was created using the WebWimp water-budget model (http://climate.geog.udel.edu/∗wimp/) (Willmott et al., 1985). The default soil water-storage capacity of 150 mm m^{-1} was not altered, but mean month precipitation and temperature data from 1986 to 2015 were used to adjust the model for the study region. Monthly precipitation totals were the mean of the values from the eight watersheds (see Section 3.2). Mean monthly temperatures were calculated for each watershed using gridded 4-km resolution monthly temperature data acquired from the PRISM Climate Group at Oregon State University (http://prism.oregonstate.edu). The final mean monthly temperatures used in the soil-water budget model were the mean of the temperatures from the eight watersheds. The model produced the following estimates for each month: change in soil moisture from the end of the previous month to the end of the current month; water deficit (i.e., unmet water demand); and surplus water (i.e., surface runoff plus percolation below the plant root zone).

3.4. Watershed delineation and topography

A digital elevation model (DEM) was used to delineate watershed boundaries and compare topographic characteristics among the watersheds. The DEM had a spatial resolution of 30 m and was acquired from the National Elevation Dataset of the United States Geological Survey (USGS). The Watershed tool in ArcGIS (Environmental Systems Research Institute) was used to delineate the watersheds. In addition, the mean slope of each watershed was calculated.

3.5. Streamflow variables

Multiple streamflow variables for the eight streams were calculated using daily streamflow data. Daily mean streamflow from 1986 to 2015 were acquired from the USGS. While over 50 years of measurements were available at Big Creek, Line Creek, Peachtree Creek, and Sweetwater Creek, this study began in 1986 since the Flint River, Sope Creek, South River, and Suwanee Creek gauges were installed between 1983 and 1986 (Table 1). The watersheds (i.e., drainage areas) of the eight gauges ranged in size from 79 km^2 for Sope Creek to 615 km^2 for Sweetwater Creek. This large range in drainage area is common among urban-streamflow studies (e.g., Brandes et al., 2005; Brown et al., 2009; Rosburg et al., 2017), and the disparity in sizes was needed in this study to capture a large range in urban development among the watersheds. Daily mean streamflow was converted from $m^3\ s^{-1}$ to mm by diving by drainage area (m^2) and then multiplying by the appropriate number seconds to achieve streamflow at multiple temporal scales. The following was calculated for each stream: (1) annual streamflow; (2) annual runoff ratio; (3) maximum streamflow; (4) baseflow index; (5) median streamflow per day of year; (6) mean monthly frequencies of high-flow days (HFDs); (7) mean and percentile values for HFD streamflow; (8) flashiness index; and (9) precipitation-adjusted annual streamflow and frequencies of HFDs. Maximum streamflow was the median value of the maximum daily streamflow for each of the 30 years, and the baseflow index was the mean value of the 30 values of the annual 7-day minimum flow divided by mean daily flow for the year (Hopkins et al., 2015b). For this study, HFDs had daily streamflow above the 95th percentile for the 10,957 days. Therefore, each stream had 547 HFDs. The R-B index was used as the streamflow-flashiness index, and the index was calculated for each year by dividing the sum of the absolute values of day-to-day changes in mean daily flow by the total discharge for the year (Baker et al., 2004). The precipitation adjustment of annual streamflow and HFD frequency involved regressing those variables against annual precipitation. The resulting residuals (i.e., observed minus predicted), which were independent of annual precipitation, were then treated as new hydrologic variables (e.g., Changnon and Demissie, 1996; Rogers and DeFee, 2005; Hubbart and Zell, 2013).

3.6. Testing for significant trends and differences

The hydroclimate variables were tested for significant trends from 1986 to 2015 as well as significant differences between 1986–2000 and 2001–2015. Trends in precipitation, streamflow, runoff ratio, frequency of HFDs, and flashiness over 1986–2015 were assessed using Kendall-Tau correlation tests ($\alpha = 0.05$; one-tailed). The Kendall-Theil robust line, the median of the slopes between all combinations of two points in the data (Helsel and Hirsch, 2002), was used to estimate changes over the 30-year period. Mann–Whitney U tests ($\alpha = 0.05$; one-tailed) were used to test for significant differences between 1986–2000 and 2001–2015.

Differences in seasonal frequencies of HFDs between 1986–2000 and 2001–2015 also were examined. Two sample chi-square tests ($\alpha = 0.05$) were conducted for each epoch-HFD combination. Contingency tables contained the following frequencies: (1) HFDs during 1986–2000; (2) HFDs during 2001–2015; (3) non-HFDs during 1986–2000; and (4) non-HFDs during 2001–2015.

3.7. Water withdrawal and wastewater discharge

Water-withdrawal and wastewater-discharge data were analyzed to better understand changes in streamflow. Permitted non-farm surface water withdrawal values for 2017 were obtained from the Georgia Department of Natural Resources (Environmental Protection Division, 2017). Permitted wastewater discharge values for 2006 and projected capacities for 2025 for wastewater treatment facilities were acquired from the 2009 Water Supply and Water Conservation Plan of the Metropolitan North Georgia Water Planning District (Metropolitan North Georgia Water Planning District, 2009). Monthly measured wastewater discharge in 2016 and 2017 for the Snapfinger and Pole Bridge wastewater treatment facilities were acquired from DeKalb County (DeKalb County Wasteshed Management, 2017).

4. Results

4.1. Population characteristics of the watersheds

The watersheds with the lowest population densities in 1990 had the largest population increases over the following decades (Table 1). The two northernmost watersheds, Big Creek and Suwannee Creek, had the largest population increases: the populations for Big Creek and Suwanee Creek nearly quadrupled and tripled, respectively, from 1990 to 2010. Those two watersheds were among the three least densely populated watersheds in 1990, but by 2010 they were close to the mean value for all the watersheds. Two southern watersheds, Line Creek and Sweetwater Creek, had roughly a doubling of population over the 20 years. The four most densely populated watersheds in 1990, Peachtree Creek, South River, Sope Creek, and Flint River, had modest population increases from 1990 to 2010; nevertheless, those four watersheds remained the four most densely populated watersheds in 2010.

4.2. Land-cover characteristics of the watersheds

Population densities are linked to the development of the watershed; therefore, changes in the amount of developed land were for the most part highly linked with population changes (Table 1). There was approximately a doubling of developed land in the Big Creek and Suwannee Creek watersheds from 1992 to 2011. Concomitantly, there was also a doubling of impervious surfaces, and the 2015 values most likely exceeded 20% for both watersheds. The Flint River watershed also had relatively large increases in both developed land and impervious surfaces. The most developed watersheds in 1992 experienced the smallest growth over the following two decades. The Peachtree Creek watershed, the most developed and impervious watershed in 1992, had the smallest increases in developed land (3%) and impervious surfaces (2%) among all the watersheds.

The increase in developed land in the eight watersheds came almost entirely at the expense of forest land (Fig. 2; Supplementary Fig. S1). All watersheds lost forest land to development. In 1992, developed land and forest land each comprised approximately 990 km^2 within the eight watersheds. By 2011, the amount of developed land increased by 300 km^2 and the amount of forest land decreased by 300 km^2. The two most rapidly urbanizing watersheds, Big Creek and Suwanee Creek, were the only two watersheds to transform from majority forest land in 1992 to majority developed land in 2011. The Flint River, Peachtree Creek, Sope Creek, and South River watersheds have been majority developed land since as late as 1992. Line Creek and Sweetwater Creek are on trajectories to becoming majority developed land in the next several decades.

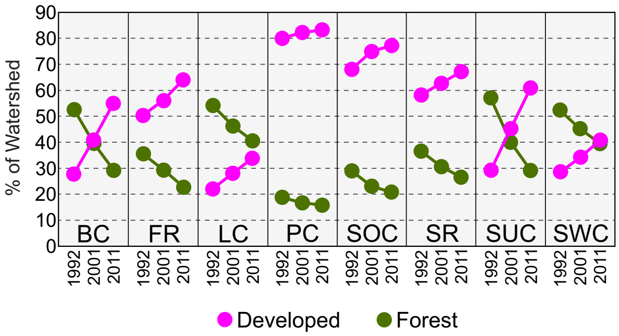

Fig. 2. Changes in the percentages of coverage by developed land and forest in the eight watersheds from 1992 to 2011. See Table 1 for descriptions of the watershed/stream abbreviations.

4.3. Climate and streamflow characteristics

The Atlanta region has a subtropical humid climate type; therefore, spring snowmelt is negligible or nonexistent, and there are distinct soil-moisture surplus and deficit seasons (Fig. 3a and

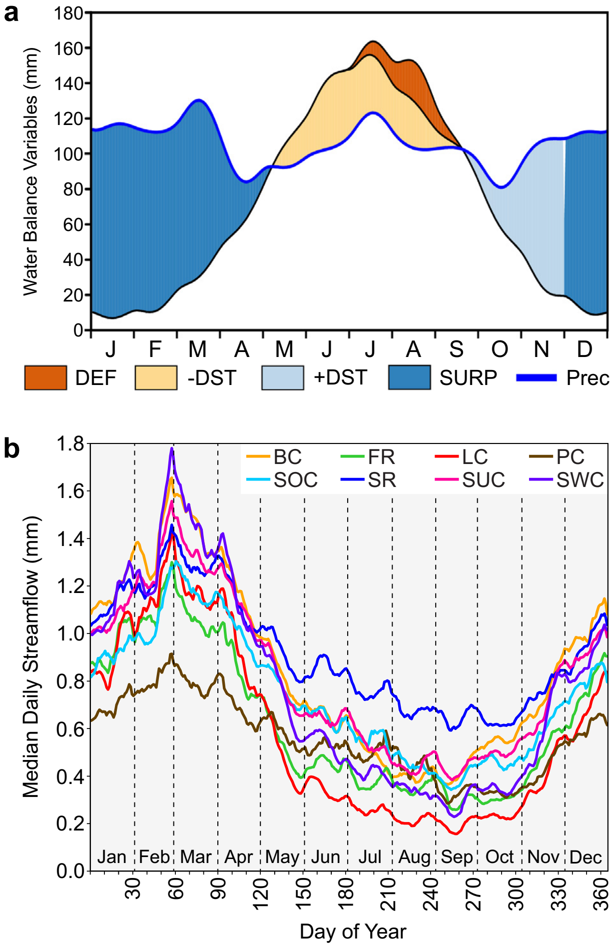

Fig. 3. (a) Soil-water balance for the Atlanta region for 1986–2015. DEF is the deficit or unmet atmospheric demand for moisture. DST is the estimated change in soil moisture from the end of the previous month to the end of the current month. SURP is surplus (i.e., surface runoff plus percolation below the plant root zone). Prec is the monthly total precipitation. (b) Median daily streamflow for the eight streams for each day of the year based on 1986–2015 data. An 11-day moving mean filter was applied to the daily values.

Table 3). The eight watersheds received between 1250 mm and 1300 mm of precipitation annually, and precipitation occurred consistently throughout the year. Over the course of a year, the soil-water surplus, which occurred from December through April, greatly exceeded the soil-water deficit, which occurred from July through September (Fig. 3a).

Despite similar precipitation totals, temperatures, and watershed slopes among the eight watersheds, there were substantial differences in annual streamflow variables (Table 3). Annual streamflow ranged from 407 mm at Line Creek to 576 mm at South River, and those two streams had runoff ratios of 0.31 and 0.45, respectively. The southernmost and least developed watersheds, Line Creek and Sweetwater Creek, had the smallest maximum flows, while the two most developed watersheds, Peachtree Creek and Sope Creek, had the largest maximum flows. Line Creek and Sweetwater Creek also had the lowest baseflow index values, and

Table 3
Topographical, climatological, and hydrological characteristics of the eight streams/watersheds in the study. Slope is mean slope of watershed. Precip. is mean annual precipitation. Temp. is mean annual temperature. Flow is mean annual streamflow. Max. Flow is the maximum daily streamflow. SWW 2017 is the permitted daily surface water withdrawal converted into annual totals. WED is the permitted daily wastewater effluent discharge in 2006 and the projected wastewater effluent discharge for 2025 converted into annual totals.

Stream/Watershed	Slope (%)	Precip. (mm)	Temp. (°C)	Flow (mm)	Runoff ratio	Max. Flow (mm)	Baseflow index	SWW 2017 (mm)	WED 2006 (mm)	WED 2025 (mm)
Big creek	7.0	1298	15.7	538	0.41	24.2	0.16	7	58	58
Flint river	4.7	1264	16.7	485	0.37	23.2	0.11	0	0	0
Line creek	5.0	1255	16.4	407	0.31	14.6	0.08	155	32	32
Peachtree creek	6.7	1260	16.5	519	0.40	34.6	0.11	0	0	0
Sope creek	6.6	1291	16.0	551	0.42	34.1	0.13	0	0	0
South river	6.5	1259	16.6	576	0.45	23.7	0.29	0	163	270
Suwanee creek	7.5	1277	15.9	510	0.39	22.7	0.15	0	22	50
Sweetwater creek	6.0	1295	16.1	480	0.36	14.6	0.09	3	2	6

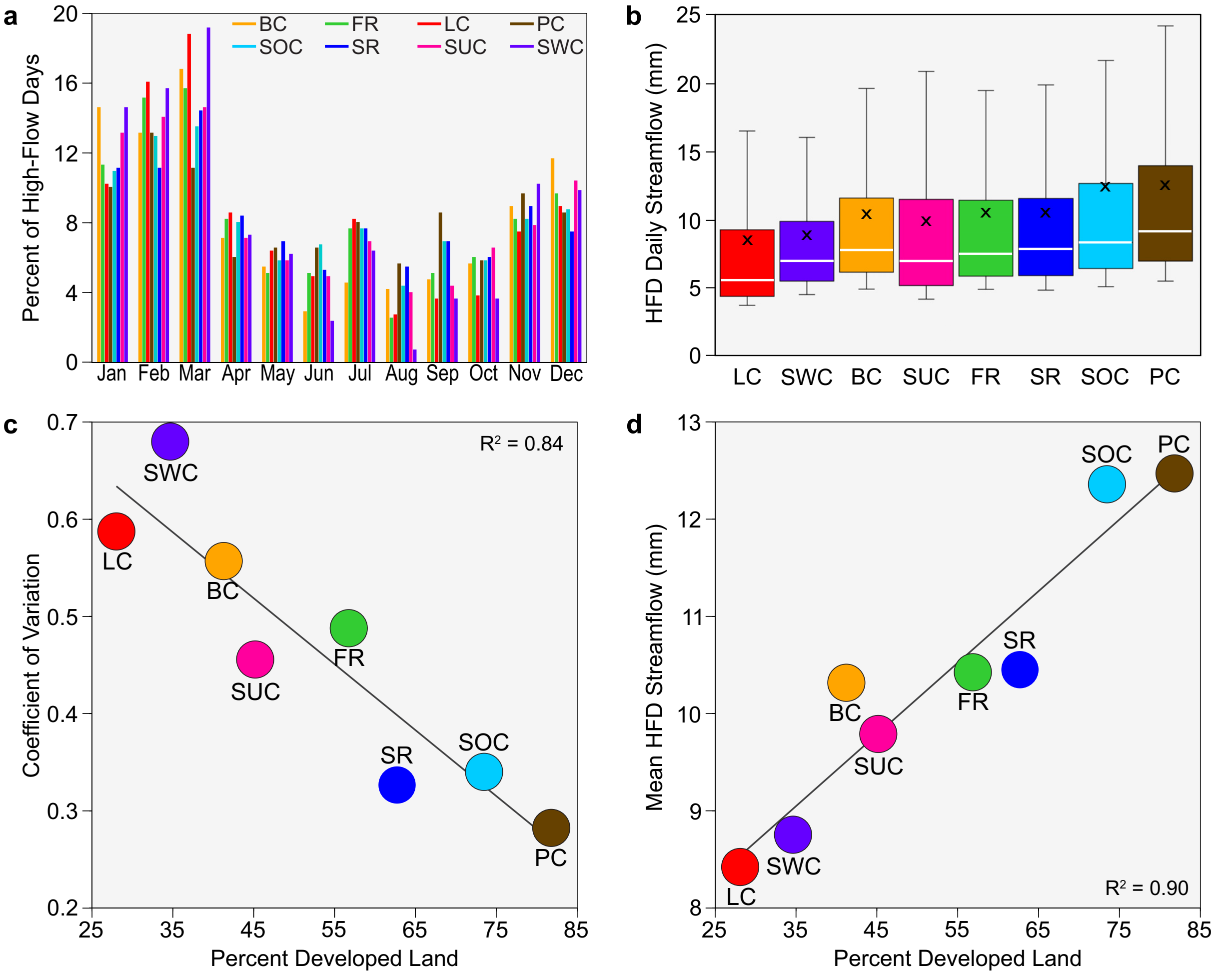

Fig. 4. (a) Percentage of high-flow days occurring in each month. (b) Box and whisker plots of daily streamflow for high-flow days, showing non-outlier minimum, first quartile, median (white line), mean (X), third quartile, and non-outlier maximum values. (c) Scatter plot of the inter-monthly coefficient of variation in high-flow day frequency versus the mean percentage of developed land from 1992 to 2011. (d) Scatter plot of mean streamflow on high-flow days from 1986 to 2015 versus the mean percentage of developed land from 1992 to 2011. All streamflow values are for 1986–2015.

on the other extreme was South River, with a baseflow index that was nearly twice as high as the next highest value.

Intra-annual variations in streamflow at most watersheds related closely to monthly variations in the soil-water balance, with major discrepancies among the watersheds occurring during the surplus and deficit seasons (Fig. 3). For the streams as a whole, streamflow was maximized in late February/early March (i.e., the peak of the soil-water surplus season) and was at a minimum in September, which was at the end of the soil-water deficit season. Three major anomalies in Fig. 4b are as follows: (1) South River had approximately 70% more discharge than the other streams from June through September; (2) Line Creek had approximately 50% less discharge than the other streams from June through September; and (3) Peachtree Creek had approximately 35% less discharge than the other streams from December through April.

The intra-annual variation in occurrence of high-flow days was related strongly to climate and development (Fig. 4a). Over 40% of the high-flow days occurred from January through March (i.e., soil-water surplus months) with March being the peak month. July, which had 15% more precipitation than the other summer months, had the most HFDs of the summer months. Compared to the other streams, the most developed streams (i.e., Peachtree Creek, Sope Creek, and South River) had approximately 50% more HFDs during the soil-water deficit months (i.e., July–September) and approximately 20% fewer HFDs during the soil-water surplus months (i.e., December–April). Accordingly, there was a strong negative relationship between development and intra-annual variability in HFD occurrence (Fig. 4c).

The more developed the watershed the more intense the HFDs (Fig. 4b, d). Peachtree Creek and Sope Creek had the largest mean,

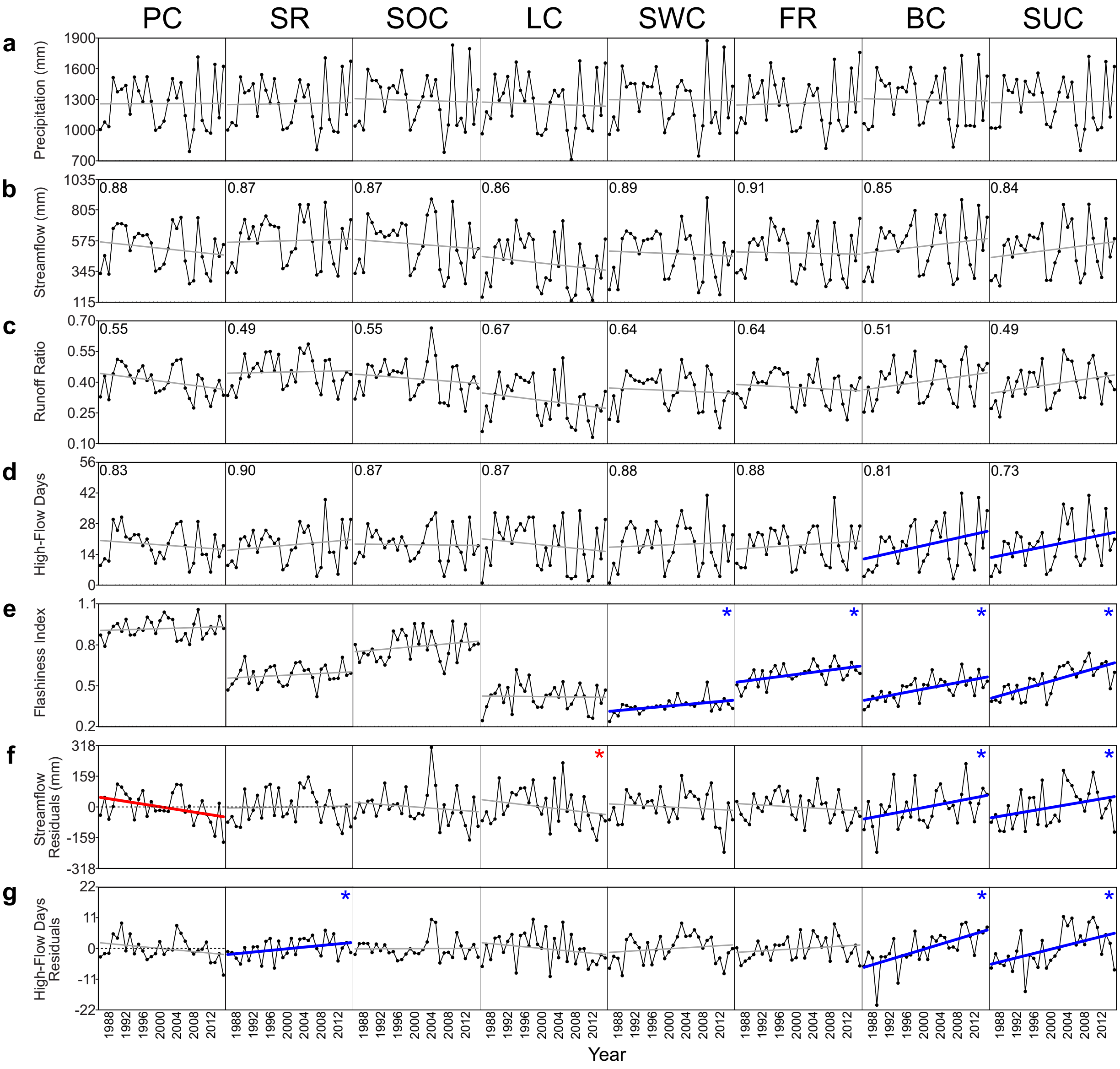

Fig. 5. Annual time series from 1986 to 2015 of (a) precipitation, (b) streamflow, (c) runoff ratio, (d) frequency of high-flow days, (e) flashiness index, (f) streamflow residuals, and (g) high-flow day frequency residuals. Precipitation was used as the predictor variable in linear-regression models to produce the residuals. Blue lines represent significant ($\alpha = 0.05$; one-tailed) increasing trends and red lines represent significant decreasing trends. Grey lines represent non-significant trends. Blue asterisks indicate significantly ($\alpha = 0.05$; one-tailed) higher values for 2006–2015 compared to 1986–1995, while red asterisks indicate significantly lower values for the 2006–2015. The numbers for streamflow, runoff ratio, and frequency of high-flow days are the correlations between those variables and annual precipitation. All correlations are significant ($\alpha = 0.05$; one-tailed).

median, first quartile, and third quartile values for HFD streamflow. Line Creek had the lowest values for those four statistics. Therefore, there was an extremely strong relationship between developed land within a watershed and HFD mean streamflow.

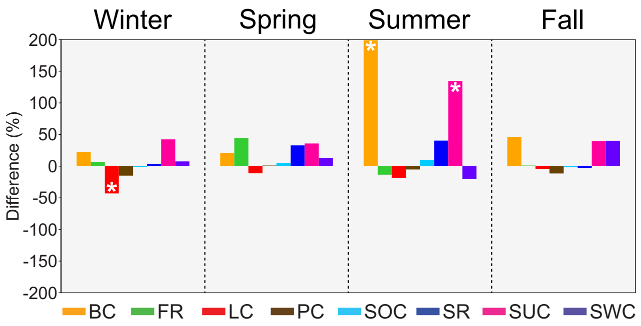

Fig. 6. Change in frequencies of high-flow days from 1986–2000 to 2001–2015 during winter (December–February), spring (March–May), summer (June–August), and autumn (September–November). Asterisks indicate significant ($\alpha = 0.05$) differences in frequencies between the two epochs.

4.4. Multi-decadal changes in streamflow

There were no significant trends from 1986 to 2015 in precipitation, unadjusted streamflow, and runoff ratio at any of the streams/watersheds (Fig. 5a–c). Streamflow was highly correlated (i.e., ≥ 0.84) with precipitation, and trends in streamflow were more substantial than trends in precipitation. Runoff ratio also was highly correlated with precipitation, as has been found by Hubbart and Zell (2013), and the inter-annual variability in precipitation masked trends in runoff ratio. For all eight streams, the inter-annual variability and trends in streamflow and runoff ratio were nearly identical.

Most of the streams had either significant trends, significant inter-epochal differences, or both for HFDs, flashiness index, HFD residuals, or streamflow residuals (Fig. 5d–g). There were significant positive trends in HFDs at Big Creek and Suwanee Creek, where HFD frequency increased by 101% and 90%, respectively, over the 30 years. The flashiness index had significant positive trends at Big Creek, Flint River, Suwanee Creek, and Sweetwater Creek, with the percent increases ranging from 20% at Sweetwater Creek to 66% at Suwanee Creek. These four watersheds had the largest percentage increases in developed land from 1992 to 2011. Removing the effects of inter-annual precipitation variability

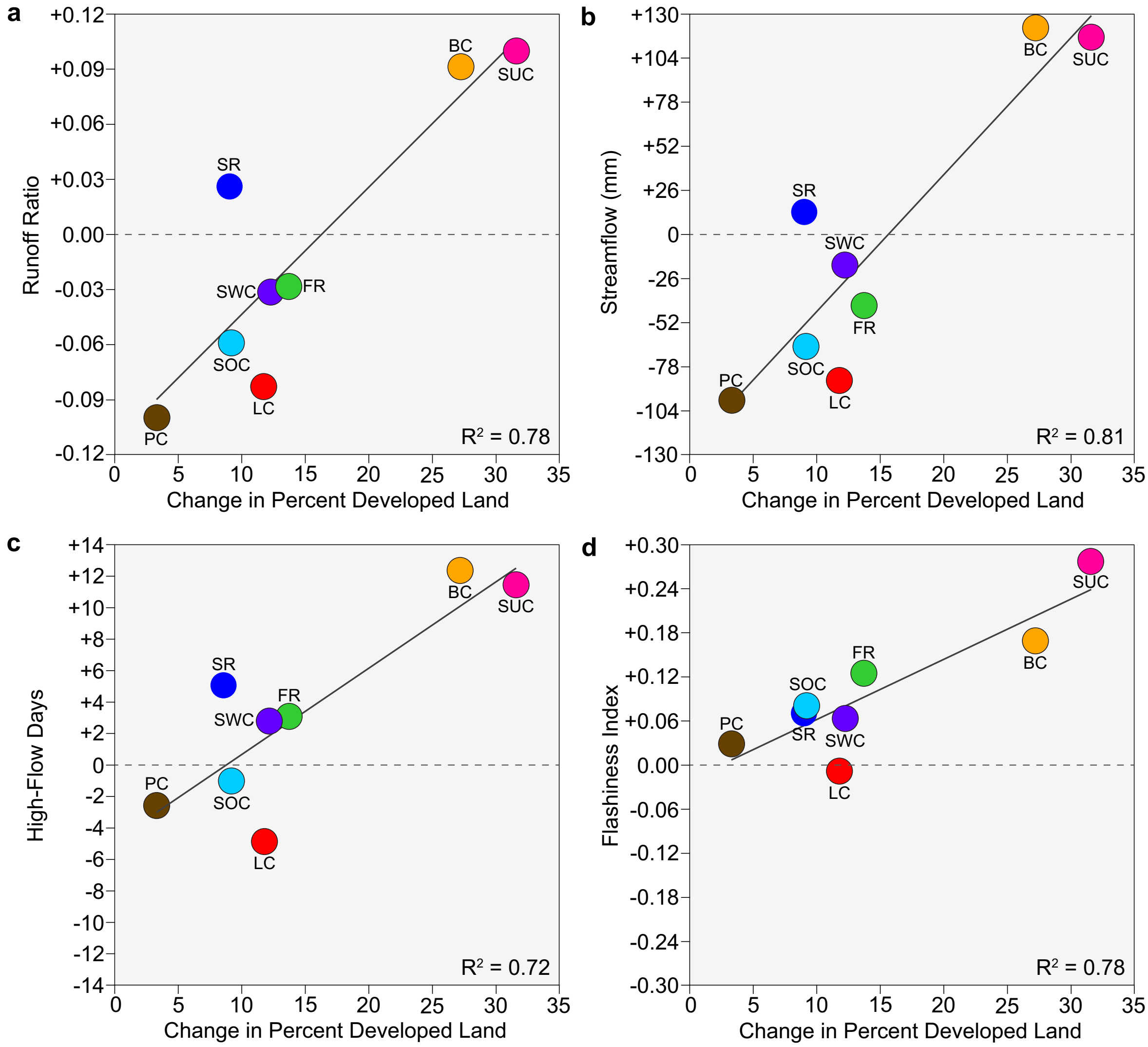

Fig. 7. Scatter plots of changes from 1986 to 2015 in (a) runoff ratio, (b) streamflow, (c) frequency of high-flow days, and (d) flashiness index versus changes in percent developed land from 1992 to 2011.

revealed significant changes in streamflow and additional significant increases in HFDs. Similar to streamflow, HFD frequency also was strongly correlated with precipitation totals. Streamflow at Big Creek and Suwannee Creek increased by 26%, while streamflow at Peachtree Creek decreased by 17%. Minimizing the influence of precipitation on HFDs confirmed the significant increase in HFDs at Big Creek and Suwanee Creek, while revealing a relatively small yet significant increase in HFDs at South River (32% increase).

At the seasonal scale, increases in HFDs were more common than decreases (Fig. 6). Big Creek and Suwanee Creek had significant increases of 200% and 135%, respectively, in HFDs in summer from 1986–2000 to 2001–2015. None of the other increases for stream/season combinations were significant. The only significant decrease occurred at Line Creek, which experienced a 40% decrease in HFDs during winter from 1986–2000 to 2001–2015.

Increased developed land was strongly positively correlated with mean streamflow, HFDs, and flashiness (Fig. 7). Big Creek and Suwanee Creek had much larger increases in percent developed land from 1992 to 2011 than the other watersheds, and Big Creek and Suwanee Creek had the largest increases in runoff ratio, mean streamflow, HFDs, and flashiness from 1986 to 2015. Only one other stream, South River, had increases in all four variables over the 30 years; it had a relatively large change in runoff ratio, streamflow, and HFDs with respect to the modest change in developed land in the watershed. Five streams had decreases in runoff ratio and streamflow, with Peachtree Creek having the largest decreases. Three streams, Peachtree Creek, Line Creek, and Sope Creek had decreases in HFDs. And with the exception of Line Creek, streams had increased flashiness over the 30 years.

5. Discussion

Increased development of watersheds in the Atlanta metropolitan area is the likely cause of increased maximum flows, flashiness of streams, and decreased intra-annual variability in frequencies of HFDs (Figs. 4 and 5). Significant positive correlations between urbanization and maximum flows have been found previously for Atlanta as well as for Raleigh, Milwaukee-Green Bay, and Dallas-Fort Worth (Brown et al., 2009). The more developed watersheds (e.g., Peachtree Creek) in the Atlanta region have had relatively more HFDs during the summer than the less developed watersheds (e.g., Sweetwater Creek); thus, HFDs are distributed more evenly throughout the year in urbanized watersheds.

Urbanization of the Big Creek and Suwanee Creek watersheds contributed to substantial increases in streamflow from 1986 to 2015. Annual streamflow increased by over 115 mm (i.e., a 26% increase) in both watersheds. The increased streamflow caused the runoff ratio to increase from approximately 0.35 to 0.45 over the past 30 years. The increased streamflow was particularly evident in the increase of HFDs: the number of HFDs increased by approximately 100% for both streams. The largest percentage-based increases in HFDs for Big Creek and Suwanee Creek occurred during the summer, thereby decreasing the intra-annual variability in HFD frequency and making those streams more similar to Peachtree Creek and Sope Creek, the two most urbanized watersheds.

The HFD results are similar to what has been found for other urbanizing watersheds in Atlanta and watersheds in other parts of the United States. Among eight small watersheds located in Gwinnett County of metropolitan Atlanta, there was a positive correlation between trends in effective impervious area and trends in peak streamflow and runoff from 2001 to 2008 (Aulenbach et al., 2017). For six urbanizing watersheds examined in Baltimore, MD, Boston, MA, and Pittsburgh, PA, there were significant increases in annual frequency of high-flow events in all watersheds over periods of at least 40 years; precipitation did not increase significantly at any of the watersheds (Hopkins et al., 2015a). And in western Washington, the 95th percentile of daily flows increased by approximately 40% from 1960 to 2010 (Rosburg et al., 2017).

Inter-basin water transfers contributing substantial effluent from two wastewater treatment plants were responsible for the relatively high streamflow, especially in the summer, at South River (Table 3 and Fig. 4). Treated wastewater supplements urban streamflow throughout the developed world (Paul and Meyer, 2001), with dramatic increases in discharge in arid and semi-arid regions (Dennehy et al., 1998; Townsend-Small et al., 2013). The present day combined discharge from the Snapfinger and Pole Bridge facilities, most of which originated as an inter-basin transfer, provides approximately 84 mm of additional annual streamflow at the South River gauge. This effluent discharge is approximately half the permitted amount (Table 3). The wastewater effluent increases annual streamflow by up to 15% and thus gives South River an artificially high runoff ratio. For example, without this excess water, the runoff ratio for 2011–2015 would have been 0.35, compared to the actual value of 0.41. Wastewater discharge from the two treatment plants might reach 352,000 m^3 day^{-1} (i.e., 270 mm annually) in 2025 (Table 3), and thus add an additional 186 mm annually to the South River and result in an extremely high runoff ratio of 0.55.

I&I is a possible cause of the relatively low streamflow at Peachtree Creek during winter and spring as well as the decreasing streamflow over the 30 years. During December–April, when the water table is high, Peachtree Creek has 35% less streamflow (i.e., approximately 54 mm) than the other streams. Annual streamflow for Peachtree Creek decreased by 100 mm from 1986 to 2015. The Peachtree Creek watershed, which has the highest population density among the watersheds and highest percentage of developed land, should have the highest density of sewage pipes. Moreover, the amount of infiltration increases proportionally with the age of the sewer (in Rödel et al., 2017), and much of the housing in the watershed is at least 40 years old (Table 1). I&I has been show to greatly affect the hydrological budget in Baltimore, another Piedmont city with a climate similar to that of Atlanta: I&I is the largest human influence on groundwater levels in the Baltimore metropolitan areas, with an annual loss of water of 29 mm for the region as a whole and annual losses of hundreds to thousands of mm in some heavily urbanized parts of Baltimore (Bhaskar et al., 2015).

Urbanization and the associated increase in wastewater effluent is the likely cause of the 30% increase in HFD frequency at South River over the past three decades. Since 1986, the population has increased by at least 12% and the watershed has become at least 9% more developed (along with an increase in the amount of impervious cover) (Table 1). Similar to Peachtree Creek and other urbanized watersheds, I&I is probably a major issue in the South River watershed, except that I&I water remains in the South River watershed and is eventually discharged at the two wastewater treatment plants upstream of the stream gauge. Wastewater effluent in general has increased from the two facilities as the watershed population has increased.

Water withdrawals are the likely cause of the relatively low streamflow of Line Creek. This is the only stream with water withdrawals for municipal consumption; as a result, it has the smallest runoff ratio and baseflow index of all the streams. The current permitted water withdrawals total approximately 100,000 m^3 day^{-1}, and if fulfilled, would reduce annual streamflow by 155 mm (Table 3). There is relatively little wastewater effluent discharge (i.e., the permitted total is less than 23,000 m^3 day^{-1}) to compensate for the above water loss. Compared with the least impacted stream, Sweetwater Creek, streamflow of Line Creek from 1986 to 2015 was 15% lower.

Direct and indirect water removal from Line Creek watershed caused streamflow to decrease by 20% from 1986 to 2015. Although there was not a significant trend in mean annual streamflow, four of the five most negative streamflow residuals occurred in the final eight years of the study period. The population of the watershed increased by 130% from 1990 to 2010 (Table 1), and since 1986, several reservoirs have been constructed within the watershed, an existing water-treatment plant has been expanded multiple times, and a new plant was completed in 2001 (Fayette County Water System, 2017). The reservoirs might cause large losses of water: even small reservoirs in the southeastern United States can account for considerable evaporative losses severely impacting hydrologic flows, especially in drier years (Ignatius and Stallins, 2011). In 2016, the Newnan Utilities pumping station on Line Creek began increasing water withdrawals by 25% over withdrawals in 2015 (Newnan Utilities, 2015). During the second half of 2012, Line Creek effectively "ran dry" above the Fayette County and Newnan Utilities water intakes, suggesting that both impacts from land use and evaporative losses from small reservoirs may be contributing to extremely low surface flows, especially in periods of drought (Emanuel and Rogers, 2013). Increased water withdrawals, land use change including urbanization, and increased impoundments in the upper Flint River basin, such as in Line Creek, are having detrimental impacts downstream, including limitations to recreational use in times of drought, disruption to environmental flows and extreme low flow events that threaten endemic and endangered species, and an increased threat of water scarcity for municipal, agricultural, and industrial withdrawals (Emanuel and Rogers, 2013; Emanuel, 2014). Moreover, these impacts further compound the issues in the so-called water wars over flows in the ACF basin between Georgia, Florida, and Alabama.

6. Conclusions

The impact of urbanization on multi-decadal changes in hydrological variables depends on a variety of factors, including climate, initial land cover, pace of development, water withdrawals, inter-basin transfers, wastewater discharges, and the extent and age of sewage pipes. This study has shown that each of those factors contributed to varying trends in precipitation-adjusted streamflow and HFDs in the Atlanta metropolitan area from 1986 to 2015. While all eight watersheds in the study had increased developed land and impervious surfaces over the 30 years, significant increases in streamflow only occurred in the two watersheds that transitioned from majority forest land to majority developed land. Watersheds that were over 60% developed at the beginning of the period and did not have wastewater discharge actually had declining streamflow, with I&I being a probable cause. These streams also did not have increases in HFDs, which was more common than increased annual streamflow among the eight streams. The only other stream without increases in HFDs was the stream with large and increasing water withdrawals for municipal consumption. HFD occurrence in the Atlanta area peaks in spring and is lowest in summer, but urbanization causes a much larger increase in HFDs during summer compared to the other seasons. Therefore, the most urbanized watersheds have the smallest intra-annual variability in HFDs. Those watersheds also had the most intense HFDs.

The diverse impacts of urbanization on streamflow within the Atlanta metropolitan area have undoubtedly been felt by a wide of range of communities. Increased HFDs in urbanizing watersheds, such as Big Creek and Suwanee Creek, contributes to greater vulnerability to flooding in many urban and suburban communities of metropolitan Atlanta. On the other hand, Atlanta, despite its relatively humid climate and seeming abundance of surface flows, is increasingly stressed by the availability of fresh water. Line Creek and other watersheds in the upper Flint River have been severely impacted in recent decades by increasing water withdrawals and diminished flows resulting from urbanization. Especially in periods of drought, the compounding downstream effects of diminished flows as exhibited in Line Creek threaten the water supply of increasing numbers of metro Atlanta residents, degrade riparian and aquatic habitats, and create disconnections in environmental flows. Moreover, both the decreased flows in the upper Flint River system and inter-basin transfers of water from the Chattahoochee basin into the upper South River watershed contribute to escalating interstate conflicts over minimum flows in the ACF basin. Consequently, a better understanding of hydraulic and hydrologic processes is essential for planning urban development, designing effective infrastructure, mitigating pollution, and managing water resources.

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at https://doi.org/10.1016/j.jhydrol.2017.10.026.

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