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RESEARCH ARTICLE

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Key Points:
- The effects of urban development on streamflow characteristics were investigated for 119 watersheds throughout Charlanta
- The extent, spatial configuration, and positioning of urbanization significantly influenced streamflow characteristics
- Land use policies that manage the extent, configuration, and positioning of urban development may help minimize streamflow alteration

Supporting Information:
- Figure S1–S2

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The Influence of Urban Development Patterns on Streamflow Characteristics in the Charlanta Megaregion

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Abstract Although it is widely recognized that urbanization has a notable impact on streamflow characteristics, the relative influence of the extent, spatial configuration, and positioning of urban development on low, high, and peak flow regimes is still not fully understood. The overarching research objective of this study was to clarify these relationships by analyzing 119 watersheds throughout the Charlanta megaregion, which stretches from Charlotte, NC to Atlanta, GA. Spatial metrics were derived from land use/land cover data sets to quantify the urban development patterns of each watershed while the streamflow characteristics were evaluated using mean daily discharge and annual peak streamflow data. Analysis of variance tests, bivariate correlations, and multivariate regression models were used to identify intraregional variability and quantify the impact of urban development patterns on streamflow characteristics while controlling for the physical differences between watersheds. The statistical analysis revealed that increasing the extent of urban development enhanced high and low flow frequency as well as annual peak unit discharge. Therefore, urbanization within Charlanta generally produced a more extreme streamflow regime. In terms of the spatial configuration of urban development, the models indicated that more contiguous developed open space increased high and low flow frequency. Finally, the positional analysis suggested that clustering impervious surfaces in source areas distant from streams increased the frequency of high flows. The study highlights the overall importance of considering the extent, configuration, and positioning of urban development when devising land use policies aimed at minimizing streamflow alteration due to urbanization.

1. Introduction

With over half the world's population currently residing in urban areas and this proportion projected to approach 66% by 2050 (United Nations, 2014), the pressures placed on the natural environment by urban development are widely evident and likely to increase in the future. The hydrologic regimes of rivers are no exception, as continued urbanization has produced notable and widespread alterations of streamflow characteristics (Burian & Pomeroy, 2010; DeWalle et al., 2000; Poff et al., 2006). The impervious surfaces, storm water drainage systems, and compacted soils common throughout urban environments typically increase peak flows, runoff volumes, and flashiness (Leopold, 1968; Sauer et al., 1984). These alterations not only endanger urban infrastructure and human lives but also threaten the ecological sustainability of urban river systems (Ashley & Ashley, 2008; Brown et al., 2009). Consequently, moderating such impacts via effective land use planning appears imperative.

One of the original techniques utilized to encourage sustainable levels of development was the identification of total and/or effective impervious area thresholds above which urbanization noticeably degraded natural streamflow characteristics (Booth & Jackson, 1997; Klein, 1979; Schueler, 1994; Schueler et al., 2009; Shuster et al., 2005; Wang et al., 2001). Although such thresholds can inform best management practices, they often fail to explicitly address how the urban development is configured spatially and positioned within watersheds (Brabec, 2009). Therefore, studies have begun exploring the influence of the spatial configuration of urban land use and the positioning of impervious surfaces, either near watershed outlets or in more distant headwaters, on streamflow characteristics to guide more precise land use planning measures.

Developing watershed headwaters is theorized to produce larger peak discharges because the time of concentration is reduced, which superposes the peaks observed in the distant portions of the watershed with those closer to the outlet (Beighley & Moglen, 2002). However, studies based upon stream gage observations have largely been unable to establish clear statistical relationships between the positioning of urban

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development and streamflow responses (Beighley & Moglen, 2002, 2003; Sauer et al., 1984; ten Veldhuis et al., 2018; Wright et al., 2012; Zhou et al., 2017). Modeling efforts evaluating hypothetical distributions of imperviousness have more successfully revealed that clustering urban development in headwater locations and source areas increases peak flows on an annual and individual storm basis (Mejia & Moglen, 2009, 2010). The hydrologic influence of the spatial configuration of urban development, rather than its relative positioning within watersheds, has been analyzed less frequently, with more fragmented and less connected urban land use configurations generally found to minimize the impacts of urbanization on streamflow (Kim & Park, 2016; McMahon et al., 2003; Olivera & DeFee, 2007).

Although past studies have highlighted the importance of urbanization in governing streamflow characteristics, this paper aims to address several notable gaps present within the literature. First, the inability of observational studies to identify consistent statistical relationships between the positioning of urban development and streamflow responses highlights the necessity of developing more nuanced methodologies for quantifying the relative positioning of impervious surfaces within watersheds. Relying upon simplistic measures, such as calculating the percentage of urban development within each quarter of a given watershed, may explain why modeling efforts have largely been more successful in elucidating these relationships. Second, the generalizability of the findings from previous studies may be limited because they often analyze a small number of watersheds (e.g., Beighley & Moglen, 2003; Olivera & DeFee, 2007; Roberts, 2016). The lack of substantial sample sizes has also prevented the widespread usage of rigorous multivariate statistical techniques, as the measures evaluating the positioning and spatial configuration of urban development are commonly used as qualitative aids when interpreting various streamflow responses (e.g., Olivera & DeFee, 2007; Wright et al., 2012). These concerns have led to numerous calls for studies with larger sample sizes to evaluate the generalizability of the relationships between urban development patterns and streamflow characteristics (Olivera & DeFee, 2007; Roberts, 2016).

Finally, apart from McMahon et al. (2003), previous research has focused primarily on how urban development patterns influence peak flows (Ferguson & Suckling, 1990; Hamel et al., 2015). Although peak flows are relevant to damaging flood events, base flow alterations can have equally important ecological ramifications (Poff et al., 2006). Additionally, the relationships between urbanization and low flow patterns remain unclear (Bhaskar et al., 2016; Brown et al., 2009; Meyer, 2005). Urban areas have traditionally been hypothesized to reduce base flow due to the increased runoff from impervious surfaces limiting infiltration and groundwater recharge (Leopold, 1968; Price, 2011; Rose & Peters, 2001). Conversely, leaky water infrastructure and irrigation can increase groundwater recharge and help sustain base flow in certain urban settings (Bhaskar et al., 2016). Conflicting results have also emerged regarding the influence of urban development on annual peak streamflow. Urbanization is generally theorized to have less influence on annual peak discharges, relative to more frequent high flows, because the natural land cover is often saturated and effectively impervious during such events (Hollis, 1975; Sauer et al., 1984; Smith et al., 2002). However, several studies have detected increasing trends in annual peak discharge due to urbanization (Sheng & Wilson, 2009; Yang et al., 2013) while others have reaffirmed that urbanization has no significant influence on annual peak streamflow (Villarini et al., 2013).

The overarching goal of this study was to provide a comprehensive assessment of the relationships between urban development patterns and streamflow characteristics by addressing the shortcomings discussed above. Spatial metrics were utilized in conjunction with multivariate regression modeling to quantitatively describe the relative influence of the extent, spatial configuration, and positioning of urban development on low, high, and annual peak flows. The following section outlines the study watersheds in more detail as well as the data and methodologies used to quantify the streamflow characteristics and urban development patterns. The results are discussed in section 3. Finally, section 4 summarizes the main findings and explores the potential urban planning implications of the research.

2. Data and Methods

2.1. Study Watersheds

In total, 119 watersheds were analyzed throughout the Charlanta megaregion, which incorporates the Atlanta (ATL), Greenville, Spartanburg, Anderson (GSP), and Charlotte (CHA) Metropolitan Statistical Areas (MSAs) along the I-85 corridor (Florida et al., 2008; Mitra & Shepherd, 2016; Shepherd et al., 2013) (Figure 1).

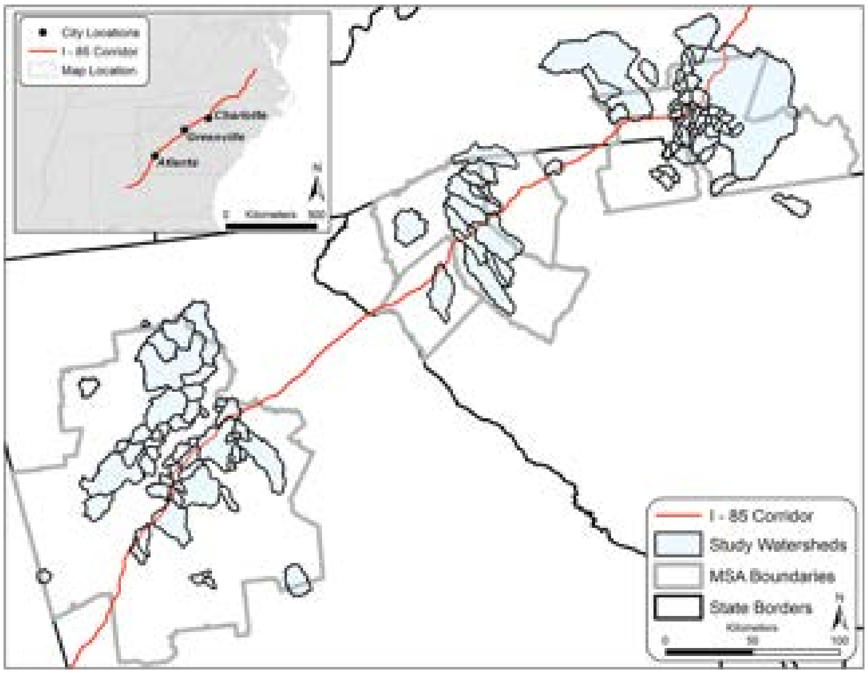

Figure 1. Location of the Charlanta Megaregion and study watersheds.

The study focused on Charlanta because its impervious footprint is projected to expand notably (Terando et al., 2014) and heighten the pressures placed on river systems if additional land use guidelines are not implemented. Future urban expansion is particularly problematic given that Charlotte and Atlanta are currently ranked as the fifth and seventh flashiest cities in the contiguous United States, respectively (Smith & Smith, 2015). Finally, analyzing the entire Charlanta megaregion also helped assess the generalizability of the relationships between urban development patterns and streamflow characteristics.

The individual watersheds included in the analysis were selected primarily based upon continuous U.S. Geological Survey (USGS) stream gage data availability between 2009 and 2013 (Figure 1). The timeframe of the analysis was centered on 2011 because it was the vintage of the land use data set used to quantify the patterns of urban development. Importantly, the 5 year study period enabled a climatologically representative precipitation sample and was brief enough to reasonably assume that the 2011 land use was representative for the entire timeframe. Specifically, the average annual precipitation over the 5 year period was 2.14 and 5.75 cm greater than the climatological normal value for Charlotte (105.74 cm) and Atlanta (126.26 cm), respectively (NWS, 2017a, 2017b). The stream gages included in the study were also required to be in the Geospatial Attributes of Gages for Evaluating Streamflow (GAGES-II) data set (Falcone, 2011), as it provided

Table 1
Statistics Describing the Characteristics of the Study Watersheds

Metropolitan area	Number	Area (km^2)	Population density (persons/km^2)	Urbanized area (%)	Mean annual precipitation (cm)	Mean annual temperature (°C)
Atlanta (ATL)	54	79.5 (242.7)	465.0 (420.1)	61.1 (26.3)	136.4 (8.7)	15.3 (0.7)
Charlotte (CHA)	49	48.5 (506.4)	354.7 (410.6)	66.4 (32.1)	118.3 (2.9)	15.5 (0.4)
Greenville-Spartanburg-Anderson (GSP)	16	198.8 (183.7)	73.8 (170.8)	18.0 (18.6)	140.8 (10.0)	15.6 (0.2)
All watersheds	119	76.8 (368.4)	340.3 (408.0)	60.8 (29.6)	130.4 (11.9)	15.5 (0.6)

Note. Median values are reported with standard deviations in parentheses. All the variables were obtained from the GAGES-II data set (Falcone, 2011) except urbanized area, which was derived from the 2011 National Land Cover Database (NLCD).

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an extensive suite of variables describing the physical characteristics of the watersheds and delineated the watershed boundaries. Characteristics of the study watersheds are detailed in Table 1. The study watersheds had a median area of 77 km^2 because large rivers highly regulated by dam infrastructure, such as the Chattahoochee, Savannah, and Catawba, were avoided. Overall, the watersheds evaluated a gradient of urban intensities, with the GSP watersheds generally exhibiting lower levels of urban development.

2.2. Quantifying Streamflow Characteristics

Mean daily discharge and annual peak streamflow data were obtained from the USGS National Water Information System for each study watershed. A peaks-over-threshold (POT) technique was used to analyze the mean daily discharge because it allowed for multiple high and low flow events within a given year (Villarini et al., 2013). This was particularly appropriate for analyzing the effects of urbanization since they are often most pronounced during more frequent, lower magnitude high flow events (Hollis, 1975). High and low flow frequency were evaluated by calculating the number of days during which the daily mean discharge remained above the 75th and below the 25th percentile for a given gage, respectively. The percentile values were based upon daily mean discharge data during the 2009–2013 study period. Threshold exceedances on consecutive days were considered only once to avoid double counting the same event. The number of exceedances was summarized from 2009 to 2013 and divided by five, producing a long-term annual average that minimized the influence of climatic variability. Although the POT analysis was likely sensitive to the specific thresholds selected, the 75th and 25th percentiles have been successfully used previously to identify high and low flow frequency (Hamel et al., 2005; Hopkins et al., 2015).

Supporting information Figure S1 provides an example of the thresholding approach for 1 year of daily streamflow data at Peachtree Creek, which is a highly urbanized watershed in Atlanta. Utilizing mean daily streamflow may have potentially underestimated the influence of urban development in certain cases, but POT analysis of mean daily discharge is a widely adopted technique used to quantify the effects of urbanization on streamflow characteristics (e.g., Diem et al., 2018; Hamel et al., 2015; Hopkins et al., 2015; Villarini et al., 2013; Yang et al., 2013). The annual peak streamflow data required less processing, as it was converted to cubic meters per second, averaged over the 5 year study period, and standardized by watershed area to produce annual average peak unit discharge (Choi et al., 2016).

2.3. Quantifying Urban Development Patterns

The metrics used to quantify the extent, spatial configuration, and positioning of urban development within each watershed were derived from the 2011 National Land Cover Database (NLCD) (Homer et al., 2015). The 2011 NLCD was selected due to its relatively high spatial resolution of 30 m and detailed urban classification scheme. Specifically, the variables describing the positioning of urban development were derived from the 2011 NLCD percent developed raster, which specifies an imperviousness value ranging from 0 to 100 for each cell. Four positioning variables were calculated to explore the potential differences between traditional and more complex approaches. First, a partitioning technique similar to past studies was performed (Beighley & Moglen, 2002). Each watershed was partitioned into a top and bottom half using one half of the longest drainage path length as the dividing threshold. The difference between the mean imperviousness of the top and bottom half was calculated, with positive values indicating that the headwaters were more heavily developed. The second positioning variable was the outlet imperviousness gradient. It was determined by measuring the distance of each pixel to the watershed outlet and calculating the relationship between those distances and the cell imperviousness values using ordinary least squares (OLS) regression. Larger positive values indicate that imperviousness increased more notably with distance from the watershed outlet. Thus, the outlet imperviousness gradient was conceptually analogous to the watershed partitioning technique although its calculation was more complex and less sensitive to arbitrary partitioning thresholds.

The third approach was a river imperviousness gradient designed specifically to evaluate the degree to which the positioning of urban development mirrored the hypothetical source clustering scenario of Mejia and Moglen (2010), which according to their modeling experiments increased peak flows more substantially than clustering development near river channels. The river imperviousness gradient was calculated by measuring the distance of each pixel to the nearest river feature, as defined by the National Hydrography Data set (NHD) flowlines, and determining the relationship between those distances and the cell imperviousness values using OLS regression. Larger positive values suggest that imperviousness increased more notably with distance from the river features, which would be indicative of source clustering. The methodology of this approach was similar to the outlet imperviousness gradient, but it assessed a fundamentally different positioning pattern. The final positioning variable evaluated the intensity of urban development within the riparian zone of each watershed by calculating the average imperviousness within 150 m of the NHD flowlines. The 150 m threshold was selected because it is the maximum recommended width of riparian buffers for flood attenuation purposes (Fischer & Fischenich, 2000).

To determine the extent and spatial configuration of urban development, spatial metrics were calculated using the FRAGSTATS software package (McGarigal et al., 2012). The spatial metrics were derived from the 2011 NLCD land cover data set, which includes 20 land use/land cover (LULC) categories with four devoted to urban land uses of various intensities. Although a wide variety of spatial metrics exist, those most frequently utilized in studies focusing on urban development were selected (Debbage et al., 2017). Table 2 describes the six class-level metrics included in the analysis, which evaluated different aspects of urban morphology. Percentage of the landscape (PLAND) is a basic composition metric that quantified the relative extent of urban development as a percentage of the total watershed area. The shape complexity of the urban land use was evaluated by the area-weighted mean shape index (AWMSI) and edge density (ED). AWMSI used a modified perimeter-area ratio to evaluate shape complexity while ED compared the total urban edge length to the watershed area. In both cases, larger values were indicative of increasingly complex and irregular urban forms.

The degree of urban fragmentation in the watersheds was determined by the patch density (PD), largest patch index (LPI), and percentage of like adjacencies (PLADJ). PD counted the number of urban patches within the watershed, which was subsequently standardized by watershed area. LPI evaluated the dominance of the largest urban patch by dividing its area by the watershed area. Finally, PLADJ provided a pixel-based measure of fragmentation by calculating the number of like adjacencies involving urban pixels relative to the total number of adjacencies involving urban pixels. Smaller LPI and PLADJ values as well as larger PD values were associated with less contiguous and more fragmented urban morphologies. Although this study focused primarily on the metrics calculated for the four NLCD urban land uses, the spatial metrics in Table 2 were derived for all the LULC categories present within each watershed.

Table 2
*Equations and Technical Descriptions of the Spatial Metrics Used to Quantify the Extent and Spatial Configuration of the Urban Development Within Each Watershed (*McGarigal et al. 2012*)*

Spatial metric	Equation	Technical description
Area-Weighted Mean Shape Index (AWMSI)	$AWMSI=\sum_{j=1}^{n}\left[\left(\frac{0.25p_{ij}}{\sqrt{a_{ij}}}\right)\left(\frac{a_{ij}}{\sum_{j=1}^{n}a_{ij}}\right)\right]$	Where p_{ij} is the perimeter of patch ij and a_{ij} is the area of patch ij (i = number of patch types, j = number of patches) Units: None
Edge Density (ED)	$ED=\frac{\sum_{k=1}^{m}e_{ik}}{A}*10,000$	Where e_{ik} is the total edge length (m) of class i in the landscape and A is the total landscape area; the result is multiplied by 10,000 to convert to hectares Units: Meters per hectare
Largest Patch Index (LPI)	$LPI=\frac{\overset{n}{\underset{j=1}{\max}}(a_{ij})}{A}*100$	Where $max(a_{ij})$ is the area (m^2) of the largest patch of the corresponding class and A is the total landscape area (m^2); the result is multiplied by 100 to convert to a percentage Units: Percent
Patch Density (PD)	$PD=\frac{n_i}{A}*10,000*100$	Where n_i is the number of patches in the landscape of patch type i and A is the total landscape area (m^2) Units: Number per 100 hectare
Percentage of Like Adjacencies (PLADJ)	$PLADJ=\left(\frac{g_{ii}}{\sum_{k=1}^{m}g_{ik}}\right)*100$	Where g_{ii} is the number of like adjacencies between pixels of patch type i and g_{ik} is the number of adjacencies between pixels of patch types i and k Units: Percent
Percentage of Landscape (PLAND)	$PLAND=\frac{\sum_{j=1}^{n}a_{ij}}{A}*100$	Where a_{ij} is the area (m^2) of patch ij and A is the total landscape area (m^2); the result is multiplied by 100 to convert to a percentage Units: Percent

Note. A patch is defined as a contiguous group of pixels that share a common land use/land cover type.

2.4. Statistical Analysis

Several statistical tests were used to analyze the variability of streamflow within the Charlanta megaregion and determine the influence of urban development patterns on streamflow characteristics. First, analysis of variance (ANOVA) tests were conducted with MSA as the grouping variable to identify if the streamflow characteristics varied across the Charlanta megaregion. ANOVA tests were performed for the three streamflow metrics as well as the variables describing the patterns of urban development and physical characteristics of the watersheds to explain any observed dissimilarities in streamflow. Tukey's honest significant difference (HSD) tests were subsequently used to identify the specific MSAs that exhibited statistically significant differences (Tukey, 1949).

The variables that characterized the physical properties of the watersheds in the ANOVA tests and additional statistical analysis described below were obtained from the GAGES-II data set (Falcone, 2011). Although numerous variables were considered, several were central to the study including the: percentage of watershed surface area covered by lakes, ponds, and reservoirs (Lake Storage), ratio of base flow to total streamflow (Base Flow Index), percentage of soils in hydrologic soil groups A and B (Soil Groups A & B), mean annual precipitation within the watershed (Mean Ann. Precip.), and percentage of total streamflow produced by Horton overland flow.

To gain a further understanding of the relationships, bivariate Pearson correlation coefficients were calculated between the three streamflow variables and each of the measures evaluating the extent, spatial configuration, and positioning of urban development. Correlations were also calculated between the streamflow metrics and the potential control variables extracted from the GAGES-II data set. More complex multivariate modeling was then explored to quantify the relative influence of urban development patterns on streamflow characteristics while controlling for potential confounding factors. The high threshold exceedances per year, low threshold exceedances per year, and annual average peak unit discharge were the dependent variables in the three OLS regression models estimated. The independent variables considered for inclusion in the models described the urban development patterns as well as the physical differences between the watersheds. The variables ultimately included in the models were selected manually based upon the bivariate analysis and regression diagnostics to avoid the potential issues associated with stepwise regression (Ssegane et al., 2012). The error terms of the models were assessed for heteroscedasticity, normalcy, and spatial autocorrelation using the Breusch-Pagan (Breusch & Pagan, 1979), Shaprio-Wilk (Shapiro & Wilk, 1965), and Moran's I tests (Moran, 1950), respectively. The degree of multicollinearity amongst the independent variables was evaluated through variable inflation factors (VIFs) (Marquardt, 1970). Finally, potential outliers were detected using Cook's D (Cook & Weisberg, 1982) and DFBETAs (Belsley et al., 1980).

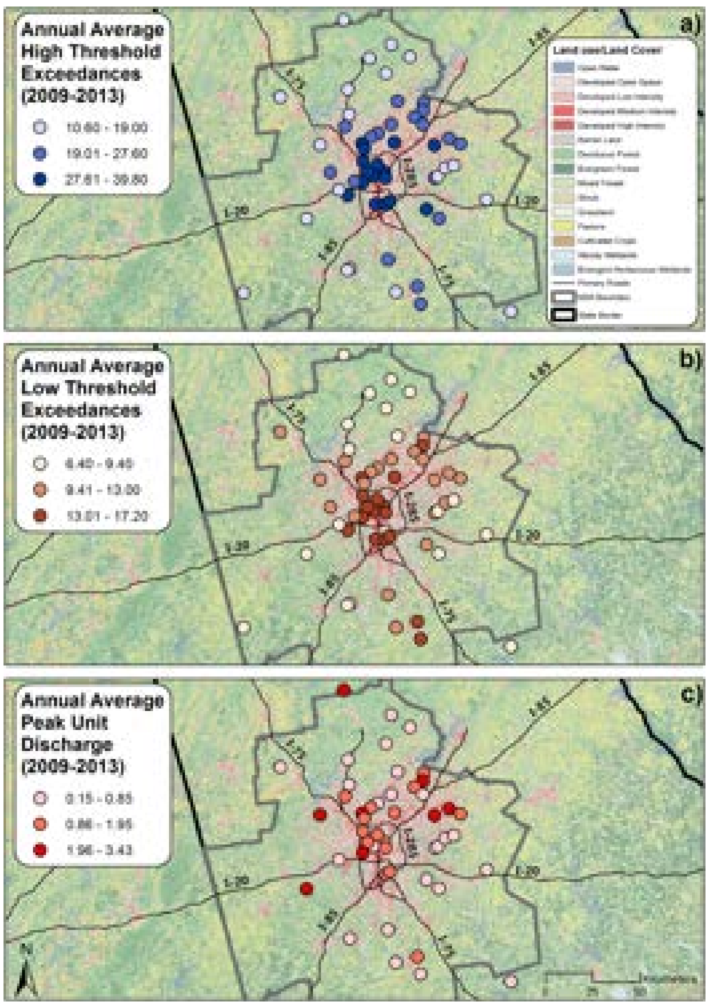

Figure 2. Spatial distribution of (a) high threshold exceedances per year, (b) low threshold exceedances per year, and (c) annual average peak unit discharge ($m^3 s^{-1}$ km^{-2}) for the Atlanta MSA.

The model diagnostics revealed that the assumptions of OLS regression were appropriate in most cases. Outliers were not a concern, as the Cook's D values of the three multivariate regression models were all less than 0.20 and the DFBETAs remained below 0.80. Multicollinearity amongst the independent variables was also not detected since the VIFs never exceeded 2. The *p*-values of the Breusch-Pagan and Shapiro-Wilk tests never fell below 0.05 so the null hypotheses of homoscedastic and normally distributed residuals were not rejected. However, the low threshold exceedances and annual average peak unit discharge models were estimated using a natural logarithm transformation of the dependent variable. The original statistical distribution of these dependent variables exhibited positive skewness, which resulted in the nontransformed models failing the diagnostic test for normally distributed residuals. Finally, Moran's I tests were performed to evaluate the degree of spatial autocorrelation amongst the residuals. A *k*-nearest neighbors approach was used

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to conceptualize the spatial relationships due to the varying density of stream gages across the megaregion. Specifically, the four gages nearest the gage of interest were considered its neighbors. This small neighborhood was utilized since spatial autocorrelation was most apparent at local rather than regional scales, which was likely attributable to the inclusion of nested watersheds in the sample. The Moran's I tests revealed that only the residuals of the annual average peak unit discharge model exhibited significant spatial autocorrelation. Therefore, a spatial error model (SEM) was also estimated for the annual peak unit discharge to enable comparisons with the OLS results (Anselin, 1988).

3. Results and Discussion

3.1. Spatial Distribution of Streamflow Characteristics and Intra-Charlanta Variability

The streamflow variables were initially mapped to gain a basic understanding of their spatial distributions throughout Charlanta. Figures 2–4 illustrate that the high and low threshold exceedances were greatest proximate to the urban cores of each MSA. Therefore, urban development throughout Charlanta appeared to increase both high and low flow frequency, although the spatial distribution of low threshold exceedances did not align with urban land uses as consistently. The overall spatial patterns also suggest that the specific percentiles selected for the POT analysis were generally sensitive to the degree of urbanization. Unlike the threshold exceedances, annual average peak unit discharge generally exhibited a more ambiguous qualitative relationship with urbanization. This highlights the potential weaker influence of impervious surfaces on annual peak streamflow (e.g., Hollis, 1975; Sauer et al., 1984). In the case of Atlanta, the spatial mismatch between urbanized areas and large peak unit discharge values was partially attributable to the average peak streamflow being influenced by the extreme 2009 flood event (Shepherd et al., 2011).

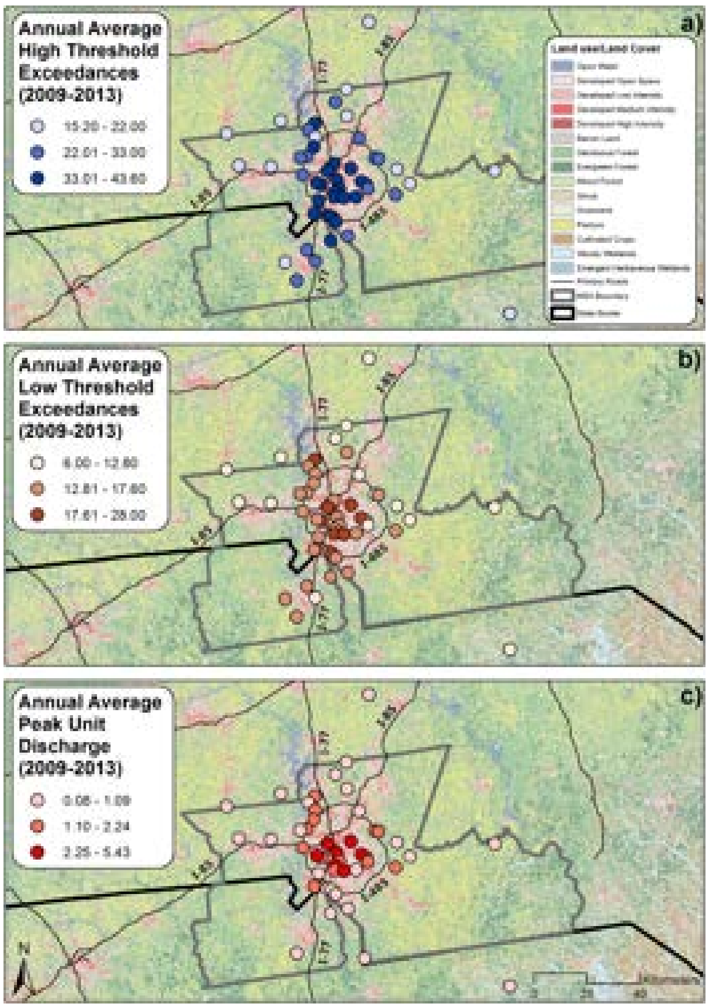

Figure 3. Spatial distribution of (a) high threshold exceedances per year, (b) low threshold exceedances per year, and (c) annual average peak unit discharge ($m^3 s^{-1} km^{-2}$) for the Charlotte MSA.

A quantitative examination of the spatial distributions was achieved by calculating correlation coefficients between the threshold exceedances and the distance to the central business district (CBD) of each MSA (Figure 5). The city halls of Atlanta, Charlotte, and Greenville served as proxies for the CBD locations (U.S. Census Bureau, 2012). The high threshold exceedances exhibited a significant negative correlation with distance to the CBD for each MSA. Loess curves fitted to the scatterplot revealed a substantial upturn in high threshold exceedances between 15 and 30 km away from the CBDs, which corresponds roughly with the location of the perimeter highways of each city (i.e., I-285, I-485, and I-185). The increase in high threshold exceedances was most gradual for Atlanta, likely reflecting the expansive low-density urban development beyond the I-285 perimeter.

The low threshold exceedances displayed weaker negative correlations with distance from the CBD that were significant for Atlanta and Charlotte. The lack of a statistically significant relationship in Greenville was largely due to the Reedy River stream gage near Waterloo, SC, which exhibited numerous low threshold exceedances despite its distance from the CBD. The enhanced low flow frequency near Waterloo likely occurred because the large areal extent of the watershed incorporated the urban core of Greenville. This highlights a shortcoming of using distance to the CBD as a proxy for urbanization, particularly for larger watersheds. When the Reedy River outlier was omitted, the correlation was significant ($r = -0.57$; $p = 0.03$) and similar to the coefficients calculated for the other MSAs. Finally, the low threshold exceedances demonstrated a less pronounced upturn within the 15–30 km window, as the relationships between distance to the CDB and low flow frequency appeared more linear.

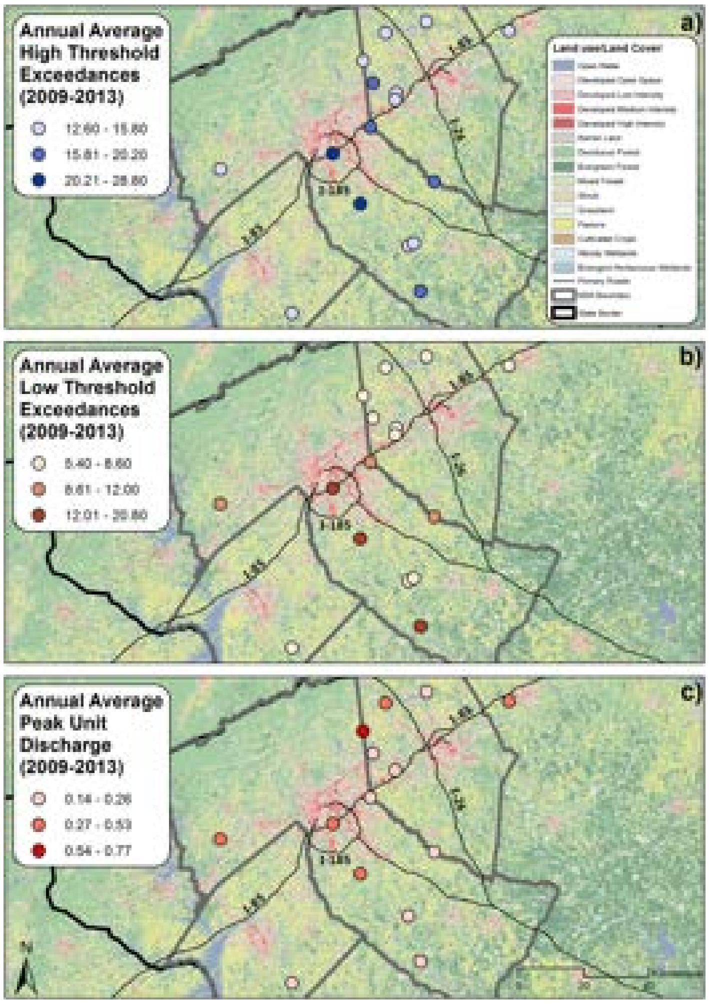

Figure 4. Spatial distribution of (a) high threshold exceedances per year, (b) low threshold exceedances per year, and (c) annual average peak unit discharge ($m^3 s^{-1} km^{-2}$) for the Greenville, Spartanburg, and Anderson MSAs.

The ANOVA and Tukey HSD tests revealed additional intraregional variability. Charlotte exhibited a significantly higher number of low and high threshold exceedances compared to Atlanta and Greenville (Figure 6a). Furthermore, the number of high threshold exceedances observed in Atlanta was significantly greater than in Greenville. These findings suggest that urban development in Charlotte altered the natural streamflow regime more substantially than in Greenville or Atlanta. The differences in annual average peak unit discharge were less notable, as Charlotte and Atlanta displayed a similar range of values (Figure 6b). However, Greenville exhibited a significantly lower annual peak unit discharge than Charlotte and Atlanta. This was largely attributable to the greater areal extent of the Greenville watersheds, which resulted in smaller values when standardizing annual peak discharge by watershed area. The raw annual peak streamflow values were also analyzed and revealed no significant intraregional differences.

The dissimilarities in the number of threshold exceedances between the Charlanta MSAs can be partly explained by differing urban development patterns. Specifically, the Greenville watersheds appeared to be less urbanized than their counterparts in Atlanta and Charlotte across all urban intensity categories (Figure 7a), although these differences were only statistically significant (p-value < 0.05) for low and medium intensity development. The lower levels of urbanization within Greenville watersheds likely contributed to the smaller number of threshold exceedances. Disparities in the extent of urban development did not explain the greater number of threshold exceedances observed in Charlotte relative to Atlanta, as the two MSAs exhibited no significant differences in the percentage of watershed area developed. Considering the contiguity of urban development helped further elucidate the variability of threshold exceedances between the MSAs (Figure 7b). The significantly less contiguous low and medium intensity development within Greenville watersheds likely further moderated high and low flow frequency. Differences in the contiguity of urban development were also observed between Atlanta and Charlotte. Specifically, Charlotte exhibited significantly higher levels of contiguity for developed open space, which likely contributed to the greater number of threshold exceedances observed in Charlotte relative to Atlanta. The important role of developed open space in governing the flood response of urbanized watersheds in Charlotte has also been identified by Zhou et al. (2017) and may potentially be related to the hydrologic properties of urban soils. These results highlight the importance of analyzing both the extent and configuration of urban development across a range of intensity levels to better understand the variable effects of urbanization on streamflow and potentially inform more detailed land use policies.

In addition to the disparate urban development patterns, differences in the natural properties of the watersheds also likely influenced the number of threshold exceedances observed in each MSA. Mean annual precipitation was significantly lower for Charlotte watersheds relative to Atlanta and Greenville (Figure 8a). Although less precipitation may have contributed to the elevated number of low threshold exceedances in Charlotte, due to the increased likelihood for prolonged dry periods, it did not explain the greater number of high threshold exceedances. This apparent discrepancy was likely due to the mean annual precipitation not fully resolving the warm season thunderstorms that are primarily responsible for floods in Charlotte (Zhou et al., 2017). The percentage of Horton overland flow and base flow provided more consistent explanations of the elevated threshold exceedances observed in Charlotte. The percentage of Horton overland flow was significantly higher in Charlotte relative to the other MSAs while base flow contributions were significantly lower (Figures 8b and 8c). A greater propensity for Horton overland flow (i.e., infiltration excess

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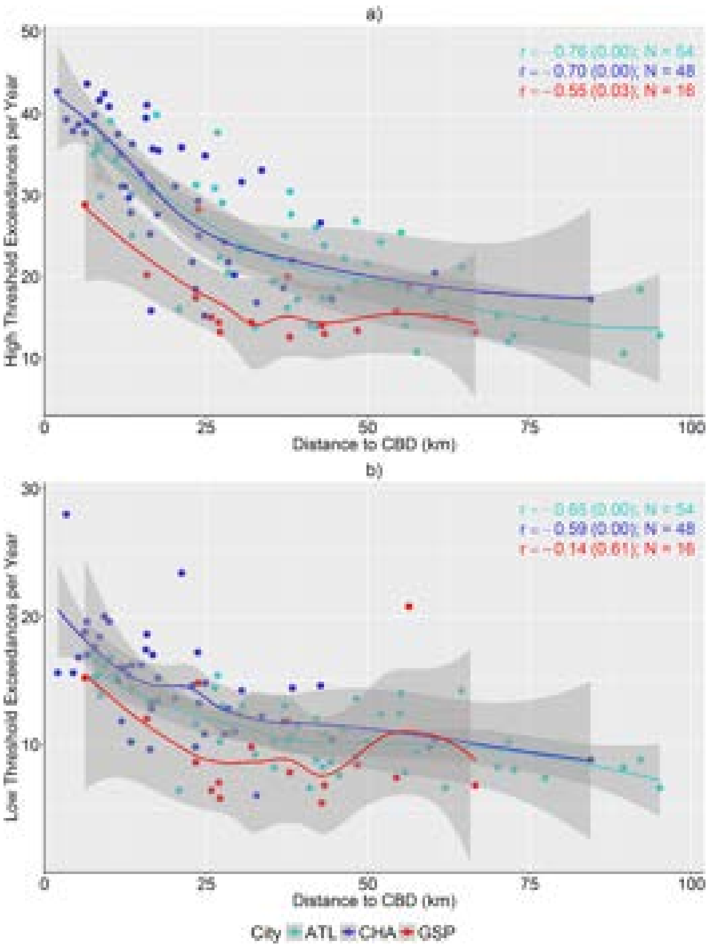

Figure 5. Relationships between (a) high and (b) low threshold exceedances and distance to the central business district (CBD) of each MSA in Charlanta. Pearson correlation coefficients (r) and sample sizes (N) are reported with *p* values in parentheses. The grey shading around the lines represents the 95% confidence interval.

flow) in Charlotte likely produced a more consistent rapid runoff response, resulting in more frequent high threshold exceedances. Additionally, the lower percentage of base flow in Charlotte suggests that streamflow was more likely to become stressed during prolonged dry periods, which would enhance low flow frequency. These hydrologic properties that potentially influenced the threshold exceedances were related to underlying geological differences between the watersheds. Charlotte watersheds contained a significantly lower percentage of hydrologic group A and B soils, which are characterized by moderate to high infiltration rates (Figure 8d). Overall, the natural factors likely worked in tandem with the differing urban development patterns to produce variable POT results within the megaregion.

3.2. Correlations Between Streamflow Characteristics and Urban Development Patterns

To initially identify the aspects of urban development that were influential in governing streamflow, correlations were calculated between the streamflow characteristics and the variables describing the urban development patterns. The POT correlation analysis revealed that more urbanized watersheds exhibited a significantly greater number of high and low threshold exceedances (Figure 9). This suggests that urbanization within Charlanta not only enhanced high flow frequency but also low flow frequency. Therefore, the reduction of groundwater recharge and base flow throughout the megaregion due to impervious surfaces inhibiting infiltration appeared to outweigh urban contributions to base flow (e.g., water infrastructure leakage, irrigation). The low threshold exceedances did exhibit weaker correlations than the high threshold exceedances with the percentage of the watershed developed, which was likely indicative of the more complex pathways through which urbanization influences low flow regimes (Bhaskar et al., 2016).

The extent of the intermediate urban classes displayed the strongest correlations with both the low and high threshold exceedances (Figures 9b and 9c). The weaker relationships for developed open space were likely attributable to the larger quantities of natural vegetation allowed within the category obfuscating the connections between urbanization and enhanced low and high flow frequency. Additionally, developed open space often incorporates forms of low-density residential development that rely upon septic tanks, which further complicates the relationship between urbanization and low threshold exceedances (Burns et al., 2005). At the opposite end of the urban intensity spectrum, high intensity development displayed weaker correlations because many of the sampled watersheds contained small percentages of such development (Figure 9d). The dotted loess curves in the scatterplot suggest that the relationships were perhaps more exponential in nature, as the number of threshold exceedances increased notably with the percentage of high intensity development until roughly 5% after which the relationships weakened. Importantly, this implies that urban modifications of high and low flow regimes may occur in watersheds with small quantities of high intensity development (e.g., 5% of the watershed area), which highlights the potential tenuous nature of threshold-based land use policies (Mejia & Moglen, 2009).

The urban configuration metrics were also significantly ($p < 0.05$) correlated with the threshold exceedances, but they were sensitive to the extent of urban development within the watersheds (PLAND). Table 3 provides the correlations, averaged over the four NLCD urban intensity classes, of each configuration metric with the high and low threshold exceedances as well as PLAND. ED exhibited the strongest correlations with the threshold exceedances, but it was evaluating an aspect of urban configuration heavily influenced by PLAND ($r = 0.97$). Although there is often some degree of redundancy between composition and configuration spatial metrics, the small areal extent of the watersheds potentially exacerbated this issue for ED. PD

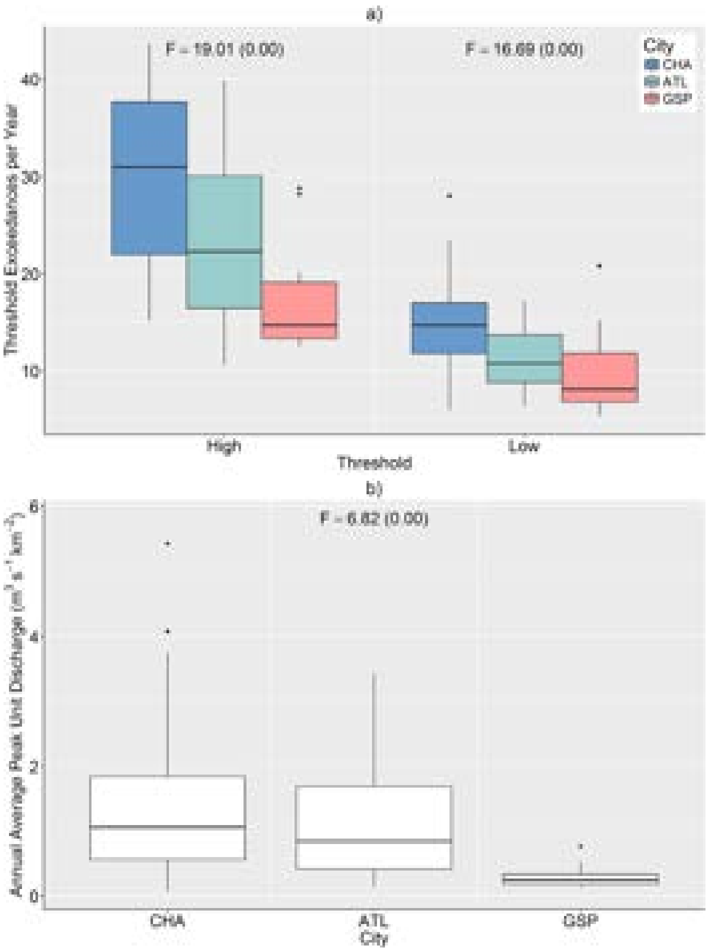

Figure 6. Differences in (a) threshold exceedances and (b) annual average peak unit discharge between the Charlanta MSAs. The *F* values from the ANOVA tests are reported with the associated *p* values in parentheses.

and PLADJ displayed stronger relationships with the threshold exceedances while being less influenced by PLAND. The positive correlations suggest that more contiguous urban development and a greater number of urban patches enhanced both high and low flow frequency. The large average correlation with the threshold exceedances exhibited by PD was driven by the patchiness of high intensity development whereas for PLADJ it was due to the contiguity of developed open space and low intensity development. This implies that the number of high intensity urban patches has a notable influence on low and high flow frequency because each patch substantially alters natural runoff processes regardless of its contiguousness. Conversely, the contiguity of less intense urban development was more relevant because a certain degree of contiguousness likely must be achieved before urbanization incorporating greater quantities of natural vegetation alters streamflow characteristics considerably.

The relationships between urban development patterns and annual average peak unit discharge were analyzed as well. The majority of the spatial metrics failed to exhibit significant correlations with the raw peak streamflow values due to the differences in watershed area, but more urbanized watersheds displayed significantly higher annual average peak unit discharge (Figure 10). The correlations, however, were smaller than those calculated for the threshold exceedances, which highlights the weaker influence of urban development on the magnitude of larger, more infrequent floods (e.g., Hollis, 1975). Additionally, this suggests that utilizing a higher threshold to quantify high flow frequency in the POT analysis would yield weaker correlations. The urban configuration metrics also generally exhibited smaller correlations with annual peak unit discharge that were occasionally not statistically significant across all four urban categories (Table 3). Nevertheless, these results indicate that urbanization within Charlanta increased the magnitude of annual peak streamflow in addition to enhancing low and high flow frequency. This supports the notion that positive temporal trends in annual peak streamflow may be due to watersheds undergoing urbanization (Sheng & Wilson, 2009; Yang et al., 2013). Collectively, the significant correlations imply that urban land use policies designed to manage the extent and configuration of urban development could potentially reduce urban alterations of low, high, and peak flows.

The final urban development pattern evaluated was the positioning of impervious surfaces throughout the watersheds. Correlations between the streamflow characteristics and the positioning variables were analyzed individually for each MSA because the results varied throughout the megaregion. Only Atlanta displayed a significant correlation between the high threshold exceedances and the imperviousness difference between the top and bottom half of the watersheds (Figure 11a). The positive correlation suggests that in Atlanta clustering urban development in distant headwaters increased high flow frequency as hypothesized by previous studies (Beighley & Moglen, 2002). However, the insignificant correlations for Greenville and Charlotte highlight the inconsistent nature of this relationship, which may partly explain the inconclusive findings of past studies using similar positioning measures (e.g., Beighley & Moglen, 2003). The relationship in Atlanta was likely significant because several of the watersheds exhibited simplistic distributions of imperviousness with distinct divisions between the top and bottom halves. Most notable were the Proctor Creek and Intrenchment Creek watersheds, which each contain a large portion of Atlanta's CBD in their headwaters (supporting information Figure S2). The urban development in the other MSAs appeared to be more complexly distributed throughout the watersheds and was thus less suitably described by mean imperviousness difference. Overall, this suggests that simplistic difference measures may be useful when the observed positioning of urban development closely mirrors idealistic scenarios, such as in Atlanta, but they may fail to capture the influence of more complex positioning patterns on high flow frequency.

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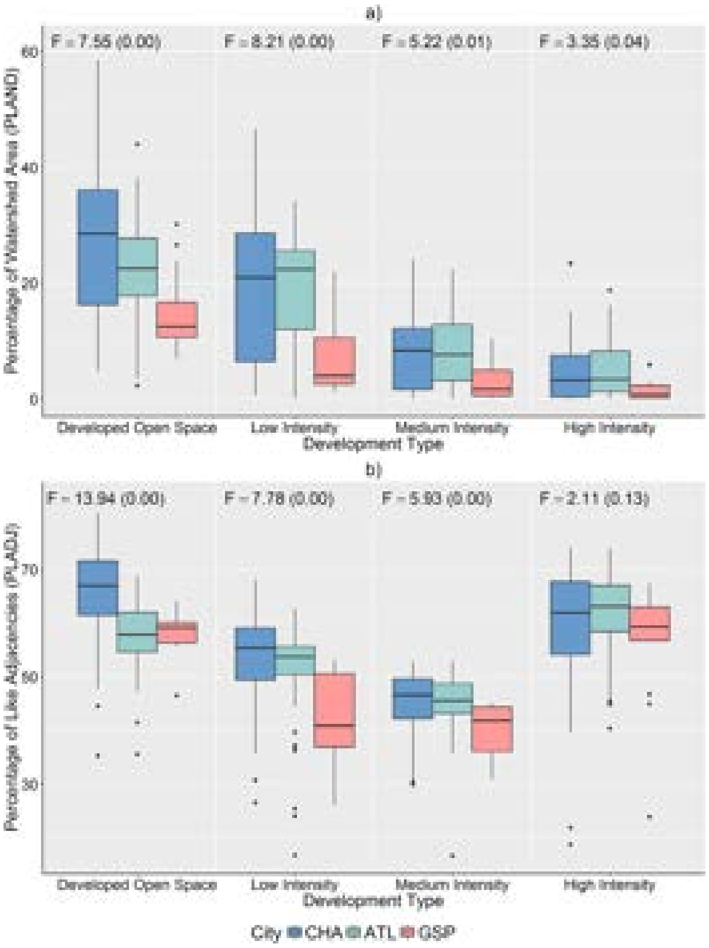

Figure 7. Differences in (a) the relative extent of urban development and (b) the contiguity of urban development between the Charlanta MSAs. The *F* values from the ANOVA tests are reported with the associated *p* values in parentheses.

The correlations between the outlet imperviousness gradient and the high threshold exceedances (Figure 11b) largely mirrored the mean imperviousness difference results, which was anticipated given that it evaluated the same fundamental positioning pattern albeit via a more complex methodology. Conversely, mean imperviousness of the riparian zone was more consistently related to the high threshold exceedances and exhibited statistically significant positive correlations for each MSA (Figure 11c). The correlations were also stronger than those calculated between the extent of urban development and high flow frequency, illustrating the importance of the positioning of urban development within watersheds. Highly vegetated riparian zones likely provided a critical buffering mechanism by attenuating surface runoff, which emphasizes the need to preserve and expand existing riparian corridors throughout Charlanta.

The river imperviousness gradient, which evaluated how rapidly imperviousness within the watersheds increased with distance from the nearest river feature, was the final positioning metric considered. It exhibited significant positive correlations with the high threshold exceedances for each MSA (Figure 11d). This suggests that enhancing the imperviousness gradient by clustering urban development in source areas distant from river features would increase high flow frequency. Therefore, these findings support the hypothesis that developing source areas increases high flows because the time of concentration is reduced, superposing the peaks observed in the distant portions of the watershed with those closer to the outlet (Beighley & Moglen, 2002). The river imperviousness gradient overall appeared to be a more robust and informative positioning metric from an urban land use planning perspective than the imperviousness difference calculation because it better acknowledged the spatial complexity of urban land use distributions within watersheds.

The relationships between the positioning variables and low threshold exceedances as well as annual peak unit discharge were also considered (Table 4). Generally, the results were similar to those observed for high flow frequency. The mean imperviousness difference and outlet imperviousness gradient only exhibited significant correlations for Atlanta, further demonstrating their inability to capture urban positioning patterns broadly relevant to streamflow characteristics. Conversely, mean imperviousness of the riparian zone and the river imperviousness gradient exhibited more consistent relationships with both the low threshold exceedances and annual peak unit discharge. The imperviousness of the riparian zone displayed significant positive correlations with the low threshold exceedances of each MSA and with annual peak unit discharge for each MSA except Greenville. This implies that the storage provided by highly vegetated riparian zones can help sustain low flows during dry periods and attenuate extreme flood events, which emphasizes the importance of land use policies protecting these corridors. Similarly, the river imperviousness gradient was significantly correlated with the low threshold exceedances and annual peak unit discharge for all the Charlanta MSAs except annual peak unit discharge in Greenville. The positive correlations indicate that clustering urban development in source areas and enhancing the river imperviousness gradient would increase annual peak streamflow and low flow frequency. While annual average peak unit discharge was potentially enhanced by a greater river imperviousness gradient due to mechanisms similar to those outlined for high threshold exceedances, the physical linkages for low flow frequency were less clear.

3.3. Multivariate Regression Models

Multivariate regression models were used to control for potential confounding factors, such as the physical differences between the watersheds, and better understand the relative influence of the extent, spatial configuration, and positioning of urban development on streamflow characteristics. Overall, the models

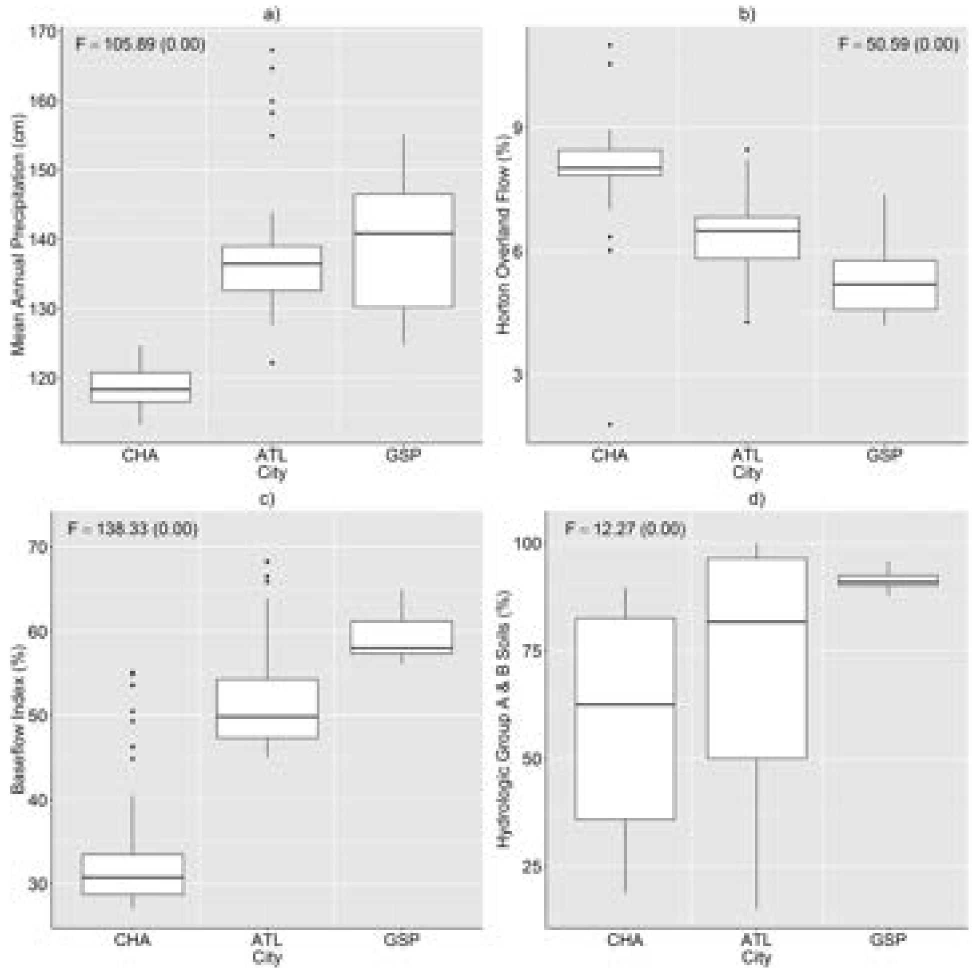

Figure 8. Differences in the natural characteristics of the Charlanta watersheds by MSA. The *F* values from the ANOVA tests are reported with the associated *p* values in parentheses.

performed well as they explained between 56 and 90% of the variability in streamflow characteristics (Tables 5 and 6). The explanatory power of the models largely mirrored the bivariate correlation results, as the R^2 was largest for the high threshold exceedances model and smallest for the annual average peak unit discharge model.

The partial slope coefficients of the high threshold exceedances model indicated that the extent, configuration, and positioning of urban development all had significant effects on high flow frequency even when controlling for physical differences between the watersheds (Table 5). A 10 percentage point increase in the extent of medium intensity development (PLAND Class 23) was predicted to enhance high threshold exceedances per year by 8.1 while a 10 percentage point increase in the contiguity of developed open space (PLADJ Class 21) was estimated to enhance high threshold exceedances per year by 2.8. A greater river imperviousness gradient (River Imp. Gradient) was also predicted to significantly elevate high flow frequency although the coefficient magnitude was modest, as a 0.01 increase in the gradient was estimated to enhance high threshold exceedances per year by 0.59. The standardized regression coefficients also suggested that the positioning of urban development was of secondary importance relative to the extent and contiguity of urbanization. Finally, the control variables had a significant moderating influence on high flow frequency. A 1 percentage point increase in the watershed area covered by lakes and/or reservoirs (Lake Storage) was predicted to reduce high threshold exceedances per year by 3.3, which was likely due to the increased storage capacity delaying runoff. Additionally, a 10 percentage point increase in the Base Flow Index was estimated to decrease high threshold exceedances per year by 1.9 because of the greater propensity for runoff to reach streams via slower subsurface pathways.

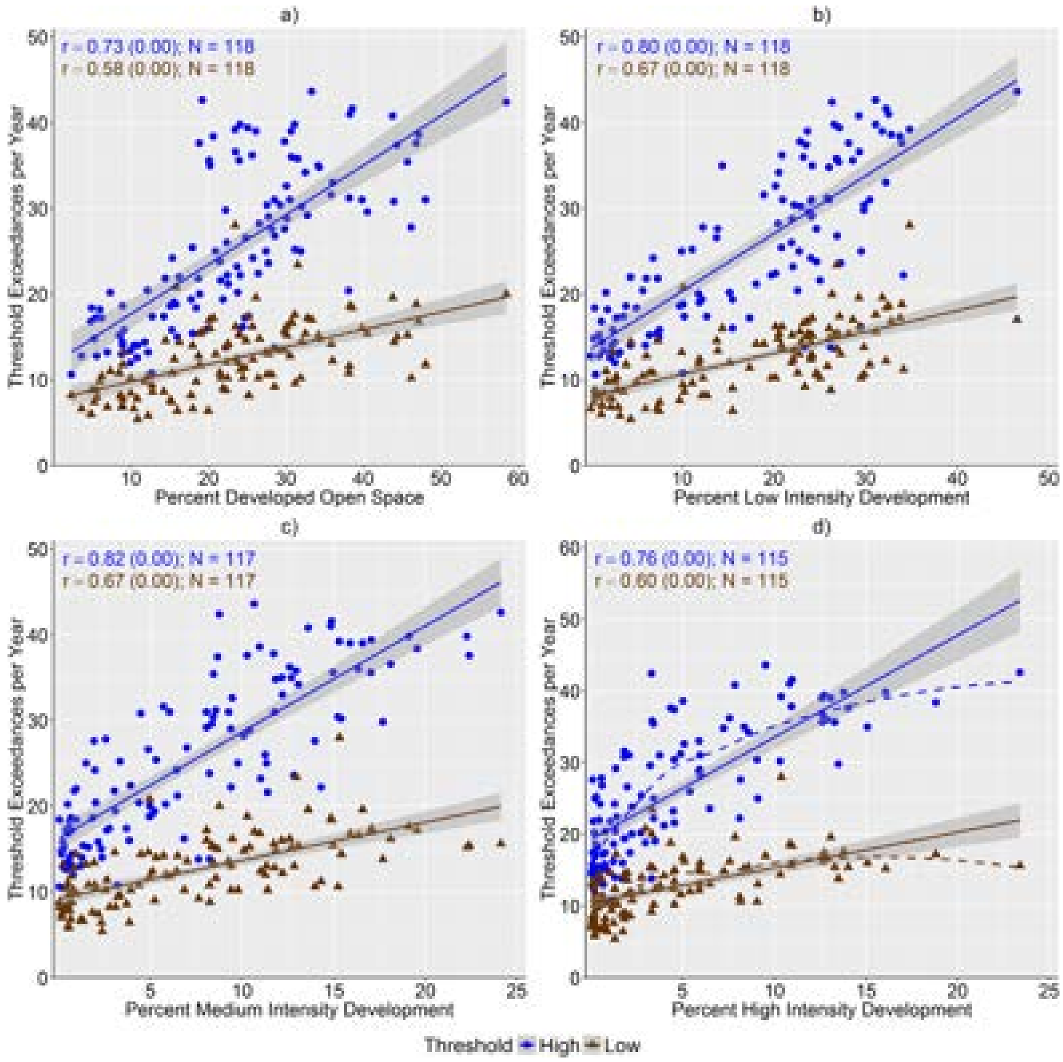

Figure 9. Relationships between the percent of the watershed developed and the threshold exceedances. Pearson correlation coefficients (r) and sample sizes (N) are reported with *p* values in parentheses. The grey shading around the lines represents the 95% confidence interval. In subplot (d), the dashed lines represent loess curves fitted to the scatterplot.

For the low threshold exceedances model, the unstandardized coefficients were much smaller in magnitude and interpreted differently due to the natural logarithm transformation of the dependent variable (Table 5). Importantly, the river impervious gradient was not significantly related to low flow frequency in the multivariate analysis and was excluded from the final model. The extent of medium intensity development (PLAND Class 23) exhibited a significant partial slope coefficient, as a 10 percentage point increase was estimated to enhance low threshold exceedances by 24%. The contiguity of developed open space (PLADJ Class 21) also significantly influenced low flow frequency with a 10 percentage point increase predicted to enhance low threshold exceedances by 11%. The partial slope coefficients of the control variables were significant and moderated low flow frequency. A 10 cm increase in mean annual precipitation (Mean Ann. Precip.) was estimated to decrease low threshold exceedances by 7%. Finally, an increase in the percentage of soils within hydrologic groups A and B (Soil Groups A & B) by 10 percentage points was predicted to decrease low threshold exceedances by 2%, which was expected since these soils are characterized by moderate to high infiltration rates and help sustain base flow.

Table 3

Correlations Between the Urban Configuration Metrics and High Threshold Exceedances, Low Threshold Exceedances, Annual Average Peak Unit Discharge, and PLAND Averaged Over the Four NLCD Urban Intensity Levels

Configuration metric	High threshold	Low threshold	Annual peak unit discharge	PLAND
PD	0.67[a]	0.54[a]	0.39[a]	0.72[a]
PLADJ	0.58[a]	0.51[a]	0.25	0.73[a]
LPI	0.52[a]	0.41[a]	0.53[a]	0.73[a]
AWMSI	0.52[a]	0.43[a]	0.19	0.75[a]
ED	0.76[a]	0.61[a]	0.45[a]	0.97[a]

[a]All four correlation coefficients used to calculate the average had a p-value < 0.05.

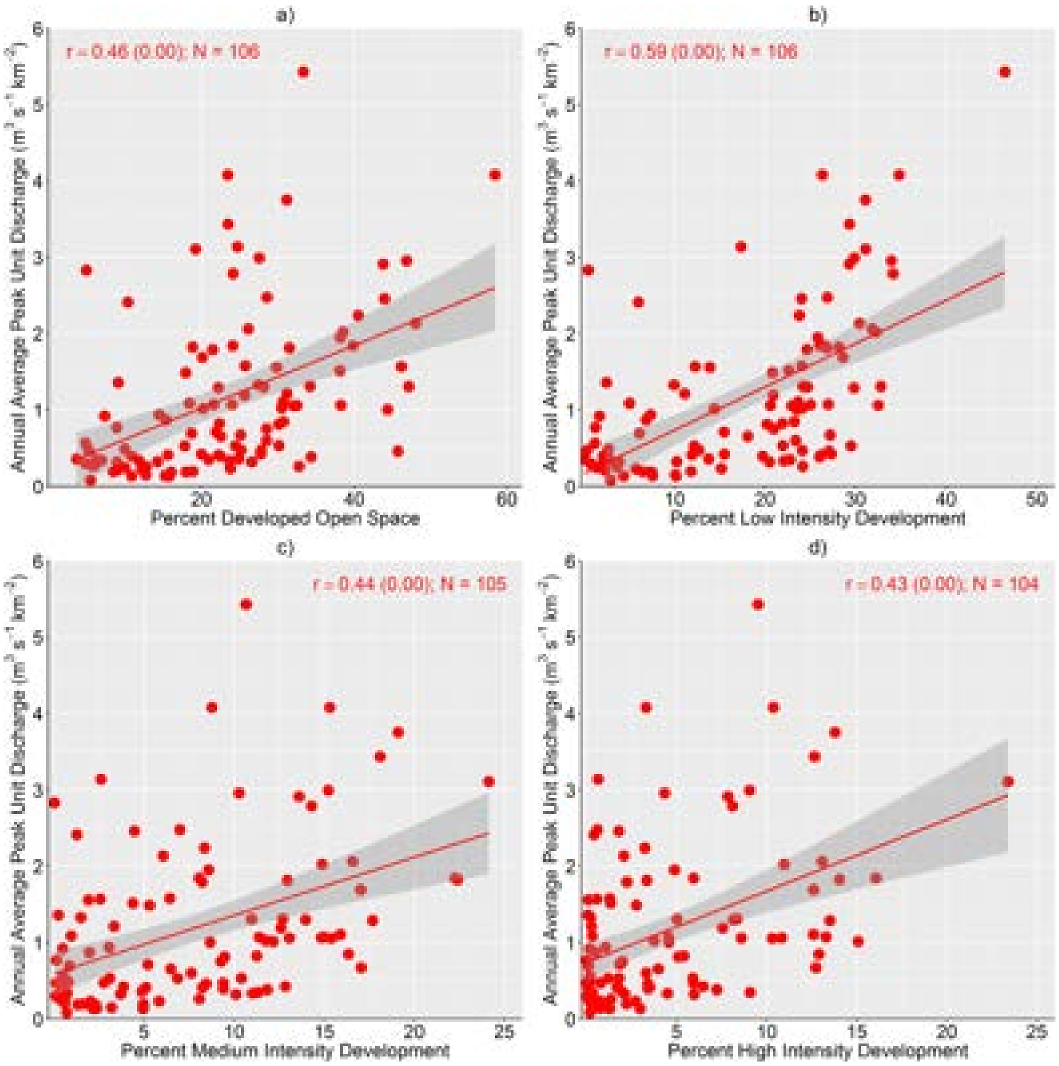

Figure 10. Relationships between the percent of the watershed developed and annual average peak unit discharge. Pearson correlation coefficients (r) and sample sizes (N) are reported with *p* values in parentheses. The grey shading around the lines represents the 95% confidence interval.

The annual average peak unit discharge results from both the OLS model and SEM are provided in Table 6. The SEM likely provided more robust estimates, as the spatial autoregressive coefficient lambda was significant and the Akaike Information Criterion (AIC) was lower. However, since the coefficient values estimated using the OLS model and SEM were similar, particularly when considering their standard errors, only the results from the OLS model are discussed further to enable more direct comparisons with the POT models. The partial slope coefficient for the extent of low intensity development (PLAND Class 22) was significant, as a 10 percentage point increase was estimated to enhance annual peak unit discharge by 29%. However, the standardized regression coefficient for the extent of urban development in the annual peak unit discharge model (0.33) was smaller than its counterparts in the high (0.54) and low (0.44) threshold models. This suggests that the extent of urban development significantly influenced peak streamflow, but the magnitude of this impact was modest relative to urban effects on more frequent high and low flow events. Additionally, the variables describing the spatial configuration and positioning of urban development were not significantly related to annual peak unit discharge within the multivariate context. This lack of significant relationships may be partly due to evaluating peak streamflow only at the watershed outlet, which likely emphasized the importance of the extent of urban development rather than its positioning or spatial configuration.

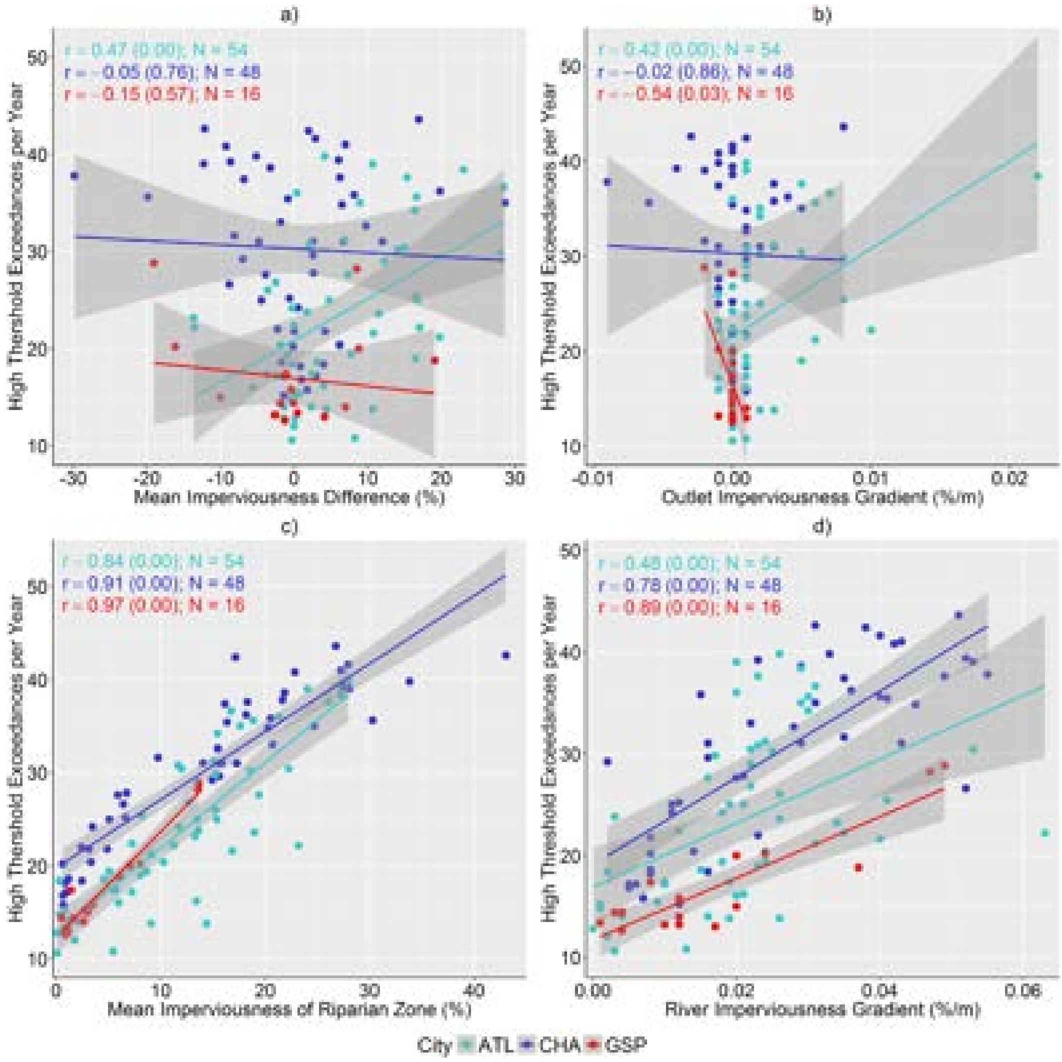

Figure 11. Relationships between the positioning metrics and the high threshold exceedances. Pearson correlation coefficients (r) and sample sizes (N) are reported with p values in parentheses. The grey shading around the lines represents the 95% confidence interval.

The remaining variables included in the model accounted for important natural differences between the watersheds that moderated annual peak unit discharge. Increasing the contiguity of woody wetlands (PLADJ Class 90) 10 percentage points was predicted to reduce peak unit discharge by approximately 46% because more contiguous woody wetlands were often indicative of unfragmented and heavily vegetated

Table 4
Correlations Between the Urban Positioning Metrics and High Threshold Exceedances, Low Threshold Exceedances, and Annual Average Peak Unit Discharge

	ATL			CHA			GSP		
Positioning metric	High threshold	Low threshold	Annual peak unit discharge	High threshold	Low threshold	Annual peak unit discharge	High threshold	Low threshold	Annual peak unit discharge
Mean Imp. Difference	0.47[a]	0.54[a]	0.24	−0.05	−0.07	−0.05	−0.15	0.24	−0.33
Outlet Imp. Gradient	0.42[a]	0.48[a]	0.33[a]	−0.02	−0.07	0.14	−0.54[a]	−0.39	−0.37
Riparian Imp.	0.84[a]	0.77[a]	0.32[a]	0.91[a]	0.71[a]	0.61[a]	0.97[a]	0.73[a]	0.00
River Imp. Gradient	0.48[a]	0.46[a]	0.30[a]	0.78[a]	0.53[a]	0.45[a]	0.89[a]	0.76[a]	−0.06

[a]p-value of correlation < 0.05.

Table 5
OLS Regression Results for the High and Low Threshold Exceedances

	High threshold exceedances			Low threshold exceedances[a]		
Independent variable	Coefficient	*p*-Value	Std. Coef.	Coefficient	*p*-Value	Std. Coef.
Intercept	12.04	~0.00		2.746	~0.00	
PLAND Class 23	0.81	~0.00	0.54	0.024	~0.00	0.44
PLADJ Class 21	0.28	~0.00	0.24	0.011	~0.00	0.25
River Imp. Gradient	59.06	0.02	0.09			
Lake Storage	−3.30	~0.00	−0.18			
Base Flow Index	−0.19	~0.00	−0.25			
Soil Groups A & B				−0.002	0.02	−0.15
Mean Ann. Precip.				−0.007	~0.00	−0.27
R^2	0.90			0.67		
Adj. R^2	0.90			0.66		
N	117			117		

[a]Note: Dependent variable was transformed by the natural logarithm.

riparian zones. Finally, a greater quantity of lake/reservoir storage (Lake Storage) and a larger proportion of base flow (Base Flow Index) also significantly reduced annual average peak unit discharge.

4. Conclusions and Urban Planning Implications

By analyzing the statistical relationships between urban development patterns and numerous streamflow characteristics across the Charlanta megaregion, this study aimed to further elucidate the role of urbanization in altering streamflow. The correlation analysis revealed that greater levels of urban development not only increased high threshold but also low threshold exceedances. Thus, urbanization within Charlanta appeared to produce a more extreme streamflow regime where both high and low flows were more frequent. This two-fold impact of urban development has clear societal and ecological ramifications. Increased high flows enhance the potential for flood damage and stream bank erosion while more frequent low flows increase the likelihood of high water temperatures and contaminant concentrations that can ultimately alter in-stream species assemblages (Bhaskar et al., 2016; O'Driscoll et al., 2010; Welty, 2009). The findings also indicated that more urbanized watersheds in Charlanta exhibited significantly greater annual average peak unit discharge, challenging the traditional notion that larger, more infrequent flooding events are not substantially influenced by urban development (Hollis, 1975). However, the correlations between the relative extent of urban development and annual peak unit discharge were weaker than the relationships with the threshold exceedances, which reaffirms that the impact of urbanization diminishes as flood recurrence interval increases.

The positioning of impervious surfaces within the watersheds emerged as an additional factor that governed streamflow characteristics. The river imperviousness gradient exhibited significant positive correlations with the threshold exceedances, highlighting its capability to describe hydrologically relevant positioning patterns. Conversely, the difference in imperviousness between the top and bottom half of the watersheds, which has been commonly used to quantify the positioning of urban development, was not consistently related to the threshold exceedances. The simplistic partitioning technique largely failed to capture the complex positioning of urban land use within the watersheds, which potentially explains the inconclusive findings produced by studies utilizing similar measures (e.g., Beighley & Moglen, 2002). Finally, the imperviousness of the riparian buffer was also a critical characteristic, as watersheds with highly developed riparian zones exhibited a larger number of high and low threshold exceedances.

Table 6
OLS and SEM Regression Results for Annual Average Peak Unit Discharge

	Annual peak unit discharge[a] (OLS)				Annual peak unit discharge[a] (SEM)		
Independent variable	Coefficient	Std. error	*p*-Value	Std. Coef	Coefficient	Std. error	p-Value
Intercept	3.310	0.674	~0.00		3.651	0.714	~0.00
PLAND Class 22	0.029	0.007	~0.00	0.33	0.023	0.007	~0.00
PLADJ Class 90	−0.046	0.008	~0.00	−0.42	−0.039	0.006	~0.00
Lake Storage	−0.267	0.126	0.04	−0.14	−0.301	0.117	0.01
Base Flow Index	−0.023	0.006	~0.00	−0.31	−0.039	0.010	~0.00
Lambda					0.634		~0.00
R^2	0.56						
AIC	202.21				181.09		
N	103				103		

Note. Lambda represents the spatial autoregressive coefficient.
[a]Note: Dependent variable was transformed by the natural logarithm.

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The multivariate models indicated that the extent, configuration, and positioning of urban development significantly influenced certain streamflow characteristics even when controlling for potential confounding factors. Furthermore, the moderate to high explanatory power of the statistical models suggests that the results can be used to inform urban land use policies aimed at minimizing the impacts of urbanization on streamflow. In terms of the extent of urban development, the findings highlighted that increasing the urbanized percentage of a watershed would enhance high and low flow frequency as well as annual average peak unit discharge. Although imperviousness thresholds appear to be a simple approach that could moderate streamflow alterations due to urbanization based upon these findings, studies have suggested that threshold-based policies can have the unintended consequence of encouraging sprawl-like development that enhances the spatial extent of hydrological impacts (e.g., Mejia & Moglen, 2009). These complexities emphasize the importance of also considering the configuration and positioning of urban development, in addition to its extent, when devising land use policies aimed at minimizing streamflow alteration due to urbanization.

The models also revealed that the configuration of LULCs can likely be optimized to reduce impacts on streamflow. For high and low threshold exceedances, the models indicated that decreasing the contiguity of developed open space would reduce high and low flow frequency. Such a configuration could be achieved via policies that encourage a greater interspersion of natural vegetation in areas of low density residential development. The configuration of urban development was less influential for annual peak unit discharge, but the modeling results suggested that the annual peaks were moderated by the presence of highly contiguous woody wetlands. This finding emphasizes the critical importance of protecting contiguous wetlands from development due to their substantial storage capacity. Finally, the positioning of urban development was most important for high flow frequency. The results indicated that enhancing the river imperviousness gradient by developing source areas distant from rivers would increase high threshold exceedances. Given that urbanization proximate to rivers also increased high flow frequency, positioning urban land use outside the riparian zone while avoiding headwater regions distant from rivers may potentially provide an optimal arrangement.

Although achieving the ideal extent, configuration, and positioning of urban development within a watershed is unlikely in reality, the overarching importance of these findings from an urban planning perspective is that all three facets of urban development patterns did significantly influence streamflow characteristics. Each aspect therefore provides one potential avenue through which land use policies can moderate the impacts of urbanization on streamflow. For example, although minimizing the total extent of urbanized land use is one technique for reducing streamflow alteration, the imposition of and adherence to an imperviousness threshold may be challenging in certain cases due to urban development pressures. In such scenarios where urbanization is deemed unavoidable, the results suggest that policies guiding the spatial configuration and/or positioning of impervious surfaces can effectively moderate streamflow alteration.

Of course, caution must be taken when extrapolating the urban planning implications of these findings to cities outside the Southeastern United States since hydrological processes are sensitive to different physiographical settings. This study also analyzed the hydrological impacts of urban development patterns largely in isolation without fully addressing the potential ramifications for other aspects of the urban system. Future research employing a broader perspective that considers the urban system in its entirety could identify potential synergies among land use management strategies. For example, decreasing the contiguity of urban development may not only reduce high and low flow frequency, as other studies have suggested it holds the potential to mitigate urban heat island intensities as well (Debbage & Shepherd, 2015; Pearsall, 2017).

Moving forward, the utilization of physically based models (e.g., Storm Water Management Model) that provide a more detailed evaluation of storm water drainage systems will be necessary to fully assess the potential efficacy of mitigation strategies based upon idealized urban development patterns. Additional statistical analysis that considers highly urbanized and suburban watersheds separately as well as seasons independently may also reveal subtle differences in how urbanization influences streamflow that are relevant to land use planning measures. Despite these avenues for future research, the current study provides an improved understanding of how urban development patterns influence high, low, and peak flows that can inform a broad suite of land use management strategies aimed at minimizing the impacts of urbanization on streamflow. Such progress appears imperative given that urban areas are projected to continue expanding and will likely be exposed to an increased frequency of extreme rainfall events as well as prolonged dry periods in the future due to climate change (Chow, 2017; Fischer & Knutti, 2015; Sheffield & Wood, 2008).

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