ORIGINAL ARTICLE

CIWEM Chartered Institution of Water and Environmental Management | Journal of Flood Risk Management WILEY

Impacts of urban drainage systems on stormwater hydrology: Rocky Branch Watershed, Columbia, South Carolina

Logan D. Ress[1] | Chen-Ling J. Hung[2] | L. Allan James[3]

[1]South Carolina Department of Health and Environmental Control, Columbia, South Carolina, USA

[2]Department of Water Resources and Environmental Engineering, Tamkang University, New Taipei City, 25137, Taiwan

[3]Department of Geography, University of South Carolina, Columbia, South Carolina, USA

Correspondence
L. Allan James, Department of Geography, University of South Carolina, Columbia, SC.
Email: ajames@sc.edu

Abstract

Increases in impervious surfaces and land-use changes associated with urbanization have long been the focus of urban hydrological research. However, studies and calculations that consider impervious surfaces alone do not encompass all factors that influence urban hydrologic response, as alternative urban structures may have a substantial effect on stormflow. This study examines several descriptors to improve estimations of hydrologic impacts of urbanization in small watersheds. Configurations of drainage densities that include storm sewers were computed for the highly urbanized Rocky Branch Watershed. Storm sewer configurations resulted in an approximate tripling of the drainage density. In addition, rainfall and stormflow data were analyzed to compare the hydrologic response of two subcatchments with varying percentages of impervious areas and drainage densities. The subcatchment with a higher percentage of impervious area produced significantly ($p < .01$) higher runoff volumes with an average runoff coefficient of 0.446, while the subcatchment with higher storm sewer densities displayed significantly shorter lag times of 9 min. In this case, the percentage of impervious area increased the volume of runoff but, storm sewer densities accelerated hydrologic responses, suggesting that hydrologically relevant metrics should be considered to accurate assess flood risk alternatives.

KEYWORDS
flood generation, hydrology, rainfall runoff, urban drainage

1 | INTRODUCTION

Understanding the hydrologic impact of urbanization on flood risks in small urban catchments is limited by a need for hydrologically relevant descriptors specific to small watersheds (Miller & Hess, 2017). Most modern urban hydrologic studies recognize the effects of increased impervious surfaces that reduce infiltration, increase runoff, and may result in major damage to both the built and natural environment. However, the isolated effects of storm sewer (SS) systems on hydrologic response are rarely quantified. They may be included in simulation

The flow data for this article are available in a supplemental file.

models, but the specific hydrologic effects of SS are integrated with other factors and obscured. Conventional SS drainage systems may contribute to flood risks downstream, but little is known about the relationship between imperviousness and SS densities.

Drainage systems integrate many hydrologic processes of the landscape through which surface and near-surface water travels, including vegetation, geologic material, stream channels, and constructed SS systems (Booth, 1991). Knowledge of the various paths that water can take and how these are affected by urbanization is needed for wise land-management planning, physically based stormwater simulation models, and flood-risk management (Dunne & Leopold, 1978; O'Driscoll, Clinton, Jefferson, Manda, & McMillan, 2010). Paving permeable land surfaces also results in degradation of water resources (Arnold Jr & Gibbons, 1996) and the proportion of rainfall that runs off; i.e., the runoff coefficient (RC), tends to be higher in urban areas (Rose & Peters, 2001; Smith et al., 2002). During storms in un-urbanized watersheds, only a fraction of the water reaches the channel, with the remainder being evaporated, transpired, or percolated deep into the groundwater system (Booth, 1991).

The area of impervious surface and the rate at which water is transported are the two guiding factors in the hydrologic alteration of an urban watershed (Leopold, 1968; Rose & Peters, 2001). Impervious surfaces, such as roads, sidewalks, rooftops, and parking lots reduce infiltration, facilitate run off, and can shorten recurrence intervals of floods by a factor of 10 of more (Hollis, 1975; Arnold Jr & Gibbons, 1996; Rose & Peters, 2001, Brabec, Schulte, & Richards, 2002; Gilbert & Clausen, 2006).

The method conventionally used to reduce flood risks locally is to develop a SS system, which is a an artificial flow network consisting of gutters, pipes, drains, culverts, and channels that transport storm runoff away from urbanized areas. However, these systems also influence the flood hydrology downstream by increasing drainage densities (total stream length/watershed area) (Burns, Fletcher, Walsh, Ladson, & Hatt, 2011; Graf, 1977; Leopold, 1968; Meierdiercks, Smith, Baeck, & Miller, 2010; Smith et al., 2002). The SS networks can be added to the existing channel network, producing a basin comprised of both natural and artificial networks (Figure 1) and can increase the efficiency of water conveyance, decrease storm lag times, and increase flood peaks downstream (Anderson, 1970; Ogden, Raj Pradhan, Downer, & Zahner, 2011 and Smith et al., 2002). Similarly, road-side gutters and ditches concentrate flows and accelerate the delivery of water downstream (Meierdiercks et al., 2010).

Increased conveyance of an urban SS system improves efficiency of the system to collect and transfer water, which may shorten lag times and increase kurtosis ("peakedness") of hydrographs (Graf, 1977; Leopold, 1968). Meierdiercks et al. (2010) simulated flows with an EPA Storm Water Management Model (SWMM) and found that drainage densities of SS systems in some small suburban watersheds of Baltimore, Maryland had a greater impact on storm-flow timing than percent impervious surface. Smith et al. (2002) examined floods in Little Sugar Creek in Charlotte, North Carolina and noted that the five largest flood peaks in the previous 74 years had occurred since 1995. They concluded that increases in drainage density had a direct effect on the flood regime of the creek, decreased the response time downstream, and ultimately increased flood magnitudes.

The combination of impervious surfaces and SS drainage systems theoretically increases total and stormflow volumes as well as magnitudes of flood peaks. Leopold (1968) proposed that expanded impervious surfaces coupled with increases in SS drainage density increase the flood potential by a multiplier of the mean annual flood (Figure 2a).

Storm hydrographs in an un-urbanized catchment tend to have slow rising and receding limbs and a low peak discharge. Implementation of a SS system increases flow velocities and decreases the lag times of stormwater arrivals. Hypothetically, if the SS system only changes the timing of the hydrograph but does not increase runoff, the area under the hydrograph curve will remain constant, but the peak discharge will increase due to the faster arrival alone (Figure 2b) (Morisawa, 1985; Putnam, 1972). However, dense SS systems may also reduce runoff losses by speeding up runoff delivery and circumventing infiltration and evapotranspiration losses. This would compound flood-risk intensifications by increasing runoff volumes and decreasing lag times. The effects of SS systems on flow volumes are not well documented and hypotheses of both accelerated flows and reduced runoff losses should be tested. It is well known that increased impervious surface areas result in a larger volume of runoff in response to decreased infiltration rates. However, a potential decrease in lag time as a
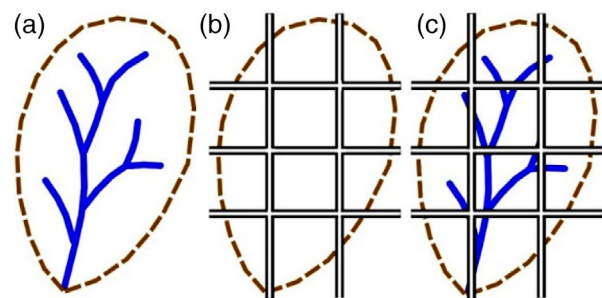
FIGURE 1 Drainage configurations. Natural (a) and artificial (b) networks may be combined in an urban drainage system (UDS) (c). *Source:* Adapted from Graf (1977)
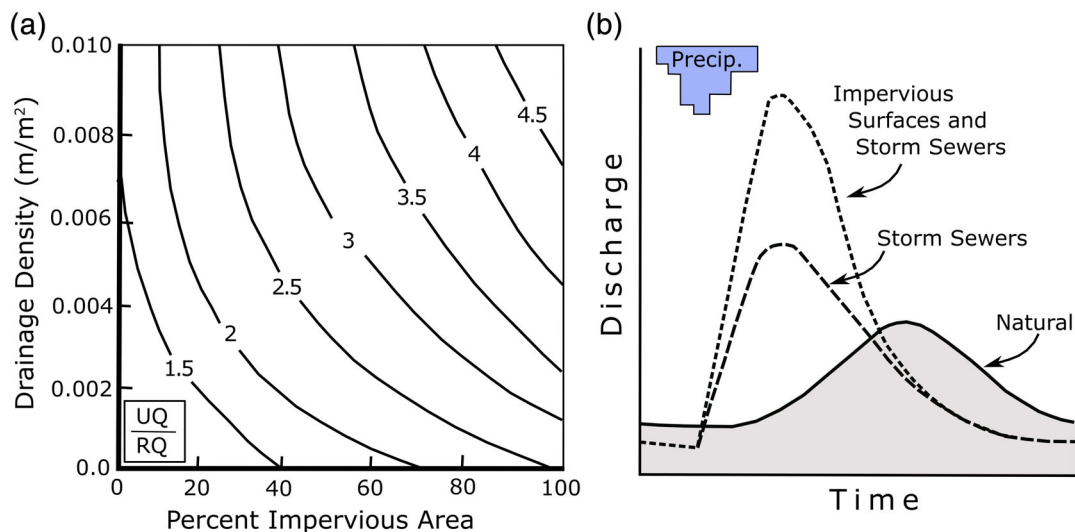
FIGURE 2 Hypothetical effects of storm sewers and PIA on runoff response. (a) Hypothetical relationship between ratios of urban vs. non-urban mean annual floods (numbers on curves) as a function of percent impervious surfaces (PIA) and percent area served by a SS system. UQ is the mean annual flood after urbanization; RQ is the mean annual flood before urbanization. *Source:* Adapted from Leopold (1968). (b) Schematic of hypothetical runoff hydrographs representing changes due to impervious surfaces and storm sewers. *Source:* Adapted from Putnam (1972)

result of increased percent impervious area (PIA) is not well documented. Both acceleration of flow by SS and increased volumes by impervious surfaces result in higher peak discharge.

Much less research has been done on the effects of roads and their connectivity to SS drainage systems and channels than on impervious surfaces or storm sewers. Palla, Colli, Candela, Aronica, and Lanza (2018) highlights the importance of examining urban drainage systems (UDS) and including these circumstantial factors in urban hydrodynamic models, as they can be used to better develop flood hazard maps. Including roadside gutters and ditches along with the SS system effectively lengthens channels and increases drainage densities as these artificial systems also concentrate stormflow and deliver water to catch basins and channels more rapidly than sheet flows (Meierdiercks et al., 2010; Miller & Hess, 2017). Issues of imperviousness, SS systems, and the UDS represent a growing problem for water resource managers, urban planners, and flood-risk managers. This study examines these hydrologically relevant metrics in an effort to improve estimations of the hydrological impacts of urbanization and the associated flood risk.

This research investigates the compounding effects of impervious surfaces, SS systems, and road stormwater runoff at the small watershed scale. Geospatial analysis is expanded beyond conventional mapping of total impervious areas (TIA) to include drainage densities of SS and road networks. These densities are combined with hydrologic analysis and model simulations to examine the interrelationships between other factors, such as slope, zoning, TIA, SS density, and road density and their potential influence on stormwater responses. New SS maps and discharge data for the study area provide an opportunity to study these relationships and to examine interactions between PIA, SS densities, and stormwater discharges. The lack of stormwater detention structures or other stormwater management make the study area an ideal catchment for this analysis. The objective is to examine the spatial configurations of impervious surfaces, SS drainage systems, and roads within Rocky Branch Watershed (Rocky Branch) in Columbia, South Carolina to better understand the combined effect that these urban features have on urban flood hydrology.

Three general research questions are raised to address the compounding effects of impervious surfaces and the UDS on hydrologic responses:

1. How do drainage networks for 60 subcatchments in Rocky Branch vary in terms of density of channels, SS, and roads, PIA, and type of urbanization (zoning)? Specifically, how does density increase with addition of SS and road systems?
2. What are the compounding hydrologic effects of combining imperviousness with SS with regards to timing of stormflow peaks and runoff volumes?
3. Do combined effects of PIA and SS density improve estimates of urban flooding, which are conventionally based solely on TIA?

2 | DATA AND METHODS

2.1 | Study area

Rocky Branch Watershed (Rocky Branch), a small (10.3 km^2) sub-watershed of the Congaree River in Columbia, South Carolina, is in the Sandhills physiographic region of the upper Coastal Plain of the southeastern USA (Swezey et al., 2016). This area has steep slopes and sandy soils and is highly affected by changes in infiltration rates that occur with increases in impervious surfaces (Hung, James, & Carbone, 2018). Rocky Branch Creek is highly urbanized as it heads near the central business district of downtown Columbia and urban residential neighbourhoods such as those around Martin Luther King, Jr. Park (Figure 3). Rocky Branch Creek is ~4.2 km in length and flows through the Five Points commercial district, southern portions of the University of South Carolina campus, and old mill neighbourhoods before entering the Congaree River (Dong Liu, 2007; Sexton, 2014; Wooten, 2008). Very little conventional storm-water mitigation has been instigated in Rocky Branch and flash flooding is a perennial problem (McCormick and Taylor, 2016).
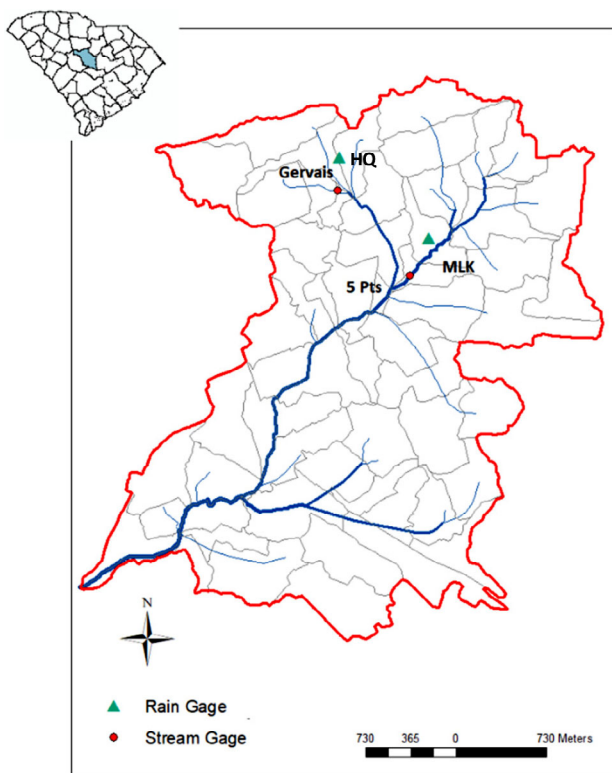
FIGURE 3 Rocky Branch Watershed in Columbia, SC displaying prominent areas including the Gervais subcatchment and Martin Luther King (MLK) subcatchment, as well as the commercial district of 5-Points, which experiences chronic flooding. Rain gages (triangles) and stream gages (circles)

Rocky Branch has serious flood risks owing to extensive imperviousness (Hung, James, & Hodgson, 2018), lack of open channels, and a dense SS system. A recent watershed assessment concluded that the "lack of open channels, limited storm-water management, and an excessive amount of impervious surfaces in the headwaters has negatively impacted the downstream network, resulting in widespread water quality and storage issues" (McCormick and Taylor, 2016, p. 13). Urbanization of this area coupled with the insufficient storage of storm water has led to chronic flooding of many urban areas, especially in the commercial district of Five Points (Morsy, Goodall, Shatnawi, & Meadows, 2016).

2.2 | Testing of hypotheses

2.2.1 | Drainage densities

Drainage densities, topography, and the degree of urbanization were computed by a variety of geospatial methods using spatial data from multiple sources. The spatial data were subdivided into 60 subcatchments and many parameters were calculated for each of the subcatchments. These subcatchments serve as the basis for spatial analysis. Drainage densities (total channel lengths/drainage area) were calculated for each subcatchment based on the same airborne light detection and ranging (LiDAR) high-resolution topographic data that were used for the watershed assessment (McCormick and Taylor, 2016). Densities for each subcatchment were calculated for three configurations: (1) pre-urban natural channels, (2) current open channels plus the SS system (SS pipes and culverts), and (3) the urban drainage system (UDS), which encompasses all parameters that might concentrate flows in channels including the current open channel, the SS system, and elements of the road network. The pre-urban natural channel was derived using a flow accumulation grid model with an accumulation threshold of 90,000 m^2 (9 ha or 10,000 3 × 3-m cells) and edited based on topographic and confluence positions using a LiDAR shaded relief map with contours. The identification of channel heads was influenced by the occurrence of swales or hollows at confluences of small headwater flow lines near the accumulation threshold. The moderately large threshold area reflects the highly permeable soils of the Sandhills physiographic region. The SS pipes, drains, culverts, and open channel in Rocky Branch were mapped in Arc Map (®ESRI) by the City of Columbia in 2013. Drainage densities of the SS system were computed for each subwatershed by summing the lengths of the pipes, drains, and culverts and dividing by the respective area.

The total UDS density was calculated by adding the lengths of open channels and selected roads to the lengths of SS pipes. Channels and roads within 30 m of any SS pipe were eliminated to avoid redundancy and over-estimation of the drainage network. Paved roads in areas not corresponding with SS systems were added to the SS maps as lines of channelized flow (Figure 4). Road crowns are often clearly discernible on LiDAR shaded relief images, indicating gutters on both sides of the roads. Most roads were mapped as a single flow line, but roads >30 m wide and those separated by a divider were mapped with two flow lines. Total lengths of the selected roads were tabulated for each of the 60 subcatchments and used to compute drainage densities.

### 2.2.2 | Catch basins, percent impervious area, slope, and zoning

Most urbanized watersheds do not have an up-to-date SS map due to the expense involved in making those maps. The existence of a recent SS map for Rocky Branch made this study possible and allows analyses of UDS characteristics that may be used to estimate densities of a SS system where SS maps might not be available. Several parameters, such as catch basin location, impervious areas, slopes, and zoning, were examined and compared to the presence or absence of SS pipes. The number of catch basins within each of the 60 subcatchments was calculated from the City of Columbia GIS SS data and compared to SS pipe lengths and impervious areas within RBW. The total impervious area (TIA) of each subcatchment was calculated by merging streets, buildings, and miscellaneous impervious surfaces, and PIA was calculated (subcatchment TIA/subcatchment area × 100%) to allow comparisons between subcatchments of different sizes. A gridded percent slope map was derived from the bare earth DEM and used to compute the mean percent slope for each subcatchment.

Zoning restriction data were derived by merging zoning maps for the City of Columbia and Richland County. Zoning classes between the City and County differ somewhat, so county classes were equated with similar City of Columbia classes and consolidated into four primary categories: commercial, industrial, residential 1 (single family/low density housing), and residential 2 (medium/high density housing) (Wooten, 2008). The area of each of the four zoning classes and the percent area of each zoning category were calculated for each subcatchment and the class with the highest percentage was used to label each subcatchment as commercial, industrial, residential 1, or residential 2.

2.2.3 | Compounding effects of imperviousness and SS system

Storm-flow hydrographs were observed for moderate magnitude storms in the Gervais subwatershed (two subcatchments) and Martin Luther King Park (MLK) subwatershed (10 subcatchments) using flow stage and discharge data. The MLK subwatershed has a relatively moderate PIA but a dense SS system, whereas the Gervais subwatershed has a high PIA and a low SS density. The hydrographs were compared with rainfall from two rain gages maintained by Richland County (Figure 3): the headquarters station collected one-, two-, and 5-min data and the MLK station collected rainfall data at one-min intervals. Streamflow data include flow stage and discharge. Flow stages at the Gervais gage were measured with a Solinst Level-logger (barometrically compensated pressure transducer) at short time intervals to provide a record that can be used to measure time to peak. Discharges were measured using a Marsh-McBirney Flo-Mate current velocity meter at the Gervais gage over a limited range of flows to establish a stage-discharge rating curve for moderate flows (Figure 5). Discharge data at MLK were measured by consultants for the City of Columbia using a bottom mounted Sontek-IQ acoustic Doppler current profiler over a range of flows.
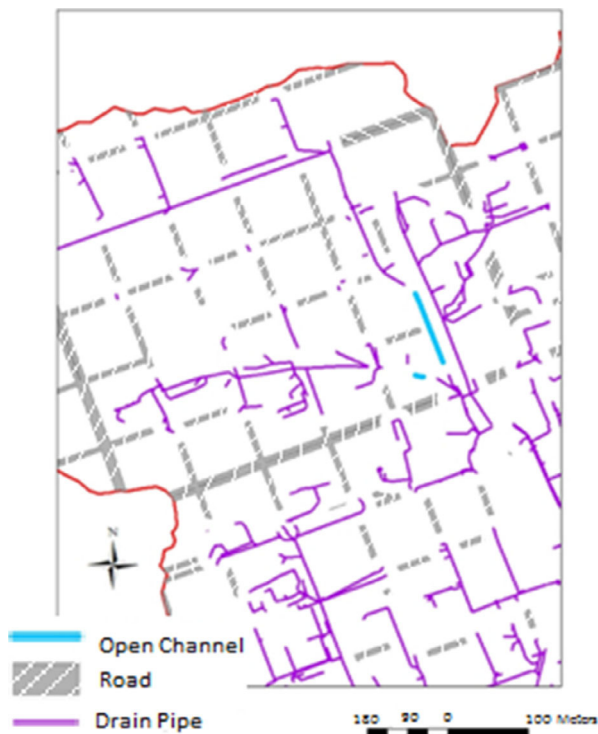
FIGURE 4 Map of selected road-side gutters and ditches (bold lines), open channels, and storm sewers
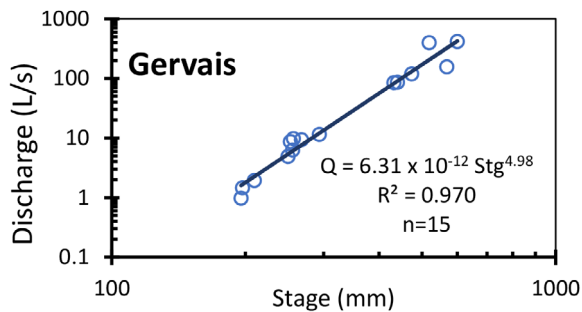
FIGURE 5 Stage-discharge rating curve for the Gervais gage (Hung, 2018)

The timing and volume of storm runoff in the two watersheds, extracted from selected storm hydrographs, were compared to test the hypotheses that high PIA (Gervais) generates more runoff and that denser SS (MLK) results in shorter lag times. Nine storm hydrographs for the MLK subcatchments and 10 storm hydrographs for the Gervais subcatchments were selected from the flow data based on coherent rainfall events and unimodal storm hydrographs to test if high PIA is associated with higher stormflow peaks and storm runoff volumes (Appendix A and B in the supplement).

Rainfall data from the Headquarters and MLK rain gages were used in conjunction with the storm hydrographs to compute rainfall centroids, lag times between the rainfall centroid and peak stage or discharge, and time-to-peak computed as the time between the beginning of rainfall and the peak stage or discharge. Lag times and time-to-peak for observed storm hydrographs were used to test if high PIA (Gervais) or SS densities (MLK) speed up hydrograph responses. The timing of runoff in the two watersheds was examined for compounding effects of SS and UDS drainage densities. Because MLK has a somewhat larger drainage area than Gervais, longer times of concentration increase lag times. This was compensated for by adjusting MLK lag times with a ratio of the times of concentration for Gervais and MLK where time of concentration is based on channel lengths. Lag times and time of concentration are often estimated as a function of maximum channel length to the divide, so lag times were standardized by a coefficient equal to the ratio of the length of Gervais and MLK basins ($L_{G}/L_{MLK} = 0.453$).

Stormflow volumes were calculated for specific storm events within each subcatchment by subtracting baseflow from total discharge. A baseflow of 0.03 m^3/s was observed over several flow events and was used as the baseflow for Gervais. No flows below 10 cm depth were recorded by the acoustic Doppler current profiler at the MLK gage, so discharge data from the acoustic Doppler current profiler was used directly as stormflow at MLK. Stormflow and rainfall volumes were used to calculate runoff coefficients (RC) for each event:

$$RC = Storm\ runoff/Total\ precipitation \qquad (1)$$

The RC is a dimensionless proportion that allows comparisons of effects of imperviousness and SS densities on stormwater volumes between watersheds of different size.

Model settings

The Environmental Protection Agency's Stormwater Management Model (SWMM Version 5) was used to simulate runoff volumes from the MLK and Gervais watersheds (Hung, James, Carbone, & Williams, 2020). The SWMM is an open-source computer model that simulates infiltration, surface runoff, and flow routing (Rossman, 2015). The model can simulate the quantity and quality of runoff in urban watersheds by utilizing urban drainage structures such as SS drain pipes, stormwater management ponds, and surface channels. The SWMM model was calibrated using three storm events and cross-validated using a separate set of three storms at three stream gauges. Observed storm events between July 1, 2016 and February, 2018 at two rainfall stations in the upper watershed were visually screened to remove events that had extreme rainfall variations through time or resulted in multi-modal hydrographs, which left six storm events. Model parameters were adjusted until differences between simulated and observed flows were minimized, or until the Nash-Sutcliffe Efficiency value reached at least 0.70 (Moriasi et al., 2007; Rosa, Clausen, & Dietz, 2015). The SWMM was used to produce total runoff, peak runoff, and the RC for six moderate magnitude storm events for each of the 30 subcatchments above Pickens in RBW. Similarly, RC was computed for nine subcatchments in and adjacent to the Gervais basin, which were compared to RCs for the 10 subcatchments in MLK basin in an independent test for differences between runoff volumes in the Gervais and MLK subcatchments.

2.2.4 | Effects of PIA and drainage densities on flood estimates

Data for large floods in small watersheds are limited, but the effects of PIA on large floods were the focus of a detailed study of regional flooding in urban basins of South Carolina (Bohman, 1992). That study analyzed flood records from many urban watersheds in the region and developed statistical models for floods of various recurrence intervals in watersheds larger than 0.47 km^2 in various physiographic regions of the state as functions of drainage area and PIA. For example, the 2-year flood

RESS ET AL.

CIWEM Chartered Institution of
Water and Environmental
Management

Journal of
Flood Risk Management—WILEY | **7 of 13**

in urban watersheds in the upper Coastal Plain was estimated as (Bohman, 1992):

$$UQ_2 = 0.0719 A^{0.554} PIA^{1.241} RQ_2{}^{0.323} \tag{2}$$

where UQ_2 is discharge (m³/s) of the 2-year flood in an urban area, A is drainage area (km²), and RQ_2 is discharge (m³/s) of the 2-year flood in rural basins of the South Carolina upper Coastal Plain, which can be calculated as (Bohman, 1990, 1992):

$$RQ_2 = 0.350 A^{0.74} \tag{3}$$

Ratios of the 2-year flood to the rural flood (UQ_2/RQ_2) computed with Equations (2) and (3) provide a measure of the impact of urbanization on moderate magnitude floods. This ratio was computed for each of the 60 subcatchments in Rocky Branch and compared with values of SS densities and UDS densities to examine the compounding effects of PIA, SS densities, and UDS densities.

3 | RESULTS

3.1 | Increases in drainage densities

The three configurations of drainage systems demonstrate substantial increases in drainage density from the pre-urban natural channel by addition of the SS system and the road network (Figure 6). This finding corroborates the hypothesis that the natural channel had a significantly lower drainage density than the modern drainages. Converting the natural channel to the SS system approximately tripled the drainage density, whereas adding the network of selected roads more than doubled

the density of the SS system and resulted in almost two orders of magnitude increase from the natural channel drainage density (Table 1). Differences between the natural drainage density and both the current open channel and SS system and the total UDS network for the 60 subcatchments were highly significant ($p < .01$) based on a Wilcoxon rank sums test. These results suggest that urbanization causes a significant increase in drainage densities though the addition of SS (Graf, 1977).

3.2 | Catch basins, percent impervious area, slope, and zoning

Relationships with the SS system to parameters, such as catch basin location, slope, PIA and zoning, were examined to explain patterns of the SS system. The number of catch basins was strongly correlated ($R^2 = 0.89$) to storm sewer length (Figure 7a). This relationship suggests that where SS drainage system maps are not available a first-approximation of SS drainage density may be based on a count of catch basins, following calibration of the relationship with a sample of drainpipe lengths for the area. Commercial zones have the highest number of catch

TABLE 1 Drainage densities for various configurations of RBW

Configuration	Drainage density (m/km²)
Pre-urbanization natural channel	3,140
Open channel and SS system	9,390
Urban drainage network (open channel, SS, and roads)	203,700
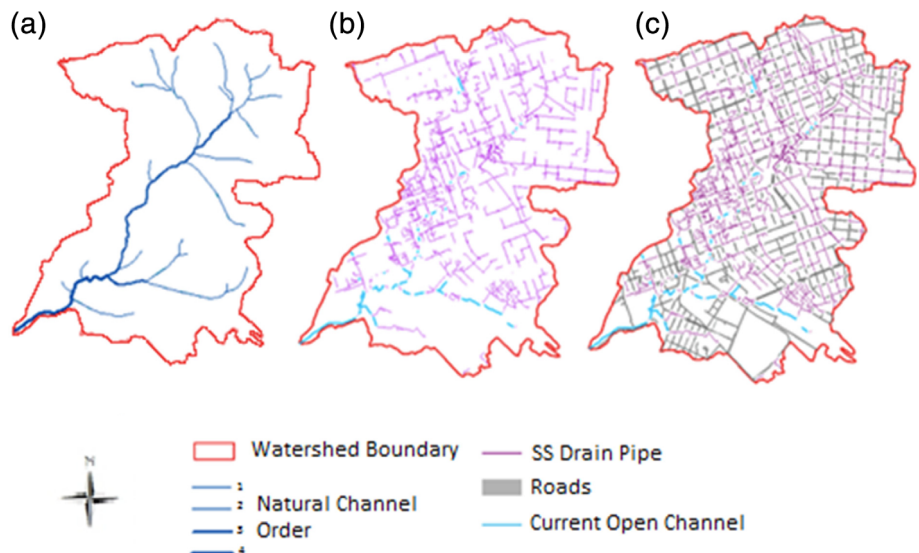
FIGURE 6 Three configurations of drainage networks with increases in density from: (a) the pre-urban natural channel, (b) the current open channel and SS system, and (c) the total urban drainage network that includes the current open channel, the SS system, and selected roads
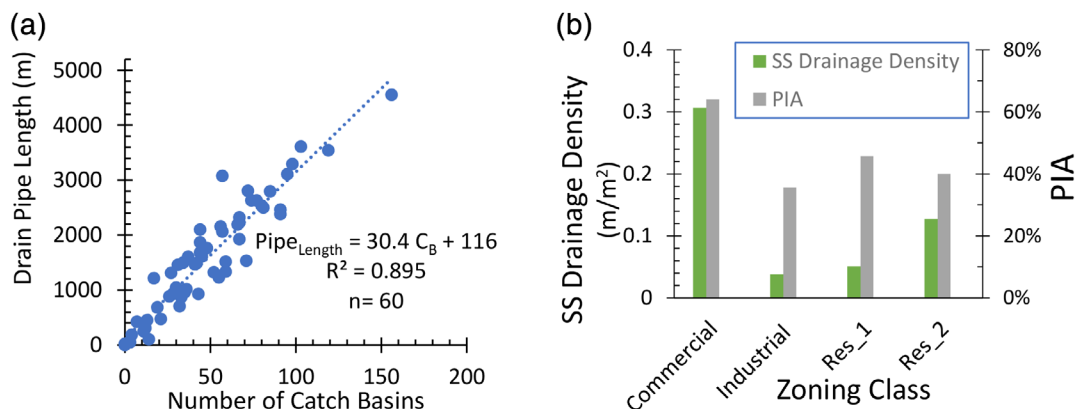
FIGURE 7 Relationship between stormsewer (drain pipe) length and catch basins for the 60 subcatchments (a) and PIA and SS density for each of the Zoning classes (b)

basins (1,524), followed by Residential 2 (621), Residential 1 (274), and Industrial (268), where Residential 1 is zoned for single family homes and Residential 2 for multiple dwelling units. PIA was not significantly correlated to drain pipe length within the watershed ($R^2 = 0.04$).

The SS drainage densities for four zoning classes show that subcatchments dominated by commercial zones have the highest SS drainage density (0.307 m/m^2), followed by Residential 2 (0.127 m/m^2), Residential 1 (0.051 m/m^2), and Industrial (0.038 m/m^2) catchments (Figure 7b). Comparing the zoning SS densities to the PIA indicates a similar pattern as SS drainage density but greater variance between classes for SS densities. Commercial has the highest PIA (64%) and Industrial has the lowest PIA (36%). Unlike SS drainage densities, however, Residential 1 (46%) has higher PIA values than Residential 2.

3.3 | Effects of imperviousness and SS system on flood timing and RCs

Topographical analysis of two contrasting groups of subcatchments, MLK and Gervais, was performed to determine the compounding effects of imperviousness and SS systems. The MLK basin is mostly residential with a mean PIA of 47% over 10 subcatchments, while Gervais is a smaller, dominantly commercial area with a mean PIA of 72% over two subcatchments. Although the MLK subcatchments have a lower PIA, they have higher SS and UDS densities (946 and 653 m/ha, respectively) compared to the Gervais subcatchments (153 and 388 m/ha, respectively). These contrasts allow comparisons of hydrologic responses to be made between PIA and drainage densities in the two watersheds.

Time to peak (time between beginning of rainfall to peak stage and discharge) and lag times (time between

centroid of rainfall to peak stage and discharge) for the 12 MLK and 11 Gervais storm hydrographs (Ress, 2018) were compared between the two basins to test the effect of drainage densities (Appendix A and B in supplement). As expected, the smaller Gervais basin had shorter mean times to peak (24 min) and lag times (14 min) than MLK (51 and 21 min, respectively) due to much shorter travel distances in the smaller Gervais basin. To standardize for the difference in size between the two catchments, the ratio of maximum channel lengths ($L_G/L_{MLK} = 0.453$) was used to compensate for the larger MLK basin size. After scaling for size, the standardized mean time to peak was 23 min for the MLK basin and standardized mean lag time was 9 min (Figure 8). A T-test showed that the standardized lag times in the MLK basin were significantly shorter than in the Gervais basin ($p < .01$). Differences in time-to-peak between the MLK basin and the Gervais basin were not significant after scaling ($p < .347$). Lag times are based on the centroid of rainfall and tend to be a more robust metric of storm timing, so based on the significantly shorter lag times for MLK, it is concluded that the subwatershed with the highest SS density has a faster runoff response than the subwatershed with the highest PIA.
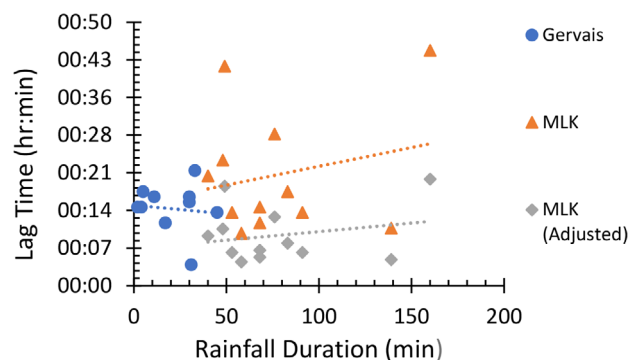
FIGURE 8 Lag time and rainfall duration for MLK and Gervais storm hydrographs

To test the effect of PIA on runoff, stormflow volumes and RCs were computed from the nine MLK and nine Gervais storm hydrographs. The average storm RC at the MLK gauge was 0.011, while the average storm RC for the Gervais gauge was 0.446, an order of magnitude greater. The difference between them was highly significant ($p < .01$) based on a Wilcoxon rank sums test. The SWMM-simulated runoff data reveal similar results for a single storm event. The RCs for the nine Gervais Basin subcatchments ranged from 0.46 to 0.71 and averaged 0.57, which was significantly larger ($p < .01$) than RCs for the 10 MLK subcatchments that ranged from 0.32 to 0.49 and averaged 0.42. These results support the hypothesis that the higher PIA of the Gervais subcatchment results in a greater increase in the proportion of rainfall that runs off than in MLK. It also indicates that PIA is more important than SS densities to increases in runoff volumes.

3.4 | Effects of imperviousness and SS system on flood estimates

PIA and drainage area have been shown to have a dominating effect on instantaneous peak flow rates of large floods in urban basins of the Southeastern USA (Bohman, 1992). After eliminating two of the 60 subcatchments that were smaller than Bohman's data range, 2-year urban/rural flood ratios (UQ_2/RQ_2) were computed with Bohman's (1992) empirical equations based on PIA and drainage area [Equations (2) and (3)]. The resulting ratios range between 5.63 and 34.9 which represents an order-of-magnitude increase in the 2-year floods in these small subcatchments based on PIA. Similarly, in a twin-watershed study, order-of-magnitude multiples between urban and forested watersheds were obtained independently based on observed discharge data from moderate-magnitude floods by Hung, James, and Carbone (2018), who concluded that the relatively large increases in stormwater peaks were due to the sandy, forested soils in unurbanized catchments. Regression of UQ_2/RQ_2 on SS densities for the 58 subcatchments in Rocky Branch shows that increases in 2-year flood magnitudes due to urbanization predicted by PIA and drainage area alone increase systematically with SS densities (Figure 9). Although this correlation is not statistically significant, SS density explains 18% of the variance in UQ_2/RQ_2 with SS density. Bohman's functions were derived independently of SS densities, so the positive trend in UQ_2/RQ_2 supports the hypothesis that SS densities increase flood peaks beyond what is caused by PIA alone and suggest that inclusion of SS densities in empirical analyses could improve flood-risk predictions.

The RC [Equation (1)] values produced by the SWMM model for six moderate magnitude storm events in the 30 subcatchments of the upper basin were compared to values of PIA and SS density to examine the effects of these factors on runoff volumes. As expected, because PIA is used by SWMM in the simulation of runoff, RC for the six storm events was positively correlated with PIA (Figure 10). The subcatchment represented by the low outlier with ~60% PIA is a very small catchment with an area of only 0.028 km^2. Regression slopes for the six storms average 0.72 indicating that the proportion of rainfall that runs off increases rapidly and predictably with increasing PIA, which reconfirms the well-established positive relationship between runoff volume and PIA (Hollis, 1975, Arnold Jr & Gibbons, 1996). Conversely, RCs were not well correlated with SS densities for the six storm events in the upper basin subcatchments. Thus, the SWMM-simulated runoff data do not support a hypothesis that runoff volumes increase with SS density beyond what is predicted by PIA.

Bivariate regressions of RC on PIA and SS density generally did not improve on the relationships between RC and PIA alone. Explained variance for multiple regressions of RC for the six storms was largely unchanged and, in five out of the six cases, adjusted R^2 values were lower than the R^2 of PIA. Also, the bivariate regression for pooled data from all six storms was not significant ($a = 5\%$). In short, runoff volumes, as measured by RC computed by SWMM modelling, were strongly correlated with PIA but were not correlated with SS density and including SS densities did not improve the prediction of RC with PIA. This supports the hypothesis that imperviousness would increase runoff volumes more than SS density and suggests that SS density had little

SS Drainage Density vs. Bohman UQ2/RQ2

U/R = 442.5 SS + 13.78
R² = 0.1824
n=58
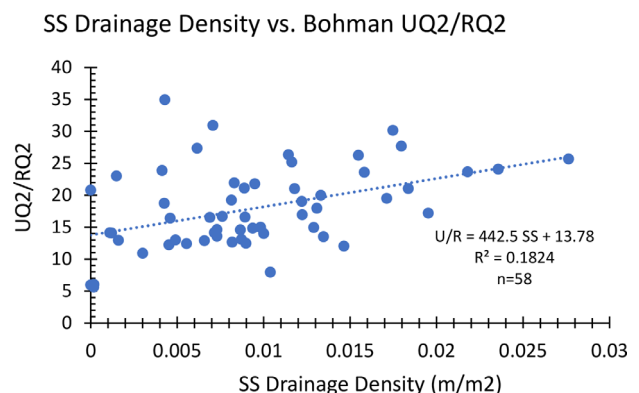
FIGURE 9 Ratios of urban 2-year floods to rural 2-year floods as a function of corresponding SS drainage densities for the 58 subcatchments in RBW. UQ_2 and RQ_2 were computed using Equations (2) and (3) (Bohman, 1992)

effect on runoff volumes for the SWMM-simulated moderate-magnitude stormflows.

To further explore interactions between PIA and SS density on runoff volumes, SS densities were plotted against PIA with SWMM-derived RC and discharge values for each MLK and Gervais subcatchment labeled (Figure 11). The RC values for each storm generally increase along the horizontal axis as PIA increases (Figure 11a), which corroborates the regression analysis and further validates the hypothesis. On the other hand,

SS density has little effect on RC, indicating that the SS system does not increase simulated runoff volumes. A similar plot of SS densities against PIA with peak discharge values labeled (Figure 11b) is somewhat analogous to Leopold's (1968) analysis (Figure 2). In this plot, SS density is substituted for Leopold's percent area serviced by storm sewers and peak discharge from SWMM simulations of a moderate magnitude storm is substituted for multiples of the mean annual flood. Leopold (1968) suggested that increases in both impervious areas and increases in areas
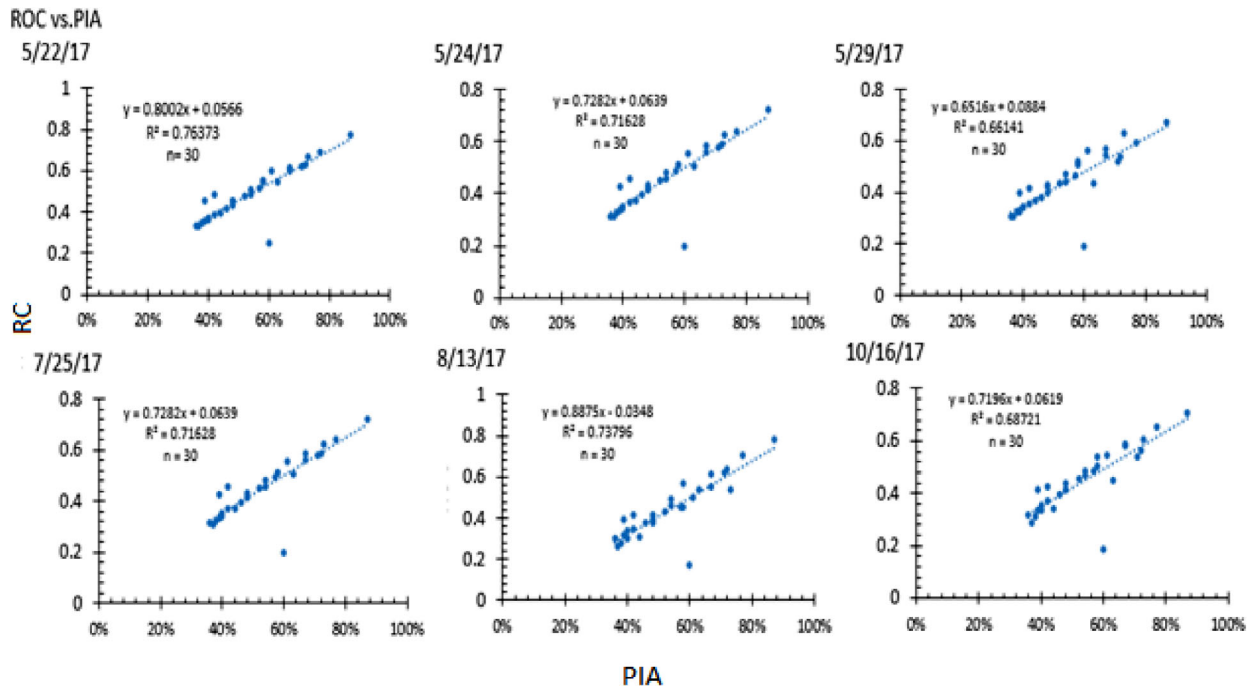

FIGURE 10 RC values from six storm events computed by SWMM model for the 30 subcatchments above Pickens compared to PIA
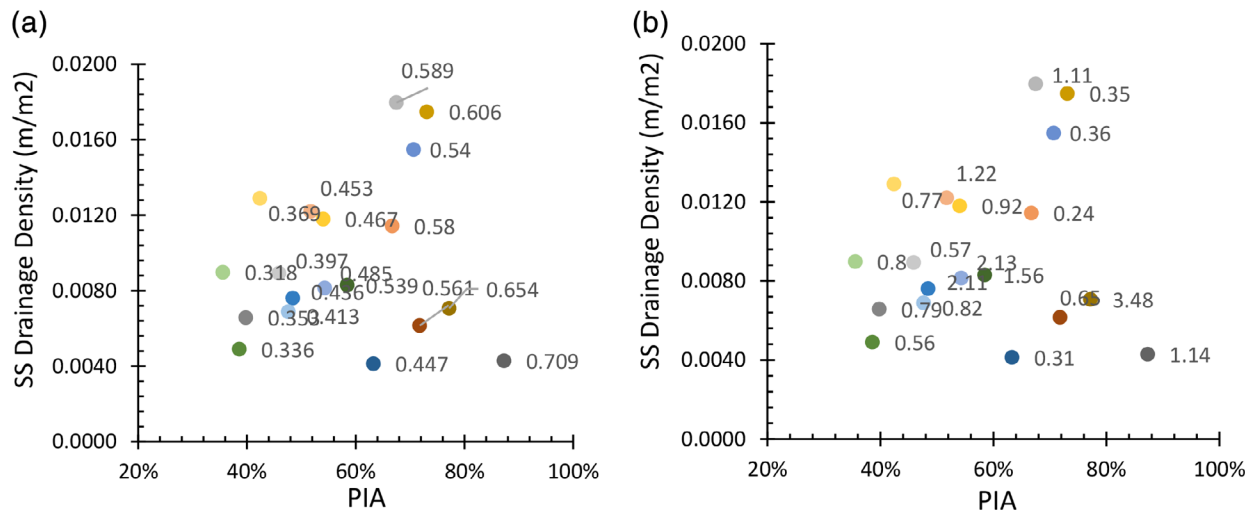

FIGURE 11 SS drainage density and PIA values for the 19 subcatchments in the MLK and Gervais sub-basin labeled with SWMM-derived runoff and discharge values. (a) Labels are RC output values (mm/mm). (b) Labels are peak discharge (CMS) for the 10/16/17 storm event

served by the storm sewer system would result in a magnification of the mean annual flood. This does not seem to apply to the subbasins studied in Rocky Branch, as peak discharges of moderate-magnitude stormflows were not strongly related to either PIA or SS densities.

4 | DISCUSSION AND CONCLUSIONS

Factors that affect urban stormflow are not restricted to impermeable surface areas. Including SS and UDS in stormwater analyses could result in a more complete understanding of the hydrologic impacts of urbanization and more effective flood-risk mitigation from a multidisciplinary perspective. Roads and SS systems concentrate and accelerate the flow of stormwater, so high drainage densities of SS and UDS may shorten stormwater arrival times. This study shows that the addition of the SS system tripled drainage densities and the addition of the entire UDS including selected roads increased drainage densities by almost two orders of magnitude. This increased connectivity of artificial channels, SS, and roads accelerates flow velocities and provides a series of metrics that can be used to assess urban flood risks. Effects of road networks on stormwater arrival times should be considered to accurately assess flood risks. Drainage densities based only on open channels underestimate conveyance in highly urbanized watersheds.

Factors that may act in conjunction with PIA to alter stormwater responses were compared between two highly urbanized subcatchments. In support of hypotheses, the MLK basin, which has moderate PIA but high SS and UDS densities, produced storms with faster adjusted peak arrival times, whereas the Gervais basin, which has moderate SS and UDS densities but very high PIA, produced significantly more runoff but with slower delivery times. Significant decreases in adjusted lag-time response in MLK support the hypothesis that the SS system speeds up arrival times of peak discharge. However, PIA and drainage densities have different effects on runoff volumes and timing and knowledge about these differences is key to wise stormwater system design and management decisions.

Differences in simulated RC values for six storm events support the hypothesis that imperviousness has a direct effect on runoff volumes in RBW. The nine Gervais subcatchments contain the highest PIA values in RBW, resulting in the largest RC values. Although, SS drainage densities had little effect on runoff volumes, they had a significant effect on shortening lag times. Empirical functions previously developed for estimating peak discharges based on PIA could be improved by including information about SS and UDS densities. Ratios of urban to rural 2-year discharges predicted by PIA-based functions are positively related to SS densities, which implies a systematic relationship between moderate-magnitude floods and SS density. Leopold (1968) suggested that increases in both impervious areas and areas served by storm sewers would magnify the mean annual flood. The details of this relationship are not supported by Rocky Branch moderate-magnitude storm data. Peak discharges were not significantly correlated with either PIA or SS densities. However, ratios of urban to rural 2-year discharges (UQ_2/RQ_2) show a modest positive effect of SS densities. This suggests that imperviousness and drainage area are not the only important factors governing urban flood responses but adding SS or UDS density to statistical models of urban flood risks could also improve results. This echoes the growing call for alternative metrics in urban hydrology that consider additional factors influencing hydrologic characteristics in small catchments to better understand the total effect of urbanization on stormflow.

Future research on long-term hydrologic responses in small urban catchments would benefit from analysis of catchments with multiple streamflow gauge records across a variety of stormwater development types and of long enough duration to compute flows with longer return frequencies such as 5- to 20-year flows. Few if any such data sets exist, but that is where the greatest uncertainties remain in assessing flood risk potential at this scale. Urban planners, water resource managers, and flood-risk managers can best make informed decisions about decreasing flood risks in urbanized watersheds if the relative risks of runoff generated from impervious areas and conveyed by SS systems and roads are fully understood.

DATA AVAILABILITY STATEMENT
The data that supports the findings of this study are available in the supplementary material of this article

ORCID
Chen-Ling J. Hung https://orcid.org/0000-0003-1885-7478
L. Allan James https://orcid.org/0000-0002-2623-1216

REFERENCES

Anderson, D. G. (1970). *Effects of urban development on floods in northern Virginia* (p. 22). Washington, DC: US Government Printing Office.

Arnold, C. L., Jr., & Gibbons, C. J. (1996). Imperious surface coverage: The emergence of a key environmental indicator. *Journal of the American Planning Association*, 62(2), 243–258.

Bohman, L. R. (1990). Determination of flood hydrographs for streams in South Carolina; Volume 1. Simulation of flood hydrographs for rural watersheds in South Carolina. *U.S. Geological Survey Water-Resources Investigations Report*, 89-4087.

Bohman, L. R. (1992). Determination of flood hydrographs for stream in South Carolina: Volume 2. Estimation of peak-discharge frequency, runoff volumes, and flood hydrographs for urban watersheds. Final Report (No. FHWA-SC-88-01, Vol. 2).

Booth, D. B. (1991). Urbanization and the natural drainage system: Impacts, solutions, and prognoses. *The Northwest Environmental Journal*, 7, 93–118.

Brabec, E., Schulte, S., & Richards, P. L. (2002). Impervious surfaces and water quality: A review of current literature and its implications for watershed planning. *Journal of Planning Literature*, 16(4), 499–514.

Burns, M. J., Fletcher, T. D., Walsh, C. J., Ladson, A. R., & Hatt, B. E. (2011). Hydrologic shortcomings of conventional urban stormwater management and opportunities for reform. *Landscape and Urban Planning*, 105(3), 230–240.

Dong Liu, E. (2007). Summary review of HEC-HMS model and updated hydrologic analysis of the Rocky Branch drainage basin in conjunction with the Rocky Branch hydraulic analysis for the city of Columbia, South Carolina. CIP Project No. SD804801 Richland County.

Dunne, T., & Leopold, L. B. (1978). *Water in environmental planning*, New York, NY: W. H. Freeman & Co.

Gilbert, J. K., & Clausen, J. C. (2006). Stormwater runoff quality and quantity from asphalt, paver, and crushed stone driveways in Connecticut. *Water Research*, 40(4), 826–832.

Graf, W. L. (1977). Network characteristics in suburbanizing streams. *Water Resources Research*, 13(2), 459–463.

Hollis, G. E. (1975). The effect of urbanization on floods of different recurrence interval. *Water Resources Research*, 11(3), 431–435.

Hung, C.-L. J. (2018). Catchment hydrology in the Anthropocene: Impacts of land-use and climate changes on stormwater runoff. Ph.D. Dissertation, University of South Carolina, SC, USA, 160pp. Retrieved from https://scholarcommons.sc.edu/etd/4812

Hung, C.-L. J., James, L. A., & Carbone, G. J. (2018). Impacts of urbanization on stormflow magnitudes in small catchments in the sandhills of South Carolina, USA. *Anthropocene*, 23, 17–28. https://doi.org/10.1016/j.ancene.2018.08.001

Hung, C.-L. J., James, L. A., & Hodgson, M. E. (2018). An automated algorithm for mapping building impervious areas from airborne LiDAR point-cloud data for flood hydrology. *GIScience & Remote Sensing*, 55(6), 798–816. https://doi.org/10.1080/15481603.2018.1452588

Hung, C. -L. J., James, L. A., Carbone, G. J., & Williams, J. M. (2020). Impacts of combined land-use and climate change on streamflow in two nested catchments in the Southeastern United States. *Ecological Engineering*, 143, https://doi.org/10.1016/j.ecoleng.2019.105665.

Leopold, L. B. (1968). *Hydrology for urban land planning: A guidebook on the hydrological effects of urban land use* (Vol. 554). Washington, D.C: Geological Survey Circular 21pp.

McCormick and Taylor. (2016). *Rocky branch watershed assessment* (pp. 1–194). City of Columbia: Utility and Engineering Department.

Meierdiercks, K. L., Smith, J. A., Baeck, M. L., & Miller, A. J. (2010). Analyses of urban drainage network structure and its impact on hydrologic response. *Journal of the American Water Resources Association*, 46(5), 932–943.

Miller, J. D., & Hess, T. (2017). Urbanisation impacts on storm runoff along a rural urban gradient. *Journal of Hydrology*, 552, 474–489.

Moriasi, D. N., Arnold, J. G., Van Liew, M. W., Bingner, R. L., Harmel, R. D., & Veith, T. L. (2007). Model evaluation guidelines for systematic quantification of accuracy in watershed simulations. *Transactions of the ASABE*, 50(3), 885–900.

Morisawa, M. (1985). *Rivers: Form and process*. London: Longman 222pp.

Morsy, M. M., Goodall, J. L., Shatnawi, F. M., & Meadows, M. E. (2016). Distributed stormwater controls for flood mitigation within urbanized watersheds: Case study of rocky branch watershed in Columbia, South Carolina. *Journal of Hydrologic Engineering*, 21(11), 05016025.

O'Driscoll, M., Clinton, S., Jefferson, A., Manda, A., & McMillan, S. (2010). Urbanization effects on watershed hydrology and in-stream processes in the southern United States. *Water*, 2(3), 605–648.

Ogden, F. L., Raj Pradhan, N., Downer, C. W., & Zahner, J. A. (2011). Relative omportance of impervious area, drainage density, width function, and subsurface storm drainage on flood runoff from an urbanized catchment. *Water Resources Research*, 47(12), W12503.

Palla, A., Colli, M., Candela, A., Aronica, G. T., & Lanza, L. G. (2018). Pluvial flooding in urban areas: The role of surface drainage efficiency. *Journal of Flood Risk Management*, 11, S663–S676.

Putnam, A. L. (1972). Effect of urban development on floods in the Piedmont Province of North Carolina. *U.S. Geological Survey Open File Report*, (72–304). Washington, DC: US Government Printing Office.

Ress, L. (2018). *Impacts of drainage systems on stormwater hydrology: Rocky Branch Watershed, Columbia, South Carolina*. Unpub M.S. thesis, Univ. South Carolina.

Rosa, D. J., Clausen, J. C., & Dietz, M. E. (2015). Calibration and verification of SWMM for low impact development. *Journal of the American Water Resources Association*, 51(3), 746–757.

Rose, S., & Peters, N. E. (2001). Effects of urbanization on streamflow in the Atlanta area (Georgia, USA): A comparative hydrological approach. *Hydrological Processes*, 15(8), 1441–1457.

Rossman, L. A. (2015). *Storm Water Management Model*, User's manual version 5.1; EPA/600/R-14/413b.

Sexton, B. (2014). Potential stormwater runoff reductions by incorporating low impact development: Rocky branch watershed, Columbia, SC. Unpub. M.S. thesis, Univ. South Carolina.

Smith, J. A., Baeck, M. L., Morrison, J. E., Sturdevant-Rees, P., Turner-Gillespie, D. F., & Bates, P. D. (2002). The regional hydrology of extreme floods in an urbanizing drainage basin. *Journal of Hydrometeorology*, 3(3), 267–282.

Swezey, C. S., Fitzwater, B. A., Whittecar, G. R., Mahan, S. A., Garrity, C. P., Gonzalez, W. B. A., & Dobbs, K. M. (2016). The Carolina Sandhills: Quaternary eolian sand sheets and dunes along the updip margin of the Atlantic coastal Plain Province, southeastern United States. *Quaternary Research*, 86(3), 271–286.

Wooten, J. (2008). Assessing the restoration feasibility of Rocky Brach Creek: an integrated watershed management approach. Unpub. M.S. thesis, Univ. South Carolina. pp. 1–72.

SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of this article.