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Impacts Of Drainage Systems On Stormwater Hydrology: Rocky Branch Watershed, Columbia, South Carolina

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IMPACTS OF DRAINAGE SYSTEMS ON STORMWATER HYDROLOGY: ROCKY BRANCH WATERSHED, COLUMBIA, SOUTH CAROLINA

by

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ABSTRACT

The effects of urbanization and associated land use changes, specifically increases in impervious surfaces, have long been the focal point of urban hydrologic research. However, studies and calculations that consider impervious surfaces alone do not encompass all factors that influence urban hydrologic response. Artificial structures such as storm sewer (SS) systems and road networks increase rates of stormwater conveyance, yet these artificial networks are rarely considered in computations of drainage densities and associated hydrologic alterations. This study examines several hydrologically relevant descriptors that can be used to better understand the impact of urbanization on small watersheds. Rainfall and stormflow data were analyzed to compare the hydrologic response of two subcatchments in a highly urbanized watershed, Rocky Branch Watershed (RBW). Subcatchments with varying characteristics of percent impervious areas (PIA) and drainage densities were analyzed in order to determine the effect of PIA, storm sewer systems (SS), and the urban drainage system (UDS) as a whole, including road-side gutters and ditches. The results from this study show that the subcatchment (Gervais) with a higher PIA produced higher runoff volumes, while the other subcatchment (MLK) with higher SS and UDS densities displayed shorter lag times following storm events. In this case, PIA increased the volume of runoff, but the SS and UDS densities accelerated the hydrologic response by conveying water at faster rates. The results from this study indicate that alternative hydrologically relevant metrics, such

as SS and UDS densities should be considered in urban stormwater management in order to minimize flood risk.

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LIST OF ABBREVIATIONS

A .... Area

ADCP .... Acoustic Doppler Current Profiler

CoC .... City of Columbia

DEM .... Digital Elevation Model

HQ .... Headquarters

H1A .... Hypothesis 1 A

H2A .... Hypothesis 2 A

H2B .... Hypothesis 2 B

Lt .... Lag Time

LiDAR .... Light Detecting and Ranging

MLK .... Martin Luther King

PIA .... Percent Impervious Area

Q2 .... Two-Year Flood

RBW .... Rocky Branch Watershed

ROC .... Runoff Coefficient

RQ2 .... Rural Two-Year Flood

SS .... Storm Sewer

TIA .... Total Impervious Area

Tp .... Time to Peak

UDS .... Urban Drainage System

USC .... University of South Carolina

USGS .... United States Geological Survey

UQ2..Urban Two-Year Flood

CHAPTER 1

INTRODUCTION

Understanding the hydrologic impact of urbanization in small urban catchments is limited by a need for hydrologically relevant descriptors specific to small watersheds (Miller and Hess 2017). Most modern urban hydrologic studies recognize the important 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 effects of storm sewer (SS) systems are rarely quantified as a factor that effects hydrologic response. Issues of imperviousness and SS systems represent a growing problem for water resources managers, urban planners, and flood-risk managers. Conventional SS drainage systems may contribute to flood risk downstream, but little is known about the relationship between imperviousness and SS densities. It has been noted that increased imperviousness causes substantial increases in moderate to extreme storm events, but increased SS drainage densities increase flood peaks are—up to a limit—most effective with moderate-magnitude storms that do not exceed flow capacities of the SS system (Ogden et al. 2011).

The SS system is the traditional method used to reduce flood risks locally through the implementation of artificial networks that transport runoff away from urbanized areas. However, SS systems also influence the flood hydrology downstream by increasing the drainage density. The addition of artificial channels, pipes, and culverts to the natural channel network increases the efficiency of water conveyance, decreases storm lag times, and increases flood peaks. Similarly, road side gutters and ditches concentrate flows and accelerate the delivery of water downstream (Meierdiercks et al. 2010). This research applies a spatial analysis to the combined effects of impervious surfaces, SS drainage systems, and roads within the Rocky Branch Watershed (RBW) in Columbia, SC.

1.1 URBANIZATION EFFECTS ON HYDROLOGY

Drainage systems encompass all aspects 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 (Dunne and Leopold 1978). Paving of permeable land surfaces ultimately results in degradation of water resources that begins with changes to the hydrologic cycle (Arnold and Gibbons 1996). During a typical rain event in an un-urbanized watershed, only a fraction of the water reaches the channel, with the remainder being evaporated, transpired, or percolated deep into the groundwater system (Booth 1991). However, the proportion of rainfall that runs off, known as the runoff coefficient (ROC), tends to be higher in urban areas (Smith et al. 2002) although exceptions have been noted (Rose and Peters 2001).

Urbanization has the greatest effect on highly permeable catchments where pavement and buildings greatly decrease infiltration (Hung et al. in review). The area of impervious surface and the rate at which the water is transported are the two guiding factors in the hydrologic alteration of an urban watershed (Leopold 1968, Rose and Peters

2001). Impervious surfaces, such as roads, sidewalks, rooftops, and parking lots reduce infiltration, facilitate run off, and shorten small recurrence intervals of floods by a factor of ten of more (Hollis 1975, Arnold and Gibbons 1996, Rose and Peters 2001, Brabec et al. 2002, Gilbert and Clausen 2006).

1.2 PIA, STORM SEWER (SS) DRAINAGE SYSTEMS, AND ROADS

Conventional SS systems are artificial flow networks consisting of gutters, pipes, drains, culverts, and channels that transport storm runoff away from developed areas. Increasingly however, studies have shown that these systems also have an impact on the hydrology by increasing drainage densities (total stream length/watershed area) of the watershed (Leopold 1968, Graf 1977, Smith et al. 2002, Meierdierck et al. 2010, Burns 2011). The SS networks can be added to the existing channel network, which increases channel densities by producing a basin comprised of both natural and artificial networks (Fig. 1.1). The connection of these artificial channels allows runoff to flow directly into the receiving waters with little to no attenuation (Burns et al. 2011).

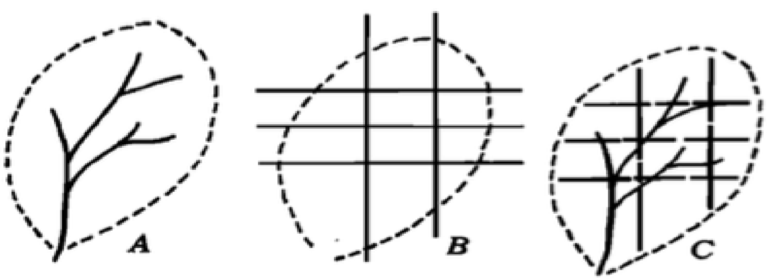

Figure 1.1: Drainage Configurations. Natural (A) and artificial (B) networks may be combined in an urban (C) watershed. From Graf (1977).

The improved efficiency of the system to collect and transfer water shortens lag times and increases kurtosis (or “peakedness”) of hydrographs (Leopold 1968; Graf

1977). 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 have a greater impact on storm-flow timing than percent impervious surface.

Smith et al. (2002) examined increasing flood peaks through time for 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 Little Sugar Creek, decreased the response time downstream, and ultimately increased flood magnitudes. 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 (Fig. 1.2).

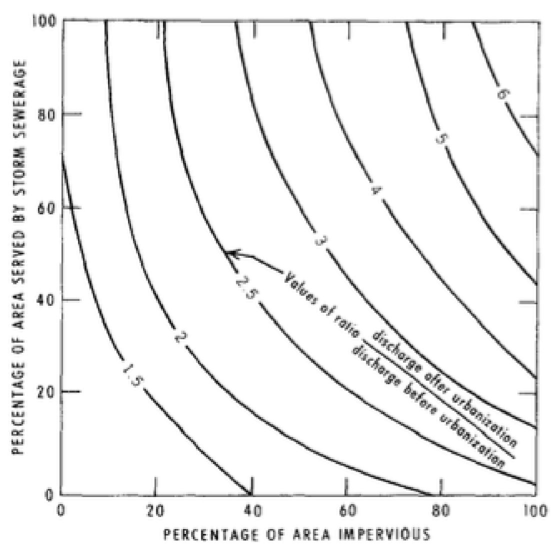

Figure 1.2: Hypothetical relationship between ratios of urban vs. non-urban mean annual floods (numbers on curve) as a function of percent impervious surfaces (PIA) and percent area served by storm-water. (Leopold, 1968).

Theoretically the combination of impervious surfaces and SS drainage systems increases total runoff, stormflow volumes, and flood magnitudes. In an un-urbanized catchment, the hydrograph has slow rising and receding limbs and a low peak. The hydrologic response to the implementation of a SS system is increased flow velocities that decrease the lag time (Lt); i.e., the time between the centroid of rainfall and the peak discharge, and the time to peak (Tp); i.e., the time between the beginning of rain and the peak discharge (NEH 2010). Theoretically, if the SS system does not decrease losses of water, only the timing of the hydrograph is altered and the area under the SS curve, which is proportional to the stormwater volume, would be equal to the area under the natural curve (Putnam 1972, Morisawa 1985). However, the effects of SS on flow volumes are not well documented, and this assumption should be tested. The hydrologic response of increased impervious surface area is a larger volume of runoff in response to decreased infiltration rates as well as a decrease in lag time. 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 research devoted to impervious surfaces or storm sewers. Hypothetically, roadside gutters and ditches can concentrate stormflows and deliver water to catch basins and channels much more rapidly than sheet flows, particularly along roads with high crowns on sloping surfaces (Miller and Hess 2017). Similarly to the SS systems, the concentration of flow along roads is rarely considered in hydrologic simulations or statistical analyses, although road networks can easily be treated as an extension of the SS system and incorporated into that analysis.

1.3 OBJECTIVES AND STATEMENT OF PURPOSE

This investigation explores the compounding effects of impervious surfaces, SS systems, and roads and the resulting hydrologic responses to rain events at the watershed scale. Geospatial analysis is expanded beyond conventional total impervious surfaces (TIA) to also include drainage densities of SS and road networks. These densities are combined with hydrologic analysis to examine the interrelationships between factors such as slope, zoning, TIA, SS density, and road density with regard to stormwater responses. Collectively, the SS and road drainages will henceforth be referred to as the urban drainage system (UDS). New SS maps and discharge data for RBW provide an opportunity to study these relationships and to examine interactions between PIA, SS densities, and stormwater discharges. A geospatial approach is combined with hydrologic analyses to examine the interrelationships between total impervious surfaces (TIA) and UDS density with factors such as slope, zoning, TIA, and SS densities in RBW. The objective is to better understand the theoretical and empirical relationships between TIA, UDS densities, basin characteristics, and storm hydrology responses. The compounding effects of impervious surfaces and the UDS system give insight into how all aspects of urbanization can impair the hydrology of a watershed by altering the hydrologic response to rain events. The SS and road network drainage densities provide alternative hydrologically relevant descriptors to increase the knowledge and overall management of small urban watersheds (Table 1).

Table 1.1 Research Questions and Corresponding Hypotheses

Research Question	Sub-Questions	Hypotheses
1. What is the nature of the drainage network for the 60 RBW subcatchments in terms of topography and degree of urbanization?	• How dense are drainages and how does density vary with addition of SS and road systems? • How does PIA relate to SS density? • How does land-use zoning relate to SS density?	A) The natural channel had a lower drainage density than the modern combined channel and SS system. B) The SS system has a lower density than urban drainage system (UDS). C) Subcatchments with high PIA have higher SS densities. D) Subcatchments in commercial zones have higher SS densities.
2. What are the compounding hydrologic effects of combining imperviousness with SS?	• Does PIA increase storm-flow peaks and runoff volumes without affecting the timing of storm-flow peak arrivals? • Do SS systems speed up storm-flow peak arrivals and increase storm-flow peaks without affecting runoff volumes? • Do combined effects of PIA and SS density differ from estimates based solely on TIA?	A) A subcatchment with high PIA and moderate SS density will have more runoff than a similar subcatchment with lower PIA and denser SS drainage density. B) A subcatchment with high PIA and moderate SS density will have longer peak discharge lag times than a similar subcatchment with lower PIA and denser SS drainage density. C) Q_2 flood magnitudes computed by PIA alone (Bohman 1990; 1992) increase with SS densities.

1.4 STUDY AREA

Rocky Branch watershed (RBW), a sub-watershed of the Congaree River, is located in Columbia, South Carolina in the Sandhills physiographic region of the upper Coastal Plain (Swezey et al. 2016). This area has steep slopes and sandy soils and is highly impacted, therefore, by changes in infiltration rates that occur with increases in impervious surfaces. Rocky Branch Creek (RBC) is highly urbanized as it heads near the central business district of downtown Columbia and urban residential neighborhoods such as those around Martin Luther King, Jr. Park (Fig. 1.3). It flows through the Five Points commercial district, southern portions of the University of South Carolina campus, and old mill neighborhoods before entering the Congaree River. RBC is approximately 4.2 km in length and RBW has an area of approximately 10.3 km^2 (Dong Liu 2007; Wooten 2008). Very little conventional storm-water mitigation has been instigated in RBC and flash flooding is a perennial problem.

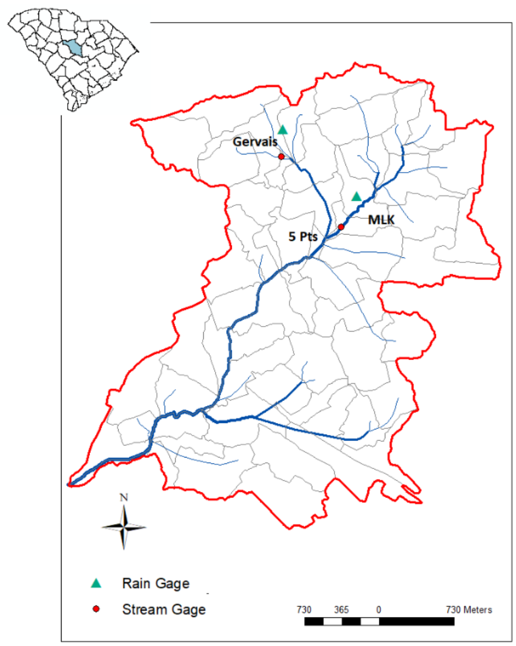

Figure 1.3 Rocky Branch Watershed in Columbia, SC displaying prominent areas including the Gervais subcatchment and Martin Luther King (MLK) subcatchment, as well as the commercial district of 5-Points, which experiences chronic flooding. Rain gages (triangles) and stream gages (circles).

Total impervious areas (TIA) and percent impervious areas (PIA) in RBW were mapped using high-resolution aerial imagery from 2007 (Wooten 2008). Drainage divides for RBW were revised using LiDAR, topography and SS maps and Wooten's

TIA and PIA values for PIA by roads, buildings, and miscellaneous surfaces (sidewalks, driveways, and parking lots) were revised accordingly, based on the new drainage divides (Sexton 2014). The PIA for the entire RBW is 49%, which reflects the high degree of urbanization that also includes extensive channelization, piping, and closed storm drains along with almost no connectivity to floodplain areas (McCormick Taylor 2016).

In addition to imperviousness, RBW has a serious problem with the 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, pg. 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 et al. 2016).

CHAPTER 2

METHODOLOGY

Drainage densities, topography, and the degree of urbanization were computed by a variety of geospatial methods using spatial data from a variety of sources. The SS pipes, drains, culverts, and open channel in Rocky Branch were mapped in Arc Map (®ESRI) by the City of Columbia (CoC) in 2013. The SS drainage system was subdivided into 60 subcatchments for RBW that serve as the basis for spatial analysis. Boundaries for the watershed and subcatchments obtained from the CoC were defined based on topographic data derived from a bare-earth digital elevation model (DEM) for Richland Country. The DEM was produced from Light Detecting and Ranging (LiDAR) topographic data flown in 2010 at 1500-1700 m AGL with a target pulse density of > 2 points per m^2 for the State of South Carolina and the U.S. Geological Survey.

2.1 DRAINAGE DENSITIES

Drainage densities (total channel lengths/drainage area) were calculated for each subcatchment for three configurations: (1) the pre-urban natural channel, (2) the current open channels and 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 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 3x3-m cells) and edited based on topographic and confluence positions using the LiDAR shaded relief and 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. Roadside gutters and ditches often concentrate flow, which act to enlarge channel lengths and increase drainage densities (Meierdiercks et al. 2010). In order to calculate the total UDS density, lengths of open channels were added to lengths of SS pipes and certain roads were selectively added. Channels and roads within a 30-m distance of any SS pipe were eliminated to avoid redundancy and over-estimation of the drainage network. Paved roads located in areas that don’t correspond with SS systems were added to the SS maps as lines of channelized flow (Fig. 2.1).

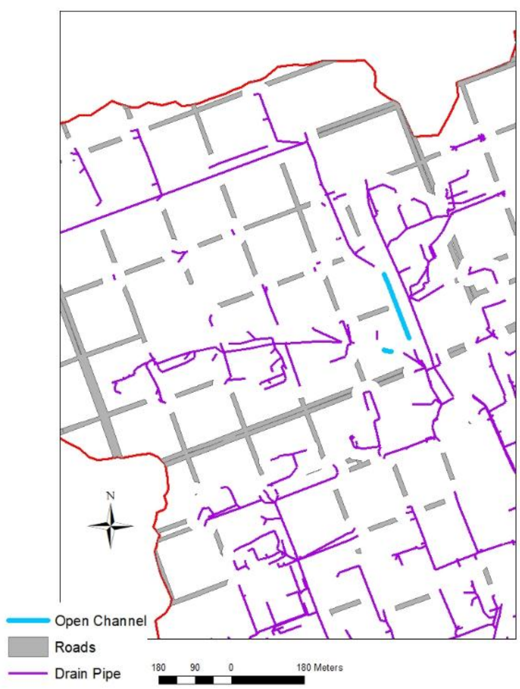

Figure 2.1 Detailed map of road-side gutters and ditches (bold lines), open channels, and storm sewers.

Road crowns are often clearly discernible on the LiDAR shaded relief images, indicating flows in gutters on both sides of those roads, but, for most roads, these were mapped as a single flow line. Larger roads, and those separated with a divider, were mapped with two flow lines. Roads that overlap with SS pipes were removed to avoid over-estimating flow lengths, which were tabulated for each of the 60 subcatchments and used to compute drainage densities.

2.2 CATCH BASINS, PERCENT IMPERVIOUS AREA, SLOPE, AND ZONING

Most urbanized watersheds do not have access to an up-to-date SS map, due to the expenses involved in making these maps. The existence of a recent SS map made this study possible and allows analyses of UDS characteristics that may be used to estimate densities of the SS system where a SS map 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 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 the PIA (subcatchment TIA/subcatchment area) was determined 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 CoC and for Richland County, which applies to a small area beyond the City limits in the southeastern portion of RBW. Zoning classes between the City and County differ somewhat, so county classes were equated with similar CoC 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 percentage 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.

2.3 COMPOUNDING EFFECTS OF IMPERVIOUSNESS AND SS SYSTEM

Storm-flow hydrographs from the Gervais subwatershed (two subcatchments) and Martin Luther King Park (MLK) subwatershed (10 subcatchments) were created using flow stage and discharge data and compared with rainfall at two rain gauges. The MLK subwatershed has a relatively moderate PIA but a dense SS system, whereas the Gervais subwatershed has a low SS density and a high PIA. Rainfall data from two sites maintained by Richland County were used: the headquarters (HQ) station near the Gervais gauge collected one-, two- and 5-minute data at various times, and the MLK station collected rainfall data at 1-mintue intervals. Streamflow data collected at the two sub-basins in RBW include flow stage and discharge (Table 2.1).

Table 2.1 Rainfall and stream gage data used. (*only moderate magnitude in channel discharges were measured for calibration of stage-discharge rating curve).

Subcatchment	**Stream Gage Source**	**Range of Stage Data**	**Range of Discharge Data**	**Rain Gage Source**	**Rain Gage Time Interval**
MLK	City of Columbia	6 months	6 months	MLK	1-min
Gervais	USGS/ USC Geography	8 years	2 years*	HQ	1-min, 2 min, 5 min

Flow stages at the Gervais gauge 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. Discharge data were measured using a Marsh-McBirney Flo-Mate current velocity meter at the Gervais gauge over a limited range of flows to establish a stage-discharge rating curve for moderate flows (Fig. 2.2). The stage-discharge rating curve was used to calculate discharge for moderate storms at the Gervais gage. Discharge data at MLK were measured by consultants for the CoC using a Sontek-IQ acoustic Doppler current profiler (ADCP) over a range of flows.

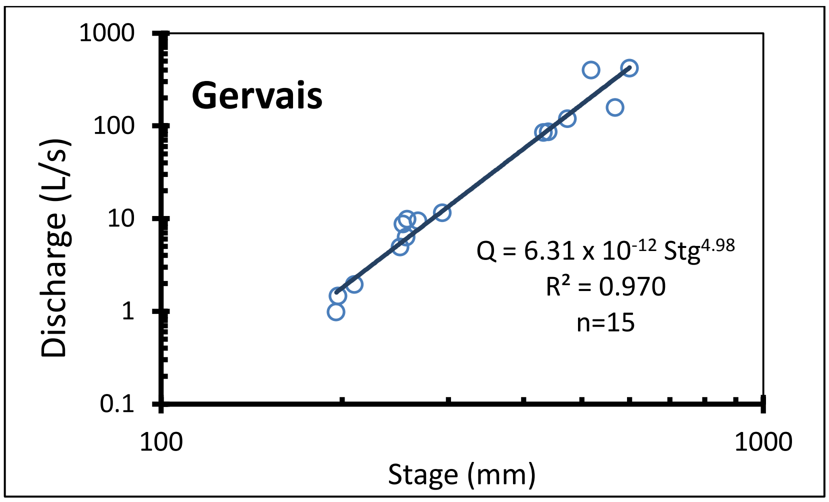

Figure 2.2 Stage-discharge rating curve for Gervais (Hung, 2018).

The volume and timing of runoff in these two watersheds was compared to test hypotheses that high PIA (Gervais) generates more runoff (H2A) and that denser SS (MLK) results in shorter lag times (H2B). Flow information from the stream gages coupled with rain data at the Gervais and MLK subcatchments were used to create hydrographs for selected rain events to examine the impacts of PIA and SS densities

(Table 2). Nine storm hydrographs for the MLK subcatchments and ten storm hydrographs for the Gervais subcatchments were selected from the flow data based on coherent rainfall events and unimodal storm hydrographs in order to test if PIA increases storm-flow peaks and runoff volumes (H2A) stormflow volumes were calculated for specific storm events within each subcatchment. Baseflow was subtracted from total discharge to develop storm hydrographs. A baseflow of 0.03 m^3 was observed over several flow events, and was used as a baseline flow value for Gervais. No baseflows below 10 cm depth were recorded by the ADCP at the MLK gage, so discharge data from the ADCP was used directly as stormflow at MLK. The volume of stormflow at each of the two gaged subcatchments was used to calculate the runoff coefficient (ROC) for each event in order to compensate for the larger size of MLK.

$$\text{ROC} = \text{Total runoff}/\text{Total Precipitation} \qquad \text{(Eq. 1)}$$

The ROC is a dimensionless proportion that allows comparisons of effects of imperviousness and SS densities on stormwater volumes (H2A) and peak discharges between watersheds of different size.

The Environmental Protection Agency's Stormwater Management Model (SWMM Version 5) was also used to examine the runoff volumes of MLK and Gervais. The SWMM model is an open-source computer model that simulates three primary processes; infiltration, surface runoff, and flow routing (Morsy et al. 2016). The model produces information about 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. Output data from Williams et al. (2018) was used to compare runoff coefficients between MLK and Gervais subcatchments. The SWMM model produced total runoff, peak runoff, and the ROC for a single storm event for each of the 60 subcatchments in RBW. The ROC for the nine subcatchments in the Gervais were compared to the ten subcatchments in MLK basin in order to further test the potential increase in runoff volumes in the Gervais subcatchments compared to the MLK subcatchments (H2A).

Rainfall data from HQ and a rain gage at MLK were used to compute rainfall centroids and to compute lag times and time to peak. Lag times were computed as the time between the rainfall centroid and the peak stage or discharge, whereas time to peak was computed as the time between the beginning of rainfall and the peak stage or discharge. Lag times and time to peak for the observed stage and discharge storm hydrographs generated from stream-flow gage records were used to test if increased PIA or SS densities speed up hydrograph responses (H2B). The timing of runoff in the two watersheds was examined for compounding effects of SS and UDS drainage densities (H2B). 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/MLK based on channel lengths.

2.4 EFFECTS OF PIA AND DRAINAGE DENSITIES ON FLOODS

Data for large floods in these small watersheds are limited, but the effects of PIA on large floods was the focus of a detailed study of regional flooding in urban basins of the Southeastern USA (Bohman 1992). That study analyzed flood records from many urban watersheds and developed a statistical model for floods of various recurrence intervals in watersheds larger than 0.47 km^2 as functions of drainage area and PIA. For example, the two-year flood in urban watersheds was found to be best estimated as (Bohman, 1992):

$$UQ_2 = 0.0385\ A^{0.554} PIA^{1.241} RQ_2^{0.323} \qquad \text{(Eq. 2)}$$

where UQ_2 is discharge (m^3/s) of the two-year flood in an urban area, A is drainage area (mi^2), and RQ_2 is discharge (ft^3/s) of the two-year flood in rural basins of the South Carolina upper Coastal Plain, which can be calculated as (Bohman, 1990; 1992):

$$RQ_2 = 25A^{0.74} \qquad \text{(Eq. 3)}$$

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

CHAPTER 3

RESULTS

3.1 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 (Fig. 3.1). As expected, this finding corroborates H1A that the natural channel had a lower drainage density than the modern drainages.

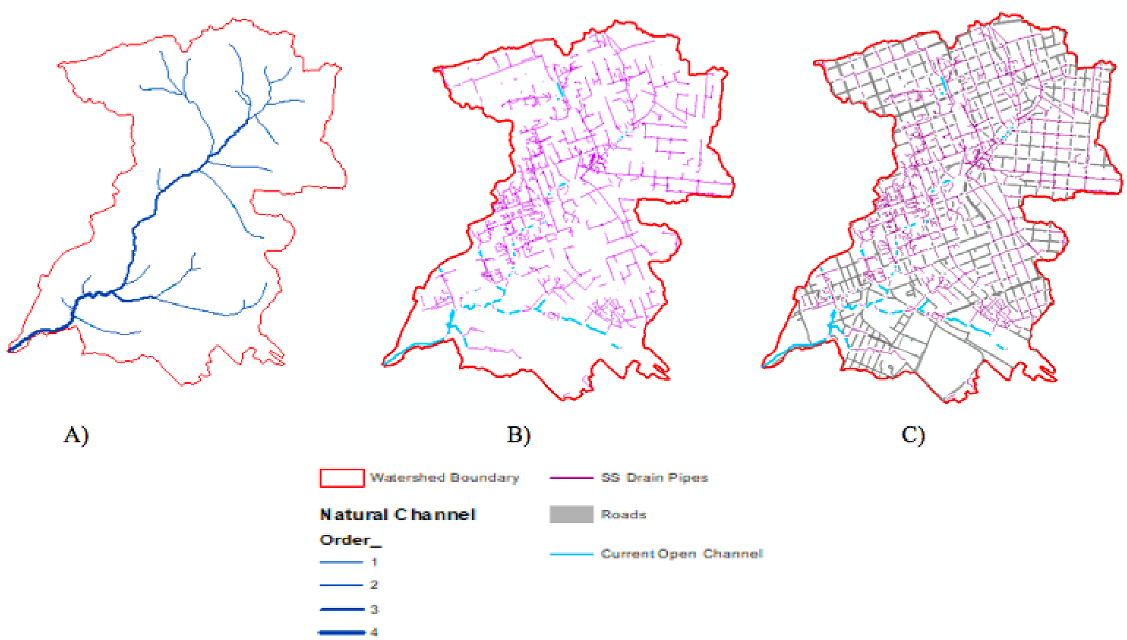

Figure 3.1 Three configurations of drainage networks with increases in density from: (A) the pre-urban natural channel, (B) the current open channel and SS system, and (C) the total urban drainage network that encompasses the current open channel, the SS system, and selected roads.

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 an order of magnitude increase in the natural channel drainage density (Table 3.1). The differences between the natural drainage density and both the current open channel and SS system and the total UDS network were highly significant ($p < 4.2 \times 10^{-8}$ and 4.8×10^{-34}, respectively). These results strongly suggest that urbanization causes a significant increase in concentrated flows that should greatly speed up the delivery of water, sediment, and pollution.

Table 3.1 Drainage densities for various configurations of RBW

Configuration	Drainage Density (m/km^2)
Pre-Urbanization Natural Channel	3,140
Open Channel and SS System	9,390
Urban Drainage Network (Open channel, SS, and roads)	20,3700

3.2 CATCH BASINS, PERCENT IMPERVIOUS AREA, SLOPE, AND ZONING

Parameters such as catch basin location, slope, PIA and zoning were examined in relationship with the SS system in order to better understand the pattern of SS system within an urbanized watershed. The number of catch basins was strongly correlated ($R^2 = 0.89$) to stormsewer length (Fig. 3.2). This relationship suggests that, where SS drainage system maps are not available, a first-approximation of SS drainage density could be made from a count of catch basins, following calibration of the relationship based on a sample of drainpipe lengths for the area. With respect to zoning ordinances, commercial zones have the highest number of catch basins (1524), followed by Residential 2 (621), Residential 1 (274), and Industrial (268). PIA and slope were not significantly correlated to drain pipe length within the watershed (R^2 = .04 and R^2 = .004, respectively). This lack of relationship does not support hypothesis H1B and H1C.

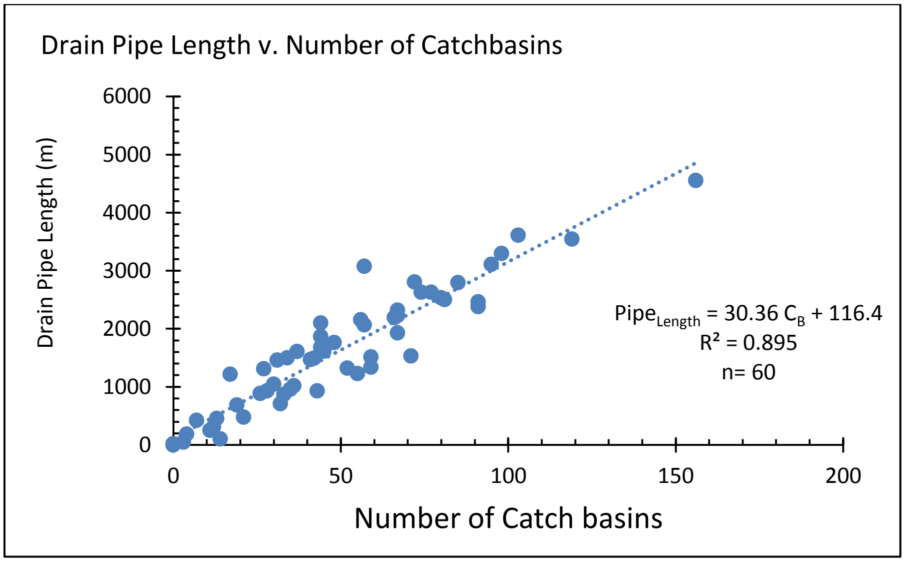

Figure 3.2 Relationship between stormsewer (drain pipe) length and catch basins for the 60 subcatchments.

The SS drainage densities for four zoning classes shows that Commercial zones contain the greatest 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) (Fig. 3.3). Comparing the zoning densities to the PIA indicates a similar pattern as SS drainage density, with Commercial having the highest PIA (64%) and Industrial having the lowest PIA (36%). Unlike SS drainage densities, Residential 1 (46%) had a higher PIA values than Residential 2 (Figure D). These relationships support hypothesis H2D that subcatchments in dominantly commercial zones have higher SS densities than those dominated by other zonings.

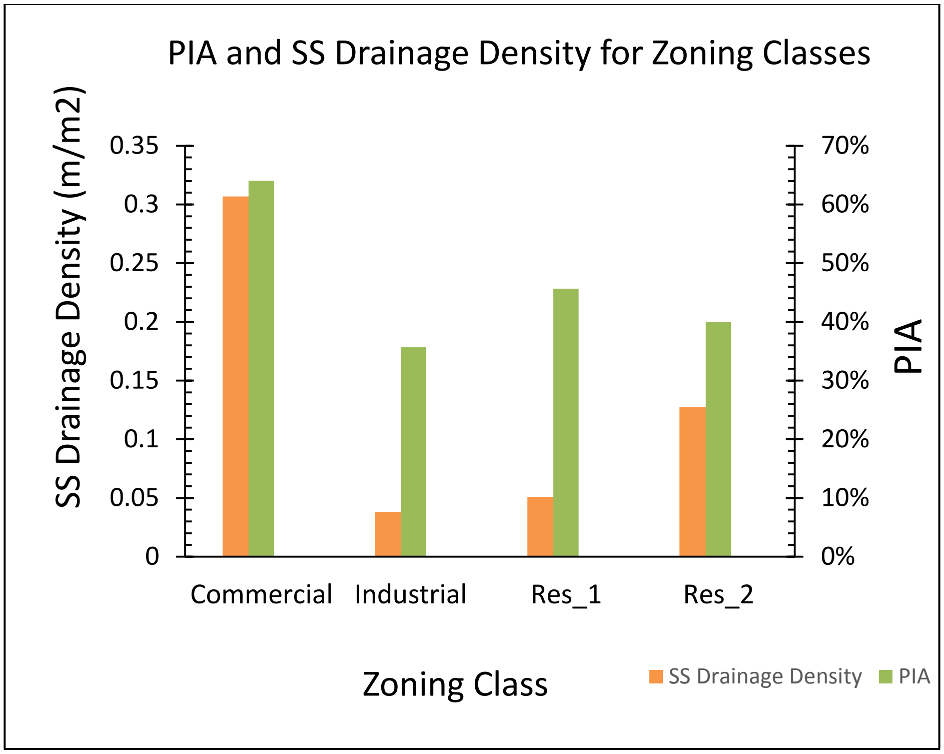

Figure 3.3 PIA and SS density for each of the Zoning classes and the number of catch basins within each zoning class

3.3 COMPOUNDING EFFECTS OF IMPERVIOUSNESS AND SS SYSTEM

Topographical analysis of two contrasting groups of subcatchments, MLK and Gervais, was performed in order to determine the compounding effects of imperviousness and SS system (Table 3.2). The MLK basin is mostly residential with a mean PIA of 47% over ten subcatchments, while Gervais is a smaller, dominantly commercial area with a mean PIA of 72% over two subcatchments. Even though the MLK subcatchments have a lower PIA, they have higher SS and total urban drainage densities (0.0946 m/m^2 and 0.0653 m/m^2, respectively) when compared to the Gervais subcatchments (0.0153 m/m^2 and 0.0388 m/m^2, respectively). These contrasts allow comparisons to be made in hydrologic responses between PIA and drainage densities in the two watersheds.

Table 3.2 Topographical characteristics of the MLK and Gervais subcatchments in RBW

Sub-divide	Area (m^2)	Length to Outlet (m)	TIA (m^2)	PIA (%)	SS Pipe Length (m)	SS Density (m/m^2)	UDS Density (m/m^2)
MLK	2,035,341	1,818	961,295	47.2%	18,693	0.0946	0.0653
Gervais	299,522	823	215,695	72.0%	2,219	0.0153	0.0388

In order to test the effect of PIA on stormwater response, the nine MLK and ten Gervais storm hydrographs were used to compute lag times, stormflow volumes, and ROC (Table 3.3 and 3.4). The average ROC for MLK was 0.011, while the average ROC for Gervais was 0.446. The difference between ROC values for Gervais and MLK was highly significant ($p < 0.00046$), Which supports the hypothesis (H2A) that higher PIA of the Gervais subcatchment results in a greater increase in runoff when compared to MLK.

The SWMM simulated runoff data revealed similar results for the single storm event; ROCs for the nine subcatchments in the Gervais Basin ranged from 0.46 to 0.71 and had an average of 0.57, while ROCs for the ten MLK subcatchments ranged from 0.32 to 0.49 and had an average of 0.42. The ROC values for the Gervais subcatchments were significantly larger than the ROC values for the MLK subcatchments ($p < 0.00063$).

In order to test the effects drainage densities, lag times and times to peak for the 13 MLK and eleven Gervais storm hydrographs (Tables 3.3 and 3.4) were compared between characteristics of the rainfall events and between the two basins.

As expected, the smaller Gervais basin had shorter mean times to peak (0:24) and lag times (0:14) than MLK (1:00 and 0:20, respectively). However, the shorter response times are largely due to much shorter travel distances in the smaller Gervais basin

Table 3.3: Rainfall and hydrograph data from MLK basin for 12 storm-events from the time period of 1/01/16 to 07/31/1

MLK

Date / Time	Time to Peak (Tp) (hr:min) Orig	Std	Lag Time (L) (hr:min) Orig	Std	Rain Duration (min)	Peak Discharge cms	
11/13/16	0:47	0:21	0:24	0:10	48	13.0	2.551
2/15/17 9:08	0:31	0:14	0:11	0:04	139	29.0	5.968
3/21/17 21:15	1:34	0:42	0:45	0:20	160	20.1	10.387
4/3/17 16:18	1:01	0:27	0:18	0:08	83	18.0	19.337
4/24/17 2:15	0:59	0:26	0:15	0:06	68	11.2	3.213
6/15/17 22:11	0:28	0:12	0:10	0:04	58	36.1	9.002
6/15/17 23:25	0:34	0:15	0:12	0:05	68	39.1	8.894
7/18/17 16:55	0:49	0:22	0:21	0:09	40	6.10	1.32
8/1/16 20:14	0:35	0:15	0:14	0:06	91	93.0	14.755
3/30/17 15:21	1:13	0:33	0:42	0:19	49	55.9	17.727
5/22/17 13:52	0:52	0:23	0:14	0:06	53	40.9	10.560
5/22/17 17:16	0:58	0:26	0:29	0:13	76	25.2	5.884
Mean:	*0:51*	*0:27*	*0:21*	*0:09*	*1:17*	*32.28*	*9.113*

Table 3.4 Hydrograph extraction data from Gervais basin for 11 storm-events from the time period of 1/01/15 to 12/31/15 (Hung et. al 2018).

GERVAIS

Date / Time	Time to Peak (Tp) (hr:min)	Lag Time (L) (hr:min)	Rain Duration (min)	Total Rainfall (mm)	Peak Stage (m)
9/21/15 22:55	0:32	0:17	30	3	0.487
10/2/15 21:08	0:24	0:12	17	4	0.637
10/10/15 15:12	0:18	0:04	31	16	0.842
10/27/15 12:00	0:16	0:15	4	2	0.476
10/27/15 18:52	0:35	0:14	45	5	0.485
10/27/15 22:03	0:16	0:15	2	2	0.446
10/28/15 8:57	0:36	0:22	33	4	0.524
11/19/15 21:09	0:28	0:16	30	4	0.338
12/14/15 16:47	0:19	0:18	5	2	0.424
12/17/15 12:42	0:20	0:17	11	3	0.439
12/23/15 14:50	0:20	0:12	17	11	0.823
Mean	*0:24*	*0:14*	*20*	*5.09*	*0.539*

In order to standardize for the difference in size between the Gervais and MLK catchments, catchment length was used as a scaling function to compensate for the larger MLK basin. Lag times and time of concentration are often estimated as a function of channel length. Therefore, lag times were standardized based on a basin length ratio. Specifically, lag times for the MLK basin were standardized by a coefficient equal to the ratio of the length of Gervais and MLK basins ($L_G/L_{MLK} = 0.4528$).

After scaling, the standardized mean time to peak was 27 minutes for the MLK basin and standardized mean lag time was 8 minutes. A T-test showed that the standardized lag times in the MLK basin were significantly shorter than in the Gervais basin ($p < 0.01$). However, although MLK standardized times to peak were longer than in the Gervais, differences in time to peak between the MLK basin and the Gervais basin were not significant after scaling ($p < 0.265$). The lack of significance in times to peak may reflect the high variability in lag times due to their computation from the onset of rainfall, which may begin with abrupt intense rainfall or with relatively small intensities. Lag times are based on the centroid of rainfall and tend to be a more robust metric of storm timing.

Time to peak and lag times were compared to various characteristics of the rainfall event, including rainfall duration, total rainfall, rainfall intensity, and the presence or absence of antecedent rain events. However, most of these parameters showed little correlation to lag time or time to peak. Rainfall duration had the strongest correlation with time to peak for both MLK and Gervais; adjusted time to peak for MLK shows how the scaling factor was used to compensate for the larger size of the MLK basin, allowing for comparison (Fig. 3.4).

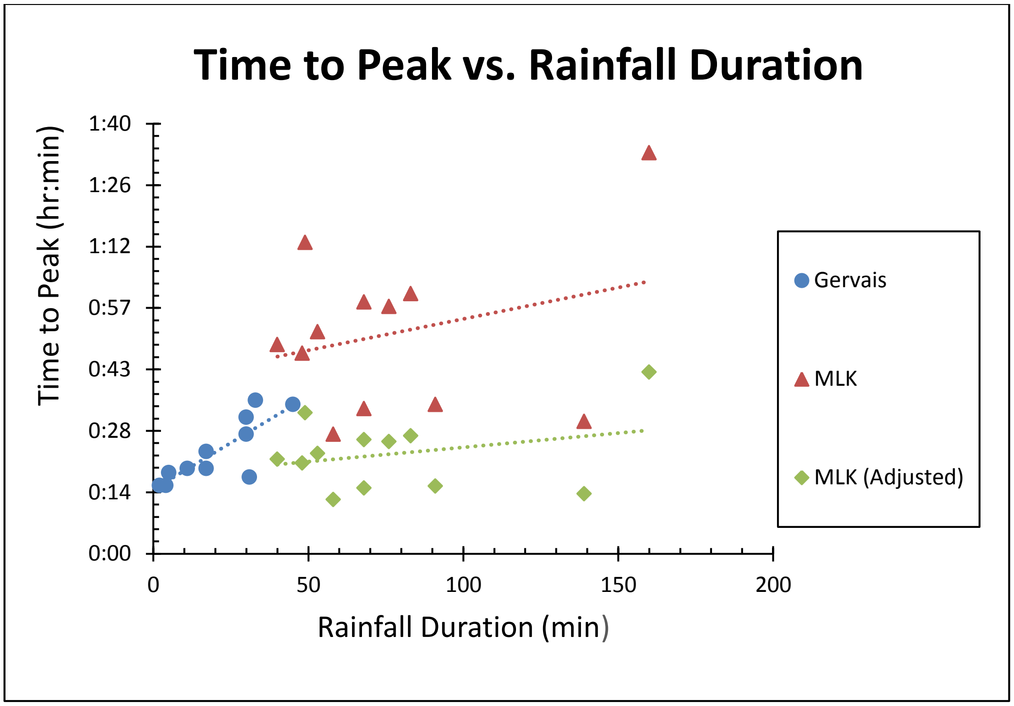

Figure 3.4 Time to peak and rainfall duration for MLK and Gervais storm hydrographs.

3.4 EFFECTS OF PIA AND DRAINAGE DENSITIES ON FLOODS

The effects of PIA on large floods in urban basins of the Southeast was shown by a study of regional flooding that tested several potential independent variables (Bohman 1992). That study found that PIA—along with drainage area—was the best predictor of flood magnitudes for urban watersheds in the region. Those functions were independent of SS densities, however, which were not included in Bohman's (1992) analysis.

A regression of UQ_2/RQ_2 flood ratios on SS densities for the 60 subcatchments in RBW shows that flood increases predicted by PIA and drainage area alone increase with SS densities (Fig. 3.5). The positive trend in UQ_2/RQ_2 supports the hypothesis (H2C) that SS density increases flood peaks beyond what is caused by PIA alone.

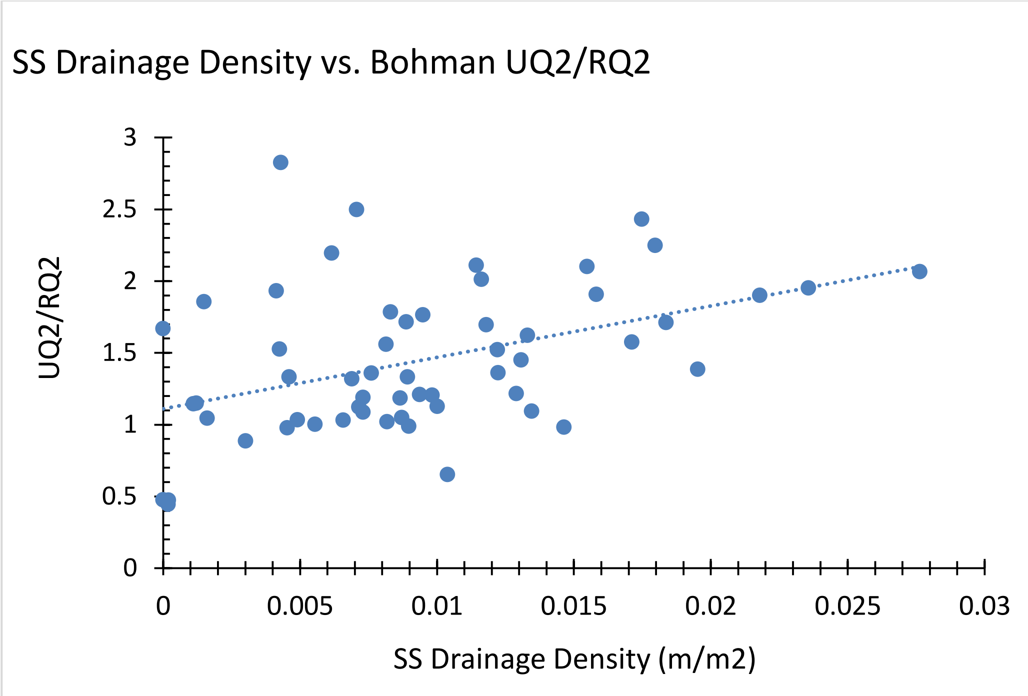

Figure 3.5 Ratios of Urban 2-year floods to rural 2-year floods as a function of corresponding SS drainage densities for the 58 subcatchments in RBW. UQ_2 and RQ_2 were computed using Equations 2 and 3 (Bohman 1992)

ROC values for all 60 subcatchments produced by the SWMM model were compared to values of PIA and SS density to further examine the compounding effects of these two urban features. Figure 3.6 shows the correlation between SS density and PIA values for the 19 subcatchments within the MLK and Gervais subcatchments labeled with the ROC value from the SWMM model.

There is an expected increase in the SWMM ROC output values for a single storm event along the horizontal axis as PIA increases, which further validates H2A. SS density, on the other hand seems to have very little effect on ROC, indicating that the SS system does not increase runoff volumes.

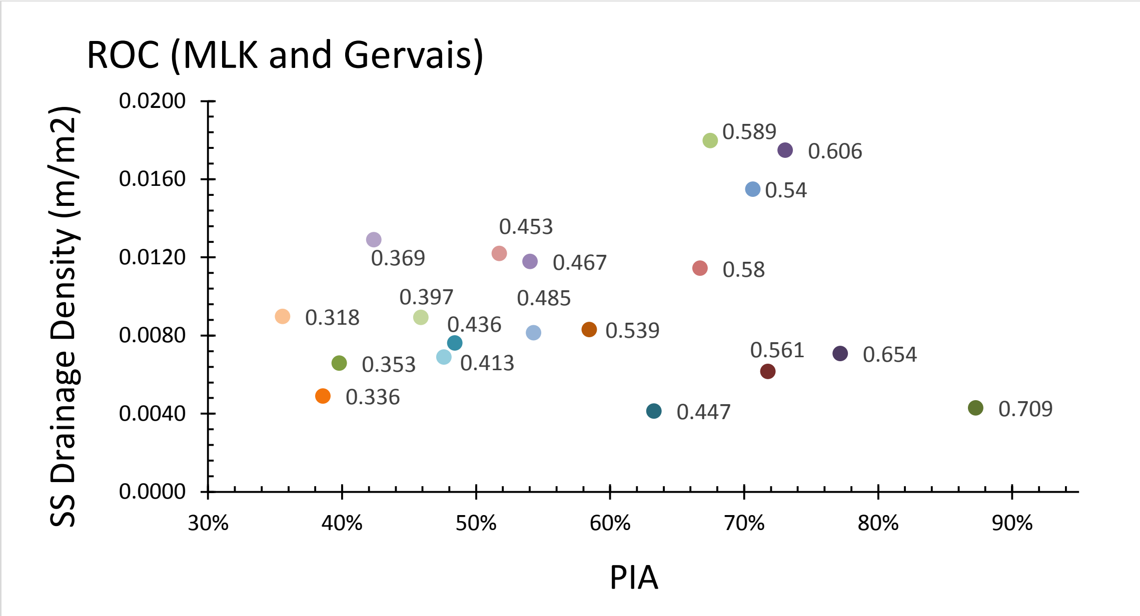

Figure 3.6 SS Drainage density and PIA values for the 19 subcatchments in the MLK and Gervais Subcatchments with SWMM ROC output values (cm/cm (units?)) for the 10/16/17 storm event.

To further explore the possible compounding effects, parameters of PIA and SS density were independently correlated to ROC values for all 60 subcatchments in RBW (Fig. 3.7 and 3.8). A somewhat strong positive correlation was seen between PIA and ROC as PIA explains 46.7% of the variance in ROC. SS density had a weaker relationship with ROC, but still displayed a positive correlation.

A multiple regression of ROC on PIA and SS density resulted in a much stronger correlation (R^2 = 0.81), indicating that the combination of these two urban features explain more variance in ROC than they do individually. This further supports H2C and suggests that PIA and SS density both have a positive effect on runoff generation but in a complementary, rather than a redundant manner.

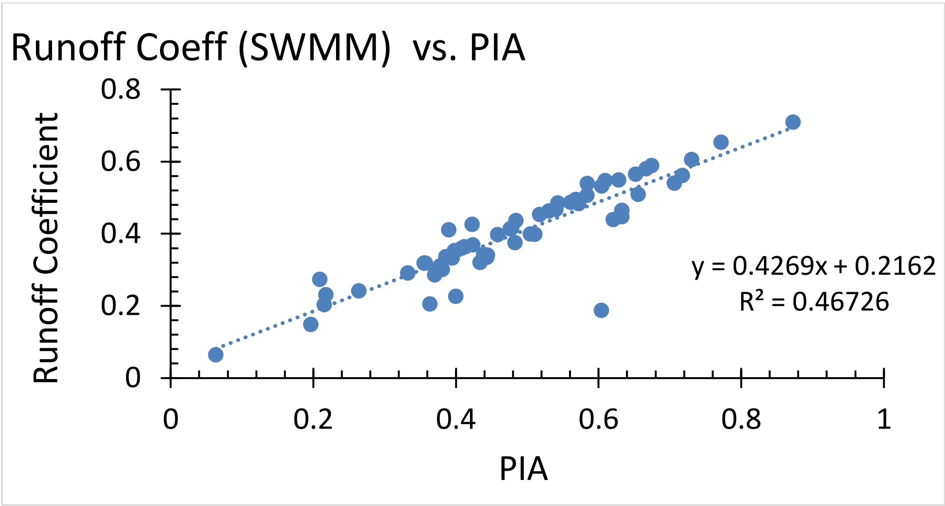

Figure 3.7 ROC values computed by SWMM model for the 30 subcatchments above Pickens compared to PIA.

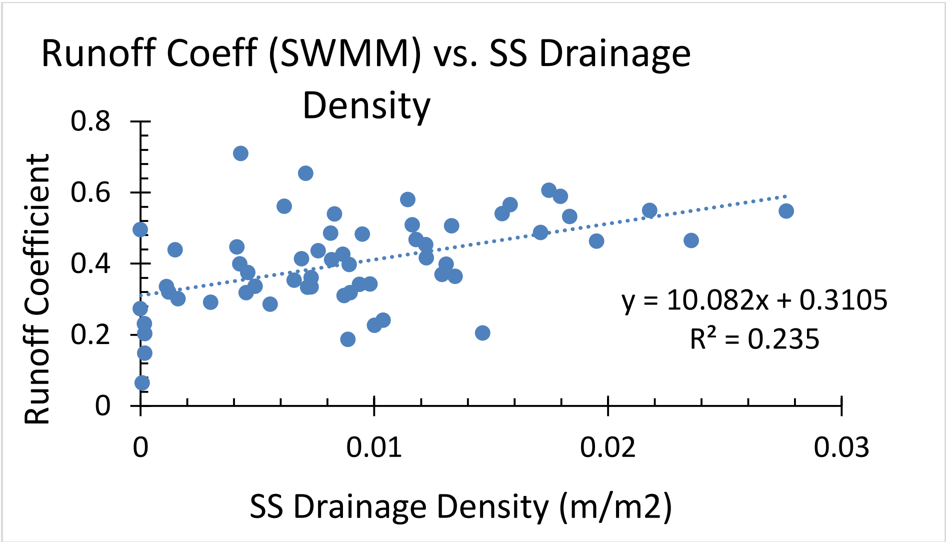

Figure 3.8 ROC values computed by SWMM model compared to SS Density.

CHAPTER 4

DISCUSSION

Hydrologic effects of urbanization on stormflow are not confined to impermeable surface areas. The density and connectivity of artificial channels, SS, and roads that accelerate flow velocities provide metrics that can be used to assess urban flood risks. In particular, the effects of road networks on stormwater should be considered in design and planning in order to proactively reduce flood risk during low/moderate flows. The three drainage density computations show that inclusion of the SS system and road networks increases drainage densities significantly by almost an order of magnitude. This suggests that in highly urbanized watersheds, such as RBW, drainage density calculations based only on open channels drastically under-estimate the ability of the watershed to transport water (Graf 1977).

One of the key factors that made this study possible was the presence of a SS map. However, most small urban catchments do not have access to such data. Spatial analysis of RBW shows that the number of catch basins within each subcatchment was the best predictor of drain pipe length with 89% accuracy:

$$\text{Pipe}_{\text{Length}} = 30.36(C_B) + 116.4 \qquad \text{Eq. 4}$$

where C_B is the number of catch basins. Catch basins are visible from the surface, so sampling the number of catch basins and lengths of SS pipe may provide a simple means of estimating SS densities where they are not mapped. While it was hypothesized that other parameters such as slope and PIA could predict SS pipe length or density, these parameters did not show statistical relationships to the SS system. Zoning was also a good indicator of SS densities and can be used as another factor in identifying areas that are likely to have higher SS densities.

Runoff volumes and ROC values corroborate hypotheses that impervious surfaces have a direct effect on the volume of runoff within urbanized watersheds. These findings are similar to many urban hydrologic studies that show impervious surfaces reduce infiltration and facilitate run off (Hollis 1975, Arnold and Gibbons 1996). The Gervais subcatchments contain the highest PIA throughout the watershed, resulting in the largest ROC value from the SWMM model output for the single storm event (0.56). These high volumes of runoff produced in the upper part of the watershed can have serious impacts downstream. Computations of lag times between MLK and Gervais indicate that the SS and UDS and the associated drainage densities also play an important role in the alteration of hydrologic response. The significant difference between the adjusted lag-time response in MLK and lag times in Gervais support H2B that the SS system and the UDS speed up arrival times of peak discharge, which can be as important as hydrologic changes caused by increases in impervious surfaces (Graf 1977; Smith, 2002).

Empirical functions developed to estimate peak discharges based on PIA (Bohman 1992) could be improved by including information about the density of SS and UDS systems. Ratios of urban to rural two-year discharges predicted by Bohman’s (1992) PIA-based functions are weakly but positively correlated with SS densities, which implies a systematic relationship with SS density that is not included in Bohman’s model.

Leopold (1968) suggested that increases in both impervious areas and increases in areas served by the storm sewer system would result in a magnification of the mean annual flood. At first glance the results from this study suggest that PIA increases runoff volumes and that the SS system has little effect on runoff volumes. However, the multiple regression analysis of runoff coefficients (ROC) from the SWMM model suggests that the combination of PIA and SS density explains hydrologic responses to urbanization, specifically increases in runoff volumes, better than PIA alone.

These results echo Miller and Hess's (2017) call for more research on other factors that influence hydrologic characteristics in small urban catchments in order to better understand the total effect of urbanization on the alteration of the watershed.

CHAPTER 5

CONCLUSION

Considering PIA alone does not give a complete picture of the hydrologic alterations caused by urbanization. This study identifies potential factors that work in conjunction with PIA to alter the hydrologic response of the watershed by comparing the Gervais and MLK subcatchments in the highly urbanized RBW.

Roads and SS systems concentrate and accelerate the flow of stormwater, so drainage densities of SS and UDS systems have a significant impact on stormwater arrival times. This study shows that when the SS system is included in calculations, drainage densities are potentially tripled and in the case of the UDS increased by almost an order of magnitude. By including these parameters in drainage density calculation, a more complete understanding of the hydrologic impacts of urbanization can be presented allowing flood risk mitigation. Practices, such as conventional and low impact development (LID) stormwater management that encourage infiltration can be used to compensate for imperviousness and high SS and UDS densities. However, PIA and drainage densities have different effects on runoff volumes and timing, so knowledge about these differences is key to wise management decisions.

As many urban hydrologic studies have shown, subcatchments with the highest PIA values exhibit the highest ROC values in the watershed. However, this study shows how the SS system and UDS also exacerbate flooding potential by speeding up arrival times of peak discharges. In support of initial hypotheses, the MLK basin, which had moderate PIA but high SS and UDS densities, displayed faster adjusted peak arrival times, whereas the Gervais basin, which had moderate SS and road densities but very high PIA, displayed significantly more runoff but slower delivery. However, this study further shows that PIA when coupled with SS density have a increase runoff generation, and work in a complementary manner to increase ROC values, making the SS system an integral actor in the hydrologic alteration of this urbanized watershed.

Alternative research in urban hydrology needs to consider other parameters, outside of PIA in order to fully explain the impacts of urbanization on the hydrology of a watershed. 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.

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