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The complexities of urban flood response: Flood frequency analyses for the Charlotte metropolitan region

Zhengzheng Zhou[1,2,3], James A. Smith[2], Long Yang[2], Mary Lynn Baeck[2], Molly Chaney[2], Marie-Claire Ten Veldhuis[4], Huiping Deng[3,5], and Shuguang Liu[1,3]

[1]Department of Hydraulic Engineering, Tongji University, Shanghai, China, [2]Department of Civil and Environmental Engineering, Princeton University, Princeton, New Jersey, USA, [3]UNEP-Tongji Institute of Environment for Sustainable Development, Shanghai, China, [4]Department of Water Management, Faculty of Civil Engineering and Geosciences, Delft University of Technology, Delft, Netherlands, [5]Department of Municipal Engineering, College of Environmental Science and Engineering, Tongji University, Shanghai, China

Key Points:

- Simple approaches to regional flood frequency analysis, based on covariates like basin area and imperviousness, do not capture key elements of urban flood response
- Mixtures of warm-season thunderstorm and tropical cyclone food agents exert a strong impact on the upper tail of flood frequency distributions in Charlotte
- Empirical analyses of observations from the dense network of gaged watersheds provide a deeper understanding of urban flood hydrology

Correspondence to:
Z. Zhou,
zz3@princeton.edu;
S. Liu,
liusgliu@tongji.edu.cn

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Abstract We examine urban flood response through data-driven analyses for a diverse sample of "small" watersheds (basin scale ranging from 7.0 to 111.1 km^2) in the Charlotte Metropolitan region. These watersheds have experienced extensive urbanization and suburban development since the 1960s. The objective of this study is to develop a broad characterization of land surface and hydrometeorological controls of urban flood hydrology. Our analyses are based on peaks-over-threshold flood data developed from USGS streamflow observations and are motivated by problems of flood hazard characterization for urban regions. We examine flood-producing rainfall using high-resolution (1 km^2 spatial resolution and 15 min time resolution), bias-corrected radar rainfall fields that are developed through the Hydro-NEXRAD system. The analyses focus on the 2001–2015 period. The results highlight the complexities of urban flood response. There are striking spatial heterogeneities in flood peak magnitudes, response times, and runoff ratios across the study region. These spatial heterogeneities are mainly linked to watershed scale, the distribution of impervious cover, and storm water management. Contrasting land surface properties also determine the mixture of flood-generating mechanisms for a particular watershed. Warm-season thunderstorm systems and tropical cyclones are main flood agents in Charlotte, with winter/spring storms playing a role in less-urbanized watersheds. The mixture of flood agents exerts a strong impact on the upper tail of flood frequency distributions. Antecedent watershed wetness plays a minor role in urban flood response, compared with less-urbanized watersheds. Implications for flood hazard characterization in urban watersheds and for advances in flood science are discussed.

Plain Language Summary We examine urban flood response through for a diverse sample of "small" watersheds (basin scale ranging from 7.0 to 111.1 km^2 in the Charlotte Metropolitan region. These watersheds have experienced extensive urbanization and suburban development since the 1960s. Our analyses are based on flood data developed from USGS stream gaging stations and are motivated by problems of flood hazard characterization for urban regions. We examine flood-producing rainfall using high-resolution radar rainfall fields. The analyses focus on the 2001–2015 period. The results highlight the complexities of urban flood response. The heterogeneities in flood response are mainly linked to watershed scale, the distribution of impervious cover, and storm water management. Warm-season thunderstorm systems and tropical cyclones are main flood agents in Charlotte, with winter/spring storms playing a role in less-urbanized watersheds. Antecedent watershed wetness plays a minor role in urban flood response, compared with less-urbanized watersheds. The results provide implications for flood hazard characterization in urban watersheds and for advances in flood science.

1. Introduction

In this study, we examine the impacts of urbanization on flood hydrology through analyses of peaks-over-threshold flood observations for a diverse sample of "small" watersheds (drainage area less than 200 km^2, see Table 1 for details) in the Charlotte metropolitan region, Mecklenburg County, North Carolina. Our

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Table 1. Summary of Watersheds Characteristics

No.	USGS ID (0214-)	Watershed Name	Drainage Area (km^2)	Impervious (%)	Land Use Type (%): Developed, High Intensity	Developed, Medium Intensity	Developed, Low Intensity	Developed, Open Space	Forests	Developed, Increased in 2001–2010	Slope (%)	Dam Number	Drainage Density (km/km^2)	Population Density Day (/km^2)	Population Density Night (/km^2)	Watershed Compactness (%)
1	6211	Statesville Creek	14.9	26.1	10.4	10.6	23.0	30.2	19.2	6	2.4	2	8.22	704	475	2.0
2	627970	Upper Irwin	23.4	32.5	10.0	14.4	37.4	23.0	8.0	4	2.9	2	11.05	830	702	2.0
3	6300	Irwin Creek	78.1	34.3	12.4	15.6	33.6	26.0	8.5	4	2.8	7	8.26	1209	658	1.9
4	6315	Taggart Creek	13.6	35.4	12.1	18.0	32.6	32.2	4.9	6	2.6	0	5.32	1121	606	2.8
5	6348	Coffey Creek	23.8	25.5	13.0	11.0	15.1	20.2	30.1	11	3.0	5	5.05	429	127	1.5
6	6409	Upper Little Sugar Creek	31.5	48.2	22.5	24.0	32.6	18.7	1.8	2	2.2	0	19.62	3555	988	1.4
7	642825	Upper Briar	13.3	23.9	3.6	9.3	34.2	47.5	4.5	4	1.9	1	23.53	788	1301	2.3
8	645022	Briar Creek	48.5	24.7	4.5	9.9	32.8	48.3	3.6	2	2.4	5	19.60	1021	1312	1.6
9	6470	Little Hope Creek	7.0	32.2	9.3	9.4	48.5	32.8	0.0	1	2.2	0	15.83	1282	1402	2.6
10	6507	Little Sugar Creek	111.1	32.0	10.3	14.1	32.8	39.4	2.9	3	2.4	8	17.06	1916	1153	1.6
11	655255	Upper McAlpine Creek	18.9	18.1	1.7	5.3	30.2	49.3	11.0	4	2.5	4	7.98	480	1094	2.9
12	6562	Campbell Creek	15.3	27.9	7.8	12.9	28.9	44.9	4.7	3	2.1	4	14.62	1072	1434	2.2
13	657975	Irvins Creek	21.8	8.2	0.5	1.8	10.1	47.9	31.0	9	2.5	1	4.61	120	340	2.6
14	6600	McAlpine Creek	100.2	19.6	4.2	8.1	23.0	46.0	15.2	5	2.7	11	7.15	589	857	2.3
15	6700	McMullen Creek	18.3	20.7	2.8	8.4	25.0	60.6	2.8	1	2.3	1	7.72	1074	927	1.6
16	678175	Steele Creek	18.3	32.0	11.8	15.0	29.6	21.2	15.6	7	1.6	0	4.43	904	386	2.0

analyses are motivated by problems of flood hazard characterization and flood frequency analysis for urban regions. Reliable flood frequency estimates are essential for densely populated urban areas. Regional flood frequency analysis procedures that have been employed for urban areas rely on quantitative characterizations of land use and land cover [*Sauer et al*., 1983; *Hawley and Bledsoe*, 2011; *Feaster et al*., 2014]. In North Carolina, for example, regression equations for estimating flood peaks at selected return intervals are represented as power law functions of drainage area and impervious fraction [*Feaster et al*., 2014]. There are different versions of regression equations that differ in the number and the nature of parameters considered [see *Sauer et al*. 1983 for more details]. These procedures provide practical tools for a range of engineering design problems. In this study, we will show that there are gaps in our understanding of urban flood peak distributions and flood response, especially in light of the heterogeneity of basin properties (e.g., drainage area, impervious coverage, and storm water management, etc.) and the mixtures of flood producing mechanisms.

The impacts of urban land surface properties on both magnitude and variability of flood peaks have been examined in previous studies [*Anderson*, 1970; *Hollis*, 1975; *Boyd et al*., 1993; *Robbins and Pope*, 1996; *Beighley and Moglen*, 2002; *Villarini and Smith*, 2010; *Mejía and Moglen*, 2010a; *Yang et al*., 2015; *Zhou et al*., 2016]. Despite the previous efforts in investigating the relationship between urbanization and urban flood response, difficulties remain in attributing specific changes in urban flood peak distributions to specific urbanization characteristics.

The impervious fraction varies markedly across urban regions (especially between different urban land cover classifications) and is an important factor for runoff generation [e.g., *Georgakakos*, 2006; *Yang et al*., 2011; *Koga et al*., 2016]. Differences in hydrologic responses among urban basins cannot be fully accounted for by differences in impervious cover. The distribution of impervious cover within a watershed and the "nature" of impervious cover (especially "hydraulically" connected versus "disconnected" impervious cover) [*Shuster et al*., 2005; *Ogden et al*., 2011] can play an important role in determining flood response [*Leopold*, 1968; *Martens*, 1968; *Liscum and Massey*, 1980; *Shuster et al*., 2005; *Moglen and Kim*, 2007; *Bell et al*., 2016].

Replacement of surface stream channels with subsurface storm drain systems is a critical feature of urban flood response [*Leopold*, 1973; *Graf*, 1977; *Smith et al*., 2002; *Gregory et al*., 2006; *Meierdiercks et al*., 2010; *Pouyat et al*., 2010]. Properties of the urban drainage network have impacts on flood response that are comparable to, or larger than, the effects of impervious cover [*Ye et al*., 2003; *Arrigoni et al*., 2010; *Wang and Hejazi*, 2011; *Deasy et al*., 2014]. It is difficult to assess the relative impacts of drainage network structure and impervious cover on flood hazards. Hydrologic and hydraulic modeling studies have provided insights to these issues for watersheds in the Charlotte metropolitan region [*Smith et al*., 2002; *Turner-Gillespie et al*., 2003; *Wright et al*., 2014b].

The nature and history of storm water management practices have large impacts on urban flood response [*Brander et al*., 2004; *Carter and Jackson*, 2007; *Gilroy and McCuen*, 2009; *Loperfido et al*., 2014; *Bhaskar et al*., 2016; *Jarden et al*., 2016; *Mogollón et al*., 2016]. Stormwater detention structures are typically designed to directly and locally impact flashiness of flood response. The impact of a system of storm water infrastructure on flood response over an urban drainage basin is more difficult to assess [*Burns et al*., 2012; *Shuster and Rhea*, 2013; *Palla and Gnecco*, 2015; *Rhea et al*., 2015; *Smith et al*., 2015; *Jato-Espino et al*., 2016]. The Charlotte metropolitan region reflects a complex pattern of storm water development ranging from older urban development with high-density storm drain networks and little detention storage to newer development in which modern storm water regulations lead to a relatively high density of storm water detention structures.

The role of antecedent watershed wetness for urban flood response remains uncertain. Some studies have suggested that urban soil moisture can affect hydrologic response [*Shi et al*., 2007; *Marchi et al*., 2010; *Stovin*, 2010; *Borga et al*., 2011; *Yang et al*., 2011], while others show that the role of antecedent watershed wetness for flood response is markedly diminished relative to predevelopment conditions [*Shuster et al*., 2005; *Smith et al*., 2013]. The implementation of modern storm water infrastructure further complicates the assessment of antecedent watershed wetness and flood response in urban watersheds [*Williams and Wise*, 2006; *Ahiablame et al*., 2012; *Fletcher et al*., 2013; *Loperfido et al*., 2014].

Rainfall is a key driver of urban flood response and flood peak distributions in urban regions [*Manley*, 1958; *Changnon et al*., 1971; *Shepherd and Burian*, 2003; *Mölders and Olson*, 2004; *Diem and Mote*, 2005; *Shepherd*, 2005; *Grimmond et al*., 2010; *Berne et al*. 2004; *Smith et al*., 2012; *Zhou et al*., 2016; *Thorndahl et al*. 2017].

Ochoa-Rodriguez et al. [2015] showed that variations in temporal resolution of rainfall inputs affect simulation of urban flood response more strongly than variations in spatial resolution (see similarly in *Yang et al*. [2016]). *Ogden et al*. [2000] argue that uncertainty in the space/time distribution of rainfall has a more significant impact on predicting runoff production in urban areas than uncertainty in urban runoff characteristics. The variability in space-time rainfall structure is closely linked to different storm types. Organized thunderstorm systems, for instance, exhibit the largest short-term rainfall rates and the largest spatial variability of rainfall rate [*Syed et al*., 2003; *Smith et al*., 2005b; *Villarini et al*., 2011; *Yang et al*., 2013; *Zhou et al*., 2014; *Llasat et al*., 2016]. *Yang et al*. [2013] found contrasting rainfall generating mechanisms that produce floods over two neighboring watersheds in Milwaukee, Wisconsin, and attributed the difference to the changing land surface properties associated with urban development.

Modeling studies have been widely used to assess the impacts of urbanization on all aspects of the water cycle [see *Mitchell et al*., 2001; *Fletcher et al*., 2013; *Elga et al*., 2015 for reviews], but modeling studies alone cannot resolve uncertainties in urban flood hydrology. A major obstacle to advances in understanding urban flood hydrology is the limited number of urban settings with dense networks of long-term instrumented watersheds. The Baltimore Ecosystem Study (BES) LTER (Long-Term Ecological Research) watersheds have provided important insights to a broad range of problems associated with urban hydrology [see, e.g., *Smith et al*., 2005a, 2005b; *Miles and Band*, 2015; *Bhaskar and Welty*, 2015]. Similarly, the Central Arizona Project (CAP) LTER watersheds have provided significant advances in understanding urban hydrology for arid/semiarid regions [see, e.g., *Roach et al*., 2008; *Hale et al*., 2015]. In Europe, long-term monitoring programs for urban hydrology have been implemented in the greater Lyon region and in the great Paris and Lyon regions [*Gasperi et al*., 2010; *Madoux-Humery et al*., 2013; *Barraud et al*., 2002], both focusing on water quality aspects of urban storm water systems. Other monitoring programs have investigated small-scale rainfall variability in relation to storm water runoff production in small urban catchments, for instance in Denmark [*Thorndahl et al*., 2006] and in the United Kingdom [*Pina et al*., 2016; *Wang et al*., 2015].

We use the exceptional observational resources of the Charlotte metropolitan region to develop a broad characterization of the land surface and hydrometeorological controls of urban flood frequency. We build on previous studies by addressing the following questions: (1) How do flood peak distributions vary across an urban area with diverse land use and development history? (2) What are the dominant flood agents and the dominant controls on the upper tail of flood peaks in urban watersheds? (3) How does flood response in urban watersheds vary with watershed scale, rainfall magnitudes, urban infrastructure, antecedent watershed wetness, and other forms of urban water storage in urban watersheds (for watershed scales less than 200 km^2)?

Our analyses suggest that hydrologic modeling approaches for urban flood frequency are an important direction to pursue in enhancing flood hazards characterizations. Our analyses are also designed to provide empirical foundations for developing “urbanized” hydrologic models that can be used for flood frequency analysis [see, e.g., *Mitchell et al*., 2001; *Ogden et al*., 2011; *Smith et al*., 2015; *Yang et al*., 2016]. Urbanized hydrologic models that accurately reproduce the key elements of flood response, combined with resampling methods using catalogs of high-resolution rainfall fields [e.g., *Wright et al*., 2014b], provide an attractive path for flood hazards assessment in diverse urban settings.

The rest of the paper is organized as follows. In section 2, we describe the 16 study watersheds and introduce the data sets used in the study. In section 3, the results and discussion, focusing on the distribution of flood frequency, mixture of flood agents and scale-dependent flood response are presented. A summary and conclusions are presented in section 4. We conclude section 4 with a discussion of implications of our analyses for development of methods used for flood hazard characterization in urban regions, and more generally for advancement of flood science.

2. Data and Methods

2.1. Study Area

The study region has experienced rapid urbanization and suburban development since the 1960s. Urban area in Mecklenburg County increased from 31.5% in 1992 to 68.3% in 2011, while forest area decreased from 55.5% in 1992 to 27.6% in 2011 [*Mecklenburg County*, 2016]. The population density reached 746 km^{-2} in 2015, with an increase of 12.4% from 2010 to 2015 [*United States Census Bureau*, 2015]. Extensive urban development has contributed to changing flood risks in the Charlotte Metropolitan region [*Smith et al*., 2002; *Villarini et al*., 2009; *Bell et al*., 2016; *Mogollón et al*., 2016; *Smith and Smith*, 2015]. A series of major floods during the 1990s [*Smith et al*., 2002; *Turner-Gillespie et al*., 2003; *Villarini et al*., 2009; *Wright et al*., 2014a] resulted in changes to flood mitigation strategies for the region. Flooding, however, remains a major problem for the region, with the 27 August 2008 flooding associated with Tropical Storm Fay providing the most notable example [*Charlotte-Mecklenburg Emergency Management*, 2010].

The 16 gaged watersheds which are the focus of our study range in drainage area from 7.0 to 111.1 km^2 (Table 1) and are contained within the Sugar Creek watershed (Figure 1). The principal subwatersheds of Sugar Creek are Little Sugar Creek (denoted No.10 in Table 1, with a gaging station at 111 km^2), McAlpine Creek (No.14, with a gaging station at 100 km^2) and Irwin Creek (No.3, with a gaging station at 78 km^2). The urban core of the study region is located in Little Sugar Creek (Figure 1). Each of these subwatersheds contains a nested network of stream gaging stations. In addition to the downstream station, Little Sugar Creek contains four gaged subwatersheds, which we denote Upper Little Sugar Creek (No.6), Upper Briar Creek (No.7), Briar Creek (No.8), and Little Hope Creek (No.9, Table 1 and Figure 1). Irwin Creek contains two gaged subwatersheds, Upper Irwin Creek (No.2) and Statesville Creek (No.1). In addition, there are three “small” watersheds in Irwin Creek, Taggart Creek (No.4), Coffey Creek (No.5), and Steele Creek (No.16), which are downstream of the 78 km^2 watershed. McAlpine Creek contains three gaged subwatersheds, which we denote Upper McAlpine Creek (No.11), Campbell Creek (No.12), and Irvins Creek (No.13). McMullen Creek (No.15) is a “small” watershed in McAlpine Creek, which is downstream of the 100 km^2 gaged watershed.

The gaged watersheds reflect a range of drainage areas, intensity of urban development, and pattern of urban development. The drainage networks of urban watersheds in the Charlotte metropolitan region include a mix of storm drain systems, concrete-lined open channels, and alluvial channels [*Turner-Gillespie et al*., 2003]. With the initiation of storm water management regulations in the 1970s, Charlotte-Mecklenburg began a period of expanded implementation of flood mitigation infrastructure. Since the 1990s, evolving best management practices (BMPs), such as storm water wetlands and ponds, have been introduced to the region [*Charlotte-Mecklenburg Emergency Management*, 2010].

We extracted land use/land cover type, impervious percentage, developed area, number of dams, and morphometric properties of gaged watersheds from the USGS GAGES II data set (Geospatial Attributes of Gages for Evaluating Streamflow, (see http://water.usgs.gov/GIS/metadata/usgswrd/XML/gagesII_Sept2011.xml for more information). The data set provides geospatial data for 9322 stream gages maintained by the USGS. Another data set of land use was obtained from the National Land Cover Data set (NLCD, http://www.mrlc.gov), reflecting the changes in land use from 1992 to 2011. Table 1 provides a summary of basin properties for the 16 watersheds. Each watershed has a USGS stream gaging station at its outlet.

Little Sugar Creek drains portions of the urban core of Charlotte, with McAlpine Creek to the east and Irwin Creek to the west. Urban development has also extended west of Little Sugar Creek to Irwin Creek and to the east in McAlpine Creek. The three watersheds exhibit different degrees of urban land use, with total urban developed land use (including low-intensity, medium intensity, and high intensity developed land) of 57% for Little Sugar Creek, 35% for McAlpine Creek, and 62% for Irwin Creek, respectively. McAlpine Creek has the largest developed open space and forest area. Developed open space (typically grass lawns around commercial, industrial and residential areas) accounts for 46% of McAlpine Creek, 39% of Little Sugar Creek, and 26% of Irwin Creek. The forest area in McAlpine Creek is more than four times larger than that of Little Sugar Creek. The increases in urban land use from 2001 to 2011 are comparable in three watersheds with 4% for Irwin Creek, 3% for Little Sugar Creek, and 5% for McAlpine Creek.

The study watersheds exhibit a range of physical characteristics. McAlpine Creek and Little Sugar Creek are approximately “100 km^2” watersheds but have contrasting watershed shapes (Table 1). The watershed compactness, which is defined as the ratio of area to the squared perimeter, reflects the shape of the watersheds. Larger values imply a more compact shape and smaller values a more elongated shape. McAlpine Creek is approximately square with compactness of 2.3%, whereas Little Sugar Creek is elongated with compactness of 1.6%. The variation in basin slope is generally small and not tied to urban development (Table 1).

The four subwatersheds in Little Sugar Creek are all highly developed (Table 1). Upper Little Sugar Creek (31.5 km^2) has the highest intensity urban land use and drains the urban core of Charlotte. Little Hope Creek

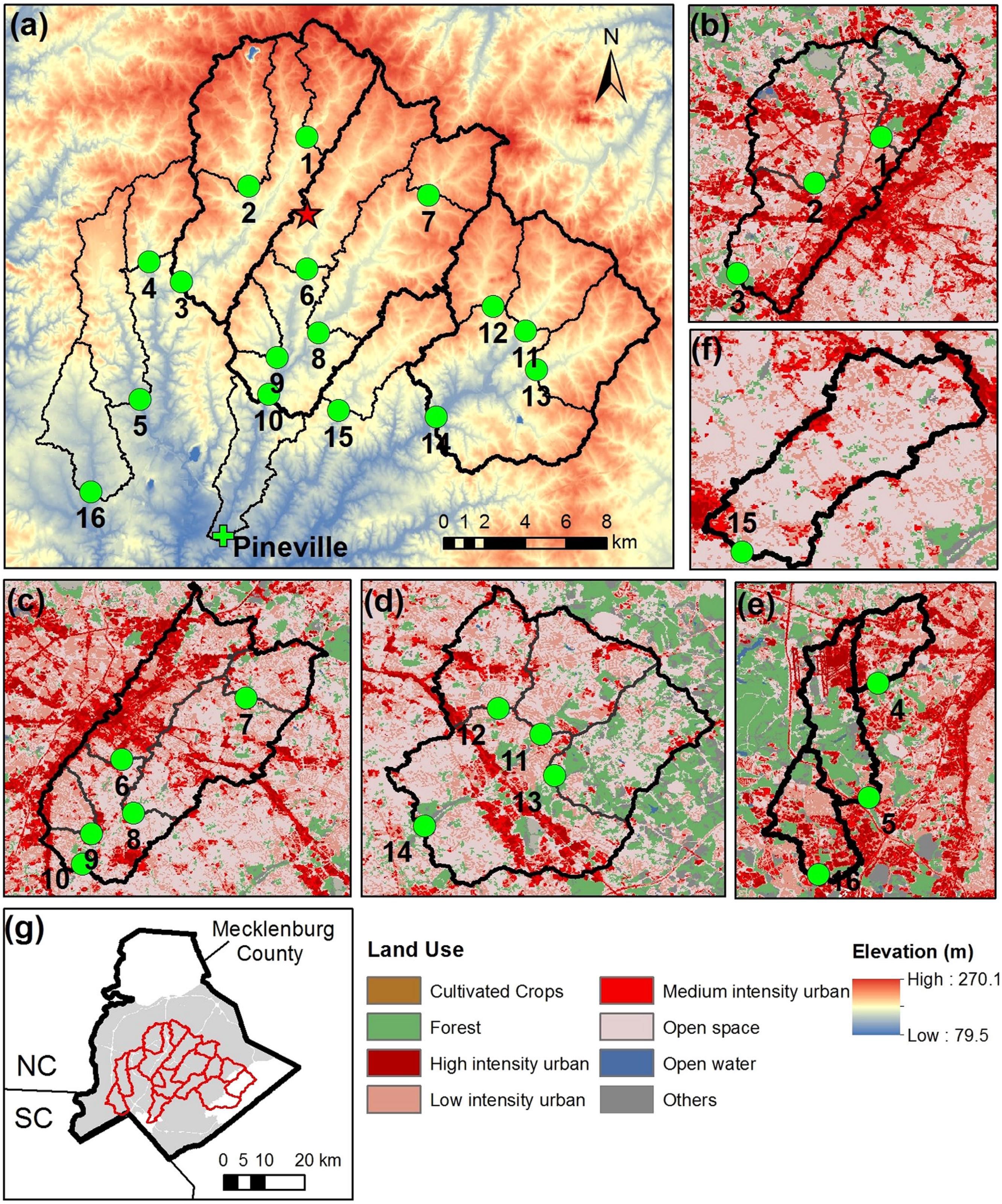

Figure 1. Location map for the Charlotte study area, with watershed boundaries and land use/land cover. The numbers of watershed are the same as those in Table 1. (a) The red star is denoted as urban core, which is located in No.6 with the largest imperviousness. (g) The black outline is the boundary of Mecklenburg County, NC and the grey area is the city of Charlotte.

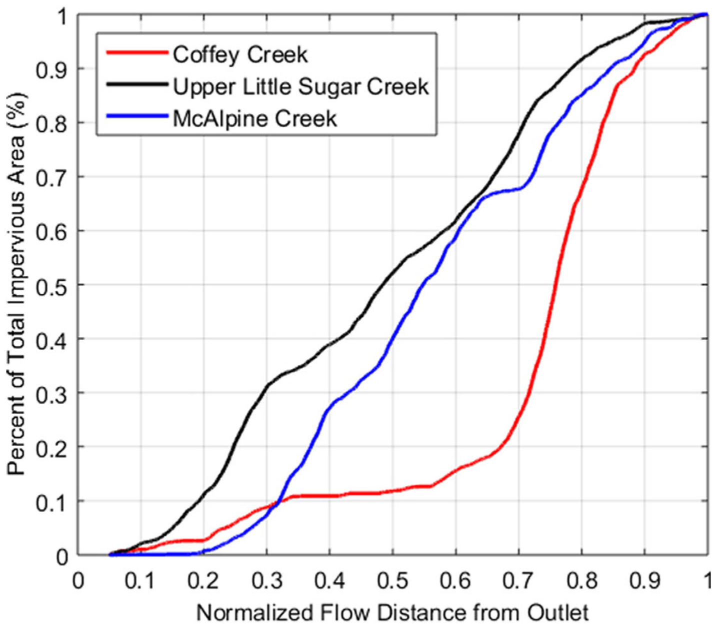

Figure 2. Distribution of impervious area as a fraction of distance from the basin outlet of Coffey Creek (No.5), Upper Little Sugar Creek (No.6), and McAlpine Creek (No.14).

has the smallest drainage area, 7.0 km^2, among the study watersheds and is dominated by "old" residential land use (i.e., developed prior to modern storm water management regulations). Briar Creek (48.5 km^2) has extensive areas of residential development, with large areas of vegetated landscape in parks and recreation areas and consequently less impervious area. Briar Creek and Upper Briar Creek have larger areas of open space and lower impervious fraction than Little Hope Creek and Upper Little Sugar Creek.

The two subwatersheds in Irwin Creek, Upper Irwin Creek (23.4 km^2) and Statesville Creek (14.9 km^2) have slightly smaller values of impervious fraction and high-intensity development than the Irwin Creek watershed as a whole. Statesville Creek has a larger portion of forest area (19.2%) than other areas of Irwin Creek (8.5% for the entire basin). The downstream watersheds of Irwin Creek, Taggart Creek (13.6 km^2) and Steele Creek (18.3 km^2), have impervious area coverage of 35% and 32%. Coffey Creek has an impervious cover of 25.5% and has second largest forested area of 30%, which is slightly less than Irvins Creek in McAlpine Creek.

Upper McAlpine Creek (18.9 km^2), Campbell Creek (15.3 km^2), and Irvins Creek (21.8 km^2) are the subwatersheds in McAlpine Creek and each has four dams. Irvins Creek is the least developed residential watershed, with the largest forest area, 31%, and the least impervious cover, 8%. McMullen Creek (18.3 km^2) stands out from the other study watersheds in having 61% of its surface classified as developed open space, by far the largest value among the 16 study watersheds (Upper McAlpine Creek is second at 49%).

The spatial distribution of impervious cover varies across the watersheds. We used the impervious area curve to examine the spatial distribution of impervious area within a watershed, which shows the percentage of the total impervious cover within the watershed at a given flow distance from the outlet [see *Meierdiercks et al.*, 2010; *Wright et al.* 2012 for details]. A curve with a steep slope at a given flow distance indicates a high degree of impervious development at that flow distance from the outlet. The impervious area curve has been used to interpret the impact of the spatial distribution of urban development on flood response [e.g., *Mejía and Moglen*, 2010a, 2010b]. The "developed high-intensity" land use type is used to represent the spatial distribution of impervious cover (Figure 1). The impervious area curves for Upper Little Sugar Creek (No.6), Coffey Creek (No.5), and McAlpine Creek (No.14) are shown in Figure 2. Upper Little Sugar Creek and McAlpine Creek have relatively uniform impervious coverage within the watershed, while Coffey Creek has a large percentage of impervious cover in the upper reaches of the watershed. Coffey Creek (23.8 km^2) has forested land use of 30.1% and developed land use of 59%. Coffey Creek, with an airport in its upper watershed, has a distinctive spatial distribution of urban land use. In the following section, we will relate features of flood response to the spatial distribution of impervious cover for the study watersheds (see more details in section 3).

2.2. Rainfall and Discharge Data

Instantaneous discharge data from the USGS were used for each of the gaged watersheds. The study region has an exceptionally dense network of stream gaging stations, including multiple watersheds with nested gaging stations at basin scales ranging from less than 10 km^2 to more than 100 km^2 [*Smith et al.*, 2002; *Turner-Gillespie et al.*, 2003; *Villarini et al.*, 2009; *Wright et al.*, 2014b]. Each station has at least 14 years of stream gaging observations (the earliest year is 1986) up to 2015 with the time interval ranging from 1 to 15 min. We linearly interpolated all streamflow records to a regular 1 min time interval and converted time stamps to Universal Time Coordinated (UTC, which is the same as Greenwich Mean Time).

High-resolution (15 min temporal resolution, 1 km^2 spatial resolution) radar rainfall fields for the period from 2001 to 2015 were derived from volume scan reflectivity fields using the Hydro-NEXRAD algorithms. Hydro-NEXRAD rainfall fields have been used in previous studies for hydrological analyses in Charlotte [*Wright et al.*, 2013, 2014a] and other regions in the United States [*Krajewski et al.*, 2011; *Kruger et al.*, 2011; *Wright et al.*, 2012; *Smith et al.*, 2013; *Villarini et al.*, 2013; *Yang et al.*, 2014]. The Hydro-NEXRAD system includes quality control algorithms, *Z-R* conversion of reflectivity to rainfall rate, time integration, and spatial mapping algorithms [e.g., *Seo et al.*, 2011].

The study region has a high-quality rain gage network maintained by the USGS, consisting of more than 70 stations [e.g., *Wright et al.*, 2014a]. In this study, volume scan radar reflectivity observations from the Greer, SC WSR-88D (Weather Surveillance Radar 88 Doppler) and 15 min rainfall accumulations from a network of 72 rain gauges in the Charlotte area are the principal data sets used for developing the radar rainfall fields (see *Wright et al.* [2013] for more details about the bias-correction procedures). We utilize rain gage observations, in combination with high-resolution radar rainfall fields to develop rainfall fields at 1 km horizontal resolution and 15 min time scale for the period 2001–2015. High-quality, high-resolution rainfall fields make it possible to resolve the temporal and spatial variation of rainfall over the Charlotte study watersheds, even for basin scales smaller than 10 km^2.

In the following sections, for the analysis of flood peaks and flood agents, the study period covers the entire time series of discharge data, which is from the 1990s (earliest year is 1986) to the end of 2015 water year. For the analysis of flood response with both rainfall and discharge data, the study period is the "warm season" (April–September) from 2001 to 2015.

2.3. Methods

We extracted discharge and rainfall time series for peaks-over-threshold (POT) flood events in each watershed. The threshold for selecting POT events was selected so that we had, on average, five events per year. Flood events were local maxima in discharge for which there was not a larger discharge in a time window of 12 h around the peak time. All POT flood events did not exceed channel capacity.

The climatology of floods and heavy rainfall was examined through analyses of the mixture of flood-producing storm systems. In this study, tropical cyclone floods were identified using the HURDAT "best track" database from the NOAA National Hurricane Center [e.g., *Jarvinen et al.*, 1984; *Kaplan and DeMaria*, 2003]. A flood was associated with a tropical cyclone if the center of circulation of the storm was within 500 km of the gaging station and the timing of the flood peak was within 14 day window around the day of the flood peak [*Smith et al.*, 2011]. The thresholds (i.e., 500 km and 14 days) were selected to reflect the spatial extent of tropical cyclone rainfall and the environmental conditions leading to the passage of the tropical cyclone.

We used cloud-to-ground (CG) lightning observations to examine the role of thunderstorms as flood agents. Cloud-to-ground lightning data were obtained from the National Lightning Detection Network (NLDN, see *Orville* [2008] for more details). CG lightning data have been used in previous studies for climatological analyses of lightning and thunderstorms over the United States [e.g., *Carey and Rutledge*, 2003; *Bentley and Stallins*, 2005; *Ntelekos et al.*, 2007; *Villarini and Smith*, 2010; *Yang et al.*, 2013]. If there were more than one cloud-to-ground lightning strike recorded over the watershed (with a spatial buffering of 5 km) within a 12 h time window around the time of flood peak, we labeled the flood as a thunderstorm flood. We excluded flood events which were identified as tropical cyclones, even if they produced lightning, from the list of thunderstorm events.

We used the Generalized Pareto distribution (GPD) [e.g., *Davison and Smith*, 1990; *Hosking and Wallis*, 1987; *Wang*, 1991] to model the distribution of threshold exceedance for POT discharge data and maximum x-hour rainfall; the cumulative distribution function is given by:

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$$F(x)=\begin{cases}1-\left(1+\varepsilon\frac{x}{\sigma}\right)^{\frac{-1}{\varepsilon}} & for\ \varepsilon\neq0,\ x\geq0\\ 1-\exp\left(-\frac{x}{\sigma}\right) & for\ \varepsilon=0,\ 0\leq x\leq\frac{\sigma}{\varepsilon}\end{cases}$$

The shape parameter of the GPD, ε, provides an index of the thickness of the upper tail of the distribution with higher values representing thicker tails and thus higher probability of higher peak discharge values. Maximum likelihood was used to estimate the shape parameter for POT flood events in each of the study watersheds [*Grimshaw*, 1993]. The Kolmogorov-Smirnov test was used to examine goodness of fit [*Kottegoda and Ross*, 2008]. Positive (negative) values of the shape parameter imply unbounded (bounded), thick-tailed (thin-tailed) distributions; a value of zero implies exponential tails [*Massey*, 1951].

3. Results and Discussion

3.1. Distributions of Flood Peaks

We examine nonstationarities in flood peaks and flood counts using the Mann-Kendall method [*Mann*, 1945; *Kendall*, 1975] and Theil-Sen method [*Helsel and Hirsch*, 1992]. Neither flood magnitudes nor flood counts exhibit evidence of significant increase during 2000–2015, which is contrast to that from the 1960s to 2000 [see *Smith et al*., 2002; *Villarini et al*., 2009]. Our analysis focus on spatial heterogeneities of urban flood response for a region with diverse urban development patterns but remains relatively static in urban footprint (see Table 1 for assessments of change in land use). Coffey Creek (No.5) experienced the most significant urbanization from 2001 to 2011, with developed land use increasing by 11%. Flood counts in Coffey Creek (Figure 3) suggest the possibility of time trend, but not statistically significant.

The absence of pronounced nonstationarities in flood peaks in the Charlotte region after the 1990s is principally due to the pace of urban development, which slowed markedly after 2000, with many watersheds having approached "full development" (Table 1). For those watersheds with fast urbanization, the addition of impervious cover is paired with introduction of storm water detention facilities. Subsequent analyses of urban flood response for the 16 study watersheds principally reflect the properties of a static or slowly varying mix of urbanization patterns.

The distributions of POT flood peaks exhibit large variation across the study watersheds (Figure 4). There are sharp contrasts in the distributions of unit discharge flood peaks among the three principal watersheds. Little Sugar Creek (No.10) has a median unit discharge flood peak, 1.1 $m^3s^{-1}km^{-2}$, that is 49% larger than the median peak for McAlpine Creek (No.14), 0.7 $m^3s^{-1}km^{-2}$. The interquartile range of flood peaks for McAlpine Creek does not overlap with the interquartile range of flood peaks for Little Sugar Creek.

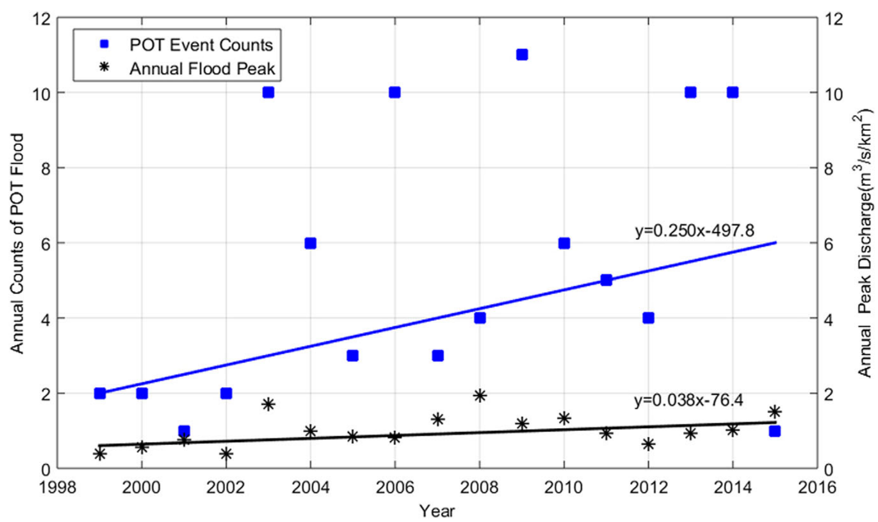

Figure 3. Time series of annual flood counts and annual maximum flood peaks for Coffey Creek (No.5) (Linear trends are calculated using Theil-Sen estimator).

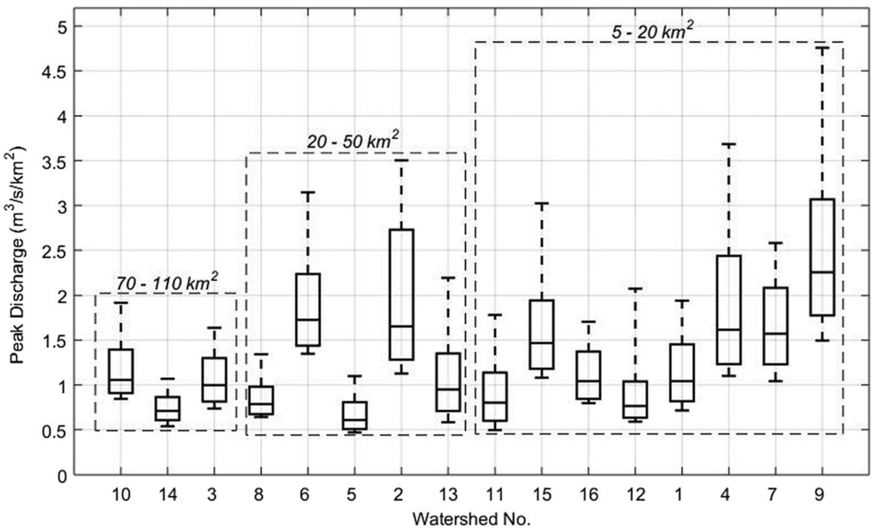

Figure 4. Box plot of peak discharge. The limits of the box represent the 0.25 and 0.75 percentiles, while the line inside represents the median value. The whiskers indicate the 0.1 and 0.9 percentiles.

(Figure 4). Unit discharge flood peak distributions for Irwin Creek are similar to those for Little Sugar Creek. McAlpine Creek not only has smaller flood magnitudes than Little Sugar Creek or Irwin Creek, it also has a much narrower distribution, implying less variability in flood magnitudes.

Not surprisingly, basin scale plays a role in determining the distribution of flood magnitudes for the 16 study watersheds, which cover an order of magnitude of basin scale from approximately 10 to 100 km^2. The smallest of the 16 study watersheds, Little Hope Creek (No.9, 7.0 km^2), located in the western portion of Little Sugar Creek, has the largest unit discharge flood peaks, with a median value of 2.3 m^{3}s^{-1}km^{-2}. The second largest flood peaks, however, are from Upper Little Sugar Creek (No.6), which at 31.5 km^2 ranks ninth in drainage area among the 16 study watershed. The smallest value of median flood peak is for Coffey Creek (No.5), which ranks sixth in drainage area.

Differences in flood peak magnitudes across the three principal watersheds are associated in part with differences in impervious fraction and high-density development. The impervious fraction is 34% in Irwin Creek and 32% in Little Sugar Creek, versus 20% in McAlpine Creek. High-intensity development is 12% in Irwin Creek and 10% in Little Sugar Creek, versus 4% in McAlpine Creek. In contrast, forest cover in McAlpine Creek (15%) is five times larger than that in Little Sugar Creek (3%), and almost twice the value of Irwin Creek (8%). McAlpine Creek is dominantly residential, as reflected in the ratio of night-time population density to day-time population density, 1.5. The ratios in Little Sugar Creek and Irwin Creek are 0.6 and 0.5, respectively, reflecting the level of commercial and industrial development in the two watersheds.

The spatial heterogeneities in flood magnitudes among the three principal watersheds are paired with large spatial heterogeneities in urban development within the watersheds (Figure 4), especially for Little Sugar Creek. Unit discharge flood peaks for Little Sugar Creek at 111 km^2 are larger than the upstream peaks for Briar Creek (No.8, 49 km^2) and substantially smaller than the peaks in Upper Little Sugar Creek (No.6, 32 km^2). Upper Little Sugar Creek has a median flood peak which is more than twice the value for Briar Creek. Not only does the interquartile range of Briar Creek not overlap with Upper Little Sugar Creek, but the 0.1 quantile flood peak for Upper Little Sugar Creek is larger than 0.9 quantile flood peak for Briar Creek. Upper Little Sugar Creek has the largest impervious fraction among the 16 watersheds, 48%, and its impervious fraction is almost twice as large as Briar Creek. Even though Upper Little Sugar Creek and Briar Creek have similar drainage densities, Upper Little Sugar Creek was largely developed before storm water management regulations, as reflected in the absence of dams in the basin (Table 1). In contrast, Briar Creek has the largest densities of dams among the four small watersheds in Little Sugar Creek, reflecting extensive development after the implementation of storm water management regulations. Upper Briar Creek (No.7) has higher flood peaks than Briar Creek with the 0.1 quantile larger than 0.75 quantile of Briar Creek. The median value for Upper Briar Creek is only slightly less than Upper Little Sugar Creek. As noted above, Briar

Creek has four dams with one dam distributed in Upper Briar Creek, implying that storm water detention structures are concentrated in the downstream portion of Briar Creek.

Similar contrasts are seen in the distributions of flood magnitudes within Irwin Creek and McAlpine Creek (Figure 4). The three small subwatersheds of McAlpine Creek (No.11, No.12, and No.13, watershed scale less than 22 km^2) generally have smaller flood peaks than small watersheds in Little Sugar Creek or Irwin Creek, but their flood distributions do not exhibit a simple dependence on impervious cover and storm water management. Irvins Creek (No.13) has larger flood peaks than Upper McAlpine Creek (No.11) or Campbell Creek (No.12), but less urban development, while Campbell Creek (No.12) has the smallest median flood peak, but the largest impervious fraction and high-intensity development.

McMullen Creek (No.15), which is a downstream tributary of McAlpine Creek, has much larger flood peaks than the other small watersheds in McAlpine Creek. The interquartile range does not overlap with Campbell Creek (No.12) or Upper McAlpine Creek (No.11). It does not have larger impervious fraction or fewer dams than the other small watersheds in McAlpine Creek. The anomalous property of McMullen Creek is the large fraction of developed open space, 61%; none of the other 15 watersheds has a value larger than 50%. McMullen Creek also has an anomalously large fraction of the watershed, 73%, with soils characterized by slow infiltration rates (see USGS GAGES II, as in section 2, for more details). For the other three watersheds soils with slow infiltration rates cover less than 41% of the basin area (figure not shown).

Coffey Creek (No.5) has anomalously small flood peaks, with flood magnitudes smaller than Irvins Creek (No.13) which has the least impervious fraction (8%) among all the watersheds and lower high-intensity development (0.5%) than Coffey Creek (13%). The flood peaks for Coffey Creek are also much smaller than the adjacent downstream watershed, Steele Creek (No.16), which has larger impervious fraction but slightly smaller high-intensity development than Coffey Creek. Coffey Creek even has slightly larger drainage density than Irvins Creek (No.13) and Steel Creek. The most distinctive feature of Coffey Creek, which we will examine more closely in connection with its even larger anomalies in response time, is the distribution of urban land use and impervious fraction within the watershed (Figure 1).

The USGS regional flood frequency equations for urban watersheds in North Carolina include drainage area and impervious cover and employ different regression equations for watersheds with basin area ranging from 0.3 km^2 to around 1000 km^2 [*Feaster et al*., 2014]. The variability of flood peak distributions among the 16 watersheds demonstrates that there is no simple relationship between flood peaks and watershed scales, highlighting the need for more sophisticated characterization of regional flood frequency equations.

We examine upper tail properties of flood distributions using the estimated shape parameters of the Generalized Pareto distribution (GPD). Two watersheds, Upper Irwin Creek (No.2) and Upper Little Sugar Creek (No.6) have negative shape parameters, -0.22 and -0.14, respectively, implying that the upper tail of flood distributions is bounded. Flood peak distributions that are bounded above have served as a foundation for developing design flood procedures [*Fernandes et al*., 2010]. Bounded flood peak distributions in urban watersheds can be tied to capacity constraints in the urban drainage system [*Smith and Smith*, 2015]. Urban watersheds in Baltimore exhibit capacity constraints that are tied to design decisions that were made in sizing the storm drain network [e.g., *Meierdiercks et al*., 2010; *Smith et al*., 2005a, 2005b]. The upper tail properties of flood distributions are likely influenced by mixtures of flood agents over the region [e.g., *Morrison and Smith*, 2002; *Villarini et al*., 2009; *Villarini and Smith*, 2010], which will be discussed in the following section. Maximum 1 h and 12 h rainfall rates for the 16 study watersheds generally show negative shape parameters (Table 2). The nature of the upper tail of flood peak distributions in urban watersheds, including their dependence on upper tail properties of basin-averaged rainfall rate, warrants additional study.

3.2. Mixtures of Flood Agents

Warm-season thunderstorm systems are the major flood agents for the Charlotte metropolitan region (Table 3), as they are in most urban regions of the U.S. east of the Rocky Mountains [*Smith and Smith*, 2015]. As noted in section 2, we exclude the tropical cyclone events which produce lightning from the list of thunderstorm events, so the percentage of thunderstorm events in Table 3 is somewhat understated. For Little Sugar Creek, more than 50% of POT flood peaks are produced by thunderstorms. The tributary watersheds of Little Sugar Creek have slightly fewer POT peaks which are produced by thunderstorms. For Irwin Creek, only 36% of POT peaks are thunderstorm events; its upstream tributaries have 40% (Upper Irwin Creek,

Table 2. Estimates of GPD Parameters for POT Flood Peak and for Maximum 1, 3, and 12 h Rainfall Rates for Each Watershed[a]

			Rainfall Rate		
No.	USGS ID (0214-)	POT Flood	Max 1 h	Max 3 h	Max 12 h
1	6211	0.27	0.24	0.36	0.47
2	627970	−0.22	−0.30	0.40	0.35
3	6300	0.15	−0.15	0.12	0.22
4	6315	0.14	−0.21	−0.01	−0.10
5	6348	0.02	0.16	0.18	−0.25
6	6409	−0.14	−0.22	−0.02	−0.02
7	642825	0.26	−0.18	−0.20	0.32
8	645022	0.30	−0.02	0.35	−0.18
9	6470	0.17	0.02	0.21	0.37
10	6507	0.20	−0.65	−0.21	−0.06
11	655255	0.36	−0.53	−0.45	−0.09
12	6562	0.77	−0.60	−1.15	−1.15
13	657975	0.03	−0.39	−0.83	−1.15
14	6600	0.20	−1.07	−1.08	−0.52
15	6700	0.35	−0.23	−0.19	−0.10
16	678175	0.16	0.02	−0.07	−0.21

[a]Note: POT flood peak uses exceedance of the median POT flood peak. Rainfall rates use the median rainfall rate at each time scale.

No.2) and 53% (Statesville Creek, No.1). McAlpine Creek and its tributaries have between 41% and 45% of flood peaks produced by thunderstorms. Coffey Creek (No.5), the watershed with anomalously small flood peaks (as discussed above) has the smallest fraction of thunderstorm peaks, 28%.

Upper Irwin Creek (No.2) and Upper Little Sugar Creek (No.6), the two watersheds that have negative shape parameters of GPD, have anomalously large fractions of warm-season storms (June–August) exceeding 50%, indicating a dominant role of thunderstorm systems in determining the upper tail of flood peak distributions for the two watersheds. Little Sugar Creek, with a 100 km^2 basin scale, also has a relatively large fraction of warm-season events, but its shape parameter is positive. The relationship of storm scale and basin scale plays an important role in determining flood response in urban watersheds and the contrasting upper tail properties of flood peak distributions in Charlotte watersheds reflects these contrasts [see *Ten Veldhuis et al*., 2017 for additional details]. For the other watersheds, the fractions of flood agents are distributed among warm-season storms, tropical cyclones, and other winter/spring extratropical systems (see also *Wright et al*. [2014b]).

Table 3. Percent of All the POT Flood Events and Numbers of Largest Five Flood Peaks Produced by Thunderstorm and Tropical Cyclone in Each Watershed

		POT Flood Peaks (%)			Top Five Flood Events (Count)		
No.	USGS ID (0214-)	Thunderstorm	Tropical Cyclone	Others	Thunderstorm	Tropical Cyclone	Others
1	6211	40	34	26	3	2	0
2	627970	53	28	19	4	1	0
3	6300	36	23	41	2	1	2
4	6315	48	19	33	3	0	2
5	6348	28	13	59	2	1	2
6	6409	51	27	23	4	1	0
7	642825	47	32	22	3	2	0
8	645022	44	31	25	2	1	2
9	6470	37	29	34	4	0	1
10	6507	53	30	18	4	1	0
11	655255	41	34	25	3	2	0
12	6562	45	35	20	4	1	0
13	657975	41	31	28	2	2	1
14	6600	41	29	31	1	2	2
15	6700	44	28	28	3	2	0
16	678175	36	19	45	0	2	3

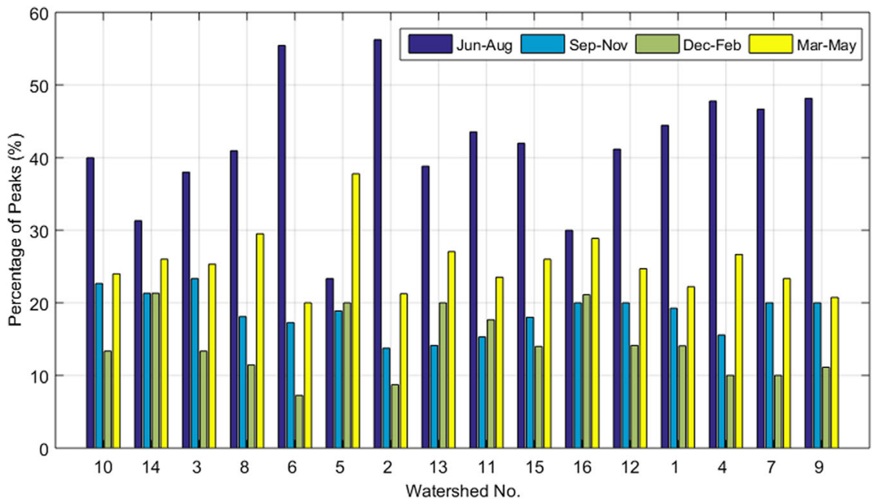

Figure 5. Seasonal rate of occurrence of flood peaks.

Tropical cyclones are another important flood agents in the Charlotte metropolitan region (Table 3). The fraction of tropical cyclone flood peaks ranges from a minimum of 13% for Coffey Creek (No.5) to a maximum of 35% for Campbell Creek (No.12). For the three principal watersheds, the fraction of tropical cyclone peaks ranges from a minimum of 23% for Irwin Creek to 29% for McAlpine Creek to a maximum of 30% for Little Sugar Creek. The frequency of tropical cyclone flood peaks in Charlotte reflects a regional maximum in tropical cyclone flood peaks that extends from South Carolina to the mid-Atlantic region [*Villarini and Smith*, 2010].

Previous studies found that for portions of the mid-Atlantic region (and for certain basin scales), tropical cyclones dominate the upper tail of flood distributions [*Villarini and Smith*, 2010]. This is not the case in Charlotte, where warm season thunderstorms remain major flood agents in the upper tail of flood distributions (Table 3). This result is similar to conclusions developed for flood-producing storms in the Baltimore region [*Ntelekos et al*., 2007]. For most watersheds, there are more warm-season thunderstorm flood peaks than tropical cyclone flood peaks in the top five flood events. We found positive correlation between the values of estimated shape parameters for the GPD and fractions of tropical cyclones over the 16 watersheds (not shown). Even though warm-season thunderstorms remain major flood agents in the upper tail of flood distribution, tropical cyclones also affect the shape of the distributions.

Winter/spring extratropical systems are also significant flood agents for some watersheds, as reflected in the fraction of flood peaks that occur during winter and spring (Table 3 and Figure 5). Among the three principal watersheds, Irwin Creek has the highest fraction of Winter/Spring flood events, 41%; in Little Sugar Creek and McAlpine Creek, winter/spring events account for 18% and 31%, respectively. Coffey Creek (No.5) has the largest fraction of winter/spring flood events, 59%. Steele Creek (No.16), which is adjacent to Coffey Creek, has the second largest fraction, 45%.

For all watersheds, there is a pronounced seasonality in flood occurrence (Figure 5). Except for Coffey Creek (No.5), other watersheds show the largest fraction of warm-season events, which are associated with tropical cyclones and thunderstorms. While Coffey Creek, as mentioned above, with the largest portion of winter/spring flood events, shows the largest fraction of spring events. The results reflect the mixtures of warm-season thunderstorm, tropical cyclone, and winter/spring extratropical system flood events.

The varying composition of flood agents leads to modest differences in basin-averaged rainfall rate distributions for POT flood events (Figure 6). Among the three principal watersheds, McAlpine Creek has the smallest median rainfall rate at 1 h time scale and the largest median rainfall rate at 12 h time scale. Coffey Creek (No.5) with the largest fraction of extratropycal storms, has the smallest median rainfall rate at 1 h time scale, reflecting the relatively lower magnitudes of winter/spring storms at short duration, while median rain rate at 12 h time scale for Coffey Creek is comparable with the other watersheds.

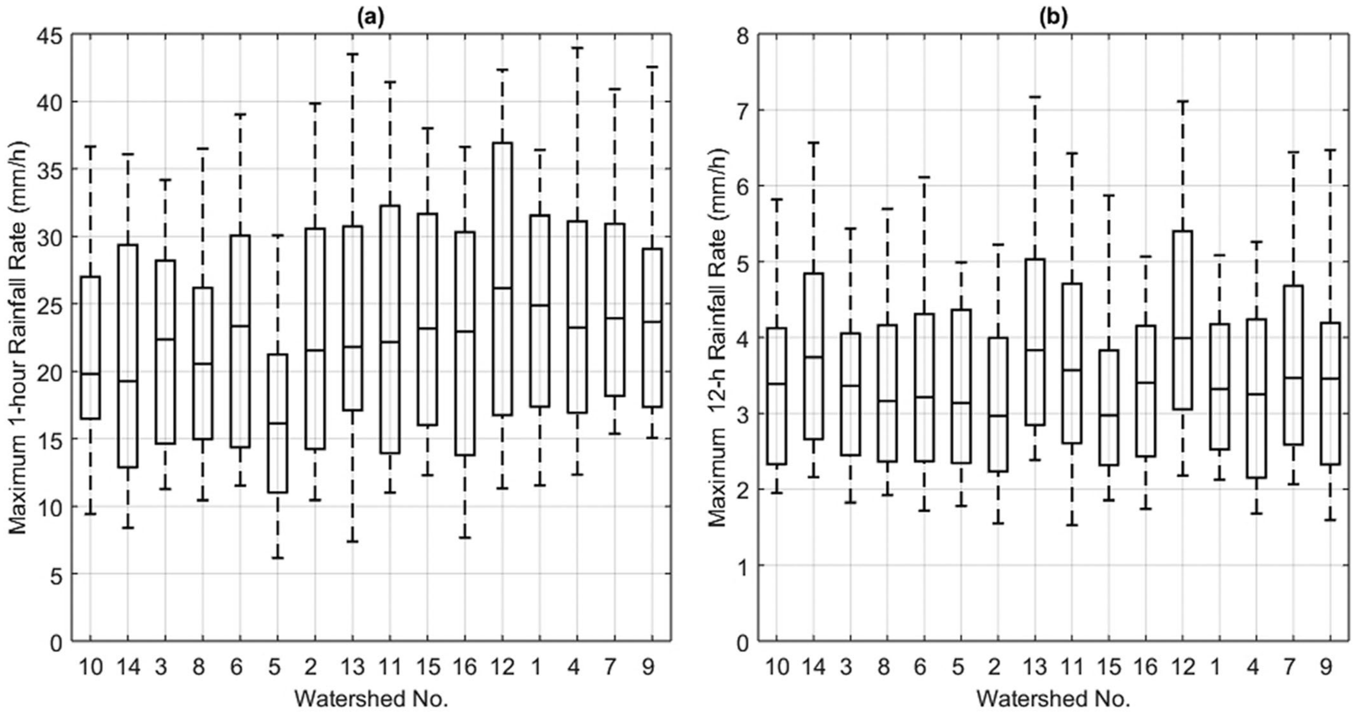

Figure 6. Box plot of maximum 1 and 12 h rainfall rate. The limits of the box represent the 0.25 and 0.75 percentiles, while the line inside represents the median value. The whiskers indicate the 0.1 and 0.9 percentiles.

3.3. Analyses of Flood Response

3.3.1. Response Time

We define response time, or lag time, as the time difference between the rainfall time centroid (based on 15 min basin-averaged rainfall time series during the period of maximum 12 h rainfall around the flood peak time) and the time of peak discharge. Generally, lag time increases with increasing watershed scale (Figure 7). Furthermore, for the watersheds with larger flood magnitudes, the lag time is generally shorter. Within the three principal watersheds, the median lag time for Little Sugar Creek, 1.5 h, is half the value for

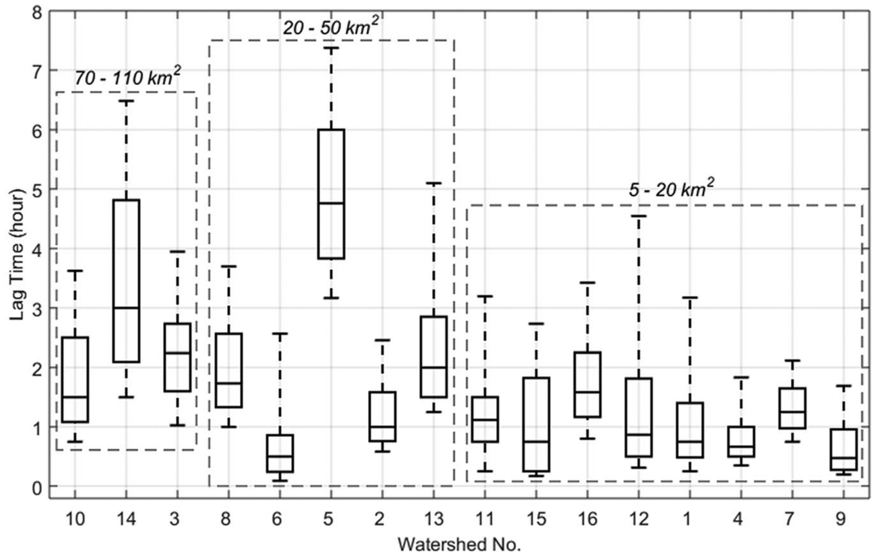

Figure 7. Box plot of lag time. The limits of the box represent the 0.25 and 0.75 percentiles, while the line inside represents the median value. The whiskers indicate the 0.1 and 0.9 percentiles.

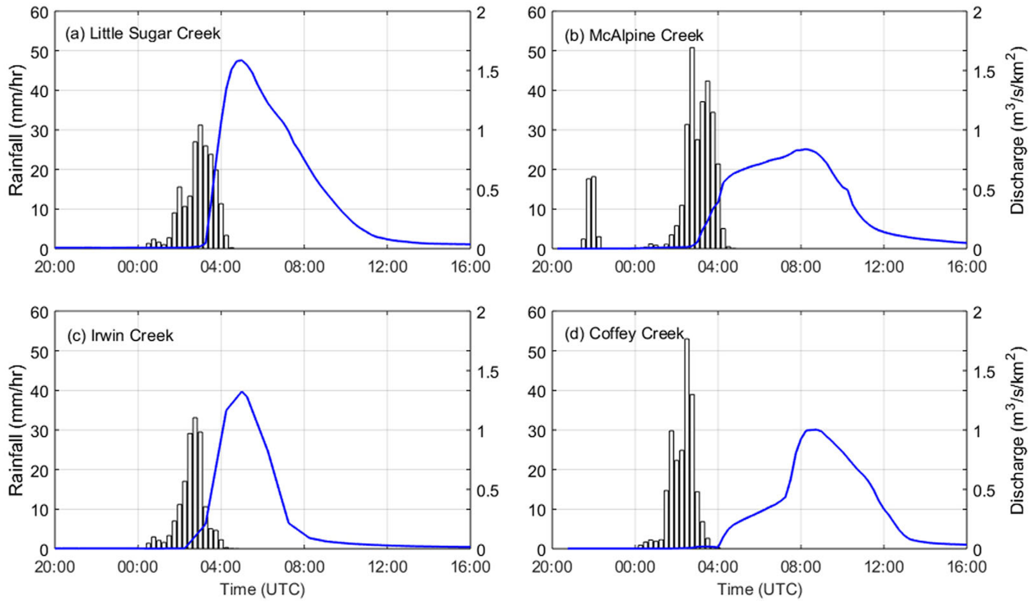

Figure 8. Time series of rainfall rate and discharge for the 17 July 2004 storm for (a) Little Sugar Creek, (b) McAlpine Creek, (c) Irwin Creek, and (d) Coffey Creek (No.5).

McAlpine Creek, 3 h, even though McAlpine Creek is smaller in size. Irwin Creek has a median lag time of 2.2 h, slightly closer to the lag time for McAlpine Creek. McAlpine Creek has the largest interquartile range, while Little Sugar Creek and Irwin Creek have similar values of interquartile range.

Little Sugar Creek has comparable lag times to those from small watersheds. Lag times for Little Sugar Creek are shorter than for its upstream tributary, Briar Creek (No.8, Figures 7 and 8). Flood peaks at the outlet of Little Sugar Creek, are largely determined by contributions from Upper Little Sugar Creek (No.6), with the paired tributary, Briar Creek, not contributing to peak response. Lag times for Upper Little Sugar Creek are the shortest among the 16 watersheds, shorter even than lag times for Little Hope Creek (No.9), which has the largest unit discharge flood peaks and smallest drainage area. The flashy flood response in Upper Little Sugar Creek is tied to the influence of a dense storm drain network, especially in the lower portion of the watershed close to the basin outlet. The goal of storm water management during the period when Upper Little Sugar Creek was developed was to move water as rapidly through the drainage network as possible (as shown in Figure 8).

As with other characteristics of flood response, the most anomalous lag time results are for Coffey Creek (No.5). The median lag time for Coffey Creek is longer than that for the three principal watersheds. The median lag time for Coffey Creek, 4.7 h, is more than 50% larger than the median lag time for the "slow" watershed, McAlpine Creek. The anomalous response time in Coffey Creek highlights the impact of spatial distribution of urban land cover. As mentioned above, the most striking feature of Coffey Creek is the concentration of high-intensity development in the upper portion of the watershed (Figures 1 and 2). The distribution of the storm drain network in Coffey Creek is closely linked to the distribution of high-intensity land use (figure not shown), which is also concentrated in the upper portion of Coffey Creek.

It is difficult to interpret the contrasting behavior of flood response across urban watersheds simply based on watershed scale or impervious fraction. McMullen Creek (No.15) and Upper Briar Creek (No.7), for example, have similar urban development and flood peak distribution, but the median lag time for Upper Briar Creek is more than twice the value for McMullen Creek. These contrasts likely reflect the differences in basin storage associated with storm water infrastructure in Upper Briar Creek and urban soils in McMullen Creek.

The contrasts in flood response between the three principal watersheds are illustrated in Figure 8 for a relatively simple flood event. Little Sugar Creek and Irwin Creek have similar rainfall magnitude and response time, 1.75 and 2 h, respectively, while the flood peak magnitude for Little Sugar Creek (1.59 $m^3s^{-1}km^{-2}$) is larger than Irwin Creek (1.33 $m^3s^{-1}km^{-2}$). The response in McAlpine Creek is attenuated, relative to the

Table 4. Summary of Correlation Between Rainfall Rate and Peak Discharge, and Rainfall and Runoff[a]

No.	USGS ID (0214-)	Peak & Maximum 1 h Rainfall Rate	Peak & Maximum 12 h Rainfall Rate	Maximum 12 h Rain and Maximum 12 h Runoff
1	6211	*0.27*	0.35	0.54
2	627970	0.35	0.34	0.56
3	6300	*0.28*	0.3	0.47
4	6315	0.54	0.36	0.69
5	6348	*−0.02*	*0.28**	*0.24*
6	6409	0.48	0.45	0.83
7	642825	*0.26**	0.35	0.58
8	645022	0.42	0.51	0.65
9	6470	0.58	0.40	0.71
10	6507	0.32	0.42	0.68
11	655255	0.58	0.56	0.52
12	6562	0.49	0.36	0.59
13	657975	0.36	0.4	0.35
14	6600	0.44	0.57	0.53
15	6700	0.48	0.34	0.69
16	678175	0.34	*0.26**	*0.28*

[a]Note Values with italic refer to the insignificant correlation. Values with * refer to the correlation at the significance level of 0.1.

Little Sugar Creek and Irwin Creek response, with a two-phase response characterized by an initial rapid hydrograph rise followed by an extended slow rise to the peak (Figure 8). We also illustrate the anomalous response in Coffey Creek (No.5), in which a period of slow rise is followed by a more rapid rise to the peak (linked to contributions from the upstream impervious portion of the watershed).

3.3.2. Rainfall-Flood Peak/Runoff Relationships

There are striking contrasts between maximum 12 h rainfall rate and peak discharge between McAlpine Creek and the more urban watersheds, Little Sugar Creek and Irwin Creek (Table 4 and Figure 9a). Peak discharge increases much more slowly with 12 h rainfall rate in McAlpine Creek (that is, for a given max 12 h rainfall rate, McAlpine Creek has lower peak discharge values than the other two principal watersheds) and there is less variability in the rainfall-flood peak relationship. For the three watersheds, the largest correlations between maximum rainfall rate (at 1 and 12 h time scales) and peak discharge are in McAlpine Creek. The 12 h correlation in McAlpine Creek of 0.57 is larger than the correlations for Little Sugar Creek, 0.42, and for Irwin Creek, 0.30. The same holds at 1 h time scale. Similar pattern of higher correlations between rainfall rate and peak discharge for less developed watersheds also hold for subwatersheds (Table 4).

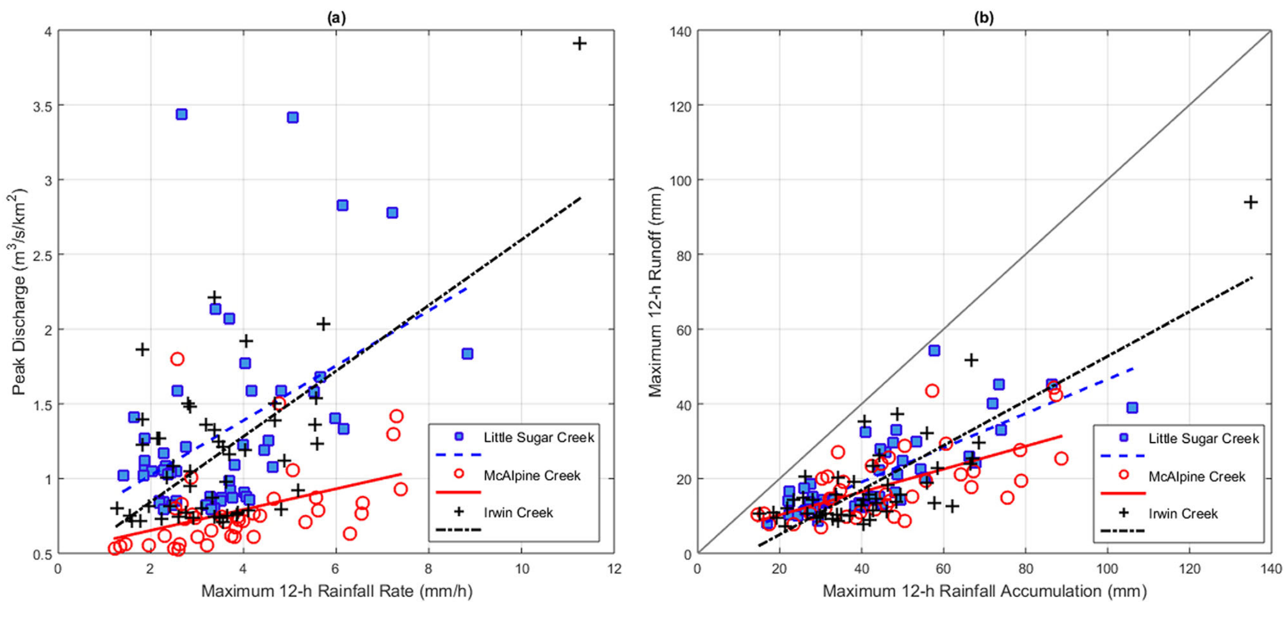

Figure 9. (a) Scatterplot of maximum 12 h rainfall rate and peak discharge; (b) Scatterplot maximum 12 h rainfall accumulation (mm) and maximum 12 h runoff (mm) for Little Sugar Creek (blue), McAlpine Creek (red) and Irwin Creek (black).

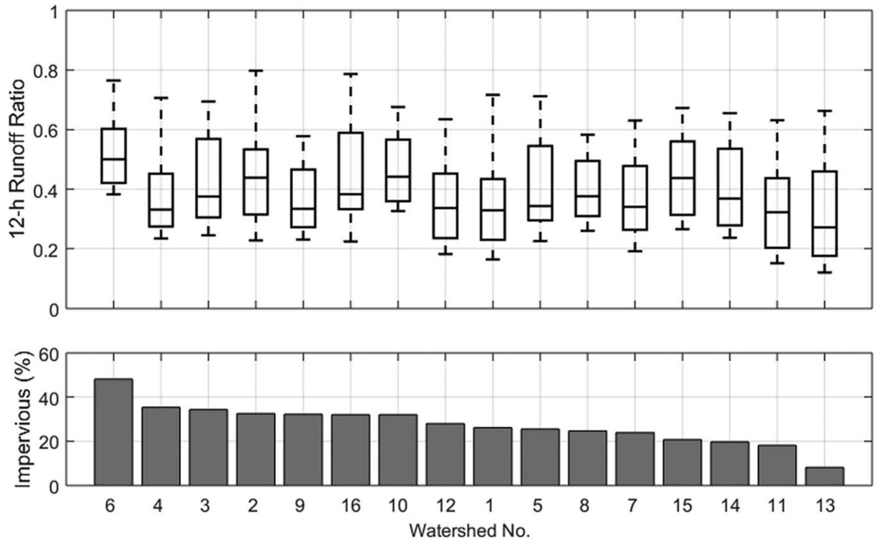

Figure 10. Box plot of 12 h runoff ratio.

The correlation between rainfall and runoff in the 16 watersheds (Table 4) exhibits sharp contrasts with results from the rainfall-flood peak correlations. Runoff generation across the watersheds is examined through maximum 12 h runoff. For the three principal watersheds, the correlations increase from 0.47 for Irwin Creek to 0.53 for McAlpine Creek to 0.68 for Little Sugar Creek (Figure 9b). Upper Little Sugar Creek has the highest correlation (0.83) between maximum 12 h rainfall and maximum 12 h runoff, while the smallest correlations are in McAlpine Creek, with Irvins Creek (No.13) having the minimum value, 0.35, among the 16 watersheds.

We compute runoff ratio for each of the POT flood events as maximum 12 h rainfall accumulation divided by maximum 12 h runoff total (Figure 10). The median runoff ratio for Little Sugar Creek (0.45) is larger than the value for McAlpine Creek and Irwin Creek (0.38). Upper Little Sugar Creek (No.6) has the largest median runoff ratio (0.50) among the 16 watersheds. Little Hope Creek (No.9) has a relatively lower runoff ratio with its median value less than the 0.1 quantile of Upper Little Sugar Creek. The runoff ratio for Briar Creek (No.8) is consistent with watersheds having similar impervious fraction. For Irvins Creek with the least impervious fraction, the median runoff ratio (0.34) is slightly lower than other watersheds. Coffey Creek (No.5) has comparable runoff ratios with other watersheds.

These analyses highlight the observed hydrologic response in a basin for a given rainfall and allow for comparison between the basins' hydrologic responses independently of rainfall depth. The results suggest that impervious fraction is a critical factor for runoff ratios but not for flood peak unit discharge. There are other basin characteristics that significantly affect event hydrologic response [see also *Yang et al*., 2013; *Smith et al*., 2013]. However, *Bell et al*. [2016] found total impervious coverage is the best predictor of both peak unit discharge and runoff ratios at the event time scale. They focused on a collection of watersheds with a wide range of impervious fractions and analyzed storm events across a wide range of storm sizes. Our results highlight striking heterogeneities in flood response to rainfall forcing over extensively urbanized watersheds in Charlotte. The weaker relationship between rainfall totals and flood peak magnitudes in more urbanized watersheds implies that the interaction of space-time rainfall distribution with basin heterogeneities is an important player in determining flood peak properties, for instance, the relative spatial distribution and motion of rainfall to storm drainage network [see e.g., *Syed et al*., 2003; *Morin et al*., 2006; *Peleg et al*., 2017; *Ten Veldhuis et al*., 2017].

3.3.3. Impact of Antecedent Watershed Wetness

The role of antecedent watershed wetness is examined using rainfall accumulations within a time window between 144 and 24 h prior to the time of flood peak. We do not find strong direct relationships between flood peak/runoff ratio and antecedent rainfall (Figure 11). There are slight increases in flood peaks and runoff ratio with increasing antecedent rainfall for McAlpine Creek (impervious fraction less than 20%).

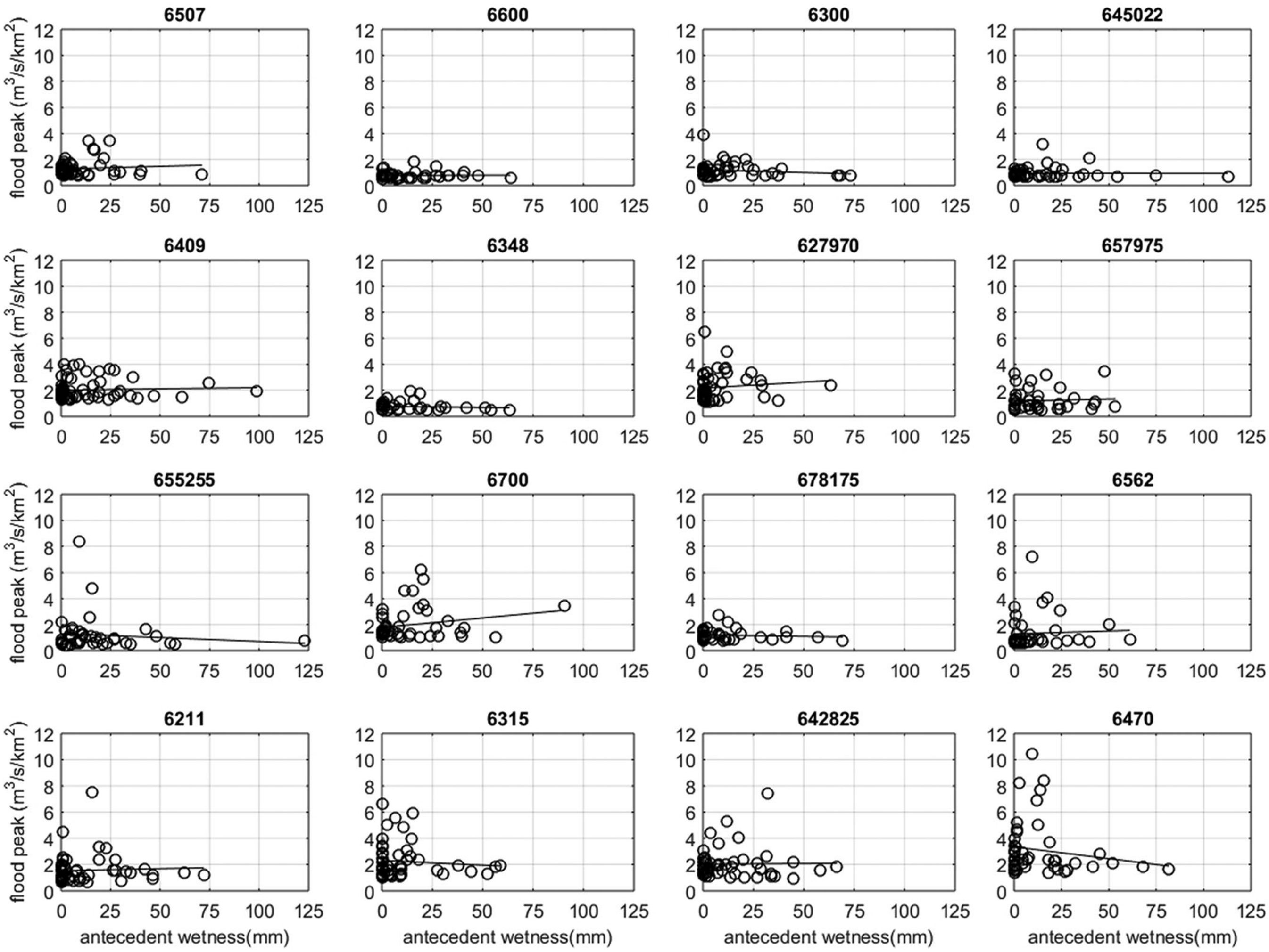

Figure 11. Three-day antecedent rainfall accumulations versus flood peak magnitudes for 16 watersheds.

To further examine the role of antecedent watershed wetness for flood response, flood events for each watershed are divided into two categories, those with and without positive antecedent rainfall. The differences of median runoff ratios between the two categories are shown in Figure 12. For Irvins Creek (No.13), the runoff ratio of flood events with antecedent rainfall is more than twice the value of flood events with no antecedent rainfall. For Upper McAlpine Creek (No.11) and McAlpine Creek, the runoff ratios without antecedent rainfall are 79% and 62%, respectively, less than those with antecedent rainfall. Similar results were obtained using minimum discharge within the time window between 48 and 24 h prior to the time of flood peak as a surrogate for antecedent watershed wetness (not shown). As with antecedent rainfall, strong direct relationships between antecedent discharge and flood magnitude or flood runoff are not found (not shown).

For the more urbanized watersheds, the differences in runoff ratios are smaller (Figure 12). With relatively higher impervious cover, the differences between runoff ratios decrease, highlighting the smaller impact of antecedent watershed wetness in highly urbanized watersheds. The results suggest that there is sensitivity of flood response to antecedent watershed wetness in the least urbanized watersheds, but the dependence on antecedent watershed wetness diminishes markedly with increasing urbanization.

3.3.4. "Downstream" Flood Response

Flood peak properties in the Charlotte metropolitan region for basin scales exceeding 100 km^2 are increasingly influenced by peak attenuation [*Smith et al.*, 2002; *Turner-Gillespie et al.*, 2003]. The hydrographs for Little Sugar Creek (111 km^2) and Pineville (127.6 km^2, see Figure 1 for the location marked by a cross) for the 5

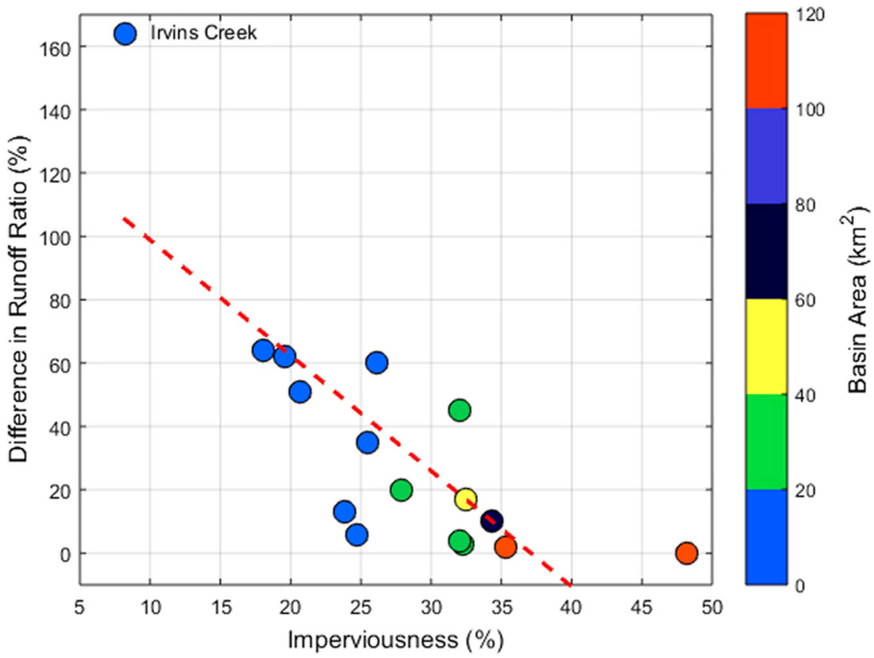

Figure 12. Scatterplot of differences in runoff ratios versus imperviousness for the 16 watersheds. Shading represents the size of each watershed. *Y* axis represents the relative difference (in percentage) of runoff ratio between with and without-antecedent rainfall events.

May 2009 flood event illustrates the typical magnitude of flood wave attenuation (Figure 13a). The flood peak decreases from 314 m^3s^{-1} for Little Sugar Creek to 157 m^3s^{-1} for Pineville with an increase in drainage area of less than 20%. The attenuation is associated with geologically controlled decrease in the longitudinal profile of the channel and expansion of the valley bottom.

A comparison of annual flood peaks for Little Sugar Creek and Pineville (all of which occur of the same day for each annual peak) illustrates the systematic attenuation of flood peaks in this stretch of Little Sugar Creek (Figure 13b). Scaling properties of flood peaks in nonurban watersheds of the eastern U.S. exhibit a

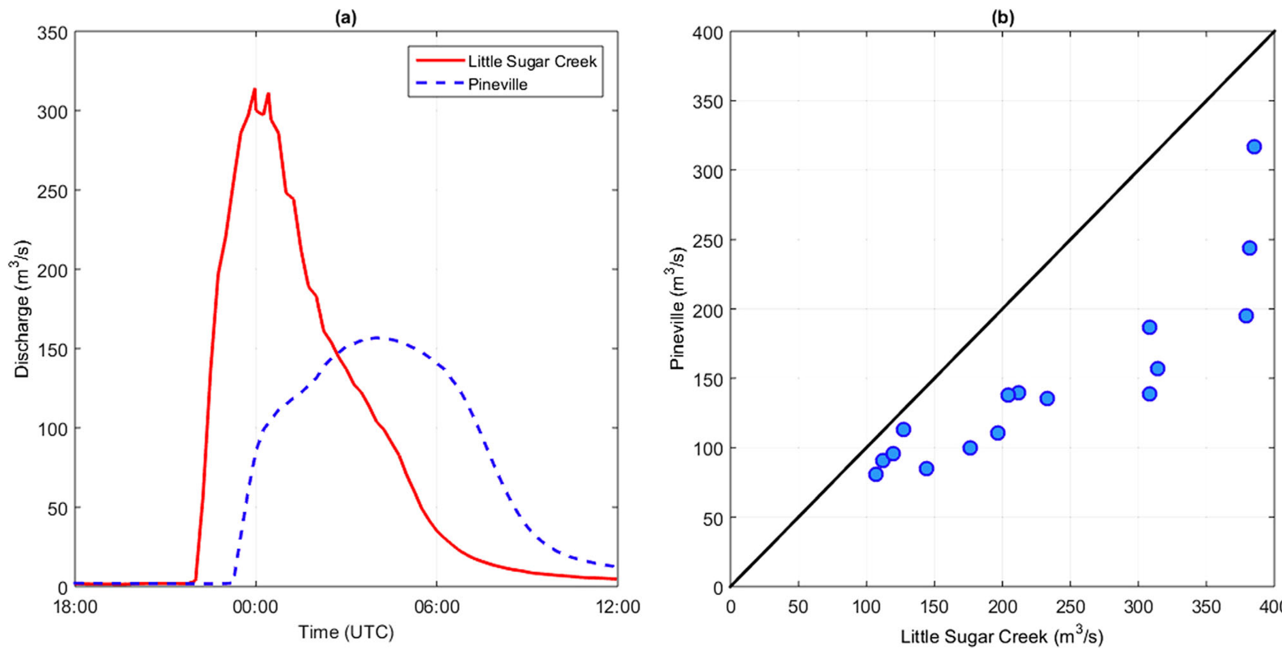

Figure 13. (a) Time series of discharge for Little Sugar Creek and Pineville for 5 May 2009 flood event and (b) Scatterplot of annual peak discharge for Little Sugar Creek versus Pineville.

peak in variability for basin scales between approximately 25 and 250 km^2 [*Smith*, 1992; *Gupta et al*., 1994], which has been linked to both space-time properties of rainfall and hydraulic processes associated with flood wave attenuation. Out results indicate that caution is needed to estimate flood peaks based on the scaling properties of flood peaks as represented by power law functions in urban watersheds [e.g., *Galster et al*., 2006]. Developing a foundation for characterizing scaling properties of flood peaks in urban watersheds will help to advance the development of regional flood frequency methods used for hazards assessment [see, e.g., *Feaster et al*., 2014], as well as urban flood science.

4. Summary and Conclusions

In this study, data-driven analyses of urban flood response are carried out based on peaks-over-threshold flood data extracted from the instantaneous USGS stream gaging observations and high-resolution radar rainfall fields. Observations cover the period from the 1990s to 2015. We examine flood response across a diverse sample of watersheds in the Charlotte metropolitan region, North Carolina. The main findings of this paper are as follows.

1. There is no simple way to characterize urban flood response in Charlotte watersheds in terms of variables that are conventionally used to represent urban development. The distributions of flood peak magnitudes, flood response times, and runoff ratios exhibit complex dependencies on land use and land cover. The spatial distribution of land cover within a watershed can exert striking controls on flood peak magnitudes and response times, as highlighted through the analyses for Coffey Creek (No.5). The hydrologic properties of "urban soils" warrant particular attention in future studies. Anomalous flood response in watersheds with extensive developed open space, along with antecedent watershed wetness controls of flood response (see item 8 below), point to the potentially important role of urban soils. These results highlight the need for advances in developing "urbanized" hydrologic models to provide a predictive understanding of urban flood response.
2. There is little evidence for pronounced nonstationarities in flood counts or flood magnitudes for the period from the 1990s to 2015. These results stand in sharp contrast to results from preceding studies that document striking increases in flood magnitudes over the previous decades. The absence of pronounced trends in flood magnitudes is tied both to the decreasing rate of land use change in Charlotte watersheds and to the impacts of modern storm water management practices in watersheds that are urbanizing. Change will continue to be an important element of flood distributions in urban watersheds, but the patterns of change will not be dominated by the sharply increasing trends in magnitude of preceding decades.
3. The hydroclimatology of urban flooding in Charlotte reflects a mixture of flood agents, including organized thunderstorms, tropical cyclones, and winter/spring extratropical systems. Warm-season thunderstorms account for the largest fraction of flood events, especially for the most urbanized watersheds. The pattern of urban development in a watershed plays a role in determining the mixture of flood agents for that particular watershed. Previous studies showed that tropical cyclones dominate the upper tail of flood distributions for watersheds in some areas of the Eastern United States. For the Charlotte watersheds, organized thunderstorms are not just prominent in the central and lower portion of flood distributions, but also account for the largest fraction of events in the upper tail of flood distributions.
4. The estimated shape parameters of the Generalized Pareto distribution for POT flood peaks are generally positive for the Charlotte study watersheds. For the most heavily urbanized watershed, the estimated shape parameters for 1 and 12 h rainfall rates are generally negative, suggesting bounded distributions. Bounded distributions of flood peaks in urban areas can arise from capacity constraints imposed by the urban drainage system. Future studies should further explore the "nature" of the upper tail of flood and rainfall distributions for urban watersheds.
5. The correlation between basin-averaged rainfall rate and flood peak magnitude is generally smaller for more developed watersheds than for less developed watersheds. The reverse holds for relationships between rainfall rate and runoff. McAlpine Creek shows the largest correlation between rainfall rate and flood peak at 12 h time scale. Upper Little Sugar Creek has the highest correlation between maximum 12 h rainfall and maximum 12 h runoff.
6. The Charlotte study watersheds exhibit striking spatial heterogeneities of flood response. The difference between variability of rainfall and flood peaks implies that the heterogeneity of land surface properties

plays an important role in urban flood response across the 16 watersheds. The three principal watersheds, Irwin Creek, Little Sugar Creek, and McAlpine Creek (with watershed scale ranging from 78 to 110 km^2), show pronounced variability in flood peak and lag time distributions. The peak discharge of Little Sugar Creek is contributed almost exclusively from the western portion of the watershed (Upper Little Sugar Creek). The eastern tributary, Briar Creek (No.8), typically peaks well after the downstream station. The spatial heterogeneities of flood response in Charlotte watersheds reflect the historical evolution of storm water management practices. Stormwater detention infrastructure substantially reduces flood peak magnitude and also smooths the peak response. At the basin scale of 100 km^2 to 200 km^2, "hydraulic" controls, characterized by flood attenuation, serve to mix the flood response, and reduce flood magnitudes.

7. The role of spatial heterogeneity of surface properties on flood response is highlighted by analyses for Coffey Creek (No.5), for which impervious cover is concentrated in the upstream portion of the watershed, with lower development in the remainder of the basin. It has lower flood magnitude than other watersheds, but exceptionally longer response times. The anomalous land surface properties also translate to anomalies in flood generating mechanisms, with winter/spring extratropical systems playing a larger role in flood hydroclimatology than for any other watersheds.
8. The importance of antecedent watershed wetness on runoff generation decreases in highly urbanized watersheds. The comparison of runoff ratio for Irvins Creek (No.13) between dry antecedent condition and moisture condition highlights the role for antecedent watershed wetness in lower development watersheds in Charlotte. Due to the expansion of impervious coverage, the impact of antecedent moisture plays a less important role in flood response.

The preceding conclusions have implications for the ways in which we pursue research on flood frequency and flood hazards in urban regions. We summarize below some of the research directions that would contribute to a better understanding of urban flood hazards and enhanced methods for flood frequency analysis in urban regions.

A consequence of the observation that there is no simple way to characterize urban flood response (item 1 above) is that regional flood frequency analysis procedures used for urban areas [see, e.g., *Feaster et al*., 2014] will inherently reflect significant errors associated with the complexity of urban flood response. This does not imply that these procedures are not important and useful, but rather that we need to expand the scope of statistical analyses used for relating flood frequency to observable properties of a watershed. There is a rapidly expanding information base on urban land use and cover, storm water management infrastructure, and urban channel morphology. Understanding and quantifying the "history" of urbanization also plays an important role in advancing methods for flood frequency analysis. Nonstationary flood frequency methods [see, e.g., *Villarini et al*., 2009] have an important role to play and can be enhanced through creative integration of quantitative information on urban development history.

Rainfall is a key driver of flood frequency and quantitative characterizations of rainfall frequency over a range of space and time scales can markedly enhance the ability to assess flood frequency in urban regions, especially for the large majority of urban regions that have sparser networks of stream gaging stations than the Charlotte metropolitan region. Long records of high-resolution radar rainfall fields, like those used in this study, can contribute to advances in methods used for rainfall and flood frequency analysis urban regions. The Stochastic Storm Transposition (SST) method developed by *Wright et al*. [2013] is an especially promising direction for flood hazard assessment. Combining SST with urban hydrologic models [*Wright et al*., 2014b] provides a path for developing flood frequency analyses continuously over urban drainage networks at scales ranging from 1 to 100s of square kilometers. Enhancing the capability to "urbanize" hydrologic models is an important step along this path.

Urban regions provide interesting settings for examining basic questions of flood science. The range of hydrologic "experiments" that have been inadvertently carried out in watersheds affected by urbanization is extensive. "Scaling" problems are especially prominent in urban regions and represent major challenges for flood science. Flood peak scaling problems in urban regions are fundamentally tied to rainfall variability in time and space and to heterogeneous land surface processes that control runoff production and transport through the urban drainage network. Urban flood science is constrained by experimental resources and the need to monitor over a broad range of spatial and temporal scales. Densely instrumented urban regions like the Charlotte study region will provide important "laboratories" for advancing flood science.

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