The Regional Hydrology of Extreme Floods in an Urbanizing Drainage Basin

JAMES A. SMITH AND MARY LYNN BAECK
Department of Civil and Environmental Engineering, Princeton University, Princeton, New Jersey

JULIA E. MORRISON
Department of Operations Research, Princeton University, Princeton, New Jersey

PAULA STURDEVANT-REES
Department of Civil and Environmental Engineering, University of Massachusetts—Amherst, Amherst, Massachusetts

DANIEL F. TURNER-GILLESPIE
Department of Civil and Environmental Engineering, Princeton University, Princeton, New Jersey

PAUL D. BATES
School of Geographical Sciences, University of Bristol, Bristol, United Kingdom

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ABSTRACT

The Charlotte, North Carolina, metropolitan area has experienced extensive urban and suburban growth since 1960. Five of the largest flood peaks in the 74-yr discharge record of Little Sugar Creek, which drains the central urban corridor of Charlotte, have occurred since August of 1995. A central objective of this study is to explain how these two observations are linked. To achieve this goal, a series of hypotheses of broad importance to the hydrology and hydrometeorology behavior of extreme floods will be examined. These hypotheses concern the roles of 1) space–time variability of rainfall, 2) antecedent soil moisture, 3) expansion of impervious area, and 4) alterations of the drainage network for extreme floods in urbanizing drainage basins. The methodology used to examine these hypotheses centers on diagnostic studies of flood response for the five major flood events that have occurred since August of 1995. Diagnostic studies exploit the diverse range of extreme precipitation forcing for the five events and heterogeneity of land surface properties for catchments with stream gauging records. The observational resources for studying flood response in the Charlotte metropolitan region are exceptional. They include two National Weather Service WSR-88D radars that were deployed in 1995, a dense network of rain gauges and stream gauges installed by the U.S. Geological Survey in 1995, and extensive land surface datasets developed by Mecklenburg County. This study focuses on the *regional* hydrology of extreme flood response, as opposed to the specific effects of individual elements of the constructed environment. Of particular interest are the hydrologic, hydraulic, and hydrometeorological controls of extreme flood response at basin scales ranging from 1 to 500 km^2.

1. Introduction

The Charlotte, North Carolina, metropolitan area (Fig. 1) has experienced rapid growth since the early 1960s (Martens 1968). A striking feature of the flood record for the region is the series of extreme floods during the 1990s. The four largest flood peaks, and five of the largest seven flood peaks, in the 74-yr discharge record of Little Sugar Creek, which drains the central urban corridor of Charlotte at a drainage area of 110 km^2, have occurred since August of 1995 (Fig. 2).

The five flood events in Little Sugar Creek since 1995 were produced by a diverse collection of storms: 1) Tropical Storm Jerry (27 August 1995), 2) an organized system of thunderstorms that repeatedly tracked over the Charlotte region (23 July 1997), 3) Hurricane Danny (24 July 1997), 4) a fast-moving, prefrontal squall line (9 April 1998), and 5) a small, relatively short-lived thunderstorm system (27 July 1998). Storm total, basin-averaged rainfall in Little Sugar Creek ranged from 50 mm for the 24 July 1997 storm to more than 180 mm for the 23 July 1997 storm. Peak rainfall accumulations

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Corresponding author address: James A. Smith, Dept. of Civil and Environmental Engineering, Princeton University, Princeton, NJ 08544.
E-mail: jsmith@princeton.edu

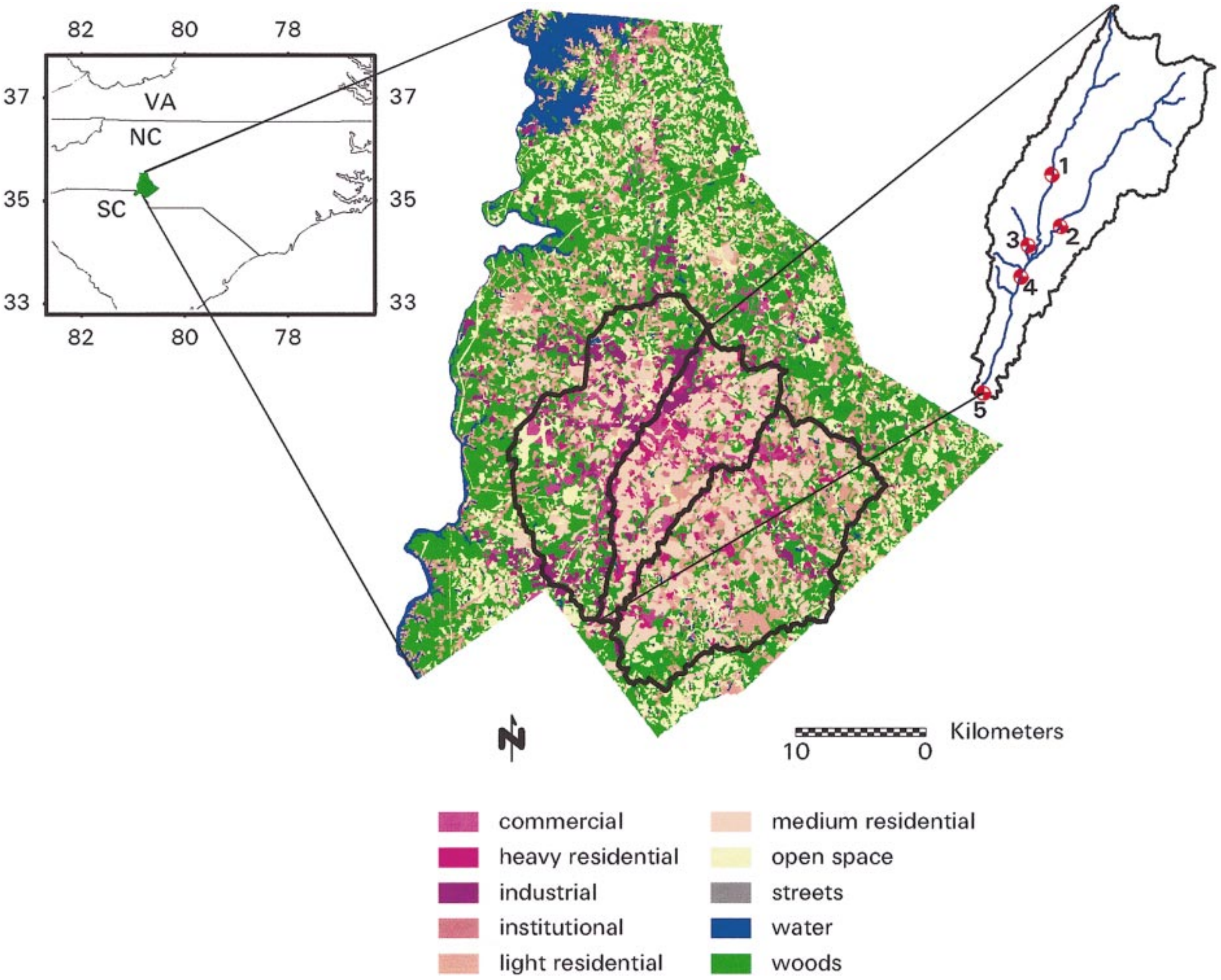

FIG. 1. Location map for Mecklenburg County, North Carolina, with LULC and drainage basin boundaries for Little Sugar Creek (middle), McAlpine Creek (eastern catchment), and Irwin–Sugar Creek (western catchment). The upper right-hand inset provides an expanded view of Little Sugar Creek with the drainage network and location of stream gauges used for analyses of 1995–98 floods. The numbers beside gauging-station locations correspond to the numbers in Table 2.

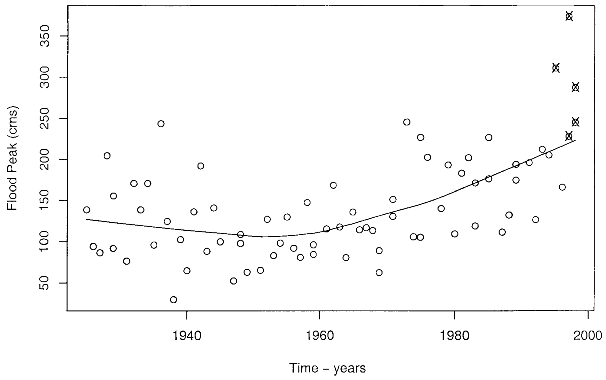

FIG. 2. Annual flood peaks (m³ s⁻¹) for Little Sugar Creek at Archdale (station 4 in Fig. 1 and Table 2). A lowess smoothing of the data is shown by the solid line. The five flood events analyzed in sections 3 and 4 are marked by an ‘‘X’’. The 24 Jul 1997 and 27 Jul 1998 peaks are not annual peaks but are included for comparison purposes.

from the 23 July 1997 storm reached 280 mm during a 12-h period, nearly doubling the daily rainfall record of 150 mm for Charlotte, which has a gauging record of more than 100 yr. In addition to the contrasts in storm total rainfall, there were also significant differences in the spatial and temporal distribution of rainfall over the Little Sugar Creek basin, as described in section 3.

A central objective of this study is to provide an explanation for the series of extreme floods in Little Sugar Creek during the late 1990s. To achieve this objective, the following hypotheses, which are of general interest to flood hydrology, will be examined:

- Increasing flood peak magnitudes in the Charlotte metropolitan region are due to increased drainage density associated with elaboration of the drainage network through streets, culverts, and other elements of the constructed environment (Graf 1977). An alternative hypothesis is that increasing flood magnitudes

TABLE 1. Summary of flood response and trends in flood response based on stream-gauging observations for annual flood peaks from 1962 to 1995 for five catchments in the Charlotte metropolitan area. USGS identification codes for the gauging stations are given in the first column. McMullen Creek is located on the western boundary of the McAlpine Creek basin (Fig. 1). Irwin Creek drains the northeastern portion of the Irwin–Sugar Creek basin. Long Creek is northwest of Little Sugar Creek. The median annual flood peak is expressed as a unit discharge, i.e., discharge divided by drainage area. The fifth column provides the linear trend in annual flood peaks, expressed as a percentage of the median flood peak from the fourth column. The V/P ratio (h) is the median value for the station, computed using procedures described in the text.

Basin	Drainage area (km^2)	V/P ratio (h)	Median flood (m^3 s^{-1} km^{-2})	Trend (% yr^{-1})
Little Sugar (02146507)	110	8.4	1.39	1.8
McAlpine (02146600)	103	13.6	0.86	2.3
McMullen (02146700)	18	5.7	1.97	3.4
Irwin–Sugar (02146300)	79	9.1	1.22	1.6
Long Creek (02142900)	43	14.1	0.89	0.4

result primarily from increasing runoff volumes associated with increases in impervious area (Leopold 1968).

- The importance of antecedent soil moisture for flood response decreases with urbanization because of the effects of increased impervious area. The importance of antecedent soil moisture diminishes with the return interval of the event (Wood et al. 1990). For very large flood events in urban areas, the role of antecedent soil moisture can be neglected in assessing flood response.
- The series of anomalously large flood peaks since 1995 resulted principally from anomalously large rainfall.

A paired objective of this study is to characterize the hydrologic, hydraulic, and hydrometeorological controls of extreme flood response and to determine their dependence on basin scale. For Little Sugar Creek and surrounding catchments, analyses span basin scales ranging from 1 to 500 km^2. This range of basin scales encompasses the region of anomalous scaling behavior of annual flood peaks for the central Appalachian region of Maryland and Virginia (Smith 1992). Scaling behavior of central Appalachian flood peaks can be characterized by a maximum scale of variability [as represented by the coefficient of variation (CV) of annual flood peaks] at approximately 100 km^2. This feature is inconsistent with simple scaling theories, which are equivalent to the index flood assumption (Smith 1992) and multiscaling theories of regional flood frequency. Explanations for this scaling property of flood response have centered on 1) space–time organization of rainfall, 2) drainage network structure, and 3) channel/floodplain processes (Smith 1992; Gupta et al. 1994; Woods and Sivapalan 1999; Morrison and Smith 2001). Analyses of scale-dependent flood response for Little Sugar Creek exploit the diverse range of extreme precipitation forcing for the five flood events since 1995 and heterogeneity of land surface properties, both natural and anthropogenic.

The observational resources for studying flood response in the Charlotte metropolitan region are exceptional. The region is covered by two National Weather Service WSR-88D (Weather Surveillance Radar-1988 Doppler) radars, both of which were deployed in 1995. A dense network of rain gauges and stream gauges was installed by the U.S. Geological Survey (USGS) in 1995 (Hazell and Bales 1997; Robinson et al. 1998). Mecklenburg County has developed extensive land surface datasets. For this study, these datasets have been adapted to provide high-resolution (5–30 m) gridded datasets of terrain elevation, impervious cover, soil texture classification, and land use–land cover (LULC).

2. Long-term trends in hydrologic response

The focus of this study is the Little Sugar Creek basin (Fig. 1), for which five USGS stream-gauging stations (see inset of Fig. 1) provide discharge observations for the five flood events during the period of 1995–98. Little Sugar Creek is one of the three main tributaries to Sugar Creek. It is bounded on the west by Irwin–Sugar Creek and on the east by McAlpine Creek (Fig. 1). The Sugar Creek catchment, downstream of the confluence of Little Sugar Creek, McAlpine Creek, and Irwin–Sugar Creek, has a drainage area of 550 km^2.

The LULC map for Mecklenburg County (Fig. 1) was developed from imagery taken during the the mid-1990s. The Sugar Creek region is characterized by an inner core of urban and dense residential land use and an outer region of lower density residential land use and forest cover (Fig. 1). The downtown core of Charlotte is located principally in the Little Sugar Creek basin, and the most intense urbanization has occurred in the northwestern portion of the basin.

Table 1 provides a summary of flood response properties and temporal trends in flood response for five drainage basins in the Charlotte metropolitan area with long stream gauging records (1962–95). Each of the five basins has a drainage area of less than 111 km^2. Two of the basins (Little Sugar Creek and Irwin Creek) have experienced significant urbanization. Four of the basins (Little Sugar Creek, Irwin Creek, McMullen Creek, and McAlpine Creek) experienced suburbanization during the period of 1962–96. Long Creek has experienced only minor suburban development and serves as a control catchment.

Leopold (1968) notes that hydrologic response to urbanization is typically characterized by increasing flood peak magnitudes, decreasing lag time, and increasing runoff volumes. These elements of hydrologic response are interpreted as a direct consequence of decreasing saturated conductivity and overland flow roughness. Graf (1977) shows that timing and magnitude of flood peaks in a suburbanizing region can be very sensitive to elaboration of the drainage network, which increases the drainage density of the basin and the hydraulic efficiency of the drainage system (see also Anderson 1970; Hollis 1988).

Marked increases in flood peak magnitudes have occurred for all areas experiencing urbanization and suburbanization (Table 1). Flood magnitude is represented in Table 1 by the median annual flood peak, expressed as a unit discharge (i.e., discharge divided by drainage area). The time trend in flood peaks, which was computed by linear regression of annual flood peak magnitude versus record year, is expressed as a percent of the median annual flood peak. The largest percent increase in flood peaks is for McMullen Creek. The 3.4% increase per year in flood peaks for McMullen Creek translates to a doubling of the median annual flood in approximately 30 years. Changes in flood peak magnitudes for Long Creek, the control catchment, are small relative to those for the other four catchments.

Basin response times are strongly tied to LULC properties (Table 1). Response time is represented by the median volume-to-peak (V/P) ratio, which is the ratio of the runoff volume associated with the annual flood peak (m^3; computed from the USGS mean daily discharge observations 1 day prior to the day of the peak discharge to 2 days after the peak discharge) to the annual flood peak ($m^3\ s^{-1}$). Bradley and Potter (1992) discuss V/P ratios as a measure of basin response time. The median response time in Little Sugar Creek at 110-km^2 scale of 8.4 h is more than 5 h faster than the response time of Long Creek at 42.5 km^2. The median response time of the suburbanizing McAlpine Creek at 102.5 km^2 is 0.5 h faster than that of Long Creek. Median flood peak magnitudes also strongly reflect LULC properties. The median (unit discharge) flood peak in McMullen Creek is 2 times the median (unit discharge) flood peak in Long Creek at drainage areas of 18.2 and 42.5 km^2, respectively. The median unit discharge flood peaks of Irwin Creek and Little Sugar Creek at 70–110-km^2 scale are approximately 50% larger than that of McAlpine Creek.

Large increases in annual runoff volume have occurred in the Little Sugar Creek basin since the early 1960s (Fig. 3; runoff is expressed as a depth by dividing annual runoff volume by drainage area). The trend line [computed using the ''lowess'' locally weighted polynomial regression and scatterplot smoothing algorithm; see Venables and Ripley (1997)] for annual runoff volume increases from approximately 400 mm in 1962 to 800 mm in 1995, representing a doubling of the annual runoff during a 33-yr period. The annual runoff ratio (that is, the ratio of annual runoff to annual rainfall) increased from 0.35 to 0.70 during this period. The largest increases in runoff volume have occurred during the autumn season (September, October, November) with roughly a tripling of runoff volume (figure not shown).

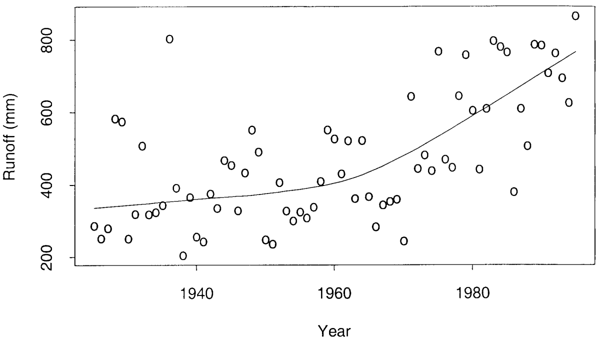

FIG. 3. Time series of annual runoff (mm) for Little Sugar Creek at Archdale (station 4 in Fig. 1) during the period of 1927–96. A lowess smoothing of the time series is provided.

It is generally difficult to relate time trends in hydrologic response to time trends in LULC (Potter 1991). For the Charlotte region, we can assess temporal changes in LULC for certain time periods. USGS 7.5-min (1:24 000) topographic maps provide insight to changing land cover in the region. The Charlotte East quadrangle was published in 1967 based on aerial photographs from 1965 and was photo-revised in 1984 based on imagery from 1984. Extensive revisions to the topographic map reflect residential development within the McMullen Creek basin to the point that we can conclude that McMullen Creek was near full development conditions by 1984. During the period of 1964–84, the McMullen Creek basin was transformed from mixed woodland/residential to dense residential. From 1984 to the present, changes in land cover within McMullen Creek have been small in comparison with the preceding 15-yr period. Changes in flood response of McMullen Creek (Table 1) are presumed to be closely linked to changes in land surface properties from 1964 to 1984. As Wolman (1967) notes, some of the changes to the fluvial system that accompany intense suburban development are episodic and have relatively rapid recovery times (1–10 yr). Other changes to the land surface, especially those that augment the drainage network, are permanent changes (Graf 1977). Persistence of elevated flood peaks into the late 1990s suggests that permanent, engineered changes to the drainage and channel system dominate McMullen Creek time trends.

The Derita quadrangle (north of Charlotte East), which was published in 1971 and was revised based on 1993 photogrammetry, provides information on time trends in Little Sugar Creek land use. Martens (1968) notes that in 1962 the most extensive impervious area

TABLE 2. Summary of basin characteristics for catchments of five stream-gauging stations in Little Sugar Creek (Fig. 1), where K_{sat} denotes the mean saturated hydraulic conductivity over the basin. The effective impervious cover for current conditions is the sum of the percent impervious and percent urban soils values (see text).

Basin	Drainage area (km^2)	Percent impervious 1962	Percent impervious 1995	Percent urban soils	K_{sat} (mm h^{-1})
Little Sugar at Medical Center (station 1, 02146409)	32	22	32	20	3.8
Brian Creek (station 2, 021465022)	49	9	25	5	5.0
Little Hope Creek (station 3, 02146470)	6.7	—	30	8	3.6
Little Sugar at Archdale (station 4, 02146507)	110	15	27	10	4.9
Little Sugar at NC 51 (station 5, 02146530)	128	—	26	9	5.5

within the Charlotte region was located in the central portion of the Little Sugar Creek basin in the downtown area. The most extensive changes to the Derita quadrangle reflect the extension of urban development into the uppermost portions of the Little Sugar Creek basin. Little Sugar Creek was gauged from 1962 to 1970 just downstream of the downtown region (at 39.9 km^2), and annual peaks were reported in Martens (1968) and subsequent data reports. Annual flood peaks ranged from 1.03 to 2.34 m^3 s^{-1} km^{-2}, with a median value of 2.03 m^3 s^{-1} km^{-2}. The stream-gauging station for Little Sugar Creek at Medical Center (31.6 km^2; Fig. 1) was installed in 1995. The annual peaks of 2.76 (April 1998), 3.21 (August 1995), and 4.76 m^3 s^{-1} km^{-2} (July 1997) all exceeded the maximum flood peak of 2.34 m^3 s^{-1} km^{-2} during the 1960s. These observations suggest significant changes in flood response from 1970 to the present within the most intensively urbanized catchment as of 1962 (Martens 1968).

Quantitative assessment of change in impervious cover for the Little Sugar Creek basin (Table 2) was based on planimetric data developed by Mecklenburg County from 1962 (reported in Martens 1968) and 1995. The algorithms used for computing the 1995 impervious area are designed to mimic those used by Martens (1968) for the 1962 analysis in which impervious area was computed manually from hard-copy planimetric maps. Impervious area is defined as any area covered by buildings, roads, and parking lots (paved areas other than roads). Impervious cover for Little Sugar Creek above Archdale increased from 15% in the early 1960s to 27% in the mid-1990s. Impervious cover for the Briar Creek catchment increased by almost a factor of 3, from 9% to 25%. Little Sugar Creek, above Medical Center, retained the highest impervious cover at 32%, but its increase was smaller than in other portions of the basin. The current impervious cover for Little Hope Creek, at 30%, is only 2% smaller than that for Little Sugar Creek above Medical Center. Contrasts in hydrologic response of these two basins play an important role in the flood response analyses of section 4.

The pattern of impervious cover (Fig. 4), in particular the contrasts between residential and urban areas, can play a role in hydrologic response. Connectivity of impervious area with the drainage system is an important element of the pattern of impervious cover. A house surrounded by vegetated lawn may have a combined impervious cover of 30%, but the contribution of this impervious cover to downstream hydrologic response will depend on connectivity with stream channels, sewers, or streets. Although the impervious fraction of suburban watersheds has approached that of urban watersheds in Mecklenburg County, significant contrasts in annual water balance remain between urban and suburban watersheds. The mean annual runoff in Little Sugar Creek at Archdale (Fig. 3) during the period of 1995–98 was more than 20% larger than those in the suburbanizing watersheds of Irwin Creek and McAlpine Creek. The mean unit discharge of Little Sugar Creek at Medical Center during the period of 1995–98 of 1.73×10^{-2} m^3 s^{-1} km^{-2} was 21% larger than the 1.44×10^{-2} m^3 s^{-1} km^{-2} value for Little Hope Creek (compare with water balance analyses of large floods in section 4).

Soil hydraulic information for Little Sugar Creek (Table 2), based on U.S. Department of Agriculture soil surveys, augments the regional picture of impervious cover and associated infiltration potential. The ‘‘urban soils’’ classification (Table 2) includes compacted soils that behave hydraulically as impervious in short-duration heavy rain. The effective impervious cover of a catchment is the fraction of impervious cover shown in the fourth column of Table 2 plus the fraction of urban soils (fifth column). The area above the Medical Center gauging station has the largest effective impervious cover of 52%. For Little Hope Creek, the effective impervious fraction is 38%.

Saturated hydraulic conductivity was estimated from soil texture classification using the Rawls and Brakensiek relationships (Rawls et al. 1993) along with masks for the zero conductivity regions that are either impervious or urban soils. Mean saturated hydraulic conductivity for Archdale is 4.9 mm h^{-1}. The mean (areally averaged) saturated hydraulic conductivity for

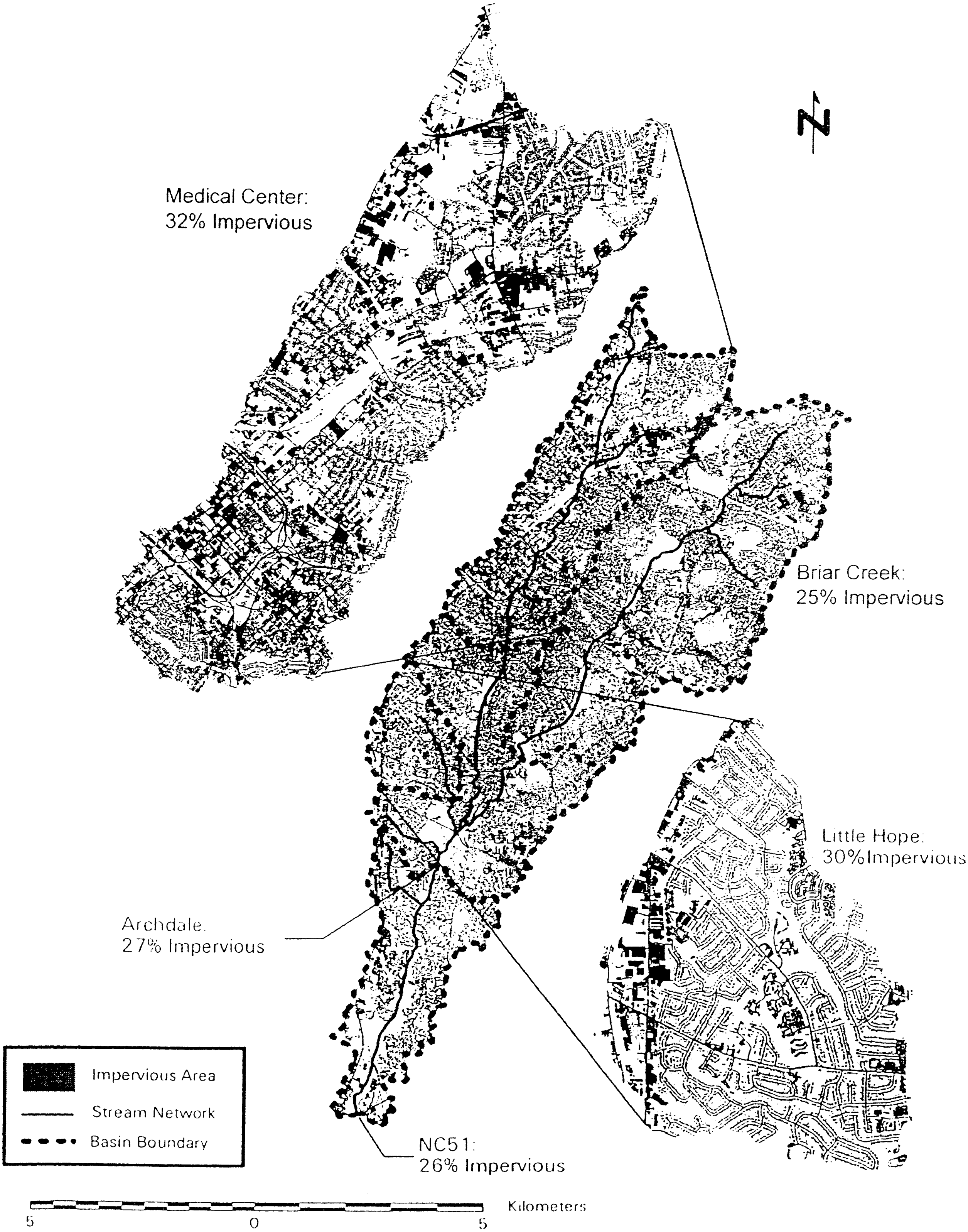

FIG. 4. Impervious area field for Little Sugar Creek with basin boundaries corresponding to the areas upstream of the five stream-gauging stations shown in Fig. 1. In the upper left-hand corner a blowup of Little Sugar Creek at Medical Center (station 1 in Fig. 1) is presented. A blowup of Little Hope Creek (station 3 in Fig. 1) is given in the lower right-hand corner. Black areas represent impervious cover; white areas represent regions with vegetation or soil cover.

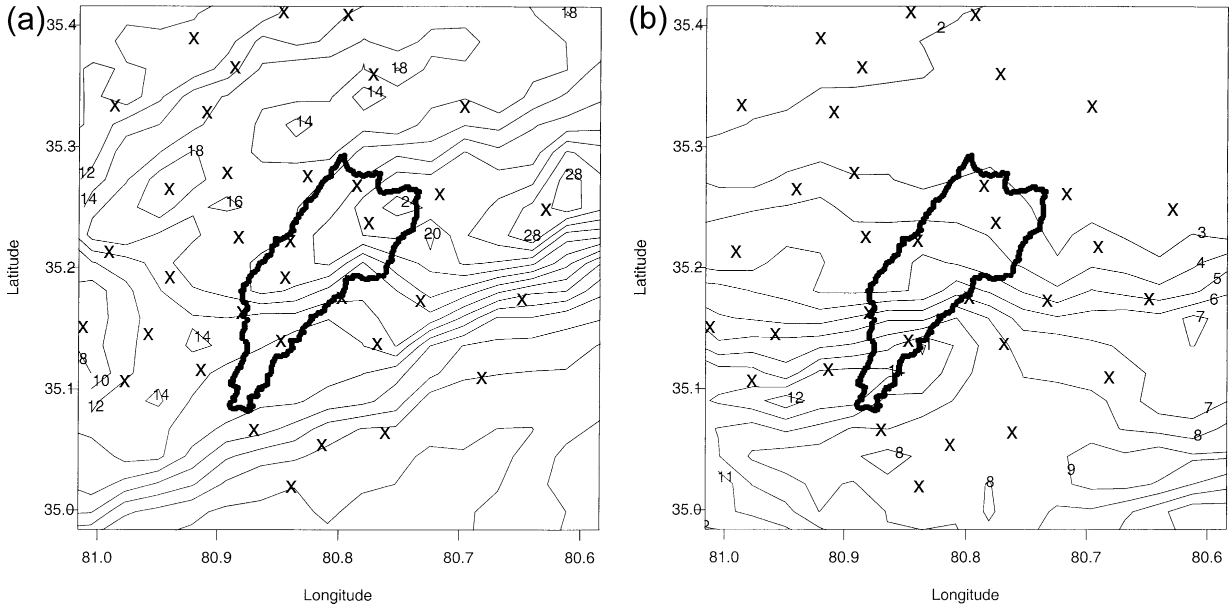

FIG. 5. Storm total rainfall fields (cm) for (a) the 23 Jul 1997 and (b) 27 Jul 1998 storms. Rain gauge locations are denoted by "X". The basin boundary of Little Sugar Creek is shown as a solid black line (see Fig. 1).

the basin above Medical Center at 3.8 mm h^{-1} is slightly larger than that of Little Hope at 3.6 mm h^{-1}. The mean saturated hydraulic conductivity for the 48% of the Medical Center area that is not effectively impervious is approximately 8 mm h^{-1}. These values will be compared in the following sections with the magnitudes of rainfall rates from the five 1995–98 storms.

3. Hydrometeorology of the five storms

The five flood events in Little Sugar Creek were produced by a diverse collection of storms. In this section we briefly describe each storm and present analyses of the spatial and temporal distribution of rainfall for each event. These analyses are linked in section 4 to flood response properties of Little Sugar Creek.

Tropical Storm Jerry produced record flooding over a broad area of the southeastern United States during 26–28 August 1995. Rainfall accumulations during a 12-h period on 27 August 1995 exceeded 200 mm in the Little Sugar Creek basin, with heaviest rainfall concentrated during two intense rain periods separated by 8 h. On 23 July 1997, heavy rainfall developed along an east–west-oriented frontal boundary, producing record rainfall in Charlotte, as storms repeatedly tracked over the region during a 12-h period [see Chappell (1988) and Doswell et al. (1996) for discussion of quasi-stationary convective systems and flash flooding]. Less than 24 h after the heavy rainfall on 23 July 1997 produced record flooding in Charlotte, Hurricane Danny grazed the region. Charlotte was spared even more catastrophic flooding because the heaviest rainfall from Danny passed to the south and east. The 9 April 1998 squall line passed through South Carolina and southern North Carolina, producing a 2-h period of heavy rainfall in Charlotte. The 27 July 1998 storm was a convective system with low echo centroid structure in radar reflectivity observations and shallow, warm cloud tops in satellite infrared observations. These storms are small but can produce extreme rainfall rates (Maddox et al. 1978; Smith et al. 1996; Peterson et al. 1999) over periods of several hours.

Rainfall analyses for the five storms are based on both rain gauge and WSR-88D reflectivity observations, with the exception of the August 1995 event for which WSR-88D volume scan reflectivity observations are not available. The USGS rain gauge network in Mecklenburg County (Hazell and Bales 1997; and Robinson et al. 1998) consists of 46 tipping-bucket rain gauges, 9 of which are in or adjacent to the Little Sugar Creek basin. Radar rainfall estimates were computed using methods described in Baeck and Smith (1998). Key elements of the procedure are rainfall rate–reflectivity (Z–R) conversion using the standard WSR-88D Z–R relationship ($Z = 300R^{1.4}$; with a 55-dBZ threshold on reflectivity observations) and a multiplicative bias correction using rain gauge storm totals from all of the rain gauges in the USGS network (and radar-based storm totals for the 1-km bins containing rain gauges). Radar-based rainfall estimates captured variability of rainfall at sufficiently fine timescales (5–15 min) and space scales (1 km; Fig. 5) to analyze response times and event water balance for gauged subbasins of Little Sugar Creek (Fig. 1).

Rainfall summaries for the five flood events (Tables 3 and 4 and Figs. 5a,b) present a contrasting picture of the series of extreme flood events during the late 1990s. The rain gauge analyses in Tables 3 and 4 are based on

TABLE 3. Rainfall summaries based on rain gauges in the Little Sugar Creek basin for five flood events. The maxima of the second to fifth columns are taken over the nine rain gauges covering the basin.

Event	Storm total max (mm)	Max 5 min (mm h^{-1})	Max 15 min (mm h^{-1})	Max 60 min (mm h^{-1})
Aug 1995	218	122	101	70
23 Jul 1997	230	161	144	78
24 Jul 1997	64	70	50	22
Apr 1998	64	76	50	35
Jul 1998	102	80	64	51

TABLE 4. Basin-averaged rainfall and fraction of storm total rainfall at rainfall rates exceeding 5, 25, 50, and 100 mm h^{-1}, based on rain gauge observations (as in Table 3).

Event	Total (mm)	% > 5 (mm h^{-1})	% > 25 (mm h^{-1})	% > 50 (mm h^{-1})	% > 100 (mm h^{-1})
Aug 1995	169	92	54	28	5
23 Jul 1997	181	97	73	43	11
24 Jul 1997	50	79	15	6	0
Apr 1998	57	94	38	5	0
Jul 1998	59	96	60	25	0

observations from the nine rain gauges in or adjacent to the Little Sugar Creek basin (no corrections were made for potential undercatch by the tipping-bucket rain gauges). The first two flood events, 27 August 1995 and 23 July 1997, were the product of excessive rainfall. In contrast, the 1998 flood events and flooding from Hurricane Danny (24 July 1997) were the product of modest rainfall accumulations, by historical standards, in Charlotte.

The 27 August 1995 and 23 July 1997 storms produced peak rain gauge accumulations in the Little Sugar Creek basin that exceeded 200 mm in 12 h. Peak rain gauge accumulations were 100 mm or less for the other three events. Basin-averaged rainfall for the 27 August 1995 and 23 July 1997 storms were 169 and 181 mm; basin-averaged rainfall for the other three events ranged from 50 to 60 mm (Table 4). The peak rainfall accumulation for the 23 July 1997 event of 280 mm, which was located approximately 10 km northeast of the Little Sugar Creek basin (Fig. 5a), nearly doubled the previous maximum daily rainfall accumulation from the Charlotte rain gauge. The median value of maximum annual daily rainfall from the Charlotte rain gauge during the 100-yr period from 1895 to 1994 is 65 mm.

The 27 August 1995 and 23 July 1997 storms produced markedly higher rainfall rates than did the other three events. Peak rainfall rates at a 5-min timescale were greater than 120 mm h^{-1} for both events. The 161 mm h^{-1} 5-min peak rainfall rate for the 23 July 1997 storm is 64% of the 100-yr, 5-min rainfall rate for Charlotte (Frederick et al. 1977) and is 111% of the 2-yr, 5-min rainfall rate. The 78 mm h^{-1} 60-min peak rainfall rate is 86% of the 100-yr, 60-min rainfall rate for Charlotte and is 181% of the 2-yr, 60-min rainfall rate (Frederick et al. 1977). For the 27 August 1995, 23 July 1997, and 27 July 1998 storms, more than 50% of storm total rainfall was delivered at 5-min rainfall rates exceeding 25 mm h^{-1} and more than 25% of storm total rainfall was delivered at rainfall rates exceeding 50 mm h^{-1}. For the 23 July 1997 storm, 78 mm of rainfall were delivered at rainfall rates exceeding 50 mm h^{-1} and 20 mm of rainfall were delivered at rainfall rates exceeding 100 mm h^{-1} (Table 4).

To characterize the temporal variability of rainfall over the Little Sugar Creek drainage basin, we utilize 5-min, 1-km radar rainfall fields to compute the following quantities: 1) the mean rainfall rate over the catchment at time t during the storm, $M(t)$; 2) the fractional coverage of the basin by rainfall rates exceeding 25 mm h^{-1} at t, $Z(t)$; and 3) the normalized distance of rainfall from the basin outlet at t, $D(t)$. The mean rainfall rate and fractional coverage time series provide basic information on rainfall mass balance and distribution of rainfall rates over the catchment. They do not provide information on the spatial distribution of rainfall relative to the basin network structure, however. The drainage network, as represented by the distance function $d(x)$, provides a natural metric for analyzing the spatial distribution of rainfall. The value of $d(x)$ for each point x within the drainage basin is computed as the sum of the overland flow distance from x to the nearest channel and the distance along the channel to the basin outlet [using the algorithms of Tarboton (1997); see additional discussion in section 4].

The normalized distance time series $D(t)$ is a function of the rainfall field $R(t, x)$ and the distance function $d(x)$. It is defined as the ratio of the rainfall-weighted centroid distance to the basin outlet $D_1(t)$ and the maximum distance from the basin outlet $d_{\max}$. The distance time series $D_1(t)$ can be represented as

$$D_1(t) = |A|^{-1} \int_A w(t, y)d(y)\, dy, \tag{1}$$

where A is the spatial domain of the drainage basin and the weight function $w(t, y)$ is given by

$$w(t, y) = \frac{R(t, y)}{|A|^{-1} \int_A R(t, u)\, du}. \tag{2}$$

The random variable $D_1(t)$ takes values from 0 to the maximum distance from the basin outlet $d_{\max}$. Values of $D(t)$ range from 0 to 1, with values close to 0 indicating that rainfall is distributed near the basin outlet; values of $D(t)$ close to 1 reflect a rainfall distribution concentrated at the far periphery of the drainage basin. If rainfall is uniformly distributed over the catchment, then the weights do not vary spatially, and we obtain the mean distance

$$d_{\text{mean}} = |A|^{-1} \int_A d(y)\, dy. \tag{3}$$

For the Little Sugar Creek basin, spatially uniform rainfall produces a value of $D(t)$ equal to 0.62.

The 23 July 1997 storm included two main pulses of heavy rainfall (Fig. 6a), at 0500–0900 and 1200–1400 UTC. The first period was characterized by a series of small storm elements passing over the basin, resulting in large temporal and spatial variability of rainfall. The second period was characterized by growth of the rain area within the Little Sugar Creek catchment. At 1320 UTC, the basin rain area exceeding 25 mm h^{-1} (Fig. 6a) reached its maximum value of 80% of the total basin area. During both periods, the rainfall distribution, as represented by the normalized distance $D(t)$, moved from the lower to the upper basin during a 2-h time period (0430–0630 and 1200–1400 UTC). This pattern and timescale of motion was important for flood response in Little Sugar Creek (as discussed further in section 4).

The temporal structure of rainfall distribution in Little Sugar Creek for the 9 April 1998 event (Fig. 6b) reflects the squall line organization of the storm (Houze 1993). The storm moved rapidly through the region and was large in linear extent relative to the dimensions of the drainage basin. The sharp spike in fractional coverage of heavy rainfall $Z(t)$ reflects passage of the main line of convection. Throughout the rainfall period, the storm exhibited relatively uniform spatial rainfall distribution throughout the basin [i.e., $D(t)$ is close to the spatially uniform value of 0.62 for Little Sugar Creek].

The spatial distribution of storm total rainfall for the 27 July 1998 event (Fig. 5b) was characterized by very large accumulations in the lower basin (120 mm) and relatively small accumulations in the upper basin (40 mm). During the 2-h period of the storm, this rainfall distribution resulted from an initial period of rainfall concentrated in the lower basin and a later period of expanding rain area, with large contributions in the upper portions of the basin. At 1220 UTC, the rain area exceeding 25 mm h^{-1} had grown to cover 80% of the basin, and the rainfall distribution was nearly uniform over the basin [i.e., $D(t)$ is close to 0.62].

The time series $M(t)$, $Z(t)$, and $D(t)$ for the 23 July 1997 storm (figures not shown) were computed for the Little Sugar Creek basin above Medical Center (31.2 km^2) and for the Sugar Creek basin (550 km^2). The principal differences in rainfall distribution with changing basin scale are tied to fractional coverage of rainfall. In decreasing the basin size from 110 to 31 km^2, we reach a scale at which flood response is dominated by periods in which the entire basin receives heavy rainfall. In converse, the increase of basin size from 110 to 550 km^2 reflects the transition from a scale at which peak periods of the storm produce fractional coverage values of heavy rainfall close to 100% to a scale at which no more than 50% of the basin receives heavy rainfall. These results have particular relevance to analyses of scaling behavior of annual flood peaks (Smith 1992; Gupta et al. 1994; Robinson and Sivapalan 1997; Woods and Sivapalan 1999). In Smith (1992), it is proposed that the 100-km^2 scale at which the peak in CV of annual flood peaks occurs for the central Appalachian region is linked to spatial organization of flood-producing rainfall. For the series of heavy rainfall events in Charlotte, the aspect of spatial organization of rainfall that varies most strikingly around a scale of 100 km^2 is fractional coverage of heavy rainfall.

4. Hydrologic response for extreme floods

Hydrologic response for extreme floods in Charlotte is examined in this section through analyses of the five flood events described in previous sections. Particular attention is given to analyses for the Little Sugar Creek basin at Medical Center, which reflects the most intense urban development within the catchment (Figs. 1, 4), and the Little Hope Creek basin, which is suburban and is dominated by residential development (Figs. 1, 4).

Hydrograph plots (Fig. 7) for the five flood events in the Little Sugar Creek basin illustrate systematic spatial heterogeneities in flood response, independent of the details of the rainfall distribution. Of most importance, flood peaks for Little Sugar Creek at Archdale (station 4 in Fig. 1) are largely determined by contributions from the urbanized western portion of the drainage basin (as represented by station 1 in Fig. 1, Little Sugar Creek above Medical Center, and the region immediately downstream). Briar Creek (station 2 in Fig. 1) peaks well after the downstream gauge at Archdale and contributes mainly to the recession at Archdale (see especially Figs. 7a,c,e). Flood peaks decrease (Figs. 7c,d) from Archdale at 110 km^2 to the most downstream gauge at North Carolina Route 51 (NC 51; 128 km^2).

Flood summaries for Little Hope Creek (Table 5) and Little Sugar Creek at Medical Center (Table 6) were carried out for seven flood periods: the two peaks from 27 August 1995 (as illustrated in Fig. 8), the two peaks from 23 July 1997 (as illustrated in Fig. 9), and the 24 July 1997, 9 April 1998, and 27 July 1998 events. For each period, the water balance is summarized by basin-averaged rainfall (mm) and runoff (mm). Flood magnitude is represented by the peak discharge, expressed as a unit discharge ($m^3\ s^{-1}\ km^{-2}$). Flood response time is represented by the lag-to-peak value, which was computed as the time difference between the peak discharge and the time centroid of basin-averaged rainfall. As detailed below, these analyses suggest that expansion of the drainage network, and the associated enhancement of hydraulic efficiency of the drainage system, is the dominant control of increasing flood peaks in Little Sugar Creek.

There are large differences in the timing of flood response between urban and suburban catchments. The median lag time of 1.0 h for Little Sugar Creek at Medical Center at 31.6 km^2 is smaller than the 1.1 h for Little Hope Creek at 6.7 km^2. Lag time was computed for a subset of flood events in Little Sugar Creek at

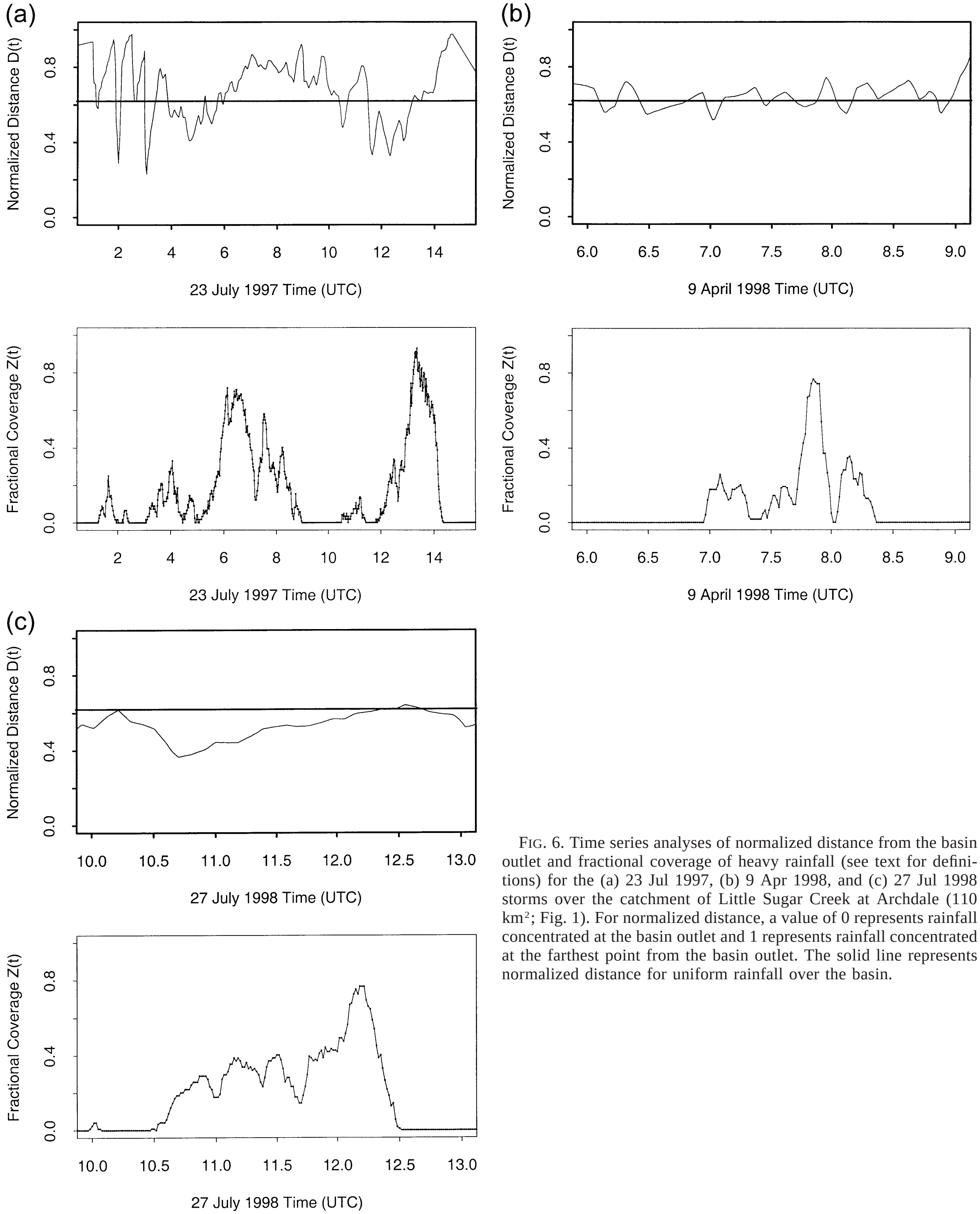

FIG. 6. Time series analyses of normalized distance from the basin outlet and fractional coverage of heavy rainfall (see text for definitions) for the (a) 23 Jul 1997, (b) 9 Apr 1998, and (c) 27 Jul 1998 storms over the catchment of Little Sugar Creek at Archdale (110 km^2; Fig. 1). For normalized distance, a value of 0 represents rainfall concentrated at the basin outlet and 1 represents rainfall concentrated at the farthest point from the basin outlet. The solid line represents normalized distance for uniform rainfall over the basin.

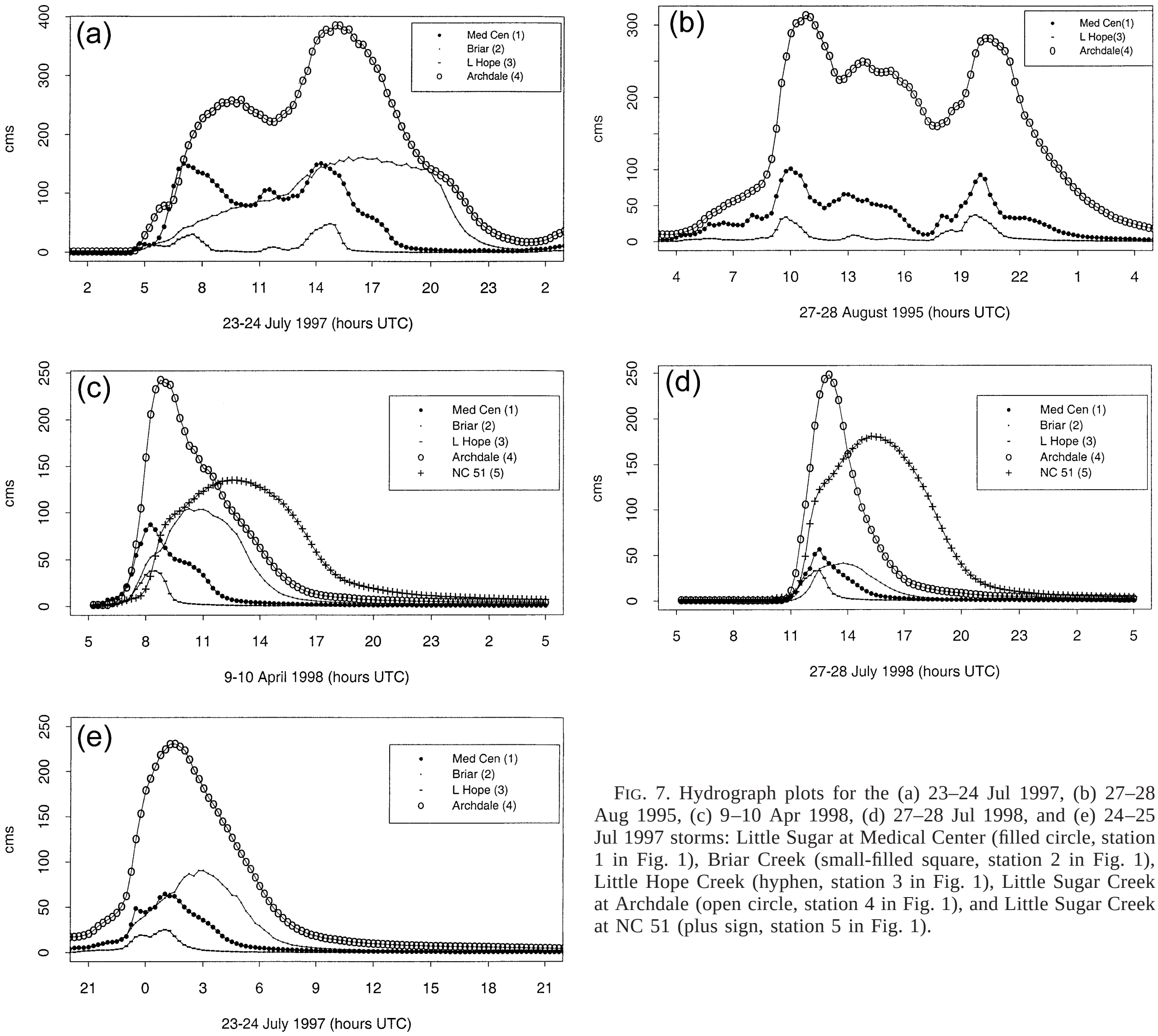

FIG. 7. Hydrograph plots for the (a) 23–24 Jul 1997, (b) 27–28 Aug 1995, (c) 9–10 Apr 1998, (d) 27–28 Jul 1998, and (e) 24–25 Jul 1997 storms: Little Sugar at Medical Center (filled circle, station 1 in Fig. 1), Briar Creek (small-filled square, station 2 in Fig. 1), Little Hope Creek (hyphen, station 3 in Fig. 1), Little Sugar Creek at Archdale (open circle, station 4 in Fig. 1), and Little Sugar Creek at NC 51 (plus sign, station 5 in Fig. 1).

Archdale, McAlpine Creek at Sardis, McMullen Creek, Irwin Creek, and Long Creek (compare with results in Table 1), yielding values of 2.8, 6.2, 2.0, 3.1, and 6.8 h, respectively.

Additional support for the conclusion that expansion

TABLE 5. Flood summaries for Little Sugar Creek at Medical Center for the five storms (note that the 23 Jul 1997 and 27 Aug 1995 events are each broken into two periods; see Figs. 9 and 10). "Runoff ratio" is the ratio of runoff ("runoff" column) to storm total rainfall ("rain" column). "Lag time," or lag-to-peak time, is the difference between the time of peak discharge and the time centroid of basin-averaged rainfall.

Little Sugar at Medical Center (event)	Rain (mm)	Runoff (mm)	Runoff ratio	Peak (m^3 s^{-1} km^{-2})	Lag time (h)
27 Aug 1995 (1)	120	66	0.55	3.2	1.0
27 Aug 1995 (2)	50	36	0.72	2.9	1.7
23 Jul 1997 (1)	134	86	0.64	4.8	2.2
23 Jul 1997 (2)	60	60	1.00	4.8	0.9
24 Jul 1997	41	33	0.81	2.0	1.2
9 Apr 1998	58	33	0.58	2.8	0.8
27 Jul 1998	39	16	0.40	1.8	0.7

TABLE 6. Flood summaries for Little Hope Creek for the seven storm periods (as described in Table 5).

Little Hope Creek (event)	Rain (mm)	Runoff (mm)	Runoff ratio	Peak (m^3 s^{-1} km^{-2})	Lag time (h)
27 Aug 1995 (1)	100	45	0.45	5.0	1.1
27 Aug 1995 (2)	60	45	0.75	5.4	1.4
23 Jul 1997 (1)	97	35	0.36	4.6	3.3
23 Jul 1997 (2)	70	55	0.80	7.2	1.1
24 Jul 1997	55	39	0.70	3.7	1.2
9 Apr 1998	61	41	0.68	5.7	0.9
27 Jul 1998	55	30	0.56	4.9	1.0

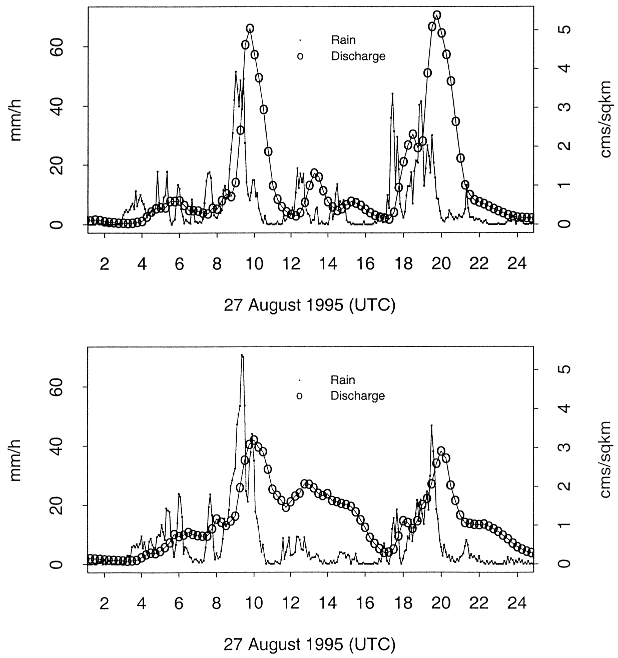

FIG. 8. Time series of basin-averaged rainfall and discharge in (top) Little Hope Creek and (bottom) Little Sugar Creek at Medical Center for the 27 Aug 1995 event.

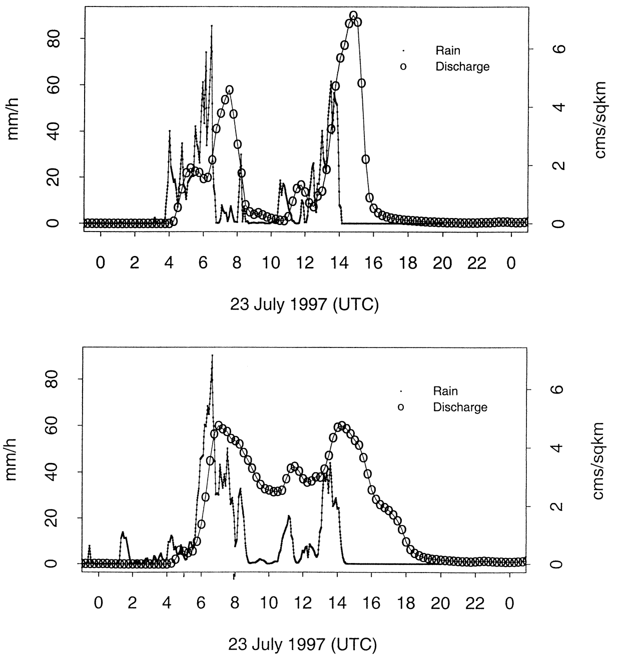

FIG. 9. Time series of basin-averaged rainfall and discharge in (top) Little Hope Creek and (bottom) Little Sugar Creek at Medical Center for the 23 Jul 1997 event.

of the drainage network (and the resulting decrease in response time) is a dominant control of increasing flood magnitudes in Little Sugar Creek is provided by two representations of the drainage network (Fig. 10). One representation (right-hand side) is derived from a high-resolution (10 m) DEM using an area-threshold algorithm. The second representation (left-hand side) includes the sewer network in addition to the natural drainage network. The cumulative drainage density for both networks is comparable (the contribution of the natural drainage network is smaller for the second representation). The role of drainage network structure (Fig. 10) for hydrologic response can be summarized through the width function (Fig. 11), that is, the number of channel links at a specified distance from the basin outlet (Rodriguez-Iturbe and Rinaldo 1997). The width function is proportional to the geomorphological instantaneous unit hydrograph (GIUH) of the basin [see Rodriguez-Iturbe and Rinaldo (1997) for assumptions linking the width function and GIUH]. The effect of urban development in Little Sugar Creek has been principally to amplify the width function in the lower section of the basin (Fig. 11). A direct consequence has been a decrease in the response time and an increase in flood magnitudes for the Little Sugar Creek basin at Medical Center and downstream.

There is little difference in the water balance of flood events between the Little Hope Creek basin and the Little Sugar basin above Medical Center. For Little Sugar Creek at Medical Center, the cumulative runoff ratio for the seven events is 0.66 (502 mm rainfall to 330 mm runoff). For Little Hope Creek the runoff ratio is 0.59 (496 mm rainfall to 291 mm of runoff) for the seven events. The difference in runoff ratio is due to the first pulse of rainfall from the largest event, the 23 July 1997 flood (Fig. 8). The 134 mm of rain in Little Sugar Creek above Medical Center for the first pulse of the 23 July 1997 storm resulted in 86 mm of runoff; in Little Hope Creek 35 mm of runoff resulted from 97 mm of rainfall. If the 23 July 1997 event is removed from the computation, the runoff ratio is 0.61 for Little Hope and 0.60 for Little Sugar Creek at Medical Center. As noted in section 2, cumulative runoff during 1995–99 was 20% larger in the Little Sugar Creek basin above Medical Center than in the Little Hope Creek basin.

The water balance results are consistent with the soil hydraulic properties (Table 2) and rainfall rate analyses (Table 3) presented in sections 2 and 3. The differences in extreme flood response between an impervious region and a pervious region with saturated hydraulic conductivity values of less than 10 mm h^{-1} (Table 2) are small for rain rates experienced during the series of extreme storms in Charlotte (Table 3). Extreme flood response in Little Sugar Creek, for both impervious and pervious regions, is dominated by infiltration excess mechanisms. Runoff ratios close to 1, especially for periods during which large portions of the basin are receiving heavy rainfall (see analyses in Fig. 6), are at odds with previous analyses of the maximum extent of saturated portions of a drainage basin (Dunne 1978). The decreasing runoff ratios between the second and third 23–24 July 1997 events are consistent with rainfall rate–controlled infil-

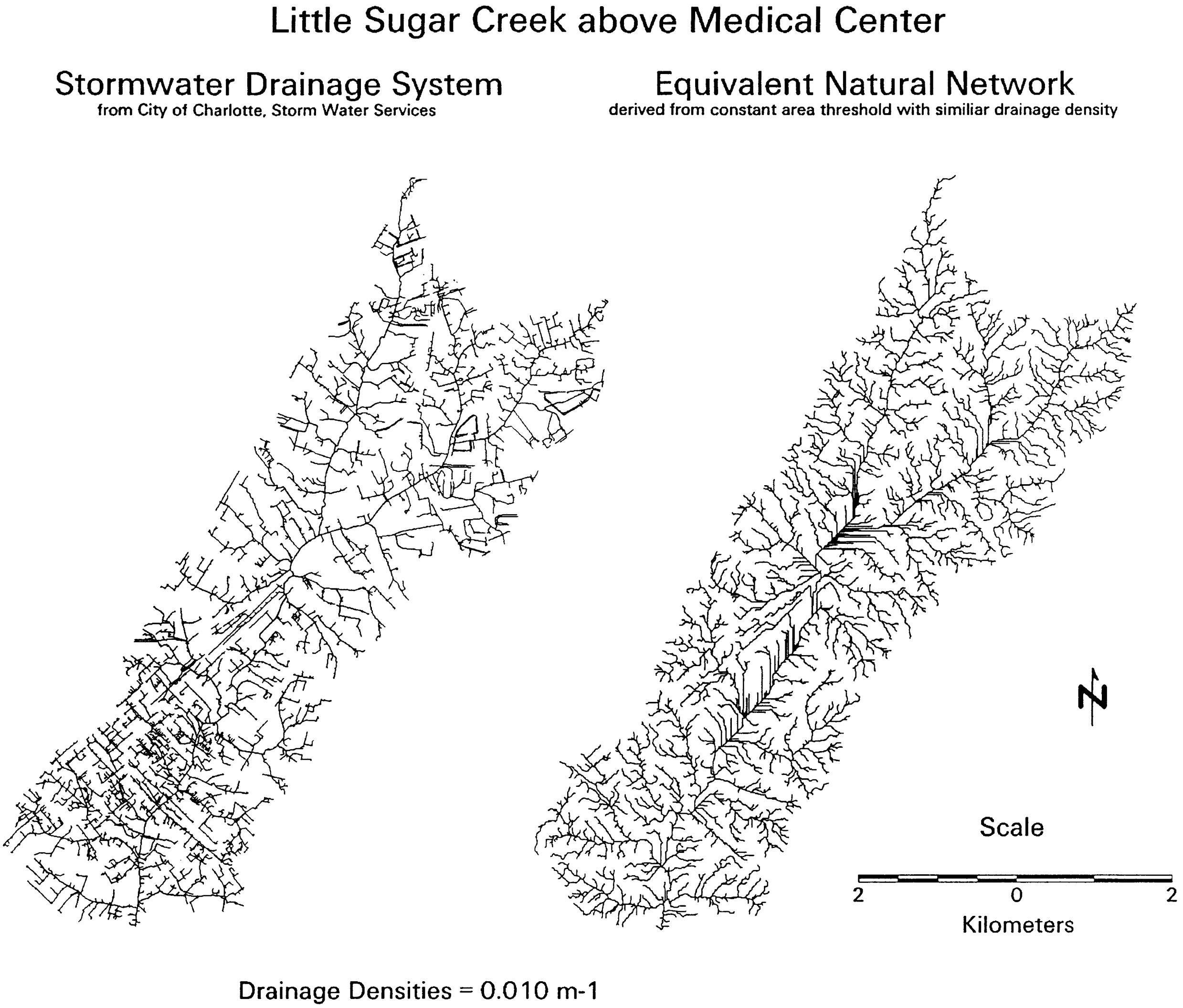

FIG. 10. The drainage network of Little Sugar Creek above Medical Center (left) including the sewer system and (right) derived from a 10-m DEM (with the same drainage density as on the left).

tration excess runoff production but are at odds with expanding saturated area control of runoff.

Antecedent soil moisture plays an important role in the flood response of Little Sugar Creek, even for extreme events in the most urbanized portion of the watershed, as illustrated by flood response for the three storm periods from 0400 UTC 23 July until 1200 UTC 24 July 1997. For Little Hope Creek, the runoff ratio increased from 36% (97 mm rain to 35 mm runoff) for the first event to 80% for the second event (70 mm rainfall to 55 mm runoff) and back to 70% for the third event (55 mm rainfall to 39 mm runoff). For Little Sugar Creek at Medical Center, the runoff ratio increased from 64% (134 mm of rainfall to 86 mm of runoff) for the first event to 100% for the second event (60 mm of rainfall and runoff) and back to 81% for the third event (41 mm of rainfall and 33 mm of runoff). For the two August 1995 rain periods, the runoff ratios increased from 55% and 45% for Little Sugar Creek at Medical Center and Little Hope Creek, respectively, during the first event to 72% and 75% for the second rain period. For Little Sugar Creek at Medical Center, 40 mm of rainfall produces 33 mm of runoff for the 24 July 1997 event (immediately following 160 mm of rainfall on 23 July) but only 16 mm of runoff for the July 1998 event.

Antecedent discharge (minimum discharge preceding flood rise), which was computed for the 27 August 1995, 23 July 1997, 9 April 1998, and 27 July 1998 events, provides a useful surrogate for antecedent soil moisture. For Little Sugar Creek at Medical Center, antecedent discharge ranged from 3.0×10^{-5} m^3 s^{-1} km^{-2} for the 23 July 1997 event to 6.8×10^{-5} m^3 s^{-1} km^{-2} for the April 1998 event. For Little Hope Creek, it ranged from 1.4×10^{-5} m^3 s^{-1} km^{-2} for the 23 July 1997 event to 5.6×10^{-5} m^3 s^{-1} km^{-2} for the April 1998 event. The consequences of high antecedent soil moisture preced-

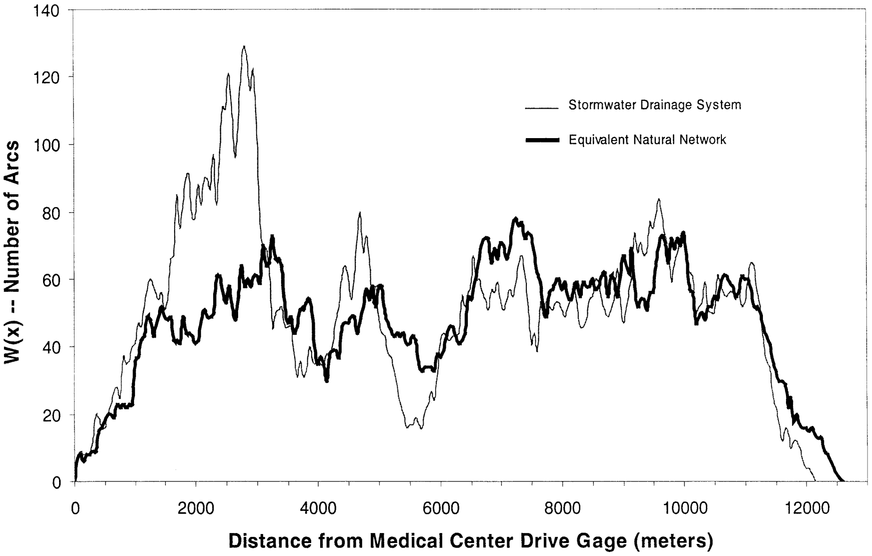

FIG. 11. The width function of the Little Sugar Creek drainage network (above Medical Center), derived from the complete stormwater drainage system (thin line; see Fig. 10) and the equivalent natural drainage network (thick line; see Fig. 10).

ing the 23 July 1997 event likely would have included catastrophic flooding in the major urban corridor of Charlotte. Runoff ratios close to 1 for the 0500–0800 UTC rainfall maximum in the upper portion of Little Sugar Creek would have produced an 0700 UTC flood peak at Medical Center of far greater magnitude than that shown in Fig. 9.

Flood response to the July 1998 and April 1998 storms (Fig. 7), combined with analyses of temporal variability of rainfall (Fig. 6), provides additional insight into the role of space–time rainfall distribution for the flood hydrology of Little Sugar Creek. The April and July 1998 floods had comparable peak discharges at Archdale (Fig. 7). The July 1998 flood was notable for its large peak discharge, relative to the storm total rainfall and runoff, especially in comparison with the April 1998 event. The volume-to-peak ratio at the Archdale gauge for the July 1998 event was 3.2 h; for the April 1998 event it was 5.0 h (c.f. the results in Table 1). The April 1998 event exhibited relatively uniform rainfall distribution (Fig. 6b). For the 27 July 1998 event, heavy rainfall was initially concentrated in the lower portion of the basin, with a trend toward more uniform distribution at the peak intensity of the storm (Fig. 6c). Storm total rainfall over the Little Sugar Creek basin for the 27 July 1998 storm (Fig. 5b) ranged from 25 mm in the upper boundary of the basin to 120 mm at the lower boundary. Runoff ratio ranged from 20%–40% in the upper basin to 60%–80% in the lower basin (Table 7). The residual term in Table 7 includes water that infiltrates into the soil column, interception storage on vegetation, and retention storage on the land surface.

TABLE 7. Basin-averaged rainfall, runoff, runoff ratio, and rainfall minus runoff for the five basins of Table 1 (and Fig. 1) during the 27 Jul 1998 storm. The final row is for the intervening area between the NC 51 gauge (station 5) and the Archdale gauge (station 4). Infiltration accounts for much of the difference between storm total rainfall and runoff (“Residual”).

Station	Rain (mm)	Runoff (mm)	Ratio	Residual (mm)
1	39.2	15.7	0.40	23.5
2	44.7	12.0	0.27	32.7
3	54.4	30.2	0.56	24.2
4	49.8	26.2	0.44	23.6
5	58.9	34.5	0.59	24.4
5 − 4	117.7	88.1	0.75	29.6

If hillslope and channel velocities were uniform over the basin, storm movement down the basin would result in maximum flood peaks at the basin outlet for a given storm total accumulation over the basin [see Ogden et al. (1995) and Smith et al. (2000) for detailed analyses]. For the Little Sugar Creek basin, however, the highest velocities are concentrated in the central and upper areas of the basin. The response time of the upper urbanized basin (at 30-km^2 scale) is approximately 1.5 h. Storm motion over a 2-h period from the lower basin to the upper basin, as occurred with the 27 July 1998 storm, would result in the upper basin contributing synchronously with the lower basin to the hydrograph at Archdale. The rainfall maximum in the lower basin (Fig. 5b) for the 27 July 1998 storm was the principal control of peak discharge for the event. As a consequence of storm motion and evolution, peak discharge at Archdale was augmented by rapidly responding portions of the middle and upper basin. Similar aspects of storm motion and evolution play an important role in flood response for the 23 July 1997 storm (see Fig. 6a and discussion in section 3).

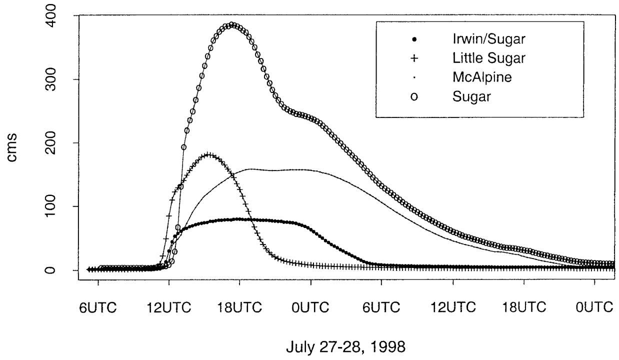

FIG. 12. Hydrographs for Irwin–Sugar Creek (169 km^2), Little Sugar Creek (128 km^2), McAlpine Creek (240 km^2), and Sugar Creek (550 km^2) during the 27 Jul 1998 flood event.

Flood-wave attenuation in the reach between Archdale and NC 51 (stations 4 and 5 in Fig. 1) is of comparable importance to urbanization effects in determining flood response properties at NC 51 [see Woltemade and Potter (1994) and Wolff and Burges (2000) for related analyses]. The July 1998 and April 1998 flood events provide clear illustration of the magnitude of attenuation in the reach between Archdale and NC 51 (Fig. 7). Flood-wave attenuation in this reach is associated with a geologically controlled drop in the longitudinal profile (Turner-Gillespie 2001) of the channel and expansion of the valley bottom. Flood-wave attenuation is also an important element of the delayed contribution of Briar Creek to Little Sugar Creek at Archdale (Fig. 7), noted at the beginning of this section (see Turner-Gillespie 2001). Geologically controlled variation in longitudinal profile and valley bottom width also play an important role in flood-wave attenuation in Briar Creek.

The regional flood response of Sugar Creek reflects the major changes in response times associated with urbanization and suburbanization (Fig. 7; Tables 5, 6), the influence of attenuating reaches (Fig. 7), and the scale-dependent space–time structure of rainfall forcing (Figs. 5, 6). Figure 12 shows time series for Sugar Creek (550 km^2) and the contributions from Irwin–Sugar Creek (169 km^2), Little Sugar Creek (128 km^2), and McAlpine Creek (240 km^2) for the July 1998 flood. Timing of the peak response at Sugar Creek reflects the rapid contributions from the urbanized portion of the basin. Attenuating reaches serve to mix the effects of upstream heterogeneities of flood response, resulting in a rapid decline in the influence of urbanization on flood response with increasing drainage area. Of fundamental importance for the flood response illustrated in Fig. 12, as with other extreme floods, is the spatial and temporal pattern of heavy rainfall (Figs. 5, 6).

5. Summary and conclusions

The seven principal observations from our work are the following.

1) There are large differences in the timing and magnitude of flood response among catchments of different land use and cover in the Charlotte metropolitan region. Differences in land use and cover do not, however, result in large differences in the water balance of flood response for the five extreme flood events. Expansion of the drainage network (Graf 1977) and the associated increase in hydraulic efficiency play a central role in controlling the increasing trend in flood magnitudes.
2) Increases in runoff associated with impervious area are important for the overall water balance of the watershed but are of secondary importance for extreme flood response in the Little Sugar Creek basin. Extreme flood response, both for pervious and impervious regions, is dominated by infiltration excess runoff mechanisms in which the magnitude of rainfall rate is much larger than saturated hydraulic conductivity values.
3) Antecedent soil moisture plays an important role in the flood response of Little Sugar Creek for extreme floods even in the most intensely urbanized portion of the basin. The most striking example is the 23 July 1997 flood peak, which resulted from rainfall accumulations that were approximately 2 times the previous daily record from the 100-yr Charlotte rain gauge record and which produced the largest flood peak in the 74-yr gauging record of Little Sugar Creek. It seems likely that the dry antecedent conditions preceding the 23 July 1997 event prevented catastrophic flooding in the major urban corridor of Charlotte.
4) Fractional basin coverage of heavy rainfall is a key element of scale-dependent flood response in the Sugar Creek basin. For small basins such as Little Sugar Creek at Medical Center (31.2 km^2), flooding results from storms with fractional coverage of heavy rainfall approaching 100% of the basin for the characteristic response times of the basin (0–2 h). For large basins, such as Sugar Creek (550 km^2), fractional coverage of the basin by heavy rainfall is small, and the heavy rainfall periods are short in comparison with basin response times (24–48 h). The drainage area of Little Sugar Creek at Archdale (110 km^2) falls in the transition range between these two extremes. It also falls near the scale of maximum variability of central Appalachian flood peaks (Smith 1992). These results suggest that fractional coverage of heavy rainfall should be examined more closely as an explanation for anomalous scaling behavior of flood peaks.
5) Storm structure and motion play an important role in the event-to-event variability in flood response. For the 23 July 1997 and 27 July 1998 events, storm motion from the lower basin to the upper basin on a timescale of approximately 2 h served to amplify peak discharge at Archdale, relative to other modes of storm motion. The link between storm structure,

motion, and peak discharge is strongly dependent on the spatially varying response times described in observation 1 of this section.

6) Attenuating reaches play a major role in the regional flood hydrologic behavior of Sugar Creek. Attenuation results primarily from geologically controlled variations in longitudinal profile and valley bottom width (hydraulic modeling studies are being carried out to examine this issue in more detail). Flood-wave attenuation serves to diminish the effects of urbanization on downstream flood response.
7) The regional flood response of Sugar Creek reflects the major changes in response times associated with urbanization and suburbanization (observation 1), the scale-dependent space–time structure of rainfall forcing (observation 4), and the influence of attenuating reaches (observation 6).

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