Methods for Estimating Peak Discharges and Unit Hydrographs for Streams in the City of Charlotte and Mecklenburg County, North Carolina

By J. Curtis Weaver

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CHARLES G. GROAT, Director

Cover: Background photograph of Little Sugar Creek near Medical Center Drive in Charlotte, North Carolina, taken by Bob Hamilton, City of Charlotte Storm Water Services, on March 20, 2003. The hydrographs are based on discharge data collected at a downstream U.S. Geological Survey streamgaging station on Little Sugar Creek. The observed hydrograph (red line) depicts the streamflow response during a storm on July 27, 1998. The unit hydrograph (blue line) depicts the streamflow response to 1 inch of rainfall excess (overland runoff to streams) and was computed using discharge and rainfall data compiled at 15-minute intervals. Total rainfall for this storm was nearly 2.10 inches (darker blue bars), and the rainfall excess was nearly 1.10 inches (lighter blue bars).

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CONTENTS

FIGURES

TABLES

CONVERSION FACTORS, TEMPERATURE, VERTICAL AND HORIZONTAL DATUMS, AND ACRONYMS

Multiply	By	To obtain
	Length	
inch (in.)	25.4	millimeter (mm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
square mile (mi^2)	2.590	square kilometer (km^2)
	Flow	
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
cubic foot per second per square mile [(ft^3/s)/mi^2]	0.01093	cubic meter per second per square kilometer [(m^3/s)/km^2]
	Volume per time	
inch per year (in/yr)	2.54	centimeter per year (cm/yr)

Temperature: In this report, temperature is given in degrees Fahrenheit (°F), which can be converted to degrees Celsius (°C) by using the following equation:

$$°C = \frac{5}{9} \times (°F - 32)$$

Vertical coordinates: Vertical coordinates in this report are referenced to the North American Vertical Datum of 1988 (NAVD 88).

Horizontal coordinates: Unless otherwise specified, horizontal (latitude and longitude) coordinates in this report are referenced to the North American Datum of 1983 (NAD 83).

Acronyms:

GIS	geographic information system
NAD 27	North American Datum of 1927
NAD 83	North American Datum of 1983
NAVD 88	North American Vertical Datum of 1988
USGS	U.S. Geological Survey

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ABSTRACT

Procedures for estimating peak discharges and unit hydrographs were developed for streams in the city of Charlotte and Mecklenburg County in response to a need for better techniques for characterizing the flow of streams. The procedures presented in this report provide the means for estimating unit hydrographs as part of the process used in watershed modeling and(or) design of stormwater-management structures. The procedures include three statistical relations for use in estimating storm peak discharge, unit-hydrograph peak discharge, and unit-hydrograph lag time. A final component of the procedures is the development of a dimensionless unit hydrograph developed from streamflow and rainfall data collected during the 1995–2000 water years at 25 streamgaging stations and up to 60 raingages in the city and county.

The statistical relation to estimate the storm peak discharge is based on analyses of observed peak discharges regressed against rainfall and basin characteristics using a database of 412 observations from 61 storm events among the 25 gaging stations. The rainfall characteristics included basin-average rainfall amounts as well as estimates of the maximum and minimum storm rainfall in the basin. The basin characteristics consisted of land-use information and other physical basin characteristics, such as drainage area, channel length, channel slope, percentage of impervious area, and percentage of the basin served by detention. The analyses resulted in a relation that can be used for estimating storm peak discharge based on drainage area, basin-average rainfall, and impervious area.

Average unit hydrographs were developed for 24 of 25 streamgaging stations, using from three to nine storms at each site. The average unit hydrograph for each station was converted into four classes of unit hydrographs with durations corresponding to one-fourth, one-third, one-half, and three-fourths of the station-average lag time. For 23 sites, the lag-time-duration hydrographs were then translated into dimensionless unit hydrographs by dividing time ordinates by the lag time and discharge ordinates by peak discharge. For each lag-time-duration class, the dimensionless unit hydrographs for the sites were combined to create an average dimensionless unit hydrograph. The four average dimensionless unit hydrographs were later tested (with estimates of unit-hydrograph peak discharges and lag times) for selection of an overall dimensionless unit hydrograph to be used at ungaged sites in the study area. The two sites where the procedures did not produce unit hydrographs that could be included in the development of the overall dimensionless unit hydrograph had the smallest drainage areas among the sites used in the investigation.

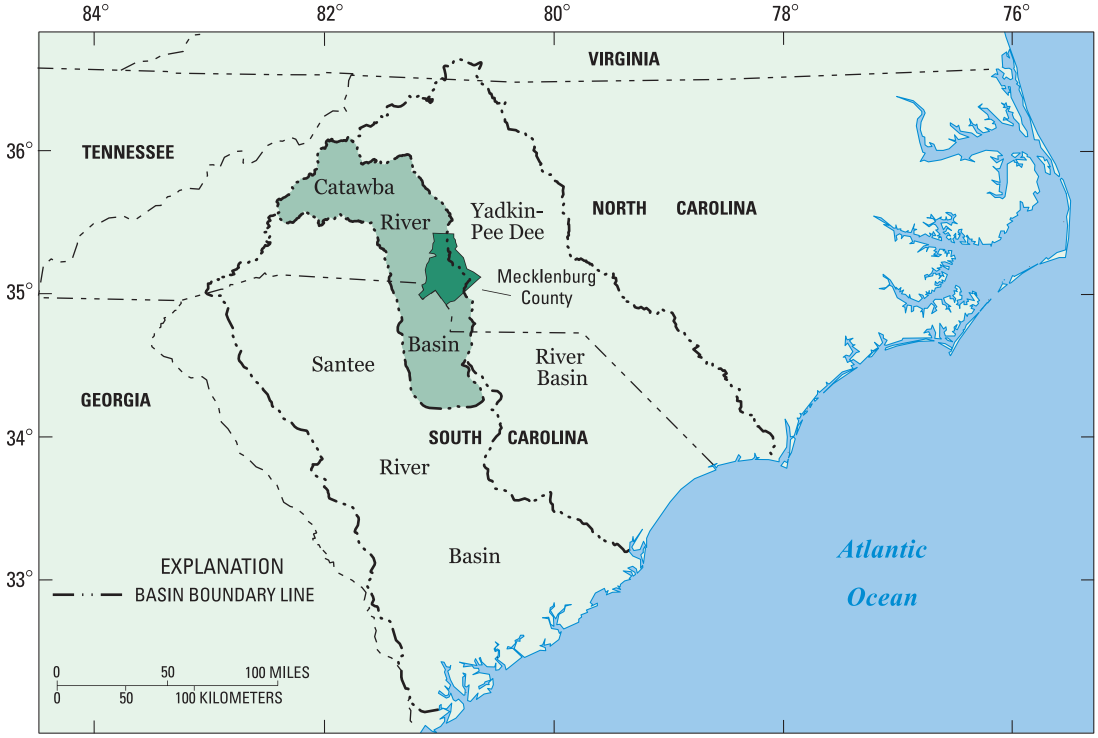
The statistical relations for estimating unit-hydrograph peak discharge and lag time were developed by regressing the dependent variables against explanatory variables that describe the basin characteristics. The statistical analyses resulted in a relation for use in estimating a unit-hydrograph peak discharge based on the drainage area. The estimation of the unit-hydrograph lag time is based on the drainage area and percentage of land use in the basin classified as “woods/brush.” Both relations have coefficients of determination (R^2 values) of 0.9 or better.

The three components for estimating a unit hydrograph are the dimensionless unit hydrograph and two statistical relations for estimating the unit-hydrograph peak discharge and lag time. These components were applied by using each of the four lag-time-duration average dimensionless unit hydrographs to determine which would be selected as the final overall dimensionless unit hydrograph for streams in the city of Charlotte and Mecklenburg County. Comparisons of the simulated and observed hydrographs were based on the following: (1) hydrograph width at 50 percent of the peak discharge, (2) hydrograph width at 75 percent of the peak discharge, (3) peak discharge, (4) time to peak discharge, and (5) volume of direct runoff beneath the hydrograph. Results of the testing indicated that the one-fourth lag-time-duration dimensionless unit hydrograph provides the best fit of data when compared with the observed hydrographs. Thus, it was selected as the final overall dimensionless unit hydrograph for the study area.

INTRODUCTION

The effects of population growth and development on runoff in the city of Charlotte and Mecklenburg County, North Carolina, have been the focus of water-resources data-collection and investigation programs conducted by the U.S. Geological Survey (USGS) since the early 1990’s. Most of the county is located in the Catawba River basin, which is part of the larger Santee River Basin that drains parts of North Carolina and South Carolina (fig. 1). The earliest records of streamflow collected in Mecklenburg County by the USGS date back to 1924, and a small number of other streamgaging stations located in the county have records dating back to 1962.

More recent USGS programs in Charlotte and Mecklenburg County have focused on the characterization of stormwater quality and quantity with the simultaneous collection of streamflow and water-quality data at network sites selected to provide a cross section of land uses throughout the county. The effects of development long have been recognized by local planning officials as increasing the probability of



Base from digital files of:
U.S. Department of Commerce, Bureau of Census,
1990 Precensus TIGER/Line Files-Political boundaries, 1991
U.S. Environmental Protection Agency, River File 3
U.S. Geological Survey, 1:100,000 scale

Figure 1. Locations of Mecklenburg County and the Catawba River basin of North and South Carolina.

flooding. However, the occurrence of widespread flooding in August 1995 and July 1997 that resulted in extensive property damage and loss of lives emphasized the need to more aggressively manage stormwater runoff, particularly during large precipitation events.

An understanding of the historical and estimated stormwater characteristics in a given area allows planning officials to have a better understanding of stream-specific flooding potentials and to better design more effective drainage structures as part of the overall infrastructure, minimizing property damage during flooding events. The increased understanding of stormwater characteristics thus allows for effective stormwater management and also permits emergency-response officials to better understand the nature of flooding during a given event, which in turn allows for the increased safety of the public. Efforts to better manage stormwater runoff can be divided into two general categories: (1) the expansion of a real-time raingage and streamflow-monitoring network to track storms and their effects on area streams, and (2) the development of a watershed modeling system to better aid in the delineation of flood-prone areas for future development conditions.

In water year[1] 2001, streamflow records were collected at 25 gaging stations in Charlotte and Mecklenburg County (Ragland and others, 2002). The USGS collected rainfall data at three locations in the county between 1988 and 1992. The network began to expand in late 1992 with 11 additional raingages to provide coverage for the lower two-thirds of the county. By the end of water year 2001, the network consisted of 67 raingages, which provided a comprehensive coverage of Mecklenburg County and the fringes of adjacent counties. The hydrologic network is equipped with communications systems that automatically transmit real-time data describing current streamflow conditions and provide early warning to local officials of flooding conditions.

The use of the Mecklenburg County watershed model (developed by Mecklenburg County) to simulate storm hydrographs requires (1) a user-defined rainfall amount (either observed or theoretical value) along with rainfall distribution over the duration of a storm, and (2) procedures for estimating the peak discharges and unit hydrographs. A unit hydrograph is defined as the direct runoff (total discharge minus base flow) resulting from 1 inch of "excess" rainfall (defined below) generated uniformly over the basin at a uniform rate during a specified period of time or duration. The shape of the unit hydrograph is a function of the basin characteristics. Unless the basin characteristics change, the unit hydrograph does not change in its shape. For a given unit hydrograph, two parameters are of primary interest to the hydrologist—the peak discharge and lag time. The lag time represents the time elapsed between the rainfall occurrence and the occurrence of peak discharge. More specifically, it is defined as the elapsed time (a constant for a basin) between the centroid of rainfall excess and centroid of the resultant runoff hydrograph (Stricker and Sauer, 1982).

To adequately account for stormwater characteristics specific to Mecklenburg County streams, there is a need for area-specific procedures to estimate peak discharges and unit hydrographs to maintain the credibility and reliability of the watershed model as a planning tool for city and county officials. Therefore, the USGS, in cooperation with the City of Charlotte and Mecklenburg County, conducted an investigation to develop techniques that can be used to estimate peak discharges and unit hydrographs for Mecklenburg County streams.

Purpose and Scope

The purpose of this report is to present techniques for estimating peak discharges and unit hydrographs for streams in the city of Charlotte and Mecklenburg County. Statistical (regression) relations were developed for estimating (1) peak discharge for a storm event based on rainfall and basin characteristics, (2) unit-hydrograph peak discharge based on basin characteristics, and (3) basin lag time for use in developing a unit hydrograph.

Streamflow data and basin characteristics at 25 sites across Mecklenburg County were combined with rainfall data from up to 61 storm events during the 1995–2000 water years to form the database used in developing the statistical relation to estimate a peak discharge for a given storm event. The study period was selected to represent streamflow conditions affected, in part, by the most current land-use patterns available in geographic information system (GIS) map coverages.

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[1] Water year is the 12-month period from October 1 through September 30 and is designated by the year in which the period ends.

Average unit hydrographs were developed for 24 of 25 streamgaging stations, which were converted into four classes of unit hydrographs with durations corresponding to one-fourth, one-third, one-half, and three-fourths of the station-average lag time. For 23 sites, the lag-time-duration hydrographs were then translated into dimensionless unit hydrographs by dividing time ordinates by lag time and discharge ordinates by peak discharge. For each lag-time-duration class, the dimensionless unit hydrographs for the sites were combined to create an average dimensionless unit hydrograph. The four average dimensionless unit hydrographs were then tested (with estimates of unit-hydrograph peak discharges and lag times) for selection of an overall dimensionless unit hydrograph to be used at ungaged sites in the study area. The two sites where the procedures did not produce unit hydrographs that could be included in the development of the overall dimensionless unit hydrograph had the smallest drainage areas among the sites used in the investigation.

Using estimated values of the unit-hydrograph peak discharge and lag time, the dimensionless unit hydrograph can be converted into a unit hydrograph for a given basin. Then, by using the discharge ordinates from a unit hydrograph multiplied by a time series of rainfall excess, the unit hydrograph can be converted into a simulated hydrograph, which can then be compared to an observed hydrograph for an actual storm event. Rainfall excess is that part of the rainfall that becomes direct overland runoff to the streams. Although this report does not present information or techniques regarding the computation of rainfall excess distribution, it does present an example application of the techniques and steps required to simulate a storm hydrograph using rainfall excess computed from observed rainfall record for an actual storm.

Previous Investigations

Other hydrologic investigations have been conducted by the USGS that addressed the quality and quantity of water resources in Mecklenburg County and its vicinity. During 1993–98, the USGS, in cooperation with the City of Charlotte and Mecklenburg County, collected and interpreted data from six to nine small urban basins in the city and county in an effort to characterize urban stormwater quantity and quality (Robinson and others, 1996, 1998; Sarver and others, 1999). Available data at nine sites during the 1993–98 studies were used to investigate the effects of land use on stormwater quality and to develop statistical relations for estimating constituent loads in Mecklenburg County streams (Bales and others, 1999). Streamflow data from six of the nine sites used in these previous studies also were used in this investigation to develop the techniques for estimating peak flows and unit hydrographs. Further investigation into the effects of land use on water quality and the transport rates of selected constituents during 1994–98 was conducted by Ferrell (2001).

During 1994–97, the USGS, in cooperation with the Charlotte-Mecklenburg Utility Department, collected water-quality data in Mountain Island Lake (Sarver and Steiner, 1998) and developed a water-quality model for the reservoir (Bales and others, 2001). Additionally, the Catawba River Basin is part of the larger Santee River Basin Study Unit (fig. 1) included in the USGS National Water-Quality Assessment (NAWQA) Program. As part of this program, water-quality data were collected synoptically and at fixed sites in the Catawba River Basin. These data are now part of a national database for assessing the patterns and trends of water quality in major river basins across the United States (Hughes, 1994; Maluk and Kelley, 1998; Maluk and others, 1998).

The USGS has conducted investigations related to the estimation of peak discharges, lag time, and(or) development of dimensionless unit hydrographs in North Carolina and other nearby states. Putnam (1972) related peak discharges (at varying recurrence intervals) to basin characteristics and discussed the development of the basin lag time for urban areas in the Piedmont of North Carolina. The methods presented by Putnam (1972) have been used by the City of Charlotte and Mecklenburg County as part of its planning for and management of stormwater (Charlotte Chamber Design Manual Task Force and others, 1993). Mason and Bales (1996) used data collected at 50 sites to develop techniques for determining a dimensionless unit hydrograph for small urban streams in North Carolina.

The USGS also has conducted similar unit-hydrograph studies in nearby states. Inman (1987) presented methods for simulating flood hydrographs for Georgia streams using data collected from 117 streamgaging stations (80 sites with drainage areas less than 20 square miles (mi^2) and 37 sites with drainage areas ranging from 20 to 500 mi^2). Inman

(2000) also presented relations for use in estimating lag time in urban Georgia streams. Bohman (1990, 1992) provided techniques for simulating flood hydrographs for rural basins and for determining peak-discharge frequency, runoff volumes, and flood hydrographs for urban basins in South Carolina. Dillow (1998) presented regional techniques for simulating peak-flow hydrographs using data collected at 81 streamgaging stations representing a range of drainage areas and basin conditions located throughout Maryland and Delaware.

Acknowledgments

The leadership and foresight in initiating and conducting this investigation are credited to Jim Schumacher, City of Charlotte, and Dave Canaan, Mecklenburg County. Additionally, significant contributions were made toward this investigation by numerous other Charlotte-Mecklenburg Storm Water Services employees, including Tony Dudley (city) and Bill Tingle (county). Numerous GIS map coverages used in the determination of land use and other basin characteristics were made available by Kurt Olmsted and other members of Mecklenburg County Land Records and Mapping Services.

Wendi S. Young, of the USGS Charlotte office, aided in this investigation by recoding the Fortran programs received for this investigation so that computations could be run on a UNIX operating system. Ms. Young also revised the input format for streamflow and rainfall data, simplifying the format for easier use in developing storm unit hydrographs.

Benjamin F. Pope, formerly of the USGS, was instrumental in the beginning phases of this investigation. In particular, Mr. Pope examined available streamflow and rainfall data to identify the 25 streamgaging stations and 61 storm events that formed the database for the statistical regression analysis used to determine storm peak discharge.

DESCRIPTION OF THE STUDY AREA

The city of Charlotte and Mecklenburg County, located in south-central North Carolina in the southern Piedmont physiographic province, encompass a combined area of about 567 mi^2. The county is bounded on the west by the Catawba River and its reservoirs—part of Lake Norman, Mountain Island Lake, and part of Lake Wylie (fig. 2). These lakes compose 21.9 mi^2 of the county area.

Charlotte is the principal municipality in Mecklenburg County and the largest city in North Carolina. The 2000 population for the incorporated areas of Charlotte was nearly 541,000, and the total population for the county was about 695,000 (U.S. Census Bureau, 2001). These recorded populations are higher by 36.6 and 36.0 percent, respectively, than corresponding 1990 population values.

The Catawba River drains approximately 75 percent of the county. The remaining 25 percent of the county is drained by the Rocky River and its tributaries (fig. 2) in the Yadkin-Pee Dee River basin (figs. 1, 2). The city area is about 237 mi^2 (or 43.5 percent) of the county's nearly 545-mi^2 land area. Most of the metropolitan area (in the southern two-thirds of the county) is drained by four large creeks—Irwin, Little Sugar, Briar, and McAlpine Creeks.

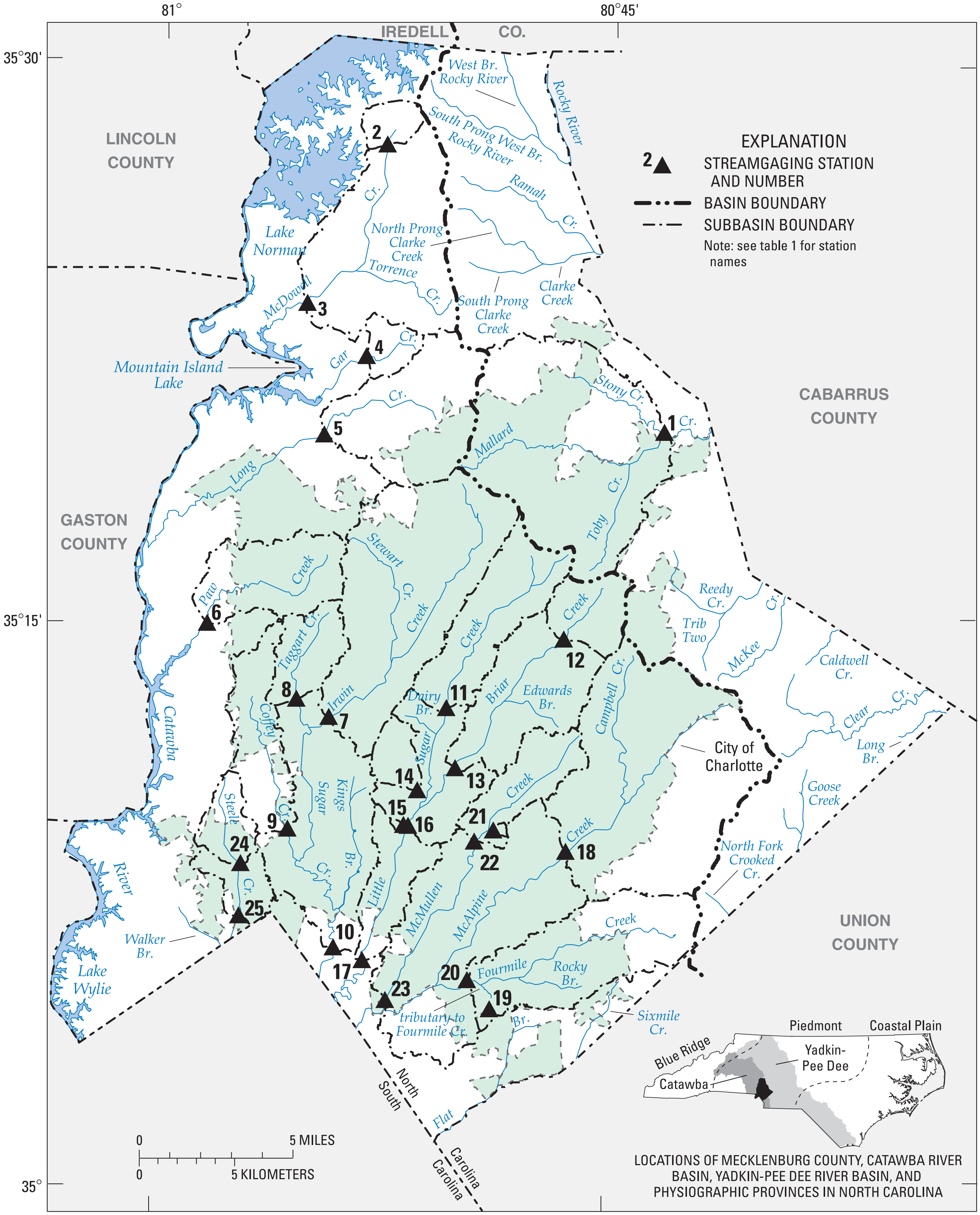
Setting and Climate

The topography of Mecklenburg County is characterized by broad, gently rolling interstream areas and by steep slopes along the drainage ways. The elevation of the county ranges from 520 feet (ft) at the State line south of Pineville, N.C., to about 830 ft in the extreme northern portion of the county (McCachren, 1980). The area is predominately underlain by granite with some slate in the southeast (LeGrand and Mundorff, 1952). The soils in the county are described as well-drained sandy loams with a clayey subsoil.

The climate of the county is characterized by hot, humid summers and short, mild winters with periods of more moderate conditions during the spring and autumn seasons. The monthly mean temperature ranges from about 40 degrees Fahrenheit (° F) in January to about 79 ° F in July (National Oceanic and Atmospheric Administration, 2000). In all areas of the county, daily maximum temperatures in the summer reach levels exceeding 90 ° F for long periods of consecutive days. Precipitation in Mecklenburg County averages about 43 inches per year (in/yr).

Data-Collection Sites

Streamflow and rainfall data used in the analyses were collected from an extensive network of streamgaging stations and raingages located



Base from digital files of:
U.S. Department of Commerce, Bureau of Census,
1990 Precensus TIGER/Line Files-Political boundaries, 1991
U.S. Environmental Protection Agency, River File 3
U.S. Geological Survey, 1:100,000 scale

Figure 2. Locations of major streams, the streamgaging network, and the extent of study basins in Charlotte and Mecklenburg County.

throughout the city of Charlotte and Mecklenburg County. Twenty-five gaging stations with drainage areas ranging from about 0.12 mi^2 to 92.4 mi^2 were selected for this study (fig. 2; table 1). Although the periods of record varied among the streamflow sites, discharge data used in the analyses generally were selected from storms during the 1995–2000 water years. On Irwin Creek (site 7, fig. 2) and Little Sugar Creek (site 11) near the central part of the city where a sufficient number of raingages were in operation prior to the 1995 water year, discharge data for a few selected storms during the 1993–94 water years were included in the unit-hydrograph analyses. The cumulative drainage areas for the selected streamgaging stations is 304 mi^2, or approximately 54 percent of the county (fig. 2). Of the 25 sites, Mallard Creek (site 1) is the only stream that drains to the Yadkin-Pee Dee River by way of the Rocky River (fig. 2). The remaining 24 stream sites are located in the Catawba River basin.

Near the beginning of the 1993 water year, the raingage network consisted of 14 data-collection sites providing coverage predominantly across the southern two-thirds of the county (fig. 3; table 2). By the end of the study period (2000 water year), a network of 60 precipitation data-collection sites throughout Mecklenburg County and in the fringes of adjacent counties provided coverage for the entire county. Although the size of the network varied during the study period, over 25 data-collection sites provided coverage of most of the county by the end of the 1994 water year. Rainfall data collected at these sites during the period of study were used in the analyses to develop a statistical relation to estimate the peak discharge for a given storm and to develop unit hydrographs for selected storm events. Further information on the raingage network is provided by Hazell and Bales (1997).

Basin Characteristics

Selected basin characteristics were compiled for use as explanatory variables in developing statistical relations to estimate peak discharges (for a storm event and the unit hydrograph) and the basin lag time. The basin characteristics used in this investigation are divided into two general categories—land-use information and physical characteristics of the basin.

Land Use

Land-use information used in this investigation indicates that the 25 streams drain basins of varying land-use characteristics; however, land use in all basins has been affected by varying degrees of growth and development. The information is based on data initially obtained from 1990 aerial photography and updated in 1998 by using building-permit data (Mecklenburg County Land Records and Mapping Services, 1998). The data are categorized into 12 land-use classifications (fig. 4).

The effect of having no basins in the study that were classified as rural (as might be expected in a more regional or statewide study) resulted in varying percentages of classifications that are practically unique for each basin. In other words, based on the 12 land-use classifications, there did not appear to be a dominant land use in most of the basins. It was considered useful, therefore, to combine some of the classifications in these urban basins (1) to aid in developing summary description (residential) for use in characterizing land use (table 3) and (2) to reduce the number of variables (residential, commercial, and industrial) for use in developing the statistical relations (see **Methods for Estimating Peak Discharges**).

The summary description was developed by using the two highest land-use percentages in each basin (table 3). If two or less land-use classifications compose more than 75 percent of the basin area, the summary description specifies the classification(s). Otherwise, the summary description identifies the basin land use as “mixed” (defined in this report as having three or more classifications that cumulatively compose more than 75 percent of the basin area). None of the basins have land use in one classification that composes more than 75 percent of the basin area. The 19 basins that have mixed land use (table 3) are predominately in the southern two-thirds of the county. A mixed land-use basin typically has a moderate-sized or larger drainage area in which many different land uses occur in the basin. Of the six basins having 75 percent or more land use in just two classifications, four basins (sites 4, 14, 15, and 19, table 3) have drainage areas that are among the smallest of the study sites.

For the summary description, land use in the basins with two classifications cumulatively occupying more than 75 percent of the basin generally were woods/brush and medium- or low-density residential classification (sites 3, 4, 9, and 19, table 3). These

Table 1. Summary of streamgaging stations and characteristics for study sites in the City of Charlotte and Mecklenburg County, North Carolina

[USGS, U.S. Geological Survey; mi^2, square mile; NC, North Carolina (highway). Period of record indicates available record of daily value discharges for sites as of September 2000. Data used in the study were collected during the 1995–2000 water years (except for sites 7 and 11 for which data were included for some storms in the 1993–94 water years). Unless otherwise specified, latitude and longitude are referenced to the North American Datum of 1983]

Site no. (fig. 2)	USGS downstream order number[a]	Station name	Latitude	Longitude	Drainage area (mi^2)	Tributary to	Period of record
1	02124149	Mallard Creek below Stony Creek near Harrisburg	35° 19'58"	80° 42'57"	34.6	Rocky River	Dec 1994 – Sept 2000
2	02142651	McDowell Creek at Westmoreland Road near Cornelius[b,c,d]	35° 27'49"	80° 52'36"	2.35	Catawba River	May 1994 – Sept 1997
3	02142660	McDowell Creek near Charlotte[e,f]	35° 23'23"	80° 55'16"	26.3	Catawba River	Nov 1996 – Sept 2000
4	0214266075	Gar Creek at McCoy Road near Oakdale[b,d,g]	35° 21'55"	80° 53'12"	2.67	Catawba River	Apr 1994 – Sept 1997
5	02142900	Long Creek near Paw Creek	35° 1943"	80° 54'35"	16.4	Catawba River	June 1965 – Sept 2000
6	02142956	Paw Creek at Wilkinson Boulevard near Charlotte	35° 14'25"	80° 58'28"	10.8	Catawba River	Oct 1994 – Sept 2000
7	02146300	Irwin Creek near Charlotte	35° 11'52"	80° 54'16"	30.7	Sugar Creek	May 1962 – Sept 2000
8	02146315	Taggart Creek at West Boulevard near Charlotte[h]	35° 12'24"	80° 55'19"	5.38	Sugar Creek	Jul 1998 – Sept 2000
9	02146348	Coffey Creek near Charlotte	35° 08'45"	80° 55'37"	9.14	Sugar Creek	Oct 1998 – Sept 2000
10	02146381	Sugar Creek at NC 51 near Pineville	35° 05'27"	80° 53'58"	65.3	Catawba River	Oct 1994 – Sept 2000
11	02146409	Little Sugar Creek at Medical Center Drive at Charlotte	35° 12'13"	80° 50'13"	11.8	Sugar Creek	Oct 1994 – Sept 2000
12	0214642825	Briar Creek near Charlotte	35° 14'10"	80° 46'16"	5.2	Little Sugar Creek	Apr 1998 – Sept 2000
13	0214645022	Briar Creek above Colony Road at Charlotte	35° 10'31"	80° 4951"	19.0	Little Sugar Creek	Dec 1995 – Sept 2000
14	02146470	Little Hope Creek at Seneca Place at Charlotte	35° 0952"	80° 51'11"	2.63	Little Sugar Creek	Dec 1982 – Sept 1990, Oct 1994 – Sept 2000
15	0214650690	Little Sugar Creek tributary above Archdale Drive near Charlotte[b,d,i]	35° 08'54"	80° 51'40"	0.12	Little Sugar Creek	Dec 1993 – Sept 1998
16	02146507	Little Sugar Creek at Archdale Drive at Charlotte	35° 08'53"	80° 51'28"	42.6	Sugar Creek	Jan 1978 – Sept 2000
17	02146530	Little Sugar Creek at Highway 51 at Pineville	35° 05'07"	80° 52'56"	49.2	Sugar Creek	June 1997 – Sept 2000
18	02146600	McAlpine Creek at Sardis Road near Charlotte	35° 08'16"	80° 46'03"	39.6	Sugar Creek	Apr 1962 – Sept 2000
19	0214666925	Fourmile Creek tributary near Providence[b,d,j]	35° 03'48"	80° 48'36"	0.27	Fourmile Creek	June 1994 – Sept 1998
20	02146670	Fourmile Creek near Pineville[k]	35° 04'37"	80° 4921"	17.8	McAlpine Creek	Jul 1997 – Sept 2000
21	0214669980	McMullen Creek tributary near Charlotte[b,d,l]	35° 08'47"	80° 48'34"	0.13	McMullen Creek	Dec 1993 – Sept 1998
22	02146700	McMullen Creek at Sharon View Road near Charlotte	35° 08'27"	80° 4912"	6.95	McAlpine Creek	Apr 1962 – Sept 2000
23	02146750	McAlpine Creek below McMullen Creek near Pineville	35° 04'00"	80° 52'12"	92.4	Sugar Creek	Apr 1974 – Sept 2000
24	0214677974	Steele Creek above State Road 1344 near Shopton[b]	35° 07'45"	80° 57'12"	3.57	Sugar Creek	Oct 1990 – Sept 1998
25	0214678175	Steele Creek at State Road 1441 near Pineville	35° 06'18"	80° 57'13"	6.73	Sugar Creek	May 1998 – Sept 2000

[a] The downstream order number (station number) is assigned by the U.S. Geological Survey and is based on a system of sequential numbers that increase in the downstream direction.

[b] Latitude and longitude for this site reported to North American Datum of 1927.

[c] Site CSW09, operated as part of previous water-quality investigation for sites in Mecklenburg County.

[d] See Robinson and others (1996, 1998), Bales and others (1999), and Sarver and others (1999) for water-quality data and other investigative results for this site.

[e] Site CSW10, operated as part of previous water-quality investigation for sites in Mecklenburg County.

[f] See Robinson and others (1998), Bales and others (1999), and Sarver and others (1999) for water-quality data and other investigative results for this site.

[g] Site CSW08, operated as part of previous water-quality investigation for sites in Mecklenburg County.

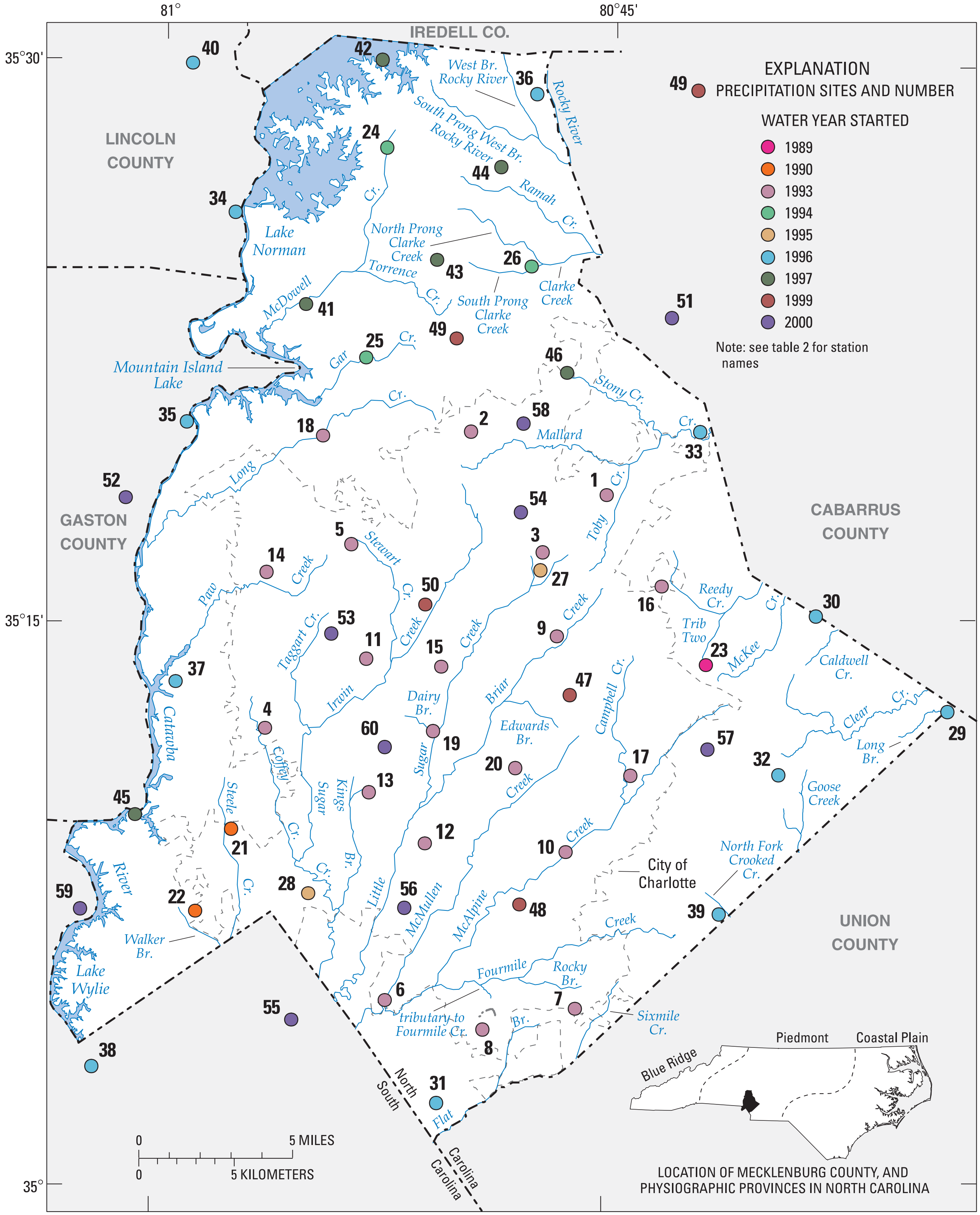
[h] Site number erroneously published as 02146308 in 1999 USGS annual data report.

[i] Site CSW02, operated as part of previous water-quality investigation for sites in Mecklenburg County. Drainage area previously published as 0.123 mi^2 (see references in footnote d above).

[j] Site CSW07, operated as part of previous water-quality investigation for sites in Mecklenburg County. Drainage area previously published as 0.266 mi^2 (see references in footnote d above).

[k] Site name previously published as “Four Mile Creek near Pineville” in 1998–2000 USGS annual data reports.

[l] Site CSW04, operated as part of previous water-quality investigation for sites in Mecklenburg County. Drainage area previously published as 0.126 mi^2 (see references in footnote d above).



Base from digital files of:
U.S. Department of Commerce, Bureau of Census,
1990 Precensus TIGER/Line Files-Political boundaries, 1991
U.S. Environmental Protection Agency, River File 3
U.S. Geological Survey, 1:100,000 scale

Figure 3. Raingage network sites in Mecklenburg County, North Carolina, October 1988 through September 2000.

Table 2. Raingage network sites in Mecklenburg County, North Carolina, October 1988 through September 2000

[WWTP, wastewater-treatment plant]

Site no. (fig. 3)	Station no.[a]	Latitude	Longitude	Location[b]	Drainage basin	Period of record[c]
1	351812080445545	35°18'12"	80°44'55"	CRN01, Fire Station 27, 111 Ken Hoffman Drive	Mallard Creek	10/92–9/00
2	351954080493445	35°19'54"	80°49'34"	CRN02, Fire Station 28, 8013 Old Statesville Road	Long Creek	10/92–9/00
3	0214620760	35°16'32"	80°47'05"	CRN03, Irwin Ceek at Starita Road at Charlotte	Irwin Creek	10/92–9/00
4	351132080562345	35°11'32"	80°56'23"	CRN04, Fire Station 30, 4707 Belle Oaks Road	Sugar Creek	10/92–9/00
5	351642080533445	35°16'42"	80°53'34"	CRN05, CMUD Admin. Bldg., 5100 Brookshire Boulevard	Irwin Creek	10/92–9/00
6	02146750	35°03'59"	80°52'12"	CRN06, McAlpine Creek below McMullen Creek near Pineville	McAlpine Creek	5/93–9/00
7	350351080454145	35°03'51"	80°45'41"	CRN07, Fire Station 9, 4529 McKee Road	Six Mile Creek	10/92–9/00
8	350314080484945	35°03'14"	80°48'49"	CRN08, St. Matthews Church, 11515 Elm Lane[d]	Four Mile Creek	10/92–9/00
9	351414080463245	35°14'14"	80°46'32"	CRN09, Fire Station 15, 3617 Frontenac Avenue	Briar Creek	11/92–9/00
10	02146600	35°08'14"	80°46'05"	CRN10, McAlpine Creek at Sardis Road near Charlotte	McAlpine Creek	11/92–9/00
11	351331080525945	35°13'31"	80°52'59"	CRN11, Fire Station 10, 2135 Remount Road	Irwin Creek	11/92–9/00
12	350823080505345	35°08'23"	80°50'53"	CRN12, Fire Station 16, 6623 Park South Drive	Little Sugar Creek	3/93–9/00
13	350947080524945	35°09'47"	80°52'49"	CRN13, U.S. Geological Survey, 810 Tyvola Road	Sugar Creek	5/93–9/00
14	351553080562645	35°15'53"	80°56'26"	CRN14, Fire Station 21, 1023 Little Rock Road	Paw Creek	3/93–9/00
15	351320080502645	35°13'20"	80°50'26"	CRN15, Charlotte-Meckleburg Government Center, 600 E. Fourth Street	Little Sugar Creek	3/93–9/00
16	351540080430045	35°15'40"	80°43'00"	CRN16, Reedy Creek Park Environmental Center, 2900 Rocky River Road	Reedy River	3/93–9/00
17	351023080435745	35°10'23"	80°43'57"	CRN17, Piney Grove Elementary School, 8801 Eaglewind Drive	McAlpine Creek	3/93–9/00
18	02142900	35°19'42"	80°54'35"	CRN18, Long Creek near Paw Creek	Long Creek	3/93–9/00
19	351132080504145	35°11'32"	80°50'41"	CRN19, Freedom Park, Cumberland Drive	Little Sugar Creek	9/93–9/00
20	351032080475245	35°10'32"	80°47'52"	CRN20, Fire Station 14, 114 N. Sharon Amity Road	McMullen Creek	9/93–9/00
21	350842080572801	35°08'42"	80°57'28"	CRN21, Kennedy Jr. High, 4000 Gallant Lane	Steele Creek	9/90–9/00
22	350623080583801	35°06'41"	80°58'20"	CRN22, Walker Branch Basin, Choate Circle	Steele Creek	9/90–9/00
23	351302080412701	35°13'02"	80°41'27"	CRN23, Harrisburg Road Landfill, 7817 Harrisburg Road	Reedy River	10/88–9/00
24	02142651	35°27'49"	80°52'36"	CRN24, McDowell Creek at Westmoreland Road near Cornelius	McDowell Creek	5/94–9/00
25	0214266075	35°21'55"	80°53'12"	CRN25, Gar Creek at SR2120 (McCoy Road) near Oakdale	Gar Creek	4/94–9/00
26	352432080473745	35°24'32"	80°47'37"	CRN26, Bradford Airfield, Huntersville-Concord Road	Clarke Creek	6/94–9/00
27	351604080470845	35°16'04"	80°47'08"	CRN27, Hidden Valley Elem. School, 5100 Snow White Lane	Little Sugar Creek	10/94–9/00
28	0214635212	35°06'57"	80°54'49"	CRN28, Unnamed tributary to Sugar Creek at Crompton Street	Sugar Creek	4/95–9/00
29	351218080331345	35°12'18"	80°33'13"	CRN29, Clear Creek Boy Scout Camp, 9408 Belt Road	Clear River	2/96–9/00
30	351455080374445	35°14'55"	80°37'44"	CRN30, Rhyne Farm, 3600 Peach Orchard Road	McKee Creek	2/96–9/00
31	350110080502045	35°01'10"	80°50'20"	CRN31, Elon Homes, 11401 Ardrey-Kell Road	Six Mile Creek	2/96–9/00
32	351028080385545	35°10'28"	80°38'55"	CRN32, Bain Elementary School, 11524 Bain School Road	Goose Creek	2/96–9/00
33	352000080414645	35°20'00"	80°41'46"	CRN33, Mallard Creek WWTP, 12400 Hwy. 29 North	Mallard Creek	12/95–9/00

Table 2. Raingage network sites in Mecklenburg County, North Carolina, October 1988 through September 2000—Continued

[WWTP, wastewater-treatment plant]

Site no. (fig. 3)	Station no.[a]	Latitude	Longitude	Location[b]	Drainage basin	Period of record[c]
34	352555080574445	35°25'55"	80°57'44"	CRN34, Cowans Ford Dam, 257 Duke Lane	Catawba River	2/96–9/00
35	0214267600	35°20'03"	80°59'12"	CRN35, Catawba River at Mountain Island Dam	Catawba River	1/96–9/00
36	352921080473245	35°29'21"	80°47'32"	CRN36, West Fork substation, 20801 Shearer Road	Rocky River	2/96–9/00
37	351247080592745	35°12'47"	80°59'27"	CRN37, Berryhill Elementary School, 10501 Walkers Ferry Road	Catawba River	2/96–9/00
38	350200081020345	35°02'00"	81°02'03"	CRN38, Tega Cay Town Hall, 7000 Tega Cay Drive	Lake Wylie	2/96–9/00
39	350634080405245	35°06'34"	80°40'52"	CRN39, Phillips Farm, 2248 Mount Harmony Church Road	Crooked Creek	2/96–9/00
40	353003080591745	35°30'03"	80°59'17"	CRN40, Westport Golf Course[e]	Lake Norman	2/96–9/00
41	0214266000	35°23'22"	80°55'16"	CRN41, McDowell Creek near Charlotte	McDowell Creek	11/96–9/00
42	353014080524945	35°30'14"	80°52'49"	CRN42, Norman Shores development[f]	Lake Norman	1/97–9/00
43	352440080505045	35°24'40"	80°50'50"	CRN43, Huntersville Elementary School, 200 Gilead Road	McDowell Creek	1/97–9/00
44	352718080484345	35°27'18"	80°48'43"	CRN44, Knox Farm, 13516 Mayes Road	Clarke Creek	1/97–9/00
45	350903081004545	35°09'03"	81°00'45"	CRN45, 12700 Withers Cove Road	Catawba River	1/97–9/00
46	352135080462045	35°21'35"	80°46'20"	CRN46, Oehler Farm, 3491 Johnston-Oehler Road	Mallard Creek	1/97–9/00
47	351229080460245	35°12'29"	80°46'02"	CRN47, Winterfield Elementary School, Winterfield Place	Briar Creek	3/99–9/00
48	350637080475645	35°06'37"	80°47'56"	CRN48, Olde Providence Elementary School, Rea Road	McAlpine Creek	3/99–9/00
49	352224080500345	35°22'24"	80°50'03"	CRN49, North Mecklenburg High School, Old Statesville Road	Long Creek	4/99–9/00
50	351502080512045	35°15'02"	80°51'20"	CRN50, Vest Treatment Plant[g]	Irwin Creek	3/99–9/00
51	352310080424845	35°23'10"	80°42'48"	CRN51, Concord Regional Airport, Aviation Boulevard	Rocky River	6/00–9/00
52	351753081011745	35°17'53"	81°01'17"	CRN52, Ida Rankin Elementary School, Central Avenue	Catawba River	5/00–9/00
53	351412080541245	35°14'12"	80°54'12"	CRN53, Harding University High School, Alleghany Street	Sugar Creek	5/00–9/00
54	351741080475045	35°17'43"	80°47'46"	CRN54, Derita Elementary School, West Sugar Creek Road	Mallard Creek	5/00–9/00
55	350324080551845	35°03'24"	80°55'18"	CRN55, Hammond Farm, Fort Mill	Sugar Creek	6/00–9/00
56	350635080513245	35°06'35"	80°51'32"	CRN56, South Mecklenburg High School, Park Road	Little Sugar Creek	5/00–9/00
57	351109080412145	35°11'09"	80°41'21"	CRN57, Lebanon Road. Elementary School, Lebanon Road	McAlpine Creek	4/00–9/00
58	352006080462845	35°20'06"	80°46'28"	CRN58, Highland Elementary School, Clemson Avenue[h]	Mallard Creek	6/00–9/00
59	350624081023345	35°06'24"	81°02'33"	CRN59, YMCA Camp Thunderbird, Lake Wylie	Catawba River	6/00–9/00
60	351104080521845	35°11'04"	80°52'18"	CRN60, Collinswood Elementary School, Applegate Road	Little Sugar Creek	4/00–9/00

[a] Station number is assigned by the U.S. Geological Survey and is based on geographic location. The "downstream order number" system is used for sites paired with a streamflow site, and the "latitude-longitude" system is used for stand-alone sites.

[b] The “CRN##” designation listed as part of the location is a site reference for the raingage established in previous investigations. See Robinson and others (1996, 1998), Bales and others (1999), and Sarver and others (1999) for further information on the raingage network.

[c] Precipitation data collection is ongoing at date of publication.

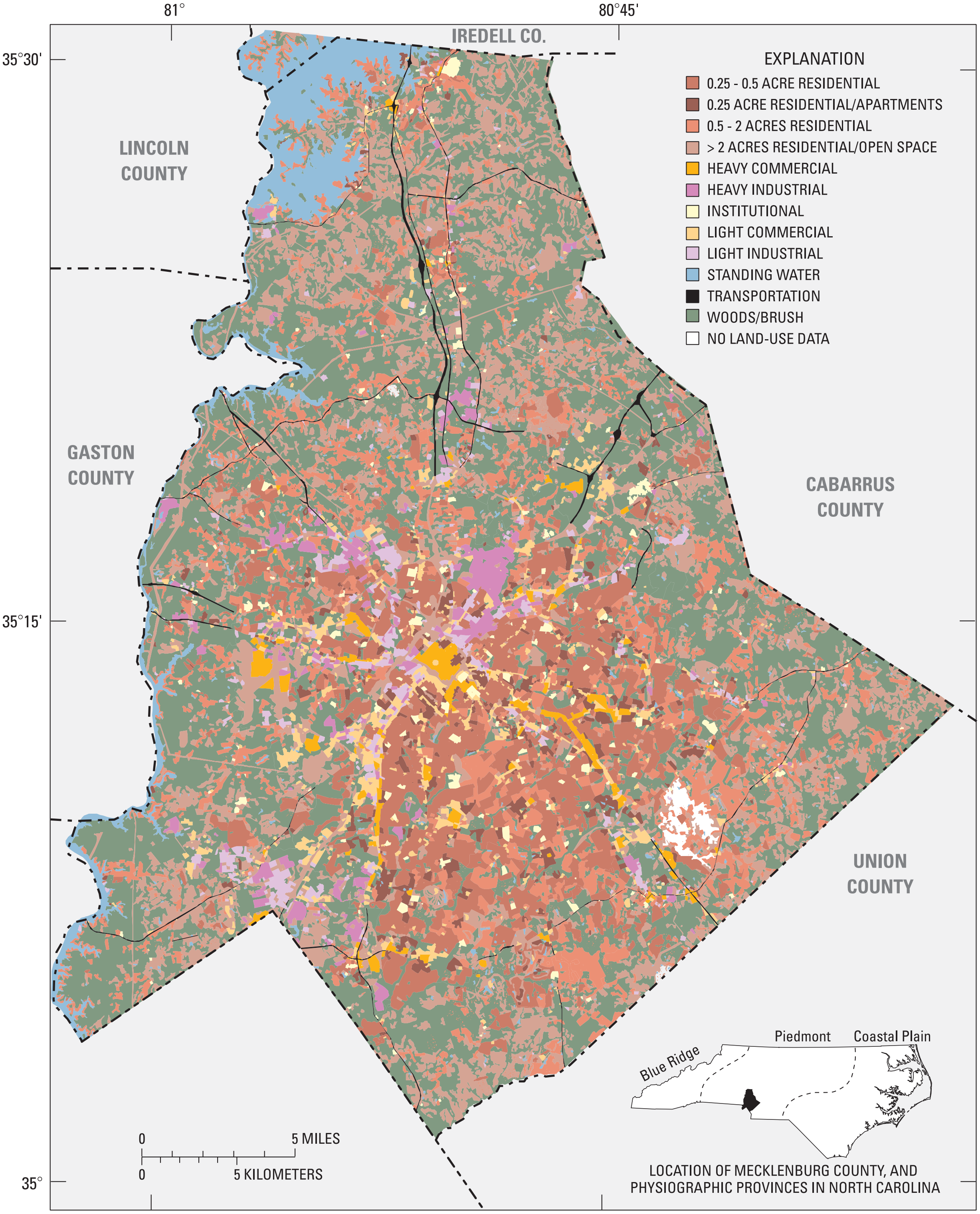
[d] Site was relocated from McAlpine Creek Elementary School (9100 Carswell Lane) in August 1994, station number 350458080493245. Previous location references also identify site as being at Tipton Rest Home.

[e] Site was relocated from Lake Norman Volunteer Fire Department (1206 Brawley School Road) in June 1996, station number 353402080543145.

[f] Previous location references also identify this site as being at Horton pool house, 21509 Norman Shores Drive.

[g] Site was relocated from Oaklawn Elementary School (Oaklawn School of Math and Science) in October 2002, station number 351503080510145.

[h] Site was relocated from Highland Elementary School (Clemson Avenue) in August 2002, station number 351441080481545.



Base from digital files of:
U.S. Department of Commerce, Bureau of Census,
1990 Precensus TIGER/Line Files-Political boundaries, 1991
Land use map from Mecklenburg County Land Records and Mapping Services (1998)
U.S. Geological Survey, 1:100,000 scale

Figure 4. Land use in Charlotte and Mecklenburg County, North Carolina.

Table 3. Land-use data for study basins in Mecklenburg County, North Carolina, 1998

[mi^2, square mile; —, minimal or no land use in this category within the basin]

Site no. (figs. 2, 4)	USGS downstream order number	Drainage area (mi^2)	Percentage of basin having indicated land use												Summary description of land use[a]
				Residential (lot size)					Industrial		Commercial				
			Woods/ brush	Greater than 2 acres	Greater than 0.5 to 2 acres	Greater than 0.25 to 0.5 acre	Less than or equal to 0.25 acre	Institu- tional	Light[b]	Heavy[c]	Light[b]	Heavy[c]	Stand- ing water	Trans- por- tation	
1	02124149	34.6	50.7	24.1	10.4	5.0	1.6	1.2	1.0	0.3	2.7	0.9	0.5	1.6	**Mixed:** Forested, medium- and low-density residential with some light commercial uses.
2	02142651	2.35	39.6	22.5	13.7	8.9	0.4	1.0	0.6	0.4	6.9	1.5	0.1	4.4	**Mixed:** Forested, medium- and low-density residential with some commercial and transportation uses.
3	02142660	26.3	42.2	35.7	9.4	4.4	0.3	0.7	0.8	0.6	1.8	0.3	0.3	3.5	**Forested and low-density residential:** with medium-density residential and some transporation, light commercial uses.
4	0214266075	2.67	56.4	29.5	10.8	2.3	—	0.6	—	—	—	—	0.4	—	**Forested and low-density residential:** with medium-density residential use.
5	02142900	16.4	46.5	20.9	14.7	1.8	0.6	0.8	3.0	4.3	1.6	0.4	0.7	4.7	**Mixed:** Forested, medium- and low-density residential with some industrial, transportation, and light commercial uses.
6	02142956	10.8	38.7	8.1	18.2	21.1	1.7	2.1	3.7	4.6	0.7	0.2	0.5	0.6	**Mixed:** Forested and medium-density residential with some low-density residential, institutional, and industrial uses.
7	02146300	30.7	23.0	15.3	9.4	21.0	3.6	1.8	7.8	8.5	6.3	2.8	0.6	0.0	**Mixed:** Forested, medium- and low-density residential with industrial and some commercial uses.
8	02146315	5.38	25.7	18.7	10.9	13.4	5.1	1.4	3.2	7.4	10.5	3.7	—	—	**Mixed:** Forested, medium- and low-density residential, and light commercial with industrial and some high-density residential uses.
9	02146348	9.14	47.7	27.4	9.1	2.5	0.4	0.0	1.7	1.3	2.2	6.7	0.9	0.1	**Forested and low-density residential:** with medium-density residential and some industrial and commercial uses.
10	02146381	65.3	32.1	18.5	7.6	14.2	2.9	1.0	6.1	6.6	7.2	3.2	0.5	0.1	**Mixed:** Forested, medium- and low-density residential with industrial and commercial uses.
11	02146409	11.8	6.8	7.9	8.0	24.3	7.6	2.4	7.8	16.2	10.3	8.7	—	—	**Mixed:** Varying density residential with industrial and commercial uses.
12	0214642825	5.2	15.6	7.3	7.6	51.7	6.0	1.6	2.7	0.8	4.4	1.9	0.3	0.1	**Mixed:** Varying but primarily medium-density residential, forested with some light industrial and commercial uses.
13	0214645022	19.0	12.2	6.4	11.7	46.9	7.7	2.5	1.4	0.4	7.1	3.5	0.2	0.0	**Mixed:** Varying but primarily medium-density residential, forested with commercial and some institutional uses.

Table 3. Land-use data for study basins in Mecklenburg County, North Carolina, 1998—Continued

[mi², square mile; —, minimal or no land use in this category within the basin]

Site no. (figs. 2, 4)	USGS downstream order number	Drainage area (mi^2)	Percentage of basin having indicated land use												Summary description of land use[a]
				Residential (lot size)					Industrial		Commercial				
			Woods/ brush	Greater than 2 acres	Greater than 0.5 to 2 acres	Greater than 0.25 to 0.5 acre	Less than or equal to 0.25 acre	Institu-tional	Light[b]	Heavy[c]	Light[b]	Heavy[c]	Stand-ing water	Trans-por-tation	
14	02146470	2.63	1.3	2.4	0.7	67.7	9.6	2.1	2.7	1.7	8.8	2.9	—	—	**Medium- and high- density residential:** with forested, light commercial, and some institutional and industrial uses.
15	0214650690	0.123	2.0	—	—	59.2	—	7.0	—	21.7	10.1	—	—	—	**Medium-density residential/heavy industrial:** with light commercial and institutional uses.
16	02146507	42.6	9.2	6.1	9.6	42.2	7.6	2.9	3.2	5.2	8.7	5.2	0.2	0.0	**Mixed:** Varying density residential, forested, commercial, and some industrial and institutional uses.
17	02146530	49.2	10.1	6.8	8.7	42.2	8.3	2.8	2.8	4.7	8.3	5.0	0.2	0.1	**Mixed:** Varying density residential, forested, commercial, and some industrial and institutional uses.
18	02146600	39.6	27.9	10.2	19.9	24.9	6.0	1.0	1.6	0.8	3.9	2.9	0.7	0.3	**Mixed:** Forested, medium- and low-density residential with some high-density residential and commercial uses.
19	0214666925	0.266	58.4	6.9	6.4	17.7	—	3.2	—	—	7.4	—	—	—	**Forested and medium-density residential:** with low-density residential and some light commercial and institutional uses.
20	02146670	17.8	39.2	15.2	20.8	17.5	1.4	0.7	0.4	0.4	1.2	1.4	1.2	0.7	**Mixed:** Forested, medium- and low-density residential with some commercial uses.
21	0214669980	0.126	—	—	9.4	17.5	27.3	43.2	—	—	2.6	—	—	—	**Mixed:** Institutional, high- and medium-density residential with some light commercial use.
22	02146700	6.95	11.2	4.6	17.0	44.7	9.7	4.0	1.3	0.1	4.9	2.4	0.1	—	**Mixed:** High- and medium-density residential, forested with some low-density residential, institutional, and commercial uses.
23	02146750	92.4	29.5	11.1	18.7	27.0	5.3	1.2	0.8	0.5	2.9	1.9	0.7	0.3	**Mixed:** Forested, medium- and low-density residential with some high-density residential and commercial uses.
24	0214677974	3.57	36.2	24.3	6.4	19.6	0.2	2.7	8.2	1.4	0.7	—	0.2	—	**Mixed:** Forested, medium- and low-density residential with some industrial and institutional uses.
25	0214678175	6.73	36.5	23.3	4.4	10.1	1.1	1.4	10.9	7.4	3.0	1.4	0.3	0.2	**Mixed:** Forested, medium- and low-density residential, industrial uses with some commercial uses.

[a] Within this table, use of the term “Mixed” to summarize the land use in a basin refers to three or more classifications occurring on more than 75 percent of the basin. Where two or less classifications occur in more than 75 percent of the basin, the summary description specifies the classification(s). None of the basins had land use characterized by one classification covering more than 75 percent of the basin. Additionally, for the purposes of the summary description, the land-use classifications “greater than 0.5 to 2 acres” and “greater than 0.25 to 0.5 acre” are termed medium-density residential. The classifications “greater than 2 acres” and “less than or equal to 0.25 acre” are termed low-density and high-density residential, respectively. See text in ***Land Use*** section for further discussion.

[b] Light is defined as less than 44 percent impervious (table 3 in Sarver and others, 1999).

[c] Heavy is defined as greater than 56 percent impervious (table 3 in Sarver and others, 1999).

basins are located in the northern, western, and southeastern parts of the county. Two other basins with two classifications composing 75 percent or more land use (sites 14 and 15) are located in the central metropolitan area. The land-use classifications in these basins are high- and(or) medium-density residential and heavy industrial uses (table 3).

While most of the basins have mixed land-use patterns, some patterns are worth noting that were evident during examination of the GIS-based map coverages. The highest percentage of woods/brush classification tends to occur in the northern half of the county and along the eastern and western borders of the county (fig. 4). Land use in much of the central part of the county, which corresponds to the primary metropolitan area, consists of varying density levels of residential use punctuated by commercial and industrial uses. The highest concentrations of heavy commercial and industrial uses occur near the central downtown areas and are drained by Irwin Creek (site 7) and Little Sugar Creek (site 11, fig. 5).

Physical Characteristics

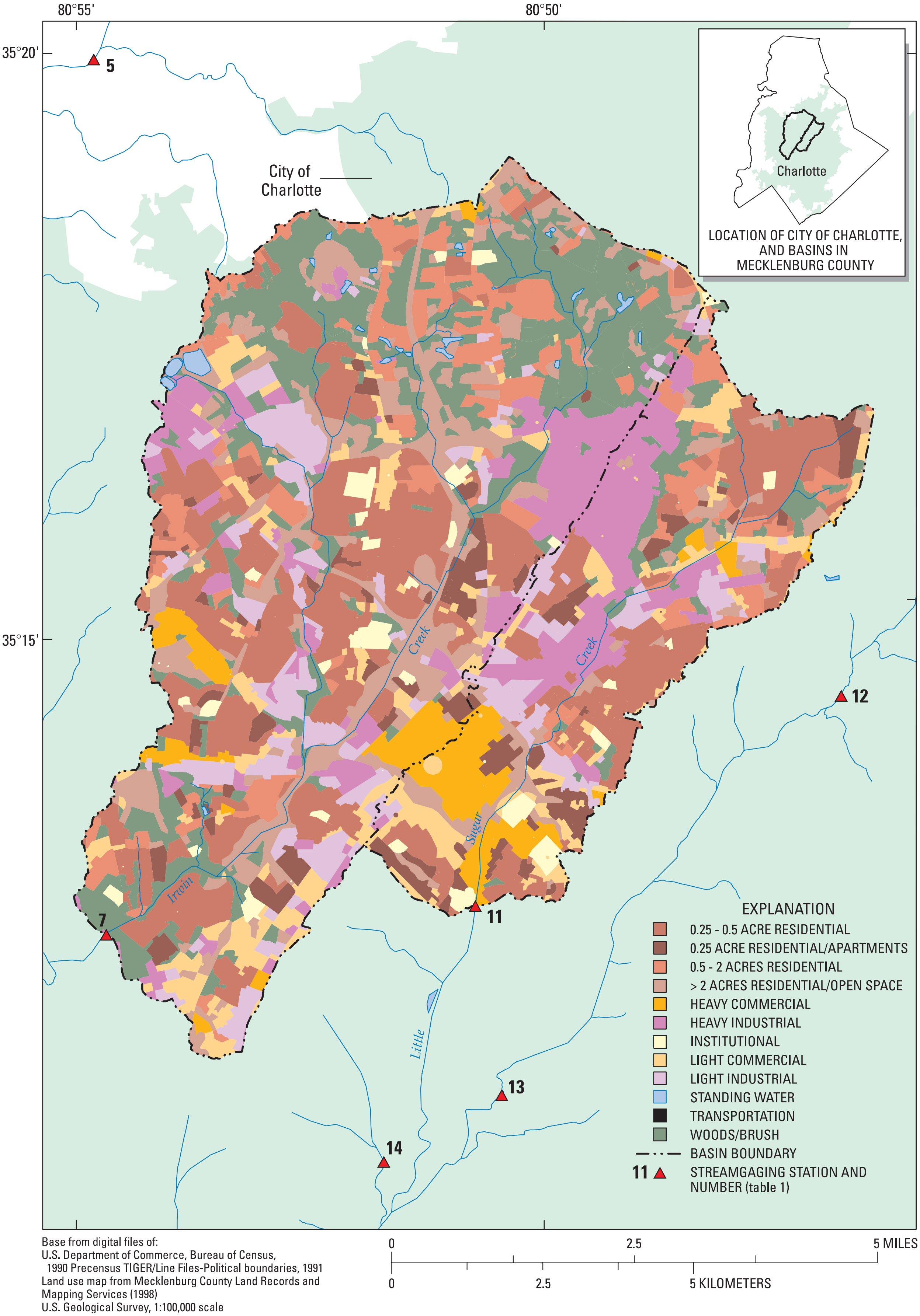
Selected physical characteristics were compiled for each of the 25 study basins. The characteristics represent measures of the basin that commonly are compiled as part of flood-frequency investigations involving the regionalization of peak discharges. The drainage area is the most common physical characteristic and, as such, typically is more readily available than the other characteristics. Drainage areas for gaging stations in North Carolina are obtained from USGS files and are based on delineations on USGS 7.5-minute topographical quadrangle maps. In addition to drainage area, other characteristics compiled for this study include channel length, channel slope, basin shape, percentage of impervious area, and percentage of the basin served by detention (table 4). With a few exceptions, these characteristics were not available for most of the basins and, thus, were computed by using GIS map coverages (Mecklenburg County Land Records and Mapping Services, 1998, 2000a–c).

The channel length, channel slope (in units of foot per mile), and basin shape were previously determined for 7 of the 25 study basins as part of a recent hydrologic investigation (Pope and others, 2001; table 4). Correspondingly, these characteristics were included in the database compiled for this investigation for sites 5, 7, 14, 16, 18, 22, and 23. At all sites, channel slope is given as measured in foot per mile, and as a percentage (table 4) for the reader's convenience in comparing slopes in this investigation with those in previous studies.

The basin shape is a dimensionless factor that characterizes the shape between a broad, rounded basin or a narrow basin. Computed as the ratio of the drainage area to the square of the channel length, smaller values of basin shape (for a given drainage area) are indicative of narrow basins; larger values indicate more rounded basins. While there is no maximum value for basin shape in the range of possible values, comparison of basin shape values for two basins reflect the shape of one basin relative to another. For example, the basin shape for the Sugar Creek basin (site 10; table 4) is computed to be 0.13, whereas the value for the Mallard Creek basin (site 1) is 0.44, indicating that the Mallard Creek basin is a more rounded basin relative to the Sugar Creek basin (fig. 6).

The impervious area in each basin is a measure of the development that has occurred within the basin. In this investigation, impervious areas were estimated by using GIS map coverages that describe the impervious surface areas (e.g., rooftops of structures, parking areas) and the transportation category from the land-use information (Mecklenburg County Land Records and Mapping Services, 1998, 2000a–c). Among the 25 study sites, impervious areas range from about 5 percent to 56 percent (sites 4 and 19, respectively; table 4). In general, basins with lower percentages of impervious areas (less than 30 percent) tend to be in the northern, western, and southern parts of the county, whereas the basins near the central metropolitan areas of Charlotte tend to have higher percentages of impervious areas. While not directly computed from land-use information, higher percentages of impervious areas are proportional to higher percentages of commercial, industrial, and residential land uses within a basin. Correspondingly, lower percentages of impervious areas are consistent with the highest percentages of woods/brush land use (site 4, tables 3, 4).

A measure of detention in each basin was included to reflect the effects of stormwater detention following rainfall events. Detention can occur in the form of a lake or pond that provides varying degrees of runoff detention, depending on the amount of storage available in the pond. Detention also can occur in the form of a manmade structure, usually in accordance with development ordinances in effect in city and(or)



Base from digital files of:
U.S. Department of Commerce, Bureau of Census,
1990 Precensus TIGER/Line Files-Political boundaries, 1991
Land use map from Mecklenburg County Land Records and
Mapping Services (1998)
U.S. Geological Survey, 1:100,000 scale

Figure 5. Land use in basins drained by Irwin Creek (site 7) and Little Sugar Creek (site 11), Charlotte, North Carolina.

Table 4. Selected basin characteristics at study sites in Mecklenburg County, North Carolina

[mi^2, square mile; ft/mi, foot per mile. Some basin characterstics were determined in previous investigations and are footnoted as appropriate; all other basin characteristics were determined during this investigation. Basin characteristics are defined in the footnotes. Channel slope is presented in units of ft/mi (used in analyses) and percent (for readers convenience)]

Site no. (fig. 2)	USGS downstream order number	Drainage area[a] (mi^2)	Channel length[b] (miles)	Channel slope[c]		Basin shape[d]	Impervious area[e] (percent)	Served by detention[f] (percent)
				(ft/mi)	(percent)			
1	02124149	34.6	8.87	24.1	0.46	0.44	20.7	13.5
2	02142651	2.35	1.75	49.5	0.94	0.77	26.2	13.8
3	02142660	26.3	8.39	11.1	0.21	0.37	16.7	8.19
4	0214266075	2.67	2.17	36.8	0.70	0.57	5.01	1.45
5	02142900	16.4	7.16[g]	19.5[g]	0.37	0.31[g]	18.1	10.4
6	02142956	10.8	7.06	28.3	0.54	0.22	20.7	6.09
7	02146300	30.7	11.3[h]	15.2[h]	0.26	0.24[h]	34.9	8.32
8	02146315	5.38	3.91	37.5	0.71	0.35	40.3	24.1
9	02146348	9.14	7.80	22.2	0.42	0.15	28.5	21.1
10	02146381	65.3	22.5	9.48	0.18	0.13	32.9	15.2
11	02146409	11.8	7.26	16.9	0.32	0.22	45.7	10.1
12	0214642825	5.2	3.39	43.3	0.82	0.45	28.5	7.08
13	0214645022	19.0	9.38	15.6	0.30	0.22	33.4	6.63
14	02146470	2.63	2.51[h]	45.7[h]	0.81	0.40[h]	38.0	11.3
15	0214650690	0.12	0.53	149	2.83	0.43	47.4	28.8
16	02146507	42.6	11.6[h]	12.5[h]	0.28	0.32[h]	38.0	8.09
17	02146530	49.2	16.4	12.2	0.23	0.18	37.8	9.54
18	02146600	39.6	8.62[h]	22.9[h]	0.42	0.52[h]	24.2	10.7
19	0214666925	0.27	0.61	109	2.07	0.73	56.0	40.6
20	02146670	17.8	9.28	17.2	0.33	0.21	22.7	7.02
21	0214669980	0.13	0.45	162	3.06	0.64	53.7	44.1
22	02146700	6.95	5.47[h]	24.2[h]	0.44	0.23[h]	31.6	7.27
23	02146750	92.4	18.1[h]	9.31[h]	0.18	0.28[h]	24.9	9.01
24	0214677974	3.57	3.21	33.3	0.63	0.35	22.3	16.7
25	0214678175	6.73	4.97	22.8	0.43	0.27	26.5	24.9

[a] Drainage area, in square miles (mi^2), is the measured area within basin divides.

[b] Channel length, in miles (mi), is the measured distance from the gage site upstream along the main channel to the basin divide. If maps did not show the channel at the basin divide, the line segments denoting the channel were extended to the basin divide before computing the length.

[c] Channel slope, in feet per mile (ft/mi), is computed between points at 10 and 85 percent of the channel length.

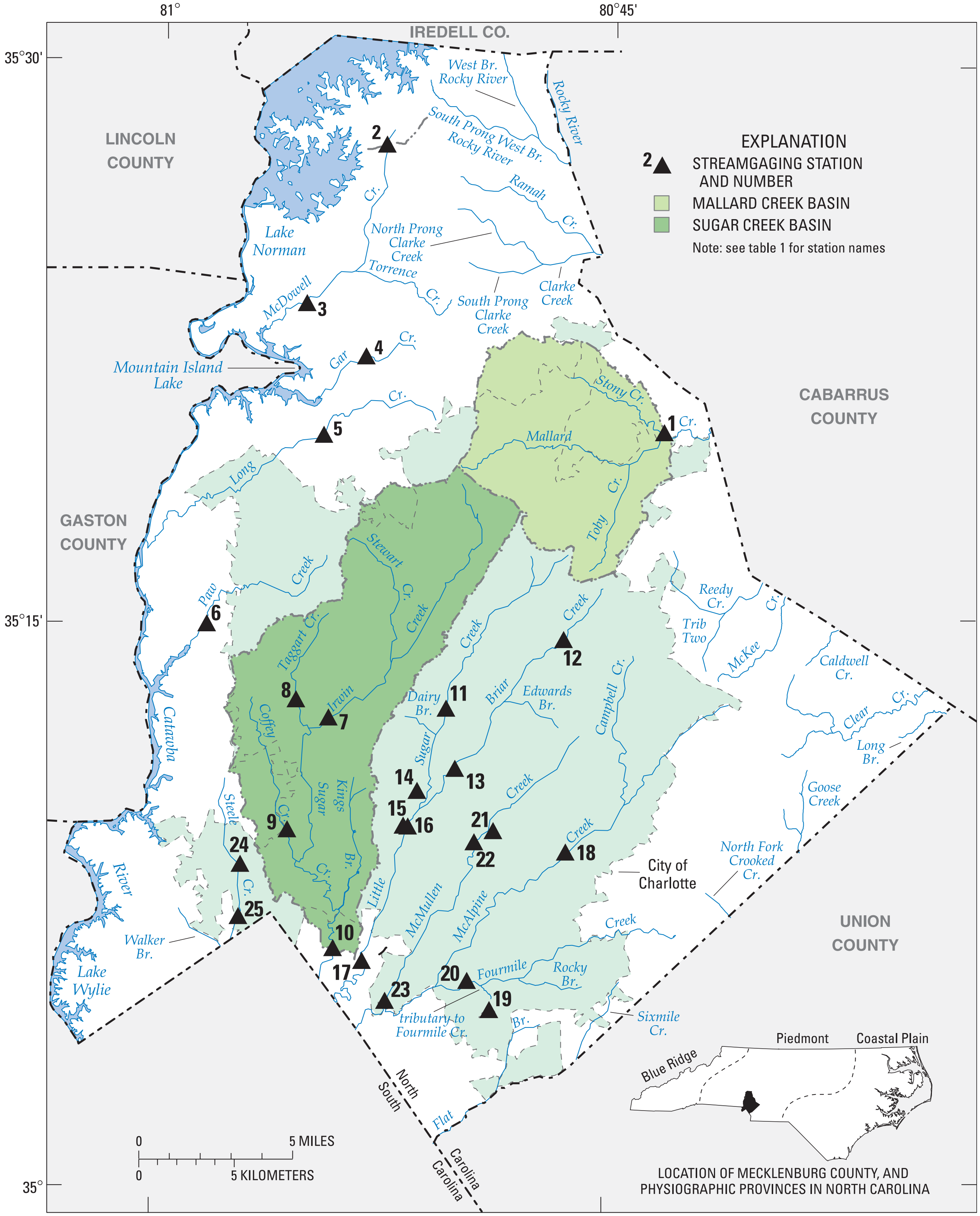
[d] Basin shape is a dimensionless value that is computed by dividing the drainage area by the square of the channel length (DA/L^2).

[e] Impervious area, in percent, is computed as the area of the basin covered by impervious surfaces.

[f] Detention, in percent, is computed as the area of the basin that is served by a detention structure.

[g] From Pope and others, 2001.

[h] Basin characteristics determined in a previous hydrologic investigation (B.F. Pope, formerly with the U.S. Geological Survey, written commun., May 8, 2001).



Base from digital files of:
U.S. Department of Commerce, Bureau of Census,
1990 Precensus TIGER/Line Files-Political boundaries, 1991
U.S. Environmental Protection Agency, River File 3
U.S. Geological Survey, 1:100,000 scale

Figure 6. The varying shapes of Mallard Creek basin (site 1) relative to Sugar Creek basin (site 10) in Mecklenburg County, North Carolina.

county jurisdictions. A manmade detention structure may be a pond used as a landscape feature in a developed area or a depression in the land surface with a constricted outlet. Because no information was available to document the locations of detention structures in Mecklenburg County, the percentages of areas served by detention were estimated by developing a GIS map coverage of the non-residential parcels developed since 1982 in the city and county (Mecklenburg County Land Records and Mapping Services, 2000a–c). The 1982 date was used because of a building ordinance passed during that year that required detention structures on non-residential parcels developed that year and beyond (Tony Dudley, City of Charlotte, oral commun., October 12, 2001). Additionally, measures of detention were included to account for the effects of lakes and ponds on detention of streamflow during stormwater runoff. The percentage of area within each basin served by detention structures ranged from less than 2 percent to about 44 percent (sites 4 and 21, respectively; table 4). Sites having the lowest and highest values of detention, correspondingly, had the lowest and nearly highest impervious areas among the basins in the investigation.

METHODS FOR ESTIMATING PEAK DISCHARGES

Regression relations were developed to estimate the peak discharge for a given storm event and the peak discharge and lag time for a unit hydrograph. For the storm peak discharge, explanatory variables included in the analyses were rainfall and basin characteristics. Explanatory variables included in the analyses for the unit-hydrograph peak discharge and lag time were basin characteristics only (see **Methods for Estimating Unit Hydrographs**). The basin characteristics compiled for each basin include land-use information and selected physical characteristics (tables 3, 4). The analyses and results of the statistical relation to estimate the storm peak discharge are discussed in this section. It should be noted that the statistical discharge relations presented in this report do not allow for the estimation of the peak discharge associated with a given flood frequency, but rather for a given storm event.

In developing statistical relations, one objective is to have explanatory (or independent) variables that have low correlations among themselves but independently demonstrate high correlation with the estimated (dependent) variable (Hatcher and Stepanski, 1994). Another objective is to present a relation having, to the extent possible, the smallest number of explanatory variables needed for estimating the dependent variables. Having a relation that meets these two objectives provides the user with a tool that is easy to use and yet allows for the estimation of a variable based on explanatory variables that account for the largest amount of variation in the predictions.

The following general procedure was used to develop the statistical relation for predicting storm peak discharge. Scatter plots were developed to show the relation between each explanatory variable (rainfall, basin characteristics) and the predictive variable (storm peak discharge, unit-hydrograph peak discharge, and lag time), which aided in the identification of the explanatory variables that potentially could be included in the statistical relations. A correlation matrix of all variables was then developed for use in assessing intervariable correlation during selection of statistical-regression models. Initial regression analysis included an “all-regression” approach to identify models with varying numbers and combinations of the explanatory variables. Using the list of possible models and the correlation matrix, one to two models were selected for further exploration. Selection of models was based on those having high coefficients of determination (R^2), explanatory variables with low intervariable correlation, and smallest possible number of variables (consistent with the objectives discussed in the previous paragraph). Scatter plots showing residuals plotted against the dependent variable and the explanatory variable(s) were examined to assess model bias. Once a potential model was selected, regression diagnostics were employed to check the validity of the model. In all regression analyses, the variables were log-transformed to (1) obtain a linear regression model, and (2) achieve equal variance about the regression line throughout the range of data (Riggs, 1968, p. 10).

Regression Data for Storm Peak Discharge

Examination of streamflow records for 25 sites (table 1) during the study period resulted in the identification of 61 storm events affecting flows at varying numbers of sites. This corresponded to an initial database of 1,525 observations. As part of the selection process, complex (multipeak) hydrographs generally were excluded from the database. Because the storm events did not result in sufficiently increased flows at all sites, the final compilation of data for use in developing a statistical relation to estimate the storm peak discharge included 412 peak-discharge observations among the 25 sites. In the final database, the observed storm peak discharges ranged from 6.30 to nearly 10,300 cubic feet per second (ft^3/s), and mean and median values were 705 and 357 ft^3/s, respectively (table 5).

Rainfall data recorded by the precipitation network during the 61 storm events were used to develop a grid composed of 100-meter cells (equivalent to about 328 feet) and showing (based on interpolation between the raingages) a continuous spatial distribution of rainfall for the area of Mecklenburg County covered by the network. For each study basin, the grid was laid over a GIS map coverage of the basin boundaries. The basin-average rainfall then was determined by averaging the interpolated rainfall amounts in the grid cells. The basin-average rainfall and the minimum and maximum rainfall amounts (based on the range of grid values) were compiled for inclusion into the statistical database. In the final database, values of basin-average rainfall ranged from 0.06 to 3.84 inches with mean and median values of 0.80 and 0.63 inch, respectively (table 5).

Streamflow and rainfall data associated with the storms that occurred in August 1995 and July 1997 were not included in the sample data used in the statistical regression analyses for storm peak discharge nor in the analyses for unit-hydrograph peak discharge and lag time. While these storms represented extreme hydrologic events, the resulting streamflows are depicted generally by complex, multipeak hydrographs resulting from (1) the prolonged periods of rainfall in the basins and (2) the storage of water during the flow recessions.

Selected land-use classifications (table 3) were combined into more general categories to reduce the overall number of explanatory variables in the statistical analyses. Specifically, the four residential classifications were combined into two categories to represent low- to medium-density (greater than 0.5 acre) and medium- to high-density (less than or equal to 0.5 acre) residential land use. Similarly, classifications for light and heavy commercial and industrial uses were compiled into percentages representing overall commercial and industrial land use. The net effect of merging the classifications was to reduce the overall number of land-use descriptors from 12 to 8 categories, thereby improving the ease of data management during the analyses. Variables used to represent physical basin characteristics include (1) drainage area, (2) channel length, (3) channel slope, (4) basin shape, (5) percentage of impervious area, and (6) percentage of the basin served by natural and manmade detention (table 5).

Statistical Analysis for Estimating Storm Peak Discharge

Examination of scatter plots showing the observed storm peak discharges in relation to the explanatory variables indicated that the strongest correlations occurred with drainage area, channel length, channel slope, basin-average and maximum rainfall, and impervious area (fig. 7). Similar scatter plots showing one-variable models with the land-use characteristics (such as, peak discharge in relation to woods/brush or peak discharge in relation to low- to medium-density residential) did not reveal high correlations with peak discharge. Such an assessment does not imply that land-use characteristics have no influence on peak discharges. Rather, the sample of observations available for this analysis did not result in land-use characteristics having correlations as high as some of the variables for rainfall and physical basin characteristics. A possible explanation for the low correlations may be the relatively narrow range of land-use characteristics associated with a sample of observations based on all study basins being generally urban as opposed to, for example, a sample of observations based on rural and urban basins with a wider range of land uses. Another possible explanation for the low correlations between the land-use characteristics and peak discharges may be the mixed land use in most of the study basins. The occurrence of mixed land use in the data sample may have diminished the high correlations that were anticipated because the observed peak discharges in the basins were affected by multiple land uses as opposed to one or two dominant land-use patterns. Other factors may be the size of the database, which was relatively small for each basin, and(or) the relatively wide range in drainage area, which appeared to be more significant than the range of land-use characteristics.

The “all-regression” analyses of 412 observations for storm peak discharge resulted in a range of two- and three-variable models with coefficients of determination (R^2 values) ranging from 0.6 to 0.8 to 10-variable or more models with R^2 values

Table 5. Statistical summary of variables used in regression analyses for streams in Mecklenburg County, North Carolina

[ft^3/s, cubic foot per second; hr, hour; in/hr, inch per hour; mi^2, square mile; mi, mile; ft/mi, foot per mile; %, percentage of basin]

Variable category	Variable and unit of measure	Number of observations[a]	Mean	Median	Standard deviation	Minimum	Maximum
		Dependent variables					
Flow	Storm peak discharge, ft^3/s	412	705	357	1,048	6.30	10,279
	Unit-hydrograph peak discharge, ft^3/s	24	2,642	1,897	1,958	135	7,247
Time	Unit-hydrograph lagtime, hr	24	4.39	3.63	2.75	0.25	11.5
		Explanatory variables					
Precipitation[b]	Basin-average rainfall, inch	412	0.80	0.63	0.59	0.06	3.84
	Basin maximum rainfall, inch	412	1.14	0.91	0.78	0.17	5.18
Physical measure	Drainage area, mi^2	25	20.1	10.8	23.1	0.12	92.4
	Channel length, mi	25	7.31	7.16	5.59	0.45	22.5
	Channel slope, ft/mi	25	38.0	22.9	40.9	9.31	162
	Basin shape, dimensionless	25	0.34	0.31	0.16	0.13	0.78
Land use	Woods/brush, %	25	27.9	29.5	17.9	0	58.4
	Institutional, %	25	3.57	1.60	8.38	0	43.2
	Standing water, %	25	0.34	0.30	0.32	0	1.20
	Transportation, %	25	0.67	0.10	1.39	0	4.70
	Commercial[c], %	25	7.24	7.30	4.94	0	19.0
	Industrial[d], %	25	6.67	3.50	7.09	0	24.0
	Low- to medium-density residential[e], %	25	24.7	26.3	11.6	0	45.2
	Medium- to high-density residential[e], %	25	28.9	22.7	21.5	2.30	77.3
Other	Impervious area, %	25	31.0	28.5	11.9	5.01	56.0
	Detention, %	25	14.6	10.4	10.6	1.45	44.1

[a] In the analyses to determine the statistical relation to estimate storm peak discharge, variables describing physical measures and land-use information were compiled from the 25 sites in the study with the storm peak discharges and precipitation variables to create a sample of data containing 412 observations. In the analyses to determine the statistical relations to estimate unit-hydrograph peak discharge, lag time variables describing physical measures and land-use information were compiled for 24 of the 25 sites (site 21 not included) with the unit-hydrograph peak discharges and lag time variables to create a sample of data containing 24 observations.

[b] Precipitation variables were included only in the statistical analysis to determine a relation to estimate the storm peak discharge. These variables were not included in the analysis for the unit-hydrograph peak discharge and lag time.

[c] The commercial category represents the summation of the percentages for light and heavy commercial land use.

[d] The industrial category represents the summation of the percentages for light and heavy industrial land use.

[e] For the purposes of the statistical regression analyses, the residential categories presented in table 3 were redefined into two classifications: low- to medium-density and medium- to high-density residential. The low- to medium-density residential category represents the summation of the percentages for “greater than 2 acres” and “0.5 to 2 acres” residential land use. The medium- to high-density residential category represents the summation of the percentages for “0.25 to 0.5 acre” and “less than 0.25 acre/apartments” residential land use. These redefined categories were established to reduce the four initial residential classifications into two classifications for ease of data management. No medium-density only (as defined in table 3) classification was used in the statistical analyses.

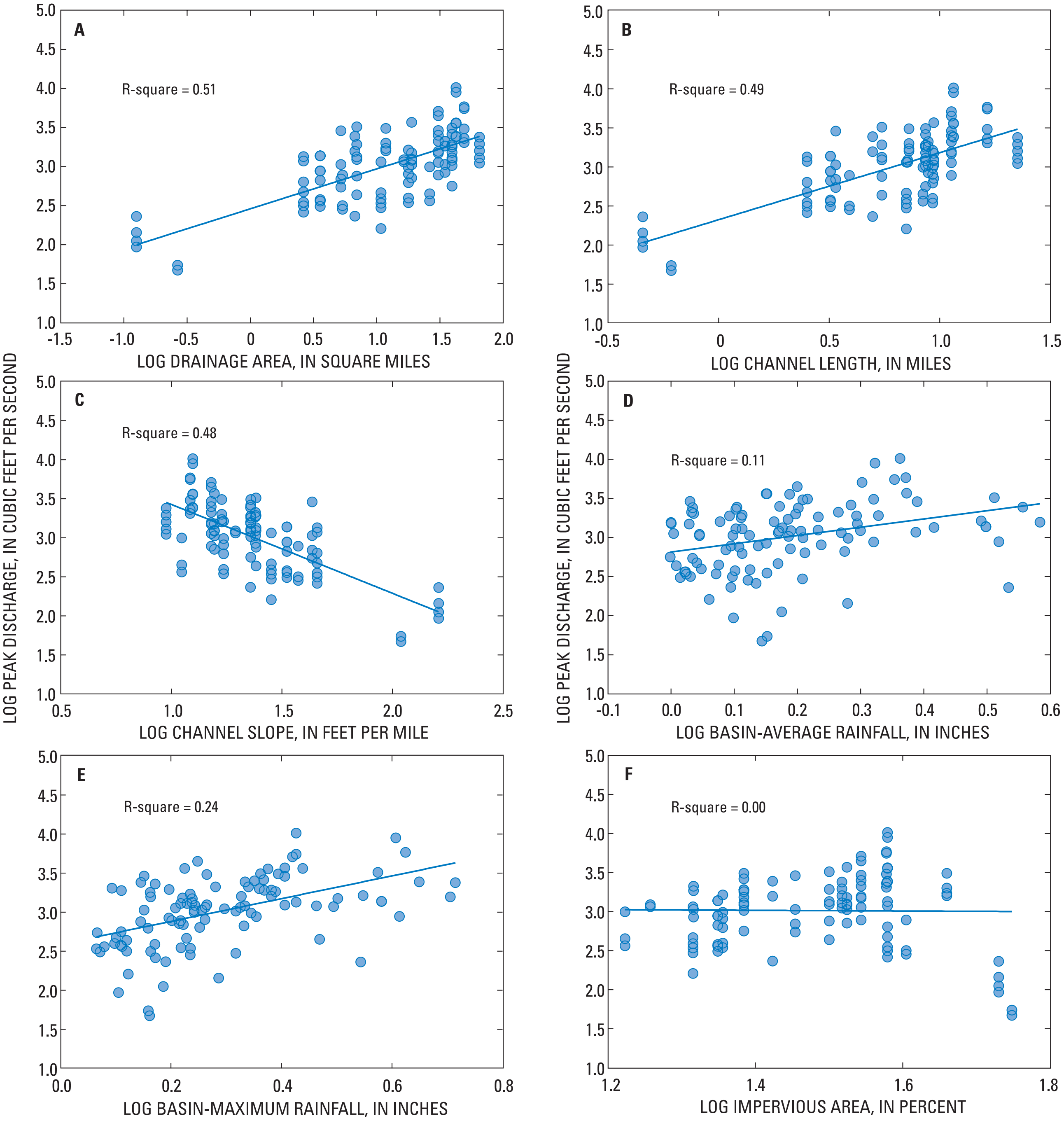


Figure 7. Relation of storm peak discharge to (A) drainage area, (B) channel length, (C) channel slope, (D) basin-average rainfall, (E) maximum rainfall, and (F) impervious area for study sites in Charlotte and Mecklenburg County, North Carolina.

of about 0.85. The coefficient of determination (R^2 value) is a measure of the proportion of variation in the estimated peak discharge (dependent variable) that is accounted for in the variation of the explanatory variables. The model selected from the list of all possible models included three variables—drainage area, basin-average rainfall, and impervious area. Drainage area and the basin-average rainfall variables accounted for the largest variation in the model. By not including the variable for impervious area, the R^2 value for the model was 0.7. Including impervious area (as an indirect measure of the land use in a basin) in the model improved the R^2 value to about 0.8. Examination of the correlation matrix also indicated low correlation among the three variables. Given that models with additional explanatory variables only improve the strength of the relation to about 0.85, the selected model appears to be an optimum model in view of the statistical objectives discussed earlier. Some improvement in the model occurred, however, when average rainfall amounts of 1.0 inch or higher (105 of 412 observations) were used. After removing two of the 105 observations that appeared to have high influence on the statistical relation, a final dataset of 103 observations was used to develop the relation to estimate storm peak discharge. The two observations removed from the analyses had the lowest peak discharge (site 19, storm of October 27, 1995) and lowest peak discharge per square mile (site 23, storm of August 19, 1995).

For the storm peak discharge, the best-fit relation was determined to be in the following form:

$$Q_{St} = 2.65 \times DA^{0.659} \times Rain_{Avg}^{1.59} \times IA^{1.07}, \quad (1)$$

where

Q_{St} is the storm peak discharge, in cubic feet per second;
DA is the drainage area, in square miles;
$Rain_{Avg}$ is the basin-average rainfall, in inches; and
IA is the impervious area in the basin, in percent.

The ranges of explanatory variables used to develop equation 1 are drainage areas from 0.12 to 65.3 mi^2, basin-average rainfalls from 1.0 to about 3.8 inches, and impervious areas from about 5 to 56 percent.

The coefficient of determination (R^2) for this model was computed to be 0.82. The average standard error for the equation describes the range about the regression line, which includes about two-thirds of the observations. For equation 1, the average standard error is about 47 percent (ranging from about -36 to +56 percent).

Residuals from the equation, defined as the difference between the observed and estimated values, were plotted against the observed variable and the explanatory variable to determine if any variable bias was evident (patterns or groupings in the plotted points). No such patterns or groupings were noticed in the plots, and the relation does not appear to be affected by variable bias. Because all sites are within a small study area (as opposed to a larger study area, such as across physiographic regions), the relation was not examined for geographic bias.

A sensitivity test was conducted to determine changes in percentages of the estimated variables, based on percentage differences in the explanatory variables (table 6). The test provides an indication of how sensitive the estimated values are to explanatory variables that vary from their true values. When the test involves two or more explanatory variables, it also provides an indication of which variable the equation is more sensitive to in the results. The test indicates that estimated values of the storm peak discharge are most sensitive to errors in the basin-average rainfall and impervious area and least sensitive to errors in the drainage area (table 6).

Table 6. Sensitivity of the estimated storm peak discharge to errors in the explanatory variables for streams in Mecklenburg County, North Carolina

Change in explanatory variable, in percent	Change in predicted storm peak discharge, in percent		
	Drainage area	Average rainfall	Impervious area
-50	-36.7	-66.8	-52.3
-40	-28.6	-55.6	-42.1
-30	-21.0	-43.3	-31.7
-20	-13.7	-29.9	-21.2
-10	-6.7	-15.4	-10.6
10	6.5	16.4	10.7
20	12.8	33.7	21.5
30	18.9	51.8	32.4
40	24.8	70.8	43.3
50	30.7	90.6	54.2

The presence of basin-average rainfall as an explanatory variable demonstrates limitations in the use of equation 1 to effectively estimate the storm peak discharge. Basin-average rainfall is a measure of the quantity of water entering a basin and is not a measure of rainfall intensity (measured in inches per hour). With the other two variables held constant, the results of the equation are the same regardless of rainfall intensity. That is, the estimated peak discharge will be the same whether rainfall occurs during a 1-hour period or 6-hour period. It has long been recognized, however, that rainfall intensity is a major factor in streamflow rates following a storm.

Relations for predicting the magnitude and frequency of floods in small urban streams in North Carolina are presented in Robbins and Pope (1996). The regression relations developed in their investigation rely on three variables—drainage area, impervious area, and an estimate of equivalent rural peak discharge (based on regression relations by Gunter and others, 1987). As previously stated, the statistical discharge relations presented in this report do not allow for the estimation of the peak discharge associated with a given frequency, but rather for a given storm event. Nevertheless, the identical use of two of the three explanatory variables determined by Robbins and Pope (1996) provides a qualitative confirmation of the explanatory variables selected in this study for use in estimating the storm peak discharge.

METHODS FOR ESTIMATING UNIT HYDROGRAPHS

A flood hydrograph for a basin can be simulated by using a unit hydrograph, defined as the direct runoff from a storm that produces 1 inch of rainfall excess. Rainfall excess is the portion of total rainfall, after interception by vegetation and infiltration into the land surface, that is direct overland runoff to streams. The principal concept underlying the application of a unit hydrograph is that each basin has one unit hydrograph that does not change (in terms of its shape) unless the basin characteristics change. Because the physical characteristics (such as, drainage area, slope, etc.) of a basin typically remain unchanged, changes in the unit hydrograph usually reflect changes in land-use patterns. Given that the unit hydrograph does not change in shape and represents streamflow response to 1 inch of runoff (rainfall excess) within a basin, flood hydrographs for actual storms can be simulated by multiplying the discharge ordinates from a unit hydrograph by the rainfall excess computed from the observed rainfall record.

In this report, the unit hydrograph is estimated by using (1) a dimensionless unit hydrograph, hereafter referred to as dimensionless hydrograph, (2) an estimate of the unit-hydrograph peak discharge, and (3) an estimate of basin lag time. The estimates of peak discharge and lag time for a unit hydrograph are based on statistical relations developed as part of this investigation.

The methods used in this study to develop unit hydrographs are based on the instantaneous unit-hydrograph method described by O'Donnell (1960). This method involves harmonic analysis of the rainfall excess and direct runoff, treating incremental rainfall (having a duration equal to the data-recording interval) as an individual storm to produce an instantaneous unit hydrograph. The O'Donnell (1960) method has been used in a number of previous USGS unit-hydrograph investigations (Inman, 1987; Bohman, 1990, 1992; Mason and Bales, 1996; Dillow, 1998) and has been coded into a series of Fortran computer programs (Stephen E. Ryan, U.S. Geological Survey, written commun., 1986) that were used in this investigation. Detailed descriptions of the steps used to derive the dimensionless hydrograph are included in Inman (1987), Bohman (1990, 1992), and Dillow (1998). These same procedures were used in this study to develop the dimensionless hydrograph presented in this report. In the discussion that follows, data from the Mallard Creek gage (site 1, fig. 2; table 1) were used to illustrate unit-hydrograph development.

Lag time represents the time between the occurrence of rainfall and the occurrence of peak discharge. By definition, used in previous investigations and in this report, the lag time is the time elapsed between the center of mass of rainfall excess and the center of mass of the resulting runoff (Inman, 1987; Mason and Bales, 1996). In the procedures used in this investigation, the lag time for a unit hydrograph is defined (and was computed) as the time corresponding to the centroid of the unit hydrograph minus one-half of the computational interval used to produce the unit hydrograph. The two definitions are mathematically equivalent and produce the same result (Mason and Bales, 1996). This definition is appropriate because the O'Donnell (1960) method treats each incremental unit of uniform rainfall as an individual storm of that incremental duration (Mason and Bales, 1996).

Development of Dimensionless Unit Hydrograph

The derivation of a dimensionless hydrograph for all streams in the study area began with the development of a station-average unit hydrograph for each study site. The criteria for selecting a storm to develop a station-average unit hydrograph for a site consisted of, to the extent possible, (1) concentrated storm rainfall that was fairly uniform throughout the basin during one period and (2) an observed hydrograph that had one peak (fig. 8). Storms in which the rainfall occurred over a long period punctuated by shorter periods of no rainfall and that resulted in complex, multipeak hydrographs generally were avoided. For each observed hydrograph, the base flow was removed by linear interpolation between the start of the rise and the end of the recession, where the rate of decreasing discharge generally becomes constant (indicating the end of the direct runoff segment in the observed hydrograph, fig. 8). At Mallard Creek (site 1), the storm of December 12, 1996, resulted in 0.65 inch of rainfall recorded at the CRN01 raingage (table 2; fig. 3) with a total peak discharge of 528 ft^3/s and peak discharge runoff of 501 ft^3/s (*total discharge minus base flow*) observed at the gage (figs. 8, 9). The rainfall excess was 0.15 inch (fig. 8), and the corresponding storm unit-hydrograph peak discharge for the storm was 3,172 ft^3/s (fig. 9). The storm unit hydrograph for this storm and all other unit hydrographs presented in this report were computed using discharge and rainfall data compiled at 15-minute intervals (0.25 hour), identical to the recording interval at many of the sites used in this investigation.

In unit-hydrograph analyses, between 3 and 10 individual storm unit hydrographs generally are needed to develop an average unit hydrograph for a site. Among the study sites, individual storm unit hydrographs were developed from a total of 228 storms, ranging from 6 to 15 storms per site (table 7). The storm unit hydrographs then were plotted and examined for selection of the unit hydrographs having consistent shapes. Of the 228 total storms, a total of

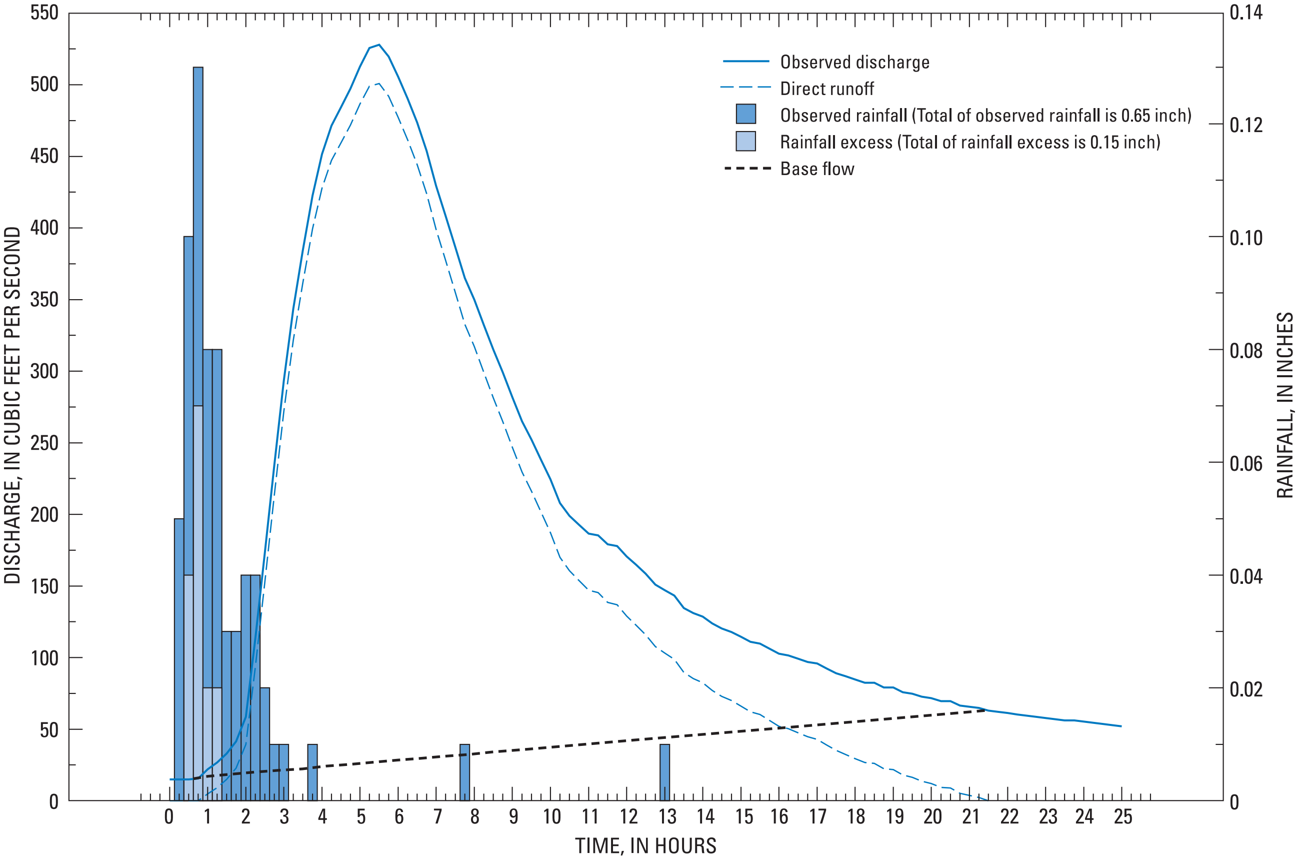


Figure 8. Observed and excess rainfall at raingage CRN01 and resulting discharge and direct runoff at Mallard Creek below Stony Creek near Harrisburg, North Carolina (site 1), for the storm of December 12, 1996.

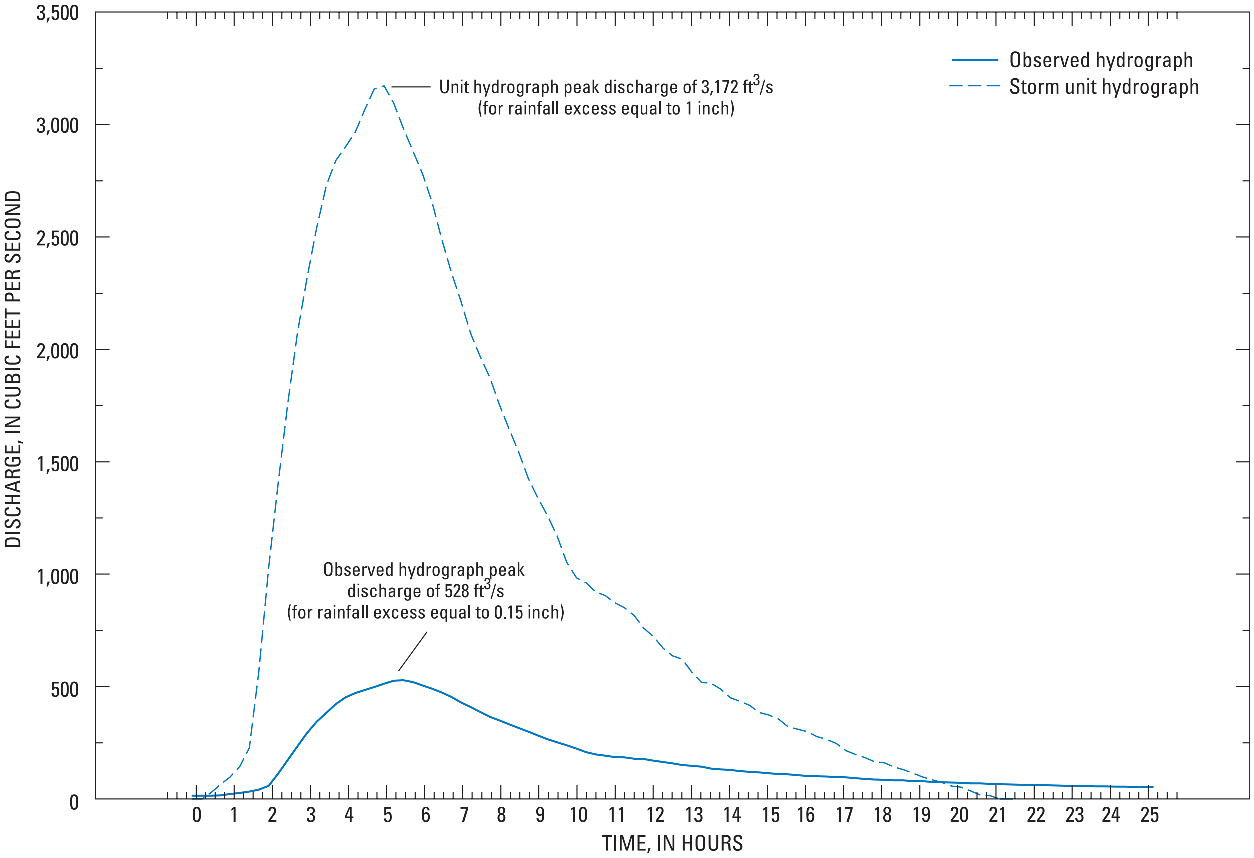


Figure 9. Observed and unit hydrographs at Mallard Creek below Stony Creek near Harrisburg, North Carolina (site 1), for the storm of December 12, 1996.

142 storms (from 3 to 9 storms per site) were used in the development of the average unit hydrograph at 24 of the 25 gaging stations. The remaining storms that were not used (86 total) were set aside for subsequent use in testing and verifying the dimensionless hydrographs.

Efforts to generate the storm unit hydrographs for site 21 resulted in errors that are likely associated with basins having very small drainage areas. As noted in the subsequent discussion, the procedures used in this investigation also did not allow for the development of lag-time-duration dimensionless hydrographs for site 15, another basin with an extremely small drainage area (thereby reducing the number of sites used in the final analyses to 23 basins). The drainage areas for sites 15 and 21 are 0.12 and 0.13 mi^2, respectively. These two sites had the smallest drainage areas among the study basins used in this investigation.

The selected storm unit hydrographs were aligned at the peaks to compute a station-average unit hydrograph for each of the 24 sites. For each station-average unit hydrograph, the peak discharge and lag time were determined at this point (table 7). The basin lag time for each station-average unit hydrograph was estimated as the average of the lag times for the storm unit hydrographs. The peak discharges for the station-average unit hydrographs ranged from 135 to nearly 7,250 ft^3/s (sites 19 and 16, respectively, table 7). In a similar manner, the lag times ranged from 0.25 to 11.5 hours (sites 15 and 23, respectively). While the lowest and highest lag times correspond to the sites having the smallest and largest drainage areas, respectively, the highest peak discharge is for a site having a drainage area about one-half the largest area among the study sites.

Storm unit hydrographs were developed for eight storms at Mallard Creek (site 1); however, only

Table 7. Summary of unit-hydrograph development for selected streams in Mecklenburg County, North Carolina

[no., number; mi^2, square mile; ft^3/s, cubic foot per second; $(ft^3/s)/mi^2$, cubic foot per second per square mile; NA, not available]

Site no. (fig. 2)	USGS downstream order no.	Drainage area (mi^2)	Development of station-average unit hydrograph					
			Number of storms considered in analyses			Station-average lag time, hours	Station-average peak discharge	
			Total	Used	Not used		ft^3/s	$(ft^3/s)/mi^2$
1	02124149	34.6	8	5	3	6.50	3,186	92.1
2	02142651	2.35	7	6	1	2.00	889	378
3	02142660	26.3	10	6	4	6.50	2,977	113
4	0214266075	2.67	14	9	5	3.25	614	230
5	02142900	16.4	9	6	3	5.25	2,608	159
6	02142956	10.8	10	7	3	4.50	2,062	191
7	02146300	30.7	12	7	5	4.00	5,595	182
8	02146315	5.38	8	8	0	2.25	1,731	322
9	02146348	9.14	7	5	2	6.00	1,599	175
10	02146381	65.3	9	3	6	10.00	4,555	69.8
11	02146409	11.8	8	4	4	2.75	2,522	214
12	0214642825	5.2	9	7	2	2.50	1,682	323
13	0214645022	19.0	14	9	5	3.50	3,204	169
14	02146470	2.63	10	7	3	1.75	1,113	423
15	0214650690	0.12	7[a]	6	1	0.25	167	1,392
16	02146507	42.6	10	5	5	3.50	7,247	170
17	02146530	49.2	7	4	3	7.00	4,981	101
18	02146600	39.6	15	7	8	4.25	6,319	160
19	0214666925	0.27	6	4	2	1.00	135	500
20	02146670	17.8	8	4	4	7.75	1,697	95.3
21	0214669980	0.13	8[a]	0	0	NA	NA	NA
22	02146700	6.95	13	7	6	2.50	1,710	246
23	02146750	92.4	7	3	4	11.50	4,514	48.9
24	0214677974	3.57	11	7	4	3.00	986	276
25	0214678175	6.73	9	6	3	3.75	1,314	195
	All sites		228[b]	142	86			

[a] The procedures used in this investigation to develop station-average unit hydrographs (site 21) and dimensionless hydrographs (site 15) did not work for sites having very small drainage areas. The drainage areas for sites 15 and 21 are the smallest among the study basins used in the investigation.

[b] Total number of storms does not include those used for site 21 because no individual storm unit hydrograph could be developed for this site using the procedures used in this investigation.

the unit hydrographs for five of the storms were used to develop the average unit hydrograph (fig. 10). The station-average unit-hydrograph peak discharge and lag time at Mallard Creek (site 1) are 3,186 ft^3/s and 6.50 hours, respectively (table 7; fig. 10).

The unit-hydrograph peak discharges were divided by drainage areas for each site. These peak discharges range from nearly 49 to 1,392 cubic feet per second per square mile [$(ft^3/s)/mi^2$] (sites 23 and 15, respectively, table 7). The basin with the lowest peak discharge per square mile (site 23) has the largest drainage area, and the basin with the highest peak discharge per square mile (site 15) has the smallest drainage area. This is consistent with previous observations that the peak discharge per square mile generally decreases as the drainage-area size increases.

Plotting the station-average unit hydrographs for selected sites (1, 2, 8, 10, 13, 16, 18, and 23) revealed some patterns related to impervious area or the size of the drainage basin (fig. 11). Sites having larger

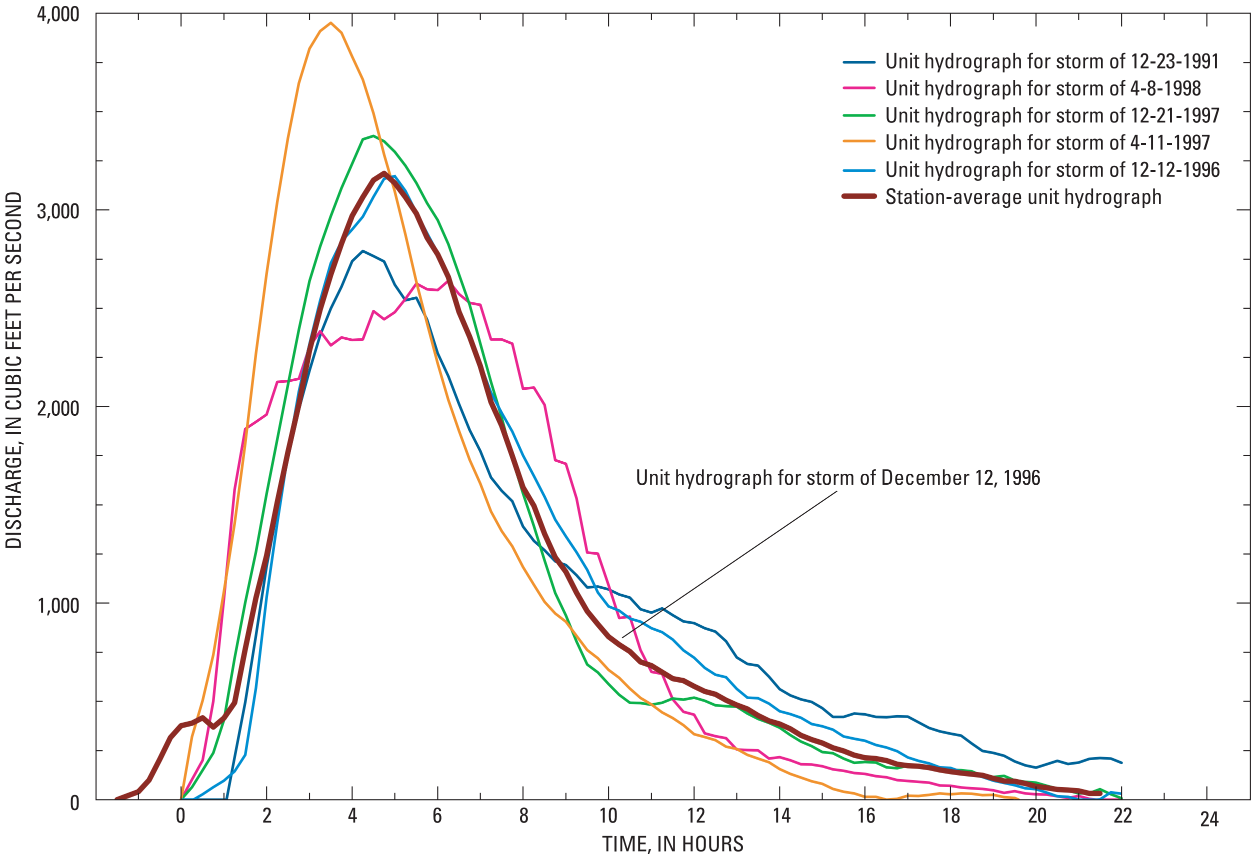


Figure 10. Storm unit hydrographs and station-average unit hydrograph for Mallard Creek below Stony Creek near Harrisburg, North Carolina (site 1).

drainage areas (for example, sites 10 and 23, table 7) had broad-shaped average unit hydrographs, whereas sites with smaller drainage areas (for example, sites 2 and 8) had narrow-shaped hydrographs. Comparison of the impervious areas of the eight selected sites offers some insight into the effects of impervious areas on lag times (by comparing the time to peak discharge). The sites for which unit hydrographs indicated the shortest time to peak discharge tend to have greater impervious areas (for example, sites 8 and 16, table 7), whereas the unit hydrograph for site 23, which has a lower impervious area, had the longest time to peak discharge. Because of the wide variation in drainage areas and impervious areas among the study basins, it is difficult to separate the effects of each factor on the peak discharges and lag times. Nevertheless, comparison of the selected sites in figure 11 provides general confirmation that larger drainage areas result in higher unit-hydrograph peak discharges and longer lag times, and basins with greater impervious areas tend to have shorter lag times.

During the initial stages of the investigation, it was anticipated that the station-average unit hydrographs would be grouped by a particular basin characteristic, such as drainage area or land-use category, prior to further analysis. However, plotting the 24 station-average unit hydrographs did not reveal any apparent patterns that would substantiate this type of grouping. Subsequently, the analysis proceeded with all 24 sites being used to develop the dimensionless hydrographs.

The station-average unit hydrographs for the 24 sites were transformed into unit hydrographs having durations corresponding to one-fourth, one-third, one-half, and three-fourths of the average lag time computed for each station, with discharge in cubic feet per second and time in hours. This transformation was necessary because the storm unit hydrographs and corresponding station-average unit hydrographs were computed using discharge and rainfall data compiled at 15-minute intervals.

The concept of duration may be thought of in terms of actual duration or design duration, thus

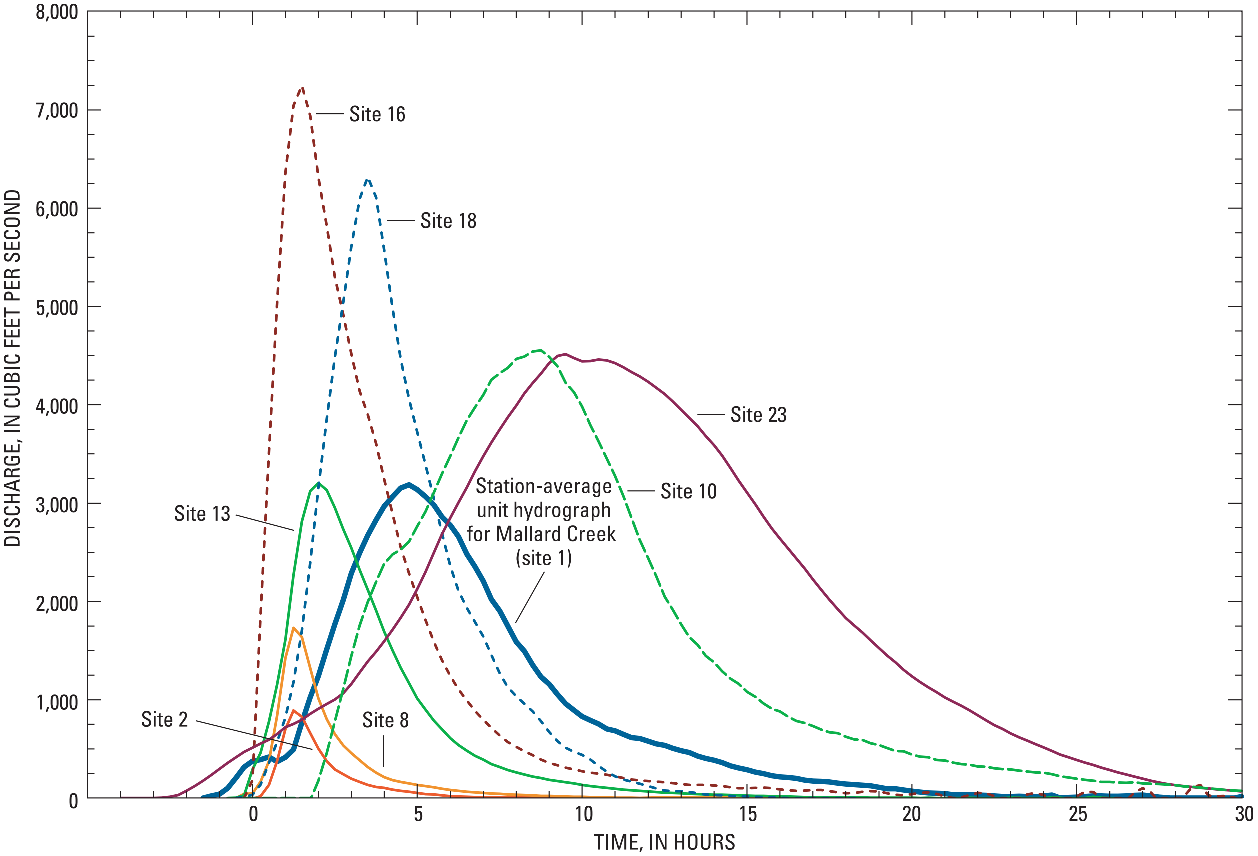


Figure 11. Station-average unit hydrographs at selected study sites in Mecklenburg County, North Carolina.

requiring further explanation to clarify the distinction between the two concepts (Inman, 1987). Actual storm duration is the time during which the rainfall excess occurs and is highly variable. A storm resulting in a 1-hour duration would produce streamflows based on 1 hour of rainfall excess. Thus, a 1-hour unit hydrograph would be the streamflow response to a storm that produced 1 inch of rainfall excess over the course of 1 hour. If the storm produced 1 inch of rainfall excess over a period of 3 hours, then the shape of the 3-hour unit hydrograph would be different from that of a 1-hour unit hydrograph. The other duration concept, unit-hydrograph design duration, is that which is considered most convenient for use in any particular basin (Inman, 1987). It is the duration for which a unit hydrograph is computed and, in this report, is expressed as a fraction of the station-average lag time (table 7), such as one-fourth, one-third, one-half, or three-fourths lag time. The fractional lagtimes are further adjusted to the nearest multiple of the original unit-hydrograph duration (in this report, 15 minutes). Completing these transformations allows for the development of unit hydrographs having more realistic durations *(see Inman, 1987, and Bohman, 1990, for formulas to complete trans-formations)*, which can be tested to determine which duration class provides a better fit against the observed data.

At the gaging station on Mallard Creek (site 1), the station-average lag time was determined to be 6.50 hours (table 7), equal to 390 minutes. The transformation of the station-average unit hydrograph into the four classes of lag-time-duration hydrographs resulted in durations of 98 minutes (1.63 hours, rounded to 1.75 hours) for the one-fourth, 130 minutes (rounded to 2.25 hours) for the one-third, 195 minutes (3.25 hours) for the one-half, and 293 minutes (rounded to 5.00 hours) for the three-fourths lag-time-duration hydrograph. The transformed hydrographs thus have 7 times, 9 times, 13 times, and 20 times the original duration (15 minutes, or 0.25 hour) used in the development of the station-average unit hydrograph at site 1 (fig. 12). As discussed above, these transformations provide a set of unit hydrographs with differing durations that can be tested to determine

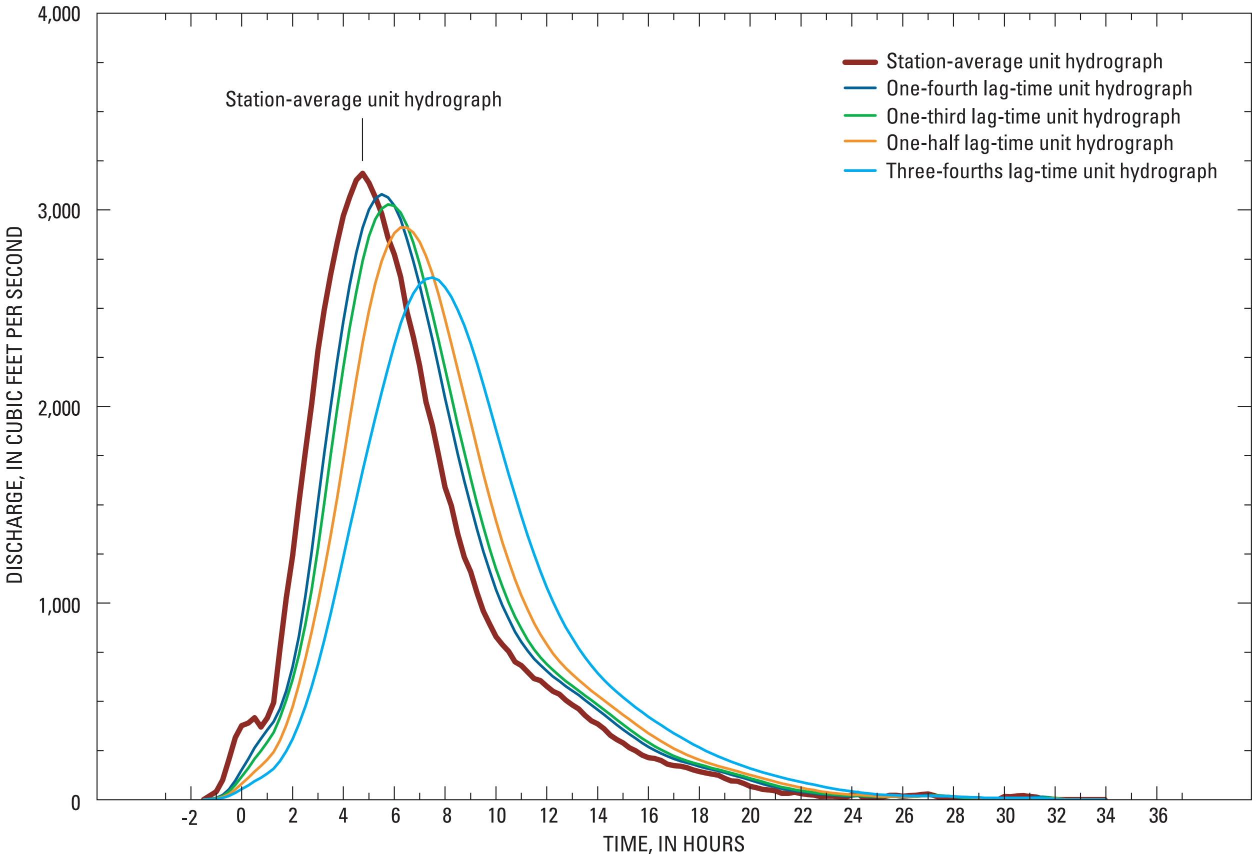


Figure 12. Station-average unit hydrograph and four classes of lag-time duration unit hydrographs for Mallard Creek below Stony Creek near Harrisburg, North Carolina (site 1).

which duration provides a better fit against the observed data. Of the 24 sites where station-average unit hydrographs were developed, the unit hydrographs for only 23 sites could be converted into the four classes of lag-time-duration hydrographs. This conversion could not be completed for site 15, which had the lowest lag time (0.25 hour, table 7) and the smallest drainage area.

After each station-average unit hydrograph was converted into the four classes of lag-time-duration hydrographs, each lag-time-duration hydrograph was reduced to a dimensionless (unit) hydrograph by dividing the discharge ordinates by the peak discharge and the time ordinates by the lag time. Next, all one-fourth lag-time-duration dimensionless hydrographs (23 total, one for each station) were aligned at the peak, and discharge ordinates were averaged to create an overall one-fourth lag-time dimensionless unit hydrograph for the study area. This step was repeated for the remaining lag-time-duration classes (one-third, one-half, and three-fourths), resulting in four average dimensionless hydrographs (fig. 13).

In addition to a dimensionless hydrograph, the estimation of unit hydrographs requires the use of statistical relations to estimate the unit-hydrograph peak discharge and lag time (described in the following sections). Thus, the resulting four lag-time-duration classes of dimensionless hydrographs subsequently were used for testing and verifying simulated hydrographs (by comparisons with the observed hydrographs) to determine which one provides the best fit for estimating flood hydrographs.

Estimation of Unit-Hydrograph Peak Discharge

Application of the dimensionless hydrograph to estimate a unit hydrograph for an ungaged site requires the peak discharge for the unit hydrograph and the basin lag time. Similar to the statistical analyses completed to develop a relation to estimate the storm peak discharge, relations for estimating the unit-hydrograph peak discharge and lag time from basin characteristics were developed. The unit-hydrograph

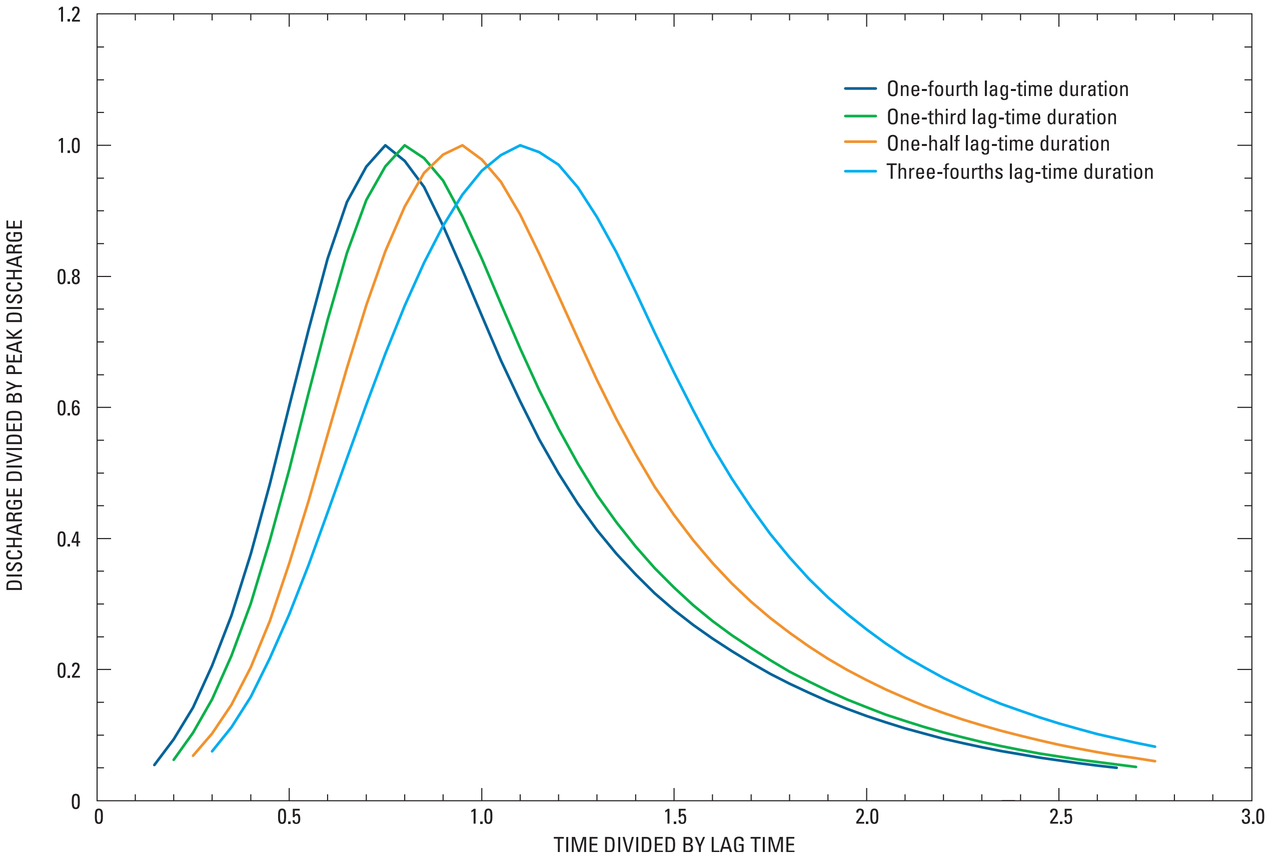


Figure 13. Average one-fourth, one-third, one-half, and three-fourths lag-time duration dimensionless unit hydrographs for study sites in Mecklenburg County, North Carolina.

peak discharges and lag times determined for the 24 sites where station-average unit hydrographs were developed (table 7) were regressed against the basin characteristics (land-use and physical characteristics) to select the explanatory variable(s) that provided the best relation. In this section, the analyses and results of the statistical relation to estimate the unit-hydrograph peak discharge are discussed. The analyses and results of the statistical relation to estimate the lag time are presented in the next section, **Estimation of Unit-Hydrograph Lag Time**.

The best-fit relation for estimating the unit-hydrograph peak discharge was determined to be of the following form:

$$Q_{UH} = 481 \times DA^{0.601}, \qquad (2)$$

where

Q_{UH} is the unit-hydrograph peak discharge, in cubic feet per second; and

DA is the drainage area, in square miles.

Drainage areas used to develop the equation ranged from 0.12 to 92.4 mi^2 (table 7). For equation 2, the coefficient of determination (R^2 value) is 0.92, and the average standard error is about 29 percent (range of -25 to +33 percent).

Residuals were plotted against the observed unit-hydrograph peak discharges and the drainage areas to determine if variable bias occurred, as evidenced by patterns or groupings in the plotted points. No such patterns or groupings were noticed in the plots, and the relation does not appear to be affected by variable bias. Because the study sites are located within a small area (as opposed to a larger area, such as across physiographic regions), the relation was not examined for geographic bias.

A sensitivity test also was completed to determine the percentage change in the estimated unit-hydrograph peak discharge based on the percentage difference in drainage area (the explanatory variable; table 8). The test provides an indication of how sensitive the dependent variable is to varying percentages of the explanatory variable from its true

Table 8. Sensitivity of the estimated unit-hydrograph peak discharge to errors in the drainage area (explanatory variable) for streams in Mecklenburg County, North Carolina

Difference in drainage area, in percent	Change in estimated unit-hydrograph peak discharge, in percent
-50	-34.1
-40	-26.4
-30	-19.3
-20	-12.5
-10	-6.1
10	5.9
20	11.6
30	17.1
40	22.4
50	27.6

value. The percentage change in estimated values of the unit-hydrograph peak discharge ranges from about -34 percent to about 28 percent, depending on the percentage differences between estimates and true values of the drainage area (table 8).

Estimation of Unit-Hydrograph Lag Time

In the analysis to assess the unit-hydrograph lag times against the basin characteristics, the best-fit relation was determined to be of the following form:

$$L_{UH} = 0.642 \times DA^{0.408} \times Woods^{0.254}, \qquad (3)$$

where

L_{UH} is the unit-hydrograph lag time, in hours;

DA is the drainage area, in square miles; and

$Woods$ is the percentage of the basin categorized as woods/brush land use.

As previously stated, the sample of drainage areas used to develop this equation range from 0.12 to 92.4 mi^2, and values of the woods/brush land-use category ranged from 1.3 to 58.4 percent (table 3, sites 14 and 19, respectively). For equation 3, the coefficient of determination (R^2 value) is 0.90, and the average standard error is about 26 percent (range from about -23 to +30 percent).

As with the previous equations, residuals were plotted against the observed lag time and the explanatory variables to determine if variable bias occurred, as evidenced by patterns or groupings in the plotted points. No such patterns or groupings were noticed in the plots, and the relation does not appear to be affected by variable bias. Again, because the study sites are located within a small area, the relation was not examined for geographic bias.

A sensitivity test was completed to determine the percentage change in estimated lag times based on percentage differences in the explanatory variables (table 9). The test provides an indication of the sensitivity of the estimated lag times to varying levels of the explanatory variables. When the test involves two or more explanatory variables, it also provides an indication of which variable the equation is more sensitive to in the results. The test indicated that estimated values of the lag time are more sensitive to errors in the drainage area.

Table 9. Sensitivity of the estimated unit-hydrograph lag time to errors in the explanatory variables for streams in Mecklenburg County, North Carolina

[mi^2, square mile]

Difference in explanatory variable, in percent	Change in estimated lag time, in percent	
	Drainage area, mi^2	Woods/brush, percent
-50	-24.6	-16.1
-40	-18.8	-12.2
-30	-13.6	-8.6
-20	-8.7	-5.5
-10	-4.2	-2.6
10	4.0	2.4
20	7.7	4.7
30	11.3	6.9
40	14.7	8.9
50	18.0	10.8

The explanatory variables used to estimate lag time for unit hydrographs in this study partly differ from some of the variables that were identified in previous USGS investigations of unit hydrographs. In the North Carolina urban unit hydrograph (Mason and Bales, 1996), the lag time was estimated by using stream (channel) length, slope, and impervious area. Inman (1987) used drainage area and slope to estimate the lag time for rural sites in Georgia but included impervious area with these two variables to estimate the lag time for the urban sites. Inman (2000) later developed lag-time equations for urban sites in four flood-frequency regions in Georgia, delineated by Stamey and Hess (1993); the equations included drainage area, slope, and total impervious area. Bohman (1990, 1992) used drainage area to estimate lag time for rural sites in South Carolina; estimates of lag time at urban sites were computed by using the ratio of channel length to slope, total impervious area, and the 2-year, 2-hour rainfall amount. At sites in Maryland, Dillow (1998) developed estimates of lag time by using variables that describe drainage area, channel slope, forest cover, and impervious area.

Testing and Verification of Simulated Hydrographs

Having completed the development of all components required for simulating a hydrograph, testing and verification procedures were carried out to simulate hydrographs by using the statistical relations and each of the four lag-time-duration classes of average dimensionless hydrographs. In applying each of the dimensionless hydrographs, the tests provided a means of identifying the dimensionless hydrograph that would be appropriate for use in estimating unit hydrographs at ungaged locations in Mecklenburg County. For each storm, simulated hydrographs were developed by using the rainfall excess (computed from the observed rainfall record) with an estimated unit hydrograph developed by using each of the four average dimensionless hydrographs along with estimates of the unit-hydrograph peak discharges and lag times.

The tests were conducted by using three categories of the storms used in the development of storm unit hydrographs. The first category was denoted as “all storms,” which consisted of all 228 storms considered in the analyses. The “all storms” category was then divided into two subcategories representing (1) the 142 storms actually used to develop the average unit hydrographs and (2) the 86 storms that were not used because the storm unit hydrographs did not produce suitably shaped unit hydrographs for use in averaging (table 7). Using the 86 storms that could not be used in the development of storm unit hydrographs for testing and verification was considered a means of more rigorously checking the fit of the estimated unit hydrographs.

The following parameters were computed from each of the simulated and observed hydrographs for comparison: (1) hydrograph width (in units of time) at 50 percent of the peak discharge, (2) hydrograph width at 75 percent of the peak discharge, (3) peak discharge, (4) time to peak discharge, and (5) volume of direct runoff beneath the hydrograph. Because of the wide range in basin sizes, normalized differences between the simulated and observed parameters were compiled for each test (in units of percent), and statistics were generated to determine the average dimensionless hydrograph that provides the best overall estimation. Statistics generated include standard error (hydrograph width only), mean error, and absolute mean error of the normalized differences for each parameter (tables 10, 11). Identification of the (1) mean arithmetic error closest to zero and (2) lowest standard error and absolute mean error for each lag-time-duration class in each storm category provided the basis for selecting the best-fit dimensionless hydrograph for simulating flood hydrographs.

Results of the hydrograph width comparisons indicated that use of the one-fourth lag-time dimensionless hydrograph to simulate flood hydrographs generally resulted in the lowest errors (table 10; fig. 14). With the exception of the 75-percent width in the “all storms” category, the “all storms” and “storms used” categories consistently identified the one-fourth lag-time dimensionless hydrograph as having the lowest errors among the four dimensionless hydrographs that were tested. In the “storms not used” category, the one-half and three-fourths lag-time dimensionless hydrographs tended to have the lowest errors (table 10). The lowest mean absolute errors were 27.0 and 30.6 percent for the hydrograph widths at the 50-percent and 75-percent levels, respectively, in the “all storms” and “storms used” categories. In the “storms not used” category, the lowest mean absolute errors were 23.8 and 28.4 percent for the hydrograph widths at the 50-percent and 75-percent levels, respectively. The highest errors tended to occur in using the three-fourths lag-time dimensionless hydrograph for simulating flood hydrographs.

Comparisons of the normalized differences in peak discharges, time to peak discharges, and direct-runoff volumes likewise indicated that use of the one-fourth lag-time dimensionless hydrograph generally

Table 10. Summary of errors related to comparisons of simulated and observed hydrograph widths at study sites in Mecklenburg County, North Carolina

[%, percent; blue shading indicates the lowest standard errors and mean absolute errors, or the mean errors closest to zero among the four lag-time-duration classes of dimensionless unit hydrographs developed for the study sites; gray shading indicates results of similar assessments completed using the dimensionless unit hydrographs from previous USGS investigations; shading of more than one value indicates identical errors or errors within 0.1 of each other]

Dimensionless unit hydrograph	Standard error, in percent, for hydrograph width at indicated peak-flow level						Mean error, in percent, for hydrograph width at indicated peak-flow level						Mean absolute error, in percent, for hydrograph width at indicated peak-flow level					
	All storms		Storms used		Storms not used		All storms		Storms used		Storms not used		All storms		Storms used		Storms not used	
	50% peak flow	75% peak flow	50% peak flow	75% peak flow	50% peak flow	75% peak flow	50% peak flow	75% peak flow	50% peak flow	75% peak flow	50% peak flow	75% peak flow	50% peak flow	75% peak flow	50% peak flow	75% peak flow	50% peak flow	75% peak flow
Charlotte																		
1/4 lag time	36.4	41.9	34.2	37.0	40.0	49.3	-2.1	0.9	-11.0	-7.5	12.7	14.8	27.0	30.6	28.3	30.7	24.8	30.4
1/3 lag time	36.4	41.7	35.1	38.1	38.7	47.4	-4.9	-3.1	-14.6	-12.7	11.1	12.8	27.9	31.7	30.1	33.0	24.4	29.6
1/2 lag time	37.6	42.5	39.2	42.6	35.1	42.5	-14.4	-15.1	-26.3	-27.5	5.2	5.2	32.0	35.8	37.0	40.2	23.8	28.4
3/4 lag time	43.8	49.6	49.4	55.4	33.3	39.0	-31.4	-36.3	-46.8	-53.9	-6.1	-7.2	42.5	48.9	52.6	59.6	25.9	31.1
Other																		
Georgia[a]	39.1	43.5	42.3	45.3	33.4	40.7	-20.0	-21.0	-33.0	-34.0	1.0	1.0	35.0	38.6	41.9	44.6	23.7	28.6
Maryland Appalachian[b]	48.0	52.4	55.4	59.6	33.7	38.9	-41.0	-43.0	-58.0	-62.0	-13.0	-12.0	49.3	53.9	61.9	66.6	28.6	32.9
Maryland Coastal Plain[b]	56.4	59.4	66.7	69.1	35.8	40.6	-57.0	-59.0	-78.0	-80.0	-23.0	-23.0	62.6	66.0	80.3	83.2	33.4	37.5
Maryland Piedmont[b]	43.0	49.4	48.2	55.0	33.2	39.2	-29.0	-35.0	-44.0	-53.0	-4.0	-6.0	41.4	48.4	50.7	58.9	25.3	30.9
N.C. urban[c]	40.2	43.4	44.4	45.4	32.5	40.0	-24.0	-21.0	-38.0	-35.0	-2.0	0.0	37.1	38.5	45.1	44.7	24.0	28.3
S.C. Blue Ridge rural[d]	36.8	41.1	37.8	39.1	35.4	44.4	-12.0	-8.0	-23.0	-19.0	6.0	10.0	30.6	32.5	34.8	35.2	23.7	28.2
SCS[e]	50.4	60.5	59.1	71.3	33.2	39.2	-46.0	-59.0	-64.0	-83.0	-15.0	-19.0	53.2	67.2	67.9	86.5	29.0	35.2
S.C. upper Coastal Plain urban[f]	36.8	41.0	37.3	39.7	36.2	43.5	-11.0	-10.0	-22.0	-21.0	7.0	9.0	30.0	32.8	33.8	35.8	23.7	27.9
Stricker-Sauer[g]	38.0	42.6	39.4	43.1	36.0	42.0	-13.0	-15.0	-26.0	-29.0	9.0	7.0	32.2	35.9	37.1	41.0	24.1	27.4

[a] From Inman (1987).

[b] From Dillow (1998).

[c] From Mason and Bales (1996).

[d] From Bohman (1990).

[e] From Soil Conservation Service (U.S. Department of Agriculture, 1972).

[f] From Bohman (1992).

[g] From Stricker and Sauer (1982).

Table 11. Summary of errors related to comparisons of simulated and observed peak discharges, time to peak discharges, and direct runoff volumes at study sites in Mecklenburg County, North Carolina

[All values in percent; blue shading indicates the mean error closest to zero or the lowest mean absolute errors; shading of more than one value indicates errors within 0.1 percent]

Dimensionless unit hydrograph	Peak discharge						Time to peak discharge						Direct-runoff volume					
	All storms		Storms used		Storms not used		All storms		Storms used		Storms not used		All storms		Storms used		Storms not used	
	Mean error	Mean absolute error	Mean error	Mean absolute error	Mean error	Mean absolute error	Mean error	Mean absolute error	Mean error	Mean absolute error	Mean error	Mean absolute error	Mean error	Mean absolute error	Mean error	Mean absolute error	Mean error	Mean absolute error
1/4 lag time	-2.8	30.9	4.6	27.5	-15.1	36.5	-17.3	27.6	-26.0	31.7	-2.9	20.8	4.7	15.5	4.0	15.4	6.0	15.7
1/3 lag time	-3.1	30.8	4.8	27.3	-16.1	37.6	-22.0	30.5	-31.3	35.6	-6.7	22.2	2.5	15.9	1.7	15.8	3.8	15.9
1/2 lag time	-5.1	31.3	3.7	27.7	-19.6	37.3	-34.1	39.4	-45.9	47.6	-14.6	25.9	-6.0	19.1	-6.8	19.6	-4.7	18.4
3/4 lag time	-7.0	31.6	3.1	27.7	-23.9	38.0	-49.6	52.6	-64.6	65.3	-24.9	31.6	-20.2	26.8	-21.0	27.8	-18.7	25.2

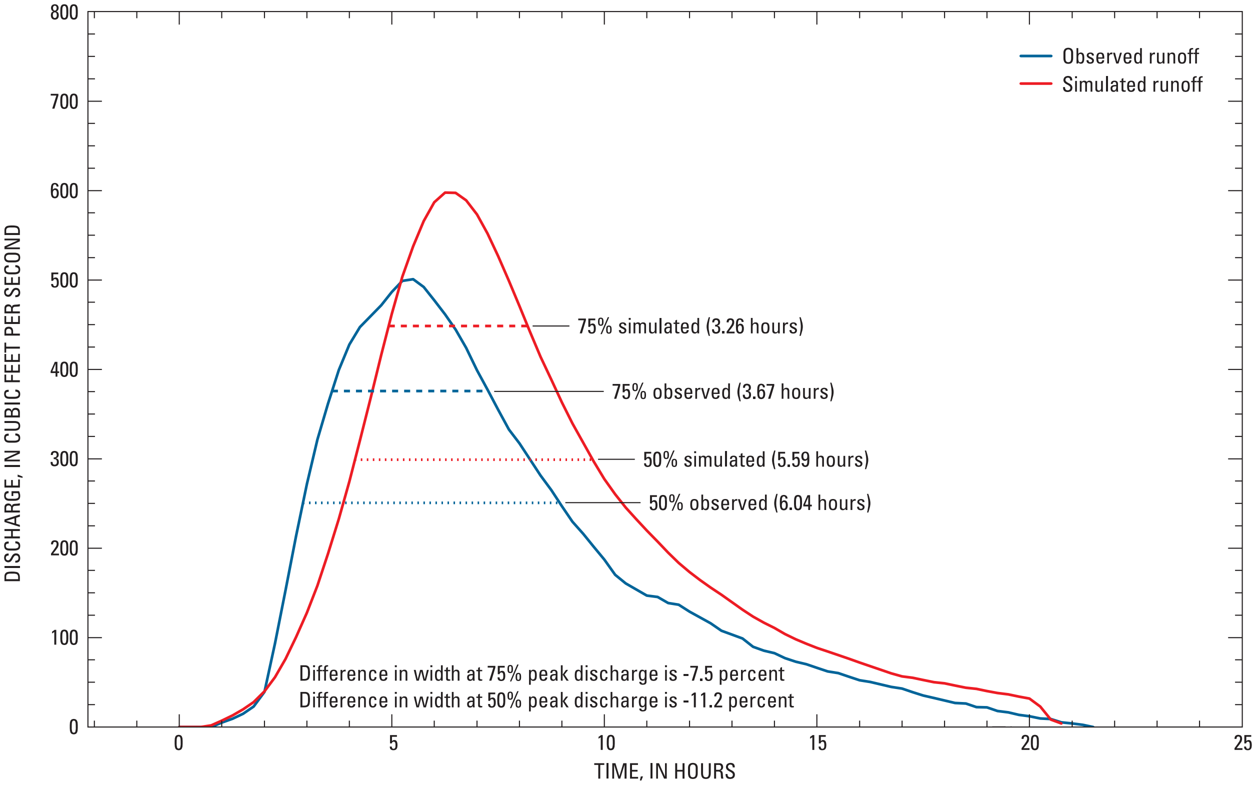


Figure 14. Comparison of hydrograph widths at 50-percent and 75-percent peak discharge runoff at Mallard Creek below Stony Creek near Harrisburg, North Carolina (site 1), for the storm of December 12, 1996.

resulted in the lowest errors (table 11). In comparing the peak discharges, the lowest mean absolute errors range from 27.3 to 36.5 percent for all lag-time-duration classes. In comparing time to peak discharges, the lowest mean absolute errors among all storm categories range from 20.8 to 31.7 percent for the one-fourth lag-time dimensionless hydrograph. In comparing the direct-runoff volumes, the lowest mean absolute errors range from 15.4 to 15.7 percent in all categories for the one-fourth lag-time dimensionless hydrograph. As with the hydrograph widths, the highest errors for peak discharges, time to peak discharges, and direct-runoff volumes tend to occur with use of the three-fourths lag-time dimensionless hydrograph.

Simulations also were carried out with dimensionless hydrographs that were developed in previous USGS investigations to assess the differences in the hydrograph widths at the 50-percent and 75-percent peak discharges (table 10). Among the dimensionless hydrographs from the previous investigations, the dimensionless hydrographs developed for South Carolina (Bohman, 1990, 1992) generally resulted in the overall best-fit simulated hydrographs. Among all categories of storms, the lowest mean absolute errors ranged from 23.7 to 33.8 percent at the 50-percent widths and from 28.2 to 35.2 percent at the 75-percent widths. However, comparisons of the lowest mean absolute errors from simulations based on the one-fourth lag-time dimensionless hydrographs for Mecklenburg County (top part of table 10) and those based on previous investigations (lower part of table) indicated that the Mecklenburg County (one-fourth lag-time) dimensionless hydrograph still resulted in the overall best-fit simulated hydrographs (table 10). The time and discharge ordinates (or ratios) for the Mecklenburg County dimensionless hydrograph are listed in table 12.

The general effects of urbanization on the development of the Mecklenburg County dimensionless unit hydrograph can be seen in a comparison with previously determined dimensionless hydrographs (fig. 15). The Mecklenburg County dimensionless hydrograph has the third earliest time to peak discharge after the South Carolina dimensionless

Table 12. Time and discharge ratios of the Mecklenburg County, North Carolina, dimensionless hydrograph

[t, time ordinate; L_{UH}, unit-hydrograph lag time; q, discharge ordinate; Q_{UH}, unit-hydrograph peak discharge. The Mecklenburg County dimensionless hydrograph is based on selection of the one-fourth lag-time-duration dimensionless hydrograph for use in streams in the county. For ungaged sites, values of L_{UH} and Q_{UH} are based on estimates determined by using the statistical relations presented in this report. Computed discharge ratios are rounded to two decimal places]

Observation	Dimensionless time ratio, t/L_{UH}	Dimensionless discharge ratio, q/Q_{UH}	Observation	Dimensionless time ratio, t/L_{UH}	Dimensionless discharge ratio, q/Q_{UH}
1	0.15	0.05	27	1.45	0.32
2	0.20	0.09	28	1.50	0.29
3	0.25	0.14	29	1.55	0.27
4	0.30	0.21	30	1.60	0.25
5	0.35	0.28	31	1.65	0.23
6	0.40	0.38	32	1.70	0.21
7	0.45	0.48	33	1.75	0.19
8	0.50	0.60	34	1.80	0.18
9	0.55	0.72	35	1.85	0.16
10	0.60	0.83	36	1.90	0.15
11	0.65	0.91	37	1.95	0.14
12	0.70	0.97	38	2.00	0.13
13	0.75	1.00	39	2.05	0.12
14	0.80	0.98	40	2.10	0.11
15	0.85	0.94	41	2.15	0.10
16	0.90	0.88	42	2.20	0.09
17	0.95	0.81	43	2.25	0.09
18	1.00	0.74	44	2.30	0.08
19	1.05	0.67	45	2.35	0.08
20	1.10	0.61	46	2.40	0.07
21	1.15	0.55	47	2.45	0.07
22	1.20	0.50	48	2.50	0.06
23	1.25	0.45	49	2.55	0.06
24	1.30	0.41	50	2.60	0.05
25	1.35	0.38	51	2.65	0.05
26	1.40	0.35			

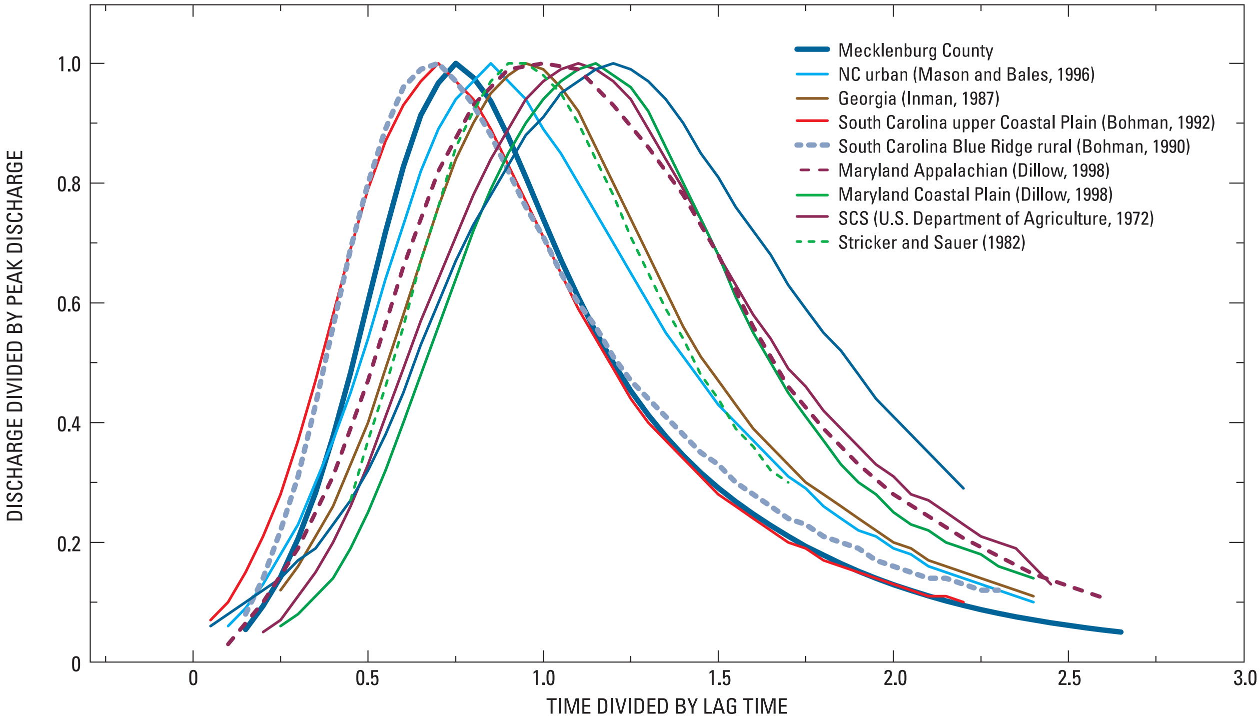


Figure 15. Mecklenburg County, North Carolina, dimensionless hydrograph (one-fourth lag-time duration) and dimensionless hydrographs from previous U.S. Geological Survey investigations.

hydrographs for rural Blue Ridge and upper Coastal Plain urban areas (Bohman, 1990, 1992). The presence of an earlier time to peak discharge for the rural Blue Ridge areas in South Carolina is apparently affected by the higher slopes that would be expected in mountainous areas. Following the Mecklenburg County dimensionless hydrograph, the next earliest time to peak discharge is associated with the North Carolina urban dimensionless hydrograph (Mason and Bales, 1996). The effects of urbanization also are reflected in the width of the Mecklenburg County dimensionless hydrographs relative to the widths depicted for the other hydrographs (fig. 15). The dimensionless hydrograph having the largest width and, correspondingly, the longest time to peak discharge is that developed for Coastal Plain areas in Maryland (Dillow, 1998).

Example Application of Methods

The following example demonstrates the steps required for estimating a unit hydrograph using the three components (statistical relations for unit-hydrograph peak discharge and lag time) presented in the preceding sections. The ranges of data used for the independent variables in the relations for unit-hydrograph peak discharge and lag time serve as general limitations in the overall application of the dimensionless unit hydrograph. As previously stated, the sample of drainage areas used to develop the relation for unit-hydrograph peak discharge range from 0.12 to 92.4 mi^2 (table 7). Similarly, the sample of drainage areas used to develop the relation for unit-hydrograph lag time range from 0.12 to 92.4 mi^2, and values of the woods/brush land-use category ranged from 1.3 to 58.4 percent (table 3, sites 14 and 19, respectively). While no basins larger than 92.4 mi^2 were used in the analyses, the application of the techniques to basins up to 100 mi^2 likely would be an acceptable extension of the range in drainage area. Therefore, a general rule of thumb for the estimation of unit hydrographs as presented in this report would be to use only basins in the city of Charlotte and Mecklenburg County with areas less than 100 mi^2 in the applications.

The site used for this example, the gage at Mallard Creek (site 1), will be treated as an ungaged site for the purpose of demonstrating the steps.

Step 1—Estimate the unit-hydrograph peak discharge. The relation developed for use in estimating the unit-hydrograph peak discharge requires the drainage area, in square miles. The drainage area upstream from the Mallard Creek gage (site 1) is 34.6 mi^2 (table 1). Equation 2 developed for estimating the unit-hydrograph peak discharge is applied as follows:

$$Q_{UH} = 481 \times DA^{0.601}$$

or

$$Q_{UH} = 481 \times (34.6^{0.601}) = 4{,}050 \text{ ft}^3\text{/s (rounded)}$$

Step 2—Estimate the unit-hydrograph lag time. The relation developed for estimating the unit-hydrograph lag time requires the drainage area and the percentage of the basin in the woods/brush land-use category. In the basin upstream from the Mallard Creek gage (site 1), the percentage of land use in this category is 50.7 percent (table 3), determined from the Mecklenburg County GIS coverage for land cover (Mecklenburg County Land Records and Mapping Services, 1998). Although this example does not describe the specific steps necessary for determining this percentage, it can be determined by using GIS techniques to overlay a map coverage of the drainage basin upstream from the site of interest with a map coverage that depicts the Charlotte-Mecklenburg land-cover information.

Equation 3 developed for estimating the unit-hydrograph lag time is used as follows:

$$L_{UH} = 0.642 \times DA^{0.408} \times Woods^{0.254}$$

or

$$L_{UH} = 0.642 \times (34.6^{0.408}) \times (50.7^{0.254})$$
$$= 7.4 \text{ hours (rounded)}$$

Step 3—Convert Mecklenburg County dimensionless hydrograph to unit hydrograph. Multiply the time and discharge ordinates for the Mecklenburg County dimensionless hydrograph (table 12) by the previously determined estimates of unit-hydrograph lag time and peak discharge, respectively (table 13; fig. 16). In this example, the discharge values are interpolated from the initial unit hydrograph at 0.25-hour intervals (consistent with the

Table 13. Example conversion of Mecklenburg County dimensionless hydrograph to unit hydrograph for Mallard Creek below Stony Creek near Harrisburg, North Carolina (site 1, fig. 1)

[t/L_{UH}, time ratio ordinate (see table 12); L_{UH}, estimated unit-hydrograph lag time; q/Q_{UH}, discharge ratio ordinate (see table 12); Q_{UH}, estimated unit-hydrograph peak discharge; ft^3/s, cubic feet per second]

Observation	t/L_{UH} (from table 12) A	L_{UH}, hours B	Time, hours A x B	q/Q_{UH} (from table 12) C	Q_{UH}, ft^3/s D	Discharge, ft^3/s C x D
1	0.15	7.4	1.11	0.05	4,050	202.50
2	0.20	7.4	1.48	0.09	4,050	364.50
3	0.25	7.4	1.85	0.14	4,050	567.00
4	0.30	7.4	2.22	0.21	4,050	850.50
5	0.35	7.4	2.59	0.28	4,050	1,134.00
6	0.40	7.4	2.96	0.38	4,050	1,539.00
7	0.45	7.4	3.33	0.48	4,050	1,944.00
8	0.50	7.4	3.70	0.60	4,050	2,430.00
9	0.55	7.4	4.07	0.72	4,050	2,916.00
10	0.60	7.4	4.44	0.83	4,050	3,361.50
11	0.65	7.4	4.81	0.91	4,050	3,685.50
12	0.70	7.4	5.18	0.97	4,050	3,928.50
13	0.75	7.4	5.55	1.00	4,050	4,050.00

Table 13. Example conversion of Mecklenburg County dimensionless hydrograph to unit hydrograph for Mallard Creek below Stony Creek near Harrisburg, North Carolina (site 1, fig. 1)—Continued

[t/L_{UH}, time ratio ordinate (see table 12); L_{UH}, estimated unit-hydrograph lag time; q/Q_{UH}, discharge ratio ordinate (see table 12);Q_{UH}, estimated unit-hydrograph peak discharge; ft^3/s, cubic feet per second]

Observation	t/L_{UH} (from table 12)	L_{UH}, hours	Time, hours	q/Q_{UH} (from table 12)	Q_{UH}, ft^3/s	Discharge, ft^3/s
	A	B	A x B	C	D	C x D
14	0.80	7.4	5.92	0.98	4,050	3,969.00
15	0.85	7.4	6.29	0.94	4,050	3,807.00
16	0.90	7.4	6.66	0.88	4,050	3,564.00
17	0.95	7.4	7.03	0.81	4,050	3,280.50
18	1.00	7.4	7.40	0.74	4,050	2,997.00
19	1.05	7.4	7.77	0.67	4,050	2,713.50
20	1.10	7.4	8.14	0.61	4,050	2,470.50
21	1.15	7.4	8.51	0.55	4,050	2,227.50
22	1.20	7.4	8.88	0.50	4,050	2,025.00
23	1.25	7.4	9.25	0.45	4,050	1,822.50
24	1.30	7.4	9.62	0.41	4,050	1,660.50
25	1.35	7.4	9.99	0.38	4,050	1,539.00
26	1.40	7.4	10.36	0.35	4,050	1,417.50
27	1.45	7.4	10.73	0.32	4,050	1,296.00
28	1.50	7.4	11.10	0.29	4,050	1,174.50
29	1.55	7.4	11.47	0.27	4,050	1,093.50
30	1.60	7.4	11.84	0.25	4,050	1,012.50
31	1.65	7.4	12.21	0.23	4,050	931.50
32	1.70	7.4	12.58	0.21	4,050	850.50
33	1.75	7.4	12.95	0.19	4,050	769.50
34	1.80	7.4	13.32	0.18	4,050	729.00
35	1.85	7.4	13.69	0.16	4,050	648.00
36	1.90	7.4	14.06	0.15	4,050	607.50
37	1.95	7.4	14.43	0.14	4,050	567.00
38	2.00	7.4	14.80	0.13	4,050	526.50
39	2.05	7.4	15.17	0.12	4,050	486.00
40	2.10	7.4	15.54	0.11	4,050	445.50
41	2.15	7.4	15.91	0.10	4,050	405.00
42	2.20	7.4	16.28	0.09	4,050	364.50
43	2.25	7.4	16.65	0.09	4,050	364.50
44	2.30	7.4	17.02	0.08	4,050	324.00
45	2.35	7.4	17.39	0.08	4,050	324.00
46	2.40	7.4	17.76	0.07	4,050	283.50
47	2.45	7.4	18.13	0.07	4,050	283.50
48	2.50	7.4	18.50	0.06	4,050	243.00
49	2.55	7.4	18.87	0.06	4,050	243.00
50	2.60	7.4	19.24	0.05	4,050	202.50
51	2.65	7.4	19.61	0.05	4,050	202.50

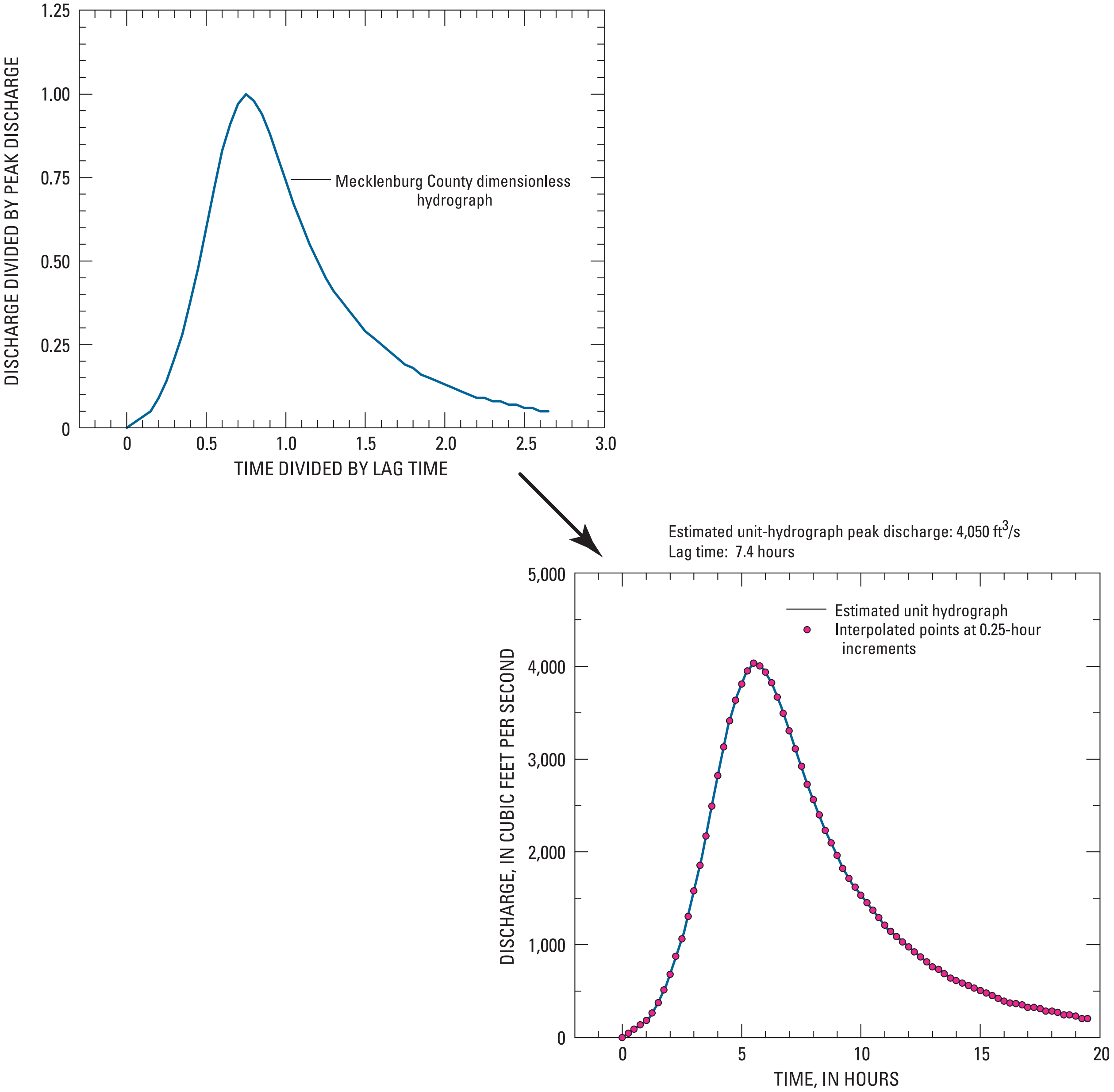


Figure 16. Example conversion of Mecklenburg County, North Carolina, dimensionless hydrograph to estimated unit hydrograph.

interval of excess rainfall values) to estimate the unit hydrograph (table 14) that will be used to develop the simulated hydrograph.

When the estimated unit hydrograph has been determined, a time series of rainfall excess (computed from observed rainfall record) is required to convert the unit hydrograph to a simulated hydrograph. In engineering hydraulic analyses, theoretical distributions of rainfall excess can be determined by using methods described by the Soil Conservation Service (U.S. Department of Agriculture, 1973) or the U.S. Army Corps of Engineers (1998). Such theoretical distributions can be used to describe the rainfall excess associated with a storm of given duration and frequency. The simulated hydrograph then can be compared to an observed hydrograph, if available, and(or) used to further investigate the discharges estimated for a given event. As part of this example, the record of rainfall excess (computed from the observed rainfall record) is applied to the estimated unit hydrograph to demonstrate the step of developing a simulated hydrograph for a given storm. As previously

Table 14. Estimated unit hydrograph for Mallard Creek below Stony Creek near Harrisburg, North Carolina (site 1, fig. 1)

[ft^3/s, cubic feet per second; discharges are interpolated at 0.25-hour increments from the initial unit hydrograph listed in table 13]

Observation	Time, hours	Discharge, ft^3/s
1	0.25	45.61
2	0.50	91.22
3	0.75	136.82
4	1.00	182.43
5	1.25	263.80
6	1.50	375.45
7	1.75	512.27
8	2.00	681.93
9	2.25	873.49
10	2.50	1,065.04
11	2.75	1,309.14
12	3.00	1,582.78
13	3.25	1,856.43
14	3.50	2,167.30
15	3.75	2,495.68
16	4.00	2,824.05
17	4.25	3,132.73
18	4.50	3,414.04
19	4.75	3,632.96
20	5.00	3,810.28
21	5.25	3,951.49
22	5.50	4,033.58
23	5.75	4,006.22
24	6.00	3,933.97
25	6.25	3,824.51
26	6.50	3,669.08
27	6.75	3,495.04
28	7.00	3,303.49
29	7.25	3,111.93
30	7.50	2,920.38
31	7.75	2,728.82
32	8.00	2,562.45
33	8.25	2,398.26
34	8.50	2,234.07
35	8.75	2,096.15
36	9.00	1,959.32
37	9.25	1,822.50
38	9.50	1,713.04
39	9.75	1,617.81
40	10.00	1,535.72
41	10.25	1,453.62
42	10.50	1,371.53
43	10.75	1,289.43
44	11.00	1,207.34
45	11.25	1,141.66
46	11.50	1,086.93
47	11.75	1,032.20
48	12.00	977.47
49	12.25	922.74
50	12.50	868.01
51	12.75	813.28
52	13.00	764.03
53	13.25	736.66
54	13.50	689.59
55	13.75	641.43
56	14.00	614.07
57	14.25	586.70
58	14.50	559.34
59	14.75	531.97
60	15.00	504.61
61	15.25	477.24
62	15.50	449.88
63	15.75	422.51
64	16.00	395.15
65	16.25	367.78
66	16.50	364.50
67	16.75	353.55
68	17.00	326.19
69	17.25	324.00
70	17.50	311.96
71	17.75	284.59
72	18.00	283.50
73	18.25	270.36
74	18.50	243.00
75	18.75	243.00
76	19.00	228.77
77	19.25	202.50
78	19.50	202.50

stated, the storm of December 12, 1996, was used in this example (fig. 17; table 15). The observed rainfall for this storm was 0.65 inch (fig. 8) and lasted about 3 hours. The rainfall excess for this storm was computed to be 0.15 inch (fig. 8) and occurred within the first 2 hours of the storm. Conversion of the estimated unit hydrograph to a simulated hydrograph resulted in a peak discharge (direct runoff) of about 598 ft^3/s, compared to the observed peak discharge runoff of 501 ft^3/s observed at the Mallard Creek gage (site 1, fig. 17).

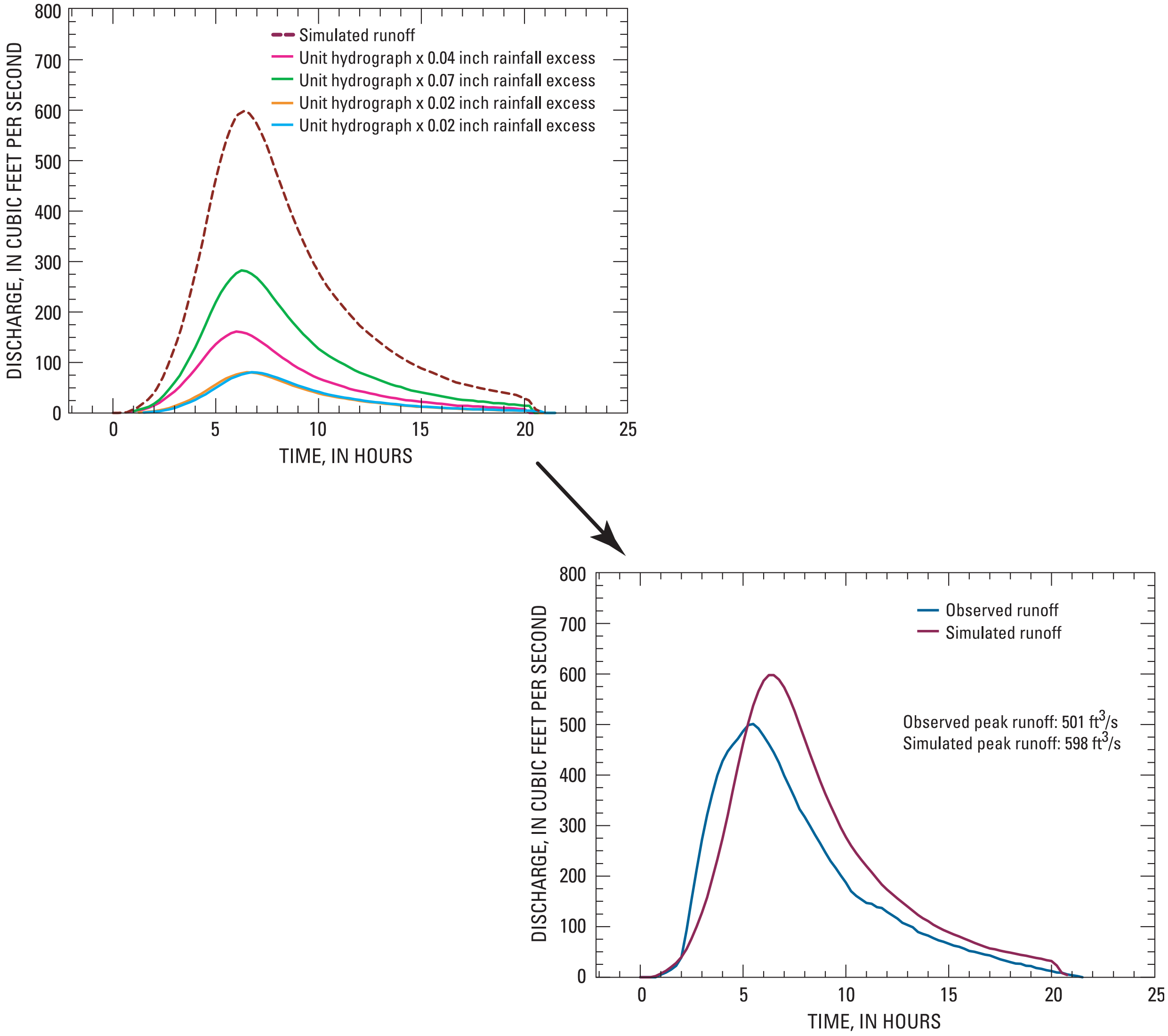


Figure 17. Simulation of discharge runoff at Mallard Creek below Stony Creek near Harrisburg, North Carolina (site 1), for the storm of December 12, 1996.

Table 15. Example conversion of unit hydrograph to simulated hydrograph (discharge runoff) using rainfall-excess record at Mallard Creek below Stony Creek near Harrisburg, North Carolina (site 1, fig. 1), for the storm of December 12, 1996

[ft^3/s, cubic feet per second; rainfall excess occurred in the first 2 hours of the 3-hour storm (see fig. 8). In this example, only four values of rainfall excess are above zero and occurred within the first 2 hours of the storm. The methods for computation of rainfall excess are not presented in this report (see ***Purpose and Scope***)]

Time, hours	Rain-fall, inches	Rain-fall excess, inches	Unit hydrograph discharge ordinates, ft^3/s (see table 14)	Rainfall excess multiplied by unit hydrograph discharge ordinates										Total discharge runoff, ft^3/s
				Time	**0.00**	**0.25**	**0.50**	**0.75**	**1.00**	**1.25**	**1.50**	**1.75**	**2.00**	
				Rainfall excess	**0**	**0**	**0.04**	**0.07**	**0.02**	**0.02**	**0**	**0**	**0**	
0.00	0	0	0.00 (*Start*)		*Start*									0
0.25	0.05	0	45.61		0	*Start*								0
0.50	0.10	0.04	91.22		0	0	*Start*							0
0.75	0.13	0.07	136.82		0	0	1.82	*Start*						1.82
1.00	0.08	0.02	182.43		0	0	3.65	3.19	*Start*					6.84
1.25	0.08	0.02	263.80		0	0	5.47	6.39	0.91	*Start*				12.77
1.50	0.03	0	375.45		0	0	7.30	9.58	1.82	0.91	*Start*			19.61
1.75	0.03	0	512.27		0	0	10.55	12.77	2.74	1.82	0	*Start*		27.88
2.00	0.04	0	681.93		0	0	15.02	18.47	3.65	2.74	0	0	*Start*	39.88
2.25	0.04	0	873.49		0	0	20.49	26.28	5.28	3.65	0	0	0	55.70
2.50	0.02	0	1,065.04		0	0	27.28	35.86	7.51	5.28	0	0	0	75.93
2.75	0.01	0	1,309.14		0	0	34.94	47.74	10.25	7.51	0	0	0	100.44
3.00	0.01	0	1,582.78		0	0	42.60	61.14	13.64	10.25	0	0	0	127.63
3.25	0	0	1,856.43		0	0	52.37	74.55	17.47	13.64	0	0	0	158.03
3.50	0	0	2,167.30		0	0	63.31	91.64	21.30	17.47	0	0	0	193.72
3.75	0.01	0	2,495.68		0	0	74.26	110.79	26.18	21.30	0	0	0	232.53
4.00	0	0	2,824.05		0	0	86.69	129.95	31.66	26.18	0	0	0	274.48
4.25	0	0	3,132.73		0	0	99.83	151.71	37.13	31.66	0	0	0	320.33
4.50	0	0	3,414.04		0	0	112.96	174.70	43.35	37.13	0	0	0	368.14
4.75	0	0	3,632.96		0	0	125.31	197.68	49.91	43.35	0	0	0	416.25
5.00	0	0	3,810.28		0	0	136.56	219.29	56.48	49.91	0	0	0	462.24
5.25	0	0	3,951.49		0	0	145.32	238.98	62.65	56.48	0	0	0	503.43
5.50	0	0	4,033.58		0	0	152.41	254.31	68.28	62.65	0	0	0	537.65
5.75	0	0	4,006.22		0	0	158.06	266.72	72.66	68.28	0	0	0	565.72
6.00	0	0	3,933.97		0	0	161.34	276.60	76.21	72.66	0	0	0	586.81
6.25	0	0	3,824.51		0	0	160.25	282.35	79.03	76.21	0	0	0	597.84
6.50	0	0	3,669.08		0	0	157.36	280.44	80.67	79.03	0	0	0	597.50
6.75	0	0	3,495.04		0	0	152.98	275.38	80.12	80.67	0	0	0	589.15
7.00	0	0	3,303.49		0	0	146.76	267.72	78.68	80.12	0	0	0	573.28

Example: 45.61 × 0.04 = 1.82

Table 15. Example conversion of unit hydrograph to simulated hydrograph (discharge runoff) using rainfall-excess record at Mallard Creek below Stony Creek near Harrisburg, North Carolina (site 1, fig. 1), for the storm of December 12, 1996—Continued

[ft^3/s, cubic feet per second; rainfall excess occurred in the first 2 hours of the 3-hour storm (see fig. 8). In this example, only four values of rainfall excess are above zero and occurred within the first 2 hours of the storm. The methods for computation of rainfall excess are not presented in this report (see ***Purpose and Scope***)]

Time, hours	Rainfall, inches	Rainfall excess, inches	Unit hydrograph discharge ordinates, ft^3/s (see table 14)	Rainfall excess multiplied by unit hydrograph discharge ordinates										Total discharge runoff, ft^3/s
				Time	0.00	0.25	0.50	0.75	1.00	1.25	1.50	1.75	2.00	
				Rainfall excess	0	0	0.04	0.07	0.02	0.02	0	0	0	
7.25	0	0	3,111.93		0	0	139.80	256.84	76.49	78.68	0	0	0	551.81
7.50	0	0	2,920.38		0	0	132.14	244.65	73.38	76.49	0	0	0	526.66
7.75	0.01	0	2,728.82		0	0	124.48	231.24	69.90	73.38	0	0	0	499.00
8.00	0	0	2,562.45		0	0	116.82	217.84	66.07	69.90	0	0	0	470.63
8.25	0	0	2,398.26		0	0	109.15	204.43	62.24	66.07	0	0	0	441.89
8.50	0	0	2,234.07		0	0	102.50	191.02	58.41	62.24	0	0	0	414.17
8.75	0	0	2,096.15		0	0	95.93	179.37	54.58	58.41	0	0	0	388.29
9.00	0	0	1,959.32		0	0	89.36	167.88	51.25	54.58	0	0	0	363.07
9.25	0	0	1,822.50		0	0	83.85	156.38	47.97	51.25	0	0	0	339.45
9.50	0	0	1,713.04		0	0	78.37	146.73	44.68	47.97	0	0	0	317.75
9.75	0	0	1,617.81		0	0	72.90	137.15	41.92	44.68	0	0	0	296.65
10.00	0	0	1,535.72		0	0	68.52	127.58	39.19	41.92	0	0	0	277.21
10.25	0	0	1,453.62		0	0	64.71	119.91	36.45	39.19	0	0	0	260.26
10.50	0	0	1,371.53		0	0	61.43	113.25	34.26	36.45	0	0	0	245.39
10.75	0	0	1,289.43		0	0	58.14	107.50	32.36	34.26	0	0	0	232.26
11.00	0	0	1,207.34		0	0	54.86	101.75	30.71	32.36	0	0	0	219.68
11.25	0	0	1,141.66		0	0	51.58	96.01	29.07	30.71	0	0	0	207.37
11.50	0	0	1,086.93		0	0	48.29	90.26	27.43	29.07	0	0	0	195.05
11.75	0	0	1,032.20		0	0	45.67	84.51	25.79	27.43	0	0	0	183.40
12.00	0	0	977.47		0	0	43.48	79.92	24.15	25.79	0	0	0	173.34
12.25	0	0	922.74		0	0	41.29	76.09	22.83	24.15	0	0	0	164.36
12.50	0	0	868.01		0	0	39.10	72.25	21.74	22.83	0	0	0	155.92
12.75	0	0	813.28		0	0	36.91	68.42	20.64	21.74	0	0	0	147.71
13.00	0.01	0	764.03		0	0	34.72	64.59	19.55	20.64	0	0	0	139.50
13.25	0	0	736.66		0	0	32.53	60.76	18.45	19.55	0	0	0	131.29
13.50	0	0	689.59		0	0	30.56	56.93	17.36	18.45	0	0	0	123.30
13.75	0	0	641.43		0	0	29.47	53.48	16.27	17.36	0	0	0	116.58
14.00	0	0	614.07		0	0	27.58	51.57	15.28	16.27	0	0	0	110.70
14.25	0	0	586.70		0	0	25.66	48.27	14.73	15.28	0	0	0	103.94
14.50	0	0	559.34		0	0	24.56	44.90	13.79	14.73	0	0	0	97.98

Table 15. Example conversion of unit hydrograph to simulated hydrograph (discharge runoff) using rainfall-excess record at Mallard Creek below Stony Creek near Harrisburg, North Carolina (site 1, fig. 1), for the storm of December 12, 1996—Continued

[ft^3/s, cubic feet per second; rainfall excess occurred in the first 2 hours of the 3-hour storm (see fig. 8). In this example, only four values of rainfall excess are above zero and occurred within the first 2 hours of the storm. The methods for computation of rainfall excess are not presented in this report (see ***Purpose and Scope***)]

Time, hours	Rain-fall, inches	Rain-fall excess, inches	Unit hydrograph discharge ordinates, ft^3/s (see table 14)	Rainfall excess multiplied by unit hydrograph discharge ordinates										Total discharge runoff, ft^3/s
				Time	0.00	0.25	0.50	0.75	1.00	1.25	1.50	1.75	2.00	
				Rainfall excess	0	0	0.04	0.07	0.02	0.02	0	0	0	
14.75	0	0	531.97		0	0	23.47	42.98	12.83	13.79	0	0	0	93.07
15.00	0	0	504.61		0	0	22.37	41.07	12.28	12.83	0	0	0	88.55
15.25	0	0	477.24		0	0	21.28	39.15	11.73	12.28	0	0	0	84.44
15.50	0	0	449.88		0	0	20.18	37.24	11.19	11.73	0	0	0	80.34
15.75	0	0	422.51		0	0	19.09	35.32	10.64	11.19	0	0	0	76.24
16.00	0	0	395.15		0	0	18.00	33.41	10.09	10.64	0	0	0	72.14
16.25	0	0	367.78		0	0	16.90	31.49	9.54	10.09	0	0	0	68.02
16.50	0	0	364.50		0	0	15.81	29.58	9.00	9.54	0	0	0	63.93
16.75	0	0	353.55		0	0	14.71	27.66	8.45	9.00	0	0	0	59.82
17.00	0	0	326.19		0	0	14.58	25.74	7.90	8.45	0	0	0	56.67
17.25	0	0	324.00		0	0	14.14	25.52	7.36	7.90	0	0	0	54.92
17.50	0	0	311.96		0	0	13.05	24.75	7.29	7.36	0	0	0	52.45
17.75	0	0	284.59		0	0	12.96	22.83	7.07	7.29	0	0	0	50.15
18.00	0	0	283.50		0	0	12.48	22.68	6.52	7.07	0	0	0	48.75
18.25	0	0	270.36		0	0	11.38	21.84	6.48	6.52	0	0	0	46.22
18.50	0	0	243.00		0	0	11.34	19.92	6.24	6.48	0	0	0	43.98
18.75	0	0	243.00		0	0	10.81	19.85	5.69	6.24	0	0	0	42.59
19.00	0	0	228.77		0	0	9.72	18.93	5.67	5.69	0	0	0	40.01
19.25	0	0	202.50		0	0	9.72	17.01	5.41	5.67	0	0	0	37.81
19.50	0	0	202.50		0	0	9.15	17.01	4.86	5.41	0	0	0	36.43
19.75	0	0	0.00		0	0	8.10	16.01	4.86	4.86	0	0	0	33.83
20.00	0	0	0.00		0	0	8.10	14.18	4.58	4.86	0	0	0	31.72
20.25	0	0	0.00		0	0	0	14.18	4.05	4.58	0	0	0	22.81
20.50	0	0	0.00		0	0	0	0	4.05	4.05	0	0	0	8.10
20.75	0	0	0.00		0	0	0	0	0	4.05	0	0	0	4.05
21.00	0	0	0.00		0	0	0	0	0	0	0	0	0	0
21.25	0	0	0.00		0	0	0	0	0	0	0	0	0	0
21.50	0	0	0.00		0	0	0	0	0	0	0	0	0	0

SUMMARY

Procedures were developed for the estimation of peak discharges and unit hydrographs for streams in the city of Charlotte and Mecklenburg County. The city and county are located in south-central North Carolina and encompass about 567 mi^2, including parts of Lake Norman, Mountain Island Lake, and Lake Wylie along the western county boundary. The Catawba River drains approximately 75 percent of the county; the remaining 25 percent of the county is drained by the Rocky River and its tributaries in the Yadkin-Pee Dee River basin. The metropolitan area, which is the largest in North Carolina and primarily occupies the lower two-thirds of the county, is mostly drained by four large creeks—Irwin, Little Sugar, Briar, and McAlpine Creeks.

Included among the procedures are (1) a dimensionless unit hydrograph for Mecklenburg County and statistical relations for estimating the (2) storm peak discharge based on rainfall and basin characteristics, (3) unit-hydrograph peak discharge based on basin characteristics, and (4) unit-hydrograph lag time, also based on basin characteristics. The dimensionless unit hydrograph can be used with estimated values of the unit-hydrograph peak discharge and lag time to determine a unit hydrograph.

Hydrologic data from a network of 25 streamgaging stations and up to 60 raingages during the 1995–2000 water years were used to assemble a database of peak discharges and rainfall amounts used in the statistical regression analyses. Information describing land-use patterns and other physical basin characteristics also were compiled for use in the analyses. Land-use data available as of 1998 identified 12 classifications of land use that were combined to reduce overall land-use information to eight categories. Physical basin characteristics included drainage area, channel length, channel slope, basin shape, impervious areas, and percentage of detention in the basins.

For the statistical relations to predict storm peak discharge, rainfall amounts from the raingage network were assembled for 61 storm events across the city and county. A geographic information system grid coverage of the county was developed for each storm to estimate rainfall amounts between the raingages. Then each storm grid was overlaid onto map coverages of the 25 basin boundaries, and basin-average rainfall was computed. Other rainfall characteristics obtained from the grid were the maximum and minimum rainfall amounts in the basin for each storm. In final form, the database contained 412 observations among the 25 gaging stations. The observed storm peak discharges ranged from 6.3 to about 10,200 ft^3/s, with mean and median values of 705 and 357 ft^3/s, respectively. Basin-average rainfall amounts ranged from 0.06 to 3.84 inches, with mean and median values of 0.80 and 0.63 inch, respectively.

Three explanatory variables were used in the statistical relation to predict the storm peak discharge—drainage area, basin-average rainfall, and impervious area. Of the 412 observations, 103 were used in the analyses, corresponding to storms having basin-average rainfall of 1 inch or higher. The statistical relation had a coefficient of determination (R^2) of 0.82 and an average standard error of about 47 percent (ranging from about -36 to +56 percent). A sensitivity test indicated that predicted values of the storm peak discharge were most sensitive to errors in the basin-average rainfall and impervious area and least sensitive to errors in the drainage area.

Station-average unit hydrographs were developed for 24 of 25 gaging stations used in the study. Among the sites, between three and nine storm unit hydrographs were used to determine the station-average unit hydrographs. Peak discharges for the average unit hydrographs ranged from 135 to nearly 7,250 ft^3/s; lag times ranged from 0.25 to 11.5 hours. At 23 of the 24 sites, the station-average unit hydrographs were converted to unit hydrographs representing one-fourth, one-third, one-half, and three-fourths duration of the lag time, which in turn were converted to dimensionless unit hydrographs. The fractional lag-time dimensionless unit hydrographs then were combined to create one average dimensionless unit hydrograph per class (one-fourth, one-third, one-half, and three-fourths). Conversion to the four classes of lag-time duration permitted investigation of unit hydrographs of more realistic durations for eventual selection of a dimensionless unit hydrograph for ungaged sites in the study area.

Statistical relations for estimating the unit-hydrograph peak discharge and lag time were developed by regressing the dependent variables against the basin characteristics (land use and physical basin characteristics) for 24 of the 25 study sites. To predict the unit-hydrograph peak discharge, the drainage area is the only required variable. The drainage areas used in the analyses range from about 0.12 to 92.4 mi^2. The resulting statistical relation for unit-hydrograph peak discharge had a coefficient of

determination (R^2) of 0.92 and an average standard error of about 29 percent (range of -25 to +33 percent).

Drainage area and percentage of land use classified as "Woods/Brush" were used in the statistical relation to estimate the unit-hydrograph lag time. The range of woods/brush land use among the study basins ranged from 1.3 to 58.4 percent. The coefficient of determination (R^2) was 0.90, and the average standard error was about 26 percent (range from about -23 to +30 percent). A sensitivity test indicated that estimated lag-time values are more sensitive to errors in the drainage area than to errors in percentages of woods/brush land use.

Each of the four average dimensionless unit hydrographs was used with estimated unit-hydrograph peak discharges and lag times to simulate hydrographs for comparison with observed hydrographs. The simulated and observed hydrographs were compared, and statistics were generated on the following parameters: (1) hydrograph width at 50 percent of the peak discharge, (2) hydrograph width at 75 percent of the peak discharge, (3) peak discharge, (4) time to peak discharge, and (5) volume of direct runoff beneath the hydrograph.

Assessments of the statistics among these parameters indicated that simulations based on use of the one-fourth lag-time-duration dimensionless unit hydrograph appears to provide the best-fit hydrograph. Thus, this dimensionless unit hydrograph was selected as the final overall dimensionless hydrograph for use for stream basins in Mecklenburg County.

SELECTED REFERENCES

Bales, J.D., Sarver, K.M., and Giorgino, M.J., 2001, Mountain Island Lake—Analysis of ambient conditions and simulation of hydrodynamics, constituent transport, and water-quality characteristics, 1996–97: U.S. Geological Survey Water-Resources Investigations Report 01-4138, 85 p.

Bales, J.D., Weaver, J.C., and Robinson, J.B., 1999, Relation of land use to streamflow and water quality at selected sites in the City of Charlotte and Mecklenburg County, North Carolina, 1993–98: U.S. Geological Survey Water-Resources Investigations Report 99-4180, 95 p.

Bohman, L.R., 1990, Determination of flood hydrographs for streams in South Carolina, Volume 1—Simulation of flood hydrographs for rural watersheds in South Carolina: U.S. Geological Survey Water-Resources Investigations Report 89-4087, 53 p.

——— 1992, Determination of flood hydrographs for streams in South Carolina, Volume 2—Estimation of peak-discharge frequency, runoff volumes, and flood hydrographs for urban watersheds: U.S. Geological Survey Water-Resources Investigations Report 92-4040, 79 p.

Charlotte Chamber Design Manual Task Force, City of Charlotte Engineering Department, Mecklenburg County Engineering Department, Debo and Associates, and Ogden Environmental and Engineering Services, 1993, Charlotte Mecklenburg storm water design manual: July 8, 1993, Charlotte, North Carolina [variously paged].

Dillow, J.J.A., 1998, Technique for simulating peak-flow hydrographs in Maryland: U.S. Geological Survey Water-Resources Investigations Report 97-4279, 39 p.

Ferrell, G.M., 2001, Effects of land use on water quality and transport of selected constituents in streams in Mecklenburg County, North Carolina, 1994–98: U.S. Geological Survey Water-Resources Investigations Report 01-4118, 88 p.

Gunter, H.C., Mason, R.R., and Stamey, T.C., 1987, Magnitude and frequency of floods in rural and urban basins of North Carolina: U.S. Geological Survey Water-Resources Investigations Report 87-4096, 52 p.

Hatcher, Larry, and Stepanski, E.J., 1994, A step-by-step approach to using the SAS® System for univariate and multivariate statistics: Cary, North Carolina, SAS Institute, Inc., 552 p.

Hazell, W.F., and Bales, J.D., 1997, Real-time rainfall measurement in the City of Charlotte and Mecklenburg County, North Carolina: U.S. Geological Survey Fact Sheet FS-052-97, 4 p.

Helsel, D.R., and Hirsch, R.M., 1992, Statistical methods in water resources: Amsterdam, Elsevier Science Publishers, 522 p.

Hess, G.W., and Inman, E.J., 1994a, Effects of urban flood-detention reservoirs on peak discharges in Gwinnett County, Georgia: U.S. Geological Survey Water-Resources Investigations Report 94-4004, 35 p.

——— 1994b, Effects of urban flood-detention reservoirs on peak discharges and flood frequencies, and simulation of flood-detention reservoir outflow hydrographs in two watersheds in Albany, Georgia: U.S. Geological Survey Water-Resources Investigations Report 94-4158, 31 p.

Holnbeck, S.R., and Parrett, C., 1996, Procedures for estimating unit hydrographs for large floods at ungaged sites in Montana: U.S. Geological Survey Water-Supply Paper 2420, 60 p.

Hughes, W.B., 1994, National Water-Quality Assessment Program—The Santee Basin and coastal drainages, North Carolina and South Carolina: U.S. Geological Survey Fact Sheet FS-94-010, 4 p.

Inman, E.J., 1987, Simulation of flood hydrographs for Georgia streams: U.S. Geological Survey Water-Supply Paper 2317, 26 p.

——— 1988, Flood-frequency relations for urban streams in Georgia: U.S. Geological Survey Water-Resources Investigations Report 88-4085, 36 p.

——— 1997, Comparison of the 2-, 25-, and 100-year recurrence interval floods computed from observed data with the 1995 urban flood-frequency estimating equations for Georgia: U.S. Geological Survey Water-Resources Investigations Report 97-4118, 14 p.

——— 2000, Lagtime relations for urban streams in Georgia: U.S. Geological Survey Water-Resources Investigations Report 00-4049, 12 p.

Jackson, N.M., Jr., 1976, Magnitude and frequency of floods in North Carolina: U.S. Geological Survey Water-Resources Investigations 76-17, 26 p.

Jennings, M.E., Thomas, W.O., Jr., and Riggs, H.C., 1994, Nationwide summary of U.S. Geological Survey regional regression equations for estimating magnitude and frequency of floods for ungaged sites, 1993: U.S. Geological Survey Water-Resources Investigations Report 94-4002, 196 p.

LeGrand, H.E., and Mundorff, M.J., 1952, Geology and groundwater in the Charlotte area, North Carolina: Raleigh, North Carolina Department of Conservation and Development, Bulletin 63, 88 p.

Maluk, T.L., and Kelley, R.E., 1998, Pesticides in the surface waters of the Santee River Basin and coastal drainages, North and South Carolina: U.S. Geological Survey Fact Sheet FS-007-98, 6 p.

Maluk, T.L., Reuber, E.J., and Hughes, W.B., 1998, Nutrients in the waters of the Santee River Basin and coastal drainages, North and South Carolina, 1973–93: U.S. Geological Survey Water-Resources Investigations Report 97-4172, 60 p.

Mason, R.R., Jr., and Bales, J.D., 1996, Estimating flood hydrographs for urban basins in North Carolina: U.S. Geological Survey Water-Resources Investigations Report 96-4085, 19 p.

McCachren, C.M., 1980, Soil survey of Mecklenburg County, North Carolina: U.S. Department of Agriculture, Soil Conservation Service, 97 p.

Mecklenburg County Land Records and Mapping Services, 1998, “Landcover98.shp” Arc/Info GIS shapefile, Charlotte, N.C.: state plane projection, scale 1:100,000, NAD83, units in feet.

——— 2000a, “Buildings” Arc/Info GIS coverage file, Charlotte, N.C.: state plane projection, scale 1:2,400, NAD83, units in feet.

——— 2000b, “Imperv” Arc/Info GIS coverage file, Charlotte, N.C.: state plane projection, scale 1:200, NAD83, units in feet.

——— 2000c, “Parcels.shp” Arc/Info GIS shape file, Charlotte, N.C.: state plane projection [source scale unknown], NAD83, units in feet.

National Oceanic and Atmospheric Administration, 2000, Climatological data annual summary—North Carolina: National Oceanic and Atmospheric Administration [issued annually].

O’Donnell, T., 1960, Instantaneous unit hydrograph derivation by harmonic analysis: International Association of Scientific Hydrology, Commission of Surface Waters, Publication 51, p. 546–557.

Pope, B.F., 1996, Simulated peak flows and water-surface profiles for Scott Creek near Sylva, North Carolina: U.S. Geological Survey Water-Resources Investigations Report 96-4226, 15 p.

Pope, B.F., Tasker, G.D., and Robbins, J.C., 2001, Estimating the magnitude and frequency of floods in rural basins of North Carolina—Revised: U.S. Geological Survey Water-Resources Investigations Report 01-4207, 44 p.

Putnam, A.L., 1972, Effect of urban development on floods in the Piedmont province of North Carolina: U.S. Geological Survey Open-File Report, 87 p.

Ragland, B.C., Barker, R.G., and Robinson, J.B., 2002, Water resources data, North Carolina, water year 2001: U.S. Geological Survey Water-Data Report NC-01-1B, 657 p.

Riggs, H.C., 1968, Some statistical tools in hydrology: U.S. Geological Survey Techniques of Water-Resources Investigations, book 4, chap. A1, 39 p.

Robbins, J.C., and Pope, B.F., 1996, Estimation of flood-frequency characteristics of small urban streams in North Carolina: U.S. Geological Survey Water-Resources Investigations Report 96-4084, 21 p.

Robinson, J.B., Hazell, W.F., and Garrett, R.G., 1996, Precipitation, streamflow, and water-quality data from selected sites in the City of Charlotte and Mecklenburg County, 1993–95: U.S. Geological Survey Open-File Report 96-150, 136 p.

——— 1998, Precipitation, streamflow, and water-quality data from selected sites in the City of Charlotte and Mecklenburg County, 1995–97: U.S. Geological Survey Open-File Report 98-67, 220 p.

Sarver, K.M., Hazell, W.F., and Robinson, J.B., 1999, Precipitation, atmospheric deposition, streamflow, and water-quality data from selected sites in the City of Charlotte and Mecklenburg County, 1997–98: U.S. Geological Survey Open-File Report 99-273, 144 p.

Sarver, K.M., and Steiner, B.C., 1998, Hydrologic and water-quality data from Mountain Island Lake, North Carolina, 1994–97: U.S. Geological Survey Open-File Report 98-549, 165 p.

Sauer, V.B., Thomas, W.O., Jr., Stricker, V.A., and Wilson, K.V., 1983, Flood characteristics of urban watersheds in the United States: U.S. Geological Survey Water-Supply Paper 2207, 63 p.

Stamey, T.C., and Hess, G.W., 1993, Techniques for estimating magnitude and frequency of floods in rural basins of Georgia: U.S. Geological Survey Water-Resources Investigations Report 93-4016, 75 p.

Straub, T.D., Melching, C.S., and Kocher, K.E., 2000, Equations for estimating Clark unit-hydrograph parameters for small rural watersheds in Illinois: U.S. Geological Survey Water-Resources Investigations Report 00-4184, 30 p.

Stricker, V.A., and Sauer, V.B., 1982, Techniques for estimating flood hydrographs for ungaged urban watersheds: U.S. Geological Survey Open-File Report 82-365, 24 p.

U.S. Army Corps of Engineers, 1998, HEC-1 flood hydrograph package: Hydrologic Engineering Center, Computer Program Document-1A user's manual, 433 p.

U.S. Census Bureau, 2001, Rankings, comparisons, and summaries: accessed January 8, 2002, at http://www.census.gov/main/www/cen2000.html

U.S. Department of Agriculture, 1972, Hydrographs: Washington, D.C., Soil Conservation Service, National Engineering Handbook, sect. 4, p. 16.1–16.26.

———1973, A method for estimating volume and rate of runoff in small watersheds: Washington, D.C., Soil Conservation Service Technical Paper 149.