Estimation of Peak-Discharge Frequency of Urban Streams in Jefferson County, Kentucky

U.S. Geological Survey

Water-Resources Investigations Report 97-4219

Prepared in cooperation with the
LOUISVILLE AND JEFFERSON COUNTY
METROPOLITAN SEWER DISTRICT

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By Gary R. Martin, Kevin J. Ruhl, Brian L. Moore, *and* Martin F. Rose

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Louisville, Kentucky

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CONVERSION FACTORS AND VERTICAL DATUM

Multiply	By	To obtain
inch (in.)	25.4	millimeter
foot (ft)	0.3048	meter
mile (mi)	1.609	kilometer
square mile (mi^2)	2.590	square kilometer
cubic foot per second (ft^3/s)	0.02832	cubic meter per second

Sea level: In this report “sea level” refers to the National Geodetic Vertical Datum of 1929 (NGVD of 1929)—a geodetic datum derived from a general adjustment of the first-order level nets of both the United States and Canada, formerly called Sea Level Datum of 1929.

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GLOSSARY

The following are definitions of selected acronyms and terms as they are used in this report; they are not necessarily the only valid definitions for these acronyms and terms.

A — Contributing drainage area (in square miles)—The drainage area that contributes surface runoff to a specified location on a stream, measured in a horizontal plane. Computed (by planimeter, digitizer, or grid method) from U.S. Geological Survey 7.5-minute topographic quadrangle maps. Sewer maps may be necessary to delineate drainage area in urban areas because sewer lines sometimes cross topographic divides.

AZ — Azimuth—Measured in degrees from north of line defining basin length.

BDF — Basin development factor—A measure of basin development that takes into account channel improvements, impervious channel linings, storm sewers, and curb-and-gutter streets. It is measured on a scale from 0 (little or no development) to 12 (fully developed). See "Computation of Basin Characteristics" and Sauer and others (1983) for a more complete description and method of computation.

BL — Basin length—The straight-line distance, in miles, measured from a specified location on a stream to the point on the drainage divide used to determine the main-channel length.

BS — Basin shape—The ratio of basin length, in miles, squared to total drainage area, in square miles.

BW — Mean basin width—Computed by dividing contributing drainage area, in square miles, by basin length, in miles.

EL — Average basin elevation index (in thousands of feet above sea level)—Determined by averaging main-channel elevations at points 10 and 85 percent of the distance from a specified location on the main channel to the topographic divide, as determined from U.S. Geological Survey 7.5-minute topographic quadrangle maps.

IA — Impervious area (in percent)—That part of the drainage area covered by impervious surfaces such as streets, parking lots, buildings, and so forth.

L — Main-channel length (in miles)—Distance measured along the main channel from a specified location on the channel to the topographic divide via the longest tributary, as determined from U.S. Geological Survey 7.5-minute topographic quadrangle maps.

Peak discharge — The maximum discharge, in cubic feet per second, from an observed or simulated discharge hydrograph.

$RI_{2,2}$ — 2-year, 2-hour rainfall amount, in inches, reported in Hershfield (1961) (1.7 inches for Jefferson County, Kentucky).

RQ_T — Equivalent rural peak discharge (in cubic feet per second)—The estimated rural peak discharge in Jefferson County with recurrence interval of T years, as computed from the regionalized regression equation developed by Choquette (1988) for Region 1 (North) in Kentucky.

RRM — USGS rainfall-runoff model. A lumped parameter model for small rural and urban basins having insignificant storage and relatively uniform areal rainfall distribution.

SL Main-channel slope (in feet per mile)—Computed as the difference in elevations (in feet) at points 10 and 85 percent of the distance along the main channel from a specified location on the channel to the topographic divide, divided by the channel distance (in miles) between the two points, as determined from U.S. Geological Survey 7.5-minute topographic quadrangle maps.

SS Main-channel sinuosity—The ratio of main-channel length, in miles, to basin length, in miles.

ST Storage area (in percent)—That part of the contributing drainage area occupied by lakes, ponds, and swamps, as shown on U.S. Geological Survey 7.5-minute topographic quadrangle maps. Temporary storage as a result of detention basins or ponding at roadway embankments is not included.

T Recurrence interval (in years)—The average interval, over a very long period of time, within which a given peak discharge is expected to be equaled or exceeded once.

UQ_T Urban peak discharge (in cubic feet per second)—The estimated urban peak discharge with recurrence interval of T years; computed from flood-frequency analysis of observed and (or) simulated long-term annual peak discharge data, or estimated from the regression equations presented in this report.

Estimation of Peak-Discharge Frequency of Urban Streams in Jefferson County, Kentucky

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Abstract

An investigation of flood-hydrograph characteristics for streams in urban Jefferson County, Kentucky, was made to obtain hydrologic information needed for water-resources management. Equations for estimating peak-discharge frequencies for ungaged streams in the county were developed by combining (1) long-term annual peak-discharge data and rainfall-runoff data collected from 1991 to 1995 in 13 urban basins and (2) long-term annual peak-discharge data in four rural basins located in hydrologically similar areas of neighboring counties. The basins ranged in size from 1.36 to 64.0 square miles. The U.S. Geological Survey Rainfall-Runoff Model (RRM) was calibrated for each of the urban basins. The calibrated models were used with long-term, historical rainfall and pan-evaporation data to simulate 79 years of annual peak-discharge data. Peak-discharge frequencies were estimated by fitting the logarithms of the annual peak discharges to a Pearson-Type III frequency distribution. The simulated peak-discharge frequencies were adjusted for improved reliability by application of bias-correction factors derived from peak-discharge frequencies based on local, observed annual peak discharges. The three-parameter and the preferred seven-parameter nationwide urban-peak-discharge regression equations previously developed by USGS investigators provided biased (high) estimates for the urban basins studied. Generalized-least-square regression procedures were used to relate peak-discharge frequency to selected basin characteristics. Regression equations were developed to estimate peak-discharge frequency by adjusting peak-discharge-frequency estimates made by use of the three-parameter nationwide urban regression equations. The regression equations are presented in equivalent forms as functions of contributing drainage area, main-channel slope, and basin development factor, which is an index for measuring the efficiency of the basin drainage system. Estimates of peak discharges for streams in the county can be made for the 2-, 5-, 10-, 25-, 50-, and 100-year recurrence intervals by use of the regression equations. The average standard errors of prediction of the regression equations ranges from ± 34 to ± 45 percent. The regression equations are applicable to ungaged streams in the county having a specific range of basin characteristics.

INTRODUCTION

As urban growth and development continues in Jefferson County, Kentucky, there is an ever-increasing need for stream discharge information in locations for which little or no hydrologic information is available. Changes associated with urban development, such as channel modifications, storm-sewer construction, and paving of pervious areas, generally lead to increased rates and volumes of surface runoff. These changes can increase flood hazards for the community in the absence of adequate hydrologic information for planning and design of structures. Peak-discharge-frequency estimates are needed by water-resources managers and engineers for (1) design of hydraulic structures such as storm sewers, channels, culverts, and bridges and (2) delineation of floodways for use in flood-plain management programs. Techniques for estimating peak-discharge frequencies for natural (rural) basins are not directly applicable to basins modified by development. Also, peak-discharge estimating procedures in which a theoretical design storm of a given frequency is used may be inappropriate because the rainfall-frequency distribution may not correspond to the peak-discharge-frequency distribution.

In 1991, the U.S. Geological Survey (USGS), in cooperation with the Louisville and Jefferson County Metropolitan Sewer District, began a study to determine and document flood-hydrograph characteristics in urban basins in the county. The objectives of this investigation were as follows.

1. Collect peak-discharge information at selected stream locations with varying urban watershed sizes in Jefferson County.
2. Calibrate rainfall-runoff models for selected local urban streamflow-gaging stations and use the calibrated models with historical meteorological data to simulate long-term series of annual peak discharges.
3. Estimate peak-discharge frequencies (recurrence intervals of 2, 5, 10, 25, 50, and 100 years) by use of the simulated peak discharges, observed peak discharges (where available), and nationwide urban peak-discharge-frequency equations (Sauer and others, 1983).
4. Compare peak-discharge-frequency estimates computed by use of the simulated annual peaks, observed annual peaks, and nationwide urban peak-discharge-frequency regression equations.
5. Attempt to develop new regression equations or confirm the applicability of existing regression equations to estimate peak-discharge frequencies of ungaged urban streams in Jefferson County, Kentucky.

Purpose and Scope

The purpose of this report is to describe techniques for estimating the magnitude and frequency (recurrence intervals of 2, 5, 10, 25, 50, and 100 years) of peak discharges for ungaged urban basins in Jefferson County, Kentucky. More specifically, the report describes (1) the collection of discharge and rainfall data for use in rainfall-runoff model calibration, (2) compilation and processing of long-term meteorological data used for simulation of the long-term discharge record with the calibrated rainfall-runoff models, (3) the alternative methods used to estimate urban peak-discharge frequencies, and (4) a comparison of results from the alternative methods of estimating peak-discharge frequencies.

Previous Studies

Previous investigations of peak-discharge frequency in Kentucky (McCabe, 1958, 1962; Speer and Gamble, 1964, 1965; Hannum, 1976; Wetzel and Bettandorff, 1986; and Choquette, 1988) focused primarily on rural locations within major river basins. Methods published previously for estimating peak-discharge frequencies in Kentucky are restricted to natural-flow streams not appreciably affected by urbanization.

Sauer and others (1983) developed regression equations for estimating peak-discharge frequencies in urban basins nationwide. These nationwide equations are based on a data set of 269 gaged basins in 56 cities in 31 states. Data from four long-term streamflow-gaging stations in Jefferson County were used in that study.

As described by Bell (1966), flood-control measures implemented by the United States Army Corps of Engineers have largely eliminated routine damages in the county caused by flooding of the Ohio River. However, localized flash floods on Ohio River tributaries in the county, such as Beargrass and Pond Creeks, can cause flooding of structures located in wide, flat overflow areas. In the eastern third of the county and a portion of the county south of Louisville, topographic relief is moderate to steep, rainfall infiltration to the soils is limited, and, therefore, rainfall moves rapidly as overland runoff to local streams. In the central part of the county and extending to the Ohio River, relief is relatively flat. Soils in much of this area are, in general, not well drained because of the nature of the subsoil and (or) the position of the water table (Zimmerman, 1966). Several drainage ditches (Northern Ditch, Spring Ditch, and Southern Ditch, for example) have been constructed in the central part of the county to improve drainage.

DATA COLLECTION

Rainfall, discharge, and evaporation data were collected in the study area. The following sections describe the data-collection sites, instrumentation, and procedures used in gathering these data.

Data-Collection Sites

Rainfall and discharge data for this study were collected at 11 partial-record (flood-hydrograph) streamflow-gaging stations, 3 long-term continuous-record streamflow-gaging stations, and at 18 rainfall-gaging stations within urban basins in Jefferson County (fig. 1, table 1). Eight of the rain gages were located at streamflow-gaging stations. Site selection was designed to ensure (1) collection of data from basins in Jefferson County outside of the combined-sewer network, (2) accessibility to a structure crossing the stream so that discharge measurements could be made during periods of high flow, and (3) positioning of sites at key locations in the basin where peak-discharge-frequency information was needed. In addition, long-term, historical, peak-discharge-frequency data for four rural basins (R1, R2, R3, and R4) (fig. 2, table 1) in hydrologically similar areas of neighboring counties were also used in the analysis.

Data-Collection Instrumentation and Procedures

The instrumentation at the streamflow-gaging stations typically consisted of a float and a counterweight inside a 12-in.-diameter aluminum stilling well to measure the stage, which was recorded using either a digital recorder or an electronic data-collection platform (DCP). Rainfall-gaging stations consisted of a tipping-bucket rain gage with a 50-square-inch opening to collect the rainfall, which was recorded using either a data logger or DCP. Measurements of discharge (streamflow) were made at each streamflow-gaging station during the study period for the purpose of developing a stage-discharge relation. Direct (current-meter) measurements of discharge were made at low-to-medium stages and at high stage whenever possible. At several sites where direct measurements at high stages were not available, however, stage-discharge relations for high stage were developed by use of indirect measurements (Dalrymple and Benson, 1984) and (or) step-backwater analysis (Shearman and others, 1986). Discharge data were computed from the recorded stage data using the stage-discharge relations. The discharge and rainfall data collected at the study sites were processed and stored using the USGS Automated Data-Processing System (ADAPS) (Dempster, 1990). A stable stage-discharge rating at high stages was not defined during the study period at one site,

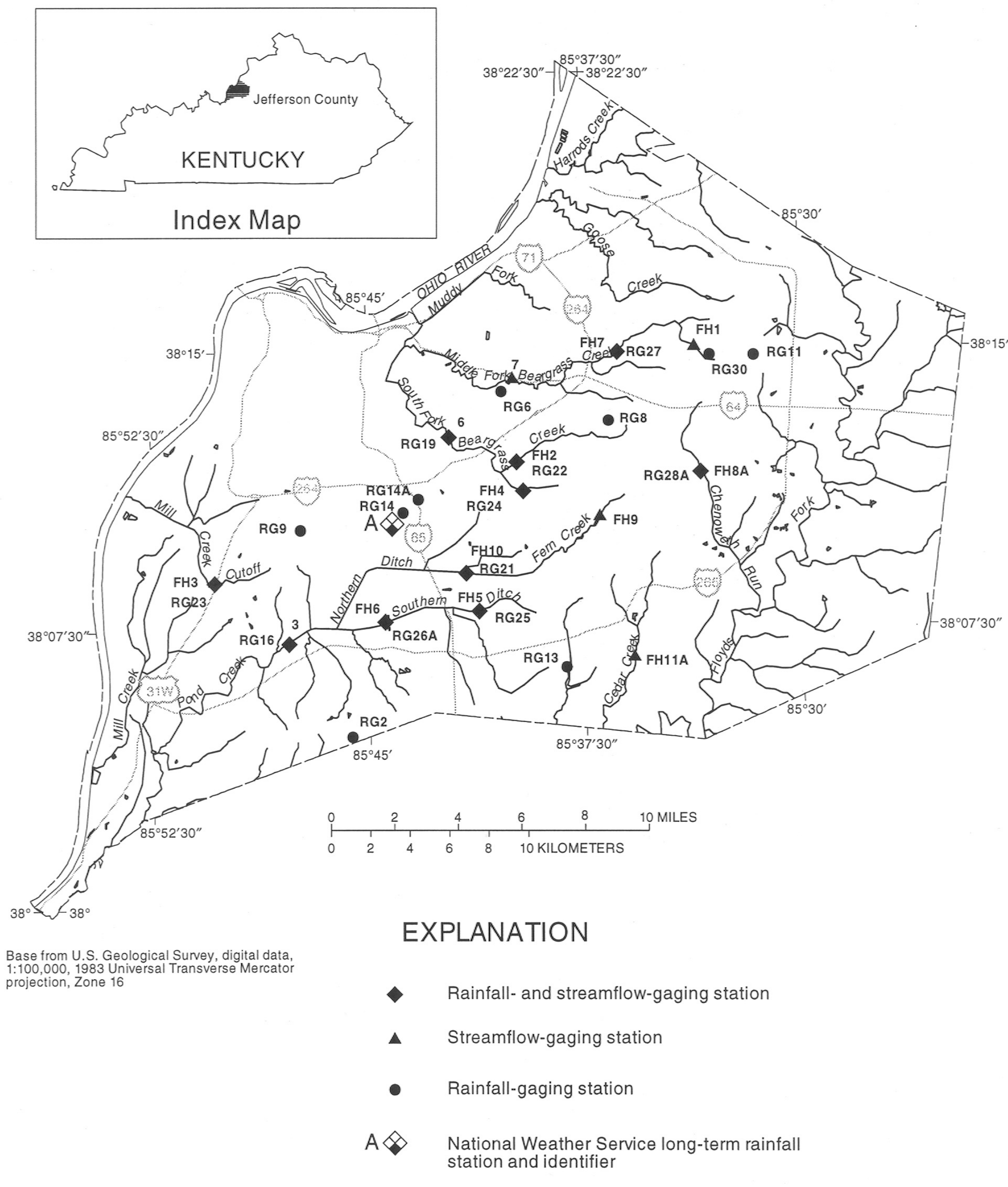

Figure 1. Approximate locations of rainfall- and streamflow-gaging stations in and around Jefferson County, Kentucky, used in the study.

Table 1. Discharge, rainfall, and evaporation data-collection sites in and around Jefferson County, Kentucky, used in the study

[USGS, U.S. Geological Survey; --, not applicable; RG, rainfall gage, D, discharge; R, rainfall; FH, flood-hydrograph gage; S, satellite telemetry; EV, evaporation; RB, rural basin]

Site identifier		USGS station number	Station name	Latitude[1]	Longitude[1]	Type of data	Period of record used
Figure 1	Figure 2						
3, RG16	--	03302000	Pond Creek at Manslick Road near Louisville	380711	854745	D, R	1964-95, 6/6/91-10/15/95
6, RG19	--	03292500	South Fork Beargrass Creek at Trevilian Way at Louisville	381241	854209	D, R	1961-95, 6/4/91-10/15/95
7	--	03293000	Middle Fork Beargrass Creek at Old Cannons Lane at Louisville	381414	853953	D	1961-95
FH1	--	03292700	Tributary to Middle Fork Beargrass Creek at Dorsey Lane near Middletown	381505	853336	D	02/07/91-10/10/95
FH2, RG22	--	03292496 S	South Fork Beargrass Creek at Bardstown Road at Buechel	381200	853946	D,R	02/08/91-10/12/95
FH3, RG23	--	03294510 S	Big Run at U.S. Highway 31 at Pleasure Ridge Park	380847	855017	D,R	03/21/91-10/12/95
FH4, RG24	--	03292498 S	Unnamed tributary to South Fork Beargrass Creek at Buechel	381112	853935	D,R	03/19/91-10/12/95
FH5, RG25	--	03301830 S	Southern Ditch at Blue Lick Road near Okolona	380800	854108	D,R	02/20/91-10/12/95
FH6, RG26A	--	03301890 S	Southern Ditch at CSX Railroad Bridge near Louisville	380742	854426	D,R	07/14/92-10/12/95
FH7, RG27	--	03292785 S	Middle Fork Beargrass Creek at Shelbyville Road at St. Matthews	381456	853616	D, D,R	1954-83, 02/22/91-10/12/95
FH8A, RG28A	--	03298135 S	Chenoweth Run at Ruckriegel Parkway at Jeffersontown	381141	853326	D,R	05/05/93-10/15/95
FH9	--	03301900	Fern Creek at Old Bardstown Road near Louisville	381032	853655	D	02/21/91-10/15/95
FH10, RG21	--	03301940 S	Northern Ditch at Preston Highway at Okolona	380901	853655	D,R	06/17/92-10/12/95
FH11A	--	03298242	Cedar Creek at Fairmount Road near Mount Washington	380643	853549	D	12/18/92-10/12/95
RG2	--	380438085453401	Camp Horine at Holsclaw Hill Road near Fairdale	380438	854534	R	05/22/91-10/15/95

Table 1. Discharge, rainfall, and evaporation data-collection sites in and around Jefferson County, Kentucky, used in the study—*Continued*

[USGS, U.S. Geological Survey; --, not applicable; RG, rainfall gage, D, discharge; R, rainfall; FH, flood-hydrograph gage; S, satellite telemetry; EV, evaporation; RB, rural basin]

Site identifier		USGS station number	Station name	Latitude[1]	Longitude[1]	Type of data	Period of record used
Figure 1	Figure 2						
RG6	--	381353085401801	Seneca Golf Course at Bon Air Avenue at Louisville	381353	854018	R	04/30/91-10/15/95
RG8	--	381306085363601	McMahan Fire Station at Taylorsville Road near Jeffersontown	381306	853636	R	05/22/91-10/15/95
RG9	--	381011085471901	Iroquois Golf Course at Taylor Boulevard at Louisville	381011	854719	R	05/22/91-10/15/95
RG11	--	381457085315401	East County Government Center at Shelbyville Road at Middletown	381451	853132	R	05/23/91-10/15/95
RG13	--	380626085380701	McNeely Lake at Park Road near Okolona	380626	853807	R	05/22/91-10/15/95
RG14	--	381039085434401	Standiford Field at Standiford Avenue at Louisville	381039	854344	R	06/07/91-07/15/94
RG14A	--	381059085431501	Gheens Academy at Preston Highway at Louisville	381059	854315	R	07/15/94-10/15/95
RG30	--	381451085330301	The Forum at Brookside near Middletown	381451	853303	R	02/04/92-02/02/95
--	A	--	Standiford Field, Louisville	381100	854400	R	1912-90
--	B	--	Dix Dam, Danville, Kentucky	374800	844300	EV	1953-95
--	C	--	Nolin River Lake, Kentucky	371700	861500	EV	1964-95
--	D	--	Lake Patoka, Dubois, Indiana	382700	864200	EV	1956-89
--	E	--	Spindletop Farm, Lexington, Kentucky	380759	842958	EV	1978-95
--	RB1	03292460	Harrods Creek near LaGrange	382650	852433	D	1968-85
--	RB2	03295845	Bradshaw Creek near Shelbyville	381055	851105	D	1976-85
--	RB3	03296500	Plum Creek near Wilsonville	380620	852614	D	1954-80
--	RB4	03297000	Little Plum Creek near Waterford	380344	852545	D	1954-77

[1]Degree, minute, and second symbols omitted.

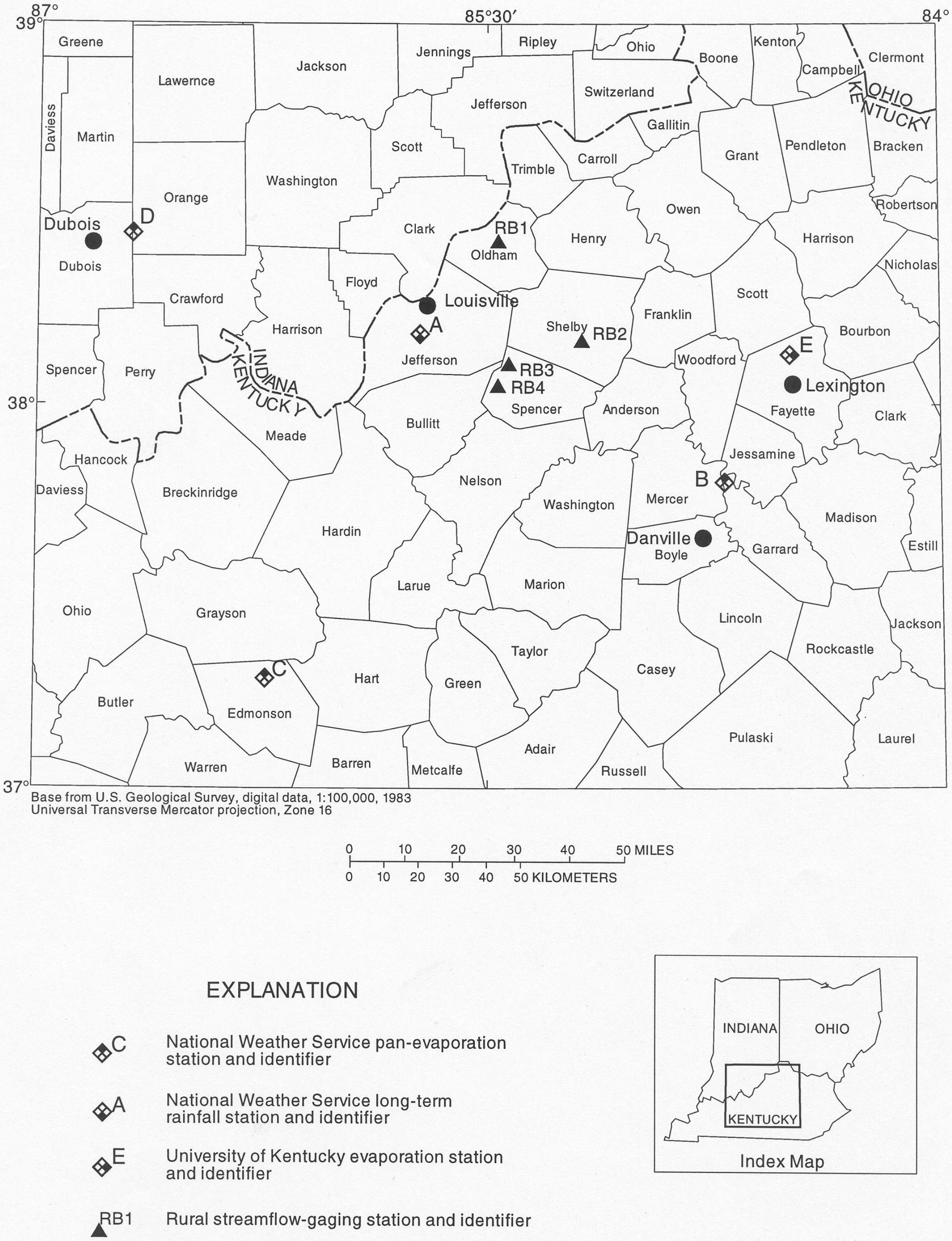

Figure 2. Approximate locations of the long-term rainfall station, evaporation stations, and the rural streamflow-gaging stations in Kentucky and Indiana, used in the study. (See table 1.)

Northern Ditch at Preston Highway at Okolona (site FH10) (fig. 1, table 1). Therefore, data from this site could not be used in the study.

Short-Term Rainfall, Discharge, and Evaporation

Rainfall and discharge data needed for the rainfall-runoff model calibration were collected from 1991 to 1995 (short-term) at urban sites in the study area (fig. 1, table 1). The USGS Rainfall-Runoff Model, referred to as RRM (originally developed by Dawdy and others, 1972), requires collection of unit[1] rainfall and unit discharge data for high-flow periods and daily rainfall and evaporation data. The recording interval for the rainfall data was 5 minutes, and the recording intervals for discharge data were 5, 15, or 30 minutes, depending on the drainage area and response time of the basin. A compilation of the unit rainfall and discharge data used for the RRM calibrations is available from the USGS. Daily rainfall was totaled from the incremental values. Unit and daily rainfall were compared to data at nearby stations as a quality-assurance check. Any missing daily rainfall totals were estimated using data from nearby rain gages.

Evaporation data are not available for Jefferson County; thus, data were estimated using daily evaporation data from the National Weather Service (NWS) stations at Dix Dam, near Danville, Kentucky; Nolin River Lake, Kentucky; Lake Patoka, near Dubois, Indiana; and a station operated by the University of Kentucky at Spindletop Farm, near Lexington, Kentucky (fig. 2, table 1). Varying periods of data were available for the pan evaporation sites; therefore, a composite of the data was used for this study.

[1]The term “unit” refers to data collected at recording intervals of less than one day.

Long-Term Rainfall and Evaporation

Long-term historical records of unit rainfall for storm periods, daily rainfall, and daily pan evaporation were needed for simulation of long-term peak-discharge data by use of the calibrated models. Five-minute rainfall data for up to five of the largest (1- to 2-day rainfall totals greater than 1 in.) storms per year at Louisville (fig. 2, table 1) were obtained from the NWS weighing-rain-gage charts for the period 1912-62. Five-minute rainfall data for storm periods from 1963 to 1990 were estimated from hourly NWS rainfall data by use of a rainfall-disaggregation technique developed by Ormsbee (1989). Even though individual peaks vary, comparisons of simulated-peak-discharge frequencies derived using observed 5-minute rainfall and using disaggregated 60-to-5-minute rainfall indicate little differences in the frequencies, on the basis of an analysis of data collected in Georgia (E.J. Inman, U.S. Geological Survey, oral commun., 1997). It is assumed that similar results would be obtained in Kentucky. Long-term daily rainfall data were obtained for the NWS station at Louisville, and long-term pan evaporation data were composited from stations in the region (fig. 2, table 1). Evaporation data for the periods of missing record (1912-52) were estimated as the average of each day of the years with available record.

ANALYSIS OF PEAK DISCHARGES AT STREAMFLOW-GAGING STATIONS

The following sections describe the steps in the analysis of peak discharges at the urban streamflow-gaging stations: (1) rainfall-runoff model calibrations using the observed short-term discharge, rainfall, and evaporation data, (2) simulation of the long-term annual peak discharges by use of the calibrated models and long-term rainfall and evaporation records, and (3) estimation of peak-discharge frequencies from the simulated annual peaks, observed annual peaks (where available), and by use of the nationwide regression equations. Similar analyses have been reported by Lichty and Liscum (1978), Inman (1983, 1988, and 1995), Franklin and Losey (1984), Sherwood (1986 and 1993), Bailey and others (1989), Bohman (1992), and Robbins and Pope (1996).

Calibration of the Rainfall-Runoff Model

The latest revision (J.M. Bergmann and others, U.S. Geological Survey, written commun., 1993) of the USGS Rainfall-Runoff Model (RRM) was used for this study. RRM, originally developed by Dawdy and others (1972), has been enhanced by Carrigan (1973), Boning (1974), and Carrigan and others (1977). RRM is a conceptual, parametric model designed for simulation of flood hydrographs on small rural or urban streams. Basic model assumptions include a relatively homogeneous basin cover with minimal storage and uniformly distributed rainfall. Lumped parameters incorporated in the model are intended to approximate, or index, the underlying physical processes affecting three components of the hydrologic cycle: antecedent soil moisture, infiltration, and surface runoff. The 11 parameters used in RRM are defined in table 2. Approximations inherent to lumped-parameter models of the underlying physical system necessarily limit the accuracy of model simulations. Further, the conceptual physical equivalence of the model can be lost in the process of model calibration. Routines for automated parameter optimization, long-term simulation, and frequency analysis are included in RRM. The input data used for model calibration included daily rainfall, daily evaporation, 5-minute rainfall, and 5-minute discharge values.

Four parameters (BMSM, EVC, RR, and DRN—see table 2 for definitions of terms) are used in the antecedent soil-moisture-accounting component of RRM to assess, on a daily basis, changes in soil moisture as a function of daily rainfall and evapotranspiration during the periods preceding storms. Infiltration is simulated using an approximation to the differential equation for unsaturated flow (Philip, 1954). Four parameters (PSP, KSAT, RGF, EIA) are used in the infiltration component in conjunction with the soil-moisture-accounting results to compute rainfall excess (runoff volume) from the 5-minute rainfall data for storm events. Three parameters (KSW, TC, TP/TC) are used in the surface-runoff-routing component with a modification of the Clark (1945) instantaneous-unit-hydrograph procedure to translate rainfall excess into the basin outflow hydrograph.

Calibration of RRM requires trial-and-error adjustment of model parameters in order to minimize differences between the simulated and observed hydrographs. Model error is computed as the sum of the squared deviations of log (base 10) transformed values of runoff volume and peak discharge. For each site, there were initially between 30 and 50 peak-discharge events above a selected minimum peak-discharge threshold available for use in calibration. The minimum peak-discharge thresholds were selected to provide a balanced sample of small and large events, and use of the threshold value typically yielded 8-10 peaks per year.

Prior to beginning calibrations, the event data were reviewed to identify obvious outliers, or nonrepresentative values. A basic assumption of RRM is the uniform distribution of rainfall over the basin during periods of runoff simulation. A truly uniform rainfall distribution is not usually realized, particularly when the basin is large and the rain falls during thunderstorms. Rainfall records at surrounding rain gages in a network of 31 rain gages in the county were reviewed to assess rainfall uniformity. Scatter plots of total event rainfall and runoff volume were reviewed to identify

Table 2. Rainfall-Runoff Model (RRM) parameters

[--, not applicable]

Parameter	Units	Definition
		Antecedent soil-moisture accounting component
BMSM	inches	Soil moisture storage volume at field capacity.
EVC	--	Coefficient to convert pan evaporation to potential evapotranspiration values.
DRN	inches per hour	A constant drainage rate for redistribution of soil moisture.
RR	--	Proportion of daily rainfall that infiltrates the soil.
		Infiltration component
PSP	inches	Minimum value of the combined action of capillary suction and soil moisture differential.
KSAT	inches per hour	Minimum saturated hydraulic conductivity used to determine soil infiltration rates.
RGF	--	Ratio of PSP for soil moisture at wilting point to that at field capacity.
EIA	--	The ratio of effective impervious area to total basin area; a measure of impervious area that is directly connected to the channel drainage system.
		Surface-runoff routing component
KSW	hours	Time characteristic of linear channel storage reservoir.
TC	minutes	Duration of the triangular translation hydrograph (time of concentration).
TP/TC	--	Ratio of time-to-peak to time of concentration.

nonrepresentative data. Data were discarded when (1) approximately uniform rainfall over the basin could not be obtained and (2) anomalies in the data were present (runoff greater than rainfall, rainfall more than approximately 10 times the runoff, snowmelt periods, plugged rainfall collectors, or recorder malfunction).

A Thiessen (1911) polygon overlay of the study basins was developed for the 18 rain gage locations. On some of the largest basins, the Thiessen polygon method was used to weight daily rainfalls at multiple rain gages in an effort to approximate a uniform rainfall record for the basin. The 5-minute rainfall data for storm periods for these basins were adjusted by use of a modified Thiessen method as described by Inman (1983).

Beginning and ending times and base flows were defined for each peak-discharge event. When possible, a series of peaks during an event was subdivided for specific analysis. Starting and limiting model parameter values were selected to begin the initial simulations. The parameters DRN, EVC, and TP/TC were fixed. DRN was set at 1.0 as was done by Alley and Smith (1982). EVC was fixed at 0.77 based on evaporation data presented by Kohler and others (1959). The value of TP/TC was fixed at 0.5 as suggested by Mitchell (1972). The starting value (0.10) and range (0.05-0.50) of KSAT were obtained from Chow (1964), and these parameters were based on the primary soil group in each basin (Zimmerman, 1991) and the corresponding Hydrologic Soil Classification (Group A, B, C, D) (Mockus, 1969). The initial values and range of BSMS also were estimated from county soils data. The initial values and ranges of the other soil-moisture-accounting and infiltration parameters—RR, RGF, and PSP—were taken from values suggested by Bergmann and others (U.S. Geological Survey, written commun., 1993). Effective impervious area (EIA), defined as the impervious area directly connected to the channel drainage system, was initially estimated to be within 75 percent of total impervious area. KSW and TC were estimated from plots of 5-minute rainfall and discharge data for 6-8 large storms per basin.

Calibration involved successive iterations of adjustments to the parameters affecting runoff volume and peak discharge, followed by adjustment of the routing parameters (KSW and TC), which affect only peak discharge. Many of the model parameters are interrelated. No unique set of parameters will provide the minimum total model error. Parameter values were manually optimized prior to use of the automatic trial-and-error parameter-optimization routine, which is based on a method devised by Rosenbrock (1960). RRM provides for optimization of parameters based on reduction of total error and reduction of bias, as measured by the slope of least-squares regression lines for (1) observed and simulated runoff volumes and (2) observed and simulated peaks.

The priority of the goals of calibration were to provide (1) unbiased estimates of runoff volume and peak discharge, (2) realistic parameter values, and (3) minimum average error of simulation. Obtaining a calibration that provides unbiased estimates is important because the model will be used to simulate peak discharges from the historical record that may be of greater magnitude than peak discharges that occurred during the calibration period. Attempting to constrain the model parameters to a physically realistic range of values would improve the likelihood of determining regional values for the RRM parameters. Results of the model calibrations are shown in figure 3 and table 3.

Simulation of Annual Peak Discharges

Annual peak discharges were simulated for each study basin using a subroutine of RRM developed by Carrigan and others (1977). The calibrated RRM parameter sets were used with the NWS long-term 5-minute event rainfall, daily rainfall, and daily evaporation data to generate a series of annual peak discharges for each study site. Rainfall during the period 1912-62 water years[2] was taken directly from the NWS weighing-rain-gage charts, whereas the event rainfall for the period 1963-90 water years was disaggregated (Ormsbee, 1989) from NWS observed hourly rainfall. Simulated annual peak discharge, rainfall corresponding to each simulated peak, and observed annual peak discharges for the four long-term streamflow-gaging stations are shown in figure 4. The plots show that the simulated peak discharges remain within a relatively stable range throughout the simulation period, affected only by the historical meteorological data. The rainfall-runoff models, calibrated for the basin characteristics present in 1991-95, simulate how the basins, at the current level of urban development, would respond to the historical series of meteorological conditions. The observed annual peak discharges at three sites (sites 3, 6, and 7) show an increasing trend

[2]Water year in U.S. Geological Survey reports dealing with surface-water supply is the 12-month period, October 1 through September 30. The water year is designated by the calendar year in which it ends. Thus, the year ending September 30, 1980, is called the “1980 water year.”

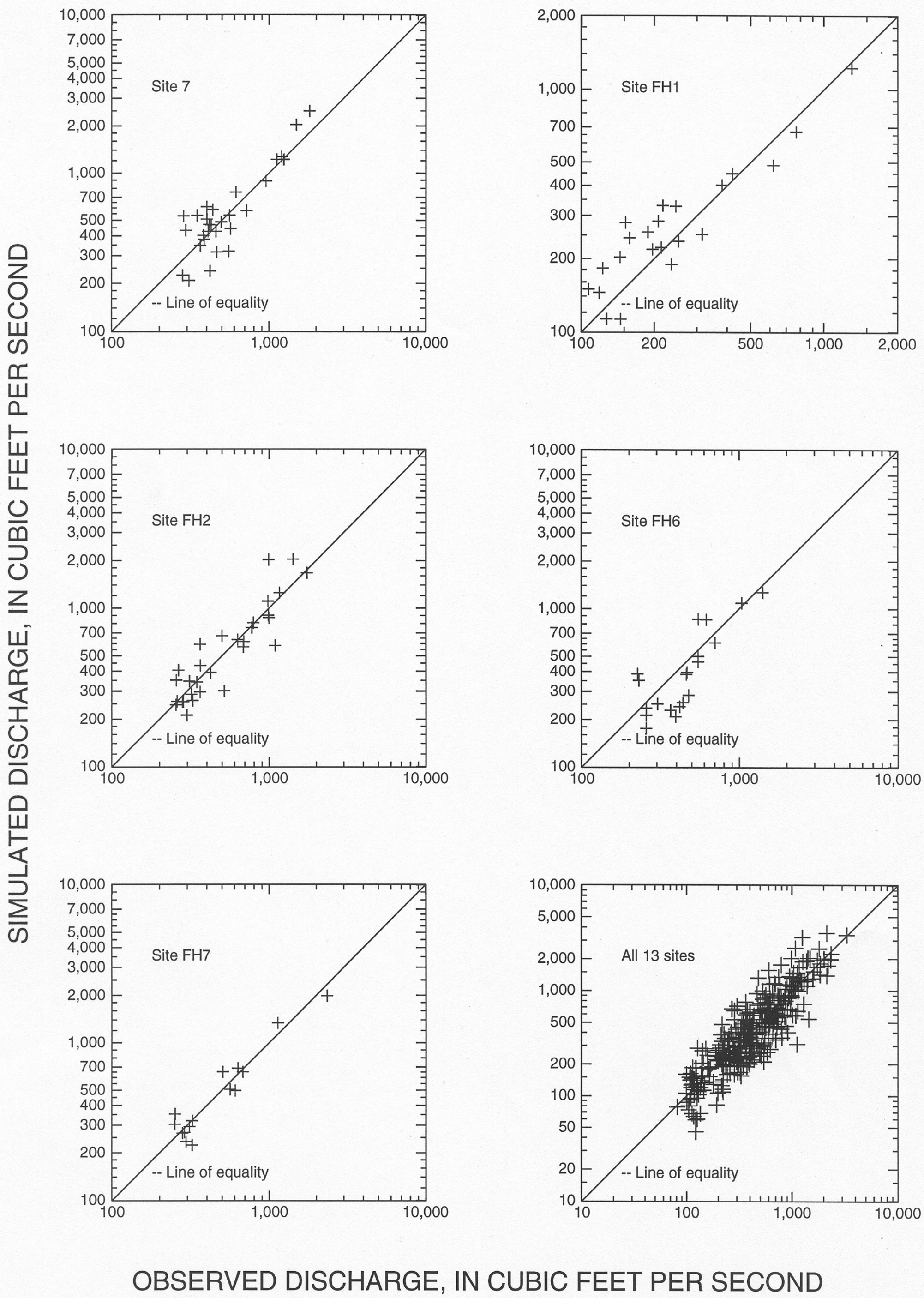

Figure 3. Comparison of observed and simulated peak discharges at selected sites and all sites combined for storms used in calibrations of the Rainfall-Runoff Model (RRM) for urban watersheds in Jefferson County, Kentucky.

Table 3. Optimized Rainfall-Runoff Model (RRM) parameter values for each study basin in Jefferson County, Kentucky

[RRM, rainfall-runoff model; fig., figure; parameters are defined in table 2; parameters DRN and TP/TC are assigned fixed values of 1.00 and 0.50, respectively, for all stations and not optimized; parameter EVC is assigned a fixed value of 0.77; SE, standard error of estimate of calibration results, based on the mean-square difference of logs of observed and simulated peaks]

Site identifier (fig. 1)	RRM infiltration, soil-moisture-accounting, and surface-runoff-routing parameters								Number of peaks	Slope of regression line	SE, in percent
	PSP	KSAT	RGF	BMSM	RR	KSW	TC	EIA			
3	0.92	0.05	16.4	2.28	0.95	7.51	481	0.05	42	0.97	47.7
6	.80	.10	10.0	8.00	.90	4.60	288	.20	32	1.00	35.8
7	1.10	.11	12.0	7.40	.95	6.70	400	.20	30	1.01	28.8
FH1	1.00	.10	10.0	8.00	.92	.89	54	.13	29	.97	33.7
FH2	1.40	.11	13.0	8.00	.90	1.83	100	.21	30	1.00	28.1
FH3	1.42	.08	18.5	10.0	.60	1.20	153	.15	36	.99	46.9
FH4	2.00	.10	11.0	5.10	.89	1.51	138	.19	29	1.01	33.4
FH5	1.90	.19	20.0	8.00	.90	1.45	108	.23	31	.98	37.7
FH6	.70	.09	9.0	8.00	.90	6.80	420	.15	20	.98	37.0
FH7	.80	.09	18.0	8.00	.78	1.56	256	.14	15	.97	18.8
FH8A	.91	.09	12.1	9.40	.90	1.18	76	.14	25	.98	45.4
FH9	.42	.12	10.8	8.30	.76	1.25	61	.08	22	1.01	54.8
FH11A	.55	.09	17.7	2.30	.95	1.09	208	.12	22	.97	47.5

in peak discharge over time. This trend could be caused by increasing urbanization over time and (or) upstream channelization.

Peak-Discharge-Frequency Analyses

The annual series of peak discharges simulated for each basin using RRM were log transformed and fitted to a Pearson-Type III distribution using procedures recommended in Bulletin 17B by the Interagency Advisory Committee on Water Data (IACWD) (1982). Skew coefficients computed from the simulated annual peaks were used at each site. The generalized skew coefficients provided in Bulletin 17B were not used for the simulated annual peaks because the values were derived from data for rural basins, which may not generally be applicable to urban basins. The low-outlier thresholds computed by use of methods recommended by the Committee excluded the 1931 annual peak from the frequency analysis at six sites. This 1931 peak was just above the low-outlier threshold at the remaining seven sites. For consistency, annual peaks just above the low-outlier threshold (generally the 1931 peak) were removed from the analysis at all sites. Peak discharges for the 2-, 5-, 10-, 25-, 50-, and 100-year recurrence intervals were computed based on the 1912-90 simulated annual peaks for each modeled basin. (See “Supplemental Data” at the end of the report.)

Peak-discharge frequencies also were estimated using observed annual peak discharge at the four long-term urban streamflow-gaging stations (3, 6, 7, and FH7) in Jefferson County using procedures recommended by the IACWD.

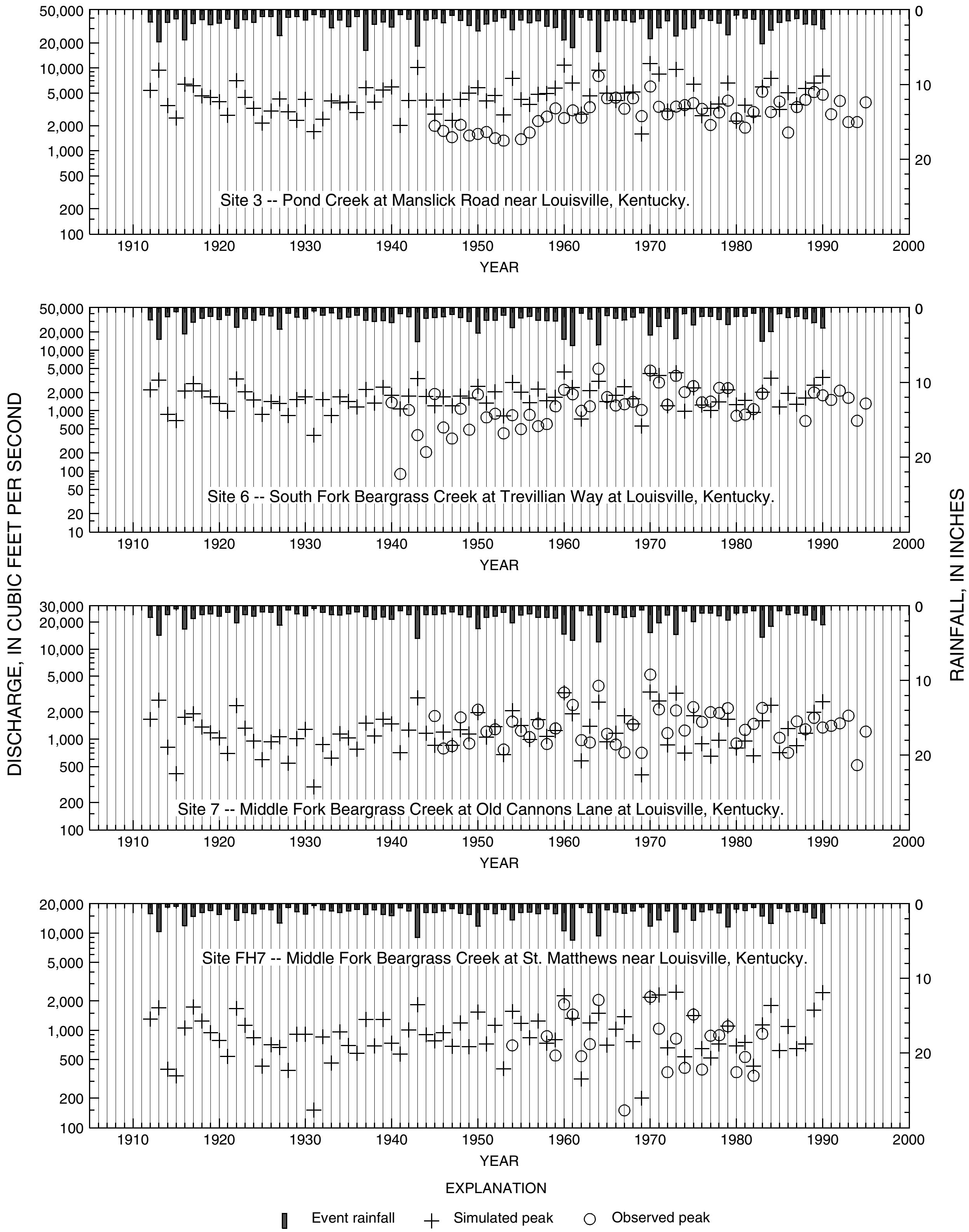

Figure 4. Simulated annual peak discharges, event rainfall, and observed annual peak discharges for selected long-term streamflow-gaging stations in Jefferson County, Kentucky.

As recommended in Bulletin 17B by the IACWD (1982), skew coefficients computed from the observed annual peaks were weighted with an estimated 'city skew' of 0.3 for Louisville, Kentucky reported by Sauer and others (1983).

Review of graphs showing the long-term observed annual peak discharges (fig. 4) indicated that urbanization and (or) channelization had most probably resulted in the increase of the annual peaks at sites 3, 6 and 7; whereas annual peaks at site FH7 appeared relatively unchanged during the period of record. The data beginning with the 1961 water year appeared relatively homogeneous for sites 6 and 7 in the Beargrass Creek Basin and were thus used for the frequency analysis. The entire record (1954-83) was used at site FH7. A channelization project in the Pond Creek Basin was completed by 1964; therefore, the period from 1964 to 1995 was used in the frequency analysis. Peak-discharge frequencies for the four rural basins were computed by Choquette (1988) as recommended for rural basins in Bulletin 17B by the IACWD.

The distribution of simulated annual-peak discharges may not duplicate the distribution of typical observed annual-peak discharges—potentially altering the mean, variance, and skew of the annual peaks and biasing the resulting frequency estimates. Previous investigators (Kirby, 1975; Lichty and Liscum, 1978; Thomas, 1982; Sherwood, 1993) have reported that simulated annual-peak discharges (for rural basins at least) tend to have less variance than observed annual peak discharges. This loss of variance, caused in part by the smoothing effect of the rainfall-runoff model and possibly rain gage under-measurement of intense rainfalls, results in a flattening of the peak-discharge-frequency curve (fig. 5). Thus, peak-discharge estimates for long recurrence intervals (100 years) based on simulated data can be considerably less than estimates based on observed data, whereas the peak-discharge estimates for short recurrence intervals (2 years and less) differ minimally.

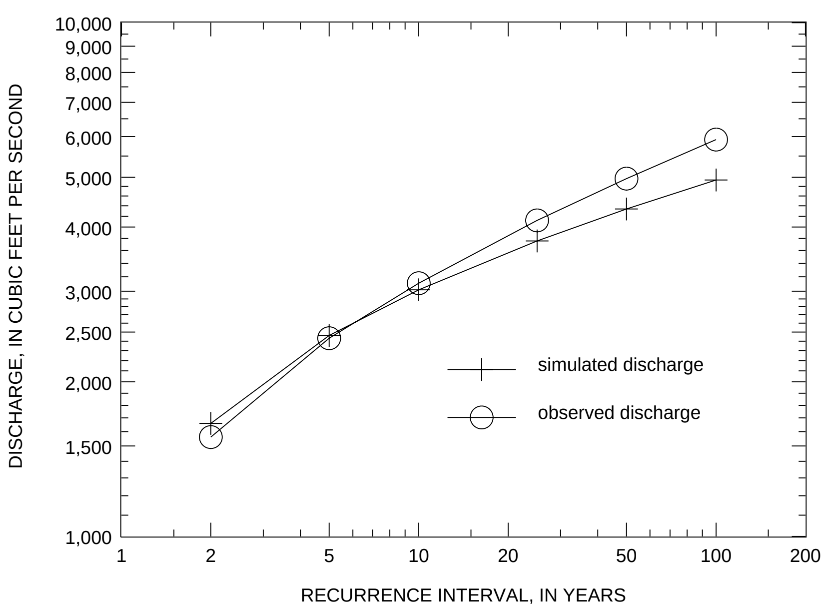

Figure 5. Comparison of peak-discharge frequencies estimated from observed and simulated annual peak discharge at South Fork Beargrass Creek at Trevilian Way at Louisville, Kentucky.

The simulated and observed annual-peak-discharge time series and computed annual-peak-discharge frequencies of each time series were compared at the four sites with observed data. The simulated-annual-peak discharges at site 3 consistently overestimated the annual peak discharge, even after 1964. This was presumably a consequence of the large basin size (64 mi^2), for which the assumption of uniform, intense rainfall over the basin would probably not be valid. The computed simulated-peak-discharge frequencies for site 3 were considered too large, and, therefore, were not used further in the analysis.

Statistics summarizing the observed and simulated annual peaks for the other three sites with long-term observed data indicated little difference in the variances (standard deviations), whereas skew for the simulated annual peaks were less than the skews for the observed annual peaks. This reduction in skew would also tend to flatten the peak-discharge-frequency curve.

Comparison of peak-discharge frequencies computed from the observed and simulated-annual-peak discharges at sites 6, 7, and FH7 indicated that for the 2-, 5-, 10-, 25-, 50-, and 100-year recurrence intervals, the average ratios of the mean observed-peak discharge to the mean simulated-peak discharge were 0.99, 1.04, 1.08, 1.14, 1.19, and 1.23, respectively. These ratios are consistent with the magnitudes of the bias-correction factors for adjustment of simulated-peak-discharge frequencies reported by previous investigators (Lichty and Liscum, 1978; Thomas, 1982; and Sherwood, 1993). It is assumed that the observed data provides the best estimate of the true peak-discharge-frequency distribution, which can not be known with certainty. Therefore, the peak-discharge frequencies for the simulated-peak discharges for the 5- through 100-year recurrence interval were multiplied by the computed bias-collection factors to adjust for the indicated bias. The peak-discharge frequencies for the observed and simulated peak discharges are presented for comparison in "Supplemental Data" at the end of the report. The values of the peak-discharge frequencies assigned for each site and used for the subsequent regression analyses are listed in table 4. For the four urban basins with long-term observed data (sites 3, 6, 7, and FH7), the peak-discharge frequencies based on the observed data were used in the regression analysis and are listed in table 4.

COMPARISON OF PEAK-DISCHARGE-FREQUENCY ESTIMATES AT STREAMFLOW-GAGING STATIONS

A comparison was made of the peak-discharge-frequency estimates based on the observed and simulated annual-peak discharges (table 4) and peak-discharge-frequency estimates computed using the nationwide regression equations (Sauer and other, 1983) for urban basins in Jefferson County, Kentucky. Sauer and others (1983) presented a set of equations based on three parameters and two sets of equations based on seven parameters. The three-parameter and the preferred seven-parameter equations were compared to the local data. The following explanatory variables were significant in the nationwide regression equations:

Preferred seven-parameter equations —
RQ_T, BDF, A, IA, SL, ST, $RI_{2,2}$

Three-parameter equations —
RQ_T, BDF, A

The terms shown in the two sets of equations are defined in the Glossary and in "Basin Characteristics."

Table 4. Peak-discharge-frequency data from long-term observed and simulated discharges for selected recurrence intervals in urban basins in Jefferson County, Kentucky

[A, contributing drainage area (in square miles); peak discharge is in cubic feet per second; recurrence interval is in years; FH, flood-hydrograph gage; RB, rural basin]

Site identifier (figure 1)	A	Peak discharge for indicated recurrence interval					
		2	5	10	25	50	100
3	64.0	3,380	4,530	5,310	6,320	7,090	7,880
6	17.2	1,560	2,430	3,110	4,120	4,970	5,920
7	18.4	1,400	2,130	2,710	3,530	4,220	4,970
FH1	1.66	557	859	1,070	1,360	1,570	1,780
FH2	7.34	1,280	2,030	2,600	3,420	4,090	4,800
FH3	3.36	518	863	1,130	1,540	1,880	2,240
FH4	3.78	642	1,020	1,310	1,730	2,080	2,450
FH5	2.75	374	612	812	1,120	1,400	1,710
FH6	18.1	1,340	2,050	2,620	3,480	4,210	4,980
FH7	6.51	742	1,290	1,710	2,320	2,810	3,350
FH8A	5.39	1,470	2,270	2,830	3,580	4,160	4,720
FH9	3.41	969	1,480	1,840	2,300	2,680	3,040
FH11A	7.73	1,630	2,450	3,070	3,900	4,570	5,240
RB1	24.1	3,470	4,440	5,010	5,690	6,150	6,590
RB2	1.36	282	630	958	1,500	2,000	2,590
RB3	19.1	2,870	4,180	5,030	6,080	6,840	7,570
RB4	5.15	1,440	2,360	3,090	4,160	5,070	6,080

Choquette (1988).

The three-parameter equations (table 5) and seven-parameter equations incorporate estimates of the equivalent rural peak discharge, RQ_T. The equations for computing RQ_T, (Choquette, 1988) in Jefferson County were originally defined using two hydrologic regions for flood frequency—Region 1 (North Kentucky) and Region 5 (East-Central Kentucky). However, it was found that for this set of 13 urban basins, use of Region 1 for the entire county provided improved urban peak-discharge-frequency estimates. Therefore, estimates of the equivalent rural peak discharges were computed using the peak-discharge-frequency regression equations (table 6) for Region 1 only. The values of equivalent rural peak discharge and peak discharge computed from the nationwide equations for the 13 urban basins in Jefferson County and the 4 rural basins in neighboring counties are shown in “Supplemental Data” at the end of the report.

Table 5. Three-parameter nationwide urban peak-discharge-frequency estimating equations (Sauer and others, 1983)

[UQ_T, peak discharge for an urban drainage basin, in cubic feet per second; A, contributing drainage area, in square miles; BDF, basin development factor, on a scale from 0 to 12; RQ_T, equivalent rural peak discharge for an urban drainage basin, in cubic feet per second; ±, plus-minus; --, not available]

Recurrence interval (years)	Peak-discharge estimating equations	Average standard error of regression (percent)	Average standard error of prediction (percent)
2	$UQ_2 = 13.2A^{.21}(13 - BDF)^{-.43}RQ_2^{.73}$	±43	±44
5	$UQ_5 = 10.6A^{.17}(13 - BDF)^{-.39}RQ_5^{.78}$	±40	--
10	$UQ_{10} = 9.51A^{.16}(13 - BDF)^{-.36}RQ_{10}^{.79}$	±41	±43
25	$UQ_{25} = 8.68A^{.15}(13 - BDF)^{-.34}RQ_{25}^{.80}$	±43	--
50	$UQ_{50} = 8.04A^{.15}(13 - BDF)^{-.32}RQ_{50}^{.81}$	±44	--
100	$UQ_{100} = 7.70A^{.15}(13 - BDF)^{-.32}RQ_{100}^{.82}$	±46	±49

Table 6. Equations for estimating equivalent rural peak discharges of urban streams in Jefferson County, Kentucky

[RQ_T, equivalent rural peak discharge for an urban drainage basin, in cubic feet per second; A, contributing drainage area, in square miles; SL, main channel slope, in feet per mile; ±, plus-minus]

Recurrence interval (years)	Equivalent rural peak discharge estimating equations[a]	Average standard error of regression (percent)	Average standard error of prediction (percent)
2	$RQ_2 = 97.4(A^{0.824})\ (SL^{0.224})\ (1.082)$[b]	±41.4	±45.6
5	$RQ_5 = 76.2(A^{0.882})\ (SL^{0.389})\ (1.072)$	±38.5	±42.2
10	$RQ_{10} = 67.8(A^{0.910})\ (SL^{0.472})\ (1.075)$	±39.3	±43.0
25	$RQ_{25} = 60.1(A^{0.940})\ (SL^{0.560})\ (1.085)$	±42.1	±46.1
50	$RQ_{50} = 55.7(A^{0.959})\ (SL^{0.617})\ (1.095)$	±44.7	±49.2
100	$RQ_{100} = 51.4(A^{0.978})\ (SL^{0.669})\ (1.109)$	±47.8	±52.8

[a]Peak-discharge-frequency regression equations for Region 1 (North) in Kentucky (Choquette, 1988).
[b]Bias correction factor for detransformation from logs (base e).

To estimate the precision of the nationwide relations with the Jefferson County data, the observed peak-discharge frequencies (table 4) and the peak-discharge-frequencies estimated from the three- and seven-parameter nationwide equations were converted to logarithms. The mean difference, or error ($\bar{x}$), and standard deviation of the difference (*S*) were determined using the logarithms. The mean error was determined by taking the difference between the observed peak discharges and the peak discharges computed using the nationwide equations and averaging the differences. The standard deviation of the errors is that computed between observed and estimated peak discharges that results from applying the nationwide equations to Jefferson County data. The root mean square error (*RMSE*) was computed as

$$RMSE = \sqrt{\bar{x}^2 + S^2}$$

and is a measure of the precision of the nationwide equations as applied to the Jefferson County basins. The values of RMSE, which approximate the standard error of estimate in this case, were converted to a percentage using information presented by Hardison (1971). These values are shown in table 7.

The mean error $\bar{x}$ is an indication of the magnitude of the bias present in the regression estimates. The three- and seven-parameter equations tended to overestimate peak discharges for the urban basins studied as indicated by positive average error (table 7). The student's t-test was used to indicate if any $\bar{x}$ values were significantly different from zero. The student's t-test indicated that these positive errors are statistically significant at the 0.01 level for the 2- and 10-year recurrence interval using the three-parameter equation. The student's t-test indicated that these positive errors are statistically significant at the 0.05 level for the 100-year recurrence interval using the three-parameter equation and for the 2-, 10-, and 100-year recurrence interval using the seven-parameter equation. A comparison of the 2- and 100-year observed peak discharge and the three- and seven-parameter nationwide regression estimates is shown in figure 6.

Table 7. Error analysis of nationwide equations applied to urban basins in Jefferson County, Kentucky

[$\bar{x}$, mean error; *S*, standard deviation of the error; *RMSE*, root mean square error; ±, plus-minus]

Recurrence interval (years)	Three-parameter equations			Seven-parameter equations		
	$\bar{x}$ (log units)	*S* (log units)	*RMSE* (log units/percent)	$\bar{x}$ (log units)	*S* (log units)	*RMSE* (log units/percent)
2	0.1352[a]	0.1655	0.2137/±52	0.094[b]	0.1568	0.1828/±44
10	.1216[a]	.1622	.2027/±49	.1081[b]	.1533	.1876/±45
100	.0996[b]	.1636	.1915/±46	.0967[b]	.1514	.1796/±43

[a]Indicates that positive average errors are statistically significant based on student's t-test at 1-percent level of significance.

[b]Indicates that positive average errors are statistically significant based on student's t-test at 5-percent level of significance.

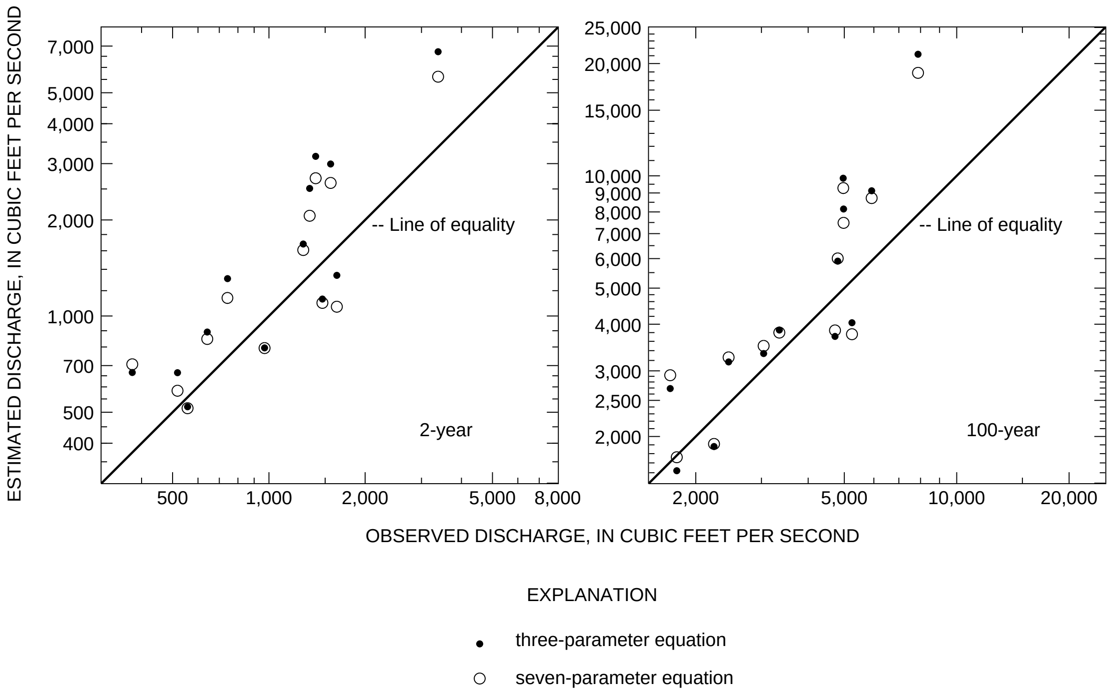

Figure 6. Comparison of 2- and 100-year observed peak discharge to peak discharges estimated using the three- and seven-parameter nationwide regression equations for urban basins in Jefferson County, Kentucky.

DEVELOPMENT OF PEAK-DISCHARGE-FREQUENCY EQUATIONS FOR UNGAGED URBAN STREAMS

Multiple-regression techniques were used to develop equations to estimate peak discharges for 2-, 5-, 10-, 25-, 50-, and 100-year recurrence intervals (the response variables) from the basin characteristics (the explanatory variables). Response and explanatory variables were log (base 10) transformed for the regression analysis in order to improve the linearity of the relations between peak discharges and basin characteristics. The regression analysis included an exploratory phase using ordinary-least-squares (OLS) regression and a final phase using generalized-least-squares (GLS) regression. GLS regression compensates for differences in the variability and reliability of, and correlation among, the peak-discharge-frequency estimates at stations included in the analysis. The final regression equations were tested for parameter bias and for sensitivity to error in the values of basin characteristics determined for the explanatory variables.

Basin Characteristics

Basin characteristics[3] that are potentially related to peak-discharge frequency determined for the study basins included contributing drainage area (A), main-channel slope (SL), impervious area (IA), basin development factor (BDF), basin storage (ST), equivalent rural peak discharge for T-year recurrence intervals (RQ_T), basin length (BL), mean basin width (BW, or A/BL), main-channel length (L), basin shape

[3]See glossary for definition of terms.

(BS), main-channel sinuosity (SS), main-channel elevation (EL), main-channel length divided by the square root of main-channel slope ($L/\sqrt{SL}$), and basin azimuth (AZ). Percent coverages of soil and land-use types also were determined for each basin. Values of basin characteristics were estimated from available digital coverages for the county and from USGS 7.5-minute topographic maps. Selected basin characteristics and the equivalent rural peak discharges are shown in table 8. These basin characteristics were included in the regression analysis because earlier analyses by Choquette (1988) and Sauer and others (1983) had indicated that these may be significant explanatory variables.

Regression Analysis

The exploratory (first) phase of the regression analysis was done using OLS regression techniques. The alternative regression models were generated by all-possible-regression and stepwise-regression procedures (Statistical Analysis System Institute, 1985) using the prospective explanatory variables listed in "Basin Characteristics." Seven factors were considered in evaluating alternative regression models, including (1) the coefficient of determination, the proportion of the variation in the response variable explained by the regression equation, (2) the standard error of the estimate, a measure of model-fitting error, (3) the PRESS statistic, a measure of model-prediction error, (4) the statistical significance of each alternative explanatory variable, (5) potential multicollinearity as indicated by the correlation of explanatory variables and the value of the variance inflation factor (Montgomery and Peck, 1982), (6) the effort and modeling benefit of determining the values of each additional explanatory variable, and (7) the hydrologic validity of the signs and magnitudes of the regression exponents.

The initial OLS exploratory phase of the regression analysis failed to yield a regression equation that explicitly included explanatory variables indicative of the intensity of urban development, such as percent impervious area (IA) and basin development factor (BDF). Apparently, the modest range of impervious area (15 to 35 percent) and BDF (3 to 7) for the 13 urban basins did not provide sufficient sample variability for the level of urbanization to be a uniquely distinguishing factor. In a test of an expanded sample variability, six nearby rural basins with negligible impervious area were added to the regression analysis. Results for this regression indicated that the best two-parameter equation included A and IA. However, it was found that the regression coefficient for IA was not significant (level of significance greater than 0.06) for this expanded sample set. BDF was also not significant when combined with A in this regression.

As an alternative to including IA or BDF explicitly in a local regression equation, peak-discharge-frequency estimates from the nationwide urban regression equations (Sauer and others, 1983), which are a function of BDF, were analyzed as explanatory variables in the sample set of the 13 urban basins in Jefferson County and 4 rural basins located in hydrologically similar areas of neighboring Oldham, Shelby, and Spencer Counties (fig. 2, table 1). OLS regressions and regional-model-adjustment procedures (Hoos, 1996) indicated that a regression against the three-parameter nationwide urban peak-discharge estimate would provide the most accurate estimates of the observed data for the 17 basins. The approach, in effect, provides a calibration of the nationwide regression equation by use of a local data set.

OLS regression is an appropriate method when estimates of the response variable (peak discharge) are independent and the variability and reliability of the response variables are approximately equal; however, the annual peak discharges at stream locations close in proximity are correlated and are, therefore, not independent. The simulated-annual-peak discharges are also correlated because the same

Table 8. Selected basin characteristics and estimated equivalent rural peak discharges for urban basins in Jefferson County, Kentucky, and rural basins in neighboring Oldham, Shelby, and Spencer Counties, used in the study

[A, contributing drainage area; SL, main channel slope; IA, impervious area; ST, basin storage; BDF, basin development factor (on a scale of 0-12); RQ_T, equivalent rural peak discharge for 2-, 5-, 10-, 25-, 50-, and 100-year recurrence intervals; fig., figure; mi^2, square mile; ft/mi, feet per mile; %, percent; ft^3/s, cubic feet per second]

Site identifier (fig. 1)	A (mi^2)	SL (ft/mi)	IA (%)	ST (%)	BDF	RQ_2[a] (ft^3/s)	RQ_5[a] (ft^3/s)	RQ_{10}[a] (ft^3/s)	RQ_{25}[a] (ft^3/s)	RQ_{50}[a] (ft^3/s)	RQ_{100}[a] (ft^3/s)
3	64.0	11.7	35.1	0.5	4	5,630	8,330	10,200	12,900	15,000	17,300
6	17.2	19.4	32.6	.2	7	2,130	3,180	3,930	4,980	5,820	6,700
7	18.4	20.0	28.8	.3	7	2,260	3,410	4,230	5,380	6,300	7,270
FH1	1.66	48.0	29.3	.1	7	381	576	719	918	1,080	1,250
FH2	7.34	38.6	32.8	.1	7	1,240	1,960	2,510	3,290	3,930	4,610
FH3	3.36	25.0	16.6	.2	3	588	832	1,000	1,240	1,420	1,610
FH4	3.78	46.3	22.6	.3	5	744	1,170	1,490	1,950	2,330	2,720
FH5	2.75	67.8	24.8	.0	3	624	1,030	1,340	1,790	2,170	2,570
FH6	18.1	19.5	18.5	.6	3	2,230	3,340	4,130	5,240	6,130	7,060
FH7	6.51	24.0	23.1	.3	6	1,000	1,470	1,800	2,250	2,610	2,980
FH8A	5.39	33.3	32.1	.1	5	926	1,410	1,770	2,260	2,670	3,090
FH9	3.41	69.3	17.4	.1	3	748	1,250	1,640	2,220	2,700	3,220
FH11A	7.73	22.2	15.1	.8	4	1,140	1,660	2,030	2,540	2,940	3,360
R1	24.1	11.7	1.0	1.0	0	2,510	3,520	4,220	5,150	5,890	6,650
R2	1.36	75.1	1.0	1.0	0	356	575	741	978	1,180	1,380
R3	19.1	14.8	1.0	1.0	0	2,180	3,140	3,800	4,710	5,430	6,180
R4	5.15	52.1	1.0	1.0	0	982	1,610	2,090	2,780	3.370	3,990

[a]Computed using the peak-discharge-frequency regression equations for Region 1 (North) in Kentucky (Choquette, 1988).

historical rainfall and evaporation record was used to generate the annual peak discharges at each site. The reliability and variability of the peak-discharge-frequency estimates varies among the sites with observed and simulated records.

The GLS regression techniques (Stedinger and Tasker, 1985; Tasker and Stedinger, 1989) weight each response variable in the data set to account for differences in the variability and reliability of, and correlation among, response variables. Application of GLS regression required estimates of the standard deviation, effective record length, and cross-correlation coefficients of the series of annual peak discharges at each site. A regional regression of sample standard deviations and drainage area was used to provide an independent estimate of the standard deviations of the annual peak discharges.

Effective record length is an indicator of the reliability of estimates of peak-discharge frequency derived from simulated data as compared to estimates derived from observed data. Estimates of effective record length for sites with simulated annual peaks (table 9) (Sherwood, 1986; Inman, 1995) were computed based on methods described by Lichty and Liscum (1978) and Hardison (1971). Actual record lengths were used at the four urban and four rural sites with long-term observed data.

Table 9. Estimated effective record lengths for 2- to 100-year recurrence intervals for urban basins with simulated annual peak discharges in Jefferson County, Kentucky

Recurrence interval (in years)	Effective record lengths (in years)
2	5
5	9
10	14
25	19
50	21
100	21

Average cross correlations of annual peak discharges were estimated using the sample cross correlations. The average Pearson correlation coefficients among (1) urban sites with simulated annual peaks, (2) urban sites with observed annual peaks, and (3) rural sites with observed annual peaks are shown in the following matrix:

	Urban		Rural
	Observed	Simulated	Observed
Urban			
Observed	0.78		
Simulated	.50	0.94	
Rural			
Observed	.29	.50	0.23

The reduced forms of the GLS regression equations for Jefferson County are shown in table 10. These reduced forms were obtained by combining the component regression equations and simplifying as follows:

$UQ_T = f(A, BDF, RQ_T)$

and $RQ_T = f(A, SL)$,

therefore, $UQ_T = f(A, SL, BDF)$.

Table 10. Equations for estimating peak discharges of ungaged urban streams in Jefferson County, Kentucky

[UQ_T, peak discharge for an urban drainage basin, in cubic feet per second; A, contributing drainage area, in square miles; S, main-channel slope, in feet per mile; BDF, basin development factor, on a scale of 0 to 12; ±, plus-minus]

Recurrence interval (years)	Peak-discharge estimating equations[a]	Average standard error of prediction (percent)
2	$UQ_2 = 442A^{0.635}SL^{0.128}(13 - BDF)^{-0.337}$	±45.4
5	$UQ_5 = 517A^{0.589}SL^{0.208}(13 - BDF)^{-0.268}$	±40.2
10	$UQ_{10} = 561A^{0.574}SL^{0.243}(13 - BDF)^{-0.235}$	±37.6
25	$UQ_{25} = 647A^{0.556}SL^{0.276}(13 - BDF)^{-0.209}$	±35.4
50	$UQ_{50} = 703A^{0.547}SL^{0.295}(13 - BDF)^{-0.189}$	±34.4
100	$UQ_{100} = 780A^{0.538}SL^{0.310}(13 - BDF)^{-0.181}$	±33.8

[a]Applicable ranges: A, 1.36-64.0; SL, 11.7-75.1; BDF, 0-7.

Model average standard errors of prediction ranged from ± 34 to ± 45 percent for the Jefferson County regression equations (table 10). The mean error, standard deviation of the errors, and the root mean square error computed from the observed and estimated peak-discharge frequencies are shown in table 11. These errors are less than the standard errors of estimate computed for application of the unadjusted three-parameter and preferred seven-parameter nationwide urban equations for the urban basins studied in Jefferson County. (See “Comparison of Peak-Discharge-Frequency Estimates at Streamflow-Gaging Stations” for additional information.)

Table 11. Error analysis of equations for estimating peak-discharge frequency for urban basins in Jefferson County, Kentucky

[$\bar{x}$, mean error; *S*, standard deviation of the error; *RMSE*, root mean square error; ±, plus-minus]

Recurrence interval (years)	$\bar{x}$ (log units)	*S* (log units)	*RMSE* (log units/ percent)
2	0.0167	0.1680	0.1688/±40.4
10	.0326	.1421	.1458/±34.6
100	.0388	.1235	.1295/±30.4

A comparison of the 2- and 100-year observed peak discharge to the estimates from the Jefferson County regression is shown in figure 7.

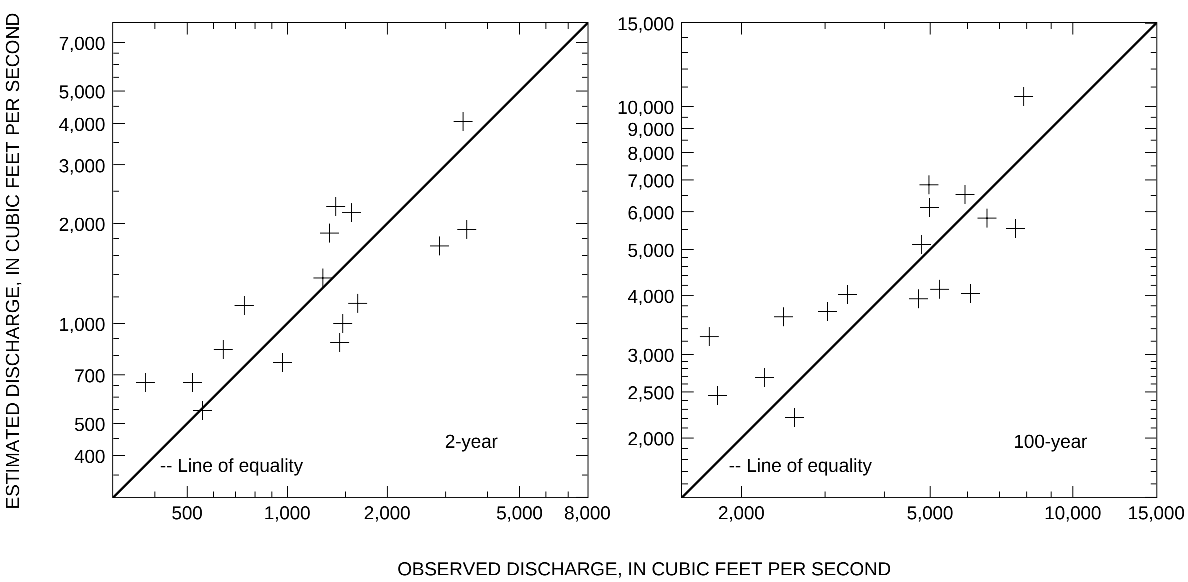

Figure 7. Comparison of 2- and 100-year observed peak discharge to peak discharges estimated using the regression equations for Jefferson County, Kentucky.

Regression Bias and Sensitivity

The regression relations were tested for variable bias by plotting the residuals (differences between the equation estimates and the observed values, as shown in table 4) against the regression estimates and the explanatory variables (A, SL, and BDF) for each equation. Inspection of these plots showed some tendency for overestimation of peak discharges for basins smaller than approximately 3 mi^2. Given that few the basins sampled were smaller than 3 mi^2 and the magnitude of the errors were consistent with errors observed for the basins larger than 3 mi^2, the regression relations were deemed acceptable.

There was also a tendency noted for the regression equations to somewhat underestimate observed peak-discharge frequencies for basins in the eastern portion of the study area (sites FH8A, FH9, FH11A, R1, R2, R3, and R4) as shown in “Supplemental Data” at the end of this report. This tendency to underestimate peak discharges in this area is also present in the statewide regression for Region 1 (Choquette, 1988) as indicated at the four rural sites that were also used in that study. Potential factors causing this underestimation tendency may include variation in the soils and (or) geologic characteristics within the study area.

The sensitivity of the equations to errors in the explanatory variables (A, BDF, and SL) was evaluated by changing each variable individually, while the other variables were held constant at the mean value. The mean values of the explanatory variables for the 17 basins used in the regression were as follows:

A = 12.3 mi^2
SL = 35.2 ft/mi
BDF = 5

The percent changes in the 2-, 10-, and 100-year computed peak discharges as a result of 10-, 25-, and 50-percent changes in the mean values of the explanatory variables are shown in table 12. The sensitivity of the regression estimates to BDF is significantly less than that reported for the nationwide regression equations (Sauer and others, 1983) and for study basins in neighboring states (Becker, 1986; Sherwood, 1993). Exponents for BDF in the Jefferson County regression equations (table 10) ranged from -0.337 to -0.181, whereas the exponents for BDF in the three-parameter nationwide equations (table 5) ranged from -0.43 to -0.32. This reduced sensitivity to BDF may be caused by the limited range of BDF sampled in this study (0-7) and (or) by potential variations in other factors, such as the amounts of temporary detention storage and the soils/subsurface characteristics within the study basins. This reduced sensitivity to BDF could lead to underestimation of peak discharges, if the equations are applied (erroneously) in basins having a BDF larger than 7.

Table 12. Sensitivity of the 2-, 10-, and 100-year computed urban peak discharges to errors in measurement of the explanatory variables in the regression equations for Jefferson County, Kentucky

[A, contributing drainage area, in square miles; BDF, basin development factor; SL, main channel slope; +, plus; -, minus]

Percent change in explanatory variable	Percent change in peak discharge for the T-year recurrence interval								
	2-year			10-year			100-year		
	A	BDF	SL	A	BDF	SL	A	BDF	SL
+50	29.4	13.4	5.3	26.2	9.2	10.3	24.4	7.0	13.4
+25	15.2	5.9	2.9	13.6	4.1	5.7	12.8	3.1	7.2
+10	6.2	2.2	1.2	5.6	1.5	2.3	5.3	1.2	3.0
-10	-6.5	-2.1	-1.4	-5.9	-1.4	-2.5	-5.5	-1.1	-3.2
-25	-16.7	-4.8	-3.6	-15.2	-3.4	-6.7	-14.3	-2.6	-8.5
-50	-35.6	-8.7	-8.5	-32.8	-6.2	-15.5	-31.1	-4.8	-19.3

ESTIMATING PEAK-DISCHARGE FREQUENCY FOR UNGAGED URBAN STREAMS IN JEFFERSON COUNTY

Peak discharges for the 2-, 5-, 10-, 25-, 50-, and 100-year recurrence intervals can be estimated, within the limitations described below, by determining the contributing drainage area, main-channel slope, and basin development factor and using the appropriate equations from table 10.

Limitations of the Method

The regression equations are applicable to basins in Jefferson County with basin characteristics within the ranges of values included in the regression sample, which are shown in table 13. The reader is cautioned against use of these equations outside this range of values, because errors considerably larger than the reported standard error of prediction (± 34 to ± 45) may result.

Table 13. Ranges of sampled basin characteristics used in developing the Jefferson County regression equations

[A, contributing drainage area, in square miles; SL, main channel slope, in feet per mile; BDF, basin development factor, on a scale from 0 to 12; --, not applicable]

Variable	Minimum	Maximum	Units
A	1.36	64.0	square miles
SL	11.7	75.1	feet per mile
BDF	0	7	--

Because the Jefferson County regression equations were developed including rural basins with a BDF of zero, the equations should be applied in lieu of using the techniques described by Choquette (1988) to estimate peak discharges for rural basins in Jefferson County with drainage areas of less than 64 mi^2. For rural basins larger than 64 mi^2, the techniques presented by Choquette (1988) should be used. The Jefferson County equations should not be used to estimate peak discharges on Mill Creek and Mill Creek Cutoff, because these streams are affected by backwater from the Ohio River.

All the basins studied have a storage area (area occupied by lakes, ponds, and swamps) of 1.0 percent or less of the contributing drainage area. The equations are not applicable on streams where peak discharges are significantly affected by such storage areas.

All the basins studied are outside areas of the county having combined sanitary and storm sewers. The equations are, therefore, not applicable to areas drained by combined sewers.

It was assumed that annual peak discharges for urban streams in Jefferson County are caused by rain falling on unfrozen ground. Periods of snowmelt were not included in the RRM calibrations. In most years, the annual peak discharges for the basins studied are caused by intense thunderstorms during the summer.

Computation of Basin Characteristics

The three basin characteristics needed for use with the peak-discharge-frequency estimating equations may be determined as follows:

A Contributing drainage area (in square miles)—The drainage area that contributes surface runoff to a specified location on a stream, measured in a horizontal plane. Computed (by planimeter, digitizer, or grid method) from U.S. Geological Survey 7.5-minute topographic quadrangle maps. Drainage areas may also be determined for available digital maps of the county. Storm-sewer maps may be necessary to delineate drainage area in urban areas because sewer lines sometimes cross topographic divides. Boundaries should be field checked when the locations of drainage divides are uncertain.

SL Main-channel slope (in feet per mile)—Computed as the difference in elevations (in feet) at points 10 and 85 percent of the distance along the main channel from a point of interest on the channel to the topographic divide, divided by the channel distance (in miles) between the two points, as determined from U.S. Geological Survey 7.5-minute topographic quadrangle maps.

BDF Basin development factor (on a scale from 0 to 12)—A measure of basin development that takes into account channel improvements, impervious channel linings, storm sewers, and curb-and-gutter streets; which provides a measure of the efficiency of the drainage system. It is measured on a scale from 0 (little or no development) to 12 (fully developed) and can be easily determined from drainage maps and field inspections of the drainage basin. The following description is based on information in reports by Sauer and others (1983) and Sherwood (1993). The basin is first divided into thirds (upper, middle, and lower) on a map of the basin (see examples, fig. 8). Each third contains approximately one third of the contributing drainage area. Peak-discharge travel times along stream reaches within thirds should be approximately equal. Subdivisions can generally be drawn by eye, without precise measurement. Then, within each third, four aspects of the drainage system are evaluated and each third is assigned a code as follows:

1. Channel improvements.—If channel improvements such as straightening, enlarging, deepening, and clearing are prevalent for the main drainage channels and principal tributaries (those that drain directly into the main channel), then a code of 1 is assigned. Any or all of these improvements would qualify for a code of 1. To be considered prevalent, at least 50 percent of the main drainage channels and principal tributaries must be improved to some degree over natural conditions. If channel improvements are not prevalent, then a code of zero is assigned.

2. Channel linings.—If more than 50 percent of the length of the main drainage channels and principal tributaries has been lined with an impervious material, such as concrete, then a code of 1 is assigned to this aspect. If less than 50 percent of these channels is lined, then a code of zero is assigned. The presence of channel linings would obviously indicate the presence of channel improvements as well. Therefore, this is an added factor that indicates a more highly developed drainage system.

3. Storm drains, or storm sewers.—Storm drains are defined as enclosed drainage structures (usually pipes), frequently used on the secondary tributaries where the drainage is received directly from streets or parking lots. Many of these drains empty into open channels; however, in some basins they empty into channels enclosed as box or pipe culverts. When more than 50 percent of the secondary tributaries within a subarea (third) consists of storm drains, then a code of 1 is assigned to this aspect; if less than 50 percent of the secondary tributaries consist of storm drains, then a code of zero is assigned. It should be noted that if 50 percent or more of the main drainage channels and principal tributaries are enclosed, then the aspects of (1) channel improvements and (2) channel linings would also be assigned a code of 1.

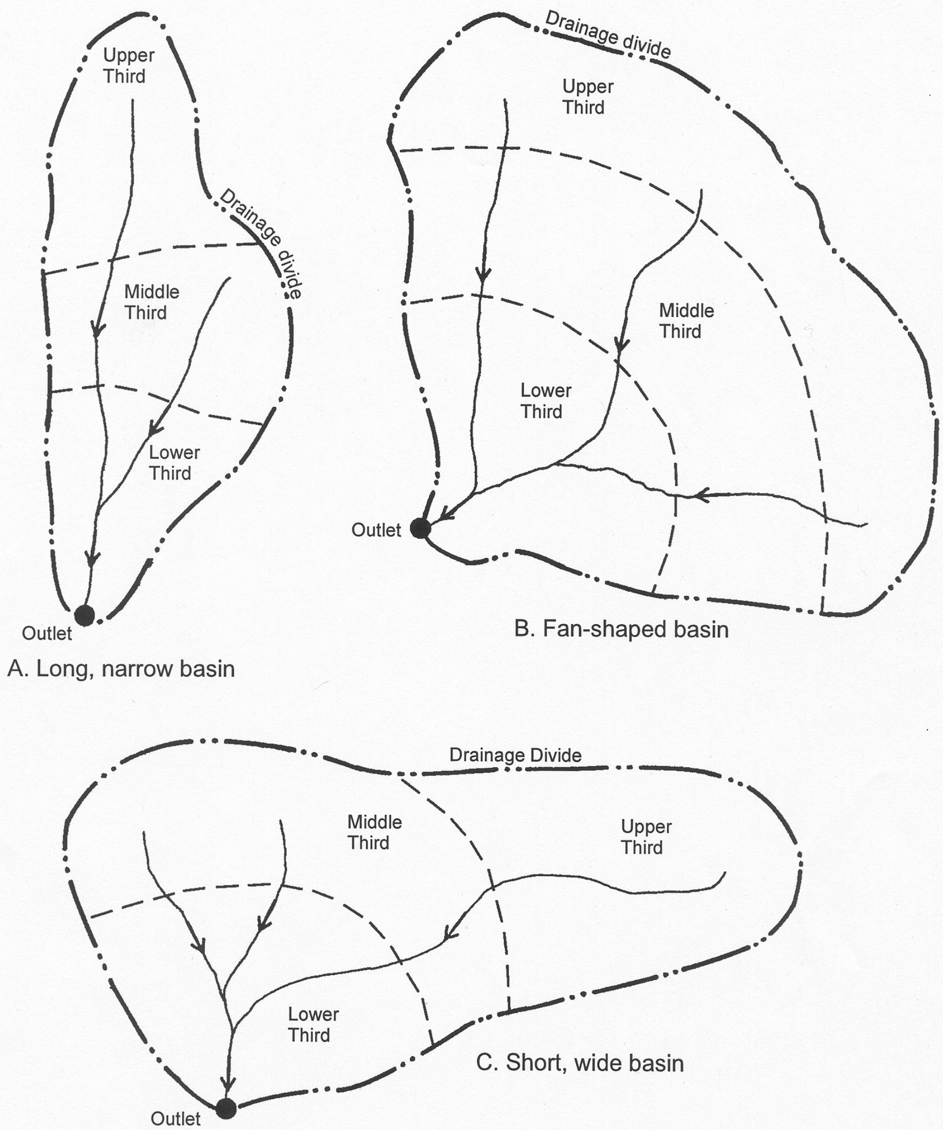

Figure 8. Schematic of typical drainage basin shapes and subdivision into thirds (from Sauer and others, 1983).

4. Curb-and-gutter streets.—If more than 50 percent of a subarea (third) is urbanized (covered by residential, commercial, and (or) industrial development), and if more than 50 percent of the streets and highways in the subarea are constructed with curbs and gutters, then a code of 1 would be assigned to this aspect. Otherwise, it would receive a code of zero. Drainage from curb-and-gutter streets frequently empties into storm drains.

The above guidelines for determining the various drainage-system codes are not intended to be precise measures. A certain amount of subjectivity will necessarily be involved. Field checking should be done to obtain the best estimate. The basin development factor (BDF) is the sum of the assigned codes; therefore, with three subareas (thirds) per basin, and four drainage aspects to which codes are assigned in each subarea, the maximum value for a fully developed drainage system would be 12. Conversely, if the drainage system were totally undeveloped, then a BDF of zero would result. Such a condition does not necessarily mean that the basin is unaffected by urbanization. If fact, a basin could be partially urbanized, have some impervious area, have some modifications to secondary tributaries, and still have an assigned BDF of zero.

The BDF is a fairly easy index to estimate for an existing urban basin. The 50-percent guideline will usually not be difficult to evaluate because many urban areas tend to use the same design criteria, and therefore have similar drainage aspects, throughout. Also, the BDF is convenient for projecting future development. Obviously, full development and maximum urban effects on peaks would occur when BDF equals 12. Projections of full development or intermediate stages of development can usually be obtained from city engineers. For the convenience of the reader, a field form for estimating BDF is shown in figure 9.

Example Computation of Peak-Discharge Frequency

Estimate the peak discharge for the 100-year average recurrence interval for an ungaged urban stream outside the areas drained by combined sewers in Jefferson County, Kentucky.

1. The following basin characteristics are determined as described in “Computation of Basin Characteristics” (p. 26).

$$A = 1.66 \text{ mi}^2$$

$$SL = 48.0 \text{ ft/mi}$$

$$BDF = 7$$

2. The basin characteristics are within the limits described in “Limitations of the Method” (p. 26).

3. Estimate the peak discharge by use of the appropriate equation from table 10 (p. 23):

$$UQ_{100} = 780A^{0.538}SL^{0.310}(13\text{-BDF})^{-0.181}$$

$$UQ_{100} = 780(1.66)^{0.538}\,(48.0)^{0.310}\,(13\text{-}7)^{-0.181}$$

$$UQ_{100} = 2{,}460 \text{ ft}^3/\text{s}$$

BASIN DEVELOPMENT FACTOR

FIELD NOTES

STATION NAME: ____________________

LOCATION: ____________________ I.D. NUMBER: ____________________

EVALUATOR: ____________________ DATE: ____________________

ASPECT	THIRD	CODE	REMARKS
Channel Improvements	Lower		
	Middle		
	Upper		
Channel Linings	Lower		
	Middle		
	Upper		
Storm Sewers	Lower		
	Middle		
	Upper		
Curb & Gutter Streets	Lower		
	Middle		
	Upper		

BDF =

Figure 9. Field form for evaluating basin development factor (BDF) (from Sherwood, 1993).

SUMMARY

As urban growth and development continues in Jefferson County, Kentucky, there is an ever-increasing need for stream discharge information in locations for which little or no hydrologic information is available. An investigation of flood-hydrograph characteristics for streams in urban Jefferson County, Kentucky, was made to obtain hydrologic information needed for water-resources management. Equations for estimating peak-discharge frequencies for ungaged streams in the county were developed by combining (1) long-term annual peak-discharge data and rainfall-runoff data collected from 1991 to 1995 in 13 urban basins and (2) long-term annual peak-discharge data in four rural basins located in hydrologically similar areas of neighboring counties. The basins ranged in size from 1.36 to 64.0 square miles (mi^2). The U.S. Geological Survey (USGS) Rainfall-Runoff Model (RRM) was calibrated for each of the urban basins. The calibrated models were used with long-term, historical rainfall, and pan-evaporation data to simulate 79 years of annual peak-discharge data. Peak-discharge frequencies were estimated by fitting the logarithms of the annual peak discharges to a Pearson-Type III frequency distribution. The simulated peak-discharge frequencies were adjusted for improved reliability by application of bias-correction factors derived from peak-discharge frequencies based on local, observed annual peak discharges. The three-parameter and the preferred seven-parameter nationwide urban-peak-discharge regression equations previously developed by USGS investigators provided biased (high) estimates for the urban basins studied.

Generalized-least-square regression procedures were used to relate peak-discharge frequency to selected basin characteristics. Regression equations were developed to estimate peak-discharge frequency by adjusting peak-discharge-frequency estimates made by use of the three-parameter nationwide urban regression equations. The regression equations are presented in equivalent forms as functions of contributing drainage area (A), main-channel slope (SL), and basin development factor (BDF), which is an index for measuring the efficiency of the basin drainage system. Estimates of peak discharges of ungaged streams in the county for the 2-, 5-, 10-, 25-, 50-, and 100-year recurrence intervals can be made by use of the regression equations. The average standard errors of prediction of the regression equations ranges from ± 34 to ± 45 percent.

The regression equations were examined for parameter and geographic bias. Inspection of plots of residuals against independent variables showed some tendency to overestimate peak discharge for basins smaller than approximately 3 mi^2. Given that few of the basins sampled were smaller than 3 mi^2 and the magnitude of the errors were consistent with errors observed for the basins larger than 3 mi^2, the regression relations were deemed acceptable. There was also a tendency noted for the regression equations to somewhat underestimate observed peak discharges in the eastern portion of the study area, as was the case for the statewide peak-discharge regression equation. Potential factors causing this underestimation tendency may include variation in the soils and (or) geologic characteristics within the study area.

The sensitivity of the regression equations to errors in the explanatory variables was evaluated. The sensitivity of the regression estimates to basin development factor (BDF) is significantly less than that reported for the nationwide regression equations and for study basins in neighboring states. This reduced sensitivity to BDF may be caused by the limited range of BDF sampled in this study (0-7) and (or) by potential variations in other factors, such as the amounts of temporary detention storage and the soils/subsurface characteristics within the study basins. This reduced sensitivity to BDF could lead to underestimation of peak discharges,

if the equations are applied (erroneously) in basins having a BDF outside the sampled range (0-7).

The regression equations are applicable to ungaged streams in the county having a specific range of basin characteristics—A ranging from 1.36 to 64.0 mi^2, SL ranging from 11.7 to 75.1 feet per mile, and BDF ranging from 0 to 7. The reader is cautioned against use of these equations outside this range of values, because errors considerably larger than the reported standard error of prediction may result. The equations are applicable to basins with minimal storage area (1.0 percent or less of contributing drainage area) that are outside the combined sewer network.

Because the Jefferson County regression equations were developed including rural basins with a BDF of zero, the regression equations should be applied in lieu of using the techniques described by Choquette (1988) to estimate peak discharges for rural basins in Jefferson County with drainage areas of less than 64 mi^2. For rural basins larger than 64 mi^2, the techniques presented by Choquette should be used. The Jefferson County equations should not be used to estimate peak discharges on Mill Creek and Mill Creek Cutoff, because these streams are affected by backwater from the Ohio River.

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SUPPLEMENTAL DATA

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Table 14. Comparison of observed, simulated, Jefferson County urban regression, nationwide urban, and statewide regression peak-discharge-frequency estimates in and around Jefferson County, Kentucky

[—, not available]

Site identifier (figure 1)	Recurrence interval (year)	Peak discharges, in cubic feet per second						
		Observed	Simulated	Simulated adjusted for bias	Jefferson County urban regression	Nationwide urban regression		Statewide regression—Region 1 (North)
						Three-parameter	Seven-parameter	
3	2	3,380	4,300	—	4,050	6,720	5,610	5,630
	5	4,530	6,240	—	5,540	10,400	8,460	8,330
	10	5,310	7,620	—	6,620	12,400	10,900	10, 200
	25	6,320	9,450	—	8,140	14,900	13,600	12, 900
	50	7,090	10,900	—	9,330	17,900	15,900	15,000
	100	7,880	12,400	—	10,500	21,200	18,900	17,300
6	2	1,560	1,660	1,660	2,150	2,990	2,610	2,130
	5	2,430	2,460	2,560	3,170	4,610	3,960	3,180
	10	3,110	3,020	3,260	3,880	5,440	5,090	3,930
	25	4,120	3,760	4,290	4,910	6,560	6,300	4,980
	50	4,970	4,340	5,160	5,700	7,780	7,420	5,820
	100	5,920	4,940	6,080	6,530	9,120	8,720	6,700
7	2	1,400	1,190	1,190	2,250	3,160	2,700	2,260
	5	2,130	1,800	1,870	3,320	4,920	4,140	3,410
	10	2,710	2,250	2,430	4,060	5,820	5,360	4,230
	25	3,530	2,870	3,270	5,140	7,050	6,660	5,380
	50	4,220	3,360	4,000	5,960	8,380	7,870	6,300
	100	4,970	3,880	4,770	6,840	9,860	9,280	7,270
FH1	2	—	557	557	547	520	515	381
	5	—	826	859	964	817	798	576
	10	—	992	1,070	1,260	977	1,030	719
	25	—	1,190	1,360	1,720	1,190	1,270	918
	50	—	1,320	1,570	2,070	1,400	1,520	1,080
	100	—	1,450	1,780	2,460	1,620	1,760	1,250

Table 14. Comparison of observed, simulated, Jefferson County urban regression, nationwide urban, and statewide regression peak-discharge-frequency estimates in and around Jefferson County, Kentucky—*Continued*

[—, not available]

Site identifier (figure 1)	Recurrence interval (year)	Peak discharges, in cubic feet per second						
		Observed	Simulated	Simulated adjusted for bias	Jefferson County urban regression	Nationwide urban regression		Statewide regression—Region 1 (North)
						Three-parameter	Seven-parameter	
FH2	2	—	1,280	1,280	1,370	1,680	1,610	1,240
	5	—	1,950	2,030	2,210	2,740	2,550	1,960
	10	—	2,410	2,600	2,810	3,330	3,340	2,510
	25	—	3,000	3,420	3,690	4,140	4,210	3,290
	50	—	3,440	4,090	4,380	4,980	5,070	3,930
	100	—	3,900	4,800	5,120	5,910	6,010	4,610
FH3	2	—	518	518	663	665	584	588
	5	—	830	863	1,110	1,010	894	832
	10	—	1,050	1,130	1,430	1,180	1,150	1,000
	25	—	1,350	1,540	1,910	1,420	1,410	1,240
	50	—	1,580	1,880	2,280	1,650	1,670	1,420
	100	—	1,820	2,240	2,680	1,880	1,910	1,610
FH4	2	—	642	642	834	891	848	744
	5	—	977	1,020	1,440	1,460	1,360	1,170
	10	—	1,210	1,310	1,880	1,790	1,800	1,490
	25	—	1,520	1,730	2,530	2,240	2,280	1,950
	50	—	1,750	2,080	3,040	2,690	2,770	2,330
	100	—	1,990	2,450	3,600	3,170	3,260	2,720
FH5	2	—	374	374	663	666	706	624
	5	—	588	612	1,220	1,140	1,160	1,030
	10	—	752	812	1,630	1,440	1,550	1,340
	25	—	985	1,120	2,250	1,850	1,970	1,790
	50	—	1,180	1,400	2,740	2,260	2,460	2,170
	100	—	1,390	1,710	3,270	2,690	2,920	2,570
FH6	2	—	1,340	1,340	1,870	2,510	2,060	2,230
	5	—	1,970	2,050	2,850	3,960	3,230	3,340
	10	—	2,430	2,620	3,540	4,740	4,230	4,130
	25	—	3,050	3,480	4,540	5,780	5,330	5,240
	50	—	3,540	4,210	5,330	6,940	6,360	6,130
	100	—	4,050	4,980	6,130	8,150	7,480	7,060

Table 14. Comparison of observed, simulated, Jefferson County urban regression, nationwide urban, and statewide regression peak-discharge-frequency estimates in and around Jefferson County, Kentucky—*Continued*

[—, not available]

Site identifier (figure 1)	Recurrence interval (year)	Peak discharges, in cubic feet per second						
		Observed	Simulated	Simulated adjusted for bias	Jefferson County urban regression	Nationwide urban regression		Statewide regression—Region 1 (North)
						Three-parameter	Seven-parameter	
FH7	2	742	903	903	1,130	1,310	1,140	1,000
	5	1,290	1,370	1,420	1,790	2,020	1,750	1,470
	10	1,710	1,700	1,840	2,250	2,380	2,250	1,800
	25	2,320	2,110	2,410	2,940	2,850	2,770	2,250
	50	2,810	2,410	2,870	3,460	3,340	2,280	2,610
	100	3,350	2,720	3,350	4,020	3,860	3,800	2,980
FH8A	2	—	1,470	1,470	1,000	1,130	1,100	926
	5	—	2,180	2,270	1,660	1,800	1,700	1,410
	10	—	2,620	2,830	2,120	2,160	2,210	1,770
	25	—	3,140	3,580	2,810	2,660	2,750	2,260
	50	—	3,500	4,160	3,350	3,170	3,290	2,670
	100	—	3,840	4,720	3,930	3,710	3,850	3,090
FH9	2	—	969	969	763	795	794	748
	5	—	1,420	1,480	1,390	1,390	1,340	1,250
	10	—	1,700	1,840	1,850	1,760	1,810	1,640
	25	—	2,020	2,300	2,550	2,260	2,360	2,220
	50	—	2,250	2,680	3,110	2,790	2,930	2,700
	100	—	2,470	3,040	3,700	3,340	3,500	3,220
FH11A	2	—	1,630	1,630	1,150	1,340	1,070	1,140
	5	—	2,360	2,450	1,830	2,070	1,670	1,660
	10	—	2,840	3,070	2,300	2,450	2,180	2,030
	25	—	3,420	3,900	3,000	2,960	2,710	2,540
	50	—	3,840	4,570	3,550	3,490	3,230	2,940
	100	—	4,260	5,240	4,120	4,040	3,760	3,360

Table 14. Comparison of observed, simulated, Jefferson County urban regression, nationwide urban, and statewide regression peak-discharge-frequency estimates in and around Jefferson County, Kentucky—*Continued*

[—, not available]

Site identifier (figure 2)	Recurrence interval (year)	Peak discharges, in cubic feet per second						
		Observed	Simulated	Simulated adjusted for bias	Jefferson County urban regression	Nationwide urban regression		Statewide regression—Region 1 (North)
						Three-parameter	Seven-parameter	
RB1	2	3,470	—	—	1,920	2,590	—	2,510
	5	4,440	—	—	2,830	3,910	—	3,520
	10	5,010	—	—	3,470	4,600	—	4,220
	25	5,690	—	—	4,380	5,450	—	5,150
	50	6,150	—	—	5,100	6,460	—	5,890
	100	6,590	—	—	5,820	7,450	—	6,650
RB2	2	282	—	—	393	341	—	356
	5	630	—	—	765	584	—	575
	10	958	—	—	1,150	734	—	741
	25	1,500	—	—	1,480	938	—	978
	50	2,000	—	—	1,830	1,140	—	1,180
	100	2,590	—	—	2,210	1,330	—	1,380
RB3	2	2,870	—	—	1,710	2,230	—	2,180
	5	4,180	—	—	2,590	3,440	—	3,140
	10	5,030	—	—	3,210	4,080	—	3,800
	25	6,080	—	—	4,110	4,900	—	4,710
	50	6,840	—	—	4,810	5,840	—	5,430
	100	7,570	—	—	5,530	6,770	—	6,180
RB4	2	1,440	—	—	875	945	—	982
	5	2,360	—	—	1,550	1,630	—	1,610
	10	3,090	—	—	2,060	2,060	—	2,090
	25	4,160	—	—	2,800	2,640	—	2,780
	50	5,070	—	—	3,410	3,260	—	3,370
	100	6,080	—	—	4,030	3,890	—	3,990