TECHNIQUES FOR ESTIMATING FLOOD-PEAK DISCHARGES FROM URBAN BASINS IN MISSOURI

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CONVERSION TABLE

For the convenience of readers who may prefer to use metric (International System) units rather than the inch-pound units used in this report, values may be converted by using the following factors:

Multiply inch-pound units	by	To obtain metric units
inch	25.40	millimeter
foot	0.3048	meter
mile	1.609	kilometer
square mile	2.590	square kilometer
cubic foot per second	0.02832	cubic meter per second
foot per mile	0.1894	meter per kilometer
gallon per day	0.003785	cubic meter per day
square foot	0.09294	square meter

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ABSTRACT

Techniques are defined for estimating the magnitude and frequency of future flood-peak discharges of rainfall-induced runoff from small urban basins in Missouri. These techniques were developed from an initial analysis of flood records of 96 gaged sites in Missouri and adjacent states. Final regression equations are based on a balanced, representative sampling of 37 gaged sites in Missouri. This sample included 9 statewide urban study sites, 18 urban sites in St. Louis County, and 10 predominately rural sites statewide. For these sites, short-term records were extended on the basis of long-term climatic records and use of a rainfall-runoff model. Linear least-squares regression analyses were used with log-transformed variables to relate flood magnitudes of selected recurrence intervals (dependent variables) to selected drainage basin indexes (independent variables).

For gaged urban study sites within the State, the flood-peak estimates are from the frequency curves defined from the synthesized long-term discharge records. Flood-frequency estimates are made for ungaged sites by using regression equations that require determination of the drainage-basin size and either the percentage of impervious area or a basin development factor. Alternative sets of equations are given for the 2-, 5-, 10-, 25-, 50-, and 100-year recurrence interval floods. The average standard errors of estimate range from about 33 percent for the 2-year flood to 26 percent for the 100-year flood.

The techniques are applicable to floodflows that are not significantly affected by storage caused by manmade activities. Flood-peak discharge estimating equations are considered applicable for sites on basins draining approximately 0.25 to 40 square miles.

INTRODUCTION

Floodflows from urban and rural basins need to be considered in the design of street and highway structures, such as bridges and culverts, in land-use planning, in establishing rates for flood insurance, and in formulating emergency evacuation plans for flood-prone areas. Urbanizing a natural drainage basin results in changes in floodflow charcteristics from the drainage basin. These changes usually include increased peak discharges, because of increased impervious area in the basin and decreased basin response times, for watersheds which do not have significant in-channel or detention storage (Sauer and others, 1983).

The most reliable estimates of floods of specified probability of occurrence at gaged sites are based on frequency analyses of streamflow-gaging station records. Estimates of flood magnitude at ungaged sites usually are based on interpretive studies of hydrologic data using statistical approaches

(Becker, 1985). For example, a study of urban basins has provided flood-estimating procedures for St. Louis County, Missouri (Spencer and Alexander, 1978), and a study of rural basins (Hauth, 1974b) has provided statewide estimating relations for peak discharges. Magnitudes of floods of given frequency are related to basin descriptors and climatic variables for both rural and urban settings.

A report by Sauer and others (1983) provides flood-peak estimating equations for urban settings on a nationwide basis. A data base of 269 gaged basins in 56 cities and 31 states containing a variety of topographic and climatic characteristics, land-use variables, indices of urbanization, and flood data was used to develop the nationwide urban flood-estimating method (Sauer and others, 1983). Twenty-five of these gaged basins were among those used earlier by Spencer and Alexander (1978) in defining flood-estimating relations for St. Louis County.

In reponse to the need to determine floodflow characteristics of urban drainage basins, the U.S. Geological Survey, in cooperation with the Missouri Highway and Transportation Commission, conducted an investigation to: (1) Determine the magnitude and frequency of flood peaks for gaged urban drainage basins, and (2) to develop techniques for estimating peak discharges at ungaged locations.

The objective of this study was to develop simple, reliable flood-peak estimating techniques based on basin characteristic factors for small urban drainage basins in Missouri. The study required investigation of the transferability of flood data from gaged sites to ungaged sites for urban areas within Missouri. Further, the study was dependent on determination of independent variables (basin characteristics, physical characteristics, or other dimensionless factors) that will adequately define floodflows from small urban areas of Missouri.

The approach of this study was to analyze flood-peak data from a sample of streams draining urban basins with areas generally less than 40 square miles. Data collected at nine sites during this study were augmented by peak-flow data from urban studies conducted in St. Louis County, Missouri (Spencer and Alexander, 1978), and in adjacent states (Perry and Hart, 1984; Neely, 1984; Sauer and others, 1983) and from a statewide rural study in Missouri (Hauth, 1974a). For the analysis of urban sites in this study, selected small rural sites were included and considered as urban sites wherein there is little or no effect of urbanization.

These analyses included defining flood-frequency relations for both urban and rural gaged sites at which relatively short-term records were collected. Reliability of the frequency relations increases with record length, therefore, rainfall-runoff models were used to synthesize long-term flood records from available long-term climatological records. Multiple-regression analysis subsequently was used to define equations for estimating flood-peak magnitudes for given frequencies at ungaged sites.

This is the final report that results from the investigation of urban-streams flood frequency and supplements earlier reports that provide rural (Hauth, 1974b) and urban (Spencer and Alexander, 1978) flood-estimating techniques in Missouri. The report presents flood-frequency information at gaged sites and simple, practical techniques for estimating flood peaks at ungaged sites. Brief documentations of the available data and of the procedures used in the data analyses, including aspects of rainfall-runoff modeling, flood-frequency analysis, and regression analysis, are presented. These topics are followed by the estimating equations, descriptions of their accuracy and limitations, and examples of their use.

ANALYTICAL PROCEDURES

Small-streams Data Collection and Analyses

The U.S. Geological Survey began collecting streamflow data in Missouri as early as 1922. During the first 20 years, only drainage areas of 50 square miles or greater were gaged. In 1948, the U.S. Geological Survey, in cooperation with the Missouri Highway Commission (now Missouri Highway and Transportation Commission), began collecting hydrologic data statewide on rural streams smaller than 10 square miles. Until 1974, the greater part of the effort was directed toward data collection with limited time and funding available for data analysis. A research study in cooperation with the Missouri Highway and Transportation Commission was initiated in 1974 to analyze these small-streams data. Hauth (1974a) used rainfall-runoff data from 43 streamflow-gaging stations to calibrate a rainfall-runoff model and extend streamflow records in time. These synthesized long-term records were included in a statewide flood-frequency analysis (Hauth, 1974b) of rural streams. An evaluation of the small-streams network (Hauth, 1980) determined that further data collection on small rural streams in Missouri would not appreciably improve the predictive capability of available regression models.

In 1970, the U.S. Geological Survey, in cooperation with the County of St. Louis, Missouri, began to collect and analyze data necessary to define the effects of urban development on surface runoff from 30 small drainage basins in St. Louis County. Results of that study were reported by Spencer and Alexander (1978).

In 1976, the small-streams program was adjusted to change the continuous-recording data-collection emphasis from the rural to the urban areas of Missouri. At that time, 11 streamflow-gaging stations were established that concurrently sampled rainfall on and runoff from urban basins. The data collected at these gaged sites and at gaged sites of previous studies (figs. 1 and 2) provide the basis for transferability of flood data to ungaged urban basins statewide.

Rainfall-Runoff Modeling

Two distinct procedures are required in using rainfall-runoff modeling to extend flood records. First, the model needs to be calibrated for a given site using representative rainfall and runoff data for the site. The calibrated model is then used with available long-term climatological records to synthesize long-term flood records at that site.

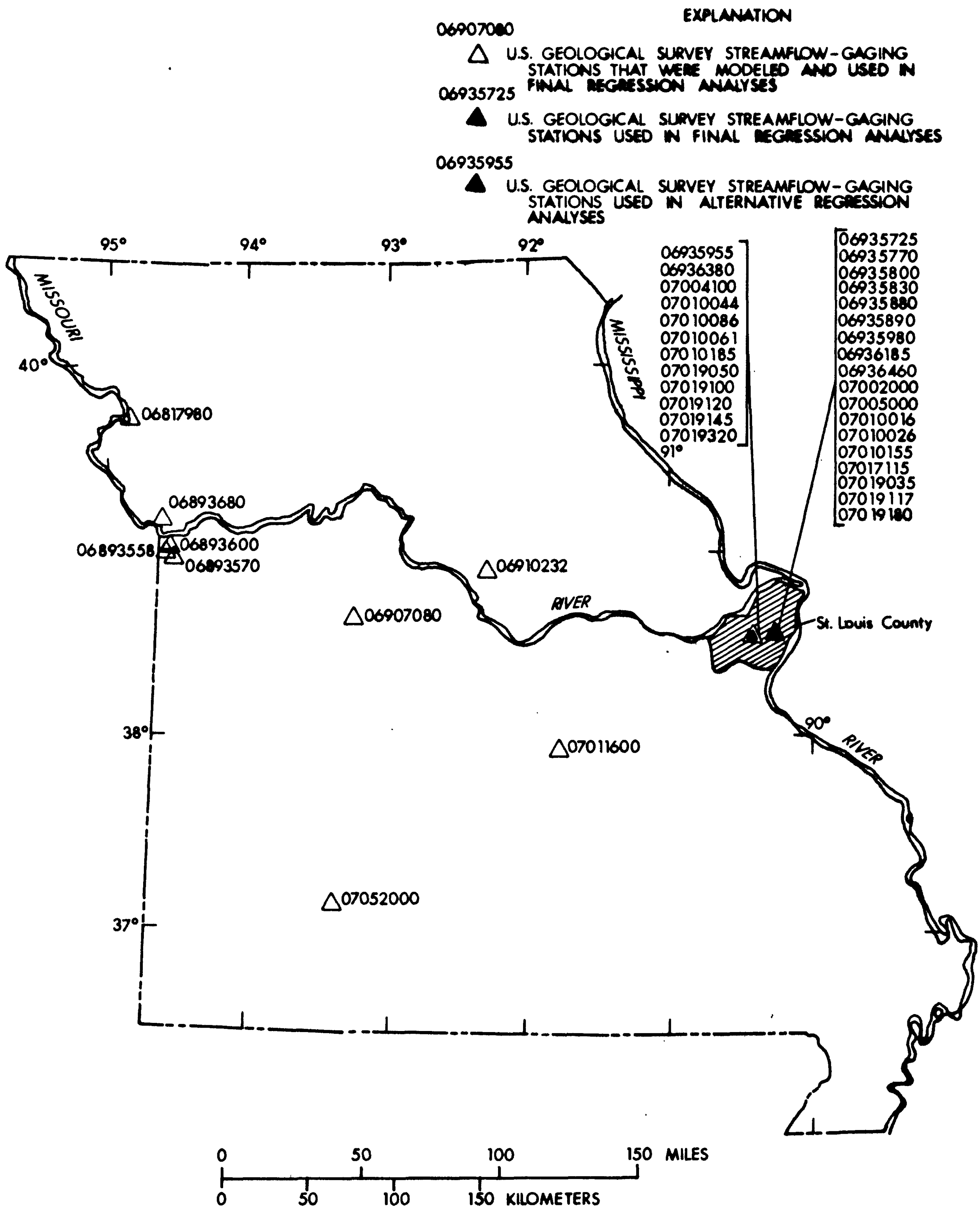

Figure 1.--Location of streamflow-gaging stations on urban basins used in flood studies.

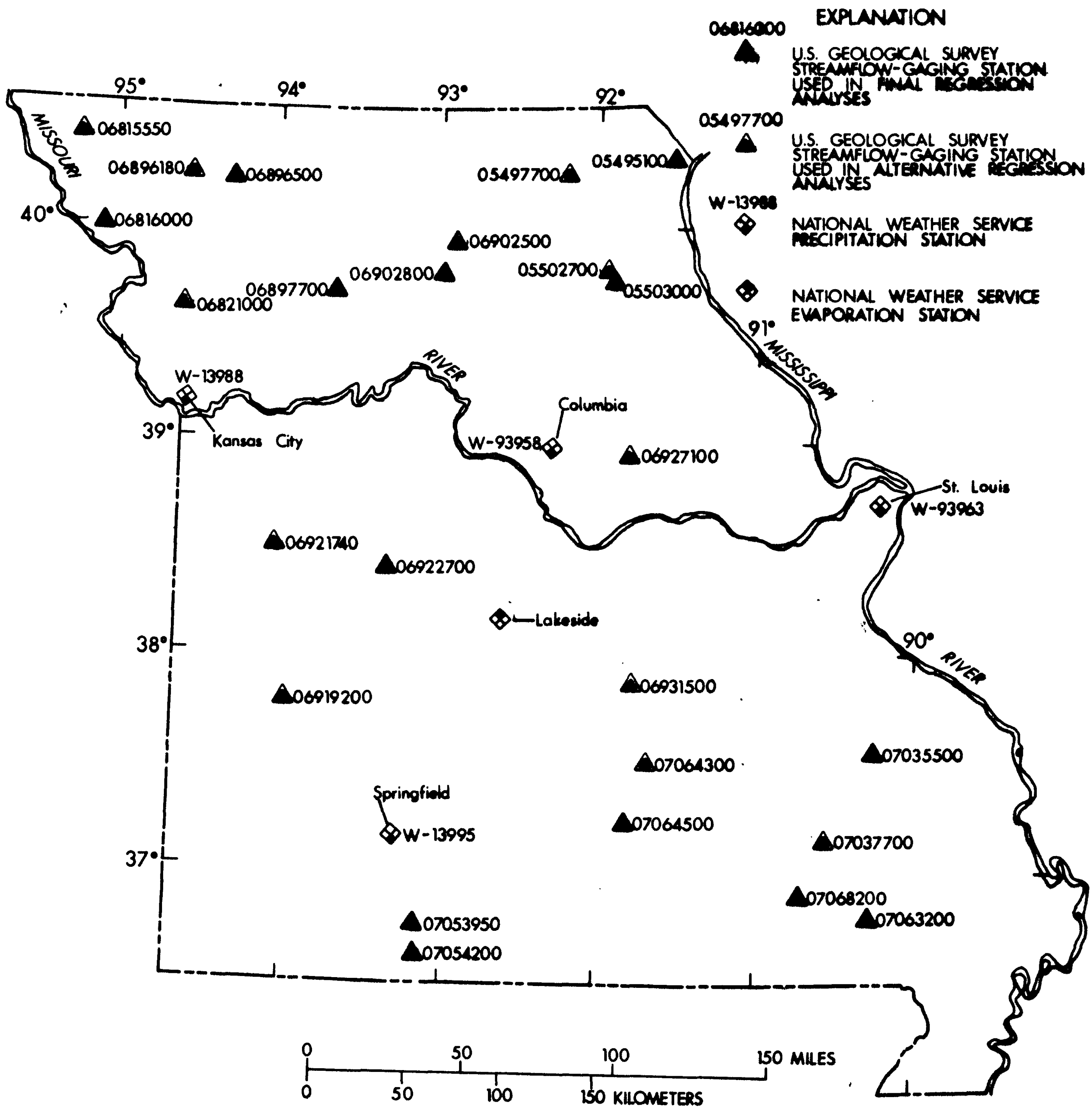

Figure 2.--Location of streamflow-gaging stations on rural basins used in support of regression analyses, and National Weather Service stations.

Model Description

The parametric rainfall-runoff model described by Dawdy, Lichty, and Bergmann (1972) was used with point-rainfall data and data on potential evapotranspiration to synthesize flood hydrographs from urban drainage basins in Missouri. The model consists of a series of mathematical equations presented in the form of computer programs (Carrigan, 1973) that describe antecedent moisture, infiltration, and surface runoff. The model uses 10 parameters (table 1) in making approximations to the physical laws governing infiltration, soil-moisture accretion and depletion, and surface streamflow. Values for these parameters, applicable to modeling streamflow at a particular site, are determined by a process of calibration using the concurrent rainfall and runoff data that have been collected at the site. Initial parameter values are assumed for the calibration process and from these the model determines optimum values based on an iterative comparison of predicted and observed runoff. Final parameter values determined for a particular site are the basis for the model with which flood peaks and runoff volumes may be simulated from long-term rainfall records. These simulated flood peaks and volumes may be used to extend the length of streamflow records at given sites which, in turn, are used in the analysis of flood magnitude and frequency.

Model Calibration

In calibrating the model, the 10 parameters usually are evaluated by the iterative optimization routine. Ideally, about 15 to 20 significant storms representative of a range of antecedent and rainfall conditions are desired for each site. Comparison of results of model calibration in this and other areas (Hauth, 1974a; Lichty and Liscum, 1978; and Becker, 1980) has indicated that a more meager calibration procedure is feasible and may be dictated to arrive at reasonable results. Spencer and Alexander (1978) determined that satisfactory calibration of urban sites in St. Louis County, Missouri, depended on a careful selection of the smaller storms (T.W. Alexander, U.S. Geological Survey, oral commun., 1985) such that adequate significance could be given to the more extreme storms. These extreme storms, though much fewer in number, tend to produce much larger peak discharges. However, sufficient numbers of the smaller storms were retained in the modeling process to ensure that proper calibrations of infiltration parameters (PSP, KSAT, and RGF) were obtained and that adequate ranges of antecedent conditions were sampled. Therefore, a fewer number of storms, but of generally larger magnitude, were used in calibration of the urban sites statewide in Missouri.

In this study, values for certain model parameters were not varied after being either assumed, based on results from prior use of the model (Hauth, 1974a; Spencer and Alexander, 1978; Becker, 1980), or measured from hydrographs. In this manner, 6 parameters (EVC, RR, DRN, KSW, TC, and TP/TC) of the 10 model parameters were directly determined, thereby leaving only 4 parameters (BMSM, PSP, KSAT, and RGF) to be determined by optimization. The practical advantage gained was that significantly fewer storms were required at a particular site for the number of storms to exceed the number of parameters being optimized.
This approach proved especially significant as nine study sites were successfully modeled as shown in table 2. The validity of parameter values obtained for these sites was judged by comparing these values with parameter values determined for 30 sites in St. Louis County (Spencer and Alexander, 1978).

Table 1.--Description of parameters used in the modeling process

Parameter	Units	Definition and Application
		Antecedent-moisture component
EVC	---	Coefficient to convert pan evaporation to potential evaportranspiration.
RR	---	Proportion of daily rainfall that infiltrates the soil.
BMSM	Inches	Soil-moisture storage volume at field capacity.
DRN	Inches per hour	Drainage parameter for redistribution of soil moisture.
		Infiltration component
PSP	Inches	Product of moisture deficit and suction at the wetted front for soil moisture at field capacity.
KSAT	Inches per hour	The minimum (saturated) hydraulic conductivity used to determine infiltration rates.
RGF	---	Ratio of the product of moisture deficit and suction at the wetted front for soil moisture at wilting point to that at field capacity.
		Surface-runoff component (routing)
KSW	Hours	Time characteristic for linear reservoir routing.
TC	Minutes	Length of the time base (duration) of the triangular translation hydrograph.
TP/TC	---	Ratio of time to peak of triangular translation hydrograph to duration of translation hydrograph.

Table 2.--Summary of calibrated rainfall-runoff model parameters for modeled urban basins

[PSP and BMSM, inches; KSAT and DRN, inches per hour; KSW, hours; TC, minutes; remaining parameters, unitless]

U.S. Geological Survey station identification number and name (fig. 1)		Parameters (See table 1 for definition and application)										Impervious area used in calibration, in percent	Standard error of simulated estimate, in percent	Number of storms used in final calibration
		PSP	KSAT	DRN	RGF	BMSM	EVC	RR	KSW	TC	TP/TC			
06817980	Blacksnake Creek at St. Joseph	4.10	0.085	1.00	15.5	3.50	0.70	0.90	0.75	57.0	0.50	13.0	24.7	15
06893558	Brush Creek at Summit Avenue at Kansas City	4.75	.190	1.00	25.0	2.25	.70	.90	.46	54.0	.50	30.0	15.5	16
06893570	Round Grove Creek at Raytown Road at Kansas City	3.50	.180	1.00	23.5	2.00	.70	.90	.85	65.0	.50	26.0	13.5	12
06893600	Rock Creek at Independence	3.00	.220	1.00	25.0	3.00	.70	.90	.75	45.0	.50	30.0	22.6	11
06893680	Mill Creek at 56th Street at Gladstone	4.95	.150	1.00	28.5	2.80	.70	.90	.57	42.0	.50	34.0	23.8	11
06907080	Brushy Creek tributary at Sedalia	3.50	.080	1.00	12.0	2.50	.70	.90	.45	30.0	.50	25.0	28.1	14
06910232	Flat Branch at Columbia	4.25	.205	1.00	27.5	3.50	.70	.90	.30	32.0	.50	30.0	27.9	12
07011600	Love Branch at Rolla	5.50	.170	1.00	25.0	3.00	.70	.90	.50	15.0	.50	26.0	16.7	16
07052000	Wilsons Creek at Scenic Drive in Springfield	5.75	.220	1.00	30.0	4.50	.70	.90	.55	130.0	.50	22.0	23.7	22

Initial calibrations indicated that the model was not satisfactorily accounting for actual hydrologic conditions. Initially, optimum percentage of impervious area was determined as part of the model calibration procedure. This resulted in model parameters for each basin that were unreasonable. Markedly improved calibrations resulted when additional considerations were applied to the modeling process. Standard errors were greatly decreased and bias was removed by: (1) Subtraction of appropriate base flows from recorded hydrographs to obtain the best estimate of direct runoff, (2) extensive screening of data, and (3) initial introduction of values for effective impervious areas into the calibrations based on measured or estimated impervious areas in basins. Percentages of impervious area used in the individual calibrations are shown in table 2.

Long-term records of rainfall and evaporation in Missouri were used to generate the long-term series of synthesized floods required to improve the flood-frequency curves at short-term streamflow-gaging sites. Long-term daily and unit-precipitation (5-minute incremental rainfall for storm periods) data for St. Louis, Columbia, Kansas City, and Springfield, Missouri were obtained from the National Climatic Data Center, Asheville, N.C. These records, which ranged from 73 to 84 years in length, provided the rainfall data for model input.

The most suitable long-term evaporation record available in Missouri is for the National Weather Service pan-evaporation gage (Lakeside) located at Lake of the Ozarks in the central part of the State (fig. 2) where operation began in 1948. A procedure described by Carrigan and others (1977) was used to fit a harmonic (sine-cosine) function to this 36-year evaporation record and then generate a synthetic, daily evaporation record for 1893 through 1983. This single, partly synthesized, evaporation record was considered adequate for flood synthesis at all modeled sites.

Optimum parameter values (table 2) determined during the calibration process were used in the model along with long-term daily rainfall, daily evaporation, and unit rainfall to produce two or more long-term series of floods at each of the nine modeled sites. The synthesized flood record based on rainfall from long-term station nearest to the site was used for seven sites. For two sites, frequency curves from flood records, based on the Springfield and Columbia, Missouri, rainfall records, were combined because of modeled site location. A simple averaging of frequency data from both synthesized flood record was determined to be adequate.

Flood-Frequency Analysis

Analysis of station data was based on the log-Pearson Type III method for fitting flood-frequency curves. Details of the log-Pearson Type III method and calculations are given by the U.S. Water Resources Council (1981). Frequency analyses of gaged data generally are the most reliable estimators of future floods and form the basis for regression relations that transfer information to ungaged sites.

The nine modeled sites for which simulated long-term peak-discharge data are available and for which flood-frequency computations have been made are shown in figure 1. Flood characteristics derived from these data are listed in table 3.

Table 3.--Basin and flood characteristics for modeled urban basins

U.S. Geological Survey station identification number and name (fig. 1)		Period of record, water years	Basin characteristics: Contributing drainage area, A, in square miles	Channel slope, in feet per mile	Impervious area, I, in percent	Basin development factor, BDF	Flood characteristics[1]: Peak discharge, in cubic feet per second, for indicated recurrence interval, in years: 2	5	10	25	50	100
06817980	Blacksnake Creek at St. Joseph	1977-83	4.32	38.1	13	0	1,130	2,220	3,100	4,330	5,340	6,400
06893558	Brush Creek at Summit Avenue at Kansas City	1979-84	14.4	27.7	30	11	4,650	7,740	10,200	13,800	16,900	20,300
06893570	Round Grove Creek at Raytown Road at Kansas City	1976-84	5.62	74.7	26	4	1,440	2,370	3,120	4,210	5,130	6,160
06893600	Rock Creek at Independence	1968-79	5.27	64.8	30	5	1,500	2,580	3,450	4,730	5,820	7,030
06893680	Mill Creek at 56th Street at Gladstone	1976-84	1.23	69.2	34	4	415	702	933	1,270	1,560	1,870
06907080	Brushy Creek tributary at Sedalia	1977-84	0.93	62.4	25	3	493	803	1,010	1,290	1,490	1,690
06910232	Flat Branch at Columbia	1976-81	3.01	49.8	30	6	1,340	2,080	2,600	3,280	3,800	4,330
07011600	Love Branch at Rolla	1977-84	1.40	73.0	26	7	451	691	866	1,110	1,300	1,510
07052000	Wilsons Creek at Scenic Drive in Springfield	1974-82	19.3	24.4	22	6	2,900	4,800	6,350	8,660	10,600	12,900

[1]Based on synthesized long-term flood records.

Flood-peak data for the 9 modeled stations were considered with urban data from 30 sites in St. Louis County (Spencer and Alexander, 1978) in the regression analysis. Climatic and basin conditions in St. Louis County were considered sufficiently representative of conditions found elsewhere in the state to allow inclusion of these data. Also, data from a representative, statewide, sampling of 25 rural sites (Hauth, 1974a) were considered, assuming a minimum impervious area of 1 percent, to increase sample size and to extend the applicability of estimating equations developed. Alternative selections of St. Louis County and rural sites were tested in the regionalization process to assure that comparable equations would be obtained and that the data were not biased. Final regressions are based on synthesized data for 9 modeled, 18 St. Louis County, and 10 rural stations to achieve a balanced urban data base for statewide regionalization. These selected stations are listed in tables 3 and 4.

Regionalization by Regression Analysis

The regional analysis of synthesized flood records by regression technique provides the means of transferring the hydrologic information available at individual gaged sites to most ungaged sites within the region where estimates may be required.

Regionalization of the flood-frequency data was based on multiple-regression methods. The relations of flood peaks to drainage basin and climatic characteristics were determined from a regression model of the form $Q=a\,A^b\,B^c\,D^d$ ..., where the dependent variable (Q) is the peak discharge and the independent variables (A, B, and C) are basin or climatic characteristics. In the equation, the constant and coefficients of regression are indicated respectively by "a" and by "b", "c", and "d". The regression constant and regression coefficients are defined, the statistical significance of each basin or climatic characteristic is evaluated, and a standard error of estimate is determined using regression-analysis techniques.

Rural basins were included in the regional analysis to extend the gaged-data sample in areal coverage. It is reasonable to consider a rural site as representing an urban site wherein the effects of urbanization are nonexistent or approach zero. However, most rural basins will have some effective impervious area. Therefore, a small percentage of impervious area, based on roads, ponds, and so forth, was determined or assumed for each rural basin used in the regression analyses. Final estimating relations for urban peak discharge were based on regression analyses using data from 37 gaged sites.

Numerous basin and climatic characteristics were considered in the regression models; however, only those of both statistical and hydrologic significance were retained in the estimating relations. To further simplify estimating relations, maintain consistency between estimating relations, and facilitate their use, uniform sets of variables were used for all flood equations defined. Variables defined as drainage area (A), basin development factor (BDF), and percentage of impervious area (I) proved most significant (95-percent confidence level) in estimating floods at ungaged urban sites in Missouri. Other independent variables considered were stream length, main channel slope, area of lakes and ponds, forested area, mean-annual precipitation, and precipitation intensity of the 100-year, 24-hour storm.

Table 4.--Basin and flood characteristics for selected rural and urban basins

U.S. Geological Survey station identification number and name (fig. 1)		Basin characteristics				Flood characteristics[1]					
		Contributing drainage area, A, in square miles	Impervious area, I, in percent	Channel slope, in feet per mile	Basin development factor, BDF	Peak discharge, in cubic feet per second, for indicated recurrence interval, in years					
						2	5	10	25	50	100
05495100	Big Branch tributary near Wayland[2]	0.70	3	80.8	0	130	239	317	416	489	561
06816000	Mill Creek near Oregon[2]	4.90	2	42.3	0	740	1,600	2,320	3,350	4,190	5,320
06896500	Thompson Branch near Albany[2]	5.58	2	30.9	0	738	1,490	2,020	2,520	2,880	3,220
06897700	Grand River tributary near Utica[2]	1.44	2	120	0	392	485	560	665	761	854
06922700	Chub Creek near Lincoln[2]	2.86	1	40.3	0	766	1,360	1,730	2,160	2,430	2,700
06935725	Wildhorse Creek at Wildhorse Creek Road at Babler State Park[3]	9.80	2	38.1	0	1,850	3,160	4,190	5,650	6,860	8,160
06935770	Bonhomme Creet at County Highway CC near Clarkson Valley[3]	11.6	3	32.3	0	2,010	3,320	4,380	5,960	7,310	8,820
06935800	Shotwell Creek at State Highway 340 near Ellisville[3]	0.81	22	84.8	5	464	728	963	1,290	1,510	1,730
06935830	Caulks Creek at State Highway 340 near Clarkson Valley[3]	17.1	5	33.6	3	3,060	5,170	6,910	9,510	11,800	14,300
06935880	Smith Creek at Mason Road at Creve Coeur[3]	4.44	18	53.5	4	1,240	1,950	2,510	3,310	3,980	4,720

Table 4.--Basin and flood characteristics for selected rural and urban basins --Continued

U.S. Geological Survey station identification number and name (fig. 1)		Basin characteristics: Contributing drainage area, A, in square miles	Basin characteristics: Impervious area, I, in percent	Basin characteristics: Channel slope, in feet per mile	Basin characteristics: Basin development factor, BDF	Flood characteristics[1]: Peak discharge, in cubic feet per second, for indicated recurrence interval, in years: 2	5	10	25	50	100
06935890	Creve Coeur Creek at State Highway 340 near Creve Coeur[3]	22.0	15	16.4	5	2,340	3,900	5,200	7,170	8,900	10,900
06935980	Cowmire Creek at Kirchner Inc. in Bridgeton[3]	3.70	20	32.1	9	1,240	1,950	2,520	3,370	4,110	4,930
06936185	Coldwater Creek at St. Louis International Airport at Bridgton[3]	7.47	32	30.1	9	1,900	2,940	3,790	5,040	6,130	7,360
06936460	Coldwater Creek at Old Halls Ferry Road at Florissant[3]	38.9	25	8.67	9	5,950	9,460	12,300	16,600	20,400	24,600
07002000	Watkins Creek at Coal Bank Road at St. Louis[3]	6.17	10	24.7	7	1,210	2,170	2,980	4,180	5,230	6,390
07005000	Maline Creek at Bellefontaine Road at Bellefontaine Neighbors[3]	24.1	25	16.4	9	4,780	7,720	10,200	14,000	17,400	21,300
07010016	River Des Peres at Hafner Place at University City[3]	5.64	25	34.4	10	2,170	3,480	4,570	6,210	7,660	9,310
07010026	River Des Peres at Pennsylvania Avenue at University City[3]	9.65	30	25.3	11	2,780	4,460	5,890	8,140	10,200	12,600
07010155	Gravois Creek at Tesson Ferry Road at Sappington[3]	12.1	32	31.1	9	3,160	5,020	6,600	9,100	11,400	14,000

Table 4.--Basin and flood characteristics for selected rural and urban basins --Continued

U.S. Geological Survey station identification number	Name (fig. 1)	Basin characteristics: Contributing drainage area, A, in square miles	Impervious area, I, in percent	Channel slope, in feet per mile	Basin development factor, BDF	Flood characteristics[1]: Peak discharge, in cubic feet per second, for indicated recurrence interval, in years: 2	5	10	25	50	100
07017115	Fox Creek at Old U.S. Highway 66 at Allenton[3]	15.6	2	41.0	0	2,230	3,760	5,020	6,890	8,490	10,300
07019035	Forby Creek at State Highway 109 at Eureka[3]	3.14	2	72.5	0	820	1,390	1,850	2,530	3,110	3,760
07019117	Fishpot Creek tributary at Sulphur Springs Road near Valley Park[3]	2.40	17	69.8	6	1,160	1,700	2,080	2,640	3,070	3,520
07019180	Grand Glaize Creek at Daugherty Ferry Road at Kirkwood[3]	19.8	22	27.2	9	3,030	4,900	6,480	8,910	11,100	13,600
07035500	Barnes Creek near Fredericktown[2]	4.03	1	114	0	929	2,040	2,850	3,560	4,040	4,510
07054200	Yandell Branch near Kirbyville[2]	0.33	2	116	0	65	158	224	318	394	474
07063200	Pike Creek tributary near Poplar Bluff[2]	0.28	5	111	0	124	210	252	305	342	376
07064500	Big Creek near Yukon[2]	8.36	1	53.3	0	1,750	2,950	3,650	4,510	5,120	5,710
07068200	North Prong Little Black River near Hunter[2]	1.23	4	61.7	0	130	245	355	565	795	1,100

[1]Modified from Hauth, 1974a, Spencer and Alexander, 1978, and Sauer and others, 1983.
[2]Rural site.
[3]Urban site.

These variables, however, were not statistically significant and were not included in the final equations. Significant basin characteristics (contributing drainage area, basin development factor, and percentage of impervious area) and flood characteristics are listed for selected stations in tables 3 and 4. Main-channel slope also is listed because slope is useful as a limiting variable of hydrologic significance.

Either basin development factor or percentage of impervious area will describe the effects of urbanization equally well in regression equations as shown by comparison of standard errors of estimate. Also, this equivalency of accuracy is shown by comparison of estimates of 100-year peak discharge (Q_{100}) using basin development factor (BDF) and percentage of impervious area (I) in figure 3.

ESTIMATING FLOOD-PEAK DISCHARGES

Peak discharges at ungaged urban sites can be estimated using one of two sets of equations relating flow magnitude to basin characteristics. Forms of the equations are:

$$Q_t = a\ A^b\ BDF^c \qquad (1)$$

and

$$Q_t = d\ A^e\ I^f \qquad (2)$$

where Q = peak discharge, in cubic feet per second;
t = recurrence interval, in years;
a and d = regression constants;
b, c, e, and f = regression coefficients;
A = contributing drainage area upstream from site, in square miles;
BDF = basin development factor; and
I = percentage of impervious area.

These alternative solutions provide the basin planners a choice of methods for flood-peak prediction. Depending on basin type and location, it may be easier to determine a basin development factor (BDF) than to determine the percentage of impervious area (I) or, conversely, the opposite may be the case.

Values for A, I, and BDF in equations 1 and 2 may be determined as follows:

(1) The contributing drainage area (A), in square miles, for any ungaged rural or urban site may be determined by delineating the drainage basin on the best available topographic maps and planimetering the area within the outline or by laying a transparent grid, having squares of known area, over a map and counting the number of squares within the basin outline. Because of the assumption that the topographic boundary actually represents the total contributing drainage area, significant diversions from or into the drainage basin will need to be accounted for by an adjustment to the drainage area. Otherwise, basin-to-basin diversions, because of storm drains going across the topographic divide, will not be reflected in estimated flows. Some field checks may be needed to determine the actual drainage boundary and area.

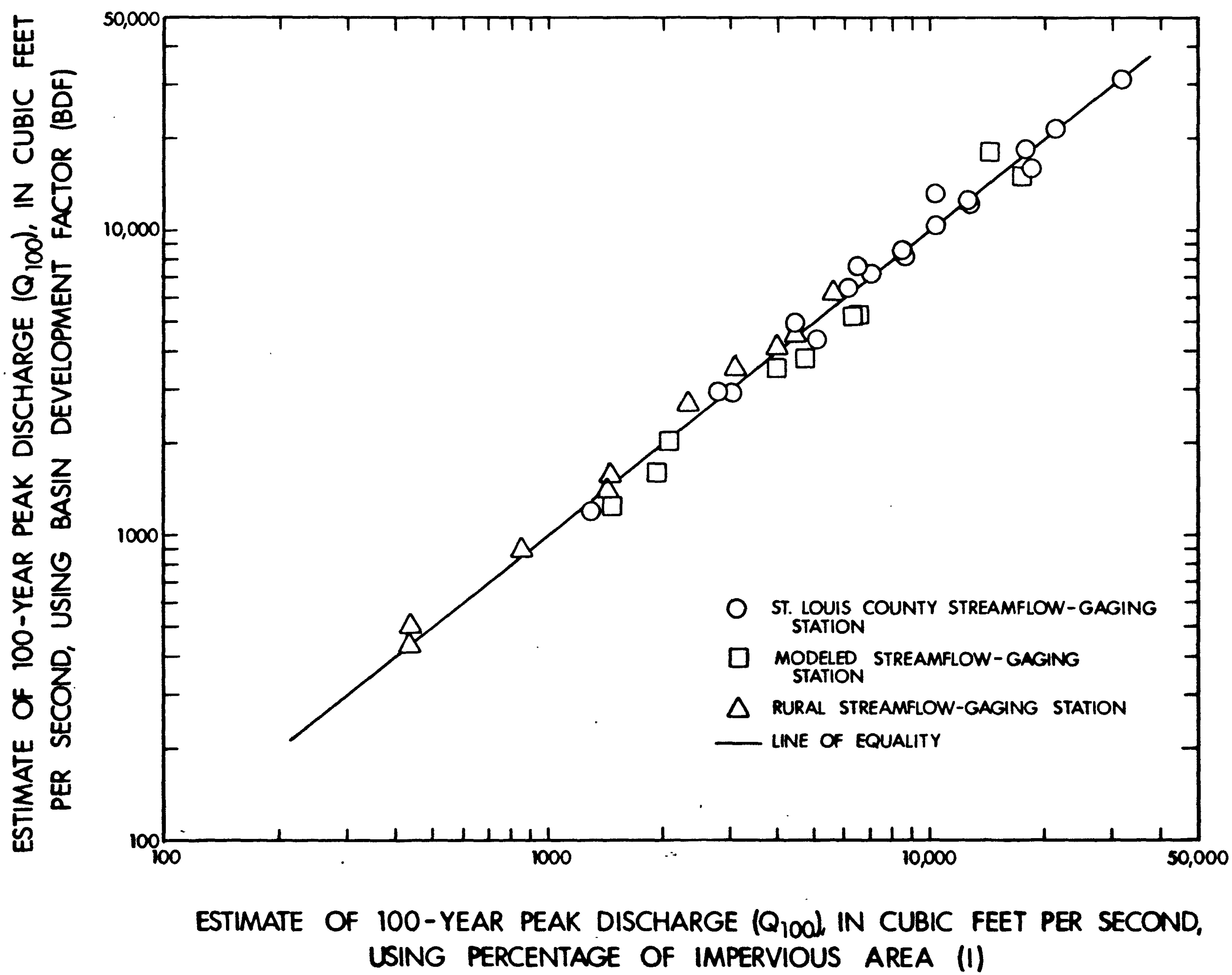

Figure 3.--Comparison of estimates of 100-year peak discharge (Q_{100}) using basin development factor (BDF) and percentage of impervious area (I).

(2) The percentage of impervious area (I), is the effective part of the contributing drainage area that is nonpervious because of buildings, streets and roads, parking lots, and other impervious areas within an urban basin. The variable, I, was determined from best available maps or aerial photographs showing impervious surfaces. Field inspections to supplement the maps were useful. Percentages of impervious area for this study were computed by various methods including a grid-overlay method. A procedure for determining percentage of impervious area was described by Spencer and Alexander (1978) as follows:

> "Aerial photomaps made in 1970 at a scale of 1:8,400 were obtained from the Wastewater Division of St. Louis County. Overlays of the drainage areas delineated on 7½-minute quadrangle topographic maps were enlarged to 1:8,400, then placed over the photomaps, and areas of similar imperviousness were outlined in color. Macroscopes equipped with scalar reticules were used to measure the roof, drive, street, and sidewalk areas on several randomly selected lots in residential areas or developments having consistent patterns. The average percentage of imperviousness was computed and assigned to the area outlined in a given color. The color outlines were planimetered and summed for the entire basin. Total imperviousness was determined from the relation of these subareas to the total."

A reasonable estimate of the effective impervious area in an urban basin in Missouri may be obtained using 7.5-minute topographic maps and application of an estimating equation, based on an alternative basin characteristic, developed by R.E. Southard (in press).

(3) The basin development factor (BDF) may be determined by using the methods described in the following exerpt from Sauer and others (1983) and the example shown in figure 4 (from Sauer and others, 1983, fig. 2, p. 7).

> "The most significant index of urbanization that resulted from this study is a basin development factor (BDF), which provides a measure of the efficiency of the drainage system. This parameter***can be easily determined from drainage maps and field inspections of the drainage basin. The basin is first divided into thirds***. Then, within each third, four aspects of the drainage system are evaluated and each 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 and indicates a more highly developed drainage system.

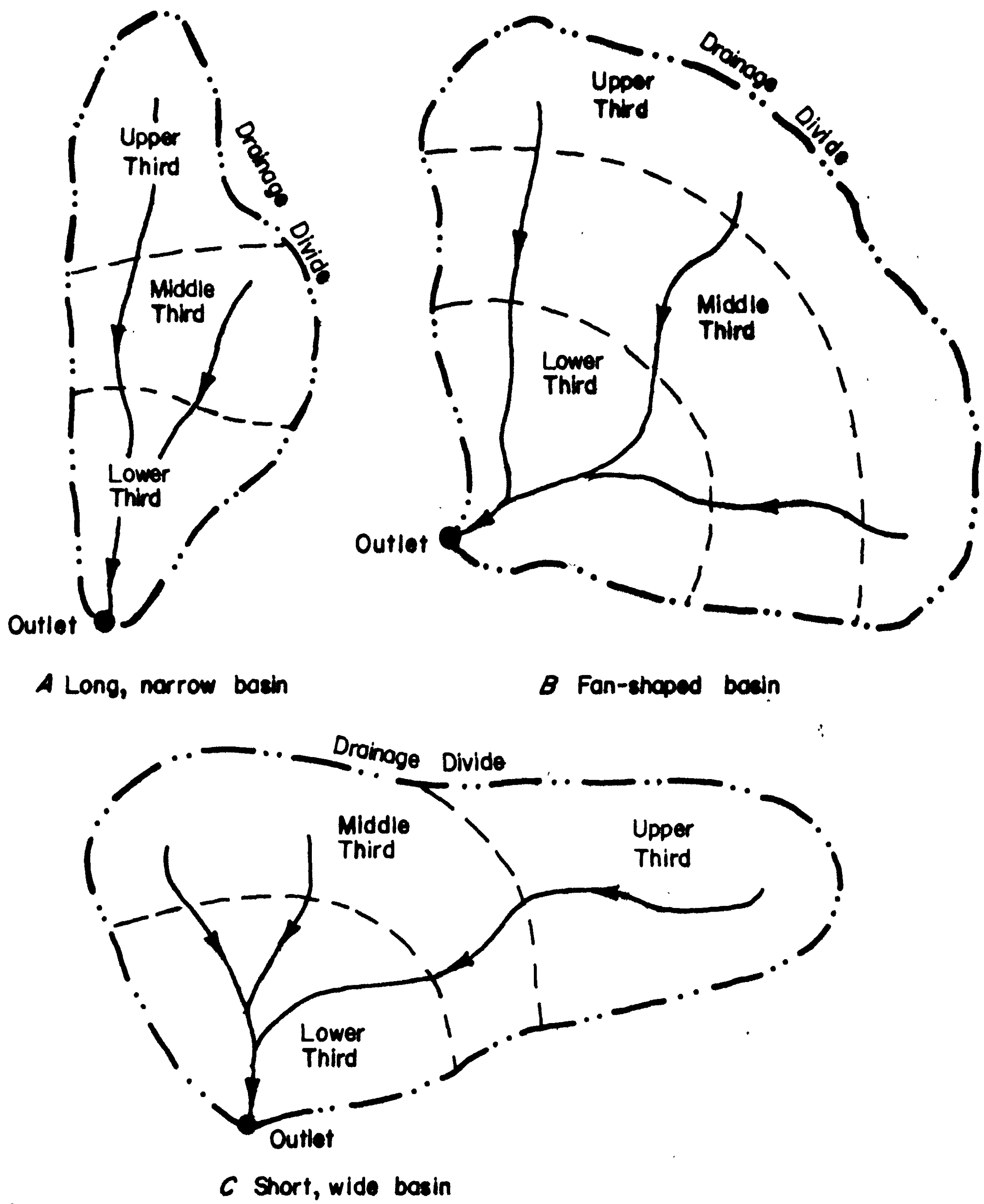

Figure 4.--Schematic of typical drainage basin shapes and subdivision into basin thirds. Note that stream-channel distances within any given third of a basin in the examples are approximately equal, but between basin thirds the distances are not equal, to compensate for relative basin width of the thirds (from Sauer and others, 1983 fig. 2, p. 7).

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 consists 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 channel improvements and channel linings would also be assigned a code of 1.

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 measurements. A certain amount of subjectivity will necessarily be involved. Field checking should be performed 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. In fact, a basin could be partially urbanized, have some impervious area, have some improvement of secondary tributaries, and still have an assigned BDF of zero. ***such a condition still frequently causes peak discharges to increase.

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 = 12. Projections of full development or intermediate stages of development can usually be obtained from city engineers."

Flood-Frequency Equations and Accuracy of Estimates

Estimates of peak discharges for the 2-, 5-, 10-, 25-, 50-, and 100-year recurrence interval floods can be computed for urban sites in Missouri by using one or the other of the following sets of equations. Alternative sets of equations of approximately equal accuracy are provided for convenience of the user.

Reliability of flood estimates at ungaged sites is indirectly indicated by the standard errors of estimate of the regression equations. Generally, this error is the result of time-sampling errors in the actual records and model error in the synthetic records used in the regression analysis. The difference between the estimated and the actual peak discharge for two-thirds of the estimates will be within plus or minus one standard error of estimate.

Equations for peak discharges based on basin development factor (BDF) and standard errors of estimate for these equations (equations 3-8) are:

Peak discharge equation	Standard error of estimate (percent)		Equation number
	Average	Range	
$Q_2 = 801\ A^{0.747}\ (13 - BDF)^{-0.400}$	32.9	+38.2, -27.6	(3)
$Q_5 = 1{,}150\ A^{0.746}\ (13 - BDF)^{-0.318}$	29.4	+33.6, -25.2	(4)
$Q_{10} = 1{,}440\ A^{0.755}\ (13 - BDF)^{-0.300}$	28.4	+32.4, -24.4	(5)
$Q_{25} = 1{,}920\ A^{0.764}\ (13 - BDF)^{-0.307}$	27.3	+31.0, -23.6	(6)
$Q_{50} = 2{,}350\ A^{0.773}\ (13 - BDF)^{-0.319}$	26.5	+30.0, -23.0	(7)
$Q_{100} = 2{,}820\ A^{0.783}\ (13 - BDF)^{-0.330}$	26.4	+29.8, -23.0	(8)

Alternative equations for peak discharges based on percentage of impervious area (I) and standard errors of estimate for those equations (equations 9-14) are:

Peak discharge equation	Standard error of estimate (percent)		Equation number
	Average	Range	
$Q_2 = 224\ A^{0.793}\ I^{0.175}$	32.3	+37.4, -27.2	(9)
$Q_5 = 424\ A^{0.784}\ I^{0.131}$	29.5	+33.8, -25.2	(10)
$Q_{10} = 560\ A^{0.791}\ I^{0.124}$	28.6	+32.6, -24.6	(11)
$Q_{25} = 729\ A^{0.800}\ I^{0.131}$	27.2	+30.8, -23.6	(12)
$Q_{50} = 855\ A^{0.810}\ I^{0.137}$	26.1	+29.5, -22.7	(13)
$Q_{100} = 986\ A^{0.821}\ I^{0.144}$	25.9	+29.2, -22.6	(14)

Peak-discharge estimates for recurrence intervals between 2- and 100-years, other than those for which equations are given, may be obtained by interpolation from a frequency curve which is a plot of discharge versus recurrence interval. Discharges needed for the frequency curve are computed using equations 3 through 8 or 9 through 14.

For St. Louis County, Missouri, peak discharge equations given by Spencer and Alexander (1978) are applicable. However, use of the preceding equations will provide virtually the same results for sites located in St. Louis County.

There always is a chance that an extremely large flood will occur during any specified period on any small stream, rural or urban. For example, in documenting the August 12-13, 1982, floods in Kansas City, Missouri and vicinity, Becker and others (1983, p. 10) stated that "Rock Creek has been subjected to two floods exceeding the 100-year recurrence interval (at Northern Boulevard) in just less than 5 years***. The fact that two 100-year floods have occurred in a 5-year time period is not contradictory***". The probability of one or more floods exceeding a flood of given return interval (the T-year flood) within a given period of years can be estimated. Procedures for making these risk estimates are given by the U.S. Water Resources Council (1981).

Limitations of Estimating Equations

Limitations of estimating equations are based on a general requirement for equivalence of the ungaged site and the data sample used in regression analysis. Basin descriptors ranged as follows in the regression equations tested:

Variable	Range of data
Contributing drainage area	0.28 to 38.9 square miles
Basin development factor	0 to 11
Percentage of impervious area	1 to 34 percent
Main-channel slope	8.7 to 120 feet per mile

Therefore, the following limitations are applicable to the estimating equations (equations 3 through 14):

(1) The equations are applicable only to sites where floodflows are relatively unaffected by storage or diversions. Therefore, they are not applicable where peak discharge is significantly affected by major manmade works, such as dams or intra-basin diversions importing or exporting flows. The applicability of the estimating equations needs to be judged by the possible effect expected on hydrograph magnitude and shape caused by such features.

(2) Estimating equations for peak discharge are considered applicable to contributing drainage areas ranging from about 0.25 to about 40 square miles. Acceptable values for basin development factor may range from 0 to 12. Values for percentage of impervious area reasonably may range from 1

to about 40 percent. Using estimating equations given herein for basins having main-channel slopes smaller or larger than the sampled range (8.7 to 120 feet per mile) may not provide reliable estimates.

(3) Peak-flow data have been collected throughout the year at gaged urban sites in Missouri. Also, synthesized peak-flow data used in the analyses are based on largest storms occurring during annual rather than seasonal periods in the long-term rainfall records. Consequently, estimating equations for peak discharge are applicable to all seasons. However, snowmelt-affected peak flows cannot be estimated on the basis of these equations because these conditions were not modeled when the records were extended.

Estimating Procedures and Examples

The procedures for making flood estimates include: (1) A search for flood data for gaged sites in tables 3 and 4 or in other publications (Spencer and Alexander, 1978; Sauer and others, 1983) or, if needed, (2) computation of required variables and use of regression equations to estimate needed flood information for sites where gaged records are unavailable.

Graphical solutions for the peak-discharge estimating equations (equations 3 through 14) are given in figures 5 through 16. Figures 5 through 10 are for solutions based on A and BDF and figures 11 through 16 are for solutions based on A and I.

To illustrate use of estimating equations the following examples are given. Example 1.--Estimate peak discharges for 25-year and 100-year floods on a small, developed basin in a city where the effects of urbanization are great. Assume contributing drainage area (A) is 3.00 square miles and that a detailed map or field reconnaissance has determined that a value of 9 is appropriate for the basin development factor (BDF).

Solution:

(1) Relations for peak discharge based on BDF are given by equations 3 through 8.

(2) For this example, use A = 3.00 and BDF = 9 in applicable equations.

(3) Compute Q_{25} and Q_{100} by substitution in equations 6 and 8.

$$Q_{25} = 1{,}920\ A^{0.764}\ (13\text{-BDF})^{-0.307} \qquad (6)$$

$$Q_{25} = 1{,}920\ (3.00)^{0.764}\ (13 - 9)^{-0.307} = 2{,}900 \text{ cubic feet per second}$$

$$Q_{100} = 2{,}820\ A^{0.783}\ (13\text{-BDF})^{-0.330} \qquad (8)$$

$$Q_{100} = 2{,}820\ (3.00)^{0.783}\ (13 - 9)^{-0.330} = 4{,}220 \text{ cubic feet per second}$$

(4) Similar results may be obtained from curves given in figures 8 and 10.

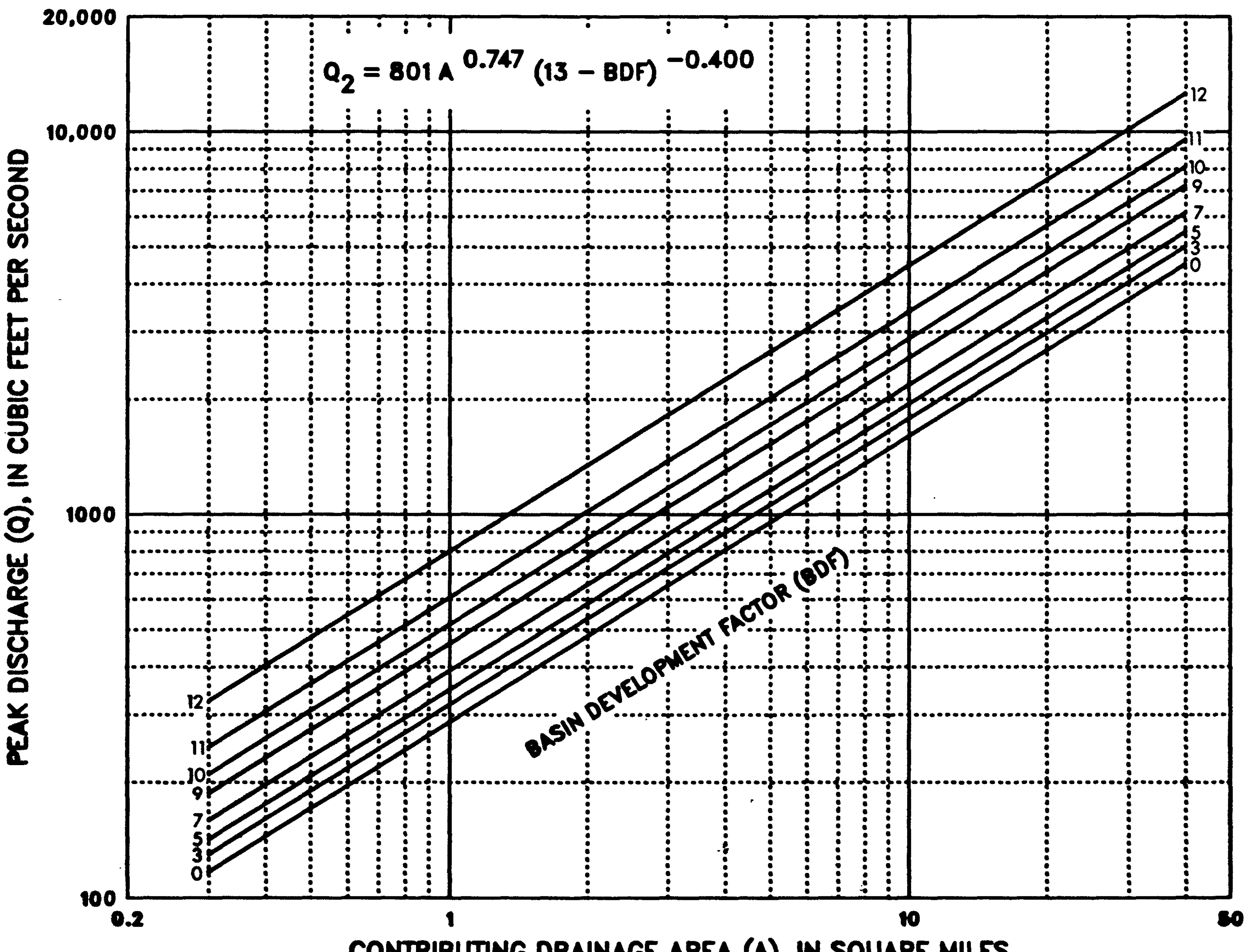

Figure 5.-- Relation of peak discharge (Q) from urban basins to contributing drainage area (A) and basin development factor (BDF) for the 2-year flood.

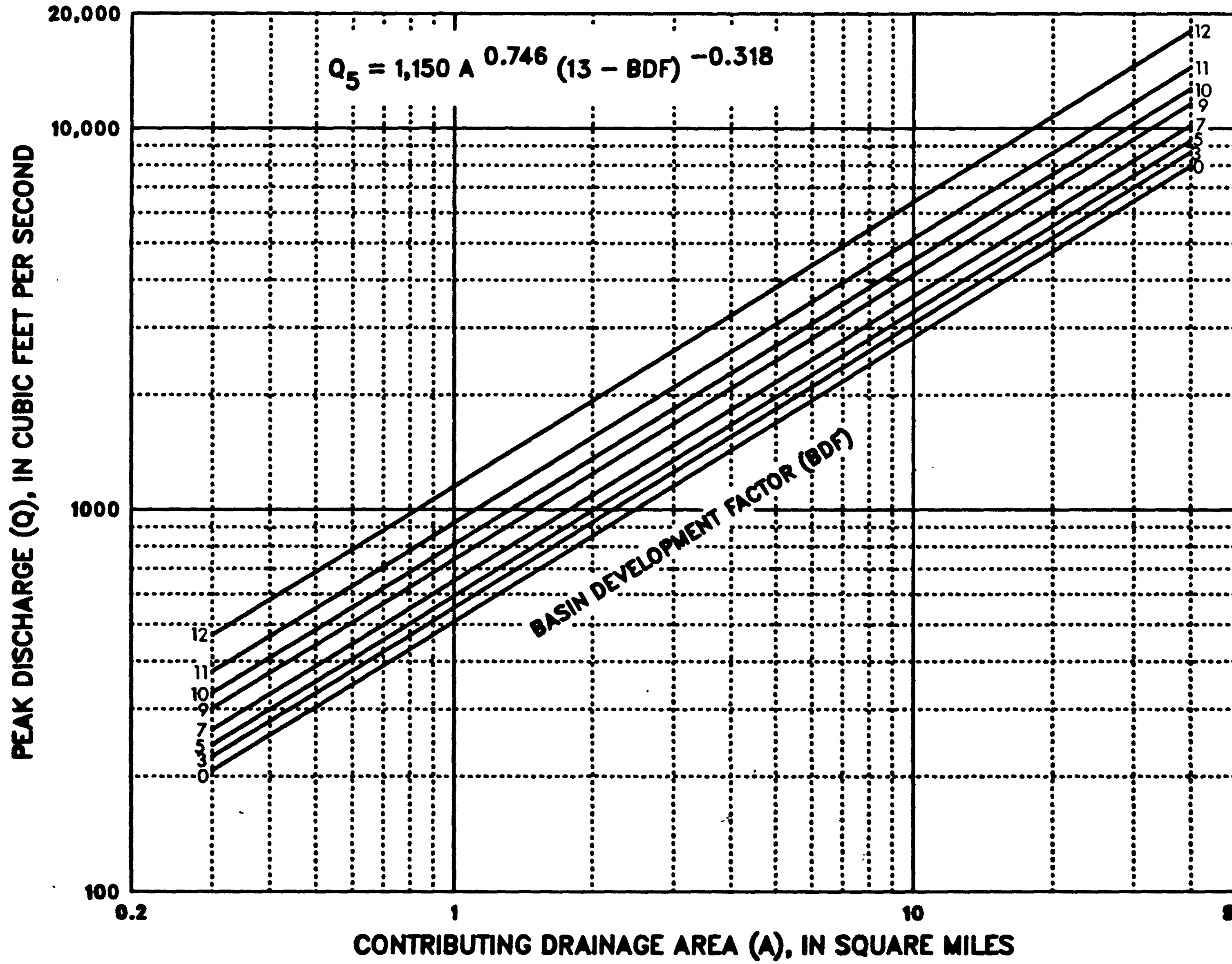

Figure 6.—— Relation of peak discharge (Q) from urban basins to contributing drainage area (A) and basin development factor (BDF) for the 5-year flood.

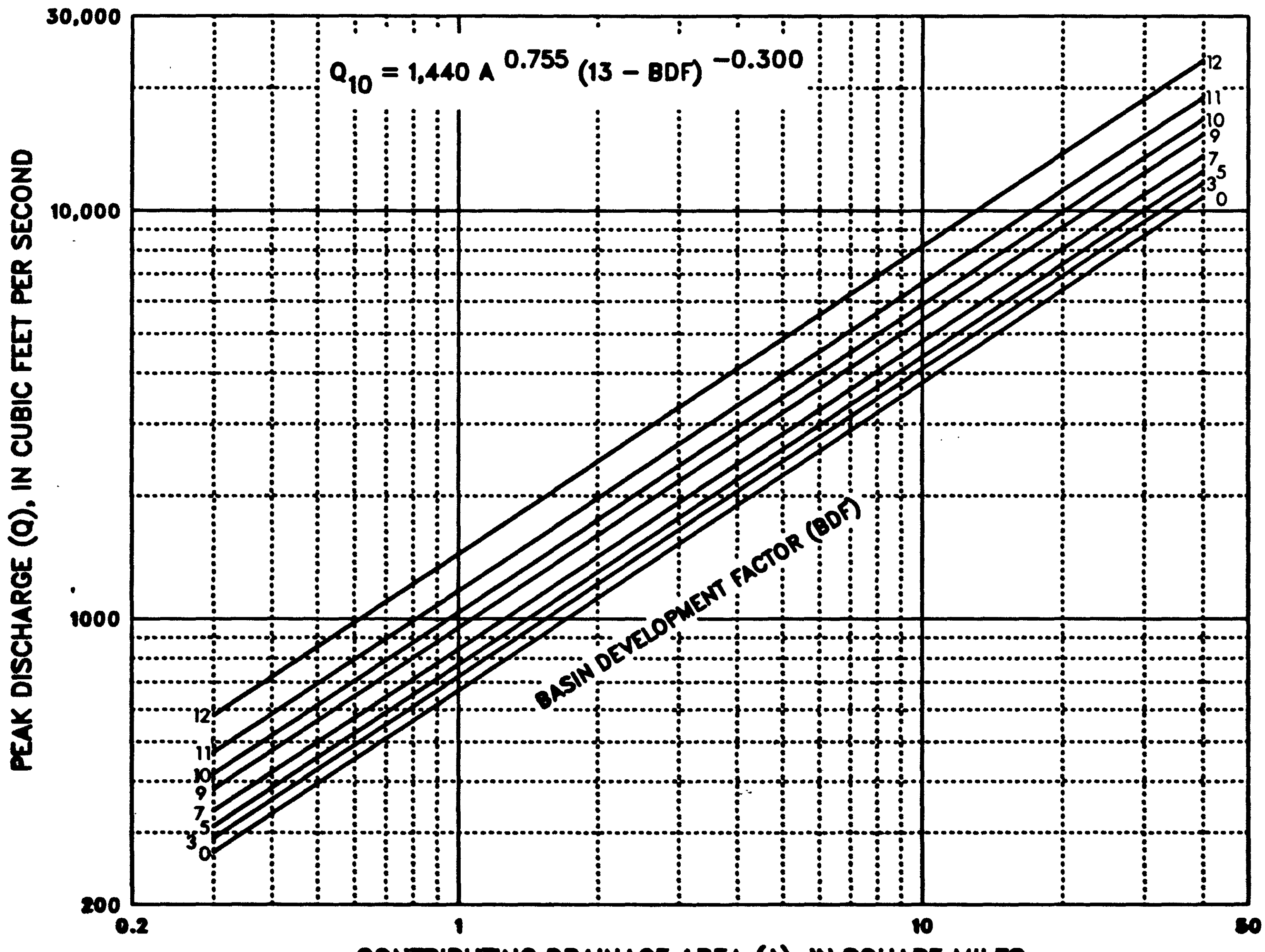

Figure 7.—— Relation of peak discharge (Q) from urban basins to contributing drainage area (A) and basin development factor (BDF) for the 10-year flood.

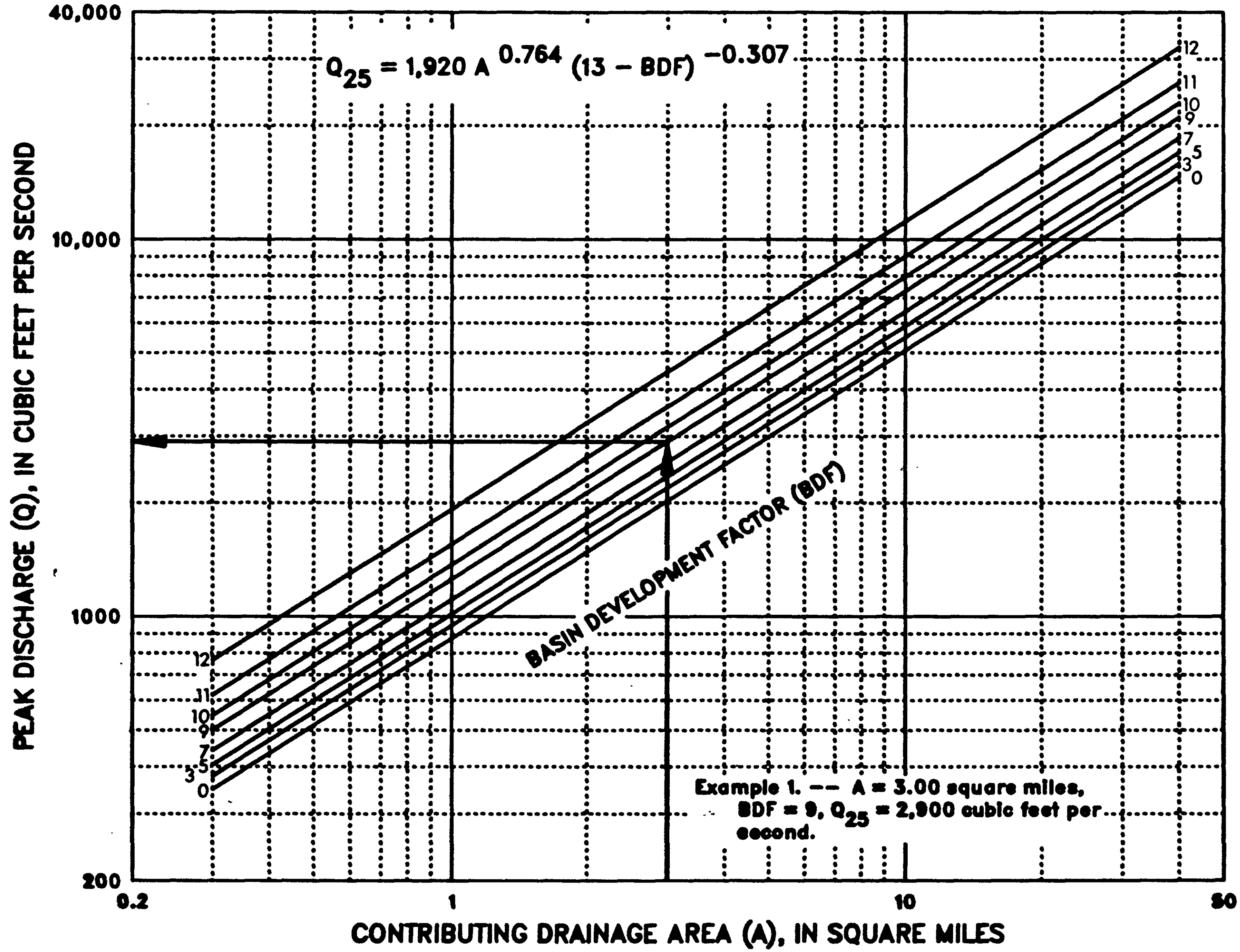

Figure 8.— Relation of peak discharge (Q) from urban basins to contributing drainage area (A) and basin development factor (BDF) for the 25-year flood.

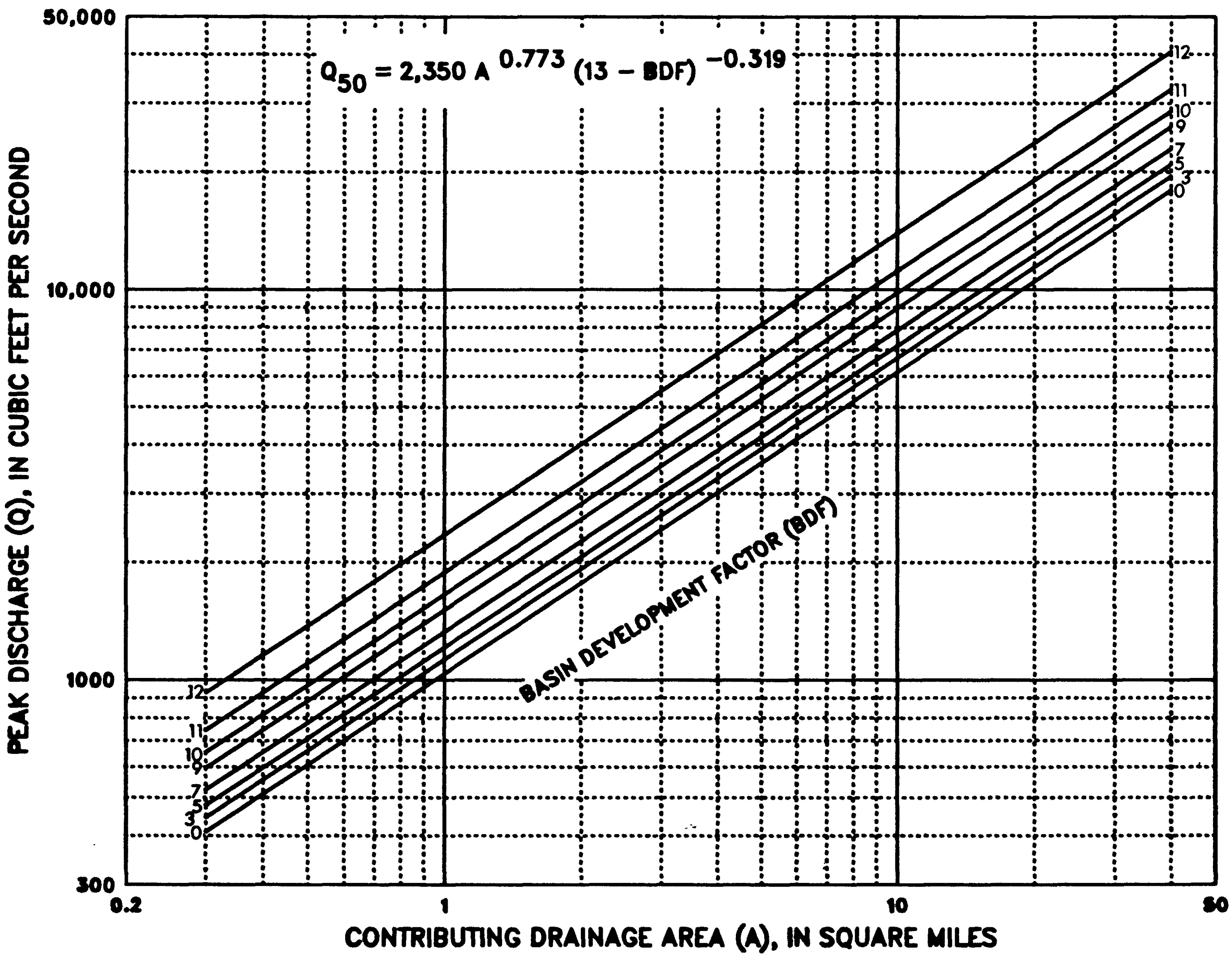

Figure 9.—— Relation of peak discharge (Q) from urban basins to contributing drainage area (A) and basin development factor (BDF) for the 50–year flood.

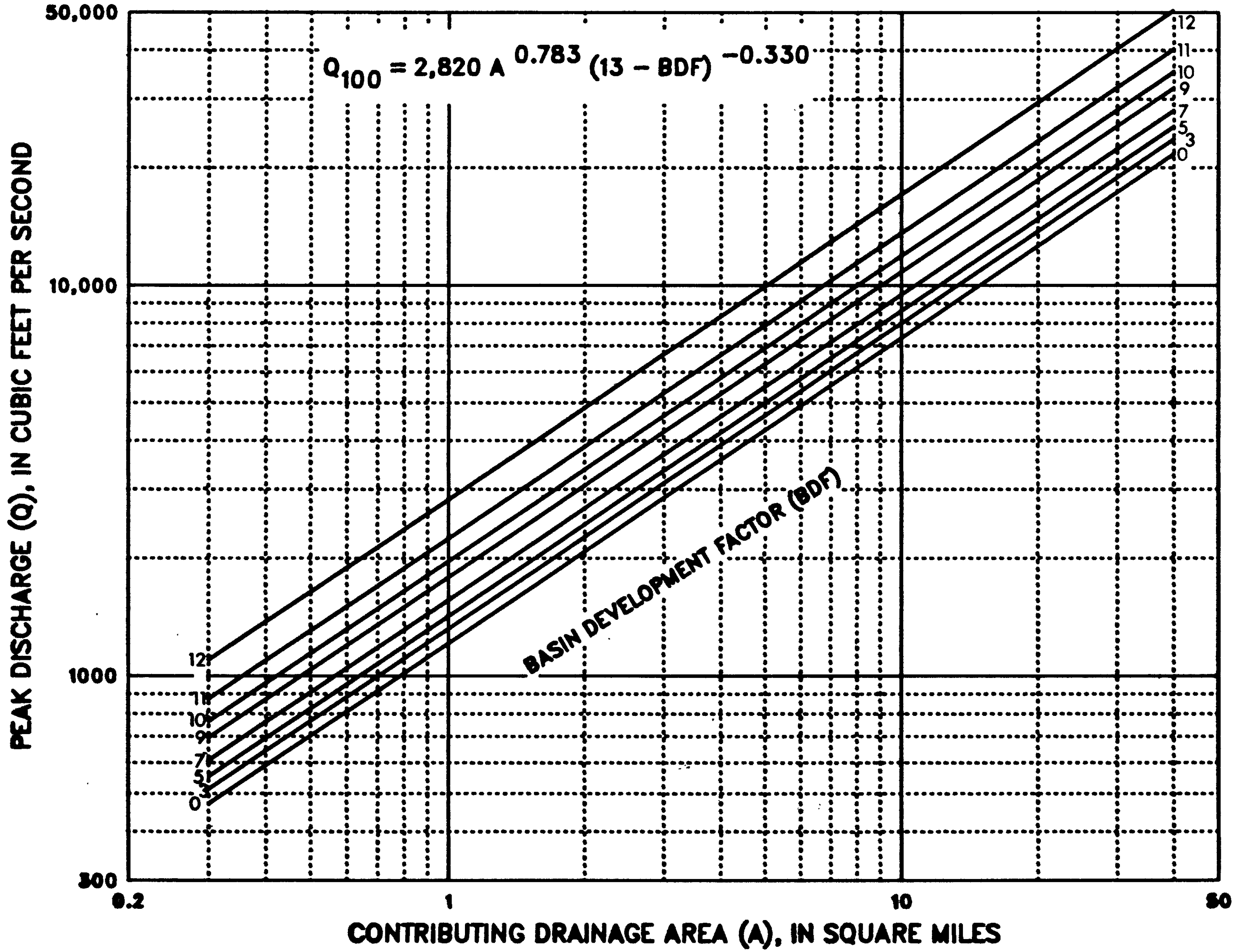

Figure 10.—Relation of peak discharge (Q) from urban basins to contributing drainage area (A) and basin development factor (BDF) for the 100-year flood.

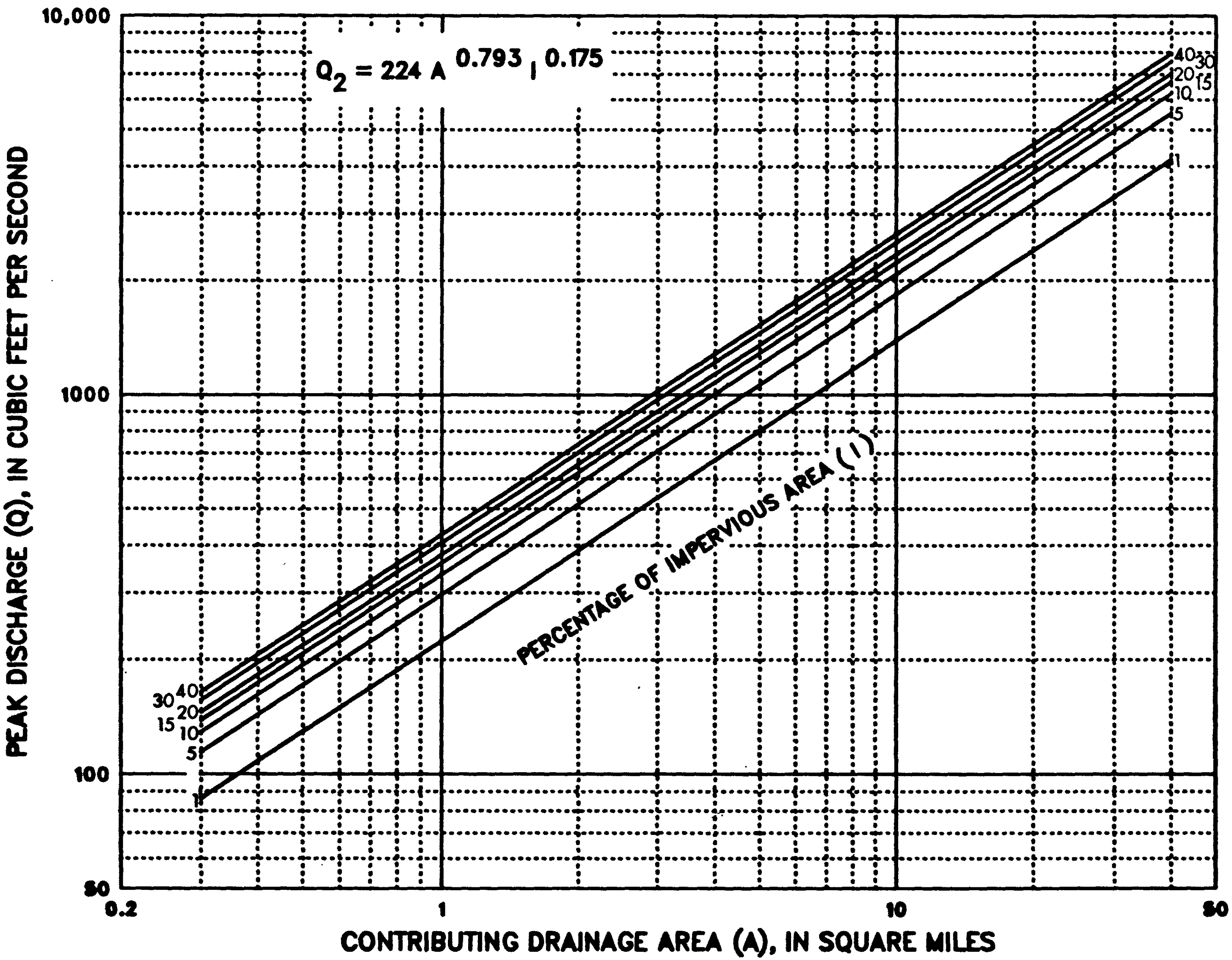

Figure 11.—— Relation of peak discharge (Q) from urban basins to contributing drainage area (A) and percentage of impervious area (I) for the 2-year flood.

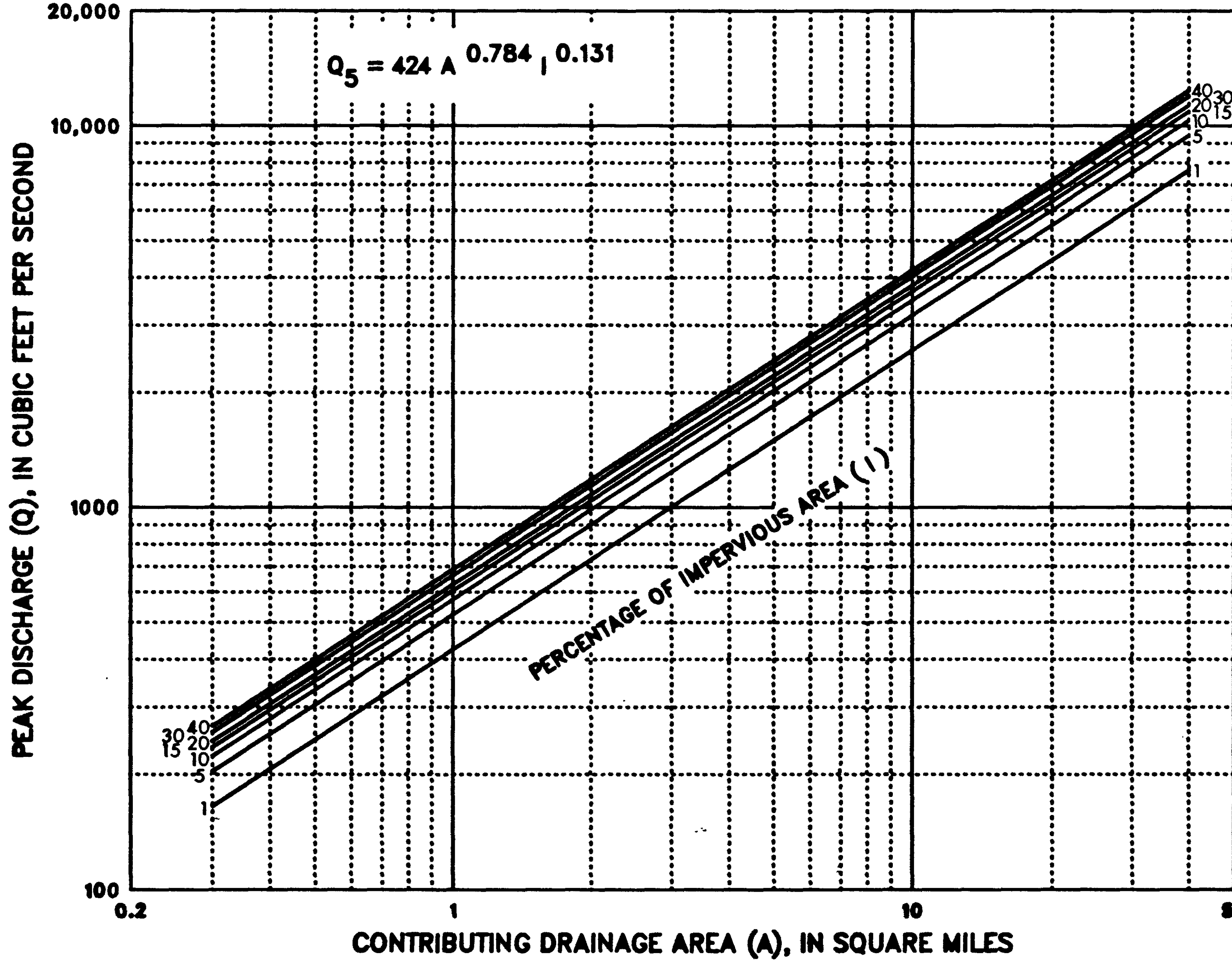

Figure 12.-- Relation of peak discharge (Q) from urban basins to contributing drainage area (A) and percentage of impervious area (I) for the 5-year flood.

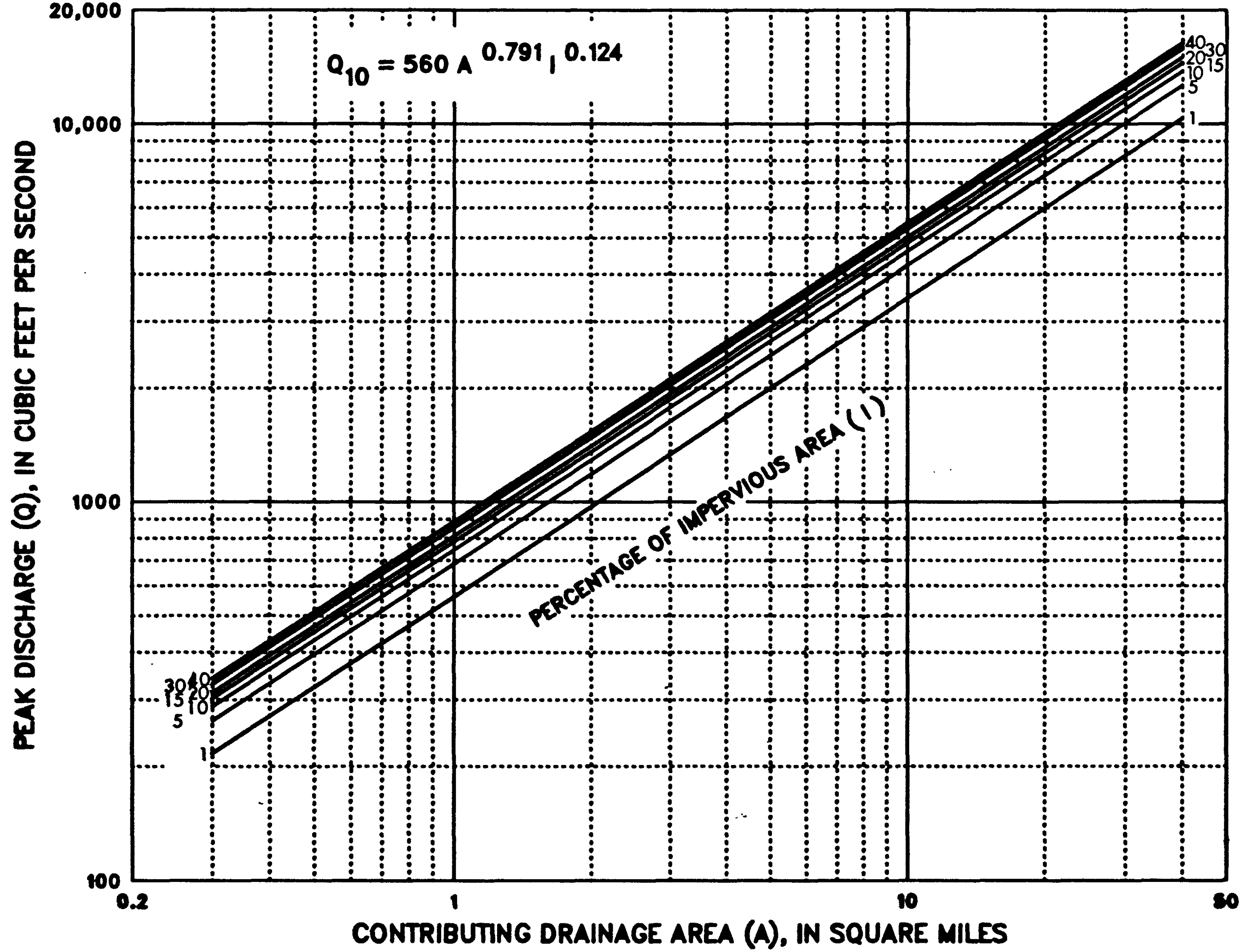

Figure 13.-- Relation of peak discharge (Q) from urban basins to contributing drainage area (A) and percentage of impervious area (I) for the 10-year flood.

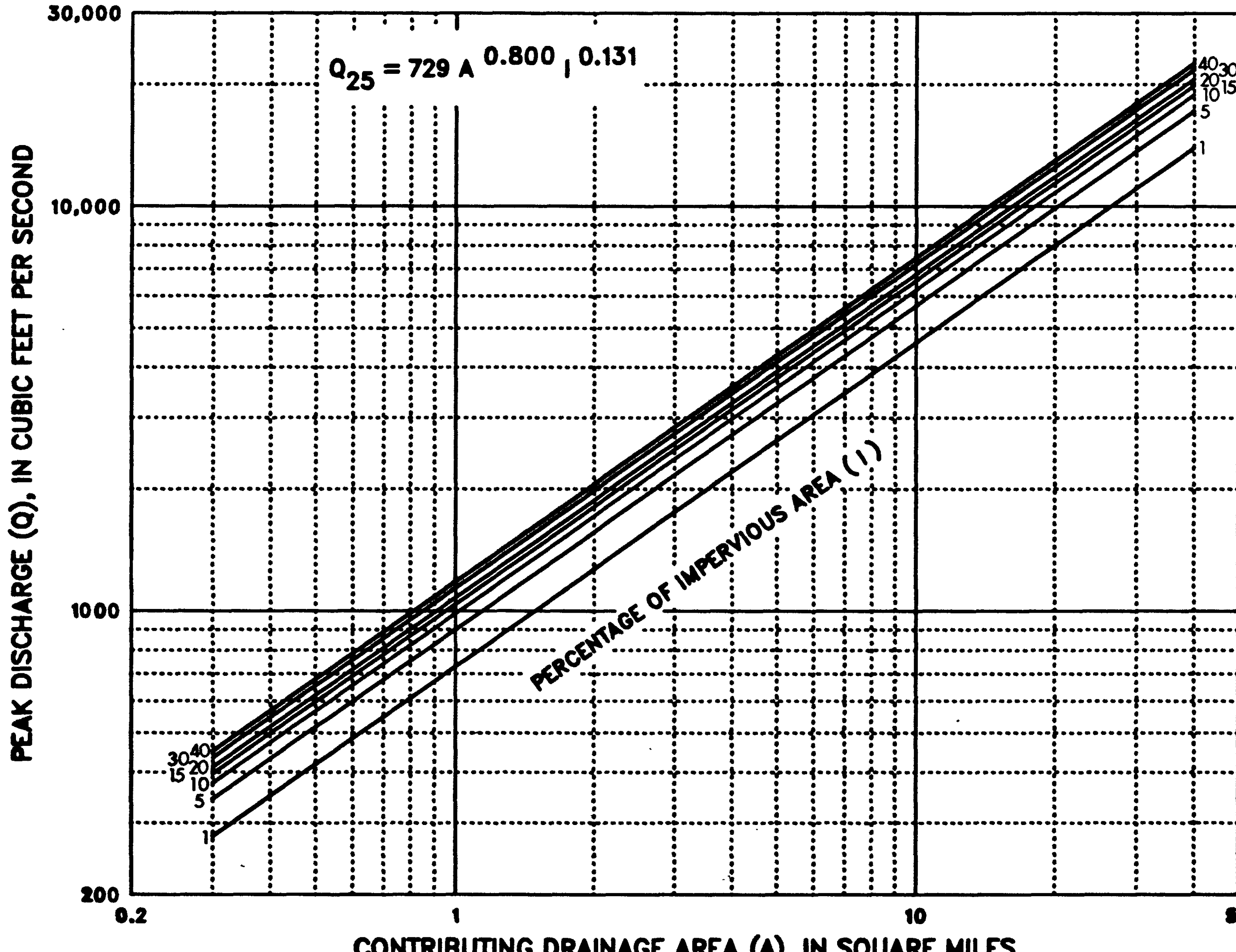

Figure 14.— Relation of peak discharge (Q) from urban basins to contributing drainage area (A) and percentage of impervious area (I) for the 25-year flood.

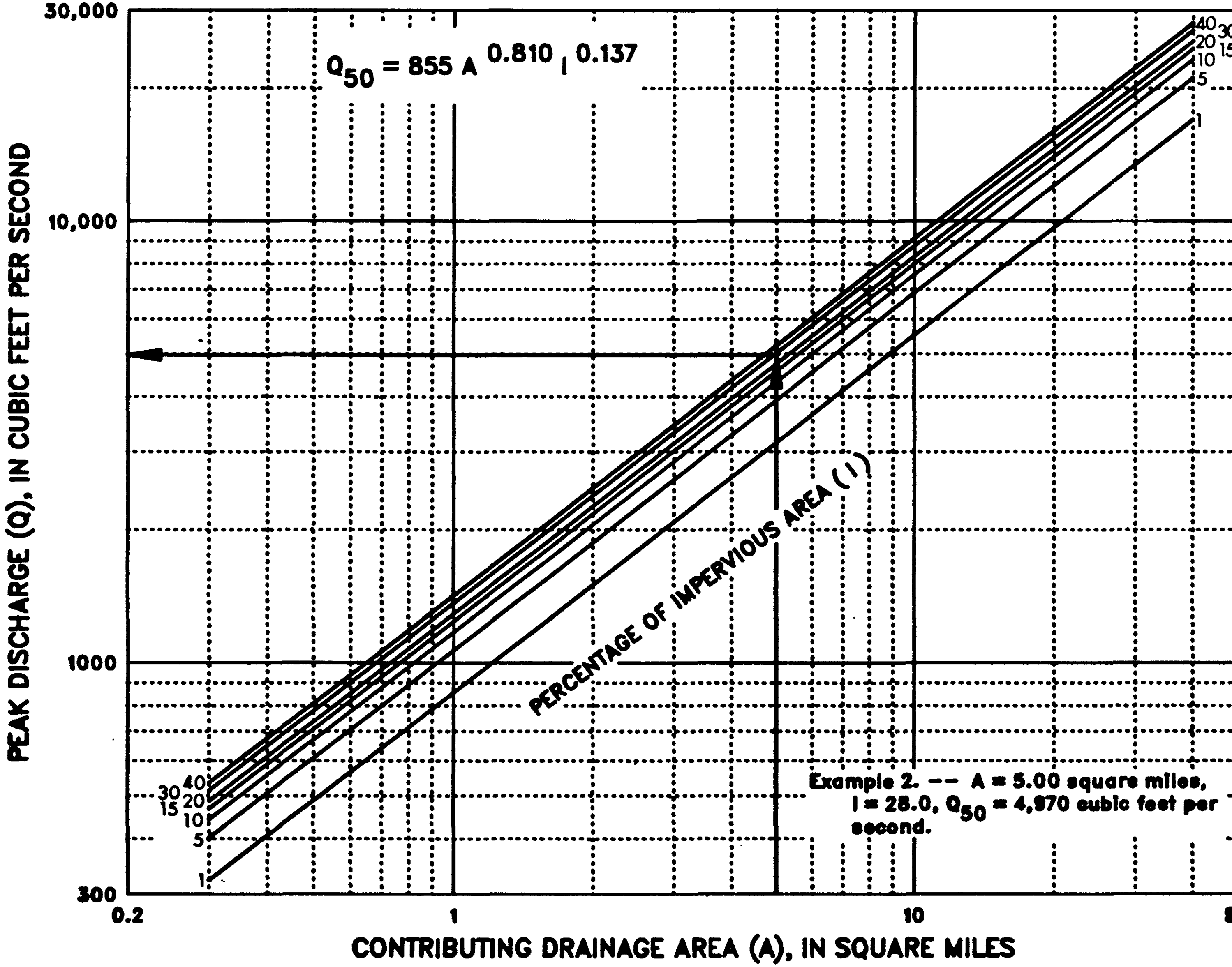

Figure 15.-- Relation of peak discharge (Q) from urban basins to contributing drainage area (A) and percentage of impervious area (I) for the 50-year flood.

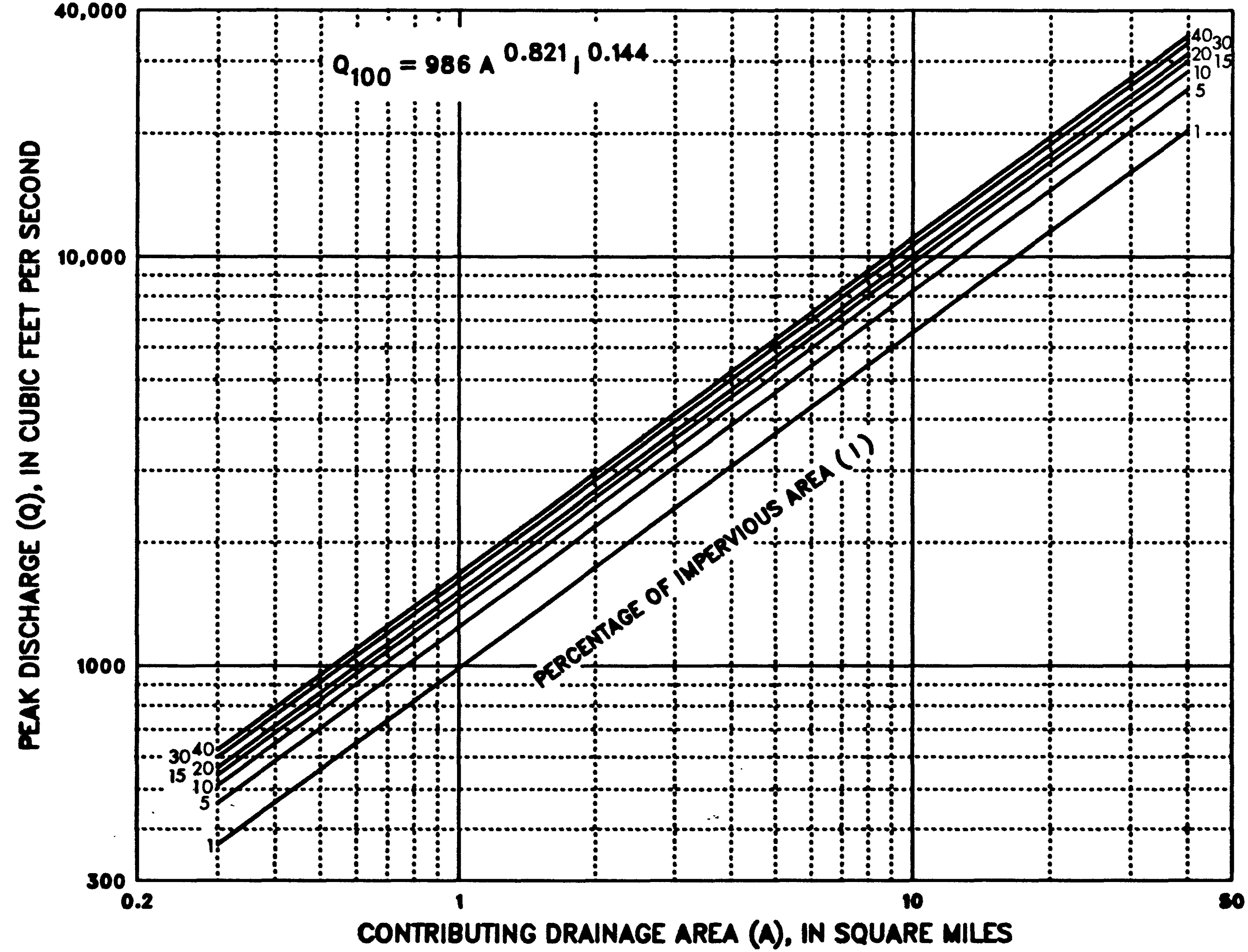

Figure 16.—– Relation of peak discharge (Q) from urban basins to contributing drainage area (A) and percentage of impervious area (I) for the 100–year flood.

Example 2.--Determine the 50-year flood to be expected on a small basin following a planned urban development. Assume that, for a total contributing drainage area of 5.00 square miles, the percentage of impervious area (I) is 28 percent.

Solution:

(1) Relations for peak discharge based on percentage of impervious area (I) are given by equations 9 through 14.

(2) For this example, use A = 5.00 and I = 28 to determine peak discharge.

(3) Compute 50-year flood using equation 13.

$$Q_{50} = 855\ A^{0.810}\ I^{0.137} \qquad (13)$$

$$Q_{50} = 855\ (5.00)^{0.810}\ (28.0)^{0.137} = 4{,}970 \text{ cubic feet per second.}$$

(4) A graphical solution is shown in figure 15.

SUMMARY

This study was directed toward definition of flood characteristics of small urban basins in Missouri. The information is needed for planning and designing drainage structures, for establishing equitable land-use regulations, and for many other uses.

Sufficient new and additional rainfall-runoff and peak-flow data were collected to provide reliable modeling of the rainfall-runoff process at nine gaged sites operated during this urban study. The rainfall-runoff model was calibrated and used with long-term climatological data to synthesize long-term flood records at each site. Analyses of data from this study and of additional data from 28 gaged sites operated as part of other studies in Missouri provided simple, accurate, and practical techniques for estimating flood characteristics at ungaged sites located in small urban drainage basins.

Flood-frequency data, developed from analyses of synthesized flood-peak records, and drainage-basin characteristics were used in multiple-regression analyses to develop regional flood-frequency equations. These equations can be used to estimate flood magnitudes for recurrence intervals of 2-, 5-, 10-, 25-, 50-, and 100-years. The standard errors of estimate range from 26 to 33 percent. These analyses have provided: (1) Flood peak-frequency data for gaged sites that can be used for further analyses (such as a volume-frequency analysis), and (2) regional regression equations for estimating flood-peak discharges using alternative estimators of urbanization effects at ungaged sites, statewide in Missouri.

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GLOSSARY

Cubic feet per second.--The rate of discharge; 1 cubic foot per second is the rate of discharge of a stream having a cross-sectional area of 1 square foot and an average velocity of 1 foot per second:

1 cubic foot per second=0.646 million U.S. gallons per day, 28.32 liters per second, or 0.02832 cubic meter per second.

Flood frequency.--The relation between return period or recurrence interval, in years, and flood-peak magnitude, in cubic feet per second.

Flood hydrograph.--A graphical representation of a stream's fluctuation in flow (in cubic feet per second) with respect to time.

Flood peak.--The highest value of the stage or discharge attained by a flood.

Flood volume.--The total runoff, in acre-feet, computed from the area under the flood hydrograph.

Main-channel slope.--Main-channel slope, in feet per mile, is the average slope between points 10 and 85 percent of the distance along the main-stream channel from the site to the basin divide.

N-year precipitation (rain).--A precipitation quantity that can be expected to occur, on the average, once every N years.

Recurrence interval.--As applied to floods, recurrence interval is the average number of years within which a given flood peak will be equaled or exceeded once. For example, a 100-year flood discharge will be exceeded on the average of once in 100 years. In terms of probability, there is a 1-percent chance that such a flood will occur in any year.

Streamflow-gaging station.--A gaging station where a record of discharge of a stream is obtained.