



Model Synthesis in Frequency Analysis of Missouri Floods

GEOLOGICAL SURVEY
CIRCULAR 708

Prepared in cooperation with the Missouri State Highway Department and
U.S. Department of Transportation, Federal Highway Administration

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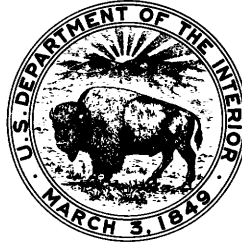
By Leland D. Hauth

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United States Department of the Interior

ROGERS C. B. MORTON, *Secretary*



Geological Survey

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FACTORS FOR CONVERTING ENGLISH UNITS TO INTERNATIONAL SYSTEM (SI) UNITS

The following factors may be used to convert the English units published herein to the International System of Units (SI) :

<i>Multiply English units</i>	<i>By</i>	<i>To obtain SI units</i>
Feet (ft) -----	0.3048	Metres (m).
Square mile (mi ²) -----	2.590	Square kilometres (km ²).
Miles (mi) -----	1.609	Kilometres (km).
Feet per mile (ft/mi) -----	.189	Metres per kilometre (m/km).
Cubic feet per second (ft ³ /s) -----	.02832	Cubic metres per second (m ³ /s).

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ABSTRACT

Synthetic flood records for 43 small-stream sites aided in definition of techniques for estimating the magnitude and frequency of floods in Missouri. The long-term synthetic flood records were generated by use of a digital computer model of the rainfall-runoff process. A relatively short period of concurrent rainfall and runoff data observed at each of the 43 sites was used to calibrate the model, and rainfall records covering from 66 to 78 years for four Missouri sites and pan-evaporation data were used to generate the synthetic records.

Flood magnitude and frequency characteristics of both the synthetic records and observed long-term flood records available for 109 large-stream sites were used in a multiple-regression analysis to define relations for estimating future flood characteristics at ungaged sites. That analysis indicated that drainage basin size and slope were the most useful estimating variables. It also indicated that a more complex regression model than the commonly used log-linear one was needed for the range of drainage basin sizes available in this study.

INTRODUCTION

This report describes technical aspects of a study to define methods for estimating the magnitude and frequency of future floods on Missouri streams. A significant part of the analytical procedure included using a rainfall-runoff model to extend short-term records of floods on small streams. The synthetic flood records generated by use of long-term climatic data in the model were then used with available flood records on large streams to define suggested relations for estimating future flood magnitudes at ungaged sites. A companion report by Hauth (1974) described the defined estimating relations and provided details on how to use the relations to obtain a design estimate, and two other reports by Hauth (1973a, 1973b) presented basic data. The purpose of

this report is to document the analytical methods used.

The economic design of drainage structures, the equitable regulation of flood-prone lands, and the establishment of realistic flood insurance rates require estimates of the magnitude and frequency of floods in the future. Many techniques have been proposed for estimating the magnitude and frequency characteristics of future floods, and the most reliable ones are based upon an assessment of past records of observed floods. In general, the longer the period of observed flood records at a site, the more reliable the future flood characteristics can be estimated at that site. To obtain estimates of future flood characteristics at ungaged sites, techniques are available for transfer of flood information from gaged sites. The accuracy of these estimates at ungaged sites also is related to the accuracy of the estimates at gaged sites and, therefore, to the length of observed flood records.

Flood magnitudes have been observed systematically in Missouri by the U.S. Geological Survey and other Federal and State agencies since 1903. A large mass of flood data has been accumulated, but these long-term data observations have been confined primarily to the large streams. A study by Sandhaus and Skelton (1968) defined methods of estimating flood magnitude and frequency, but, because of the short period of records available on small streams, the technique was considered applicable only for estimates on streams draining more than 50 mi² (130 km²). In a study of the adequacy of available Missouri streamflow records, Skelton and Homyk (1970) determined a need for a longer period of flood records on drainage areas of less than 50 mi² (130 km²).

One suggested alternative to awaiting the assembly of long-term flood records on small streams is to use available long-term climatic records in a rainfall-runoff model to estimate long-term flood records. The runoff process is a complex phenomena. A mathematical model allowing a reasonably accurate description of the process is also complex. It was not until the advent of the digital computer that the use of mathematical models describing the rainfall-runoff process became practical.

The rainfall-runoff model used in this study was developed by the Geological Survey specifically for the purpose of modeling flood-runoff hydrographs from small watersheds. Details of its computational routine, necessary assumptions, and reliability have been described by Dawdy, Lichty, and Bergmann (1972). Primary characteristics of this model are that it is deterministic, structure imitating, digital, and relatively simple. Only 10 parameter values must be evaluated to calibrate the model to any specific drainage site. The parameters were conceived as real and measurable characteristics of the contributing watershed, but in practice the parameters are evaluated from a period of concurrent precipitation and runoff records for each site by an internal and automated optimization routine.

Information available in Missouri offered an ideal situation for testing the use of the rainfall-runoff modeling approach to defining flood-frequency estimating relations. Observations of concurrent rainfall and runoff began on a few small-stream sites as early as 1948, and the data collection program was enlarged and continued until, at the time of this study, an average of 10 years of observations were available for 43 sites that drain from 0.10 to 10 mi² (0.26 to 25.9 km²) located in a variety of topographic settings. Continuous-recorder charts of precipitation averaging 70 years in length have been obtained by the National Weather Service at four areally dispersed sites, and sufficient pan-evaporation data were available to provide long-term climatic inputs needed for model synthesis. Long-term flood observations on larger streams draining up to 14,000 mi² (32,300 km²) were already available for analysis.

Flood-frequency characteristics defined from the 43 synthesized small-stream records and

the observed long-term records on large streams were used as dependent variables in a multiple-regression analysis to define relations for estimating flood characteristics at ungaged sites. The results of this analysis showed that drainage area and main-channel slope are the most effective indices for estimating floodflows in Missouri, but also indicated the inadequacy of the assumption of a simple linear relation between the logarithms of flood characteristics and the logarithms of basin characteristics. Such an assumption is commonly used nationwide and was found satisfactory for a limited range of basin sizes in Missouri. An alternate curvilinear model form suggested by Creager, Justin, and Hinds (1947) was found satisfactory for use with the broad range of basin sizes.

The study described in this report is the first operational use of the rainfall-runoff model in defining flood-frequency estimating techniques. The experiences gained are documented as an aid to others who may be planning similar investigations. This study involves three distinct operations that are described first. They are as follows:

1. Model calibration, or the evaluation of model parameters, for each of the 43 small-stream sites.
2. Synthesis of long-term flood-peak records.
3. Regression of flood characteristics on basin characteristics.

To remain within the scope of this study, and within bounds of the time and resources available, it was sometimes necessary to choose among alternative courses and to ignore some potential useful choices. Some of those potential useful choices where additional research may be beneficial are discussed in a subsequent section.

The opinions, findings, and conclusions expressed in this report are not necessarily those of the Federal Highway Administration.

ACKNOWLEDGMENTS

This report was prepared under the cooperative highway research program with the State of Missouri, Robert N. Hunter, Chief Engineer, and the U.S. Department of Transportation, Federal Highway Administration. Long-term daily precipitation records and storm reductions to 5-minute increments were

obtained from the National Oceanic and Atmospheric Administration (NOAA), Environmental Data Service, National Climatic Center, at Asheville, N.C.

R. W. Lichty and P. H. Carrigan, Jr., hydrologists of the U.S. Geological Survey, provided valuable technical advice and assistance during the preparation of the report.

MODEL DESCRIPTION

The model estimates the flood hydrograph that a drainage basin will produce in response to a specific rainfall sequence. It utilizes a set of mathematical relations approximating the physical laws governing three components of the hydrologic cycle—antecedent soil moisture, infiltration, and surface-runoff routing.

The antecedent soil-moisture component continually assesses the changes in soil moisture as a basis for determining the portion of subsequent rainfall that becomes surface runoff. The changes in moisture storage are assessed on a daily basis during nonstorm periods and on a unit-time basis during storm periods. For each site, a unit-time increment of 5, 10, or 15 minutes is selected so that it provides a suitable degree of refinement in the computations and in the synthetic output hydrograph.

The infiltration component of the model determines the portion of a unit-time rainfall observation that becomes surface runoff. In the surface-runoff component, this rainfall excess is then distributed in time to form the outflow

hydrograph by using a modified Clark routing method.

Ten parameter values control the operation of the model and must be evaluated to calibrate the model to a specific drainage site. These parameters are constants and limits in the mathematical relations, and table 1 lists them and describes the conceptual function of each.

The model contains a trial-and-error, hill-climbing type of parameter optimization technique. The general method is that a set of assumed parameter values is first used to synthesize a flood record for a period of time when concurrent rainfall, pan-evaporation, and flood records are available. The optimization scheme compares the synthesized record with the observed flood record, then automatically changes one parameter value, repeats the computations, and compares the newly synthesized record with the observed record. The process of individually changing parameter values and computing a new synthesized record is repeated until the comparison of synthesized and observed records cannot be improved. The range of values any parameter can assume is limited by the investigator.

Synthetic and observed flood records are compared by means of an objective function. This function is the sum of squares of logarithms of differences between observed and synthesized values of the peak flows, or of the storm volumes, or of a combination of the peak and volume. Thus, the parameter-evaluation

TABLE 1.—*The 10 model parameters and their applications in the modeling process*

Parameter	Units	Definition and application
Antecedent moisture component		
EVC -----	-----	Coefficient to convert pan evaporation to potential evapotranspiration values.
RR -----	-----	Proportion of daily rainfall that infiltrates the soil.
BMSM --- Inches -----	Inches	Soil moisture storage volume at field capacity.
DRN -----	-----	Drainage parameter for redistribution of soil moisture (fraction of KSAT).
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 base of the triangular translation hydrograph.
TP/TC ---	-----	Ratio of time to peak to base length of the triangular translation hydrograph.

procedure develops a nonlinear least-square solution to the optimum set of parameter values.

Once the parameters are evaluated for a specific drainage site, a long-term record of precipitation and pan evaporation may be put into the model to synthesize a flood record.

Many assumptions are required to calibrate and use the rainfall-runoff model. Some of the more important ones are:

1. Uniform distribution of rainfall over the drainage area.
2. Accurate input data.
3. Runoff unaffected by ice or snowmelt.
4. No changes have destroyed the homogeneity of flood records during the period used in model calibration.
5. Available long-term rainfall and evaporation records are applicable to the drainage basin.

To the extent possible, measuring techniques and operational procedures are designed to minimize the effect of deviations from these assumptions. An obvious limitation is the adequacy of a single rain gage for representing the areal distribution of rainfall on a drainage basin. Most floodflows on small drainages in Missouri and other Midwestern States are produced by localized high-intensity thunderstorms. The variability of these storm rainfalls over a drainage basin is probably a function of the ratio of storm size and movement to size of drainage basin. To limit the effects of the assumption of uniform areal rainfall distribution, the model was calibrated only for basins draining less than 10 mi² (25.9 km²).

METHODS OF STUDY

The analysis included three distinct operations. The first was to evaluate the model parameters through a calibration process. The second was to synthesize a long series of annual flood peaks from long-term rainfall records and to define the flood-frequency curves. The last was to define by multiple-regression analysis the relations between the 2-, 5-, 10-, 25-, 50-, and 100-year flood magnitudes and drainage-basin characteristics as a basis for flood frequency estimates at ungaged sites.

MODEL CALIBRATION BASIC DATA

Calibration of the rainfall-runoff model to any specific site requires concurrent data on streamflow, precipitation, and evaporation. Sufficient data were available for calibrating the model for 43 sites with drainage areas draining less than 10 mi² (25.9 km²). Table 2 lists in downstream order the 43 sites together with their drainage areas, calibration period, time increment, and number of storms used in calibration, and figure 1 shows the location of the sites.

In the extreme southeast part of the State, no rainfall-runoff data have been collected because of the inability to define stage-discharge relationships of small drainage areas. However, flood-frequency estimating relations presented later in this report are based upon information from this region for drainage areas greater than 10 mi² (25.9 km²) so that the estimating relationships have statewide applicability.

All stage and rainfall records used in this study were recorded on strip charts. One rain gage was located in each basin. Two types of rain-gage records were used: (1) a tipping-bucket gage that recorded to the nearest 0.1 inch (2.5 mm) synchronously with the stage-recorder gage and on the same chart, and (2) a weighing-type gage placed somewhere within the basin, not necessarily at the stream gage, and recorded on a separate chart.

PARAMETER EVALUATION

The parameter evaluation was accomplished in three phases. During phase one, the parameters shown in table 1 as controlling the volume of runoff (PSP, KSAT, DRN, RGF, BMSM, EVC, RR) were automatically adjusted until the volumes of observed runoff were reproduced with minimum variance (minimum objective function). These parameters were then held constant through phase two, in which the parameters controlling the shape of the synthetic hydrograph (KSW, TC, TP/TC) were readjusted until the observed peaks were reproduced with minimum variance. In phase three, routing parameters were held constant and volume parameters were readjusted until the best fit of observed versus

TABLE 2.—Gaging stations for which the model was calibrated

Station number	Station name	Drainage area (mi ²)	Period of continuous records (yrs)	Unit time increment (min)	Number of storms used in calibration
05495100---	Big Branch Tributary nr Wayland, Mo	0.70	1964-69	5	16
05497700---	Bridge Creek nr Baring, Mo	2.54	1961-64	5	15
05502700---	Easdale Branch nr Shelbyville, Mo	.71	1969-70	5	18
05503000---	Oak Dale Branch nr Emden, Mo	2.64	1956-69	15	25
06815550---	Staples Branch nr Burlington Junction, Mo	.49	1967-69	10	8
06816000---	Mill Creek nr Oregon, Mo	4.90	1951-70	15	30
06820000---	White Cloud Creek near Maryville, Mo	6.06	1949-70	15	28
06821000---	Jenkins Branch nr Gower, Mo	2.72	1950-70	15	29
06896180---	DeMoss Branch nr Stranberry, Mo	.38	1959-65	5	12
06896500---	Thompson Branch nr Albany, Mo	5.58	1955-70	15	28
06897700---	Grand River Tributary nr Utica, Mo	1.44	1966-70	5	24
06902500---	Hamilton Branch nr New Boston, Mo	2.51	1955-70	15	28
06902800---	Onion Branch nr St. Catherine, Mo	1.04	1961-66	10	11
06907200---	Shaver Creek Tributary nr Clifton City, Mo	1.65	1961-64	5	13
06908300---	Trent Branch nr Waverly, Mo	.97	1959-62	5	15
06909700---	Petite Saline Creek Tributary nr Bellair, Mo	.49	1964-69	5	16
06910250---	Traxler Branch nrolumbia, Mo	.55	1960-64	5	14
06918700---	Oak Grove Branch nr Brighton, Mo	1.30	1956-70	10	18
06919200---	Sac River Tributary nr Caplinger Mills, Mo	.14	1962-70	5	12
06921740---	Brushy Creek nr Blairstown, Mo	1.15	1960-70	10	31
06922700---	Chub Creek nr Lincoln, Mo	2.86	1964-70	15	24
06925200---	Starks Creek nr Preston, Mo	1.30	1956-70	15	13
06925300---	Prairie Branch nr Decaturville, Mo	1.48	1969-70	10	18
06926200---	Van Cleve Branch nr Meta, Mo	.75	1956-70	10	12
06927100---	Doane Branch nr Kingdom City, Mo	.54	1959-62	5	13
06928200---	Laguey Branch nr Hazelgreen, Mo	1.58	1958-70	15	18
06931500---	Little Beaver Creek nr Rolla, Mo	6.41	1948-70	15	14
06935800---	Shotwell Creek nr Ellisville, Mo	.81	1962-70	10	30
07011200---	Love Creek nr Salem, Mo	.89	1959-70	5	9
07011500---	Green Acre Branch nr Rolla, Mo	.62	1947-70	5	27
07015500---	Lanes Fork nr Rolla, Mo	.22	1952-70	5	19
07017500---	Dry Branch nr Bonne Terre, Mo	3.35	1955-70	15	29
07019100---	Murphy Branch nr Crystal City, Mo	.45	1960-64	5	8
07035500---	Barnes Creek nr Fredericktown, Mo	4.03	1955-70	15	26
07037700---	Clark Creek nr Piedmont, Mo	4.39	1956-70	15	23
07053950---	Ingentron Hollow nr Forsyth, Mo	.65	1962-66	5	9
07054200---	Yandell Branch nr Kirbyville, Mo	.42	1966-70	5	12
07054300---	Gray Branch nr Lutie, Mo	.27	1959-62	5	11
07063200---	Pike Creek Tributary nr Poplar Bluff, Mo	.28	1959-64	5	11
07064300---	Fudge Hollow nr Licking, Mo	1.72	1959-70	5	6
07064500---	Big Creek nr Yukon, Mo	8.36	1949-70	15	29
07068200---	North Prong Little Black River nr Hunter, Mo	1.23	1964-70	5	18
07185500---	Stahl Creek nr Miller, Mo	3.86	1950-70	15	25

simulated peaks was achieved. Parameters determined in phase three were used in the synthesis of long-term peak discharges.

Initial magnitudes of each parameter were selected on the basis of the watersheds' climate, geology, soil, and basin cover. Constraints were placed on the range in which some initial parameters were allowed to vary during calibration. For example, Kohler, Nordenson, and Baker (1959) computed an average pan-evaporation coefficient for Missouri of about 0.7; therefore, this parameter was constrained to keep its magnitude within a range of 0.5 to 0.9. Initial magnitudes of routing parameters were determined from observed discharge hydrographs, and constraints were placed on

these magnitudes to keep them within a range consonant with experience at each location. The range in which the remaining parameters were allowed to vary during calibration was set to allow the best fit of a plot of the final observed versus simulated peak discharge.

An important step in the operational procedure of parameter evaluation was a screening process to identify and eliminate those storms having large errors in the recorded data. All storms were included in the first phase one and phase two computations, and the recorded storm precipitation was compared with the observed and simulated runoff hydrographs for each storm. Storms then were eliminated from subsequent calibration work if the runoff vol-

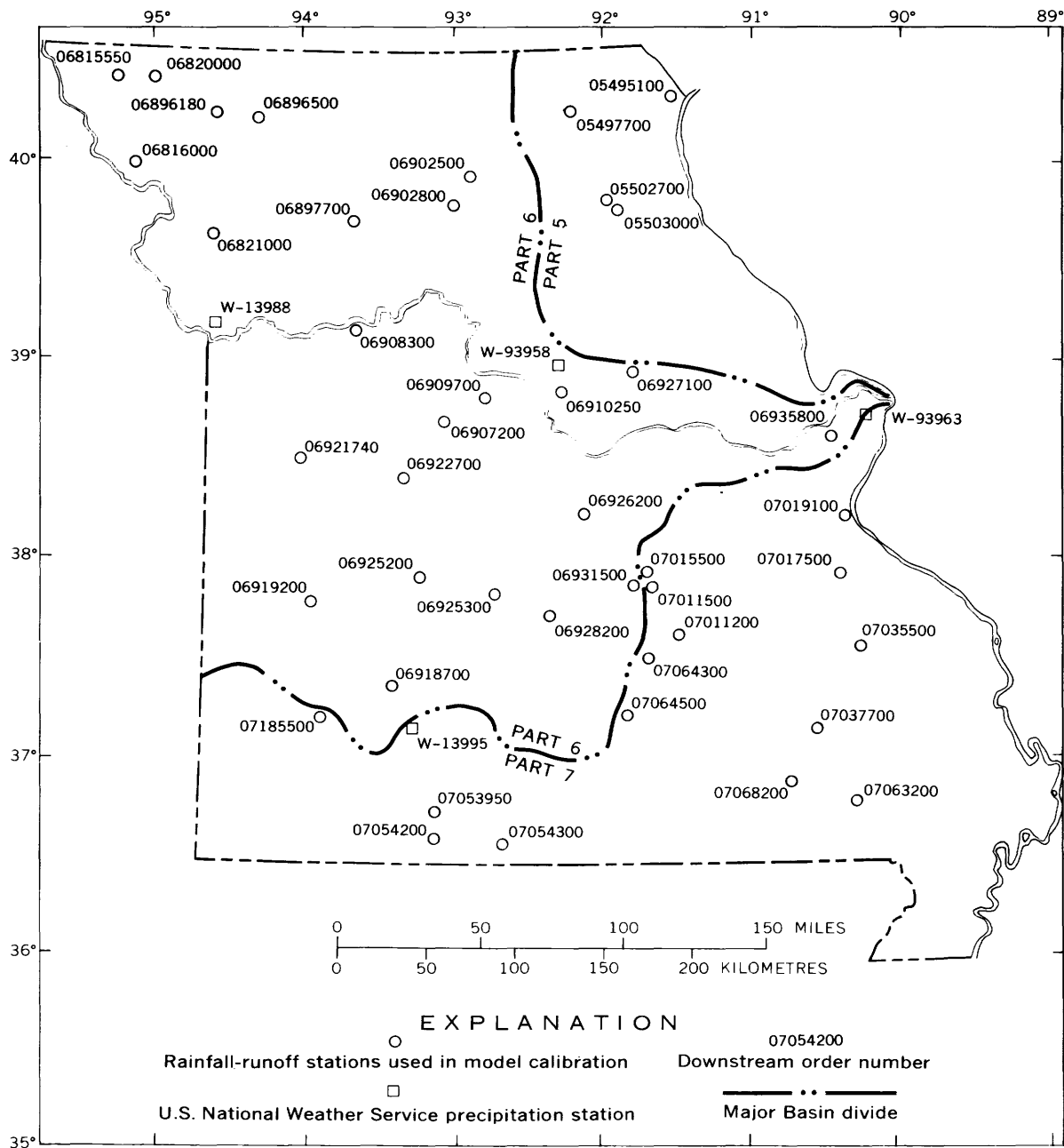


FIGURE 1.—Location of gaging stations where basic rainfall-runoff and precipitation data have been collected in Missouri.

ume exceeded the precipitation, if the precipitation exceeded the runoff by an abnormal amount, or if other obvious data problems appeared. The evaluation of parameters by phase one and phase two was then repeated as many times as necessary on the reduced set of storms. Although the screening process was somewhat

subjective, the elimination of these storms—for which recorded precipitation obviously was not representative of basin precipitation—was considered essential to establishment of the optimum set of parameter values for model calibration.

A final set of parameter values was determined from the screened storm data by a phase three computation (readjustment of volume parameters holding phase two routing parameters constant). A plot was then prepared of observed peaks versus synthesized peaks and was used to graphically check for possible bias in calibrated model results. The average standard deviation of differences between observed and synthesized peaks was about 35 percent.

Model calibration was completed for each station in downstream order (ascending station numbers). Experience gained early in the process allowed more efficient calibration of downstream stations and perhaps allowed parameters to be defined with more confidence and meaning. Table 3 lists the stations in downstream order and the best-fit parameter values.

SYNTHESIS OF FLOOD RECORDS

A calibrated model can be used to estimate the flood peak resulting from any selected storm rainfall and associated antecedent moisture conditions; therefore, a long record of rainfall and evaporation is needed to generate a long series of synthetic flood peaks. Four long-term, continuously recording rainfall gages have been operated in Missouri by the National Weather Service. These records provide the basic rainfall data for model input and are identified in table 4.

One relatively long record of daily pan evaporation collected at Lakeside, Mo., near Lake of the Ozarks, was processed to provide needed evaporation inputs.

PROCESSING RAINFALL RECORDS

Model synthesis requires records of daily precipitation for nonstorm periods and unit precipitation for storm periods. Daily precipitation records for each of the four sites were available from the National Climatic Data Center, Asheville, N.C., and were processed and placed in computer storage.

Unit precipitation information could be attained only by coding data from original recorder charts, a tedious, relatively time consuming, and therefore expensive, process. To provide a realistic basis for synthesizing an annual series flood record, unit data must be

available for all storms that might conceivably produce the largest peak flood during any water year (October 1 to September 30). To minimize costs, however, it was desirable to limit the number of storms selected. R. W. Lichty (written commun., 1973) has studied the problem of identifying those storms likely to cause an annual maximum flood and the effect of the number of identified storms on the resulting frequency curves. For basins with lag times of about three-quarters of an hour, he concluded that three storms each year identified as the maximum daily or 2-day total rainfalls would produce a frequency curve not significantly different from one based on unit data for a great many more storms. For basins with lag times of less than three-quarters of an hour, Lichty suggested that the number of storms identified for reduction to unit data should be increased to four or possibly five per year.

A computer program supplied dates of the storms that would possibly cause the maximum annual flood peak by identifying the five largest daily or 2-day total rain catches in each water year in each of the daily precipitation records. A reduced number of dates was then selected for the reduction of rainfall recorded charts to unit data by considering for each storm the antecedent rainfalls, the comparative total rainfalls, the hourly intensities, and similar available information. Table 4 shows the number of storms in each record for which the National Climatic Data Center, NOAA, of Asheville, N.C., prepared computer inputs of 5-minute unit precipitation data.

All the information on daily and unit precipitation for each of the four long-term rain-gage sites was presented in a report by Hauth (1973a).

PROCESSING EVAPORATION RECORDS

A daily evaporation record is required for model synthesis. The longest available record in Missouri is for the Lakeside, Mo., pan-evaporation gage located at Lake of the Ozarks, which began operation in February 1948.

A computer program developed within the U.S. Geological Survey analyzed the available evaporation record to determine a harmonic (sine-cosine) function, which then generated a

TABLE 3.—*Summation of model parameters*

Station number	Parameters (see table 1)									
	PSP	KSAT	DRN	RGF	BMSM	EVC	RR	KSW	TC	TP/TC
05495100	4.17	0.051	0.63	16.6	4.73	0.70	0.84	1.22	87.5	0.51
05497700	1.45	.028	.29	17.8	6.12	.67	.88	1.50	226	.20
05502700	1.62	.027	.16	4.86	37.8	.66	.84	.89	63.0	.93
05503000	1.39	.037	.26	18.8	2.97	.69	.70	1.92	69.6	.40
06815550	1.27	.030	.10	10.1	10.8	.67	.76	.76	42.0	.64
06816000	3.85	.096	.22	10.6	4.77	.67	.79	.74	66.0	.49
06820000	2.40	.050	.72	10.5	1.20	.76	.77	2.00	122	.55
06821000	1.46	.067	.77	13.6	5.16	.72	.70	.87	52.0	.95
06896180	2.19	.069	.96	8.50	4.84	.78	.66	.90	33.0	.20
06896500	1.15	.070	.36	9.09	2.12	.62	.83	2.50	118	.80
06897700	3.7	.040	.18	9.33	5.47	.66	.76	2.30	94.5	.74
06902500	.98	.020	.09	3.84	3.59	.63	.79	2.00	94.5	.84
06902800	3.48	.030	.29	13.5	8.35	.74	.70	1.38	78.0	.98
06907200	2.56	.040	.15	2.92	2.25	.67	.84	1.27	67.0	.87
06908300	2.06	.070	.63	12.8	12.2	.71	.84	.34	54.0	.97
06909700	8.64	.21	.76	4.43	3.40	.72	.90	.60	49.0	.84
06910250	1.94	.050	.22	13.6	5.52	.71	.77	.35	55.0	.85
06918700	1.99	.060	.31	27.2	4.12	.62	.68	1.23	26.0	.78
06919200	2.52	.060	.84	14.8	2.43	.77	.84	.64	85.9	.36
06921740	1.92	.050	.33	5.67	5.13	.70	.68	.80	30.0	.80
06922700	.60	.02	.17	2.62	14.8	.72	.73	1.69	19.2	.67
06925200	2.57	.05	.50	12.2	4.8	.69	.85	2.31	126	.50
06925300	4.48	.14	.51	15.8	7.14	.69	.74	1.36	34.2	.68
06926200	2.07	.10	.91	12.3	37.0	.82	.81	.24	26.6	.93
06927100	2.79	.050	.05	16.7	7.11	.70	.90	2.12	60.0	.34
06928200	2.53	.030	.24	7.07	2.82	.61	.87	1.14	37.8	.59
06931500	4.10	.050	.47	11.7	2.40	.52	.85	.84	75.0	.50
06935800	2.35	.040	.36	17.4	3.00	.74	.69	.69	44.1	.96
07011200	1.58	.030	.15	6.11	27.7	.79	.64	2.12	34.7	.75
07011500	2.22	.050	.33	11.9	3.93	.77	.87	.49	32.3	.97
07015500	.68	.050	.09	5.70	8.66	.71	.94	.94	98.7	.67
07017500	1.82	.060	.82	5.55	4.07	.63	.86	1.56	26.1	.40
07019100	5.70	.12	.49	13.8	3.78	.73	.68	.40	24.3	.96
07035500	.84	.060	.13	16.4	4.29	.71	.74	.77	77.0	.86
07037700	2.28	.060	.79	58.3	5.83	.64	.88	1.77	20.2	.55
07053950	2.37	.070	.91	7.90	7.29	.80	.61	.54	66.0	.81
07054200	5.81	.16	.48	6.06	3.47	.58	.51	.66	25.7	.90
07054300	3.64	.10	.82	14.3	2.92	.63	.82	1.16	41.2	.88
07063200	1.93	.060	.19	6.92	10.9	.80	.66	.63	26.1	.18
07064300	.17	.050	.36	14.0	27.4	.95	.72	.66	66.0	.62
07064500	2.49	.040	.67	9.15	2.34	.63	.81	1.85	101	.62
07068200	21.2	.080	.28	16.4	3.98	.64	.58	1.09	59.4	.96
07185500	2.05	.050	.30	19.7	3.46	.71	.87	1.98	117	.72

TABLE 4.—*U.S. National Weather Service first-order precipitation stations used in synthesis of peak-flow data*

Station number (fig. 1)	Station name	Period of continuous record	Number of events selected
W13988	Kansas City WSO	1893-1970	217
W93963	St. Louis WSO	1893-1970	190
W93958	Columbia Region WSO	1902-70	222
W13995	Springfield WSO	1905-70	182

synthetic daily evaporation record for the 1893 to 1948 period. Experience has shown that model outputs are relatively insensitive to the day-to-day variations in evaporation data and that an evaporation record may be applicable to large regions. The partly synthesized evaporation record used in this study was considered

to be adequate for flood-peak synthesis at the 43 sites considered.

DEFINING SYNTHETIC FLOOD FREQUENCIES

Four series of synthetic annual peaks were generated for each of the 43 sites by putting into the calibrated model the data from each of

the four long-term rainfall gages and the evaporation gage. Each of the four series of peaks was then tested in pairs (Kansas City and St. Louis, Kansas City and Columbia, and so forth) for statistical distribution differences via the Cramer-von Mises Two-Sample Test as described by Conover (1971). In no instance could the hypothesis that the samples are identical be rejected at the 1-percent level of significance, and in only one station pairing could the hypothesis be rejected at the 5-percent level. These results indicate that there was no apparent advantage or reason to use one rain-gage record in preference to another and that an average of the four frequency relations would be justified.

To define the average synthesized frequency curve, four individual curves were computed by mathematically fitting a Pearson Type III distribution to the logarithms of each of the four annual peak series using techniques recommended by the U.S. Water Resources Council (1967). The 2-, 5-, 10-, 25-, 50-, and 100-year recurrence interval peak magnitudes from each curve then were averaged to form the synthetic curve for each site.

In addition to the synthesized records, the observed flood-peak record was available to aid in definition of the frequency characteristics at each site. Observation and testing indicated that these relatively short records could be of value. Firstly, because the observed data are of sufficient length to define reliably the magnitude of flood peaks in the range of the 2- to 10-year recurrence intervals. Secondly, because statistical analysis of the synthetic frequency curves indicates that the variance between curves decreases with increasing recurrence interval—that is, the model defines the extreme floods with more consistency than the smaller floods. A log-Pearson Type III distribution was also fitted to the observed flood series.

A graphical weighting procedure was employed to combine the observed and synthesized frequency curves into a final curve. Both the average synthetic data curve and the observed data curve were plotted on a probability graph, and a curve was drawn from the 2-year observed value to merge smoothly with the average synthetic curve at a point generally greater than the 10-year recurrence interval. Figure 2

shows the relationships for Thompson Branch near Albany (06896500) and the final curve obtained by this graphical process. Each curve was judged individually in an effort to provide the best possible estimate of the frequency characteristics to use in the regression analysis. A summary of the flood characteristics for the 43 sites is given in table 5.

REGIONAL REGRESSION ANALYSIS

Flood data at a sample of gaged sites provide a basis for estimating flood characteristics at ungaged sites. The technique of transferring data used in this study defines from this sample some equations relating flood magnitudes to numerical indices describing characteristics of the contributing drainage basins. Separate equations are defined for selected points on the frequency relation, such as the 2-, 10-, and 50-year recurrence interval peak magnitudes. Drainage-basin indices describe the size, shape, slope, soil characteristics, vegetative cover, climate, and so forth. They are indices that can be evaluated from topographic, geologic, and climatic maps and from other readily available sources, and they logically can be expected to be related to the differences in floodflows at the various gaged sites. Planners and designers may then solve the defined equation to estimate the flood characteristics of an ungaged site by evaluating appropriate basin indices.

Many recent studies throughout the Nation have defined flood-estimating equations based upon a model of the form:

$$Q_t = bA^{b_1}B^{b_2}\dots N^{b_n}$$

where

Q_t = flood magnitude having a t -year recurrence interval,

$A, B, \dots N$ = drainage-basin indices, and
 $b, b_1, b_2, \dots b_n$ = constants for a given t .

Constants are evaluated most easily by multiple-regression analysis when the variables are transformed to logarithms to form a linear relation:

$\log Q_t = \log b + b_1 \log A + b_2 \log B + \dots b_n \log N$. Regression analysis techniques also provide a measure of the accuracy of the equation, known as the standard error of estimate, and test the significance of the b coefficient of each independent variable. Only those independent vari-

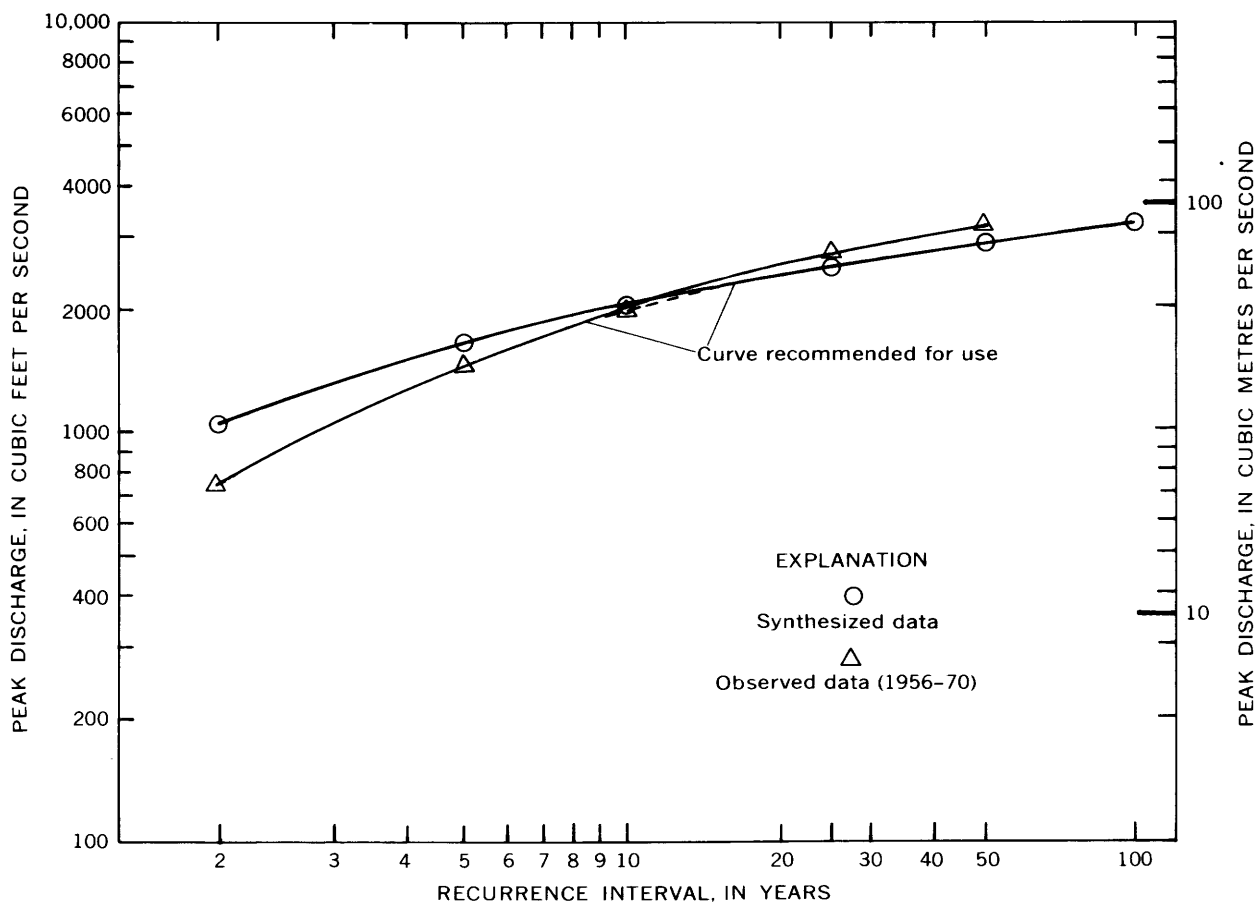


FIGURE 2.—Flood-frequency curves for Thompson Branch near Albany, Missouri.

ables are retained in an estimating equation that have a coefficient that is significantly different from zero at the 95-percent confidence level.

Sandhaus and Skelton (1968) previously used the log-linear model form to define flood-estimating relations for Missouri streams. They provided separate relations for estimating magnitudes of floods having six selected recurrence intervals ranging from 1.2 to 50 years. They found only the coefficients of drainage-area size and main-channel slope to be significant, and they found the assumption of a linear relation between the logarithms of the variables to be acceptable. Standard errors of estimate ranged from 50.7 percent for the smaller floods to 36.9 percent for the larger floods. Because of the limited data on small streams, the relation for estimating floods larger than 25-year recurrence interval was

not considered applicable to streams draining less than 50 mi² (130 km²).

In this study, data for the 43 small-stream sites were analyzed by multiple regression using the log-linear model form. Separate relations were defined for recurrence intervals of 2, 5, 10, 25, 50, and 100 years. Drainage-basin indices considered as independent variables were:

Drainage area (A), in square miles, as planimeted on the best available topographic maps.

Main-channel slope (S), in feet per mile, between points 10 and 85 percent of the distance upstream from the gage to the basin border.

Main-channel length (L), in miles, from the gaging station to the basin divide.

Mean-basin elevation (E), in feet above mean sea level.

TABLE 5.—Station frequency data

Station number	Station name	Drainage area (mi ²)	Magnitude of flood, in cubic feet per second, for indicated recurrence interval, in years					
			2	5	10	25	50	100
05495100--	Big Branch Tributary nr Wayland, Mo -----	0.70	130	239	317	416	489	561
05497700--	Bridge Creek nr Baring, Mo -----	2.54	399	800	860	1,030	1,460	1,650
05502700--	Easdale Branch nr Shelbyville, Mo -----	.71	399	495	577	689	771	852
05503000--	Oak Dale Branch nr Emden, Mo -----	2.64	693	993	1,190	1,450	1,660	1,870
06815550--	Staples Branch nr Burlington Jct., Mo -----	.49	142	316	435	525	586	645
06816000--	Mill Creek nr Oregon, Mo -----	4.90	740	1,600	2,320	3,350	4,190	5,320
06820000--	White Cloud Creek nr Maryville, Mo -----	6.06	729	1,680	2,260	2,820	3,220	3,580
06821000--	Jenkins Branch nr Gower, Mo -----	2.72	638	1,350	1,700	2,120	2,420	2,700
06896180--	DeMoss Branch nr Stanberry, Mo -----	.38	145	207	248	305	345	383
06896500--	Thompson Branch nr Albany, Mo -----	5.58	738	1,490	2,020	2,520	2,880	3,220
06897700--	Grand River Tributary nr Utica, Mo -----	1.44	392	485	560	665	761	854
06902500--	Hamilton Branch nr New Boston, Mo -----	2.51	576	941	1,210	1,580	1,780	1,980
06902800--	Union Branch nr St. Catherine, Mo -----	1.04	231	390	494	623	718	809
06907200--	Shaver Creek Tributary nr Clifton City, Mo --	1.65	480	887	1,070	1,290	1,450	1,610
06908300--	Trent Branch nr Waverly, Mo -----	.97	339	670	890	1,140	1,290	1,430
06909700--	Petite Saline Creek Tributary nr Bellair, Mo --	.49	136	191	242	325	408	504
06910250--	Traxler Branch nr Columbia, Mo -----	.55	277	456	564	678	755	825
06918700--	Oak Grove Branch nr Brighton, Mo -----	1.30	182	392	567	820	1,020	1,160
06919200--	Sac River Tributary nr Caplinger Mills, Mo --	.14	47.0	70.0	89.0	112	127	142
06921740--	Brushy Creek nr Blairstown, Mo -----	1.15	498	768	959	1,140	1,280	1,400
06922700--	Chub Creek nr Lincoln, Mo -----	2.86	766	1,360	1,730	2,160	2,430	2,700
06925200--	Starks Creek nr Preston, Mo -----	1.30	822	1,270	1,530	1,840	2,060	2,330
06925300--	Prairie Branch nr Decaturville, Mo -----	1.48	190	310	425	633	850	1,110
06926200--	Van Cleve Branch nr Meta, Mo -----	.75	255	545	722	947	1,110	1,280
06927100--	Doane Branch nr Kingdom City, Mo -----	.54	111	185	233	293	335	376
06928200--	Laquey Branch nr Hazelgreen, Mo -----	1.58	409	860	1,100	1,320	1,490	1,640
06931500--	Little Beaver Creek nr Rolla, Mo -----	6.41	1,240	2,340	3,430	5,280	6,060	6,800
06935800--	Shotwell Creek nr Ellisville, Mo -----	.81	365	520	617	755	848	933
07011200--	Love Creek nr Salem, Mo -----	.89	121	265	370	505	598	671
07011500--	Green Acre Branch nr Rolla, Mo -----	.62	306	509	616	737	818	890
07015500--	Lanes Fork nr Rolla, Mo -----	.22	71.5	121	152	193	218	240
07017500--	Dry Branch nr Bonne Terre, Mo -----	3.35	660	1,290	1,700	2,220	2,550	2,820
07019100--	Murphy Branch nr Crystal City, Mo -----	.45	130	221	300	435	572	732
07035500--	Barnes Creek nr Fredericktown, Mo -----	4.03	929	2,040	2,850	3,560	4,040	4,510
07037700--	Clark Creek nr Piedmont, Mo -----	4.39	753	1,230	1,680	2,400	2,940	3,500
07053950--	Ingenthron Hollow nr Forsyth, Mo -----	.65	197	360	481	598	679	757
07054200--	Yandell Branch nr Kirbyville, Mo -----	.42	65.1	158	224	318	394	474
07054300--	Gray Branch nr Lutie, Mo -----	.27	50	97.5	132	178	212	245
07063200--	Pike Creek Tributary nr Poplar Bluff, Mo ----	.28	124	210	252	305	342	376
07064300--	Fudge Hollow nr Licking, Mo -----	1.72	100	360	600	970	1,300	1,620
07064500--	Big Creek nr Yukon, Mo -----	8.36	1,750	2,950	3,650	4,510	5,120	5,710
07068200--	North Prong Little Black River nr Hunter, Mo.	1.23	130	245	355	565	795	1,100
07185500--	Stahl Creek nr Miller, Mo -----	3.86	637	1,120	1,440	1,820	2,090	2,340

Forest cover (F), expressed as the proportional part of the drainage area covered by forests as shown on the topographic map.

Mean-annual precipitation (P), in inches.

The maximum 24-hour rainfall, ($I_{24,2}$), in inches, having a recurrence interval of 2 years (2-year, 24-hour rainfall) from U.S. Weather Bureau Technical Paper 40 (1961).

Soil infiltration index (S_i), in inches, determined by the Soil Conservation Service.

Upon testing all independent variables, only the coefficient to drainage area remained significant at the 95-percent confidence level.

Standard errors ranged from 25.4 to 42.6 percent, indicating that the assumption of a linear relation between logarithms of the variables was reasonable.

It had been anticipated that equations defined from data for the 43 small-stream sites would be useful for estimating flood characteristics of ungaged sites draining less than 10 mi² (25.9 km²) and that the Sandhaus and Skelton relations would be used for estimates on larger streams. Comparison of the estimates obtained by the two sets of equations showed, however, that there was a discontinuity for sites having drainage areas of sizes between 10 and 100 mi² (25.9 and 259 km²). No simple,

yet logical, system of using the two sets of equations was apparent, and their utility for obtaining design discharge estimates was rejected.

Recognizing that a continuous relation should exist between flood and basin characteristics for the complete range of basin sizes, data for a sample of large streams were included with the small-streams data for a combined analysis. Flood characteristics were evaluated for 109 large-stream sites where floodflows are considered to be virtually natural and a sufficient number of annual peaks had been recorded to adequately define the 50- to 100-year flood. Frequency then was analyzed by fitting a Pearson Type III distribution to the logarithms of annual peaks using a regional average coefficient of skew of -0.5 , as suggested by Hardison (1974). Data on the size and main-channel slope of the large-stream sites were available from the Sandhaus and Skelton study (1968).

Definition of estimating equations based upon the combined large- and small-stream data indicated that the assumption of a linear relation between the logarithms of the variables was inadequate. The defined log-linear relations tended to overestimate flood magnitudes at intermediate size sites. Alternative curvilinear models and variable transformations were therefore tested on the data.

The most satisfactory model found was one suggested by Creager, Justin, and Hinds (1947):

$$Q_t = bA^{b_1}A^{b_2}S^{b_3},$$

where A is drainage-basin size and S is main-channel slope. By logarithmic transformation of the variables the model becomes:

$$\log Q_t = \log b + b_1 A^{b_2} \log A + b_3 \log S.$$

Although the constants in this relation cannot be evaluated directly by linear multiple-regression analysis, repeated trial and error solutions indicated that when $b_2 = -0.02$, multiple-regression analysis to determine remaining constants provided relations having a minimum standard error of estimate.

Table 6 summarizes the final set of best-fit equations. To simplify use of these equations,

Hauth (1974) provided graphical solutions, one of which is shown in figure 3 as an example.

TABLE 6.—*Summary of regression analyses*

Recurrence interval of flood peak	Equation	Standard error of estimate (percent)
2-year -----	$Q=53.5A^{0.851A^{-0.02}}S^{0.356}$	38.6
5-year -----	$Q=64.0A^{0.856A^{-0.02}}S^{0.450}$	34.7
10-year -----	$Q=67.6A^{0.905A^{-0.02}}S^{0.500}$	34.5
25-year -----	$Q=73.7A^{0.924A^{-0.02}}S^{0.542}$	35.0
50-year -----	$Q=79.8A^{0.926A^{-0.02}}S^{0.560}$	33.3
100-year -----	$Q=85.1A^{0.934A^{-0.02}}S^{0.576}$	33.3

The defined relations are considered useful for providing design flood estimates at ungaged sites in Missouri having characteristics within the range of experience in the sample data—that is, they are useful at sites where floodflow is virtually natural, where drainage areas range from 0.1 to 14,000 mi² (0.26 to 32,300 km²), and where main channels have slopes between 1 and 300 ft/mi (0.19 and 56.7 m/km). The relations should not be used at sites where floodflows are significantly affected either by the works of man, such as the development of urban centers, reservoirs, and improved channel, or by backwater of larger streams, as might be expected near the mouth on tributary channels. The relations also are not useful for main-stream sites on the Mississippi and Missouri Rivers, but alternate design estimating techniques previously have been provided for those rivers and for some regulated streams by Patterson and Gamble (1968), Patterson (1964, 1966), and Matthai (1969).

DISCUSSION

This first operational use of the rainfall-runoff model proved the practicality of record extension for use in regional frequency analysis. Valuable experience was gained, but many questions and problems arose. A general discussion of some of the more important observations is presented here. Many of the techniques used in this study were necessarily selected on an intuitive basis and perhaps will be useful in future studies, yet it is hoped that this discus-

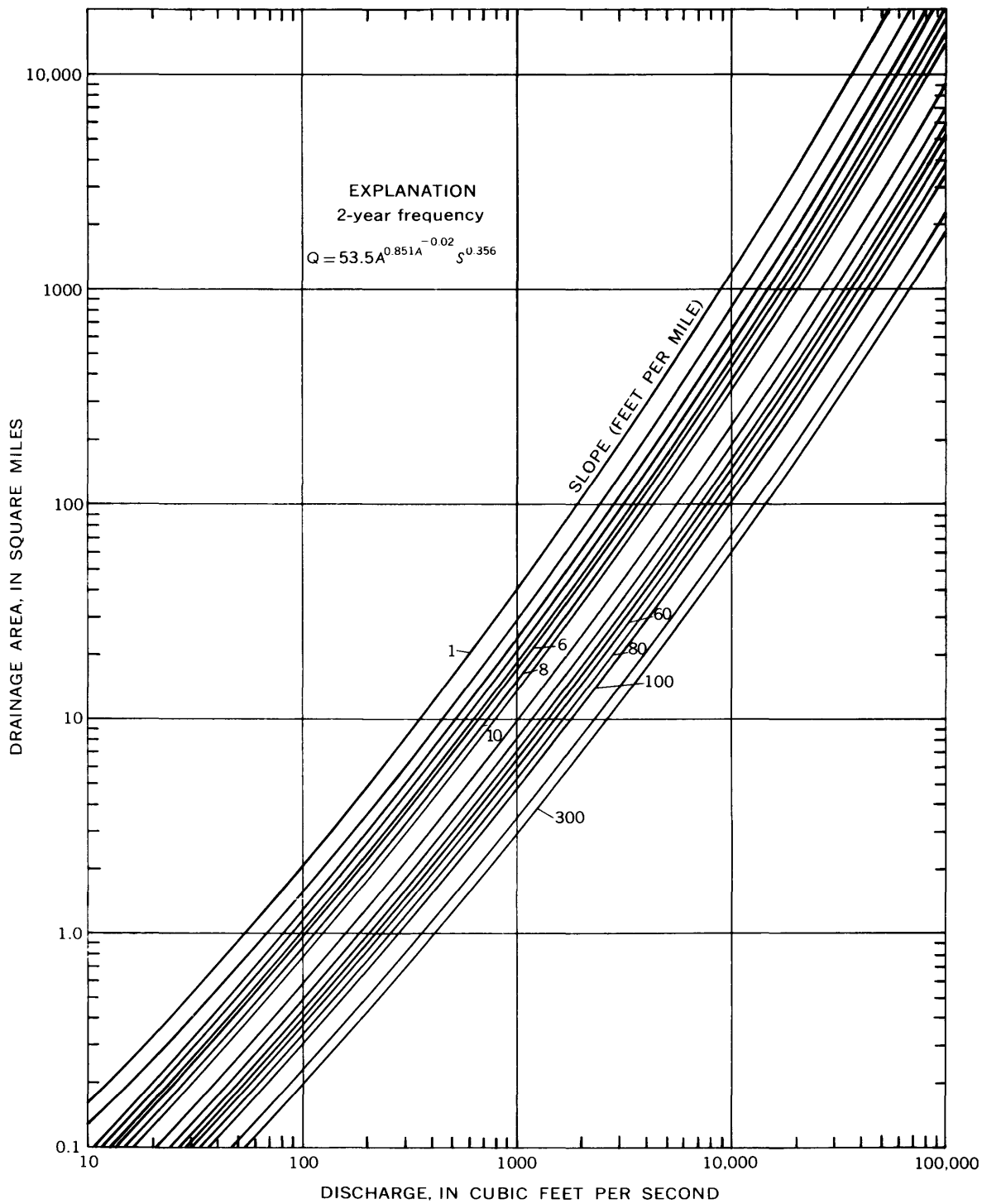


FIGURE 3.—Graphical solution of the 2-year equation.

sion also can suggest areas of beneficial future research.

PARAMETER EVALUATION

Parameter evaluation was the most complex operation in the study and the one requiring the most arbitrary judgments. Development of improved guidelines for parameter evaluation could be of significant benefit.

Information on the probable magnitude and possible range of parameter values is needed for efficiency of calibration. At first it was difficult to estimate initial parameter values, but as experience was gained the efficiency in parameter evaluation increased. The data shown in table 3 will be of value to subsequent analysts in areas near Missouri, but it would be useful to know the variation in parameter values is associated with basin characteristics. A relatively simple approach would be to use the values in table 3 as dependent variables in a multiple-regression analysis. Results would not only aid the efficiency of parameter evaluation at short-record sites, but conceivably could allow model calibration for ungaged sites.

Information on the sensitivity of output results to changes in parameter values would also assist future investigators. For example, the routing parameter TP/TC was observed during this investigation to exert little influence on output results. Although no detailed sensitivity investigation was undertaken, on the basis of experience with the earlier calibration this parameter was virtually ignored during latter parts of the study. More detailed study might indicate no need to use the parameter value TP/TC in any model calibration and might set relative priorities for calibration of other parameters.

A knowledge of the amount of information needed for effective model calibration would be of great importance to other stream flood investigations. In this study, from 8 to 31 storms were used. Research studies might test the effectiveness of lesser calibration data as a basis for knowing how long data collection programs should be operated. A related study of criteria to judge the effectiveness of individual storms and number of individual storms during the data collection period also would be helpful.

Lacking any technical basis, the storm screening process used in this study to include or to omit storms in the calibration process was judged necessary to obtain the most effective set of model parameters. This screening process required considerable effort in recalibration on a reduced number of storm events. It would be interesting to test how much differently the results might be if there had been no screening.

The three-phase calibration scheme in which storage and routing parameters were calibrated separately was devised for efficiency on a rational basis. Alternate schemes are available and might have been selected. They ranged in complexity from direct calibration in a single operation to calibration of parameters in multiphase operations where alternate parameter groups are identified. Research studies might suggest the most effective scheme.

RECORD SYNTHESIS

Experience in synthesizing records by using long-term climatic data in a calibrated model defined some unexpected problems.

The most perplexing problem was the inability to distinguish between the frequency curves defined from the four long-term precipitation records. Additional study to define whether any significant difference exists within the rainfall records themselves would be of interest. Such a study might suggest which available long-term rainfall records in an area are effective for model synthesis and, therefore, the ones which should be reduced for model use.

Techniques of combining frequency curves should be investigated. Intuitively, observed records should have some weight in defining the middle range of an annual series frequency curve. Experience with the model-synthesized records indicates that larger floods may be more reliably estimated than the average-size floods. Some technical basis is needed for combining and weighting the observed and synthesized data in frequency analysis.

One other practical problem that could benefit from additional study and could improve operational guidelines is the selection of storms to be reduced to unit data. Perhaps investigation of the unused unit data in the four Missouri long-term rainfall-runoff records could identify criteria and thereby save the data-

reduction effort necessary in similar future studies.

REGRESSION ANALYSIS

The nonlinearity of the relation between the logarithms of the floods and basin characteristics was surprising. Perhaps alternate model forms would be as effective or more effective than the one used, but of more interest is the reality of the nonlinear model form. Is it a relation that would be defined if long-term records were available at the small-stream sites, or is it a form that results from some idiosyncrasy in the rainfall-runoff model? For example, it is conceivable that the use of a single rain-gage record with the necessary assumption of uniform areal precipitation may tend to overestimate the flood magnitudes in the larger basins (approximately 10 mi² or 26 km²), thereby causing the apparent curvilinear regression.

The standard errors of estimate of the regression relations defined in this study are considerably improved over the standard errors of relations previously defined for Missouri. It must be noted, however, that these newly defined relations are based upon synthesized flood records that are highly correlated among themselves. This cross-correlation will reduce significantly the time sampling errors inherent in observed records; but it remains to be shown whether or not the improved standard errors actually indicate a more reliable estimate of future floodflows.

SUMMARY AND CONCLUSIONS

This study has demonstrated the utility and practicality of using a rainfall-runoff model of small-stream floods to define techniques of estimating flood magnitude and frequency at ungaged sites. Short-duration records of concurrent rainfall and runoff defined parameters that are used in a mathematical model and that define each basin's response to rainfall. Long-term climatic data then were put into the model to generate long-term peak-flow records. Results obtained from this process indicate that there is a rational consistency of parameter values from basin to basin throughout the State. The average standard error of estimate from all calibrations, which in general indi-

cates the ability to mathematically define the basin response, was about 35 percent.

Synthetic annual peak discharges were obtained at each gaging station by transferring long-term rainfall data (an average of 70 years) from four locations. Statistical tests indicated that the synthetic peaks based upon the four different rainfall records were identically distributed and that a simple averaging of synthetic frequency curves was justified. An examination of available short-term rainfall records throughout the State shows a few rainfall intensities to be greater than those from the four long-term records and demonstrates the time sampling error inherent in hydrologic data. Extreme storms such as these can cause extreme runoff, and the recurrence intervals for these floods are difficult to define within a short observed record. However, by using a longer period of rainfall with the calibrated model, a long series of annual peaks were generated as improved time samples for definition of frequency curves at each site.

Simple regression of the logarithmic transforms of streamflow characteristics versus logarithmic transforms of drainage area proved to be linear for basins used in the synthesis. However, when data for small and large basins were combined, a nonlinearity occurred. Linearity of regression was then ob-

tained by the model equation $Q_t = bA^{b_1 A^{-0.02}} S^{b_2}$. A map plot of residuals suggests the statewide applicability of the equations. Equations defined in this study are based upon more data and a more rigorous analysis than those presented in the report by Sandhaus and Skelton (1968).

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