RAINFALL-RUNOFF MODELING AND PRELIMINARY REGIONAL FLOOD CHARACTERISTICS OF SMALL RURAL WATERSHEDS IN THE ARKANSAS RIVER BASIN IN COLORADO

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GEOLOGICAL SURVEY

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Lakewood, CO 80225

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METRIC CONVERSIONS

Inch-pound units in this report may be converted to metric units by the following conversion factors:

Multiply	*By*	*To obtain*
inch (in.)	25.40	millimeter (mm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
square mile (mi^2)	2.590	square kilometer (km^2)
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
acre-foot (acre-ft)	1.233×10^{-3}	cubic hectometer (hm^3)

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ABSTRACT

Both recorded and synthetic rainfall-runoff and annual peak-discharge data for 17 rural watersheds were analyzed to evaluate the magnitude, frequency, and volume of floods in the plains region of the Arkansas River basin in Colorado. Flood-frequency relations from analysis of recorded data were weighted or combined with flood-frequency relations from analysis of synthetic data to provide improved estimates of selected flood characteristics for 15 of these watersheds. The 10-, 25-, 50-, and 100-year peak discharges were regionalized using multiple-regression and station-year methods. Regression relations were developed to determine peak discharge from effective drainage area (standard error of estimate 30 to 50 percent) and flood volume from peak discharge (standard error of estimate 62 percent) for ungaged basins between 0.5 and 15 square miles in size. Using these two flood characteristics, a dimensionless hydrograph method provides synthetic hydrographs very similar in shape to recorded flood hydrographs.

INTRODUCTION

The magnitude and frequency of flood discharges and volumes are major considerations in the design of highway bridges and culverts. Extensive streamflow data available for large perennial streams have generally provided the flood information necessary for the design of major drainage structures. Previous reports on the estimation of the flood characteristics of Colorado streams include Patterson (1964, 1965), Patterson and Somers (1966), Matthai (1968), Livingston (1970), and Hedman, Moore, and Livingston (1972). The methods described by these reports, however, do not generally apply to very small watersheds, particularly those having ephemeral streams. McCain and Jarrett (1976) presented regression equations applicable to basins within the plains region of Colorado with drainage areas greater than 1 square mile. These equations, however, were based only on limited data for small watersheds; only 2 of 36 watersheds studied had areas less than 30 mi^2. Procedures described by the U.S. Soil Conservation Service (1975, 1977) apply to small watersheds but are based primarily on theoretical rainfall-runoff relationships developed for regions extending over many States rather than local hydrologic areas within any particular State such as Colorado.

Purpose and Scope

In 1968, the U.S. Geological Survey, in cooperation with the Colorado Division of Highways and the Federal Highway Administration, began a study to monitor runoff from small rural watersheds resulting from intense thunderstorm activity in the plains and plateau regions of Colorado, and to provide improved techniques of estimating their flood characteristics. The data-collection phase of this study was limited to natural-flow streams that have drainage areas between 0.5 and 30 mi^2, and that do not experience significant snowmelt flood discharges (generally below about 8,000-ft altitude). Using these criteria, sites were selected in the plains region of eastern and extreme plateau regions of western Colorado as shown in figure 1.

This report summarizes the data collection and preliminary data analysis for the plains region of the Arkansas River basin in Colorado, shown as the shaded area in figure 1. Future reports will address the flood characteristics of similar areas in Colorado, such as in the South Platte River basin and the plateau region of western Colorado. A companion study on the flood characteristics in foothill regions, generally from about 8,000 to 9,000 ft in the Arkansas River basin, is currently being conducted on streams that experience mixed-population (rainfall and snowmelt) floods (R. D. Jarrett, U.S. Geological Survey, oral commun., 1980).

Acknowledgments

Installation of the rainfall-runoff stations in eastern and extreme western Colorado was facilitated by the cooperation of municipal and county governments, the Colorado Division of Highways, and numerous private individuals. The author particularly wishes to thank Mr. Del Roupp of the Colorado Division of Highways for assistance and support in the planning and execution of the study.

DATA COLLECTION

The collection of rainfall and runoff data on small rural watersheds in the plains region of the Arkansas River basin in Colorado began with the instrumentation of four sites in June 1969. By April 1970 the total network of 17 stations was in operation (fig. 1 and table 1). The total drainage areas of the sites varied from 2.34 to 17.0 mi^2 and averaged 6.88 mi^2. All stations were operated seasonally, generally April through September.

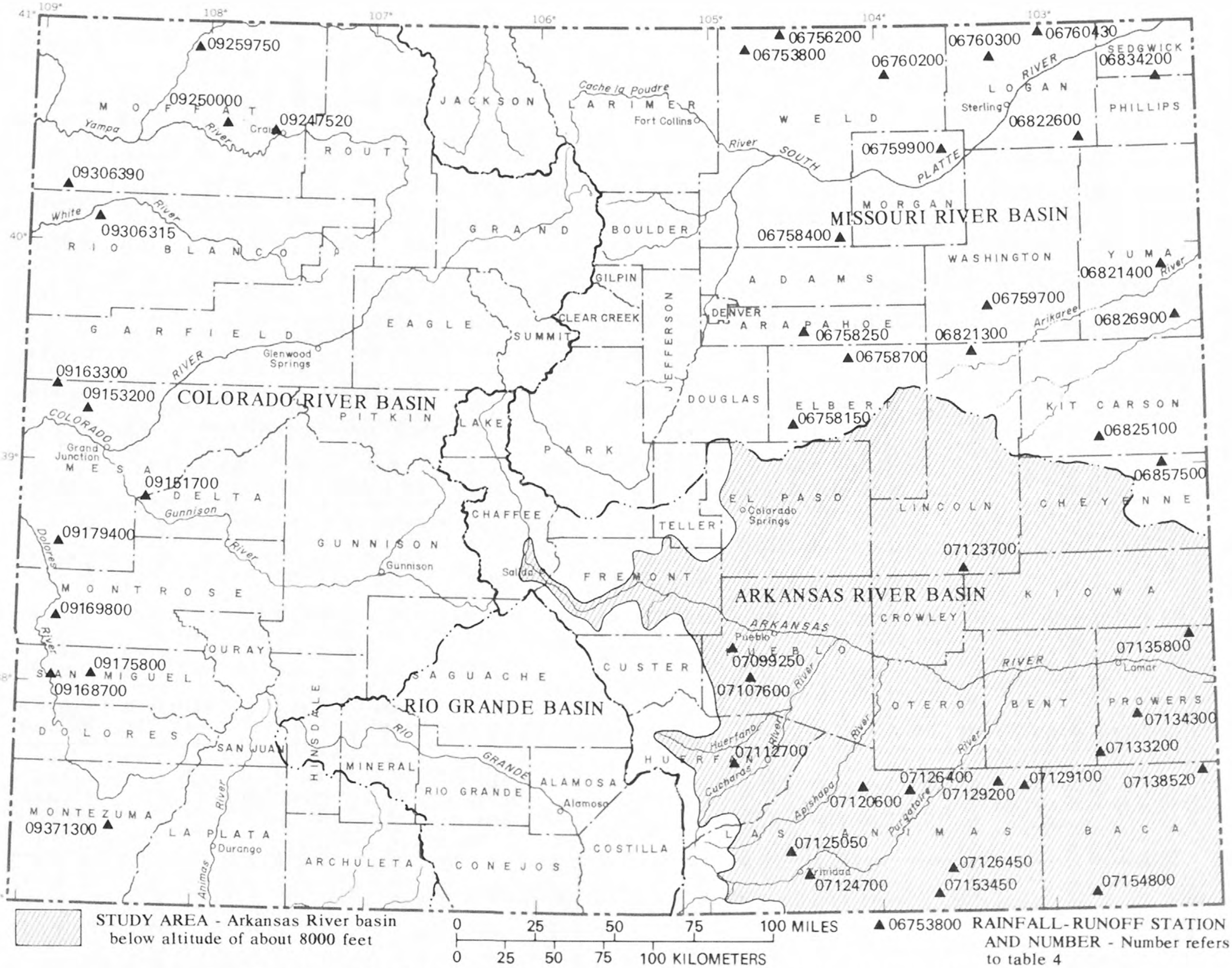

Figure 1.--Distribution of rainfall-runoff stations and location of study area.

Table 1.--*Rainfall-runoff stations in the Arkansas River basin*

U.S. Geological Survey Station number	Station name	Total drainage area, in square miles	Period of seasonal record[1]	Location[2]		Basis of stage-discharge relation
				Latitude	Longitude	
07099250	Soda Creek near Livesey, Colo------	8.35	Apr. 1970-Nov. 1978	38°11'46"	104°50'44"	Step-backwater analysis.
07107600	St. Charles River tributary near Goodpasture, Colo----------------	2.87	Mar. 1970-Nov. 1978	38°04'05"	104°46'33"	Do.
07112700	Butte Creek near Delcarbon, Colo---	3.10	Apr. 1970-Nov. 1978	37°42'24"	104°51'58"	Do.
07120600	Timpas Creek tributary near Thatcher, Colo-------------------	6.56	Mar. 1970-Oct. 1977	37°34'18"	104°06'10"	Do.
07123700	Mustang Creek near Karval, Colo[3]---	10.4	June 1969-Oct. 1978	38°33'54"	103°31'18"	Do.
07124700	Gray Creek near Engleville, Colo--	8.46	Mar. 1970-Nov. 1978	37°09'36"	104°25'38"	Do.
07125050	Tingley Canyon Creek near Ludlow, Colo----------------------------	6.22	Mar. 1970-Nov. 1978	37°16'48"	104°32'04"	Do.
07126400	Red Rock Canyon Creek near Bloom, Colo----------------------------	4.14	Mar. 1970-Oct. 1978	37°33'24"	103°50'20"	Do.
07126450	Tobe Arroyo near Tobe, Colo-------	8.93	Mar. 1970-Oct. 1977	37°11'43"	103°36'33"	Do.
07129100	Rule Creek near Ninaview, Colo----	7.07	Mar. 1970-Nov. 1978	37°33'57"	103°10'26"	Do.
07129200	Muddy Creek tributary near Ninaview, Colo----------------------------	3.31	Mar. 1970-Nov. 1978	37°35'56"	103°19'48"	Do.
07133200	Clay Creek tributary near Deora, Colo----------------------------	2.34	Mar. 1970-Oct. 1978	37°43'27"	102°44'24"	Do.
07134300	Wolf Creek near Carlton, Colo-----	13.9	June 1969-Oct. 1978	37°52'30"	102°28'54"	Do.
07135800	Wild Horse Creek tributary near Hartman, Colo-------------------	6.28	June 1969-Oct. 1977	38°15'45"	102°09'42"	Do.
07138520	Little Bear Creek tributary near Lycan, Colo---------------------	17.0	June 1969-Nov. 1978	37°37'48"	102°07'30"	Do.
07153450	Longs Canyon Creek near Tobe, Colo----------------------------	4.56	Mar. 1970-Oct. 1978	37°05'24"	103°41'09"	Do.
07154800	Cimarron River tributary near Edler, Colo---------------------	3.50	Mar. 1970-Oct. 1978	37°05'10"	102°45'38"	Culvert analysis.

[1]Gages operated from about April 1 through about September 30 (no winter records).
[2]See figure 1 for station location.
[3]Prior to March 28, 1972, at site 450 feet downstream.

Instrumentation

Each of the 17 stations consisted of stage (flood-hydrograph) and rainfall recorders, both located at the downstream limit of the study watershed. Stage, recorded in hundredths of feet, was measured inside a 4-inch stilling-well pipe by a small float connected directly to a digital recorder; runoff entered the pipe through numerous 1/4-inch holes drilled at several levels in the pipe. Rainfall, recorded in hundredths of an inch, was measured inside a 3-inch pipe by a small float connected directly to a digital recorder; rainfall entered the pipe from a 5-inch by 10-inch rectangular collector located on top of the shelter. The digital recorders punched all data on 16-channel paper tape at 5-minute time intervals. A single cam-type timer was used to activate both rain and stage recorders, thus assuring time-synchronous data.

Theoretical Stage-Discharge Relations

Recorded stage data was converted to discharge through use of theoretical stage-discharge relations. For most stations, these relations were determined by step-backwater analyses as described by Bailey and Ray (1966). Because changes in channel configuration may affect this type of theoretical relation, sites were resurveyed and step-backwater analyses were revised throughout the study following major flood events or evident channel changes. The stage-discharge relation for station 07154800 was determined by culvert analysis as described by Bodhaine (1968). The basis of the stage-discharge relation for each station is given in table 1.

In addition to the theoretical stage-discharge relations developed for each site, indirect determinations of peak discharge were obtained during the study to provide additional stage-discharge information for significant flood events. A total of 12 such determinations was made at 11 of the 17 study sites.

STATION FLOOD-FREQUENCY ANALYSIS

When annual flood information is available at a site, a relation can be developed between flood magnitude, expressed in terms of either peak discharge (cubic feet per second) or runoff volume (acre-feet), and frequency of occurrence, expressed in terms of recurrence interval. Recurrence interval is the average interval of time, usually in years, within which the given flood will be equaled or exceeded once (Chow, 1964). A uniform technique by which this relationship is developed has been established by the U.S. Water Resources Council (1977). These guidelines are generally accepted by Federal and State agencies and were used to develop the flood-frequency relations presented in this report. The following guidelines are noteworthy:

1. The log-Pearson Type III distribution, applied to the annual flood series, should be used.

2. A generalized skew coefficient is recommended for analysis of short records, while a weighted skew coefficient is recommended for longer records.

3. Probability calculations are modified for incomplete records and zero-flow years.

4. The existence of low outliers is statistically judged and is corrected for inprobability calculations.

Analysis of Recorded Floods

Seasonal flood data for the 17 study sites were recorded during 8 to 10 consecutive years as shown in table 1. The average record length was about 9 years. The range in annual maximum discharges recorded at each site is shown in figure 2. The maximum peak discharge recorded during the study was 7,880 ft^3/s at the Wolf Creek near Carlton station (07134300) on August 23, 1969. In terms of runoff per unit area, a maximum of 866 $(ft^3/s)/mi^2$ was recorded at the Muddy Creek tributary near Ninaview station (07129200) on May 20, 1977. No flow occurred at 13 sites during at least one water year of the study.

Peak-discharge Frequency

Results of the frequency analysis of the recorded annual peak discharges for each site are shown in table 2. These analyses indicate probable 100-year peak discharges ranging from 270 to 14,400 ft^3/s. A comparison between the range in flood frequency (10- to 100-year peak discharges) from this analysis and the range in recorded annual peak discharges is shown for each site in figure 2. The frequency analysis of the recorded floods indicates 15 sites experienced one or more floods greater than the expected 10-year peak discharge (the total years of station record for the study was 155).

Flood Volume

In addition to information on expected peak discharges, designers of bridges and culverts may require estimates of flood volumes when planning for embankment storage or flood detention. Although empirical methods are frequently used to make these volume estimates, the large number of recorded flood hydrographs obtained during this study provided sufficient data from which more accurate prediction techniques were developed. This section describes only the analysis of recorded flood volumes; analysis of synthetic flood volumes will be discussed in subsequent sections.

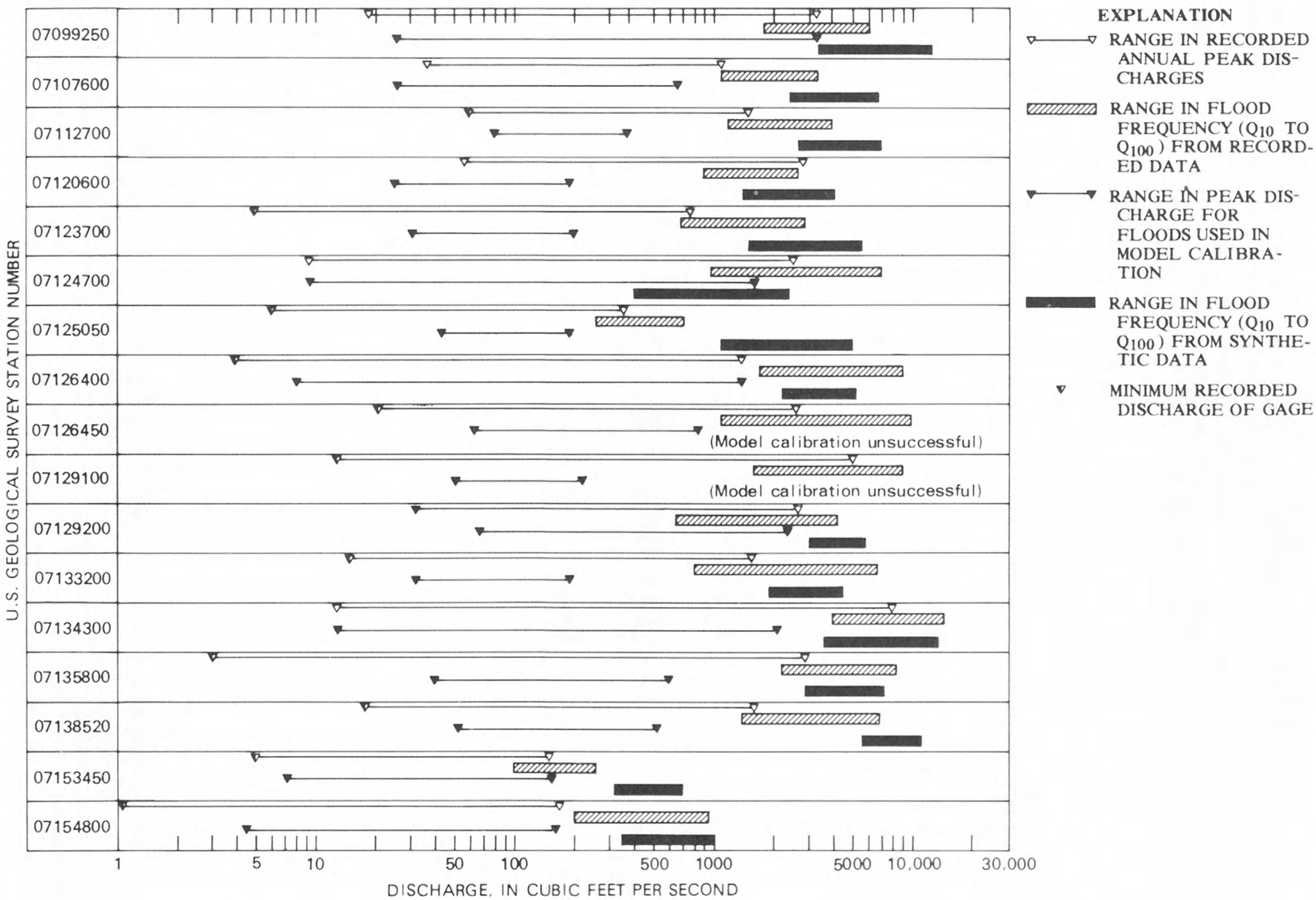

Figure 2.--Ranges in discharge for recorded annual peak flows, floods used in model calibration, and flood frequencies from recorded or synthetic data.

Table 2.--*Observed, synthetic, and weighted flood-frequency relations*

[All values are peak discharge, in cubic feet per second, for indicated recurrence interval]

U.S. Geological Survey station number[1]	Observed flood-frequency relation				Synthetic flood-frequency relation				Weighted flood-frequency relation			
	10-years	25-years	50-years	100-years	10-years	25-years	50-years	100-years	10-years	25-years	50-years	100-years
07099250	1,800	3,140	4,490	6,170	3,360	6,070	8,840	12,350	2,420	4,900	7,750	11,730
07107600	1,060	1,800	2,530	3,430	2,400	3,850	5,200	6,800	1,600	3,030	4,530	6,460
07112700	1,230	2,090	2,920	3,930	2,690	4,140	5,410	6,860	1,810	3,320	4,790	6,570
07120600	900	1,480	2,040	2,710	1,380	2,250	3,080	4,080	1,090	1,940	2,820	3,940
07123700	690	1,330	2,010	2,920	1,500	2,680	3,930	5,600	1,010	2,140	3,450	5,330
07124700	980	2,370	4,170	6,880	400	900	1,520	2,440	[2]980	[2]2,370	[2]4,170	[2]6,880
07125050	260	420	560	720	1,120	2,170	3,340	4,970	[3]1,120	[3]2,170	[3]3,340	[3]4,970
07126400	1,700	3,600	5,800	8,880	2,160	3,170	4,080	5,160	1,880	3,340	4,510	5,530
07127450[4]	1,140	3,300	5,900	9,900	-----	-----	-----	------	-----	-----	-----	------
07129100[4]	1,600	3,550	5,850	9,000	-----	-----	-----	------	-----	-----	-----	------
07129200	650	1,510	2,600	4,200	3,030	4,040	4,860	5,760	1,600	3,030	4,300	5,600
07133200	810	2,120	3,900	6,730	1,920	2,800	3,580	4,460	1,250	2,530	3,660	4,690
07134300	3,910	7,070	10,300	14,400	3,630	6,290	9,800	13,540	3,800	6,600	9,920	13,630
07135800	2,200	4,020	5,920	8,360	2,890	4,330	5,660	7,220	2,480	4,210	5,720	7,330
07138520	1,450	2,950	4,640	6,940	5,630	7,640	9,330	11,170	3,120	5,760	8,160	10,750
07153450	100	160	210	270	320	460	590	740	[3]320	[3]460	[3]590	[3]740
07154800	200	410	640	950	350	560	770	1,020	260	500	740	1,010

[1]Station names and locations given in table 1; locations are shown in figure 1.
[2]Synthetic flood-frequency relation not used in determining weighted values (see "Dependent Variables" in text).
[3]Observed flood-frequency relation not used in determining weighted values (see "Dependent Variables" in text).
[4]Synthetic and weighted flood-frequency relation not shown because model calibration was unsatisfactory (see "Calibration of Rainfall-Runoff Model" in text).

Although nonuniform rainfall distribution, rainfall intensity and duration, and soil-moisture conditions result in variations in runoff volume for floods of the same magnitude, a relation between peak discharge and flood volume was determined from the 61 largest flood-hydrographs recorded at the 17 sites. These hydrographs were characteristically the result of short-duration, high-intensity rainfall typical of convective storms or thunderstorms, but not typical of frontal-type storms. For these events, peak discharges ranged from 53 to 3,300 ft^3/s and flood volumes ranged from 3 to 150 acre-ft. The relation is:

$$V=0.112Q_P^{0.922} \qquad (S_e=60,\ R=0.79) \qquad (1)$$

where: V=flood volume, in acre-feet;

Q_P=peak discharge, in cubic feet per second;

S_e=average standard error of estimate, in percent; and

R=correlation coefficient.

In a previous study of 105 floods on small Wyoming basins, Craig and Rankl (1978) found the following similar relation:

$$V=0.131Q_P^{0.878} \qquad (S_e=55,\ R=0.90) \qquad (2)$$

Analysis of Synthetic Floods

Accuracy in estimating the magnitude and frequency of floods at a site improves with the number of years of flood information on which the analysis is based. The time-sampling error associated with an estimate of the 100-year peak discharge based on 10 years of station data is considerably greater than if it were based on 50 years of station data. For example, Livingston (1970) found that for streams in the mountainous region of Colorado the standard error for the 25-year peak discharge decreased from 24 percent with 10 years of record to 11 percent with 50 years of record.

To improve the flood-frequency relations for stations in this study, a rainfall-runoff simulation model, described in detail by Dawdy, Lichty, and Bergmann (1972), was calibrated and used to synthesize a long-term annual flood series for 15 of the sites.

Description of Modeled Rainfall-Runoff Data

From all rainfall-runoff data collected at the 17 study sites, a data set consisting of 141 floods was selected for use in the calibration of the rainfall-runoff model. Selection of floods for inclusion in this data set was based on (1) the relative compatibility of rainfall totals or intensities with runoff volumes or peak discharges, (2) the reliability of recorded stage and rainfall data, (3) the time between beginning of rainfall and recording of runoff as an indication of uniform precipitation over the basin, and (4) the preference for larger rainfall-runoff events during which the entire watershed responds. The range in the peak discharges of the floods used for model calibration is shown for each station in figure 2. These 141 floods ranged in peak discharge from less than 10 ft^3/s to 3,300 ft^3/s, but only 20 floods occurring at just 10 of the sites had unit discharges exceeding 100 $(ft^3/s)/mi^2$.

For the 141 storms, the average and maximum total rainfall amounts recorded at 5-minute intervals is shown in figure 3. Greatest average total precipitation was 0.16 inch (1.9 in./hr) occurring in the interval between 5 and 10 minutes after the storm began, and the "average storm" lasted about 45 minutes. The maximum rainfall accumulation recorded in a 5-minute time period was 0.51 inch (6.1 in./hr).

The seasonal occurrence of the 141 floods is shown by 10-day intervals in figure 4 for the approximate period May to September. About 78 percent of these floods occurred between May 21 and August 18 (about 28 percent occurred between July 20 and August 8). In a similar analysis of flood occurrences in the Front Range Urban Corridor of Colorado, Hansen, Chronic, and Matelock (1978) found 83 percent occurred between May 21 and August 18.

The rainfall-runoff simulation model requires daily precipitation and daily evaporation in addition to unit (5-min) storm rainfall and runoff data. Daily precipitation was as recorded either at the site or at the nearest U.S. Weather Service station during missing record periods. Daily evaporation was from the closest of either Pueblo City Reservoir or John Martin Reservoir, National Weather Service stations 6743 and 4388, respectively. For the period of seasonal station operation, these data and the observed unit storm data are used to calibrate the infiltration, soil-moisture accounting, and surface-runoff-routing components in the model.

Calibration of Rainfall-Runoff Model

The calibration phase of the modeling process resulted in an optimum set of 10 parameters for each basin. An explanation of each parameter and its application in the modeling process is modified from Litchy and Liscum (1978, p. 35) in the following tabulation:

MODEL PARAMETERS AND VARIABLES AND THEIR APPLICATION IN THE MODELING PROCESS

Parameter	Variable	Units	Application
BMSM-----	--------	Inches----	Soil-moisture storage at field capacity. Maximum value of base moisture storage variable, BMS.
RR-------	--------	----------	Proportion of daily rainfall that infiltrates the soil.
EVC------	--------	0.69------	Pan evaporation coefficient.
DRN------	--------	1.00------	Drainage factor for redistribution of saturatated moisture storage, SMS, to base (unsaturated moisture storage, BMS, as a fraction of of hydraulic conductivity, KSAT.
---------	BMS-----	Inches----	Base (unsaturated) moisture storage in active soil column. Simulates antecedent moisture content over the range from wilting-point conditions, BMS=0, to field capacity, BMS-BMSM.
--------	SMS-----	Inches----	"Saturated" moisture storage in wetted surface layer developed by infiltration of storm rainfall.
---------	FR------	Inches per hour----	Infiltration capacity, a function of KSAT, PSP, RGF, BMSM, SMS, BMS.
KSAT----	--------	Inches per hour----	Hydraulic conductivity of "saturated" transmission zone.
PSP-----	--------	Inches----	Combined effects of moisture deficit, as indexed by SMS, and capillary potential (suction) at the wetting front for BMS equal to field capacity, BMSM.
RGF------	--------	Hours-----	Ratio of combined effects of moisture deficit, as indexed by BMS, and capillary potential (suction) at wetting front for BMS=0=wilting point, to the value associated with field capacity conditions, PSP.
KSW------	--------	Hours----	Linear reservoir recession coefficient.
TC-------	--------	Minutes--	Time base (duration) of triangular translation hydrograph.
TP/TC----	--------	0.50-----	Ratio of time to peak of triangular translation hydrograph to duration of translation hydrograph, TC.
---------	SW------	Inches---	Linear reservoir storage.

The final values of these parameters are given in table 6 for each of the 17 study sites. (Tables 6-9 are in the Supplemental Data section of this report.) The values of one soil-moisture accounting parameter, DRN, and one routing parameter, TP/TC, were held constant for all sites at 1.00 and 0.50 units, respectively. Another soil-moisture accounting parameter, EVC, was determined from Kohler, Nordenson, and Baker (1959) to be 0.69 for all sites. All other parameter values were determined by optimization in the modeling process.

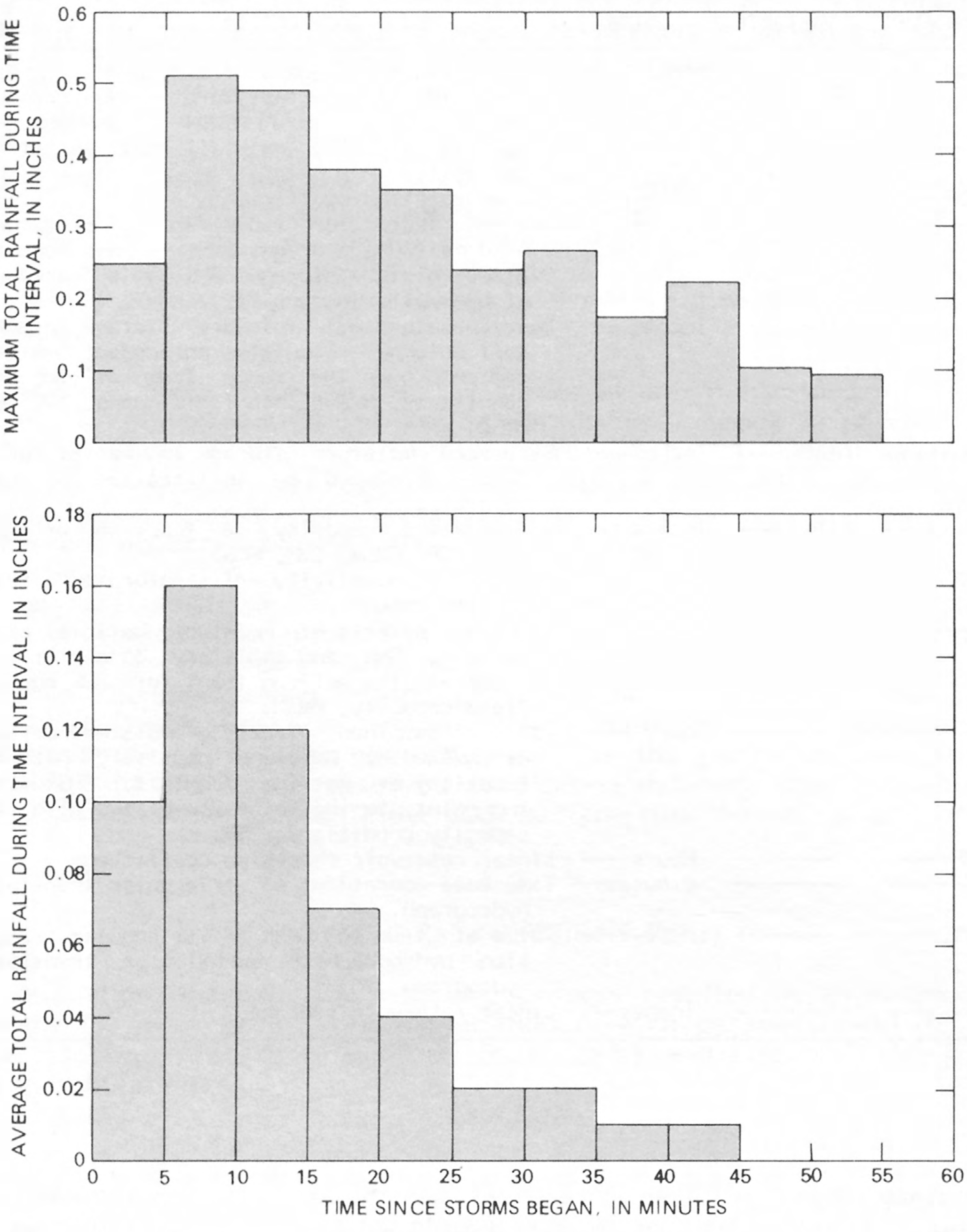

Figure 3.-- Average and maximum rainfall by 5-minute intervals for 141 storms.

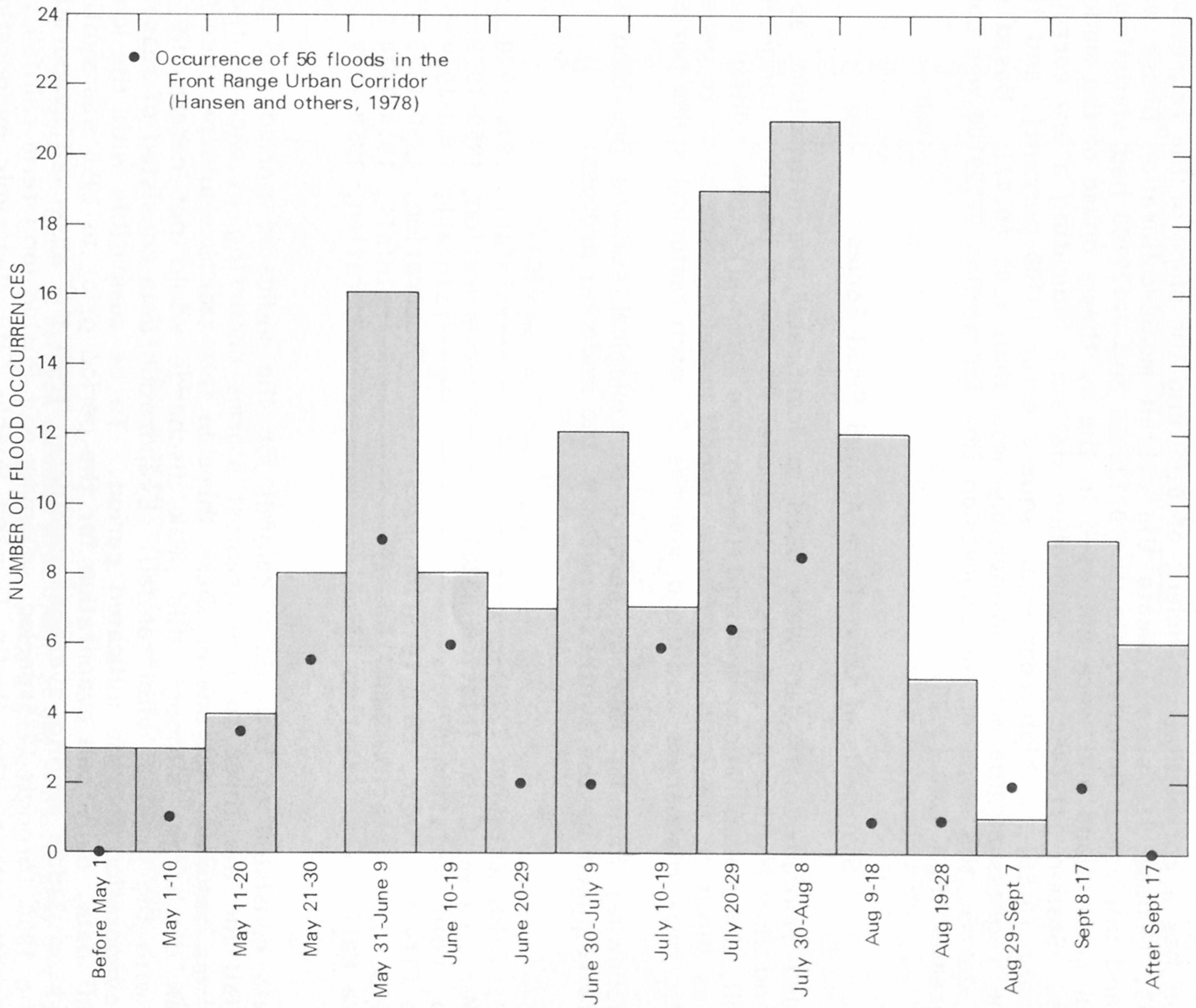

Figure 4.--Seasonal occurrence of the 141 floods used to calibrate rainfall-runoff model.

The correlation coefficient, root mean square error, and slope of the regression line between recorded and synthetic peak discharges for the calibration of each site, all of which are measures of the relative success of the calibration, also are given in table 6. The relation between recorded and synthetic peak discharge for all 141 floods used in the calibration process is shown in figure 5. This relation has a correlation coefficient of 0.90 and the slope of the regression line is 0.93. These statistics indicate the overall model-calibration phase was successful and unbiased. However, stations 07126450 and 07129100 had statistically unsuccessful calibrations and were not used in the synthesis phase of the modeling process. Station 07126450 had calibration statistics indicating a low correlation coefficient (0.56), a high root mean square error (J100 percent), and the slope of the regression line was considerably less than 1.00 (0.47). Based on only three storms, the slope of the regression line for station 07129100 was considerably greater than 1.00 (3.20).

Synthesis of Long-Term Annual Flood Series

Recorded rainfall-runoff data were used to "calibrate" the infiltration, soil-moisture, and flow-routing parameters in the model for the 15 basins. Long-term daily rainfall, daily evaporation, and unit (5-min time interval) storm rainfall were then used as input to the calibrated rainfall-runoff model of each basin to generate synthetic peak discharges and flood volumes for each historical storm period.

The following National Weather Service climatological stations provided the climatic data required by the synthesis phase of the modeling process:

Denver, Colo. (station 2220)------------------------rainfall, 1898-1970
John Martin Dam, Colo. (station 4388)------------evaporation, 1950-1975
Pueblo, Colo. (station 6740)------------------------rainfall, 1900-1969
Pueblo City Reservoir, Colo.(station 6743)-------evaporation, 1950-1975
Amarillo, Tex. (station 23047)----------------------rainfall, 1914-1974
Wichita Falls, Tex. (station 13966)--------------evaporation, 1950-1974

Rainfall data consisted of both daily rainfall for the indicated period and unit storm rainfall for the three to five greatest storms occurring in each of these years. It was assumed that one of these three to five storms would produce the annual peak discharge, although this peak discharge would not necessarily be associated with the greatest total rainfall. Evaporation data consisted of seasonal daily pan evaporation for the indicated period. To be compatible with the long-term rainfall data, daily pan evaporation for the period prior to 1950 was synthesized based on 3-day moving averages calculated from the observed evaporation data for the 1950 through 1975 period. Denver and Pueblo long-term rainfall was used along with either John Martin Dam or Pueblo City Reservoir evaporation, while Amarillo long-term rainfall was used along with Wichita Falls evaporation.

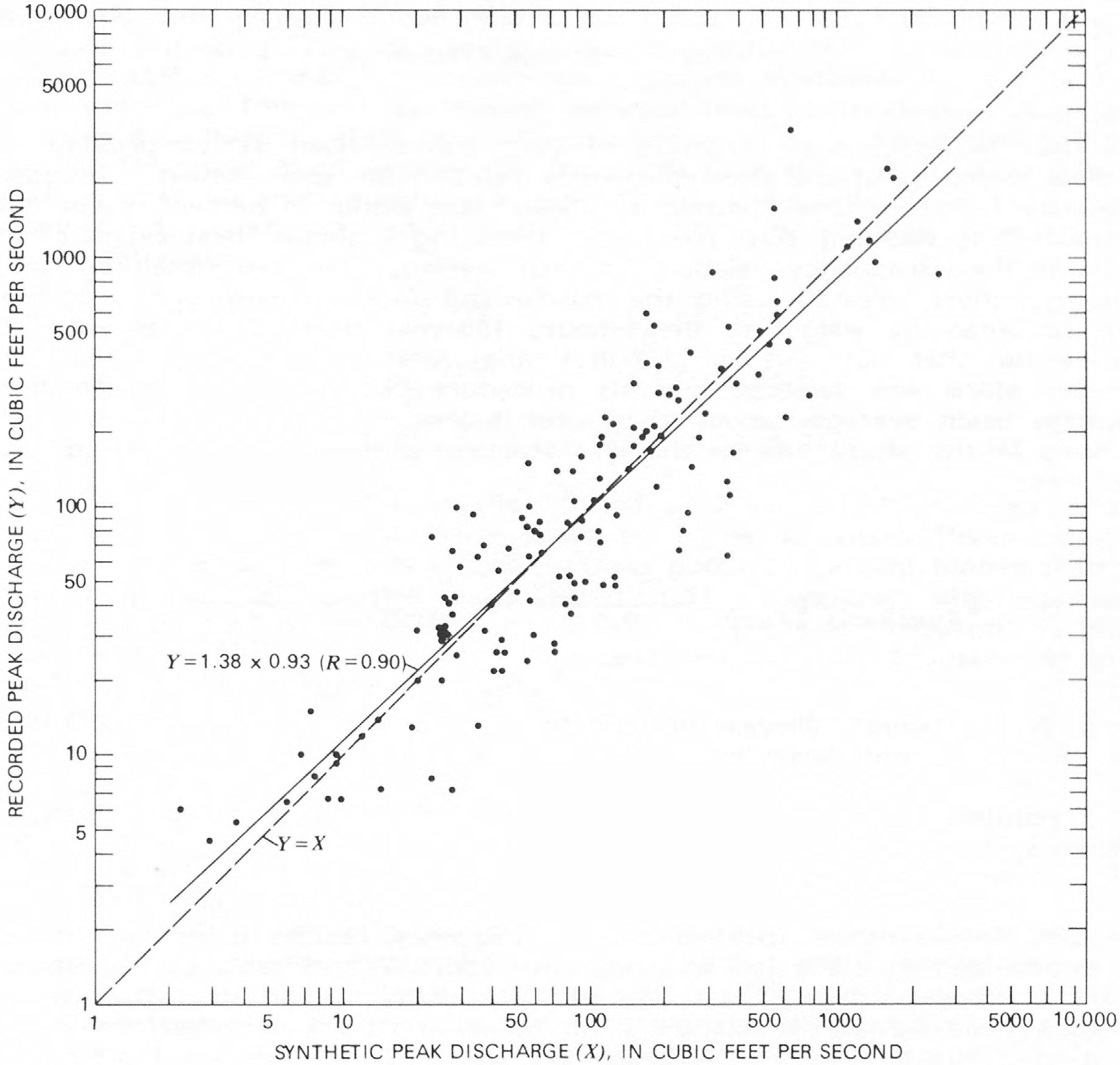

Figure 5.--Relation between recorded peak discharge and synthetic peak discharge from model calibrations using 141 floods.

For each basin, the synthesis phase resulted in the simulated peak discharge and flood volume for a total of over 10,000 floods derived from the long-term rainfall data for Denver, Pueblo, and Amarillo. These data were included in both a frequency analysis of the annual-flood series and a regression analysis of flood volume.

Peak-Discharge Frequency

The flood-frequency analysis of each annual-flood series provided three separate estimates of the flood-frequency relation for each station. Because the frequency results of the "Denver synthesis" was within 20 percent of the "Pueblo synthesis," it was not considered in determining a single "best-estimate" of the synthetic flood-frequency relation for each station. The two remaining synthetic relations, those created using the Pueblo and Amarillo long-term precipitation, were combined by weighting the 1-hour, 100-year precipitation at each station relative to that for Pueblo (2.7 in.) and Amarillo (3.5 in.). The 1-hour, 100-year storm was selected for this procedure because storms recorded in the Arkansas basin averaged about 45 minutes in length (fig. 3) and because primary emphasis in the study was on the less frequent storms. The weighting equation used was:

$$Q_{Synthetic} = Q_{Pueblo} \frac{3.5 - I_{1,100}}{0.8} + Q_{Amarillo} \frac{I_{1,100} - 2.7}{0.8} \qquad (3)$$

where: $I_{1,100}$=1-hour 100-year precipitation intensity. (See section on Independent Variables and table 8.)

For precipitation intensities less than 2.7 inches, full weight was given to the "Pueblo synthesis."

The final synthetic peak-discharge frequency results using this procedure are summarized in table 2. As shown in figure 2 and table 2, the values for synthetic flood-frequency relations were generally larger than the values for recorded flood-frequency relations. In terms of runoff per square mile of contributing drainage area, the average (15 stations) 100-year flood discharge was found to be 1,140 $(ft^3/s)/mi^2$ from the synthetic data and 959 $(ft^3/s)/mi^2$ from the recorded data. For the 15 stations modeled, the comparisons shown in figure 2 indicate that four sites experienced a flood greater than the synthetic 10-year peak discharge (155 years of station record), and that only 2 stations (07099250 and 07124700) had a calibration event with a frequency of occurrence greater than once in about 10 years.

Flood Volume

As previously discussed, the rainfall-runoff model produces both peak discharge and flood volume during the synthesis phase. A simple linear regression of the volume associated with each peak discharge was completed to determine if the synthetic data might yield a relation similar to that developed from the recorded data (equation 1). This analysis was accomplished using data from first only the "Pueblo syntheses," then only the "Amarillo syntheses," and finally the combined syntheses ("Denver syntheses" were not used as previously discussed). The "Pueblo syntheses" yielded 1,044 floods ranging in peak discharge (Q_P) from 3 to 12,900 ft^3/s and flood volume (V) from 0.98 to 1,884 acre-ft. For the 521 floods from the "Amarillo syntheses" peak discharges ranged from 5 to 15,680 ft^3/s and flood volumes ranged from 0.98 to 3,893 acre-ft. The following relations were determined:

Pueblo data: $V=0.141Q_P^{0.919}$ (S_e=62, R=0.92) (4)

Amarillo data: $V=0.139Q_P^{0.964}$ (S_e=56, R=0.93) (5)

Combined data: $V=0.123Q_P^{0.958}$ (S_e=62, R=0.93) (6)

Of these three equations, the relation based only on the "Pueblo syntheses" (equation 4) is probably most representative of the Arkansas River basin in Colorado and results in estimated flood volumes about 23 percent higher than the relation based on the recorded data (equation 1). Compared with equation 1 results, the equation developed from the "Amarillo syntheses" (equation 5) yields volume estimates twice as great while the combined equation (equation 6) gives results 30 to 60 percent greater.

REGIONAL FLOOD-FREQUENCY ANALYSIS

Very seldom is flood-frequency information required at or near a gaging station where data are available for a station flood-frequency analysis. More typically, particularly for small drainage basins in the arid West, data of this type are required at an ungaged site. As a result, station flood-frequency information is many times regionalized (areally extrapolated) for planning and design purposes. For the Arkansas River basin in Colorado, examples of recent regional flood-frequency analyses include Patterson (1964) and McCain and Jarrett (1976). For this study the results of two regionalization methods are discussed in the following sections: multiple-regression analysis with basin characteristics and station-year analysis of recorded floods.

Multiple-Regression Method

One of the most effective ways presently known for defining streamflow characterisitcs on a regional basis is to relate them to basin and climatic characteristics by use of multiple-regression techniques applied to past data (Benson and Carter, 1973). Multiple-regression analysis of flood data generally includes log transformation of the data and, therefore, results in an equation of the form

$$Y = aX_1^{b_1} X_2^{b_2} \ldots X_i^{b_i} \tag{7}$$

where:

Y=flood characteristic (dependent variable),

a=regression constant,

X_1, $X_2 \ldots X_i$=basin and climatic characteristics (independent variables), and

b_1, $b_2 \ldots b_i$=regression coefficients.

The application of this method to the 15 stations for which synthetic flood-frequency relations were developed is discussed in the following sections.

Dependent Variables

The dependent variables selected for regression analysis were a weighted 10-year (Q_{10}), 25-year (Q_{25}), 50-year (Q_{50}), and 100-year (Q_{100}) peak discharge for each of 15 study basins (table 2). Results of two different flood-frequency analyses have been discussed thus far: analysis of recorded annual flood series and analysis of synthetic annual flood series. Lichty and Liscum (1978) developed a method of computing a weighted average of the observed and synthetic flood-frequency relations based on an analysis of variance; the weighted result by this method was determined to be an improved estimate of the flood characteristic. Because of the very large time-sampling error (short period-of-record) experienced in this study, application of this variance-weighting method only was success ful for the 10-year and 25-year frequencies. The weighting factors used for the 50-year and 100-year frequencies were determined by judgment based on the 10- and 25-year factors and the results of previous studies (Thomas and Corley, 1977). The following are the weighting factors used:

Flood characteristic	*Observed*	*Synthetic*
Q_{10}	0.60	0.40
Q_{25}	.40	.60
Q_{50}	.25	.75
Q_{100}	.10	.90

The weighted flood-frequency relation was determined by this method for 12 basins as shown in table 2. For example, the weighted Q_{50} for station 07120600 is 0.25 times 2,040, plus 0.75 times 3,080, or 2,820 ft^3/s. For station 07124700 full weight was given to the observed flood-frequency relation because the synthetic flood-frequency relation was too low in comparison with relations for other stations; in fact, the synthetic 100-year flood was exceeded in 1965 by a flood recorded at a site about 1 mile downstream (see table 7, Gray Creek near Trinidad). Similarly, full weight was given to the synthetic flood-frequency relation for stations 07125050 and 07153450 because the observed 100-year flood was less than the synthetic 10-year flood.

Independent Variables

The following independent variables or basin and climatic characteristics were defined for each basin and used in the multiple-regression analysis:

1. Total drainage area, A, in square miles--the total topographic drainage area of the basin.
2. Effective drainage area, A_E, in square miles--the contributing drainage area for more frequent (less than Q_{25}) floods (that is, the total area less the drainage areas for all flood-detention reservoirs in the basin).
3. Elevation, E, in feet--the elevation above sea level of the gage site or point of interest.
4. Maximum relief, R_M, in feet--the elevation difference between the highest point in the basin and the gage site or point of interest.
5. Mainstem length, L, in miles--the length of the main channel from the study site to the basin divide.
6. Streambed slope, S_S, in feet per mile--the slope of the main channel from the study site to a point about 10-channel widths upstream.
7. Channel slope, S_C, in feet per mile--the average slope of the main channel computed by the 85 percent/10 percent method described by Benson (1962).
8. Basin slope, S_B, in feet per mile--the average slope of the effective drainage area (A_E) obtained by measuring the lengths of all 100-ft contour lines in the basin, multiplying by 100, and dividing by the effective drainage area.
9. Channel width at maximum depths of 1 ft or 5 ft, W_{D1}, and W_{D5}, in feet--the average width obtained by measuring the channel width 1 ft or 5 ft above the thalweg at 10 locations at the gage or study site, each spaced about one channel width apart.
10. Precipitation intensity for 1-hour 100-year, 6-hour 100-year, and 24-hour 100-year storms, $I_{1,100}$, $I_{6,100}$, and $I_{24,100}$, in inches--the average basin precipitation intensities for the indicated duration and recurrance interval as given by Miller, Frederick, and Tracey (1973).

For each of the 15 stations in the multiple-regression analysis, the values of all independent variables are shown in table 8.

Discussion of Regression Results

Although initial multiple regressions considered all 13 basin characteristics, final analyses included only those independent variables that were statistically significant at the 5-percent level and that were not highly correlated with another variable. The most significant variables in these relations were A_E, E, S_S, and S_C. Because the regression equations containing E, S_S, and S_C in addition to A_E had average standard errors of estimate and correlation coefficients essentially the same as the equations containing only A_E, only the following relations between each selected flood characteristic and effective drainage area are reported:

$$Q_{10} = 525A_E^{0.68} \quad (S_e=46.8,\ R=0.81) \quad (8)$$

$$Q_{25} = 920A_E^{0.73} \quad (S_e=42.8,\ R=0.85) \quad (9)$$

$$Q_{50} = 1{,}280A_E^{0.77} \quad (S_e=39.8,\ R=0.88) \quad (10)$$

$$Q_{100} = 1{,}680A_E^{0.81} \quad (S_e=37.1,\ R=0.90) \quad (11)$$

To determine if these relations might be improved, the Q_{100} and Q_{10} residuals (observed value minus calculated value) for each of the 15 stations were studied to detect trends associated with their areal distribution or with the magnitude of the effective drainage area. Residuals were found to be generally negative for those stations in the southern one-half (Las Animas and Baca Counties) and positive in the remainder of the study area (fig. 1). Thus, regression equations 8 to 11 may have a tendency to over-predict in the south and under-predict in the north. In addition, the relation between the residual and the effective drainage area indicates nonlinearity between observed and calculated values. Because of the limited sample size (n=15) and the lost degrees of freedom in statistical analysis, the data could not be regionalized based on both location and effective drainage area. The effect of drainage area was found to be most significant and, therefore, the data were regionalized for two ranges of basin size (1) 0.50 to 2.99 mi^2, and (2) 3.00 to 15.0 mi^2. Selection of these two particular ranges was arbitrary to allow for adequate sample sizes of 6 and 9, respectively, and the regressions were done graphically to prevent a discontinuity at 3.0 mi^2. Following are the final equations:

For $0.50 \leq A_E < 3.00$:

$$Q_{10} = 500 A_E^{0.89} \quad (S_e=41.1,\ R=0.96) \quad (12)$$

$$Q_{25} = 840 A_E^{0.97} \quad (S_e=40.1,\ R=0.98) \quad (13)$$

$$Q_{50} = 1{,}140 A_E^{1.01} \quad (S_e=40.2,\ R=0.99) \quad (14)$$

$$Q_{100} = 1{,}550 A_E^{1.07} \quad (S_e=34.0,\ R=0.99+) \quad (15)$$

For $3.00 \leq A_E \leq 15.0$:

$$Q_{10} = 830 A_E^{0.41} \quad (S_e=48.6,\ R=0.61) \quad (16)$$

$$Q_{25} = 1{,}560 A_E^{0.44} \quad (S_e=39.8,\ R=0.70) \quad (17)$$

$$Q_{50} = 2{,}280 A_E^{0.47} \quad (S_e=35.4,\ R=0.78) \quad (18)$$

$$Q_{100} = 2{,}930 A_E^{0.50} \quad (S_e=29.7,\ R=0.84) \quad (19)$$

On the basis of the statistical measures (S_e and R) of the ability of these equations to predict the flood characteristics, these regionalized equations should provide better overall estimates than equations 8 to 11. As previously mentioned, further regionalization of these data could not be accomplished because of the lost degrees of freedom in the statistical analysis. However, an analysis of stations in the South Platte River basin is currently underway and may provide sufficient additional information to refine these relationships or justify further regionalization of regression results (D. R. Minges, U.S. Geological Survey, oral commun., 1980).

The results of the multiple-regression analysis for the regionalized 100-year flood discharge (equations 15 and 19) for drainage areas from 0.5 to 15 mi² are shown in figure 6. Also shown are the weighted values for Q_{100} at the 15 stations used in the analysis, the recorded peak discharges for 34 miscellaneous small watersheds in the region (table 7), the maximum potential floodflow in the region (Crippen and Bue, 1977), and the estimated Q_{100} relation for the plains region of Colorado given by McCain and Jarrett (1976) for a basin slope of 115 ft/mi. The results of the station-year method and the 28 nonstudy stations will be discussed in later sections of this report. The maximum potential flood is, of course, considerably higher than the regression relations given by equations 15 and 19. The relation developed by McCain and Jarrett (1976) generally is in close agreement with the regression results, except for drainage areas less than about 2 mi² where their estimates of peak discharge are as much as 100 percent higher for a 1 mi² basin. Figure 6 shows frequency of occurrence for about 14 of the 34 floods on miscellaneous watersheds was greater than 100 years according to equations 15 and 19.

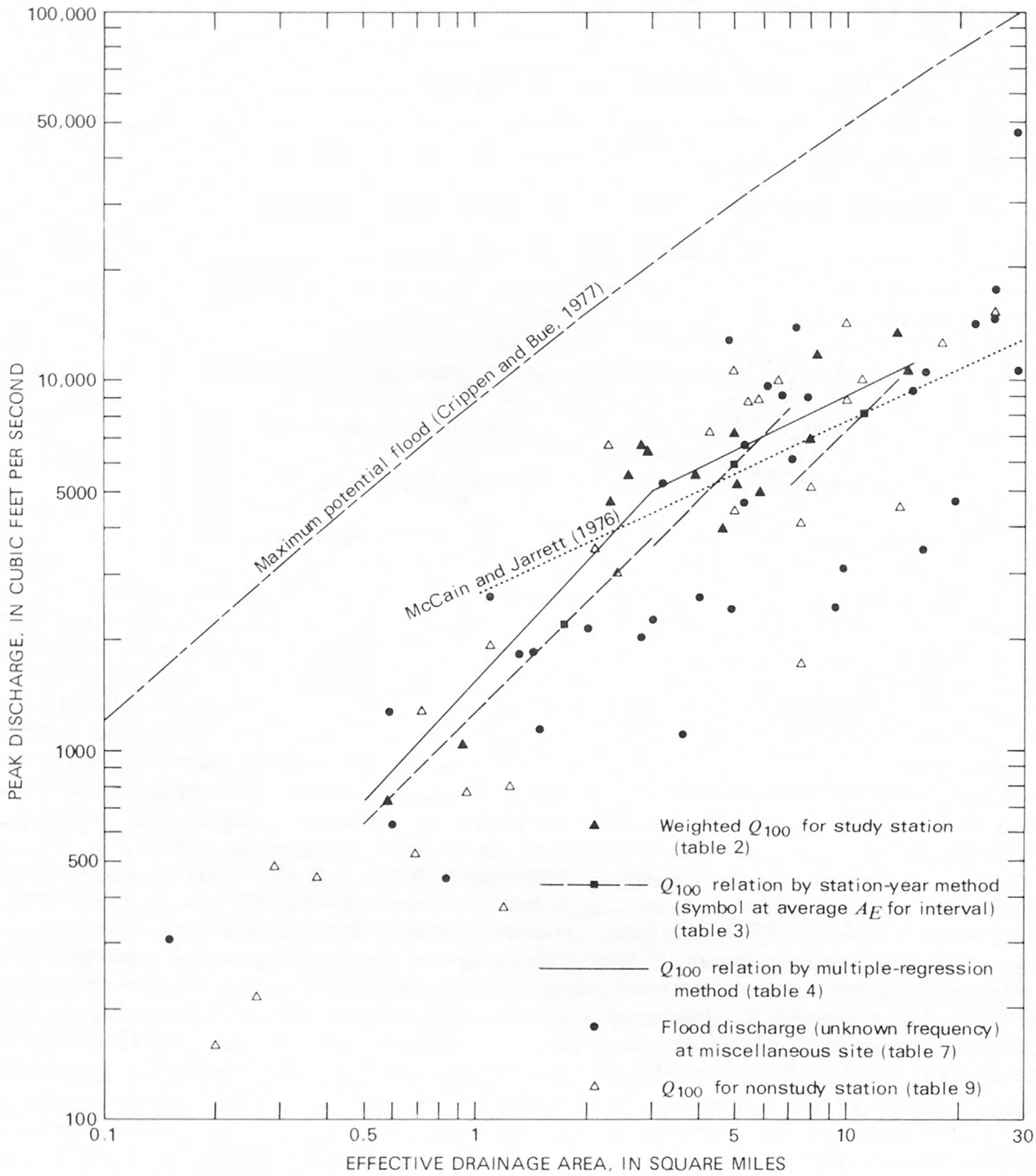

Figure 6.--Relation between effective drainage area and Q_{100} by the station-year and multiple-regression methods. The Q_{100} for 15 study and 28 nonstudy stations and the the peak discharge of floods of unknown frequency at 34 miscellaneous sites are also shown.

Station-Year Method

Dalrymple (1960) suggests that the station-year method of precipitation analysis can be profitably applied to flood-frequency studies. By this method, described in detail by Clarke-Hafstad (1938), records for a number of stations are combined into a single record with a length equal to the total number of station years involved. Use of this method, however, requires that the stations used have homogeneous flood-frequency characteristics and that annual station data are random or from different storms (Chow, 1964). As previously discussed, the regression analysis did not detect significant areal trends and it is, therefore, assumed that the nonmountainous area of the Arkansas River basin in Colorado has relatively homogeneous flood characteristics. The intense thunderstorms that produce runoff on the small study basins are typically localized in nature, and examination of the station data indicates the annual peak discharge rarely occurred on the same day at more than two or three of the stations. The average interstation correlation coefficient (Matalas and Gilroy, 1968), based on the annual flood series, was determined to be 0.2, also indicating general randomness or independence within the annual flood series.

The objective of the station-year method of analysis was to develop an improved regional flood-frequency relation using only recorded data. This relation is not intended to be used for predictive purposes at ungaged sites, but rather as a comparison with the regression results that involved extensive use of synthetic data.

Because runoff characteristics and, therefore, flood-frequency relationships vary with size of drainage area, the station-year analysis was done by grouping the stations by effective drainage area, similar to the multiple-regression analysis. The groups selected were (1) 0.50 to 2.99 mi^2, (2) 3.00 to 7.00 mi^2, and (3) 7.01 to 15.0 mi^2, with average drainage areas of 1.74, 5.00, and 11.0 mi^2, respectively. (Record lengths for the three data sets were 55, 62, and 32 years, respectively.) For the data to be compatible, all peak discharges were expressed as runoff per square mile of effective drainage area, the most significant factor in determining flood magnitude. Results of a frequency analysis of these data are summarized in table 3. For the 100-year peak discharge, average runoff was found to range from 1,240 $(ft^3/s)/mi^2$ for the first group (average A_E=1.74 mi^2) to 724 $(ft^3/s)/mi^2$ for the third group (average A_E=11.0 mi^2).

The station-year results both for the drainage-area range of the group from which they were derived, and for the average effective area within the range are shown in figure 6. As was found with the regression results, these results also indicate a non-linear relation with drainage area. For the average areas of each group station-year results are 9 to 23 percent less than, but remarkably similar to, the regression results. The relation by McCain and Jarrett (1976) is within about 8 percent for the average drainage areas of 5.00 and 11.0 mi^2, but indicates about 57 percent greater discharge for a 1.74-mi^2 basin.

Table 3.--*Results of station-year method*

Range in size of effective drainage area, A_E, in square miles	Flood characteristic	Station-year result, in cubic feet per square mile	Peak discharge, in cubic feet per second	
			For range in A_E	For average A_E
0.50 to 2.99	Q_{10}	316	158- 945	550
(average A_E=1.74)	Q_{25}	588	294- 1,758	1,020
	Q_{50}	872	436- 2,607	1,520
	[1]Q_{100}	1,240	620- 3,708	2,160
3.00 to 7.00	Q_{10}	211	633- 1,477	1,060
(average A_E=5.00)	Q_{25}	464	1,392- 3,248	2,320
	Q_{50}	765	2,295- 5,355	3,820
	[1]Q_{100}	1,196	3,588- 8,372	5,980
7.01 to 15.0	Q_{10}	170	1,192- 2,550	1,870
(average A_E=11.0)	Q_{25}	328	2,299- 4,920	3,610
	Q_{50}	499	3,498- 7,485	5,490
	[1]Q_{100}	724	5,075-10,860	7,960

[1]Results shown in figure 6.

TECHNIQUES FOR ESTIMATING THE CHARACTERISTICS OF FLOOD FLOWS FOR SMALL WATERSHEDS

The purpose of the analysis of flood data collected on small watersheds in the Arkansas River basin during the 10-year study period was to provide improved estimates of the magnitude and frequency of flood flows, and the volumes associated with these floods. Based on this preliminary analysis, the following sections briefly discuss the best methods of estimating these flood characteristics for small ungaged rural watersheds. To aid users in application of these results, table 4 summarizes the necessary equations.

Magnitude and Frequency of Peak Discharges

Peak discharges were studied using (1) a multiple regression method applied to flood-frequency estimates which were based on recorded data from the study basins and synthetic data from a calibrated rainfall-runoff model, and (2) a station-year method applied only to recorded station data. The results of this study indicate that equations 12 to 19, which are based on the multiple-regression method, will statistically provide the best estimates of the magnitude and frequency of floods on small rural watersheds in the Arkansas River basin. These equations are given in table 4 and are applicable to rural drainage basins ranging in size from about 0.5 to 15 mi^2; they are recommended in preference to previously developed methods for estimating flood characteristics on small ungaged basins in this region. To improve estimates for sites at or near gaging stations where flood-frequency information is available, equations given by Sauer (1974) or McCain and Jarrett (1976), are recommended.

Table 4.--*Summary of equations for estimating the characteristics of flood flows from small rural watersheds in the Arkansas River basin*

Peak discharge (Q_P) in cubic feet per second,

0.5- to 3.0-square-mile basins:

$Q_{10} = 500 A_E^{0.89}$	(S_e=41.1)[1]
$Q_{25} = 840 A_E^{0.97}$	(S_e=40.1)
$Q_{50} = 1{,}140 A_E^{1.01}$	(S_e=40.2)
$Q_{100} = 1{,}550 A_E^{1.07}$	(S_e=34.0)

3.0 to 15.0-square-mile basins:

$Q_{10} = 830 A_E^{0.41}$	(S_e=48.6)
$Q_{25} = 1{,}560 A_E^{0.44}$	(S_e=39.8)
$Q_{50} = 2{,}280 A_E^{0.47}$	(S_e=35.4)
$Q_{100} = 2{,}930 A_E^{0.50}$	(S_e=29.7)

Flood volume (V), in acre-feet

$V = 0.141 Q_P^{0.919}$	(S_e=62)

Synthetic hydrograph constants: discharge constant (Q'), in cubic feet per second per discharge unit; time constant (T'), in minutes per time unit.[2]

$$Q' = Q_P/60$$

$$T' = 0.748 V/Q'$$

[1]Average standard error of estimate, in percent.

[2]Dimensionless hydrograph time and discharge units, and an example application of the synthetic hydrograph procedure, given in table 5.

As an example, suppose an estimate of Q_{25} was required for an ungaged basin with a effective drainage area of 8.25 mi^2. As indicated in table 4, equation 17 should be used, the resultant estimate of Q_{25} being 3,950 ft^3/s.

Flood Volumes

The relationship between peak discharge and flood volume was studied using both recorded and synthetic flood data. The analysis of recorded data produced equation 1, while the analysis of synthetic data produced three relations of which equation 4 was judged to provide the best results. Both equations 1 and 4 are quite similar. However, because the synthetic data base is (1) much broader with respect to number and size of floods, and (2) a better estimate of the magnitude of rare floods (such as Q_{100} as previously discussed), equation 4 will probably provide the best overall estimates of flood volume from peak discharge for small ungaged basins in the study area. This relationship is given in table 4 and is applicable to peak discharges less than about 13,000 ft^3s. For example, the volume for a 3,950-ft^3/s peak discharge, previously determined to be Q_{25} for an 8.25 mi^2 basin, is estimated using equation 4 to be 285 acre-ft.

Synthetic Hydrograph

Methods thus far have been discussed by which the magnitude and volume of floods can be estimated for small ungaged watersheds in the Arkansas River basin in Colorado. These flood characteristics can be further used to develop a complete synthetic hydrograph as described by Commons (1942). The dimensionless hydrograph developed by Commons was refined for small watersheds in Wyoming by Craig (1970). This refined hydrograph, called the composite mean dimensionless hydrograph, has a volume of 970 square units, a rise time of 12 time units, and a time base of 70 time units.

The dimensionless time and discharge units of the synthetic hydrographs are given in table 5, which also shows an example calculation of the synthetic hydrograph for Q_{25} (peak discharge, 3,950 ft^3s; flood volume, 285 acre-ft) on an 8.25 mi^2 basin. The equations necessary for computing the discharge and time constants are given in table 4. As shown in footnote 2 of table 4, the flow and time constants for this example are calculated using these equations to be 65.8 ft^3/s per discharge unit and 3.24 min per time unit, respectively. The general shape of the resulting hydrograph, shown in figure 7, compares favorably with an observed 3,300-ft^3/s flood that occurred September 13, 1976, at station 07099250, also an 8.25-mi^2 basin; this flood would have a recurrence interval of about 20 years. Comparisons with other observed flood hydrographs also indicated this technique provides satisfactory results.

Accuracy and Limitations

The statistical accuracy of the equations developed in this preliminary analysis of the rainfall-runoff data for the Arkansas River basin is indicated by the standard errors of estimate (S_e) and correlation coefficients (R) shown in table 4.

Table 5.--*Calculated synthetic hydrograph for the estimated 25-year peak discharge on an 8.25-square-mile basin*

Dimensionless hydrograph[1]		Constants[2]		Synthetic hydrograph[3]	
Time unit, t	Discharge unit, q	Time constant T', in minutes	Discharge constant Q', in cubic feet per second per flow unit	Time (txT') in minutes	Discharge (qxQ'), in cubic feet per second
0	0	3.24	65.8	0	0
3	5.6	3.24	65.8	10	368
5	13	3.24	65.8	16	855
7	25	3.24	65.8	23	1,640
10	49	3.24	65.8	32	3,220
11	57	3.24	65.8	36	3,750
12	60	3.24	65.8	39	3,950
13	59	3.24	65.8	42	3,880
14	55	3.24	65.8	45	3,620
18	38	3.24	65.8	58	2,500
23	23	3.24	65.8	75	1,510
30	12	3.24	65.8	97	790
40	5.2	3.24	65.8	130	342
50	2.0	3.24	65.8	162	132
60	.5	3.24	65.8	194	33
70	0	3.24	65.8	227	0

[1]Modified from Craig (1970).

[2]Based on an estimated 25-year peak discharge of 3,950 ft^3/s and flood volumes of 285 acre-ft (see text), the time and discharge constants are calculated as follows:

$$Q' = \frac{Q_P}{60} = \frac{3,950}{60} = 65.8 \text{ ft}^3\text{/s per discharge unit, and}$$

$$T' = \frac{0.748V}{Q'} = \frac{0.748\ (285)}{65.8} = 3.24 \text{ min per time unit.}$$

[3]Synthetic hydrograph shown in figure 7.

Sufficient data were not available for split-sample testing in this analysis and, consequently, there is uncertainty associated with these statistical measures of reliability. As an indication of the prediction accuracy of equations 15 and 19, table 9 and figure 6 compare the observed and the estimated 100-year flood discharges for 28 stations within and adjacent to the Arkansas River basin in Colorado which were not used in this analysis. Six of these stations are partially urbanized basins located in the Denver-Boulder metropolitan area. All of the remaining nonstudy stations have watersheds similar to those studied, and are

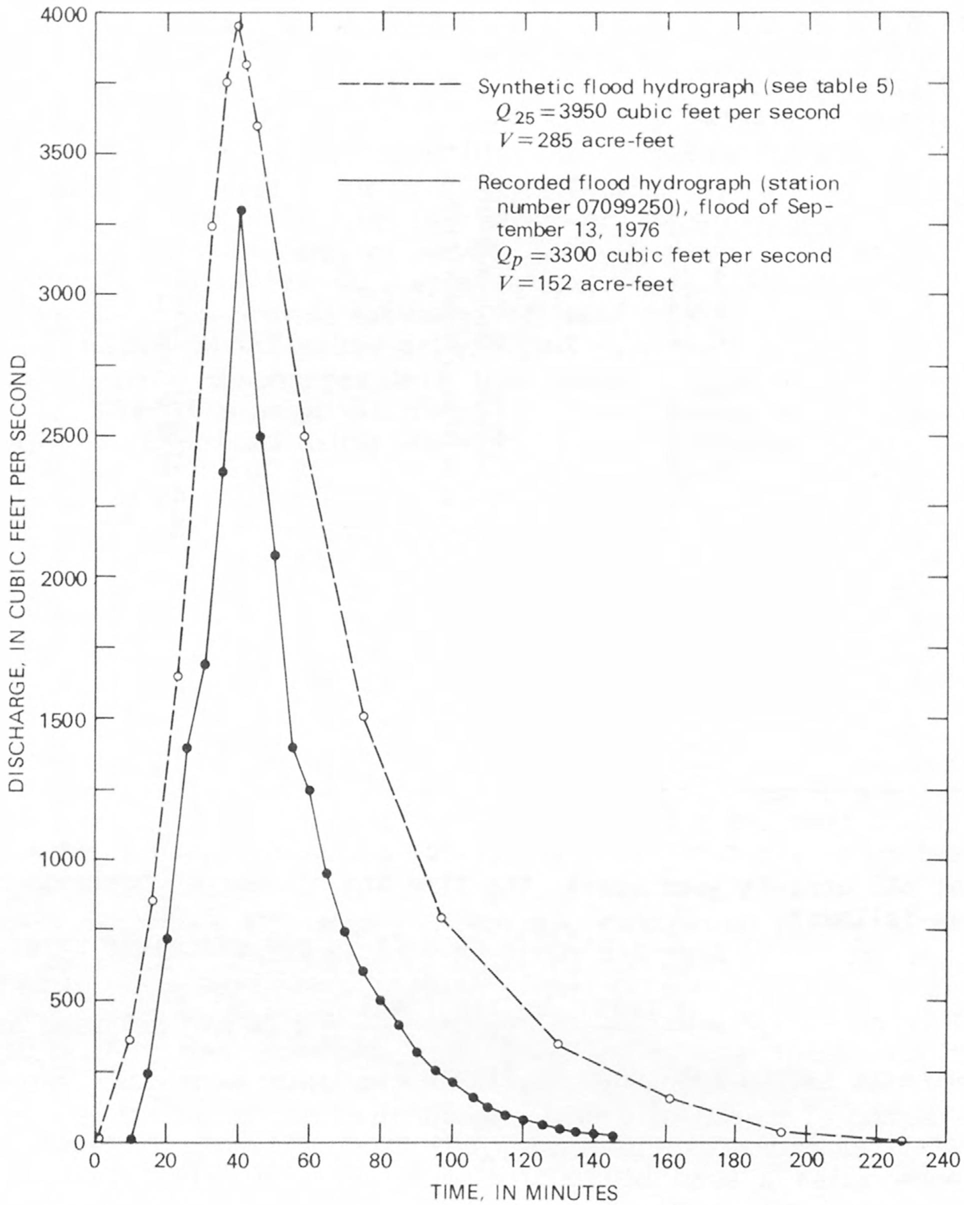

Figure 7.--Comparison of a synthetic hydrograph with a recorded hydrograph for an 8.25-square-mile basin.

located in nonmountainous areas within about 60 miles of the study area. Although there is considerable scatter about the regression line it must be remembered that the observed Q_{100} for these stations is based on relatively short periods of record (8 to 26 years; average about 16 years) and is consequently subject to considerable time-sampling error as previously discussed. The Q_{100} as indicated by the observed flood-frequency relation was less than the regional results for 11 of the 15 stations studied in this analysis. In general, then, figure 6 indicates an unbiased relation, and also provides a limited test of equations 15 and 19 on additional basins in the study area and in adjoining States and river basins. This type of test could not be performed on the other peak-discharge relations or on the flood volume relation.

Based on the drainage areas sampled, the regression equations presented are applicable to basins with effective drainage areas ranging in size from about 0.50 to 15.0 mi^2 that are in the plains region of the Arkansas River basin of Colorado. However, figure 6, along with table 9, indicates these results also may apply to basins as small as about 0.2 mi^2 or as large as about 30 mi^2, or located near the study area but within adjoining States or river basins. It is emphasized that the effective drainage area as used throughout this analysis excludes sub-basins above detention reservoirs or other manmade structures within the basin that would affect flood peaks. The effective drainage area must, therefore, be carefully determined from maps or aerial photographs showing such features.

The data and analysis presented in this report have only dealt with rural basins with natural-flow characteristics. Although the effects of urbanization are not specifically addressed in this study, planners and designers are sometimes required to estimate the flood characteristics of small basins that have some urban development. Good agreement between the observed and estimated Q_{100} for the six small urban basins is indicated in figure 6 and table 9. Although urbanization within a basin generally results in larger peak discharges for a particular recurrence interval, it would appear these effects are relatively minor for Q_{100}, when effective impervious area is less than about 30 percent. Effective impervious areas are impervious areas which are connected and do not drain to pervious areas (Ellis and Alley, 1979).

This analysis has focused on the characteristics of flood flows resulting from typical thunderstorm activity and the results may not apply to floods resulting from frontal-type storms. The user is cautioned that the results and equations discussed herein are preliminary and may be revised after analysis of new data.

SUMMARY AND CONCLUSIONS

A network of 17 stations provided an average of about 9 annual flood peaks per station and 141 rainfall-runoff events in a study to evaluate the magnitude and frequency of flood discharges and volumes for small rural basins in the Arkansas River basin of Colorado. From these recorded data, station flood-frequencies and the relation between peak discharge and flood volume were determined. In addition, a rainfall-runoff model was calibrated for 15 of the watersheds, and used to produce a long-term synthetic annual flood series. From these synthetic data, station flood-frequencies and the relation between peak discharge and flood volume were again determined. An improved estimate of the flood-frequency relation for each station was determined by statistically combining the relations developed from the recorded and the synthetic data. Flood-frequency results were then regionalized using both a multiple-regression method and a station-year method. Lastly, a dimensionless hydrograph technique was tested to determine if estimated flood characteristics could be used to develop a reliable synthetic hydrograph.

The principal conclusions of this preliminary analysis are:

1. The results of the multiple-regression and station-year methods were found to be in close agreement; depending on drainage area size, the station-year results were 9 to 23 percent lower for the 100-year peak discharge. The regression results should be used to provide the regional estimates of flood characteristics at ungaged basins.

2. The magnitude and frequency of floods can be estimated from the effective drainage area with a standard error of estimate of 30 to 50 percent. The relations are generally applicable to basins ranging in size from about 0.5 to 15 mi^2, but separate equations for basins less than and greater than 3 mi^2 were found to give better results.

3. For any peak discharge less than about 13,000 ft^3/s, flood volume can be estimated with a standard error of estimate of about 62 percent.

4. Using estimated peak discharge and flood volume, a method developed by Craig (1970) provides synthetic flood hydrographs with shapes very similar to the flood hydrographs observed in this study.

5. The flood-frequency and flood-volume relations reported are only applicable to rural basins with natural-flow conditions. However, urbanization resulting in less than 30 percent effective impervious area may not significantly affect these flood characteristics.

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SUPPLEMENTAL DATA

Table 6.--*Results of calibration*

U.S. Geological Survey station number[1]	Number of events in calibration	Infiltration parameters[2]			Soil-moisture-accounting parameters[2]			
		PSP, in inches	KSAT, in inches	RGF	BMSM, in inches	RR	DRN	EVC
07099250	9	2.809	0.085	13.02	1.027	0.96	1.00	0.69
07107600	14	1.624	.056	11.93	1.889	.94	1.00	.69
07112700	3	1.643	.056	8.670	3.028	.95	1.00	.69
07120600	14	1.484	.064	11.19	3.751	.95	1.00	.69
07123700	10	3.429	.113	17.78	4.952	.97	1.00	.69
07124700	7	3.987	.312	29.70	1.139	.97	1.00	.69
07125050	6	3.426	.109	15.65	1.215	.97	1.00	.69
07126400	11	2.272	.053	12.74	1.032	.95	1.00	.69
07126450	3	1.931	.064	13.81	1.011	.95	1.00	.69
07129100	3	3.987	.156	29.69	1.226	.95	1.00	.69
07129200	6	1.293	.052	8.654	1.033	.95	1.00	.69
07133200	3	2.263	.080	14.60	2.837	.95	1.00	.69
07134300	9	3.686	.125	18.78	1.692	.97	1.00	.69
07135800	9	1.519	.094	13.52	2.298	.95	1.00	.69
07138520	9	2.024	.064	10.29	1.029	.94	1.00	.69
07153450	14	1.602	.071	10.06	3.750	.98	1.00	.69
07154800	11	3.973	.068	19.52	1.206	.95	1.00	.69

[1]Station names and locations given in table 1; locations are shown in figure 1.

[2]Parameters defined in detail by Lichty and Liscum (1978, p. 35) and on page 13 of this report.

[3]Calibration unsuccessful (see text).

of rainfall-runoff model

Surface-runoff-routing parameters[2]			Statistics for calibration of peak discharge		
KSM, in hours	TC, in minutes	TP/TC	Correlation coefficient	Root mean square error in percent	Slope of regression line
0.405	27.00	0.50	0.82	94	0.92
.315	22.50	.50	.82	70	.78
.315	27.00	.50	.75	49	.85
1.28	26.65	.50	.81	46	.67
.360	29.25	.50	.79	53	.74
.360	15.75	.50	.88	79	1.10
.577	27.00	.50	.81	38	.79
.813	60.19	.50	.92	65	1.07
.765	82.88	.50	.56	>100	[3].47
.646	33.08	.50	.82	51	[3]3.20
.405	36.00	.50	.87	69	.90
.450	40.50	.50	.98	18	1.16
.488	39.00	.50	.92	66	1.06
.651	53.32	.50	.79	83	.79
1.88	140.4	.50	.72	67	.83
.898	69.30	.50	.85	47	.89
.653	20.25	.50	.87	64	.80

Table 7.--*Historical peak discharges for 34 miscellaneous small rural watersheds in the South Platte and Arkansas River basins*

Site name (U.S. Geological Survey station number, if applicable)	Contributing drainage area, in square miles	Date	Peak discharge in cubic feet per second
SOUTH PLATTE RIVER BASIN (PART 6)			
Black Wolf Creek near Wray, Colo------	25.0	July 17, 1962	17,800
Kiowa Creek at Elbert, Colo. (06758000)-------------------------	28.6	May 30, 1935	43,500
Kiowa Creek at K-79 Reservoir near Eastonville, Colo. (06757600)-------	3.20	July 30, 1957	5,250
Kiowa Creek Subwatershed No. J-33 near Eastonville, Colo. (06757700)-------	1.12	June 17, 1965	2,600
Kiowa Creek Subwatershed No. Q-51 near Elbert, Colo. (06757800)------------	.59	June 17, 1965	1,270
Kiowa Creek Subwatershed No. R-3 near Elbert, Colo. (06757750)------------	2.82	June 17, 1965	2,010
North Branch Indian Creek near Max, Nebr---------------------------------	4.76	July 31, 1962	12,900
Piney Creek near Melvin, Colo---------	21.9	June 16, 1965	14,100
South Fork Sappa Creek tributary near Goodland, Kans (06844800)-----------	4.0	June 7, 1962	2,600
ARKANSAS RIVER BASIN (PART 7)			
Black Squirrel Creek near Peyton, Colo-------------------------------	16.3	June 17, 1965	10,400
Blue Ribbon Creek near Pueblo, Colo---	6.7	June 3, 1921	9,130
Boggs Creek near Livesey, Colo--------	24.9	June 3, 1921	14,500
Cameron Arroyo near Livesey, Colo-----	7.3	June 3, 1921	13,900
Canadian River tributary near Hebron, N. Mex----------------------------	2.01	June 17, 1965	2,130
Carrizozo Creek tributary near Kenton, Okla-------------------------------	.15	July 6, 1958	307
Chicorica Creek above Malloya Dam, N. Mex----------------------------	9.3	May 18, 1955	2,450
Chicorica Creek tributary near Raton, N. Mex----------------------------	1.33	June 17, 1965	1,810
Cimarron Creek tributary in Cimarron, N. Mex----------------------------	1.44	June 5, 1958	1,870
Cimarron River tributary (No. 3) near Kenton, Okla-----------------------	4.9	July 6, 1958	2,410
Colorado Canyon near Jensen, Colo-----	9.88	1954	3,100

Table 7.--*Historical peak discharges for 34 miscellaneous small rural watersheds in the South Platte and Arkansas River basins*--Continued

Site name (U.S. Geological Survey station number, if applicable)	Contributing drainage area, in square miles	Date	Peak discharge in cubic feet per second
ARKANSAS RIVER BASIN (PART 7)--Continued			
Grasmack Arroyo near Trinidad, Colo---	3.6	June 17, 1965	1,090
Grey Creek near Trinidad, Colo--------	16.0	June 17, 1965	3,540
Hogans Gulch near Eden, Colo----------	6.1	August 7,1904	9,640
Osteen Arroyo near Swallows, Colo-----	7.8	June 3, 1921	9,060
Raton Creek near Morley, Colo---------	5.27	June 16, 1965	4,660
Rush Creek near Swallows, Colo--------	19.6	June 3, 1921	4,670
Smith Arroyo near Granada, Coolo------	29.1	June 17, 1965	10,600
Springer Arroyo near Colfax, N. Mex---	3.00	June 17, 1965	2,280
Templeton Gap near Colorado Springs, Colo--------------------------------	7.1	May 17, 1922	6,120
Turkey Creek Canyon near Cimarron, N. Mex------------------------------	5.25	June 16, 1965	6,660
Unnamed Draw No. 1 near Alfalfa, Colo--------------------------------	.84	July 22, 1954	447
Unnamed Draw No. 2 near Alfalfa, Colo--------------------------------	1.49	July 22, 1954	1,130
Unnamed Arroyo No. 1 near Livesey, Colo--------------------------------	15.2	June 3, 1921	9,400
Unnamed Arroyo No. 2 near Pueblo, Colo--------------------------------	.6	June 3, 1921	633

Table 8.--*Basin characteristics used in multiple-regression analysis*

[See text for explanation of symbols used in table]

U.S. Geological Survey station number[1]	A, in square miles	S_E, in square miles	E, in feet	R_M, in feet	L, in feet	S_S, in feet per mile	S_C, in feet per mile	S_B, in feet per mile	W_{D1}, in feet	W_{D5}, in feet	$I_{1,000}$, in inches	$I_{6,100}$, in inches	$I_{24,100}$, in inches
07099250	8.35	8.25	5,280	910	6.4	35	121	386	31	164	2.5	3.5	4.5
07107600	2.87	2.87	5,230	600	3.4	72	111	512	20	56	2.5	3.5	4.5
07112700	3.10	2.84	6,230	490	3.3	52	115	368	20	42	2.6	3.5	4.5
07120600	6.56	4.59	5,340	470	6.0	20	78	317	24	144	2.6	3.8	4.6
07123700	10.4	5.04	4,790	310	6.1	56	54	123	38	111	2.9	3.9	4.8
07124700	8.46	7.90	6,180	3,450	7.2	79	390	1,050	18	32	2.7	3.8	5.0
07125050	6.22	5.83	6,220	1,240	5.3	45	177	908	18	59	2.4	3.3	4.1
07126400	4.14	3.86	4,910	540	3.6	29	96	167	12	32	3.1	4.3	5.1
07126450	8.93	6.54	5,780	900	6.6	20	127	424	18	49	2.9	4.8	5.7
07129100	7.07	5.54	4,600	600	3.6	25	68	547	13	34	3.0	4.8	5.5
07129000	3.31	2.62	4,630	420	2.9	34	90	764	21	42	3.2	4.6	5.4
07133200	2.34	2.27	4,280	280	3.0	32	81	194	18	50	3.4	5.0	5.8
07134300	13.9	13.7	3,860	450	10.7	17	37	185	36	44	3.0	5.0	6.0
07135800	6.28	4.94	3,790	260	6.0	20	38	100	17	28	3.1	5.1	6.3
07138520	17.0	14.6	3,720	260	7.4	15	25	42	19	160	3.4	5.3	6.7
07153450	4.56	.58	5,760	580	.91	13	84	386	11	44	3.1	4.6	5.6
07154800	3.50	.92	4,510	130	1.6	28	38	142	13	175	3.3	5.2	6.7

[1]Station names and locations given in table 1; locations are shown in figure 1.

Table 9.--*Observed and estimated 100-year peak discharge for 28 nonstudy stations within and adjacent to the Arkansas River basin in Colorado*

U.S. Geological Survey Station number	Station name	Years of record	Location		Contributing drainage in square miles	100-year peak discharge, in cubic foot per second	
			Latitude	Longitude		Observed	Estimated[1]
06710200[2]	Big Dry Creek tributary at Littleton, Colo--------------	11	39°35'46"	104°57'06"	0.95	760	1,470
06711580[2]	Harvard Gulch tributary at Englewood, Colo--------------	9	39°39'34"	104°58'16"	.72	1,290	1,090
06711600[2]	Sanderson Gulch tributary at Lakewood, Colo--------------	11	39°41'19"	105°04'54"	.38	460	550
06714310[2]	Sand Creek tributary at Denver, Colo-----------------	9	39°47'07"	104°50'31"	.29	490	200
06728350[2]	Goose Creek at Boulder, Colo---	9	40°01'35"	105°16'19"	.69	540	410
06728400[2]	Boulder Creek tributary at Boulder, Colo------------	10	39°58'48"	105°14'41"	.20	160	280
06758700	Middle Bijou Creek near Dear Trail, Colo------------	18	39°29'33"	104°09'46"	2.27	6,790	3,730
06821300	North Fork Arikaree Creek near Shaw, Colo--------------	18	39°31'12"	103°26'35"	5.72	9,110	7,010
06844800	South Fork Sappa Creek tributary near Goodland, Kans---	22	39°19'14"	101°37'57"	4.98	10,670	6,540
06845900	Little Beaver Creek tributary near McDonald, Kans----------	10	39°46'00"	101°22'20"	2.12	3,590	3,460
06847600	Prairie Dog Creek tributary at Colby, Kans---------------	22	39°23'28"	101°02'43"	7.53	4,160	8,040
06857500	Big Timber Creek near Arapahoe, Colo---------------	18	38°59'36"	102°17'06"	10.0	8,870	9,270
06858700	North Fork Smoky Hill River tributary near Winona, Kans--	21	39°01'51"	101°17'07"	1.13	1,960	1,770
07126450	Tobe Arroyo near Tobe, Colo----	8	37°11'43"	103°36'33"	6.54	9,900	7,490
07129100	Rule Creek near Ninaview, Colo-	9	37°33'57"	103°10'26"	5.54	9,000	6,900

07138600	Whitewoman Creek tributary near Selkirk, Kans-----------	21	38°31'30"	101°37'16"	7.59	1,740	8,070
07138800	Lion Creek tributary near Modoc, Kans------------------	21	38°28'48"	101°03'00"	1.19	380	1,870
07154650	Tesequite Creek near Keaton, Okla------------------------	15	36°53'52"	102°54'04"	25.4	14,660	14,770
07155100	Cold Springs Creek near Wheeless, Okla---------------	15	36°46'20"	102°48'16"	11.0	10,010	9,720
07155510	Flagg Springs tributary near Boise City, Okla-------------	8	36°52'30"	102°31'10"	5.15	4,590	6,650
07155900	North Fork Cimarron River tributary near Elkhart, Kans-----	21	37°11'27"	101°53'54"	10.0	14,700	9,260
07156600	Cimarron River tributary near Moscow, Kans-----------------	22	37°20'07"	101°03'00"	8.00	5,200	8,290
07156700	Cimarron River tributary near Santanta, Kans---------------	16	37°16'15"	100°55'36"	2.41	3,100	3,970
07201000	Raton Creek at Raton, N. Mex---	24	36°55'38"	104°26'23"	14.4	4,640	11,120
07201450	Green Mountain Arroyo near Raton, N.Mex-----------------	8	36°47'00"	104°15'42"	18.2	12,460	12,500
07213700	Canadian River tributary near Mills, N. Mex-----------	24	36°10'00"	104°15'47"	4.20	7,370	6,000
07227295	Sand Draw tributary near Clayton, N. Mex--------------	26	36°23'30"	103°19'05"	1.25	790	1,970
07232550	South Fork tributary near Guyman, Okla-----------------	13	36°40'06"	101°29'54"	.26	220	370

[1]Computed using equations 15 or 19 given in text.

[2]Partly urbanized basin (less than 30 percent effective impervious area (data from C. V. Reeter, U.S. Geological Survey, written commun., 1980).

GPO 831-323

Livingston--RAINFALL-RUNOFF MODELING OF SMALL RURAL WATERSHEDS IN THE ARKANSAS RIVER BASIN IN COLORADO