UNITED STATES
DEPARTMENT OF THE INTERIOR
GEOLOGICAL SURVEY

ANALYSIS OF RUNOFF FROM SMALL DRAINAGE BASINS IN WYOMING

By Gordon S. Craig, Jr., and James G. Rankl

OPEN-FILE REPORT 77-727

(pending publication as U.S. Geological Survey water-supply paper.)

Prepared in cooperation with the
WYOMING HIGHWAY DEPARTMENT and the
U.S. DEPARTMENT OF TRANSPORTATION
FEDERAL HIGHWAY ADMINISTRATION

Cheyenne Wyoming

September 1977

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ABSTRACT

A flood-hydrograph study has defined the magnitude and frequency of flood volumes and flood peaks that can be expected from drainage basins smaller than 11 square miles in the plains and valley areas of Wyoming. Rainfall and runoff data, collected for 9 years on a seasonal basis (April through September), were used to calibrate a rainfall-runoff model on each of 22 small basins. Long-term records of runoff volume and peak discharge were synthesized for these 22 basins.

Flood volumes and flood peaks of specific recurrence intervals (2, 5, 10, 25, 50, and 100 years) were then related to basin characteristics with a high degree of correlation. Flood volumes were related to drainage area, maximum relief, and basin slope. Flood peaks were related to drainage area, maximum relief, basin slope, and channel slope.

An investigation of ponding behind a highway embankment, with available storage capacity and with a culvert to allow outflow, has shown that the single fast-rising peak is most important in culvert design. Consequently, a dimensionless hydrograph defines the characteristic shape of flood hydrographs to be expected from small drainage basins in Wyoming. For design purposes, a peak and volume can be estimated from basin characteristics and used with the dimensionless hydrograph to produce a synthetic single-peak hydrograph. Incremental discharges of the hydrograph can be routed along a channel, where a highway fill and culvert are to be placed, to help determine the most economical size of culvert if embankment storage is to be considered.

SYMBOLS USED IN THIS REPORT

A	Drainage area, square miles.
a	Constant of regression.
b_1	Drainage area coefficient.
b_2	Basin slope coefficient.
b_3	Maximum basin relief coefficient.
b_4	Channel slope coefficient.
C	Empirical value which determines rate of decay between g and f.
CK	Exponent dependent on the day of the year.
f	Minimum value of CK.
FR	Infiltration capacity for a unit time.
g	Maximum value of CK.
IWW	Number of days in year.
MDH	Mean dimensionless hydrograph.
N or n	Frequency of an event.
q	Point discharge in cubic feet per second used in MDH.
q'	Flow units.
Q	Peak discharge in cubic feet per second.
Q'	Discharge constant.
$\hat{Q}$	Peak discharge, estimated from equations using basin characteristics
$\tilde{Q}$	Peak discharge, computed from equation 9 using a specific volume frequency.
Q_n	Peak discharge of specific frequency; n = 2, 5, 10, 25, 50, or 100.
QR	Rate of runoff generated from excess precipitation.
R_m	Maximum basin relief, feet.
S_B	Basin slope, feet per mile.

$S_{10/85}$	Channel slope, feet per mile.
SR	Supply rate of rainfall for infiltration.
t	Time in minutes.
t'	Time in units.
T	Day of the year.
T'	Time constant.
V	Volume of runoff in acre-feet.
V'	Volume constant.
V_n	Volume of runoff of specific frequency; n = 2, 5, 10, 25, 50, or 10
W	Number of days from beginning of record.
X	Seasonal precipitation.
Y	Seasonal evaporation.

INTRODUCTION

Purpose and Scope

Streamflow data have been collected for many years on large perennial streams in Wyoming and other western states, thus providing information for road and bridge designers. However, very little information is available on small ephemeral streams. Because small drainages are encountered more often than large streams in most road construction projects, they are a major concern to the designer. In 1964 the U.S. Geological Survey, in cooperation with the Wyoming State Highway Department and the Federal Highway Administration, initiated a study of flood hydrographs in Wyoming. The purpose was to investigate runoff from small drainage basins, less than 11 square miles, and to develop methods that would be helpful in the design of hydraulic structures.

Previous reports concerning the estimation of flow characteristics for Wyoming streams include statewide reports by Carter and Green (1963), Wahl (1970), and Druse and Wahl (written commun. 1972). In addition, a series of published reports that cover entire river basins, parts of which are in Wyoming, include: Thomas and others (1963), Snake River Basin; Patterson (1966) and Matthai (1968), Missouri River Basin; Patterson and Somers (1966), Colorado River Basin; and Butler and others (1966), the Great Basin. These reports are concerned only with the frequencies of flood peaks and are not applicable for use on very small drainage basins. Lowham (1976) has prepared a statewide report on flood-peak frequencies that supersedes the above-mentioned reports. There are no known studies or reports about total storm runoff volumes on ephemeral streams, as presented in this report, that are applicable to streams in Wyoming.

This report provides methods to estimate runoff-volume and flood-peak frequencies for small drainage basins in Wyoming. The area of investigation was confined to the large valleys and plains, where most roads are built and where very little streamflow information is available. The study was made on a seasonal basis (April 1 to September 30), because this is the period of thunderstorm activity and high-intensity rainfall, which cause the high-runoff events. Snowmelt runoff is usually not significant on small drainage basins at lower elevations, although exceptions occasionally are possible.

A total of 49 drainage basins were instrumented for this study (fig. 1); 14 of these basins were omitted from the analyses because of insufficient data. During the 9-year period of record, the number of hydrographs recorded on any one basin ranged from none to as many as 30. Three hydrographs from each of 35 basins were used in the peak discharge-runoff volume study. Seven or more hydrographs from each of 28 basins were used in the study of dimensionless hydrographs. Twelve or more hydrographs, with associated rainfall, from each of 22 basins were used in the calibration of the rainfall-runoff model. Following is a list of the 49 study basins in Wyoming:

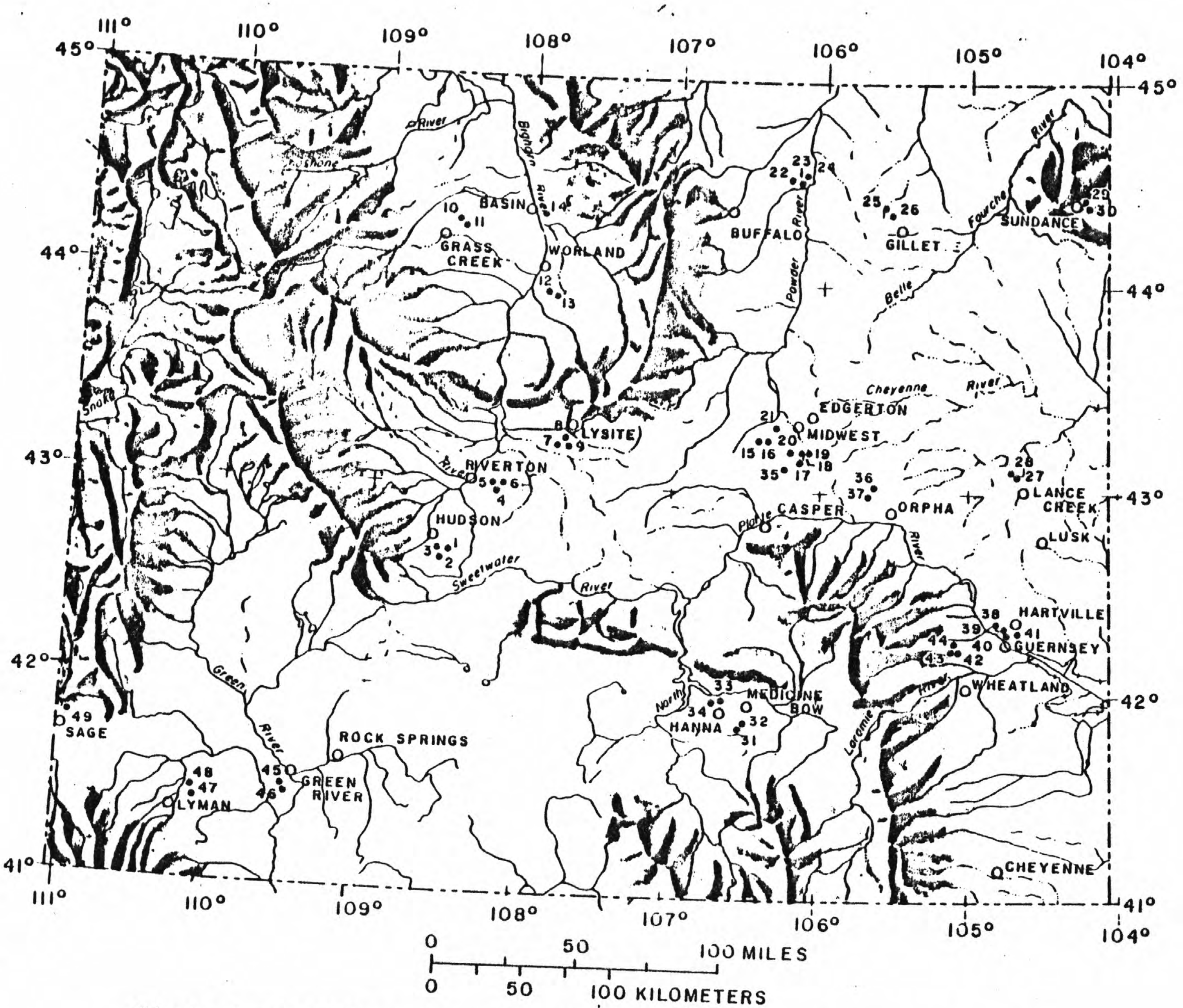


Figure 1.--Locations and numbers of 49 small basins studied. (See p. 6 for list of basin names and numbers.)

Basin No.	Basin name
1	Monument Draw at upper station, near Hudson a/
2	Monument Draw at lower station, near Hudson
3	Coal Mine Draw tributary near Hudson b/
4	West Fork Dry Cheyenne Creek at upper station near Riverton
5	West Fork Dry Cheyenne Creek tributary near Riverton
6	West Fork Dry Cheyenne Creek near Riverton a/
7	Dead Man Gulch tributary near Lysite b/
8	Dead Man Gulch near Lysite b/
9	Badwater Creek tributary near Lysite
10	Gillies Draw tributary near Grass Creek
11	Murphy Draw near Grass Creek
12	North Prong East Fork Nowater Creek near Worland
13	North Prong East Fork Nowater Creek tributary near Worland
14	Nowood River tributary No. 2 near Basin
15	Dead Horse Creek tributary near Midwest
16	Dead Horse Creek tributary No. 2 near Midwest
17	Bobcat Creek near Edgerton b/
18	Coopers Draw near Edgerton b/
19	Seven L Creek near Edgerton b/
20	East Teapot Creek near Edgerton
21	Dugout Creek tributary near Midwest
22	Headgate Draw at upper station, near Buffalo

Basin No.	Basin name
23	Headgate Draw at lower station, near Buffalo a/
24	Powder River tributary near Buffalo b/
25	Box Draw tributary near Gillette b/
26	Rawhide Creek tributary near Gillette a
27	Lance Creek tributary near Lance Creek
28	Pritchard Draw near Lance Creek
29	Ogden Creek near Sundance a/
30	Sundance Creek tributary at Sundance a/
31	Third Sand Creek tributary near Medicine Bow b/
32	Third Sand Creek near Medicine Bow
33	Medicine Bow River tributary near Hanna
34	Willow Springs Draw tributary near Hann
35	McKenzie Draw tributary near Casper
36	Frank Draw tributary near Orpha
37	Sage Creek tributary near Orpha
38	Deadmans Gulch near Guernsey a/
39	Fish Canyon near Guernsey b/
40	Black Canyon near Guernsey a/
41	Sparks Canyon near Hartville b/
42	Piney Creek tributary at upper station, near Wheatland a/
43	Piney Creek tributary at lower station, near Wheatland a/
44	Rabbit Creek near Wheatland b/
45	Telephone Canyon near Green River a/
46	Telephone Canyon tributary near Green River a/
47	Mud Spring Hollow tributary near Lyman
48	Mud Spring Hollow near Church Butte, near Lyman
49	Twin Creek tributary near Sage a/

a/ Not used in analyses--insufficient data.

b/ Basins not modeled--limited data--used in some analyses.

The objectives of this study were to:

1. Define the magnitude and frequency of flood volumes to be expected from small drainage areas in Wyoming.

2. Define the characteristic shape of flood hydrographs in relation to the physical characteristics of the basin.

3. Develop a rational method of accounting for the effect of embankment storage (ponding behind highway embankments) which will be useful in culvert design.

The general procedure for this study to attain the above objectives was based on the following assumptions:

1. The time allotted to data collection (10 years) would be sufficient to determine the frequency of volumes of runoff events.

2. The characteristic shape of a runoff hydrograph could best be described by a dimensionless hydrograph for each basin and possibly by a single dimensionless hydrograph for the entire study area.

3. The type of dimensionless hydrograph that uses values of peak discharge and runoff volume for simulating hydrographs would be usable with the volume-frequency relations.

4. There should be a relationship between peak discharge and runoff volume to provide a method of determining one from the other.

5. Embankment storage could best be studied by routing discharge hydrographs of various shapes through a hypothetical ponding area with a simple culvert opening for relief.

The general procedure indicated above was not considered at the beginning of the study but evolved as the study progressed. At times new concepts or changes in old concepts forced a change in procedure.

This report summarizes the project activities in chronological sequence. The first sections describe procedures of data collection and techniques of frequency analysis on available records. Subsequent sections define techniques of estimating floodflow characteristics as follows:

1. Relations for estimating flood peaks and flood volumes of specified frequency at ungaged sites.

2. Relations for estimating flood volumes where flood peaks are known from other information, or for estimating flood peaks from known volumes.

3. The average flood hydrograph to be expected from given volume and peak information.

These sections are followed by descriptions of the effects of storage behind highway embankments and techniques for using this storage in culvert design.

Limitations of Study

The following limiting conditions were used in the study. It is recommended that methods and procedures described in this report not be used beyond these limits.

1. The size of drainage areas studied ranged from 0.69 square miles to 10.8 square miles.

2. The area of investigation was confined to the plains and large-valley areas of Wyoming.

3. The study was made on a seasonal basis (April through September) to investigate runoff from rainfall. Runoff from snowmelt, generally not significant, was not studied.

4. Some selectivity was used in determining hydrographs to use in developing the mean dimensionless hydrographs to avoid multipeak events or unusually shaped hydrographs.

5. The investigation of flow through culverts was restricted to simple box culverts with inlet control.

Acknowledgments

The authors are indebted to numerous individuals for their assistance through the course of this project. A special acknowledgment is made to David R. Dawdy, U.S. Geological Survey, for his time and effort spent on discussion and modification of the rainfall-runoff model in its application to conditions in Wyoming.

This project was financed with research funds provided by the Wyoming Highway Department and the Federal Highway Administration. The work was performed by personnel of the U.S. Geological Survey. The opinions, findings, and conclusions expressed in this report are those of the authors and not necessarily those of the Wyoming Highway Department or the Federal Highway Administration.

Use of Metric Units of Measurement

The computations and compilations in this report were made with English units of measurements. The equivalent metric units are given in the text and illustrations where appropriate. English units only are shown in tables where, because of limited space, the showing of both English and metric units would not be feasible. To convert English units to metric units, the following conversion factors should be used:

English	Multiply by	Metric
Depth or diameter in inches (in)	2.540	centimeters (cm)
Length in feet (ft)	.305	meters (m)
Length in miles (mi)	1.609	kilometers (km)
Area in square miles (mi^2)	2.590	square kilometers (km^2)
Volume in acre-feet (acre-ft)	1233.	cubic meters (m^3)
	1.233×10^{-3}	cubic hectometers (hm^3)
Discharge in cubic feet per second (ft^3/s)	.0283	cubic meters per second (m^3/s)

DATA COLLECTION

Description of Area

The State of Wyoming is large, rectangular, and variable topographically. Several mountain ranges, part of the northern Rocky Mountains, are quite prominent within the State. The greater part of Wyoming consists of large intermontane valleys and high plains. An unusual feature of Wyoming is that major rivers flow out of the State in all four directions. Most precipitation occurs in the mountains, mainly as snow in the fall, winter, and spring. The accumulated snow or snowpack is the main source of streamflow for the major rivers. The intermontane valleys and high plains usually receive less than 16 inches of precipitation each year; many areas receive less than 10 inches. Although some of the precipitation in these areas is snow, the greater part is rain from thunderstorms, which are quite variable in intensity and frequency, during summer. Aside from the major rivers and a few smaller ones originating in the mountains, practically all other streams are ephemeral or intermittent.

The areas of investigation are the larger intermontane valleys and the high plains. Areas not included in the study are Yellowstone and Grand Teton National Parks, the Great Divide Basin, all mountain ranges, and much of eastern Wyoming where numerous stock ponds affect natural runoff. The study basins are in remote areas, invariably on land used for cattle and (or) sheep grazing. Ground cover is mainly sagebrush, grass, and cactus, with some low brush thickets and few, if any, trees. Many water courses start as grassy swales, becoming erosion gullies and eventually stream channels farther downstream.

Although relief does not vary greatly in most of the basins studied, a few have sharp increases in relief near their perimeters, where erosion gullies are quite prominent. The generally open exposure of the basins to sun and wind result in rapid drying and high evaporation of soil moisture in the basins.

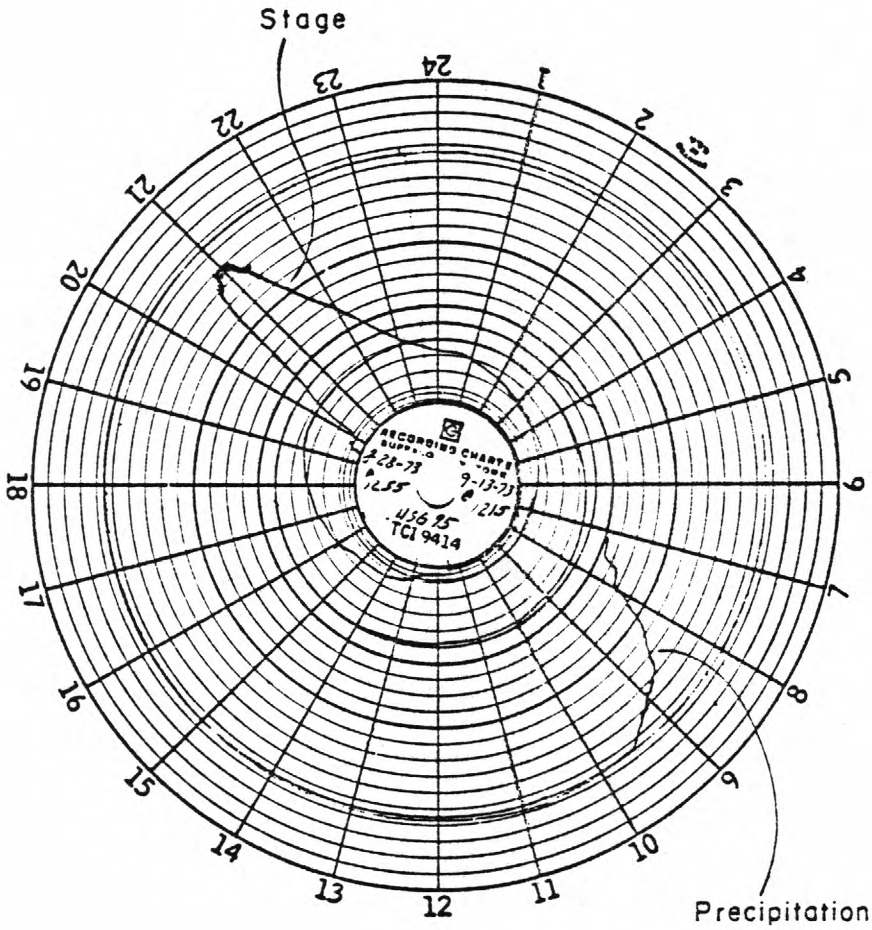
Instrumentation

Instrumentation and data collection on 49 small drainage basins (fig. 1) was begun in 1965. An inexpensive recorder that would collect rainfall and graphically record both rainfall and stage was installed on the bank of each runoff channel at the basin outlet. A similar instrument, modified to collect and record only rainfall, was installed near the upper end of each basin, except when two or three adjacent basins were selected as a cluster; then only one common rainfall-recording instrument was installed. Plastic wedge-shaped storage gages were placed on basin divides to supplement the rain gaging network, but because interpretation of individual storms was difficult, they were not very helpful.

Types of Records

The stage-rainfall instrument graphically recorded on a circular chart the runoff hydrograph, originating at zero and eventually returning to zero. The graph of the rainfall rose continuously, circling continuously after each rainfall event, but not returning to zero until the reservoir was drained during a field inspection when the chart was changed. With the two styluses opposite each other, the rainfall for a runoff occurrence would be fairly obvious on the chart (fig. 2). The recording rain gage at the upper end of the basin graphically recorded the rainfall for each event, which required correlation with runoff. Rainfall at the recording rain gage requires some interpretation because it can occur earlier or later than at the runoff gaging point. It also can occur in greater or lesser amounts or intensity than at the runoff gaging point. For many thunderstorms, rainfall recordings of two gages were averaged and assumed to represent uniform rainfall on the basin.

Stage-discharge relations were developed by current-meter measurements of low flows when possible, by indirect measurements of peak flows, and by step-backwater analyses through a range of flows. The remote stations were inaccessible during high flows and had no facilities to allow for direct current-meter measurements of peak flows. Discharge hydrographs were obtained by applying the stage-discharge relations to values of stage picked from the charts at 5-minute increments.



EXPLANATION

Peak of Sept. 2, 1973
Stage = 7.03 ft
Peak discharge = 970 ft^3/s
Volume = 65.53 acre-ft
Precipitation = 2.44 in

Figure 2.--Example of graphical record from a stage-rainfall recording instrument on McKenzie Draw tributary near Casper, Wyo.

STATION FREQUENCY ANALYSIS

Runoff Volume

One objective of this study was to define the magnitude and frequency of flood volumes to be expected from small drainage basins in Wyoming. Data collected for small basins in Wyoming indicated considerable variation in runoff volume from like amounts of point rainfall data, even for the same basin. One problem is that while point rainfall data are projected as uniform rainfall over a basin, in many cases rainfall distribution is not uniform. The assumption of uniform rainfall is considered reasonable because point data can be too high as well as too low and over a period of time it is expected to average out. Usually, the greater volumes occur from the larger total rainfalls, permitting the assumption that the annual maximum runoff volume does result from the annual maximum rainfall occurrence. This is not always correct, however, because other conditions change sufficiently to increase or decrease the runoff volume from a particular rainfall. A procedure for approximating changes in conditions within a drainage basin and estimating runoff volume or peak discharge from rainfall has been developed and is used in the digital models described in this report.

Rainfall-Runoff Model

Rainfall-runoff modeling has been used to synthesize long-term runoff records from long-term rainfall records. The long-term rainfall records are available from National Weather Service stations throughout the United States. Short-term rainfall and runoff data, collected simultaneously on small drainage basins, are used to calibrate the model. Each basin is calibrated separately. Once calibrated, the model utilizes the long-term rainfall record to generate a synthetic long-term runoff record, equivalent in time.

A model developed by D. W. Dawdy, R. W. Lichty, and J. M. Bergmann (1972) was adapted for use in this study. This parametric model originally used seven parameters to simulate physical conditions in a drainage basin in the process of estimating rainfall excess. Four parameters were used to account for antecedent moisture conditions and three were used to determine infiltration. For this study, three additional parameters were incorporated into the model to account for a variation in infiltration with time. This modification, described in the next section, considers a change in soil conditions as a seasonal variation to reduce infiltration, and is applicable in a semiarid region. The interpretation was based on visual observation of a consistent change in soil appearance through each field season and the consideration of many high-runoff events that occurred in late summer.

Modification of Model Applied to Wyoming

Since the first attempt at basin-model calibration in March 1971, numerous attempts were made to change the model to improve the results. Converting the probability distribution of infiltration in the rainfall-runoff relation to a nonlinear relation and adding time-distribution equations were the only changes to show a modeling improvement. The results of testing the two models for four small drainage basins in Wyoming are listed in table 1.

The rainfall-runoff model simulates runoff from rainfall for small drainage basins. A basic assumption is that rainfall occurs uniformly over a drainage basin. When rain falls on a soil, it either infiltrates, goes into detention storage, or becomes surface runoff. Infiltration occurs throughout a basin at varying rates; however, Dawdy and others (1972) used a method first presented by Crawford and Linsley (1966, p. 210) to convert point potential infiltration to net infiltration over a basin, with net infiltration being the average throughout the basin. The equations are:

$$QR = \frac{SR^2}{2FR} \quad \text{for dry conditions } SR<FR \tag{1a}$$

$$QR = SR - \frac{FR}{2} \quad \text{for wet conditions } SR \geq FR, \tag{1b}$$

where QR is the rate of runoff generated from excess precipitation that does not infiltrate,

SR is the supply rate of rainfall for infiltration,

FR is the infiltration capacity for a unit time.

The schematic representation of the relations is shown in figure 3.

Although a straight-line relationship is implied, this is not necessarily true. It is more likely that such a relationship is nonlinear in both distribution and time.

Table 1.--Comparison of approximate standard error of estimate (in percent) of the volume objective function as determined from the two models.

	North Prong East Fork Nowater Creek	East Teapot Creek	Pritchard Draw	Dugout Creek tributary
Modified	65	25	59	30
Original	68	32	84	44

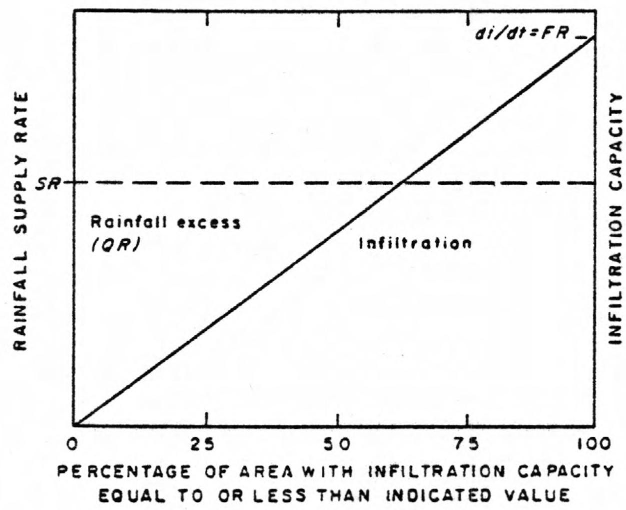


Figure 3.--Relation that determines rainfall excess (QR) as a function of maximum infiltration capacity (FR) and supply rate of rainfall (SR). (From Daudy, Lichty, and Bergmann, 1972, p. B7.)

Calibrations of several small drainage basins in Wyoming were improved in simulation when nonlinear relationships were used. The nonlinear effect is suggested because of a change in soil conditions through the period of investigation, May 1 to September 30. The fluffy soil of May is gradually compacted by rainfall intensity to a hard surface by late summer. The surface is further hardened by drying. If comprehensive data on rainfall were available, the compaction could be computed. Because these data are not available, a suggested approach to the problem is to use time as a variable and to develop relationships of QR to SR, for given FR, for conditions modeled by equations 1a and 1b.

$$QR = \frac{SR^{CK}}{CK(FR)^{CK-1}} \quad \text{for dry conditions} \quad SR<FR \qquad (2a)$$

$$QR = SR-(CK-1)\frac{FR}{CK} \quad \text{for wet conditions} \quad SR\geq FR \qquad (2b)$$

and the exponent CK would be determined by:

$$CK = f+(g-f)e^{-T/C} \qquad (3)$$

which is a time-decay equation with:

CK = Exponent dependent on the day of the year

T = The day of the year

f = Minimum value of CK

g = Maximum value of CK

C = Empirical value which determines rate of decay between g and f.

In the rainfall-runoff model, values of f, g, and C are entered as parameters and final values are determined through an optimization procedure. The resulting values for four calibrated basins are shown in table 2.

A schematic representation of the decrease in infiltration capacity for the time period is shown in figure 4.

The computation of T (day of the year) is from the FORTRAN statement:

```
T = W-(W/IWW)*IWW-45                                   (4)
```

where W = Number of days from beginning of record

IWW = Number of days in year

All variables should be declared integers.

Table 2.--Optimized values of parameters f, g, and C for four calibrated drainage basins. These values are used to determine CK.

Parameter	North Prong East Fork Nowater Creek	East Teapot Creek	Pritchard Draw	Dugout Creek tributary
f	1.41	1.62	1.34	1.30
g	1.91	1.63	1.91	1.83
C	26.4	24.8	16.5	17.6

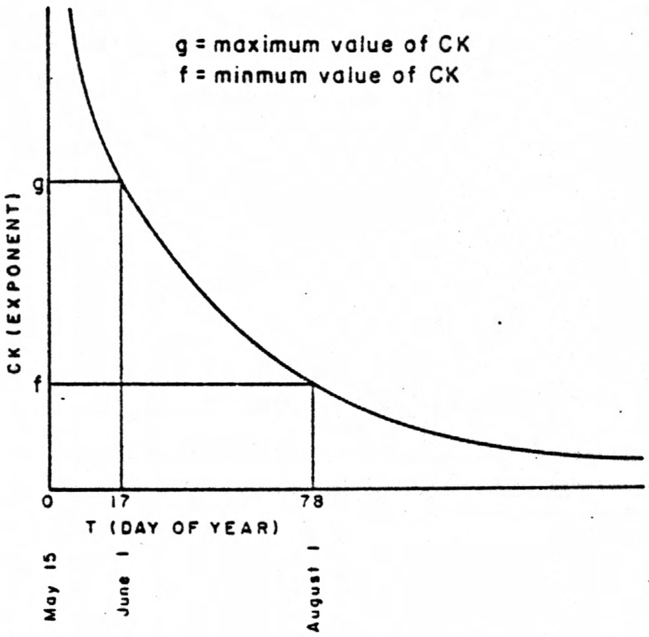


Figure 4.--Relationship of rate of decay of CK to time.

The study of small drainage basins in Wyoming started April 1, 1965, used as day 1. Because the study was primarily of runoff from thunderstorms and these occur from late May to September, storms prior to May 15 invariably are associated with snow and were not used. For this reason, equation 4 subtracts the 45 days from April 1 to May 15. In figure 4, May 15 is shown as the starting time of 0, June 1 becomes day 17, and August 1 becomes day 78.

It should be emphasized that equation 4 is a FORTRAN statement and must be computed sequentially. The term in parentheses (W/IWW) is computed first and must result in an integer (decimals less than 1 become 0 and decimal parts of a number are dropped). The asterisk denotes multiplication which is computed second, then subtracted as indicated. A sample computation for June 1, 1965 would be:

W = 62 days (April 1, 1965 to June 1, 1965)

IWW = 365 days in year

$$T = 62 - (\frac{62}{365})*365-45$$

$$T = 62-(0)*365-45$$

$$T = 62-0-45$$

T = 17 day of year.

The value of CK will vary for the date of each runoff event. The probability distribution of infiltration also changes as shown schematically in figure 5.

Use of the Model

The model is used with data from a point rainfall gage and data on daily potential evapotranspiration to predict flood volumes and peak rates of runoff for small drainage areas. To generalize, there are two phases to the model:

1. An input of daily rainfall, daily pan evaporation, unit discharge for a specified event, and unit rainfall for the precipitation that caused the event, are used to determine values of 10 specified parameters. The parameters theoretically represent physical aspects of a drainage basin whose applied effects can best simulate runoff volumes. Unit data are discharges and accumulated rainfall at 5-minute time intervals. Values of three additional parameters for simulating peak flows by means of a routing procedure are also determined.

2. An input of the optimized values of the above-mentioned parameters, together with long-term daily rainfall, daily evaporation, and unit rainfall for selected annual rainfall events from a long-term rainfall record at a major National Weather Service station, are used to simulate an equivalent long-term record of annual runoff events.

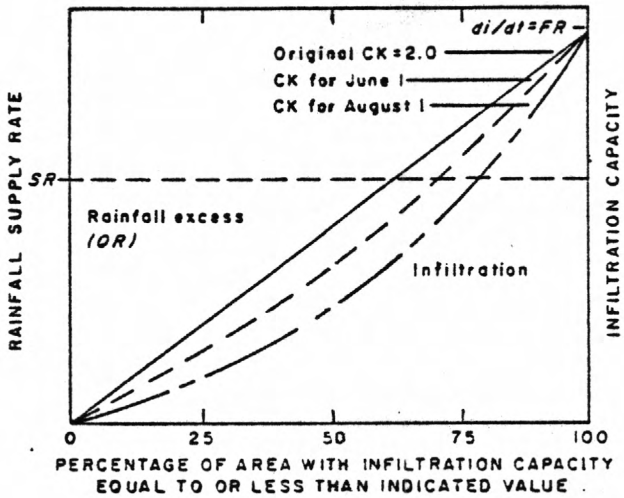


Figure 5.--Variations in the relation that determines rainfall excess (QR) as a function of maximum-infiltration capacity (FR) and the supply rate of rainfall (SR) for Wyoming.

Table 3 lists the final values of the modeling parameters used in the long-term synthesis of runoff volumes. Table 4 lists the final values of the modeling parameters used in the long-term synthesis of flood peaks. The reader is referred to U.S. Geological Survey Professional Paper 506-B by Dawdy, Lichty, and Bergmann (1972) for a comprehensive explanation and derivation of the parameters.

The speed of the digital computer facilitates the modeling process of combining parameter values with available long-term rainfall data to predict long-term runoff data. The synthesized long-term runoff data are then used to develop frequency relations for flood volumes or peak rates of runoff for the drainage basins being investigated. In this study a 73-year rainfall record for the National Weather Service station at Cheyenne was used to generate an equivalent long-term runoff record for seasonal flood volumes and peak discharges. Actually, the study was concerned with rainfall from thunderstorms, which invariably have the high-intensity rainfall that produces the high-runoff events on small drainage basins. Because snowfall and snow accumulation are not predominant on small nonmountainous basins in Wyoming and snowmelt runoff does not produce the significant events, this study was limited to a seasonal basis, April 1 to September 30. Table 5 provides a listing of volume frequencies for each modeled basin. The climatic adjustments (described in the following section) to the long-term rainfall and evaporation data are also listed. Table 6 provides a listing of peak frequencies for each modeled basin. The basins are listed in tables 5 and 6 by increasing drainage area size.

Table 3.--Final modeling parameters used in long-term synthesis of runoff volumes.

Station	Parameters									
	PSP	KSAT	DRN	RGF	BMSM	EVC	RR	CKMN	CKMX	CKEX
1. W.F. Dry Cheyenne Cr	2.608	0.069	0.082	10.25	3.542	0.317	0.444	1.392	1.510	49.98
2. Dugout Cr trib	2.039	.023	.211	9.192	49.80	.656	1.043	1.287	1.920	18.30
3. Frank Draw trib	4.391	.042	.998	17.67	5.735	.525	1.500	1.898	1.998	99.68
4. Gillies Draw trib	8.807	.032	.139	7.792	22.54	.986	.934	1.611	1.627	5.838
5. Dead Horse Cr trib No. 2	4.925	.017	.032	17.18	4.487	.508	.311	1.305	1.350	5.973
6. Sage Creek trib	6.948	.042	.953	25.15	7.234	.996	1.033	1.663	1.899	39.38
7. Nowood R. trib No. 2	3.953	.092	.687	14.92	2.020	.388	1.440	1.402	2.000	27.92
8. Dead Horse Cr trib	4.008	.029	.141	15.81	2.354	.311	1.471	1.330	1.377	8.923
9. W.F. Dry Cheyenne Cr trib	1.920	.082	.057	12.24	24.20	.711	.730	1.706	1.738	41.32
10. Willow Springs Draw trib	17.68	.105	.132	19.86	12.11	.375	1.379	1.420	2.000	33.14
11. McKenzie Draw trib	4.918	.039	.147	15.09	1.683	.690	.900	1.665	1.936	15.03
12. NPEF Nowater Cr trib	3.545	.026	.347	14.76	16.43	.791	.364	1.518	1.902	24.70
13. Murphy Draw	17.33	.028	.145	31.66	8.284	.910	.936	1.363	1.365	5.017
14. Medicine Bow R. trib	6.965	.086	.070	11.74	6.000	.524	1.009	1.459	1.478	21.02
15. Headgate Draw	8.519	.021	1.000	27.22	6.069	.700	1.107	1.790	2.000	13.84
16. NPEF Dowater Cr	2.326	.016	.129	17.13	43.76	.975	.529	1.731	1.971	42.61
17. Pritchard Draw	20.48	.058	.037	17.27	12.08	.500	.560	1.380	1.383	5.049
18. East Teapot Cr.	3.935	.040	.995	14.45	3.838	.793	1.492	1.606	1.975	29.23
19. Badwater Cr trib	2.539	.105	.022	17.65	6.214	.933	.903	1.589	1.589	24.97
20. Monument Draw	2.225	.099	.017	16.72	2.408	1.065	.100	1.523	2.000	39.52
21. Mud Spring Hollow	8.708	.029	.014	22.11	2.885	.505	1.119	1.643	1.643	45.72
22. Third Sand Cr	7.149	.084	.012	13.53	2.867	.388	1.480	1.476	1.938	7.696

Table 4.--Modeling parameters used in long-term synthesis of peak discharge

Station		Routing parameters		
		Storage	Translation hydrographs	
		KSW	Tc	Tp
1.	W.F. Dry Cheyenne Cr	0.276	81.84	2.86
2.	Dugout Cr trib	.161	33.85	31.02
3.	Frank Draw trib	.638	52.98	21.74
4.	Gillies Draw trib	.384	11.46	1.39
5.	Dead Horse Cr trib No. 2	.547	11.91	9.28
6.	Sage Creek trib	.354	50.99	11.86
7.	Nowood R trib No. 2	.225	40.87	34.86
8.	Dead Horse Cr trib	.639	58.78	1.87
9.	W.F. Dry Cheyenne Cr trib	.341	87.66	8.88
10.	Willow Springs Draw trib	.225	28.97	22.70
11.	McKenzie Draw trib	.289	83.66	14.20
12.	NPEF Nowater Cr trib	.231	65.67	7.01
13.	Murphy Draw	.387	11.35	7.14
14.	Medicine Bow R trib	.339	68.08	66.22
15.	Headgate Draw	.082	19.21	15.49
16.	NPEF Nowater Cr	.330	82.08	73.11
17.	Pritchard Draw	.226	41.85	5.99
18.	East Teapot Cr	.213	52.48	.98
19.	Badwater Cr trib	.170	76.50	15.49
20.	Monument Draw	.446	147.74	1.49
21.	Mud Spring Hollow	.857	8.22	.17
22.	Third Sand Cr	.347	68.18	48.86

Table 5.--Volume frequencies for the 22 modeled basins

Station no.	Station name	Drainage area (mi^2)	Calibration results (percent standard error)	Climatic adjustment of long-term data: Daily precipitation (in)	Unit precipitation (in)	Daily evaporation (in)	From synthetic long-term record of volumes — Frequency based on log-Pearson Type III distribution: V_2 (ac-ft)	V_5 (ac-ft)	V_{10} (ac-ft)	V_{25} (ac-ft)	V_{50} (ac-ft)	V_{100} (ac-ft)
06238760	W.F. Dry Cheyenne Cr.	0.69	19.3	0.58	0.65	1.18	6.88	11.9	15.8	21.3	25.9	30.7
06313180	Dugout Cr. trib.	.71	19.1	.85	.77	1.05	18.4	29.6	37.4	47.5	55.2	62.9
06648720	Frank Draw trib.	.79	19.6	.82	.88	1.05	5.35	13.3	21.2	34.7	47.4	62.6
06266320	Gillies Draw trib.	1.30	17.3	.59	.73	.84	10.8	20.0	27.5	38.6	48.0	58.4
06312920	Dead Horse Cr. trib. #2	1.34	23.3	.85	.77	1.05	25.4	41.0	52.7	69.2	82.6	96.9
06648780	Sage Cr. trib.	1.38	20.9	.82	.88	1.05	5.00	10.8	15.9	24.0	31.2	39.4
06274190	Nowood R. trib #2	1.51	19.1	.41	.62	.84	7.81	15.6	21.6	29.6	35.7	41.9
06312910	Dead Horse Cr. trib.	1.53	21.3	.85	.77	1.05	40.8	67.7	87.3	114	134	155
06238780	W.F. Dry Cheyenne Cr. trib.	1.85	13.7	.58	.65	1.18	10.1	19.7	28.0	40.6	51.4	63.4
06634950	Willow Springs Dr. trib.	1.98	22.1	.81	.73	1.18	6.34	13.6	19.2	27.0	33.0	39.1
06644840	McKenzie Draw trib.	2.02	28.7	.85	.77	1.05	12.6	26.9	39.8	60.2	78.5	99.8
06267270	N.P.E.F. Nowater Cr. trib.	2.11	14.6	.52	.65	.84	17.4	32.5	44.2	60.4	73.4	87.0
06266460	Murphy Draw	2.32	25.2	.59	.73	.84	16.8	28.3	37.4	50.2	60.9	72.4
06634910	Medicine Bow R. trib.	3.01	22.9	.81	.73	1.18	21.8	39.5	53.9	75.4	93.9	114
06316480	Headgate Draw	3.32	23.5	.66	.85	1.05	13.3	29.0	43.7	67.3	88.7	114
06267260	N.P.E.F. Nowater Cr.	3.77	21.6	.52	.65	.84	39.9	75.4	103	141	171	202
06382200	Pritchard Draw	5.12	24.5	.84	1.00	1.05	57.6	98.0	130	175	212	253
06313050	East Teapot Cr.	5.44	19.7	.85	.77	1.05	41.5	87.0	126	184	233	287
06256670	Badwater Cr. trib.	5.86	25.8	.47	.65	1.18	22.5	42.2	58.8	83.8	105	129
06233360	Monument Draw	8.23	22.4	.90	.81	1.18	48.7	97.9	136	187	228	269
09221680	Mud Spring Hollow	8.83	18.9	.49	.58	1.25	22.6	45.7	65.9	98.0	127	160
06631150	Third Sand Cr.	10.8	22.0	.69	.62	1.18	72.0	148	214	314	403	501

Table 6.--Peak frequencies for the 22 modeled basins

Station no.	Station name	Drainage area (mi^2)	Calibration results (percent standard error)	Climatic adjustment of long-term data: Daily precipitation (in)	Climatic adjustment of long-term data: Unit precipitation (in)	Climatic adjustment of long-term data: Daily evaporation (in)	From synthetic long-term record of peaks — Frequency based on log-Pearson Type III distribution: Q_2 (cfs)	Q_5 (cfs)	Q_{10} (cfs)	Q_{25} (cfs)	Q_{50} (cfs)	Q_{100} (cfs)
06238760	W.F. Dry Cheyenne Cr.	0.69	35.4	0.58	0.65	1.18	51	98	139	202	259	323
06313180	Dugout Cr. trib.	.71	33.5	.85	.77	1.05	277	473	617	813	968	1,127
06648720	Frank Draw trib.	.79	39.4	.82	.88	1.05	38	104	178	319	468	664
06266320	Gillies Draw trib.	1.30	34.8	.59	.73	.84	125	264	395	613	818	1,065
06312920	Dead Horse Cr. trib. #2	1.34	36.0	.85	.77	1.05	227	411	565	798	1,000	1,227
06648780	Sage Cr. trib.	1.38	23.7	.82	.88	1.05	49	117	186	307	424	568
06274190	Nowood R. trib. #2	1.51	34.5	.41	.62	.84	105	205	286	404	501	606
06312910	Dead Horse Cr. trib.	1.53	50.4	.85	.77	1.05	223	386	524	733	917	1,127
06238780	W.F. Dry Cheyenne Cr. trib.	1.85	33.0	.58	.65	1.18	68	145	219	345	466	615
06634950	Willow Springs Dr. trib.	1.98	38.8	.81	.73	1.18	96	225	335	495	625	762
06644840	McKenzie Draw trib.	2.02	57.9	.85	.77	1.05	84	218	366	650	952	1,351
06267270	N.P.E.F. Nowater Cr. trib.	2.11	23.7	.52	.65	.84	166	351	518	785	1,025	1,303
06266460	Murphy Draw	2.32	43.5	.59	.73	.84	189	355	500	725	926	1,158
06634910	Medicine Bow R. trib.	3.01	44.6	.81	.73	1.18	180	367	549	865	1,175	1,564
06316480	Headgate Draw	3.32	21.7	.66	.85	1.05	289	773	1,310	2,329	3,397	4,792
06267260	N.P.E.F. Nowater Cr.	3.77	37.0	.52	.65	.84	309	650	950	1,415	1,823	2,284
06382200	Pritchard Draw	5.12	46.9	.84	1.00	1.05	610	1,164	1,659	2,451	3,177	4,031
06313050	East Teapot Cr.	5.44	33.9	.85	.77	1.05	418	997	1,583	2,606	3,607	4,843
06256670	Badwater Cr. trib.	5.86	29.7	.47	.65	1.18	198	430	644	992	1,310	1,683
06233360	Monument Draw	8.23	48.8	.90	.81	1.18	232	502	736	1,092	1,399	1,738
09221680	Mud Spring Hollow	8.83	35.5	.49	.58	1.25	151	352	569	982	1,421	2,008
06631150	Third Sand Cr.	10.8	30.1	.69	.62	1.18	492	1,006	1,514	2,404	3,291	4,411

Transfer of Long-Term Rainfall Data

The accuracy of the rainfall-runoff model in synthesizing a flood record is dependent on how well the model parameters (determined through calibration) represent the physical conditions of each drainage basin. That is, runoff-producing effect of the long-term rainfall data, when the data are transferred to the remote basins, are controlled by the values of the basin parameters. Furthermore, the accuracy of results is also dependent upon the accuracy of transferring long-term rainfall data, made difficult by a lack of National Weather Service stations with long records in locations near the study sites.

Because Wyoming has numerous mountain ranges and large plains areas, it cannot be expected that identical rainfall patterns will occur at all sites in the State. Also, the long-term National Weather Service station for rainfall data, located in Cheyenne in the southeast corner of the State, cannot be considered as ideally situated to represent the entire State. However, the Cheyenne station does have the longest available record (73 years), and it can be related to the other Weather Service stations in the State.

The daily amounts of precipitation used in calibrating the model to each small drainage basin were recorded at 13 sites, listed in table 7, which are in the vicinity of the basins. Daily precipitation was used in the model to determine antecedent conditions for runoff and, in Wyoming, runoff was found to be quite sensitive to antecedent conditions. Mean annual precipitation for the 13 weather stations ranges from 6 to 14 inches while Cheyenne has a mean annual precipitation of 15 inches. To use Cheyenne as a long-term station, an adjustment to the daily amounts of precipitation was needed to better reflect conditions on the small drainage basins in the study. The adjustment used at each of the 13 stations was the ratio of the mean annual precipitation to that of Cheyenne. These ratios, from 41 percent to 90 percent, when applied to the long-term daily data provided more realistic antecedent conditions for generating long-term runoff on the study basins.

Data for this project were collected on a seasonal basis (April through September 30). Data from 73 weather stations in Wyoming were compared using a ratio of mean seasonal precipitation to the Cheyenne mean seasonal and a ratio of mean annual precipitation to the Cheyenne mean annual. A relationship among 55 stations, representing the areas where the study basins are located, indicated no significant difference between seasonal and annual ratios. The remaining 18 stations are in mountainous areas or are outside the area of investigation. Figure 6 shows the location of the 73 weather stations.

Table 7.--Ratios used for transferring long-term rainfall data from National Weather Service stations to the study basins.

Station	Elevation (ft)	Precipitation: Mean annual (in)	Mean annual Ratio to Cheyenne	50-year, 6-hour (in)	50-year, 6-hour Ratio to Cheyenne
Cheyenne	6,126	15.06	1.00	2.6	1.00
Basin	3,837	6.21	.41	1.6	.62
Church Butte	7,075	7.35	.49	1.5	.58
Echeta	4,000	[a] 10.0	.66	2.2	.85
Glenrock	4,948	12.34	.82	2.3	.88
Grass Creek	5,579	8.83	.59	1.9	.73
Lance Creek	4,412	12.61	.84	2.6	1.00
Lander	5,563	13.58	.90	2.1	.81
Lost Cabin	5,415	[a] 7.0	.47	1.7	.65
Medicine Bow	6,560	10.44	.69	1.6	.62
Midwest	4,850	12.85	.85	2.0	.77
Riverton	4,954	8.81	.58	1.7	.65
Seminoe Dam	6,838	12.18	.81	1.9	.73
Worland	4,061	7.76	.52	1.7	.65

[a] From map of mean annual precipitation in Wyoming as of 1965 (NWS, Cheyenne, Wyo., written commun., 1966).

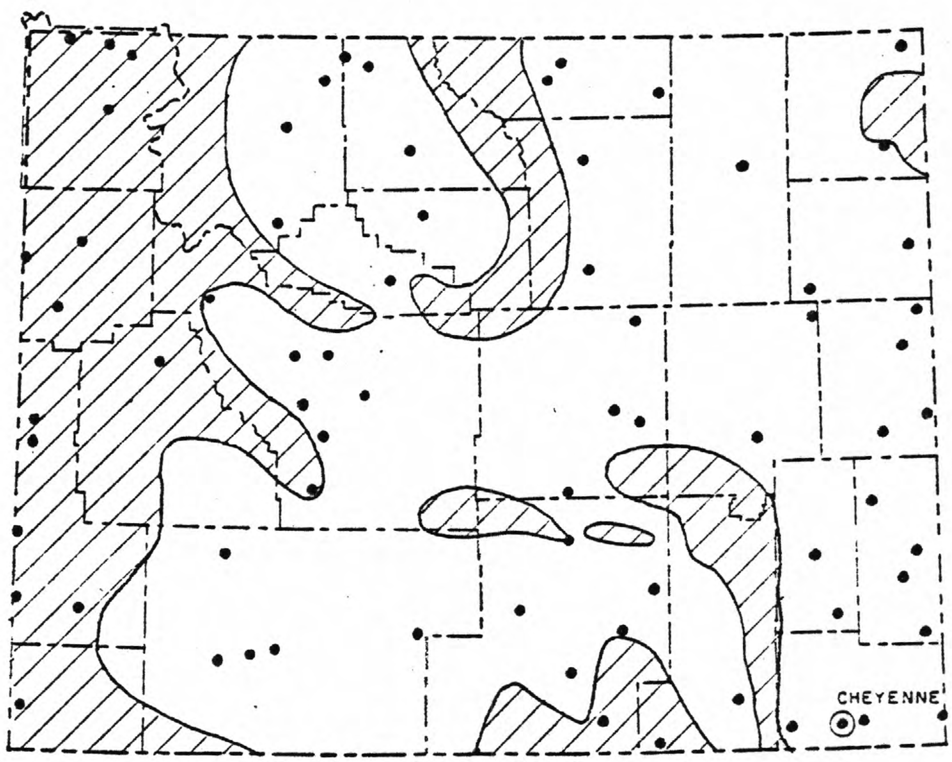


Figure 6.--Locations of National Weather Service stations in Wyoming used in the comparison of seasonal precipitation to annual precipitation. Crosshatched areas are mountainous or outside the area of investigation.

The largest storm generally will produce the greatest runoff. However, the two factors, high total rainfall and high intensity, do not always occur together; when they do, that combination will produce the greatest runoff. A study of runoff volumes showed that storms with the largest total rainfall can produce the greatest volumes, while lesser storms with high rainfall intensities can produce the highest peaks. It was previously determined that Cheyenne has a higher mean annual precipitation than the stations used in the calibration. The records also show that Cheyenne has larger storms and (or) higher intensity storms. From the long-term record for Cheyenne, the largest storms for each year were selected as potentially capable of producing the annual peak runoff. When a single storm would unquestionably produce the annual maximum rainfall, only that one storm was used. Generally, two or three storms were chosen. The same rainfall data are used in the rainfall-runoff model to generate either long-term annual peaks or long-term annual runoff volumes. When two or more storms in the same year are used, it is not unusual for one storm to produce the annual peak while a different storm produces the annual volume.

In order to transfer rainfall recorded at Cheyenne to each remote drainage basin for generating runoff, an adjustment was considered necessary. Rather than use the ratios of the mean annual precipitation, as was done for daily values of rainfall totals, an adjustment was needed that would have a lesser effect on rainfall intensity. From the 73-year precipitation record for Cheyenne, 133 storms were used to generate runoff. The average duration per storm was 4.7 hours. An analysis was made of depth-duration frequency maps of Wyoming (National Oceanic and Atmospheric Admin., 1974) for 6-hour and 24-hour durations and 2-, 5-, 10-, 25-, and 100-year recurrence intervals. By interpolation, the 50-year, 6-hour frequency duration was selected as most applicable. The ratio of the 50-year, 6-hour occurrence at each weather station to that at the Cheyenne weather station provided the adjustment factor. Values for the 50-year, 6-hour frequency duration at each station and for the ratio to Cheyenne are listed in table 7. For 9 of the 13 stations, this ratio was higher than the ratio of the mean annual precipitation and, when applied, would have a lesser effect on the intensities than would the ratio of the mean annual precipitation. Intensities for the remaining four stations would be reduced by using this ratio, but these are stations with comparatively high ratios of mean annual precipitation, so the reductions are not great.

Transfer of Long-Term Evaporation Data

Only seven weather stations in Wyoming have evaporation data for 20 years or more and only 12 stations have any evaporation data. The longest evaporation record available (60 years through 1973) is for Archer, located about 9 miles east of the Cheyenne weather station. The proximity of this station to Cheyenne and the length of record made it ideal for use in the long-term runoff simulation phase of the rainfall-runoff model. However, because the same period and length of record are needed for precipitation and evaporation, the evaporation record for Archer had to be extended backward from 1913 to 1901. This extension was made by developing a correlation between 6-month periods of evaporation and 6-month periods of precipitation, for 15 years of selected record as shown in figure 7. Certain years were selected to increase the range of the comparison. Two years of excessive precipitation with high evaporation were considered nonrepresentative and were not used. The equation determined from a correlation of 13 years of record was

$$y = 49.40 - 1.217\,x$$

where: x = seasonal precipitation

y = seasonal evaporation

with a correlation coefficient of 0.93 and a standard error of 13 percent.

The same 13 years were used to compute the average evaporation for each day. The daily values were adjusted by a ratio of the computed evaporation from the equation and the mean evaporation for the 13 years. This procedure resulted in reduced evaporation values for seasons of above-normal precipitation and increased evaporation values for seasons of below-normal precipitation.

The evaporation data for Archer were not used in the initial calibration of the study basins. Instead, four stations closer to the basins were used (table 8).

Evaporation data are collected only during warm weather, or seasonally, which fits the seasonal aspect of this study. Because temperature and wind have great effect on evaporation, there is considerable variation in evaporation in Wyoming. The long-term evaporation record for Archer was adjusted using a ratio of mean evaporation at the calibration station to mean evaporation at Archer. This ratio is listed in table 8.

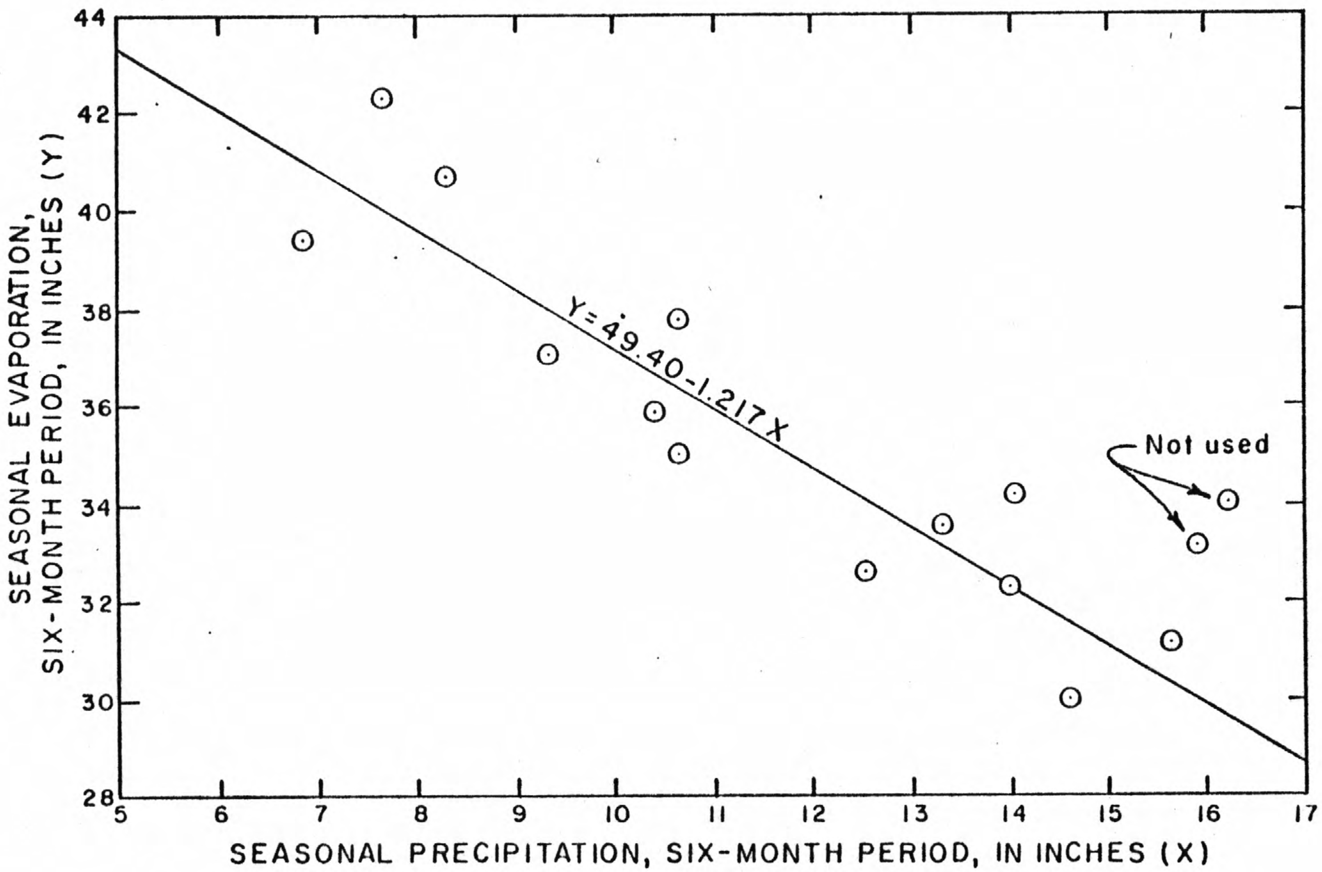


Figure 7.--Relationship of seasonal evaporation to seasonal precipitation for 15 years of selected record. The 2 years showing excess precipitation and high evaporation were not considered in the correlation.

Table 8.--National Weather Service stations with evaporation data used in this study.

Station	Years of record	Elevation (ft)	Mean seasonal evaporation (in)	Ratio to Archer	Area covered
Archer	60	6,010	41.54	1.00	
Gillette 2E	11	4,556	43.75	1.05	Eastern Wyoming
Green River	15	6,089	52.09	1.25	Green River Basin
Heart Mountain	22	4,790	34.71	.84	Bighorn Basin
Pathfinder	31	5,930	49.10	1.18	Central Wyoming

REGIONAL FREQUENCY ANALYSIS

Regional analysis deals with extending records in space, as opposed to extending them in time. Regional analysis provides a method for transferring information obtained at gaged sites to an ungaged site, where information is needed. According to Riggs (1973), "multiple regression is directly useful as a regionalization tool because the discharge (or volume) can be related to basin characteristics, leaving residuals that may be considered as due to chance. The regression line averages these residuals. Thus, in one operation, the effects of differing basin characteristics are preserved and the chance variation is averaged."

Basin Characteristics

Basin characteristics, used as independent parameters in the regression analyses, are summarized in table 9 and are defined below. Areas were planimetered from the best available topographic maps. Measurements of length along channel, basin perimeter, or contour lines were obtained by stepping with draftsman's dividers set at a scale interval of 200 feet.

A - Drainage area, in square miles.

R_m - Maximum relief in basin, in feet; the difference in elevation between the channel at the gage and the highest point in the basin, determined from topographic maps.

S_B - Basin slope, in feet per mile, obtained by measuring the lengths (in miles) of all contour lines within the drainage boundary, multiplying by the contour interval in feet, and dividing by the drainage area in square miles. Reasonable accuracy can be obtained on most topographic maps by measuring only the 100-foot contour lines.

$S_{10/85}$ - Main-channel slope, in feet per mile, determined from elevations at points 10 and 85 percent of the distance along the channel from the gaging station to drainage-basin divide.

L_m - Main channel length, in miles, from the gaging station to the drainage-basin divide.

C_r - Circularity ratio, dimensionless; the ratio of basin area to the area of a circle having the same perimeter as the basin.

P_m - Basin perimeter, in miles; the length of the drainage area boundary.

L_{ca} - A measured length in miles along the main-stem channel from the gaging station to the point opposite the centroid of the total drainage area (Chow, 1969).

F_m - Maximum fall in channel, in feet; the total difference in elevation between the channel bottom at the gage and the point where the extended main channel reaches the drainage boundary.

Table 9.--Characteristics[1] of 22 basins

Drainage area (A) in square miles (mi^2); maximum relief (R_m) in feet (ft); basin slope (S_B) in feet per feet (ft/ft); main-channel slope ($S_{10/85}$) in feet per feet (ft/ft); circularity ratio (C_r) dimensionless; maximum channel length (L_m) in miles (mi); basin perimeter (P_m) in miles (mi); length to centroid along channel (L_{ca}) in miles (mi); maximum fall in channel (F_m) in feet (ft).

Station no.	Station name	A (mi^2)	R_m (ft)	S_B (ft/mi)	$S_{10/85}$ (ft/mi)	C_r	L_m (mi)	P_m (mi)	L_{ca} (mi)	F_m (ft)
06233360	Monument Draw near Hudson	8.23	594	719	59.1	0.4458	7.97	15.23	3.79	519
06238760	W.F. Dry Cheyenne Creek near Riverton	.69	173	240	76.6	.3898	1.93	4.71	.88	173
06238780	W.F. Dry Cheyenne Creek trib. near Riverton	1.85	316	356	88.2	.6424	2.39	6.01	1.27	258
06256670	Badwater Creek trib. near Lysite	5.86	627	483	85.5	.5570	4.85	11.49	1.82	627
06266320	Gillies Draw trib. near Grass Creek	1.30	375	720	204	.5727	1.35	5.34	.68	325
06266460	Murphy Draw near Grass Creek	2.32	483	431	106	.4764	3.20	7.82	1.35	423
06267260	N.P.E.F. Nowater Cr. near Worland	3.77	320	771	71.3	.6315	3.05	8.66	.97	310
06267270	N.P.E.F. Nowater Cr. trib. near Worland	2.11	338	634	79.7	.5262	3.54	7.10	1.59	322
06274190	Nowood River trib. #2 near Basin	1.51	405	437	140	.4734	2.73	6.33	1.25	405
06312910	Dead Horse Cr. trib. near Midwest	1.53	287	847	62.3	.4409	3.28	6.60	1.84	287
06312920	Dead Horse Cr. trib. #2 near Midwest	1.34	320	922	73.9	.5877	2.25	5.35	1.02	233
06313050	East Teapot Creek near Edgerton	5.44	430	612	92.9	.6492	2.69	10.26	1.24	380
06313180	Dugout Creek trib. near Midwest	.71	201	831	97.2	.5868	1.40	3.90	.61	171
06316480	Headgate Draw near Buffalo	3.32	550	929	102	.5363	3.55	8.82	1.71	390
06382200	Pritchard Draw near Lance Creek	5.12	436	[2] 618	[3] 92.4	.7996	3.67	9.30	2.53	436
06631150	Third Sand Cr. near Medicine Bow	10.8	680	609	75.5	.4463	6.27	17.43	3.25	575
06634910	Medicine Bow R. trib. near Hanna	3.01	504	550	132	.4959	3.79	8.73	1.92	483

[1] From latest topographic maps available.
[2] Estimated, using correlation with Army Map Service (scale: 1:250,000) maps.
[3] From aerial photographs.

Table 9.--Characteristics[1] of 22 basins--continued

Station no.	Station name	A (mi²)	R_m (ft)	S_B (ft/mi)	$S_{10/85}$ (ft/mi)	C_r	L_m (mi)	P_m (mi)	L_{ca} (mi)	F_m (ft)
06634950	Willow Springs Draw trib. near Hanna	1.98	543	719	161	0.4286	2.39	7.62	1.34	430
06644840	McKenzie Draw trib. near Casper	2.02	346	498	100	.7454	2.19	5.83	1.02	346
06648720	Frank Draw trib. near Orpha	.79	337	414	121	.5130	2.01	4.40	.90	337
06648780	Sage Creek trib. near Orpha	1.38	318	355	94.0	.4194	2.92	6.43	1.50	308
09921680	Mud Spring Hollow near Church Butte near Lyman	8.83	752	608	66.5	.3749	8.11	17.20	5.12	607

[1] From latest topographic maps available.

The basin characteristics defined above were used in regression analyses to develop relations for estimating peak discharge or runoff volume.

Regression Analysis

The purpose of regionalization is to define relationships that can be used to estimate runoff at ungaged sites. In this study a rainfall-runoff model was used to produce a synthetic long-term runoff record from an actual long-term rainfall record. The synthesized peaks and volumes were used in the development of station frequency curves. From these curves, specific frequencies were selected for regression analysis of basin characteristics in a regional study. Because only one long-term rainfall record (Cheyenne) was used, the results of this regional analysis appear better than they might otherwise be. Cheyenne was selected as the base rain gage because it had the longest record and because it had the open exposure (less influenced by nearby orographic effects) to provide a better analogy to the study basins. The adjustments described in the preceding section in transferring the rainfall data to other weather stations in Wyoming were primarily to reduce the amounts and intensity of Cheyenne rainfall data. The transferred data at some weather stations were used to develop long-term runoff records at two or more gaged sites, resulting in interdependency of synthesized flood occurrences among these sites. Because of this interstation correlation, discussed by Matalas and Benson (1961), the slope of a regional relation is better defined than that of a relation obtained from a purely random sample, but its position (intercept) is less well defined.

The regression model used in regional frequency analysis is of the form,

$$Q_n \text{ or } V_n = aA^{b1}B^{b2}C^{b3}............,$$

the log transform of which is linear. Peak discharges and runoff volumes with recurrence intervals of 2, 5, 10, 25, 50, and 100 years for 22 small basins were selected for analysis. Independent variables were chosen on the basis of logical physical relationship to streamflow for small drainage basins and tested for significance using a "step-forward" regression program. The basin characteristics were used in regression analyses to develop relations for estimating peak discharges or runoff volumes. (See the section on Basin Characteristics.) The basin characteristics determined to be most significant in estimating peak discharge were drainage area, basin slope, maximum basin relief, and main-channel slope. The correlation coefficients ranged from 0.89 to 0.92 and the standard errors of estimate from 32 to 38 percent.

Estimates of peak discharge are mainly dependent on drainage area and basin slope, with correlation coefficients of 0.81 to 0.88 and standard errors of 37 to 48 percent, respectively. The addition of maximum basin relief and channel slope, in that order, improved the correlation and reduced the standard error by small amounts of from 1 to 6 percent. The designer would have to decide whether the increase in correlation and reduction in standard error warranted the inclusion of the variables in the equation.

Drainage area, maximum basin relief, and basin slope proved to be the most significant parameters for estimating runoff volume. The correlation coefficients ranged from 0.92 to 0.93 and the standard errors of esti-ate from 30 to 32 percent.

In an analysis of residuals the residual variations indicated an areal randomness and were probably due to chance variation or some untested basin characteristics. Geographical subregions were not apparent in this study.

Table 10 lists the regression constants, correlation coefficients, and standard errors of estimate for the specified recurrence intervals of peak discharges and runoff volumes.

The results of the step-forward regression for the significant basin characteristics are listed in tables 11 and 12. Surprisingly, maximum basin relief was the second most significant parameter (drainage area being the first) for estimating runoff volume. It was significant enough to increase correlation coefficients by amounts ranging from 12 percent for the 2-year volume to 5 percent for the 100-year volume, with similar reduction in the standard errors of estimate. Basin slope also had a significant effect in the volume estimations, with the correlation coefficient increasing by amounts ranging from 9 percent for the 2-year volume to 3 percent for the 100-year volume. The standard error of estimate for basin slopes decreased by 6 to 7 percent.

The coefficients b_1, b_2, and b_3 used in the equations for estimating runoff volumes, were all found to be significant at the 1-percent level of significance. For the equations for estimating peak discharges, only the coefficients b_1 and b_2 are significant at the 1-percent level. The coefficients b_3 and b_4 show a deterioration in the level of significance; b_3 ranges from the 1-percent level in estimating Q_2 to the 10-percent level in estimating Q_{100}, and b_4 ranges from the 10-percent level in estimating Q_5-Q_{50} to the 20-percent level in estimating Q_2 and Q_{100}.

Table 10.--Mathematical model and applicable coefficients for use in determining a design discharge or volume.

Mathematical model

$$Q_n \text{ or } V_n = a\, A^{b_1}\, S_B^{\,b_2}\, R_m^{\,b_3}\, S_{10/85}^{\,b_4}$$

Flow characteristic	Regression constant (a)	b_1	b_2	b_3	b_4	Correlation coefficient	Average standard error of estimate (percent)
Q_2	34.06	1.134	1.216	-1.609	0.539	0.88	40
Q_5	30.77	1.105	1.135	-1.412	.588	.91	33
Q_{10}	32.99	1.094	1.080	-1.308	.603	.92	32
Q_{25}	37.73	1.086	1.012	-1.192	.613	.92	33
Q_{50}	43.88	1.084	.962	-1.118	.616	.91	34
Q_{100}	50.25	1.082	.914	-1.047	.615	.90	37
V_2	568	1.242	.898	-1.716	----	.91	37
V_5	529	1.190	.806	-1.490	----	.93	31
V_{10}	552	1.168	.750	-1.380	----	.93	30
V_{25}	584	1.142	.687	-1.260	----	.93	30
V_{50}	630	1.128	.641	-1.186	----	.92	31
V_{100}	666	1.115	.601	-1.119	----	.92	32

NOTE: Use of metric equivalents for basin characteristics would not provide correct answers.

Table 11.--Results of flood-volume regression analysis

Drainage area (A) in square miles (mi^2); basin slope (S_B) in feet per mile (ft/mi); maximum relief (R_m) in feet (ft); constant of regression (a); drainage-area coefficient (b_1); maximum-relief coefficient (b_2); basin-slope coefficient (b_3); standard error of estimate (SE).

Levels of significance: 0.1 percent ****
1.0 percent ***
2.0 percent **
5.0 percent *

Flow characteristics	Basin characteristics			Coefficients				Correlation coefficient	Average SE (percent)
	A (m^2)	S_B (ft/mi)	R_m (ft)	a	b_1	b_2	b_3		
V_2	x	---	---	9.62	0.689 ****	------	-----	0.70	61
V_2	x	x	---	52.53×10^{-3}	.593 ****	0.834 *	-----	.79	54
V_2	x	---	x	94.97×10^{3}	1.312 ****	------	-1.630 ***	.82	49
V_2	x	x	x	5.68×10^{2}	1.242 ****	.898 ***	-1.716 ****	.91	37
V_5	x	---	---	18.08	.713 ****	------	------	.76	52
V_5	x	x	---	16.64×10^{-2}	.627 ****	.705 **	------	.83	46
V_5	x	---	x	52.30×10^{3}	1.253 ****	------	-1.412 ***	.86	42
V_5	x	x	x	5.29×10^{2}	1.190 ****	.806 ****	-1.490 ****	.93	31
V_{10}	x	---	---	24.87	.727 ****	------	------	.79	49
V_{10}	x	x	---	31.54×10^{-2}	.646 ****	.699 **	------	.85	43
V_{10}	x	---	x	39.84×10^{3}	1.226 ****	------	-1.307 ***	.87	40
V_{10}	x	x	x	5.52×10^{2}	1.168 ****	.750 ***	-1.380 ****	.93	30

Table 11.--Results of flood-volume regression analysis--continued

Flow characteristics	Basin characteristics			Coefficients				Correlation coefficient	Average SE (percent)
	A (mi^2)	S_B (ft/mi)	R_m (ft)	a	b_1	b_2	b_3		
V_{25}	x	---	---	34.71	.739****	------	------	0.81	46
V_{25}	x	x	---	63.69 x 10^{-2}	.666****	.640*	------	.86	41
V_{25}	x	---	x	29.30 x 10^3	1.195****	------	-1.194***	.88	39
V_{25}	x	x	x	5.84 x 10^2	1.142****	.687***	-1.260****	.93	30
V_{50}	x	---	---	42.82	0.748****	------	------	.82	45
V_{50}	x	x	---	1.03	.680****	0.597*	------	.86	40
V_{50}	x	___	x	24.40 x 10^3	1.178****	------	-1.124***	.88	38
V_{50}	x	x	x	6.30 x 10^2	1.128****	.641***	-1.186***	.92	31
V_{100}	x	---	---	51.58	0.756****	------	------	.83	44
V_{100}	x	x	---	1.56	.692****	.560*	------	.86	40
V_{100}	x	---	x	20.53 x 10^3	1.162****	------	-1.061**	.88	38
V_{100}	x	x	x	6.66 x 10^2	1.115****	.601***	-1.119***	.92	32

NOTE: Use of metric equivalents for basin characteristics would not provide correct answers.

Table 12.--Results of flood-peak regression analysis

Drainage area (A) in square miles (mi^2); basin slope (S_B) in feet per mile (ft/mi); maximum relief (R_m) in feet (ft); main-channel slope ($S_{10/85}$) in feet per mile (ft/mi); constant of regression (a); drainage-area coefficient (b_1); basin-slope coefficient (b_2); maximum-relief coefficient (b_3); channel-slope coefficient (b_4); standard error of estimate (SE).

Level of significance: 0.1 percent ****, 1.0 percent ***, 2.0 percent **, 5.0 percent *, 10 percent +, 20 percent ++, >20 percent °

Flow characteristics	Basin characteristics				Coefficients					Correlation coefficient	Average SE (percent)
	A (mi^2)	S_B (ft/mi)	R_m (ft)	$S_{10/85}$ (ft/mi)	a	b_1	b_2	b_3	b_4		
Q_2	x	---	---	---	96.21	0.582***	-----	------	------	0.62	64
Q_2	x	x	---	---	65.90×10^{-3}	.448***	1.166***	------	------	.81	48
Q_2	x	---	x	---	27.39×10^{3}	.965***	-----	-1.001°	------	.68	61
Q_2	x	---	---	x	2.39×10^{2}	.554***	-----	------	-0.195°	.63	66
Q_2	x	x	x	---	27.98	.870****	1.208****	-1.118*	------	.87	41
Q_2	x	x	---	x	18.23×10^{-2}	.416***	1.170***	------	- .223°	.82	49
Q_2	x	---	x	x	34.31×10^{3}	1.207***	-----	-1.450+	.493°	.70	62
Q_2	x	x	x	x	34.06	1.134****	1.216****	-1.609***	.539++	.88	40

Table 12.--Results of flood-peak regression analysis--continued

Flow characteristics	Basin characteristics A (m^2)	S_B (ft/mi)	R_m (ft)	$S_{10/85}$ (ft/mi)	Coefficients a	b_1	b_2	b_3	b_4	Correlation coefficient	Average SE (percent)
Q_5	x	---	---	---	199.6	.612****	-----	------	------	0.69	56
Q_5	x	x	---	---	21.54 x 10^{-2}	.486****	1.093****	------	------	.86	40
Q_5	x	---	x	---	15.25 x 10^3	.905***	-----	- .768°	------	.72	54
Q_5	x	---	---	x	2.58 x 10^2	.604***	-----	------	- .055°	.69	57
Q_5	x	x	x	---	24.82	.817****	1.126****	- .877*	------	.90	35
Q_5	x	x	---	x	31.22 x 10^{-2}	.474****	1.095****	------	- .081°	.86	41
Q_5	x	---	x	x	19.55 x 10^3	1.172***	-----	-1.263+	.544°	.74	54
Q_5	x	x	x	x	30.77	1.105****	1.135****	-1.412***	.588+	.91	33
Q_{10}	x	---	---	---	292.8	.632****	-----	------	------	.72	53
Q_{10}	x	x	---	---	43.62 x 10^{-2}	.512****	1.042****	------	------	.87	37
Q_{10}	x	---	x	---	11.81 x 10^3	.883***	-----	- .655°	------	.74	52
Q_{10}	x	---	---	x	2.81 x 10^2	.634****	-----	------	.008°	.72	54
Q_{10}	x	x	x	---	26.47	.799****	1.070****	- .759*	------	.90	34
Q_{10}	x	x	---	x	47.06 x 10^{-2}	.510****	1.042****	------	- .017°	.87	38
Q_{10}	x	---	x	x	15.27 x 10^3	1.158***	-----	-1.166°	.561°	.76	52
Q_{10}	x	x	x	x	32.99	1.094****	1.080****	-1.308***	.603+	.92	32

Table 12.--Results of flood-peak regression analysis--continued

Flow characteristics	Basin characteristics: A (mi^2)	S_B (ft/mi)	R_m (ft)	$S_{10/85}$ (ft/mi)	Coefficients: a	b_1	b_2	b_3	b_4	Correlation coefficient	Average SE (percent)
Q_{25}	x	---	---	---	441.1	0.660****	-----	------	------	0.75	50
Q_{25}	x	---	---	---	97.81×10^{-2}	.547****	0.978****	------	------	.88	37
Q_{25}	x	---	x	---	85.11×10^{2}	.865***	-----	-0.537°	------	.76	50
Q_{25}	x	---	---	x	3.15×10^{2}	.670****	-----	------	0.072°	.75	52
Q_{25}	x	x	x	---	30.16	.786****	1.002****	- .634†	------	.90	35
Q_{25}	x	x	---	x	78.40×10^{-2}	.554****	.977****	------	.048°	.88	38
Q_{25}	x	---	x	x	11.86×10^{3}	1.146****	-----	-1.059°	.574°	.78	50
Q_{25}	x	x	x	x	37.73	1.086****	1.012****	-1.192**	.613†	.92	33
Q_{50}	x	---	---	---	575.4	0.679****	-----	------	------	.76	50
Q_{50}	x	x	---	---	171.3×10^{-2}	.572****	.931***	------	------	.87	38
Q_{50}	x	---	x	---	79.71×10^{2}	.857***	-----	- .466°	------	.77	50
Q_{50}	x	---	---	x	3.47×10^{2}	.695****	-----	------	.108°	.76	52
Q_{50}	x	x	x	---	35.04	.783****	.952****	- .558††	------	.89	37
Q_{50}	x	x	---	x	115.8×10^{-2}	.585****	.930***	------	.086°	.87	39
Q_{50}	x	---	x	x	10.38×10^{3}	1.141***	-----	- .992°	.579°	.79	50
Q_{50}	x	x	x	x	43.88	1.084****	.962****	-1.118*	.616†	.91	34

Table 12.--Results of flood-peak regression analysis--continued

Flow characteristics	Basin characteristics				Coefficients					Correlation coefficient	Average SE (percent)
	A (mi^2)	S_B (ft/mi)	R_m (ft)	$S_{10/85}$ (ft/mi)	a	b_1	b_2	b_3	b_4		
Q_{100}	x	---	---	---	731.1	0.699****	-----	------	------	0.77	50
Q_{100}	x	x	---	---	288.6×10^{-2}	.597****	0.886***	------	------	.87	40
Q_{100}	x	---	x	---	69.50×10^{2}	.852***	-----	- .399°	------	.77	51
Q_{100}	x	---	---	x	3.78×10^{2}	.720****	-----	------	0.141°	.77	52
Q_{100}	x	x	x	---	40.12	.781****	.904***	- .486°	------	.88	39
Q_{100}	x	x	---	x	167.2×10^{-2}	.615****	.884***	------	.120°	.87	41
Q_{100}	x	---	x	x	90.61×10^{2}	1.136***	-----	- .927°	.580°	.79	50
Q_{100}	x	x	x	x	50.25	1.082****	.914***	-1.047†	.615††	.90	37

NOTE: Use of metric equivalents for basin characteristics would not provide correct answers.

Among independent variables there is a fairly high correlation between drainage area and maximum basin relief. The other variables indicate little cross correlation. The correlation matrix is shown below.

	A	S_B	R_m	$S_{10/85}$
A	1.00	-----	-----	-----
S_B	.27	1.00	-----	-----
R_m	.83	.25	1.00	-----
$S_{10/85}$	- .37	- .08	.03	1.00

Graphical representation of the equations for each specified peak discharge are shown in figures 8 to 13 and for each specified runoff volume in figures 14 to 19. An example is shown on each graph to indicate the proper direction for each step. Each graph represents a specific equation relating the basin characteristics. The example is for Badwater Creek tributary near Lysite, Wyo., for which the following parameters have been determined:

$A = 5.86\ mi^2$

$S_B = 483\ ft/mi$

$R_m = 627\ ft$

$S_{10/85} = 85.5\ ft/mi$

Enter the graphs with drainage area (5.86 mi^2) on the bottom scale and move vertically upward to basin slope (483 ft/mi). Move horizontally to maximum relief (627 ft). On the flood-peak graphs move downward to channel slope (85.5 ft/mi). Move horizontally to the right edge of graph for the resultant discharge. On the flood-volume graphs move downward to the bottom edge of graph for the resultant volume. The following results were obtained for this example:

1. $Q_2 = 160\ ft^3/s$
2. $Q_5 = 370\ ft^3/s$
3. $Q_{10} = 580\ ft^3/s$
4. $Q_{25} = 950\ ft^3/s$
5. $Q_{50} = 1{,}320\ ft^3/s$
6. $Q_{100} = 1{,}760\ ft^3/s$
7. $V_2 = 21$ acre-ft
8. $V_5 = 43$ acre-ft
9. $V_{10} = 62$ acre-ft
10. $V_{25} = 92$ acre-ft
11. $V_{50} = 117$ acre-ft
12. $V_{100} = 145$ acre-ft

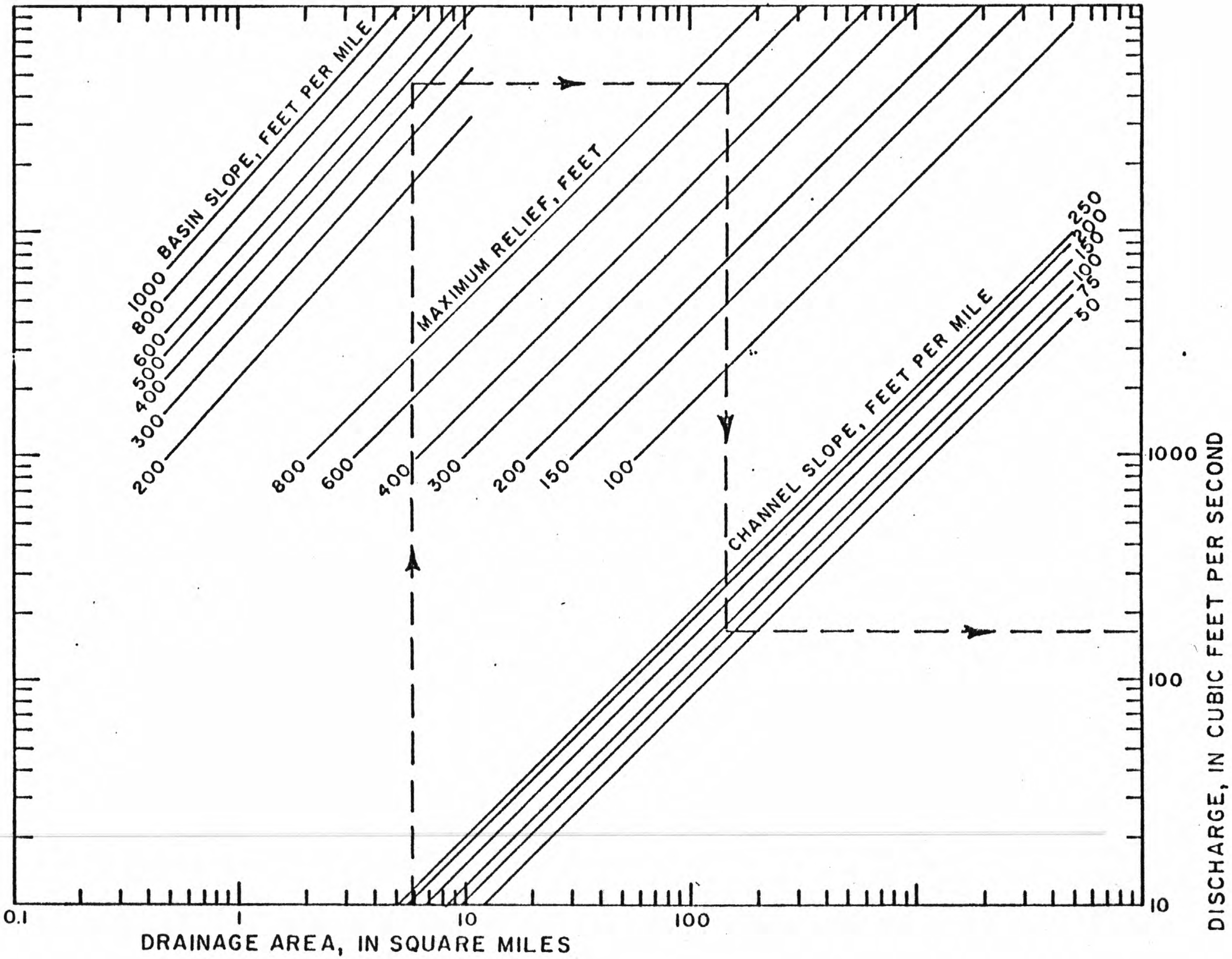


Figure 8.--Relation of 2-year flood peak to drainage area, basin slope, maximum relief, and

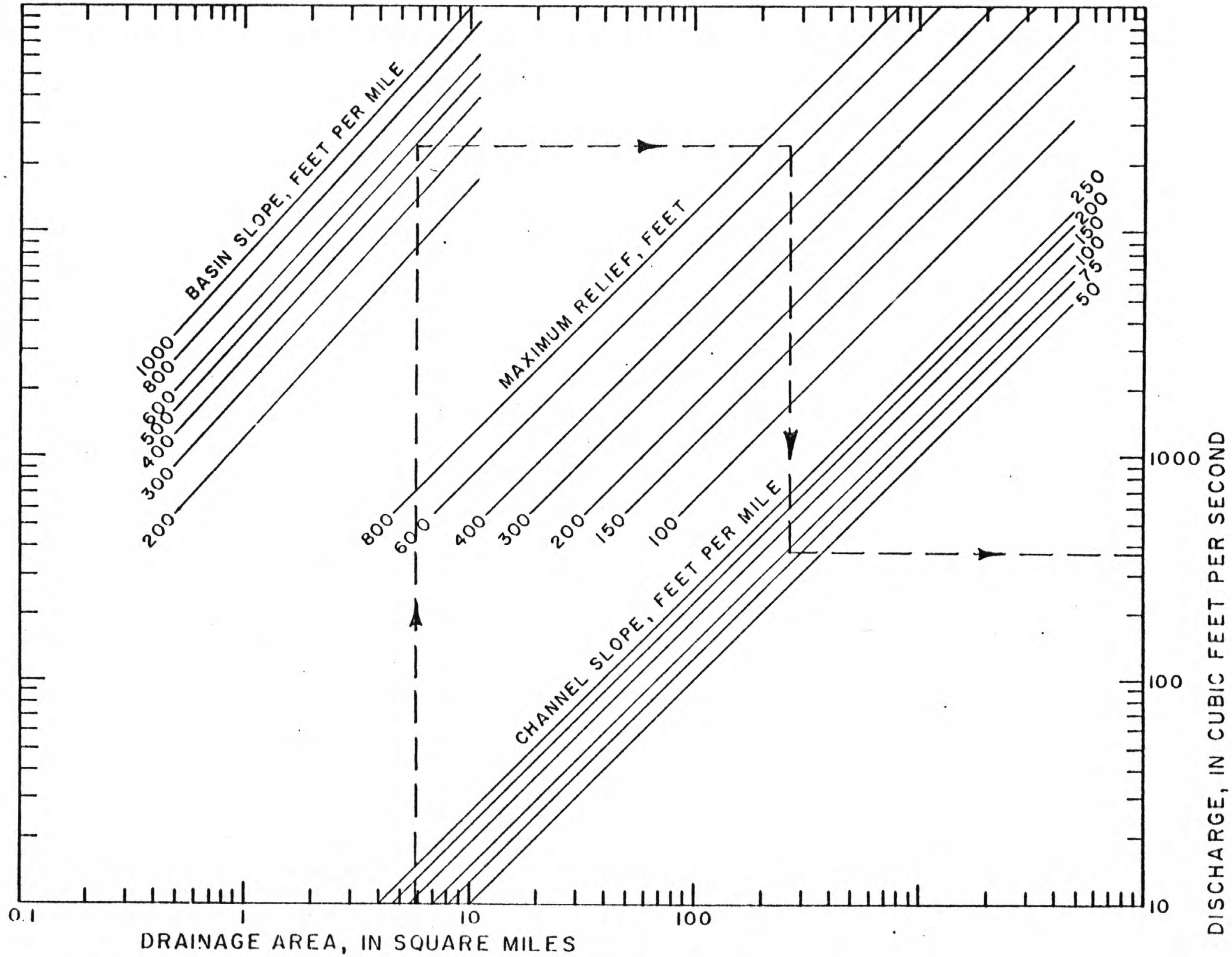


Figure 9.--Relation of 5-year flood peak to drainage area, basin slope, maximum relief, and channel slope.

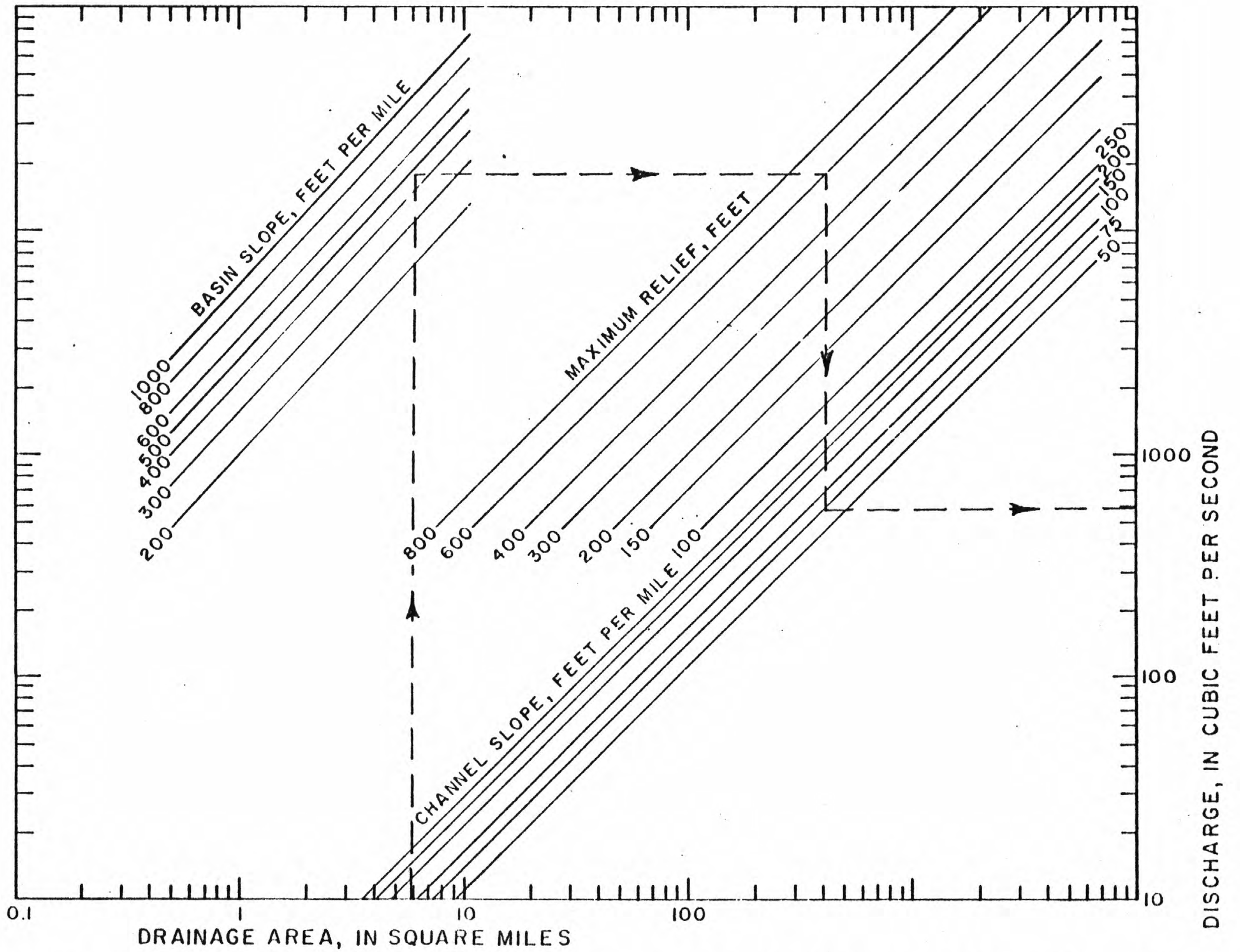


Figure 10.--Relation of 10-year flood peak to drainage area, basin slope, maximum relief, and channel slope.

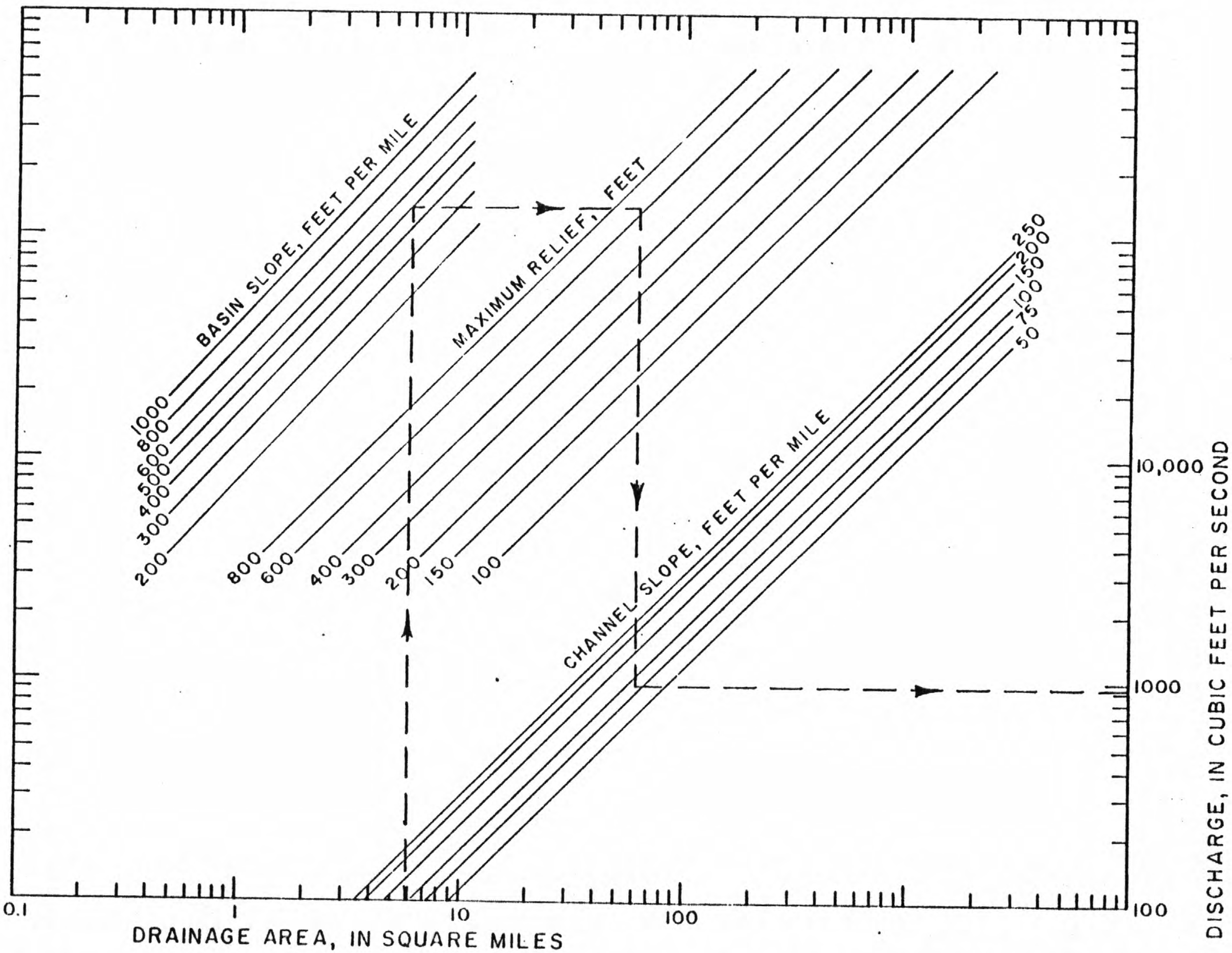


Figure 11.--Relation of 25-year flood peak to drainage area, basin slope, maximum relief, and channel slope.

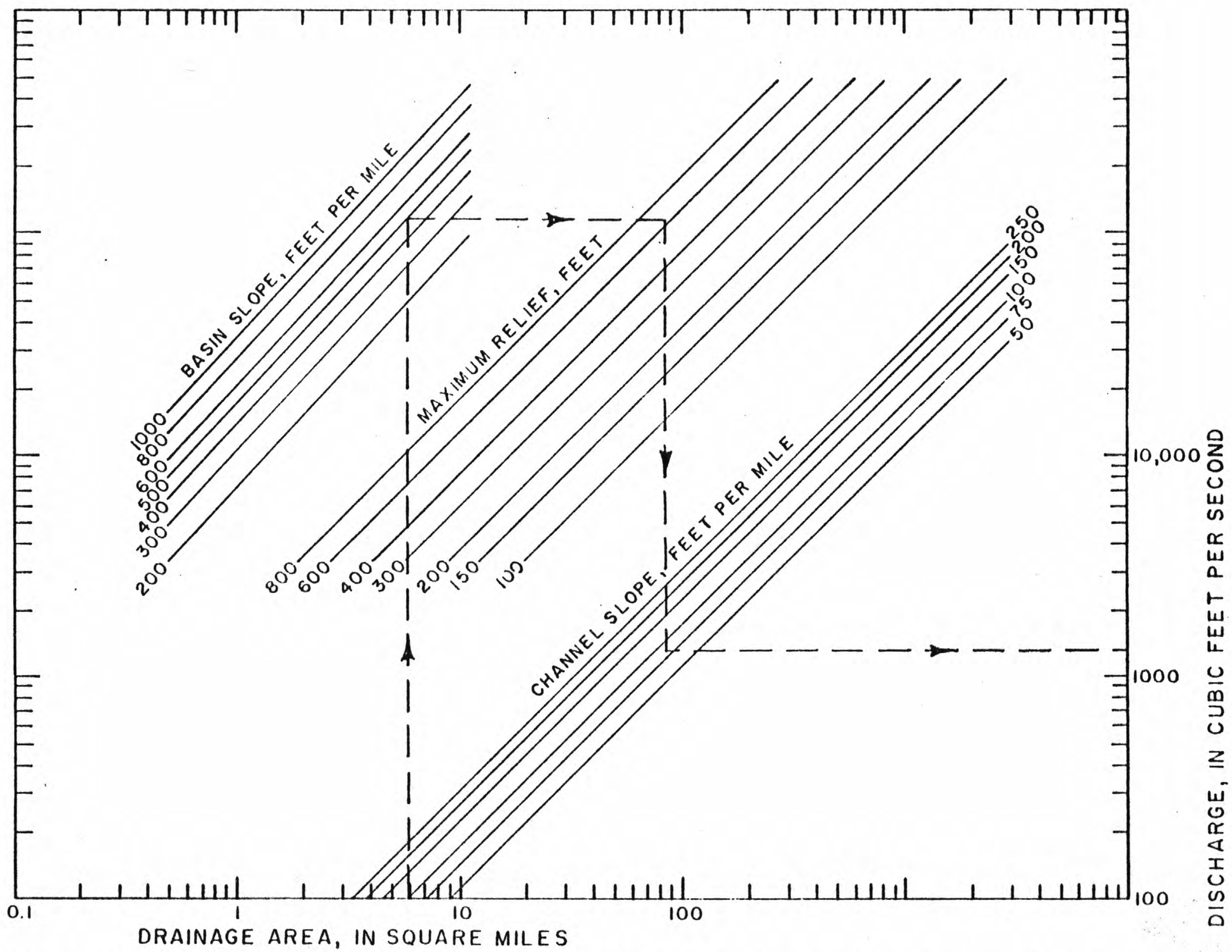


Figure 12.--Relation of 50-year flood peak to drainage area, basin slope, maximum relief, and channel slope.

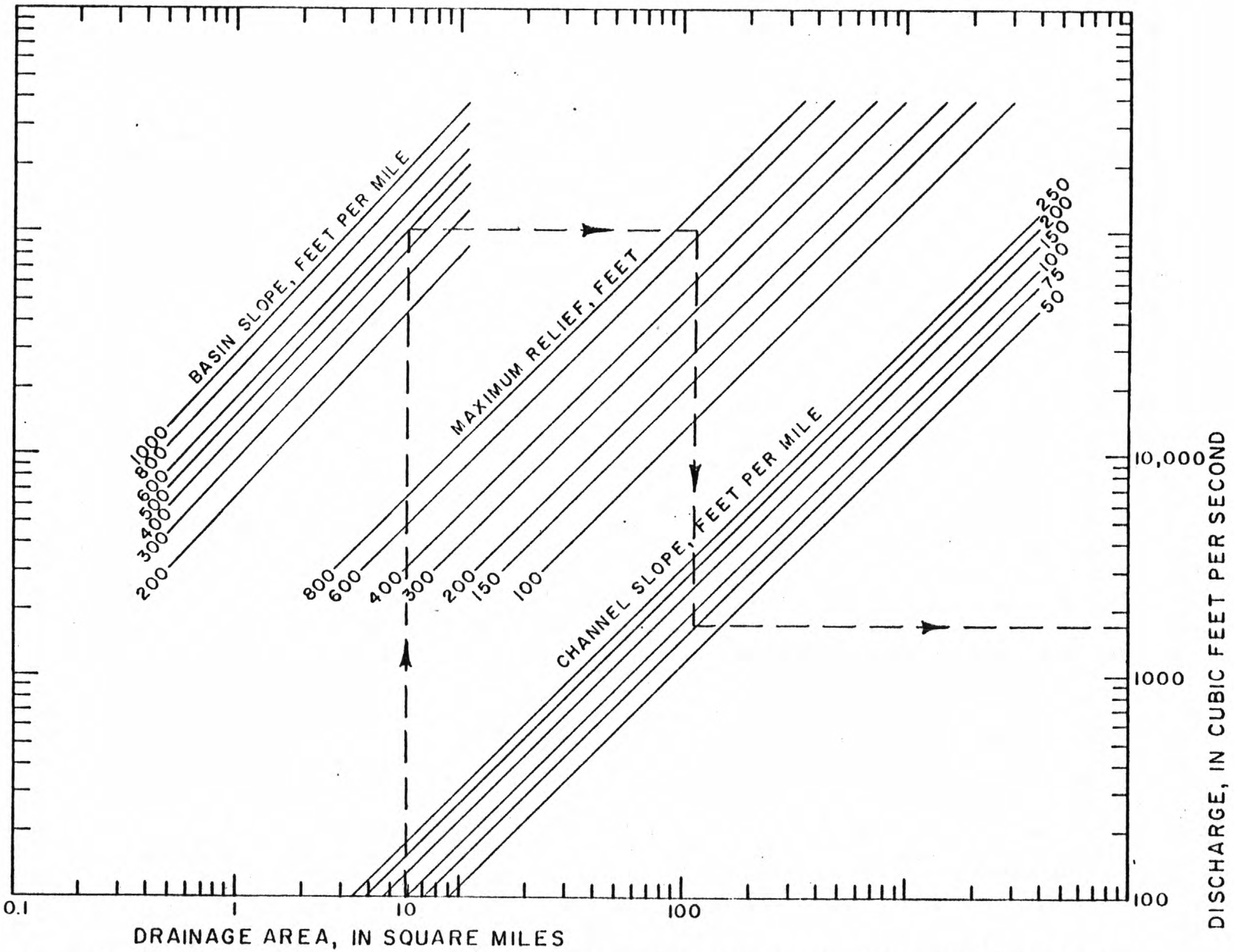


Figure 13.--Relation of 100-year flood peak to drainage area, basin slope, maximum relief, and channel slope.

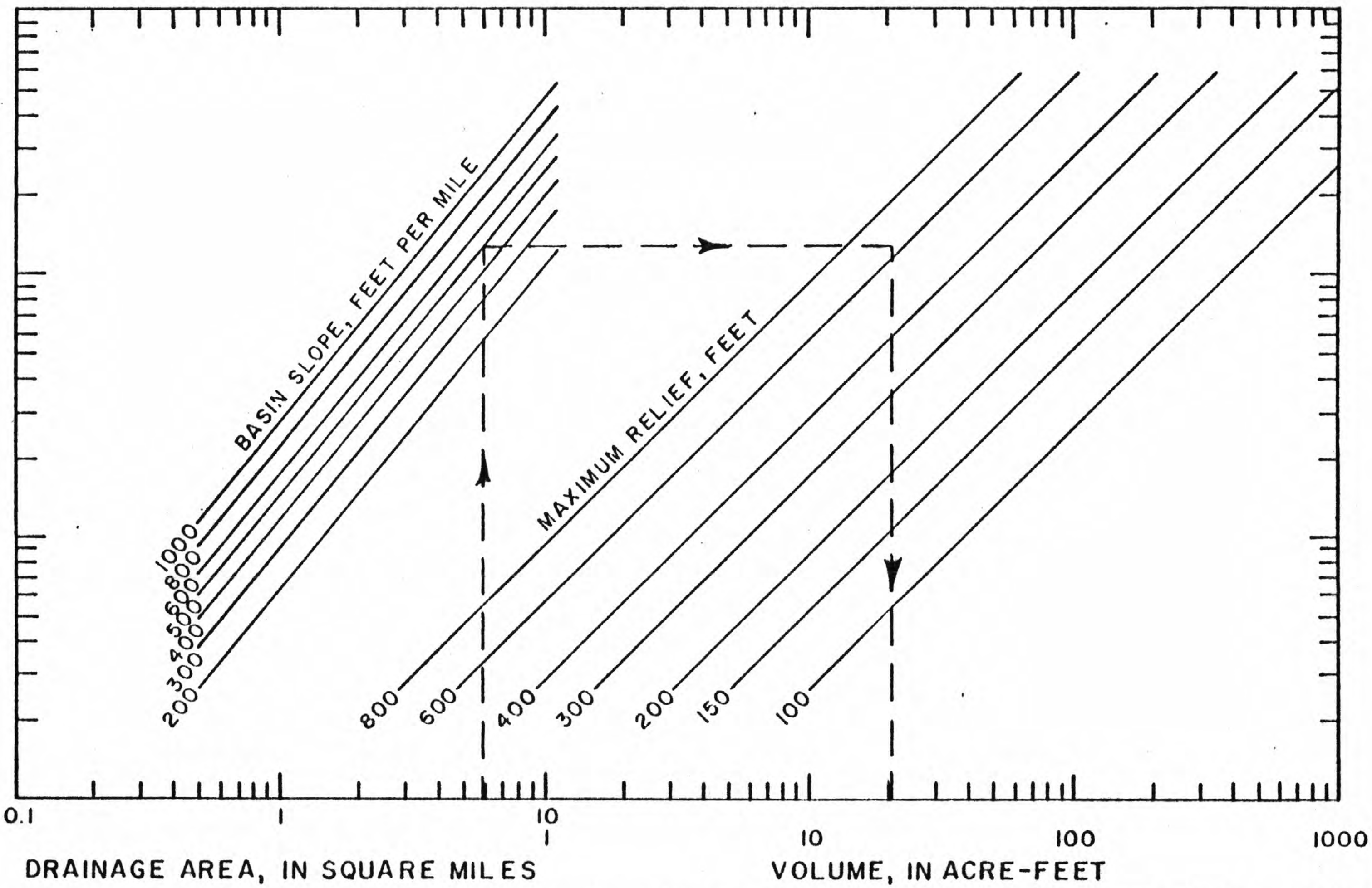


Figure 14.--Relation of 2-year flood volume to drainage area, basin slope, and maximum relief.

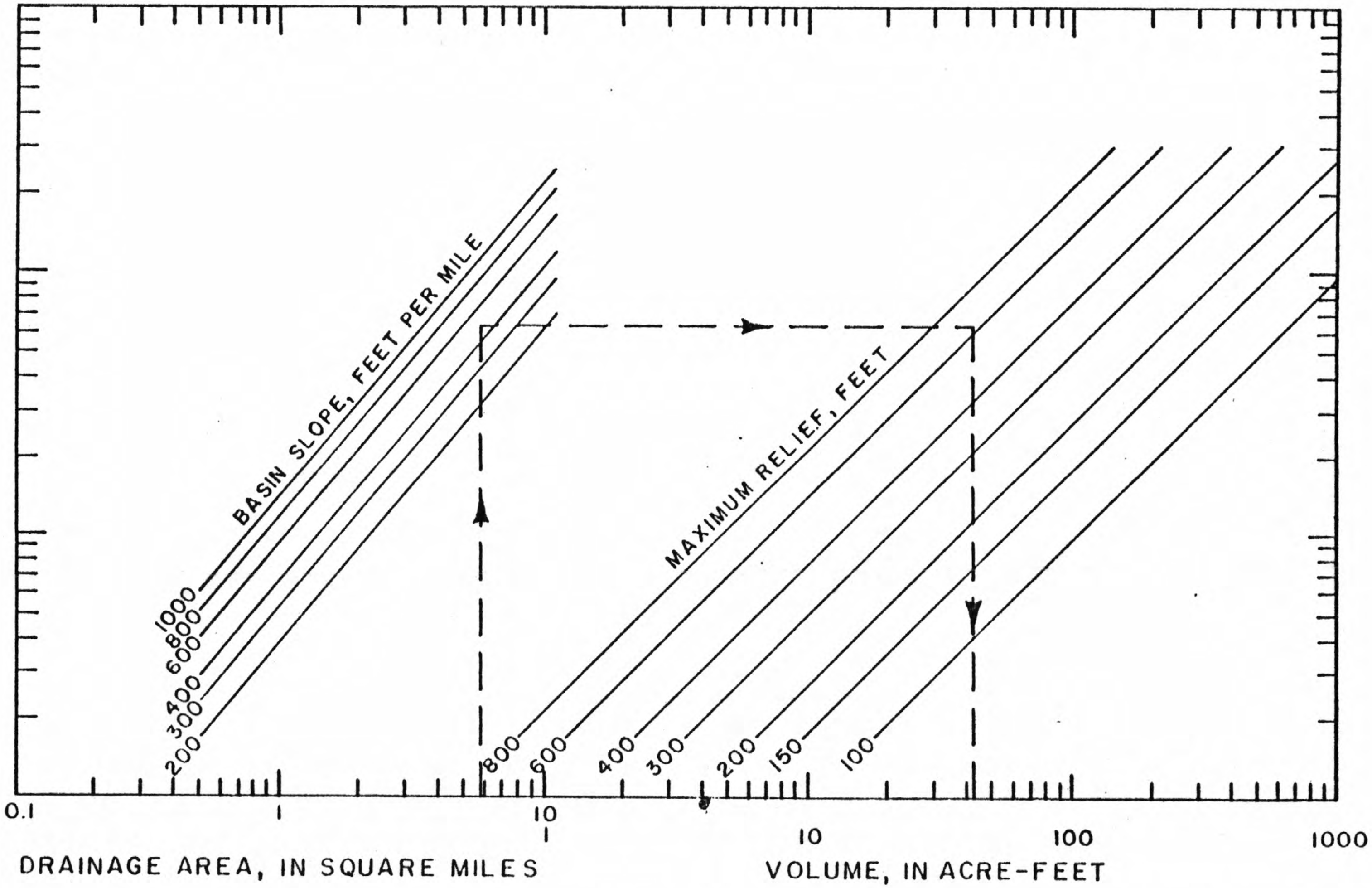


Figure 15.--Relation of 5-year flood volume to drainage area, basin slope, and maximum relief.

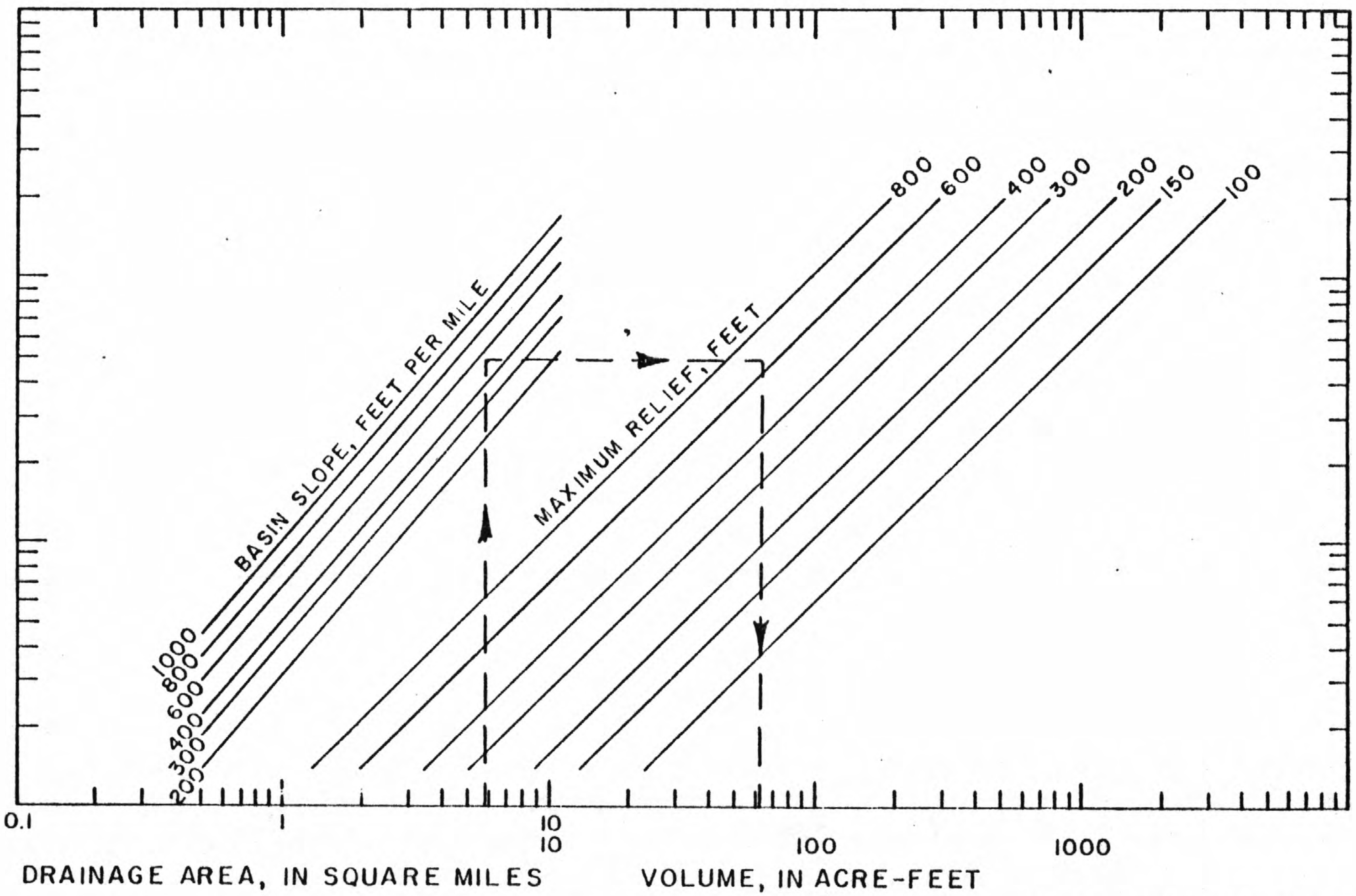


Figure 16.--Relation of 10-year flood volume to drainage area, basin slope, and maximum relief.

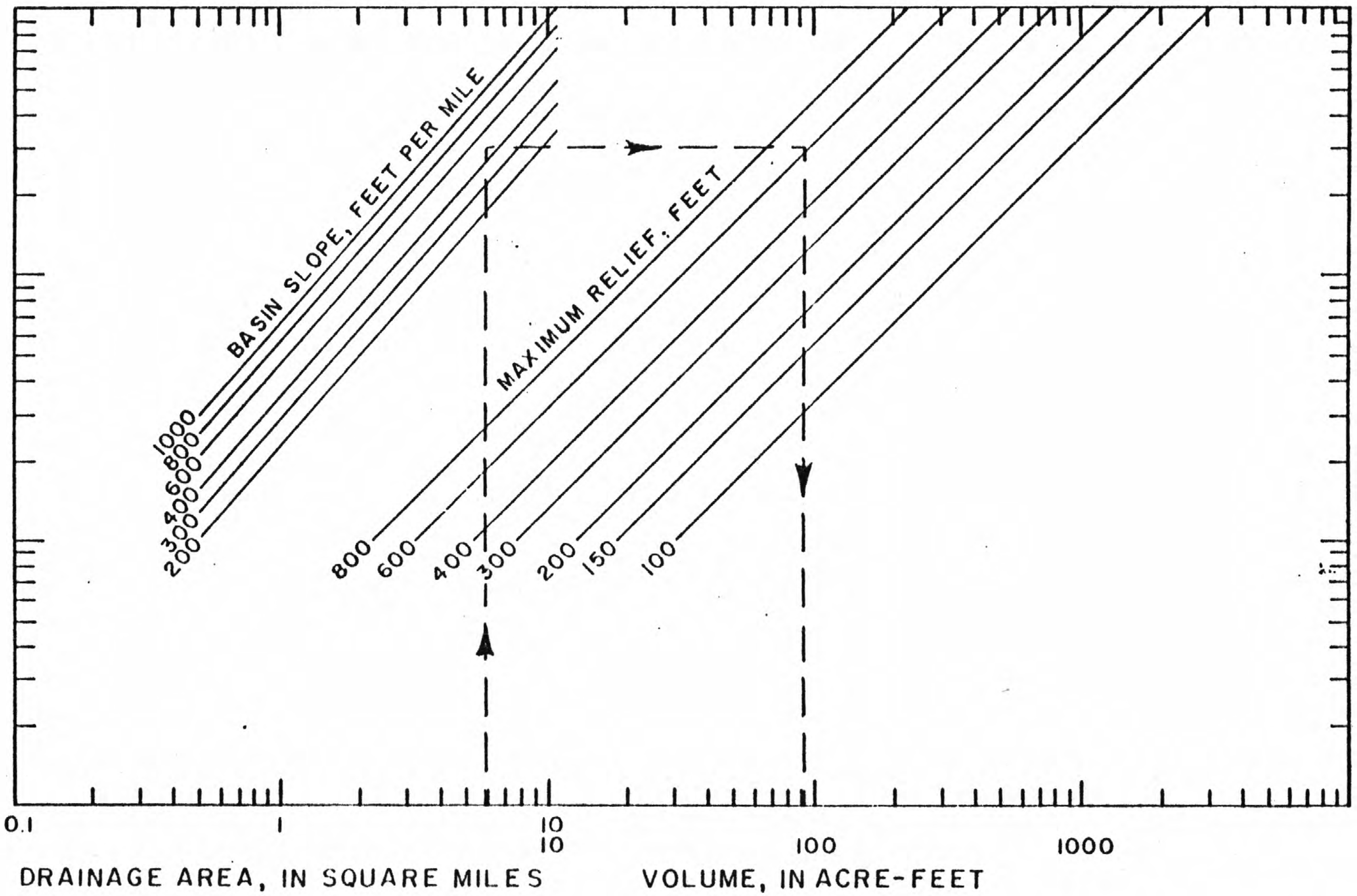


Figure 17.--Relation of 25-year flood volume to drainage area, basin slope, and maximum relief.

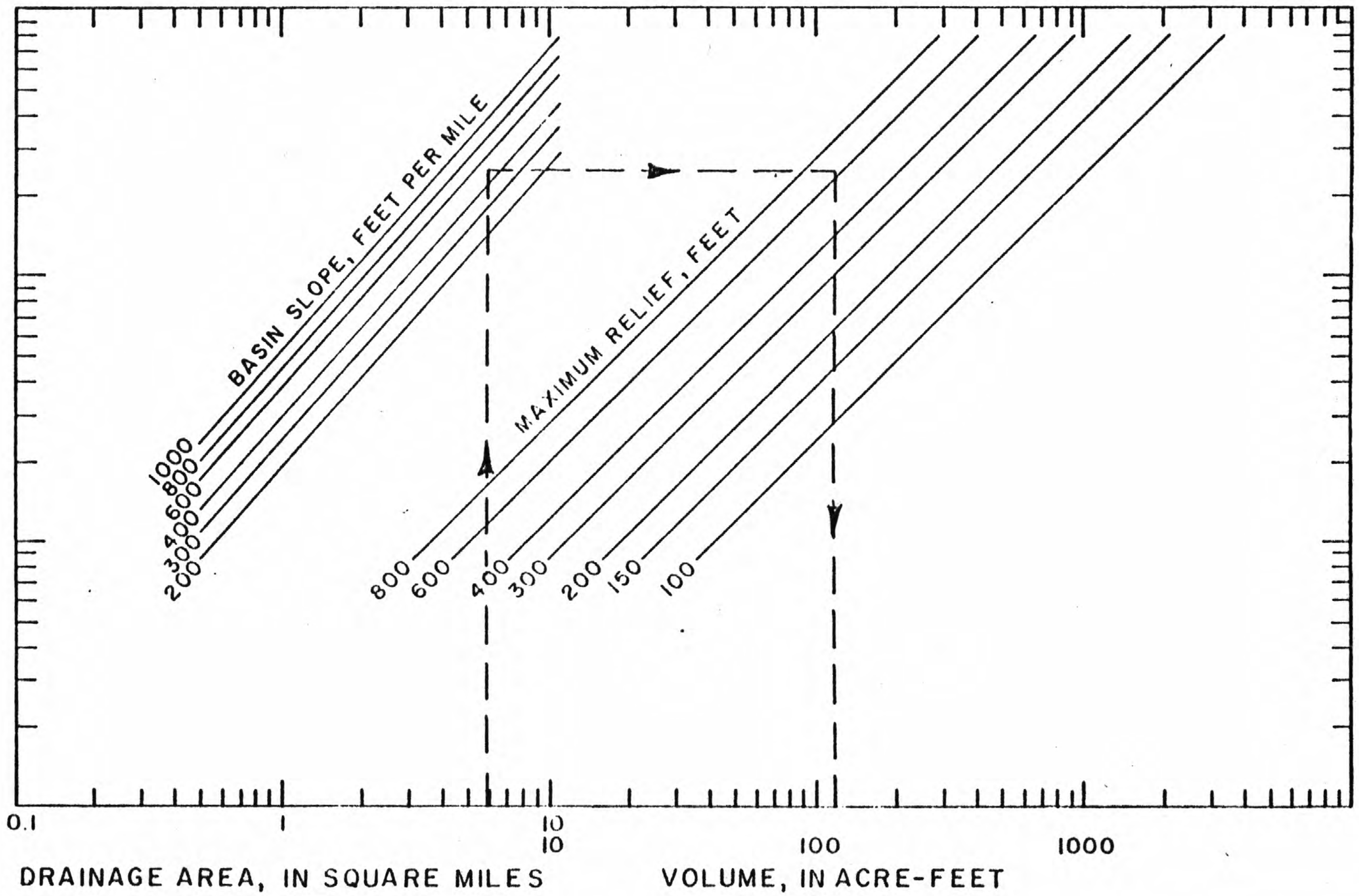


Figure 18.--Relation of 50-year flood volume to drainage area, basin, slope, and maximum relief.

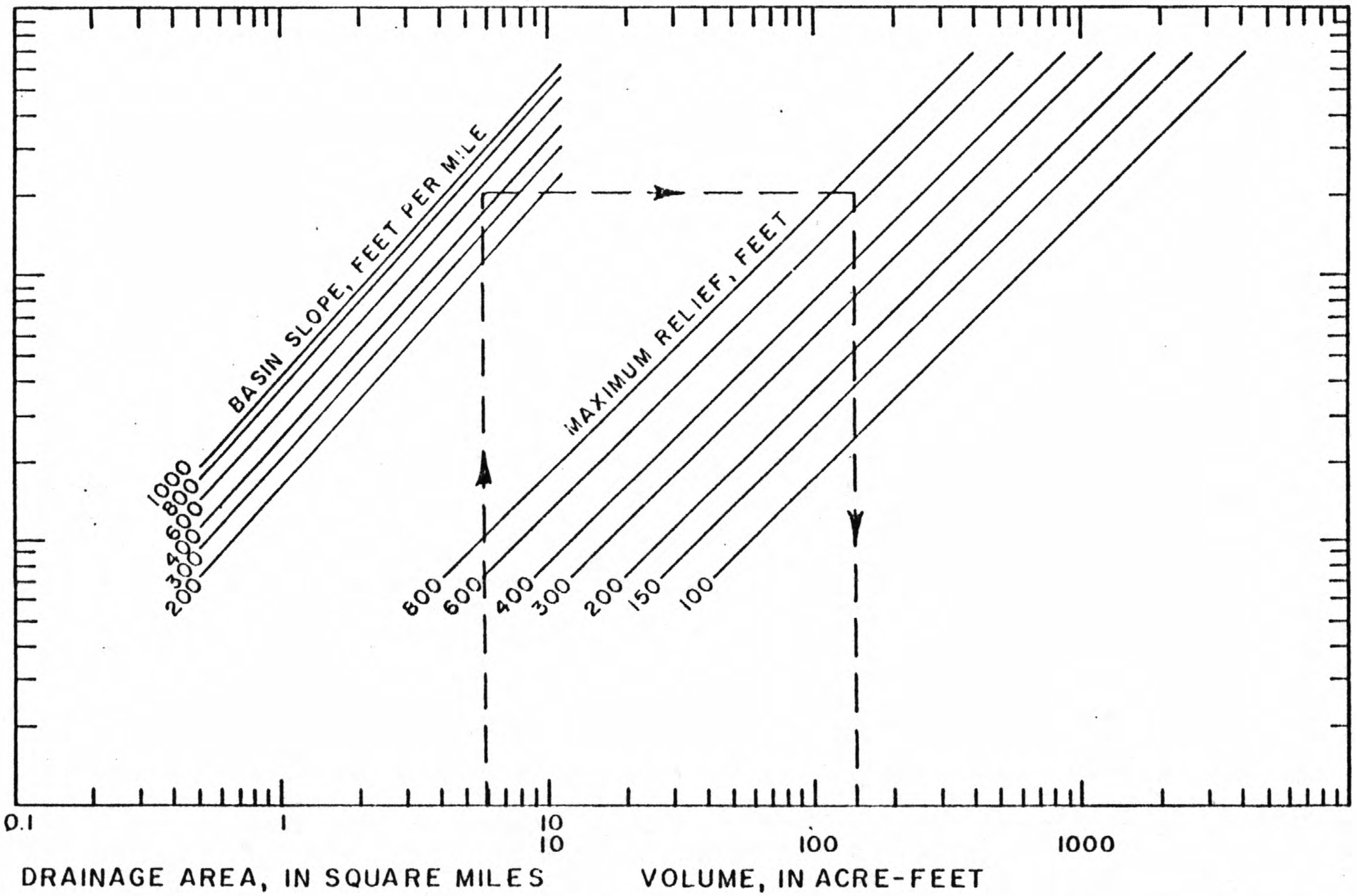


Figure 19.--Relation of 100-year flood volume to drainage area, basin slope, and maximum relief.

RELATIONSHIP OF PEAK DISCHARGE TO RUNOFF VOLUME

Estimation of the flood hydrograph requires knowledge of flood-volume and flood-peak magnitudes. Although the values might be estimated from relations defined in the previous section, flood volumes at some sites in Wyoming possibly can be estimated from more reliable flood-peak information, if it is available. Also, it might be possible to estimate a flood peak from a flood volume rather than from basin characteristics. In this section, relations were defined to test those possibilities.

The problem in relating peak discharge to volume lies in the many variations of conditions prior to and during the occurrence of a runoff event. The degree of saturation of the soil, the timing and intensity of the rainfall, and the direction of the storm in relation to the basin all affect the size of the peak and volume of runoff. In the model calibration of the drainage basins, it was assumed that these various conditions were accounted for if the conditions were present during the period of record used in the model. It should be understood that not all possible conditions can be accounted for on all basins. The effect of modeling is that of averaging conditions and reactions for the basin.

Graphs from rain-recording instruments showing increases or decreases in the rainfall intensities may explain some of the variations in shape of the runoff hydrograph. A runoff hydrograph from a small drainage basin will usually reflect changes in the rainfall pattern, but these variations cannot be anticipated and cannot be incorporated into a design hydrograph. It can be shown that the simple fast-rising hydrograph has the greatest potential for causing problems at culverts and bridges. (See Embankment storage.) The composite MDH (Mean Dimensionless Hydrograph) (discussed in next section of this report) produces such a graph.

Because peak discharge and runoff volume are both essential to the composite MDH, a relationship between peak discharge and volume is desirable. A study of runoff hydrographs from 35 drainage basins indicates that such a relationship exists. Three hydrographs from each basin were selected, on the basis of shape, with the emphasis on simple, fast-rising peaks. Invariably, these peak flows were the highest recorded events for each basin. Some culling of peak hydrographs was necessary because of variations in the runoff. Most peak flows with long runoff duration were eliminated. A few double-peak hydrographs were used, if the two peaks occurred within a short time span; otherwise, the peaks were separated and usually the highest one was used in the study. Runoff hydrographs with small rises on the rising or on the recession limb were used only if these features could be removed. If these features were too prominent, the hydrograph was not used.

The 105 hydrographs used in the study defined a peak discharge-volume relationship with a correlation coefficient of 0.90 (fig. 20). The equation is:

$$Q = 18.66\ V^{0.914}, \qquad (9)$$

where V = runoff volume in acre-feet, and

Q = peak discharge in cubic feet per second.

The standard error of estimate averages 57 percent. Table 13 shows computed results, equations, and resultant discharges for selected values of runoff volume.

While equation 9 provides a means of determining a discharge from a volume, it is not suitable for determining a volume from a discharge. In hydrologic studies, it is easier to determine a peak discharge than a volume for a runoff occurrence, unless a graphical record is available. One solution is to consider

$$V = f(Q)$$

with volume as the dependent variable and using the same 105 events of discharge and volume used to determine equation 9. The relationship can be defined by

$$V = 0.131\ Q^{0.878} \qquad (10)$$

which has the same correlation coefficient of 0.90 and an average standard error of 55 percent. This provides a reasonable value of runoff volume.

Other Runoff Parameters

Runoff duration and hydrograph rise time were considered as other runoff parameters. It was found that average values of either would improve a relationship between peak discharge and runoff volume, when used in a multiple regression. Although the improvement was significant, there was no easy way to estimate these two parameters for an ungaged site. Basin parameters did not correlate reasonably with runoff duration or hydrograph rise time in this investigation. A relationship between discharge and volume for runoff durations of 2 to 7 hours was found similar to equation 9 and produced discharges slightly lower (within 5 percent of discharges obtained using equation 9) in a range of volumes from 10 to 100 acre-ft.

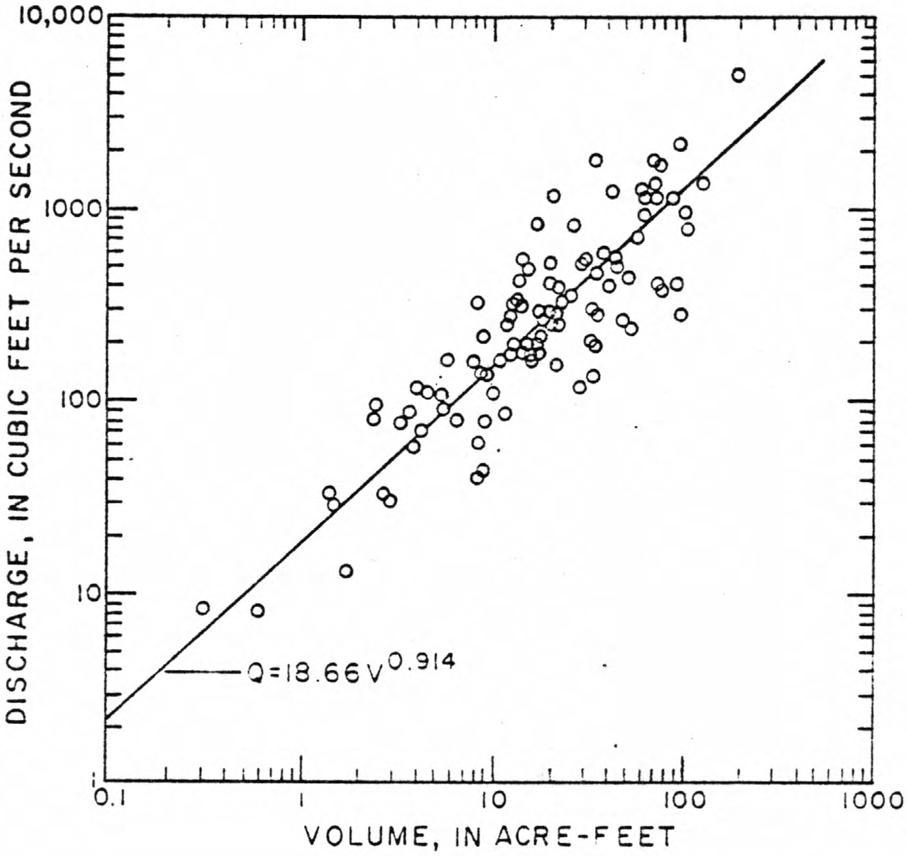


Figure 20.--Relation of runoff volume to peak discharge for 35 small drainage basins in Wyoming.

Table 13.--Results of two-variable regression on peak discharge and runoff volume

(Comparison of selected highest recorded events from each basin[1])

Event	Number of stations	Number of events	Corr. Coef.	Percent Av. SE	Percent +SE	Percent -SE	Equation	Values of Q for		
								V = 10	V = 50	V = 100
First Highest	35	35	0.87	57	72	42	$Q = 23.04\ V^{0.894}$	181	761	1,414
Second Highest	35	35	.89	57	72	42	$Q = 21.41\ V^{0.864}$	157	629	1,145
Third Highest	35	35	.88	54	68	40	$Q = 17.73\ V^{0.872}$	132	537	983
Total	35	105	0.90	57	72	42	$Q = 18.66\ V^{0.914}$	153	666	1,256

[1] Most long-duration, double-peak, or small-additional-rise effects eliminated.

NOTE: Use of metric equivalent for independent variable would not provide correct answer.

Comparison of Results

A comparison was made to see how well a peak discharge for a specified recurrence interval, estimated from the equations using basin parameters, would compare with a peak discharge computed using equation 9, with a volume of the same specified recurrence interval. The 50-year peak discharge was determined for each of the 22 modeled basins from the basin parameters. The 50-year runoff volume was also determined from the basin parameters for each basin. This value was used in equation 9 to determine a peak discharge for each basin. The discharge computed from equation 9 was plotted against the Q_{50} estimated from the basin parameters. The results of comparing the N-year event are shown below:

N	Relationship
2	$\hat{Q} = 0.767\ \tilde{Q}^{0.963}$
5	$\hat{Q} = .905\ \tilde{Q}^{.965}$
10	$\hat{Q} = .981\ \tilde{Q}^{.970}$
25	$\hat{Q} = 1.026\ \tilde{Q}^{.982}$
50	$\hat{Q} = 1.038\ \tilde{Q}^{.993}$
100	$\hat{Q} = 1.058\ \tilde{Q}^{1.002}$

Statistically, for the 25-, 50-, or 100-year event, there is no significant difference between the discharge estimated from basin parameters and the discharge computed from the equation relating to volume (equation 9). At the 5-percent level of significance, the slope of each relation is not significantly different from 1.00 and the intercept is not significantly different from zero. Relationships for the 2-year, 5-year, and 10-year events are weaker, to the extent that equation 9 predicts higher discharges from the 2-year, 5-year, and 10-year runoff volumes. A weakness in the discharge-volume relation is that low-runoff occurrences reflect the variability of rainfall more than the high flows.

The relation between discharge and volume for the higher flows shows less scatter because these occurrences are more dependent on larger storms that cover the entire basin. Data from the larger storms were used in synthesizing the long-term runoff records used in the development of flow frequencies. The relationships of flow frequencies to basin characteristics would therefore be more consistent in estimating specific frequencies of discharge or volume, especially the 2-year, 5-year, and 10-year events, from the basin characteristics.

This analysis indicates that for best results a design volume or discharge should be determined using basin characteristics in the appropriate mathematical model. If a hydrograph is needed for design purposes, the discharge and volume for the same design frequency should be used with the composite MDH method to develop the hydrograph, as described in subsequent sections.

MEAN DIMENSIONLESS HYDROGRAPH

Investigations of runoff resulting from rainfall on 28 small drainage basins in Wyoming indicate that a standard dimensionless hydrograph can be used to produce usable synthetic hydrographs of single-peak runoff occurrences. The 22 modeled basins and 6 other basins, all having a minimum of 7 usable hydrographs, were used to study hydrograph shape. As a result, mean dimensionless hydrographs were developed for individual drainage basins, following which a single composite mean dimensionless hydrograph was developed for the 28 drainage basins. The application of this hydrograph is similar to that of the Commons (1942) dimensionless hydrograph, which was based on floods in Texas and has been successfully compared with observed hydrographs of floods in New York, Connecticut, Pennsylvania, and other areas. The Wyoming composite hydrograph (Craig, 1970) has produced synthetic hydrographs that compare well with observed runoff hydrographs from Wyoming, Arizona, and New Mexico. All streams used to develop and test the method are ephemeral.

Composite Mean Dimensionless Hydrograph

The peak discharge in cubic feet per second and the volume of runoff in acre-feet are needed to produce a synthetic hydrograph. Discharge and time-factor constants are determined from the peak discharge and volume of recorded hydrographs. The constants then are multiplied by increments of discharge and time from the dimensionless hydrograph to obtain the plotting points of the synthetic hydrograph. The synthetic peak discharge always has the same value as the actual peak; therefore, the peak must be known.

Commons' dimensionless hydrograph, developed empirically, used a horizontal (time) scale of 100 units and a vertical (rate-of-flow) scale of 60 units. The area under the curve was 1,196.5 "square units" (time units multiplied by rate-of-flow units). The value of one "square unit" in acre-feet was obtained by dividing the total floodflow (volume) in acre-feet by 1,196.5. The value of one unit of flow in cubic feet per second was obtained by dividing the peak flow in cubic feet per second by 60. The rising limb and recession limb of the Commons hydrograph appear characteristic of most streams, large or small, but the long recession is more indicative of large streams that are sustained by flow returning from overflow or storage on flood plains or from ground water in the stream banks.

The ephemeral streams investigated in this Wyoming study do not reflect this large storage effect; consequently, a few changes were employed in developing a mean dimensionless hydrograph for each stream. In order to produce a characteristic hydrograph shape of small ephemeral streams in semiarid areas, an arbitrary value of 1,000 square units was used for the volume, and Commons' value for the peak was retained as 60 flow units. However, unlike the Commons method, where the time scale was fixed, time was allowed to vary with the magnitude of the runoff occurrence. An average time value was determined for each dimensionless hydrograph. The values for volume, peak discharge, and time were used to convert individual observed runoff hydrographs to dimensionless form.

A dimensionless hydrograph was developed for each site by averaging points on the abscissa (time scale) at selected ordinate (discharge scale) points. These 28 dimensionless hydrographs were combined by averaging abscissa points for selected ordinate points, making a smooth final composite hydrograph. Finally, ordinate points were determined for selected abscissa points to best describe the composite mean dimensionless hydrograph. A total of 298 hydrographs from the 28 drainage basins were used to develop the final composite hydrograph. The planimetered volume was 970 square units with a rise time of 12 time units. The average time of the base was 70 time units. This composite hydrograph, shown in figure 21, was then tested using data from stations not used in its development.

Description of the Method

The composite hydrograph (fig. 21) is used to synthesize a hydrograph, provided that the peak discharge, Q, in ft^3/s (cubic feet per second), and the volume, V, in acre-ft (acre-feet), are known. The method consists of two steps. First, a discharge constant, Q', a volume constant, V', and a time constant, T', are computed, using the peak (60 flow units) and volume (970 square units) from the composite hydrograph:

$$Q' = \frac{Q}{60} = ft^3/s \text{ per flow unit} \qquad (11)$$

$$V' = \frac{V}{970} = \text{acre-ft per square unit, and} \qquad (12)$$

$$T' = 726 \frac{V'}{Q'} = \text{min per time unit,} \qquad (13)$$

where square units = flow units X time units, and 726 is a constant for converting acre-feet to cubic feet and seconds to minutes.

The second step is to compute the actual plotting points, t and q, for the synthetic hydrograph. Sixteen plotting points were selected to define the entire hydrograph, as shown in figure 21. The coordinates of these points on the composite hydrograph in figure 21 are designated at t' and q'. Once a set of values of t' and q' has been selected it is used in synthesizing every new hydrograph. For each of the 16 points

$$t = t'T', \text{ and} \qquad (14)$$

$$q = q'Q', \qquad (15)$$

where t is time in minutes,

t' is time in units,

q is discharge in cfs,

q' is flow units, and

T' and Q' are as previously defined.

The values of t' and q' are strictly empirical and define the composite hydrograph.

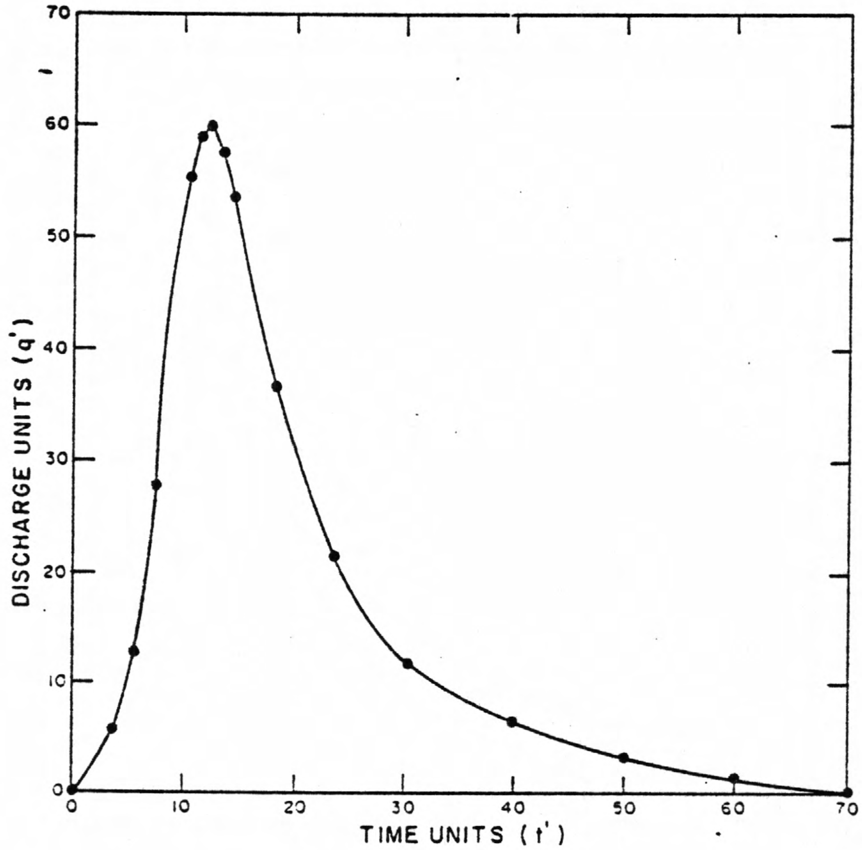


Figure 21.--Composite mean dimensionless hydrograph developed from data for 28 small drainage basins in Wyoming. Dots indicate the increments of time and the discharge units used in producing a synthetic hydrograph.

The method can best be shown by developing a synthetic hydrograph for an actual runoff occurrence. On June 10, 1965, a peak flow was recorded on Pritchard Draw near Lance Creek, in eastern Wyoming. The peak discharge was 1,280 ft^3/s and the volume was computed as 67.17 acre-feet. From equations 11, 12, and 13, Q', V', and T' were determined as follows:

$$Q' = \frac{1,280}{60} = 21.33 \text{ ft}^3\text{/s per flow unit,}$$

$$V' = \frac{67.17}{970} = 0.069 \text{ acre-ft per sq unit, and}$$

$$T' = 726 \frac{V'}{Q'} = 726 \times \frac{0.069}{21.33} = 2.35 \text{ min per time unit.}$$

Selected increments of time units, t' (table 14), and corresponding discharge units, q', the 16 points shown in figure 21, are multiplied by constants T' and Q', respectively, to determine the time, t, and corresponding discharge, q, for points on the synthetic hydrograph. The listed values of t' and q' were used in synthesizing all hydrographs shown in this report.

Figure 22 shows the comparison of the synthetic hydrograph with the observed hydrograph for the above development and for another peak that occurred July 13, 1966. The time scales of the synthetic hydrographs were adjusted slightly to provide better comparison of the main part of the hydrographs.

Selected Comparisons

The general similarity of the shape of the hydrographs also was apparent from comparisons in other areas in Wyoming. Figure 23 shows comparisons of observed and synthetic hydrographs in areas independent of the areas used to develop the composite mean dimensionless hydrograph.

To test the method in similar areas outside of Wyoming, observed runoff data were also obtained from New Mexico and Arizona. Synthesized hydrographs are shown in comparison with selected observed hydrographs for these areas in figure 24. The consistently close agreement of these and many other comparisons is quite remarkable. Although only drainage basins of less than 11 square miles were investigated, it is possible the MDH method is valid for drainage basins of various sizes. A hydrograph synthesized for a peak flow on a drainage basin of 57 square miles in Arizona showed very close agreement with the natural hydrograph. Although the concept of a standard hydrograph shape is subject to criticism from a strictly hydrologic point of view, the comparisons to date indicate that the concept is valid for design purposes on small, semiarid, ephemeral streams.

Table 14.--Determination of time, t, and corresponding discharge, q, for points on the synthetic hydrograph for Pritchard Draw near Lance Creek, Wyoming

[t = t'XT'; q = q'XQ'. Symbols explained in text.]

t' (time units)	T' (min per time unit)	t (min)	q' (flow units)	Q' (cfs per flow unit)	q (cfs)
0	2.35	0	0	21.33	0
3	2.35	7.1	5.6	21.33	119
5	2.35	12	13	21.33	277
7	2.35	17	25	21.33	533
10	2.35	24	49	21.33	1,045
11	2.35	26	57	21.33	1,216
12	2.35	28	60	21.33	1,280
13	2.35	31	69	21.33	1,258
14	2.35	33	55	21.33	1,173
18	2.35	42	38	21.33	811
23	2.35	54	23	21.33	491
30	2.35	70	12	21.33	256
40	2.35	94	5.2	21.33	111
50	2.35	118	2.0	21.33	43
60	2.35	141	0.5	21.33	11
70	2.35	164	0	21.33	0

Plot t versus q to obtain the synthetic hydrograph.

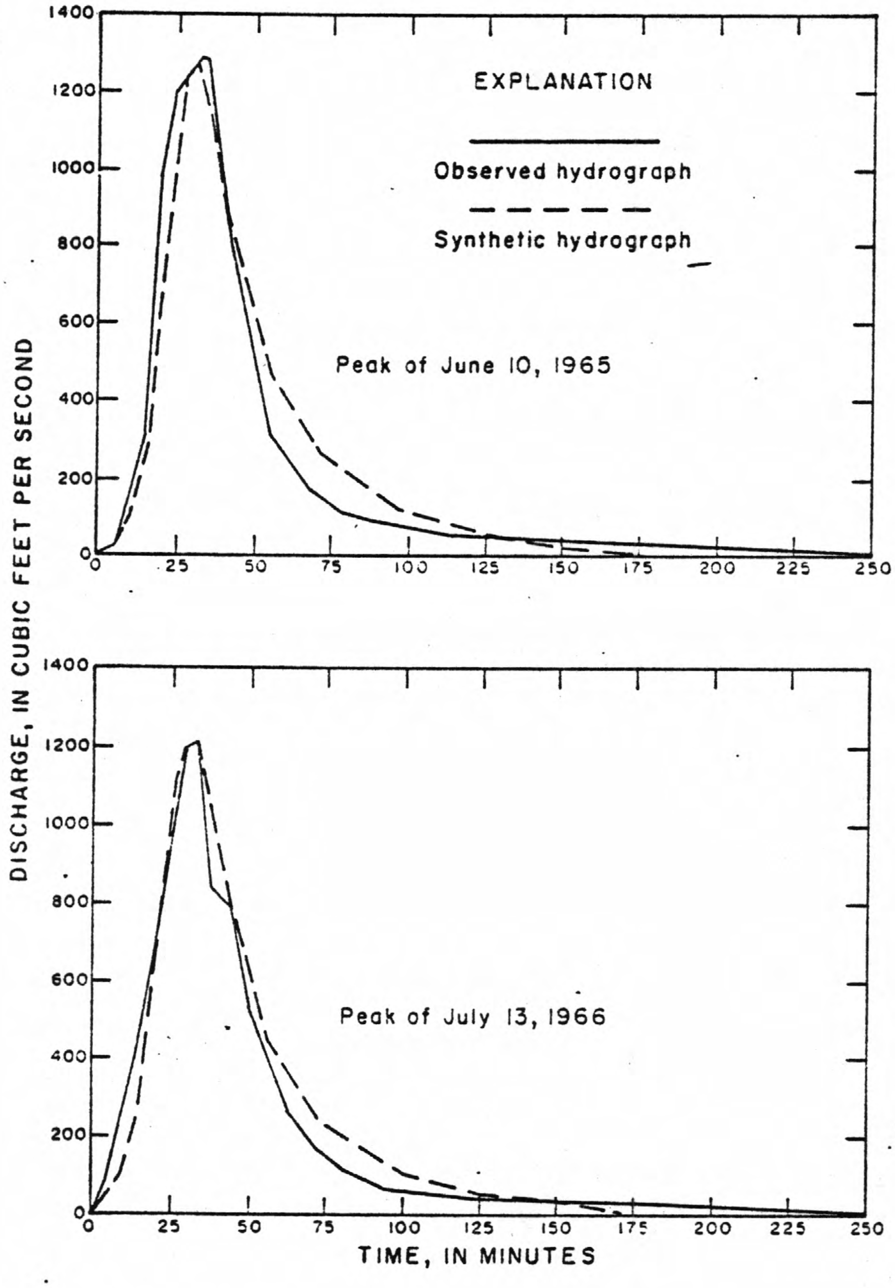


Figure 22.--Comparison of observed and synthetic hydrographs for two runoff occurrences on Pritchard Draw near Lance Creek, Wyo.; drainage area 5.12 square miles.

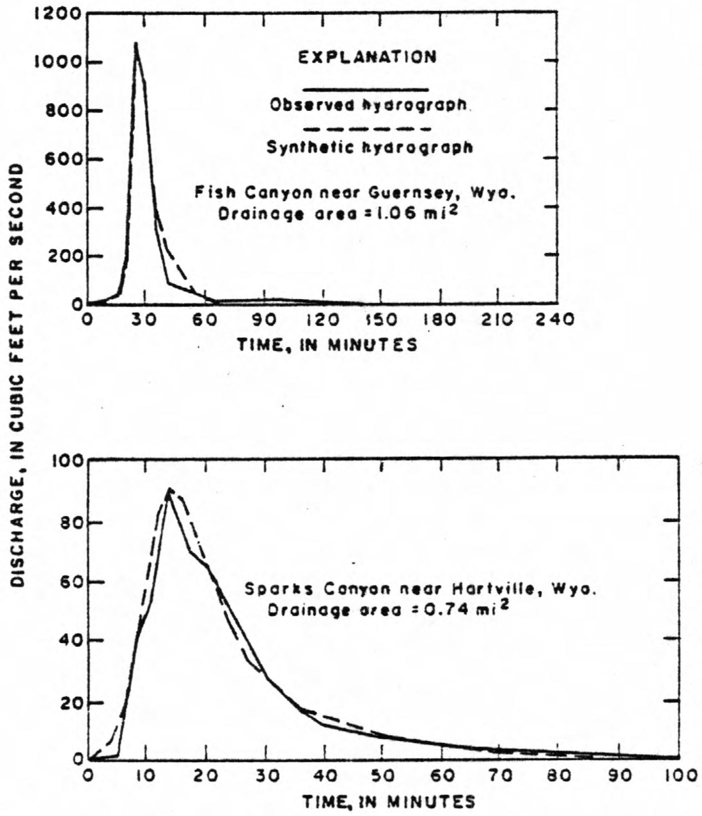


Figure 23.—Comparison of observed and synthetic hydrographs for areas in Wyoming not used in the development of the composite dimensionless hydrograph.

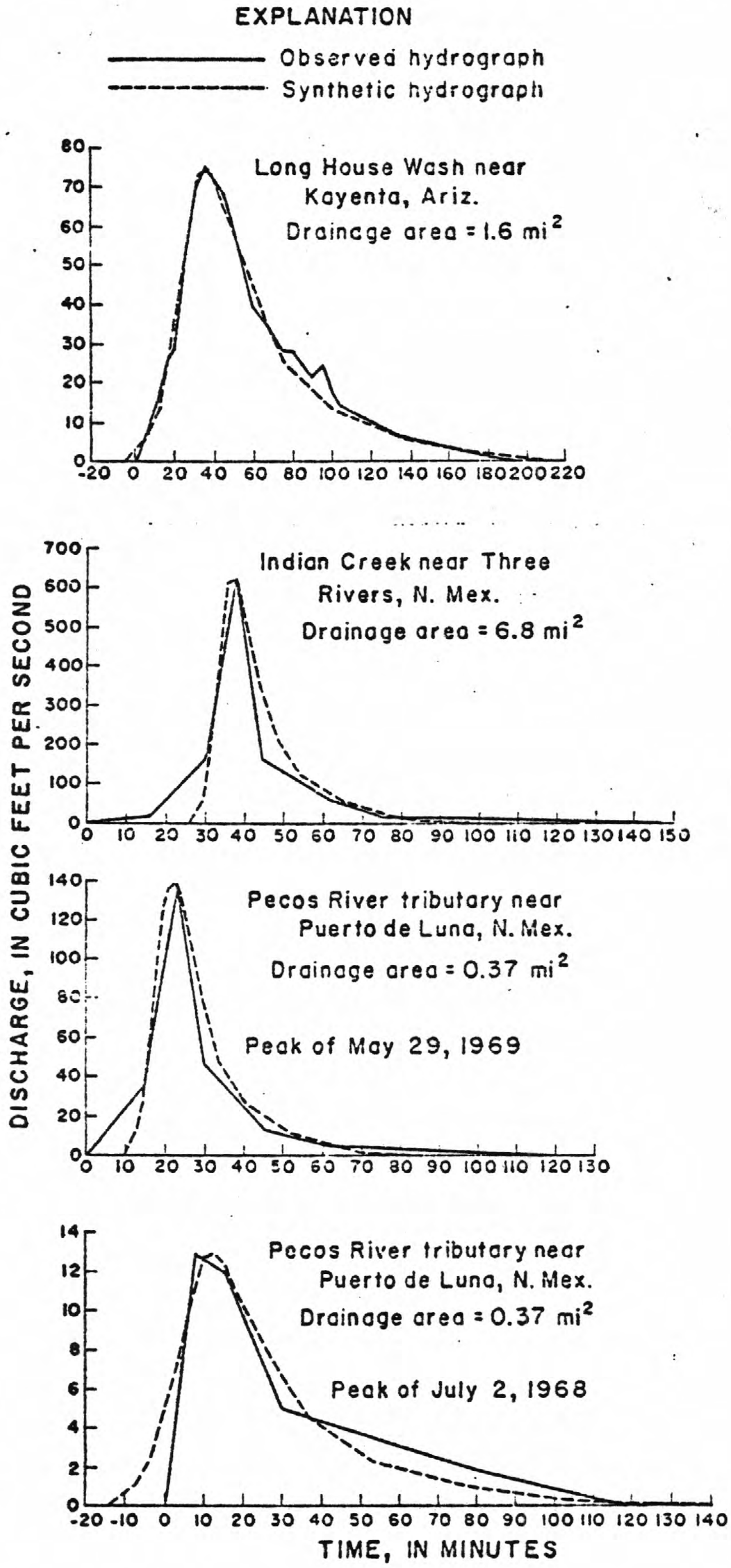


Figure 24.--Comparison of observed and synthetic hydrographs for runoff occurrences in Arizona and New Mexico.

PONDING BEHIND HIGHWAY EMBANKMENTS

Embankment Storage

A potential exists for temporarily storing flood waters behind highway embankments in undeveloped areas throughout the western states. Many miles of roadways have been and are being built crossing numerous water courses for each mile of roadway constructed. These water courses range from grassy swales to deeply eroded gulches and may contain water only a few times a year. For small drainage areas, culverts are placed under the roadway to provide an outlet for this runoff. In general, the size of a culvert is such that it is capable of safely permitting passage of a certain d-sign flood such as a 10-year flood, a 25-year flood, or a 50-year flood. A reduction in culvert size would reduce the amount of runoff the culvert could carry and cause ponding of water by the upstream embankment. Because the culvert would continue draining, the ponding would only be temporary. In rural areas, the ponding would not cause adverse effects, and a savings would be realized in the cost of the smaller size culverts. A certain amount of available storage space is necessary on the upstream side of the embankment to permit the ponding.

Ponding behind highway embankments was studied by routing incremental discharges of flood hydrographs through box culverts of various sizes with an artificial storage area upstream. The storage area was a hypothetical wedge-shaped area in which the width and bottom slope could be varied (fig. 25).

Method of Analysis

Box culverts of sizes 4 x 4 ft, 5 x 5 ft, and 6 x 6 ft were used to investigate the flow through culverts. Critical depth was assumed at the culvert entrance to avoid assumptions of other culvert features such as slope and roughness. Various types of culvert flow are described in Bodhaine (1968). Two types of culvert flow were considered. A low-head flow for a headwater depth ratio up to 1.2 and high-head flow for ratios above 1.5. A transitional change was used between ratios 1.2 and 1.5. The culverts were assumed to have square entrances and to be set flush in a vertical headwall. A simple type of culvert entrance was used to avoid the many corrections to the entrance coefficient normally used when considering rounding, beveling, projection, etc. The only entrance coefficient needed is for horizontal contraction for low-head flow and vertical contraction for high-head flow. A constant coefficient was used for low-head flow and a variable coefficient was used for the transition flow to and throughout the high-head flow range.

It should be emphasized that culverts with outlet control or with flows changing from inlet to outlet control can produce reactions differing from this analysis, which concerns only inlet control.

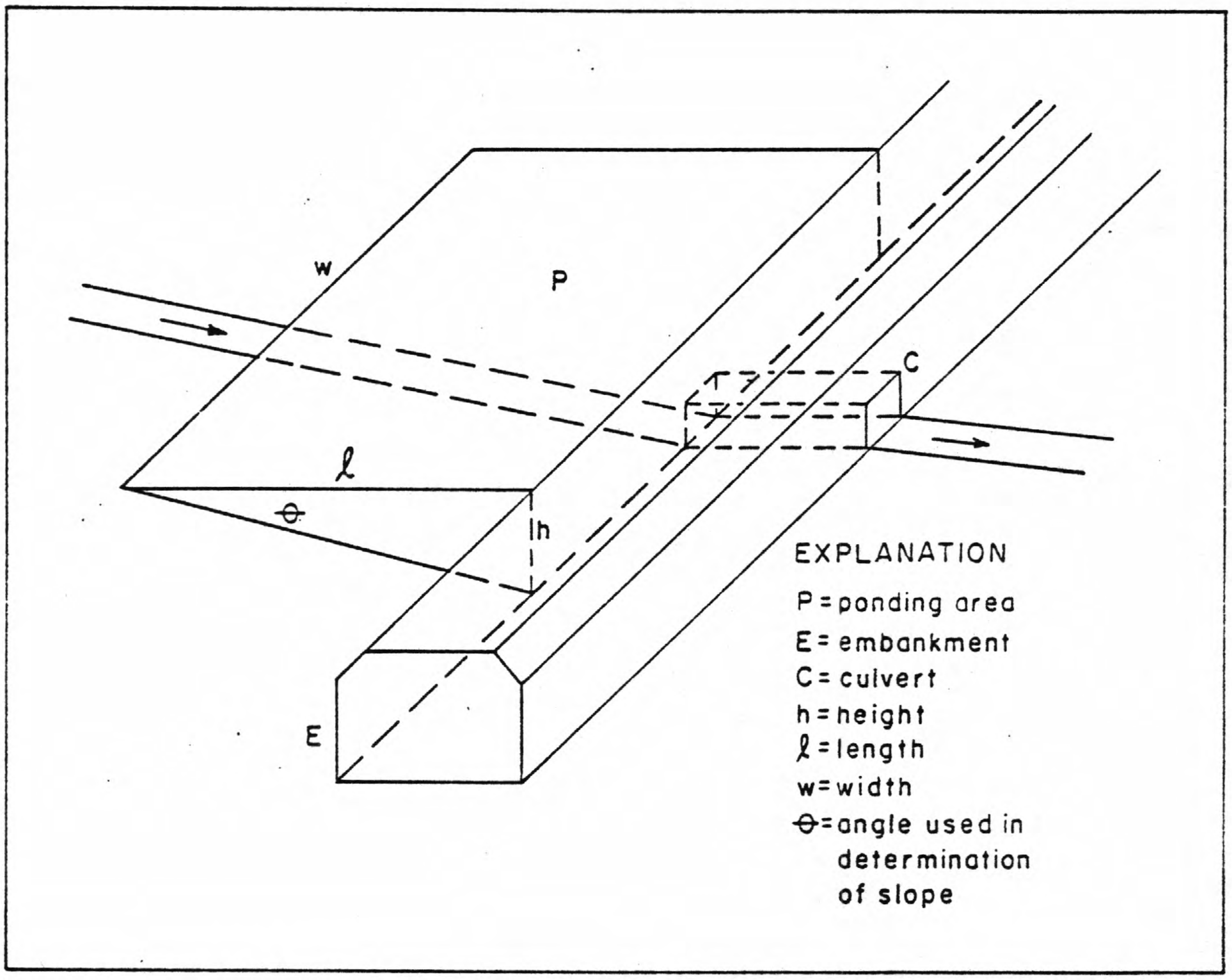


Figure 25.--Schematic representation of wedge-shaped ponding area with box-culvert relief.

The hypothetical wedge-shaped storage area and box culverts were used in the analysis to simplify the computations. The water-surface elevation of the storage pond changes continuously as a reaction to the inflow and culvert outflow. The width and bottom slope of the ponding area are constant through a specific routing trial, but they can be varied prior to any trial. Several single-peak synthetic hydrographs were routed through the pond-and-culvert routine to determine maximum elevation of the pond and maximum outflow of the culvert. The initial pond width was 60 feet and the slope was equal to 0.02 ft/ft. Other tests were made for an increase of width to 100 feet or an increase in slope to 0.03 ft/ft. Routing tests were made for all three culvert sizes. Table 15 contains the results of the tests. Figure 26 shows culvert discharge rating curves for the culvert sizes investigated, as determined from the data of table 15. The reactions to increases in the pond width and bottom slope are noted. Results indicated that for high-head flows, the pond water-surface elevation (head) decreased as the culvert size increased, decreased as the width of the pond increased, but increased as the slope of the pond bottom increased.

An increase in the pond head would have several effects which could not be evaluated in this study but should be noted; they were: Additional losses through infiltration into the storage area bottom and the highway embankment, additional water pressure against the embankment, and an increase in the velocity of the culvert outflow.

A comparison of the routing of multipeak runoff hydrographs with single-peak runoff hydrographs of the same peak discharge and volume showed that the single-peak flow creates a higher water level in the pond and, consequently, a greater culvert outflow peak than the multipeak flow, all other conditions being constant. (See figures 27, 28, and 29.) With single-peak flows of equal magnitude, the one with the greatest volume causes the highest water level in the pond. (See figure 30.) The MDH method was used to synthesize single-peak runoff hydrographs from the peak discharge and volume of multipeak flows so comparisons could be made of embankment ponding and culvert flows of each type. The results indicate that the single-peak flood hydrograph should be used when designing structures to handle flood runoff from small drainage basins.

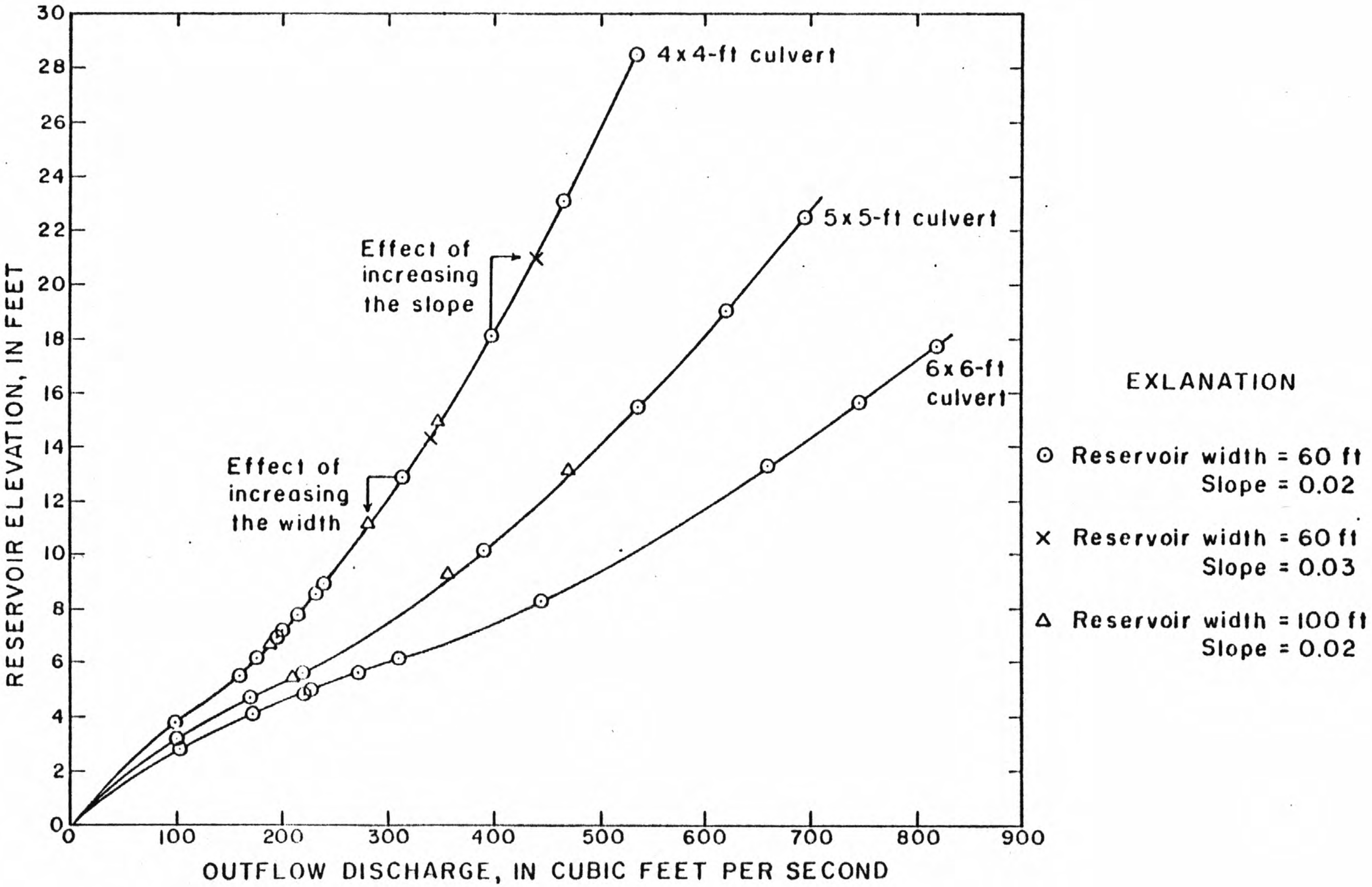


Figure 26.--Culvert discharge rating curves for the culvert sizes investigated with the hypothetical wedge-shaped ponding area showing the effect of changes in the width and slope of the ponding area.

Table 15.--Results of routing single-peak synthetic hydrographs through the various reservoir and culvert sizes.

Culvert size (ft)	Q Peak (ft^3/s)	V Volume (ac-ft)	Reservoir Width (ft)	Reservoir Slope (ft/ft)	Reservoir Elevation (ft)	Storage (ac-ft)	Time to peak Inflow (min)	Time to peak Outflow (min)	Q at time o outflow pea (ft^3/s) Inflow	Q at time o outflow pea (ft^3/s) Outfl
4 X 4	1,000	101.26	60	0.02	28.5	28.0	54	87	543	538
5 X 5	1,000	101.26	60	.02	22.5	17.4	54	75	704	697
6 X 6	1,000	101.26	60	.02	17.7	10.7	54	67	824	818
4 X 4	1,000	54.21	60	.02	23.1	18.4	29	50	475	471
5 X 5	1,000	54.21	60	.02	19.0	12.5	29	43	628	621
6 X 6	1,000	54.21	60	.02	15.6	8.38	29	38	770	747
4 X 4	1,000	29.00	60	.02	18.2	11.4	16	28	421	401
4 X 4	1,000	29.00	60	.03	21.0	10.2	16	27	457	444
4 X 4	1,000	29.00	100	.02	15.0	12.9	16	29	386	350
5 X 5	1,000	29.00	60	.02	15.5	8.27	16	24	564	537
5 X 5	1,000	29.00	100	.02	13.2	9.94	16	26	493	473
6 X 6	1,000	29.00	60	.02	13.3	6.06	16	21	714	659
4 X 4	511	25.66	60	.02	12.9	5.77	27	39	323	317
4 X 4	511	25.66	60	.03	14.4	4.78	27	37	355	344
4 X 4	511	25.66	100	.02	11.2	7.15	27	42	286	283
5 X 5	511	25.66	60	.02	10.2	3.61	27	34	403	393
5 X 5	511	25.66	100	.02	9.25	4.91	27	36	371	357
6 X 6	511	25.66	60	.02	8.31	2.38	27	31	451	447
4 X 4	229	22.32	60	.02	7.16	1.77	50	59	202	201
4 X 4	229	22.32	100	.02	6.73	2.60	50	62	190	188
5 X 5	229	22.32	60	.02	5.55	1.06	50	53	221	220
5 X 5	229	22.32	100	.02	5.53	1.76	50	56	212	210
6 X 6	229	22.32	60	.02	4.87	.82	50	52	223	223
4 X 4	103	10.48	60	.02	3.80	.50	55	57	99	99
4 X 4	103	10.48	60	.03	3.72	.32	55	56	102	101
5 X 5	103	10.48	60	.02	3.23	.36	55	56	102	101
6 X 6	103	10.48	60	.02	2.80	.27	55	56	102	102

Table 15.--Results of routing single-peak synthetic hydrographs through the various reservoir and culvert sizes--continued

Constant volume with reservoir width = 60 ft, slope = 0.02 ft/ft

Culvert sixe (ft)	Q Peak Qp (ft^3/s)	V Volume (ac-ft)	Reservoir elevation (ft)	Max. Qp outflow (ft^3/s)
4 X 4	360	11.71	8.57	233
6 X 6	360	11.71	6.15	311
4 X 4	300	11.71	7.80	216
6 X 6	300	11.71	5.62	272
4 X 4	249	11.71	6.90	195
6 X 6	249	11.71	4.94	227
4 X 4	180	11.71	5.52	160
5 X 5	180	11.71	4.66	170
6 X 6	180	11.71	4.09	173

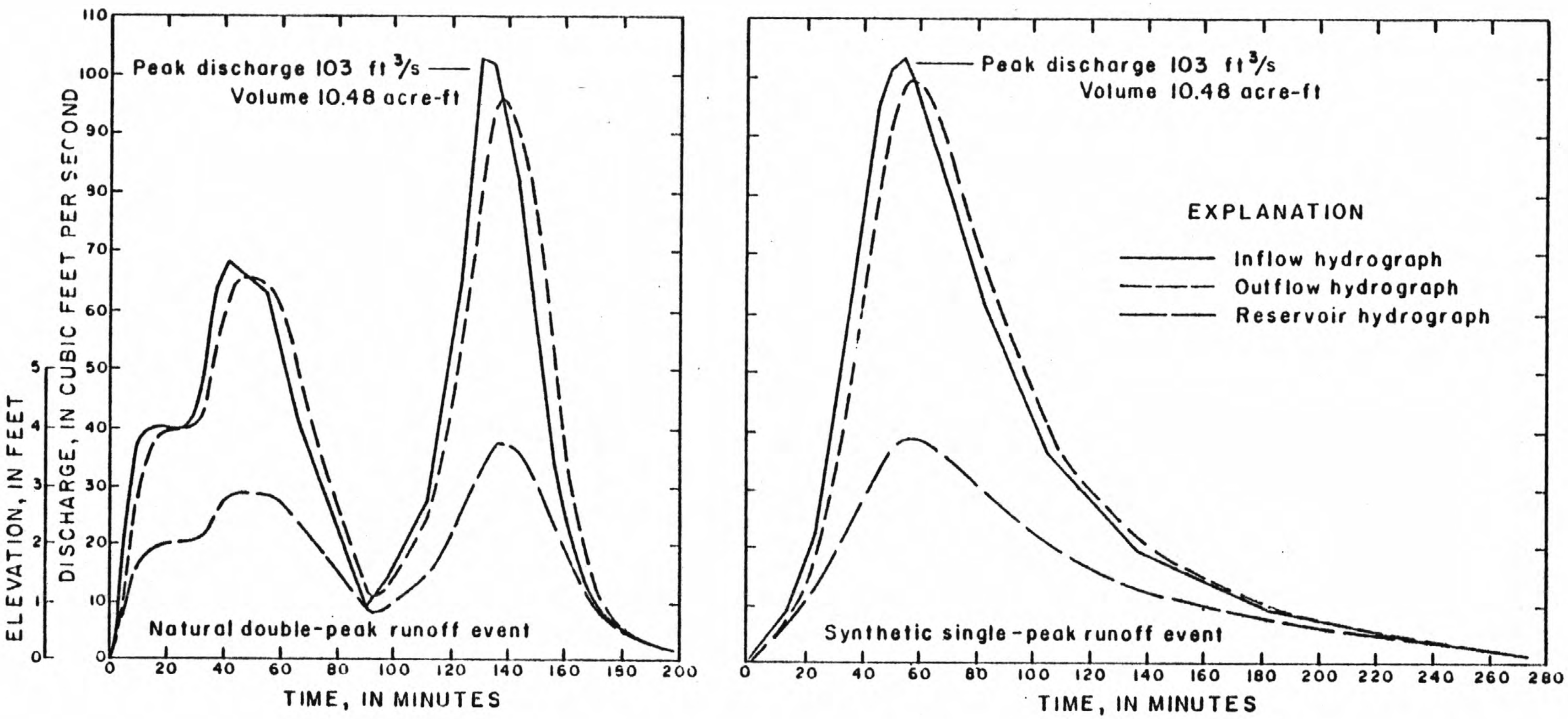


Figure 27.--Comparison of a natural double-peak runoff hydrograph (Norwood River tributary No. 2 near Basin, Wyo., June 22, 1967) to a synthesized single-peak hydrograph of the same magnitude and volume when routed through the ponding area and a 4 x 4-foot culvert. This is a low-head flow condition.

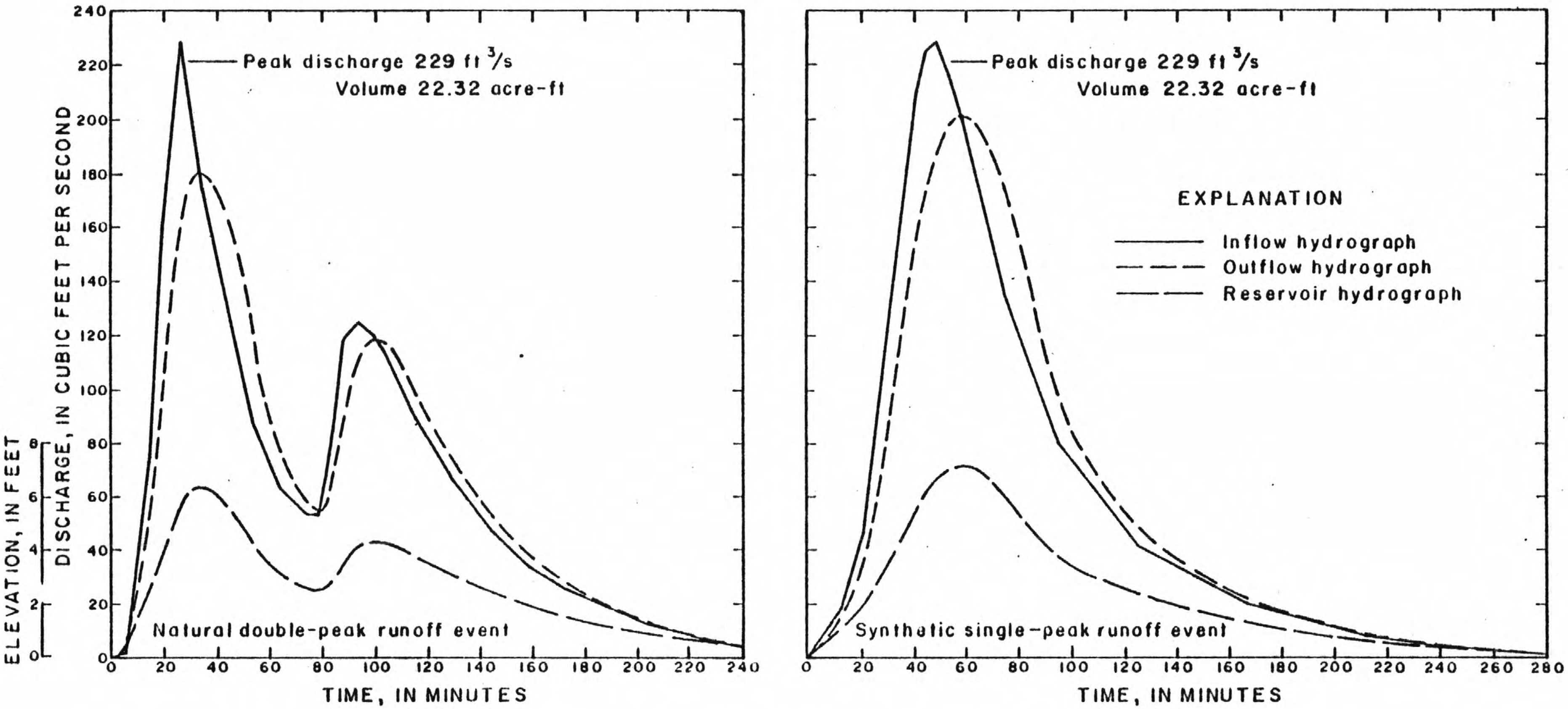


Figure 28.--Comparison of a natural double-peak runoff hydrograph (Sage Creek tributary near Orpha, Wyo., July 25, 1965) to a synthesized single-peak hydrograph of the same magnitude and volume when routed through the ponding area and a 4 x 4-foot culvert. This is a high-head flow condition.

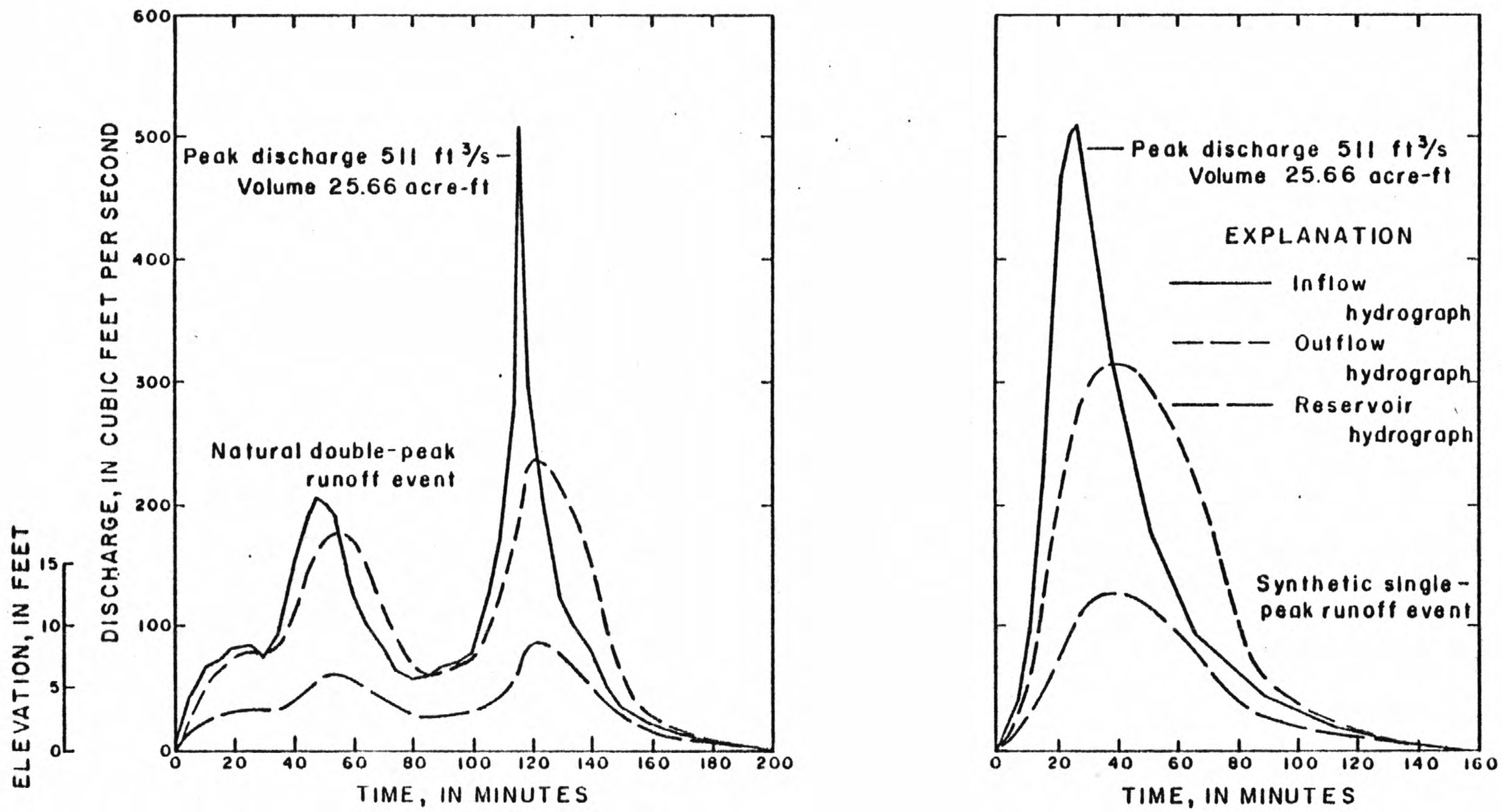


Figure 29.--Comparison of a natural double-peak runoff hydrograph (Badwater Creek tributary near Lysite, Wyo., June 14, 1967) to a synthesized single-peak hydrograph of the same magnitude and volume when routed through the ponding area and a 4 x 4-foot culvert. This is a high-head flow condition.

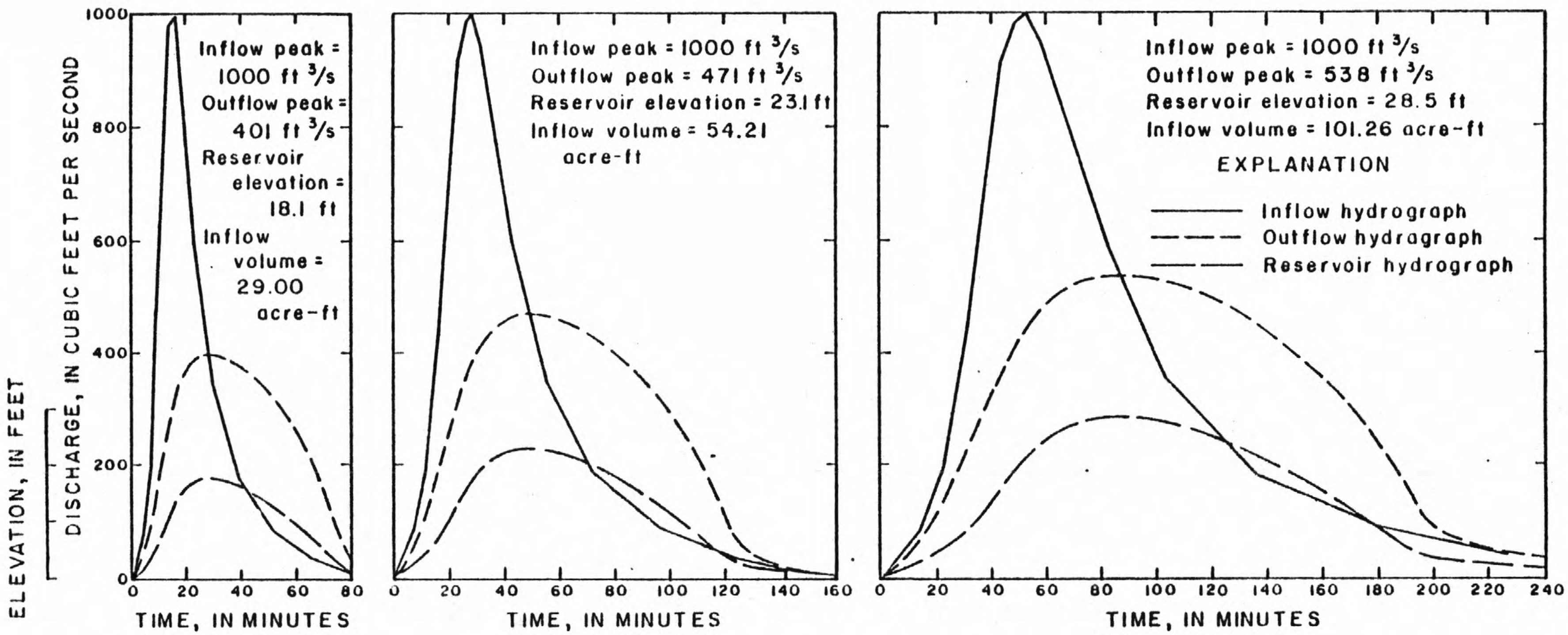


Figure 30.--A comparison of single-peak hydrographs of equal magnitude but different volumes routed through the ponding area and a 4 x 4-foot culvert. The flow with the greatest volume causes the highest water level in the ponding area.

APPLICATION OF RESULTS

The methods described above are applicable throughout the study area for small drainage areas as large as 11 square miles. As an example, and for a comparison with results from a log-Pearson Type III frequency determined on a small basin, Hay Draw near Midwest, Wyo., was selected. A crest-stage gage was maintained at this site, and a frequency study has been made. The drainage area is 1.60 square miles and 13 years of record were used in the frequency study. The 2-, 5-, 10-, and 25-year peak frequencies will be compared.

The computations follow:

1. The basin characteristics (drainage area, basin slope, maximum basin relief, and channel slope) were determined from the best available topographic maps.

$$A = 1.60 \text{ mi}^2$$
$$S_B = 778 \text{ ft/mi}$$
$$R_m = 290 \text{ ft}$$
$$S_{10/85} = 130 \text{ ft/mi}$$

2. The equations for the desired frequencies were used.

$$Q_2 = 34.06\, A^{1.134}\, S_B^{1.216}\, R_m^{-1.609}\, S_{10/85}^{0.539}$$
$$Q_2 = 286 \text{ ft}^3/\text{s}$$
$$Q_5 = 30.77\, A^{1.105}\, S_B^{1.135}\, R_m^{-1.412}\, S_{10/85}^{0.588}$$
$$Q_5 = 576 \text{ ft}^3/\text{s}$$
$$Q_{10} = 32.99\, A^{1.094}\, S_B^{1.080}\, R_m^{-1.308}\, S_{10/85}^{0.603}$$
$$Q_{10} = 827 \text{ ft}^3/\text{s}$$
$$Q_{25} = 37.73\, A^{1.086}\, S_B^{1.012}\, R_m^{-1.192}\, S_{10/85}^{0.613}$$
$$Q_{25} = 1{,}210 \text{ ft}^3/\text{s}$$

3. The results were compared with Q_2, Q_5, Q_{10}, and Q_{25} from the station frequency using the log-Pearson Type III distribution.

Station frequency; $Q_2 = 300$ ft^3/s

from equation; $Q_2 = 286$ ft^3/s

Station frequency; $Q_5 = 634$ ft^3/s

from equation; $Q_5 = 576$ ft^3/s

Station frequency; $Q_{10} = 920$ ft^3/s

from equation; $Q_{10} = 827$ ft^3/s

Station frequency; $Q_{25} = 1{,}350$ ft^3/s

from equation; $Q_{25} = 1{,}210$ ft^3/s

The maximum spread between discharges ranges from less than 5 percent for the Q_2 to less than 12 percent for the Q_{25}.

If it were desirable to develop a design hydrograph at this site, it would be necessary to compute a volume to use with the design-peak discharge. Consider the 25-year volume for use with the 25-year peak discharge. The basin characteristics are available (listed above), so the following computations would be made:

$$V_{25} = 584\ A^{1.142}\ S_B^{0.687}\ R_m^{-1.260}$$

$$V_{25} = 76.4 \text{ acre-ft.}$$

Using the dimensionless hydrograph method, the flow units and time units would be computed as:

$$Q' = \frac{1210}{60} = 20.17 \text{ ft}^3\text{/s per flow unit}$$

$$V' = \frac{76.4}{970} = 0.0788 \text{ acre-ft per sq unit}$$

$$T' = 726\ \frac{V'}{Q'} = 726 \times \frac{.0788}{20.17} = 2.84 \text{ min per time unit}$$

From a prepared table to facilitate computations, the incremental time and discharge for the synthetic hydrograph would be computed. These increments, plotted on a linear graph, would provide the design hydrograph (fig. 31).

UNITS OF TIME	MINUTES PER TIME UNIT	MINUTES	UNITS OF FLOW	FT³/s PER FLOW UNIT	FT³/s
0	2.84	0	0	20.17	0
3		9	5.6		113
5		14	13		262
7		20	25		504
10		28	49		988
11		31	57		1150
12		34	60		1210
13		37	59		1190
14		40	55		1110
18		51	38		766
23		65	23		464
30		85	12		242
40		114	5.2		105
50		142	2.0		40
60		170	0.5		10
70	2.84	199	0	20.17	0

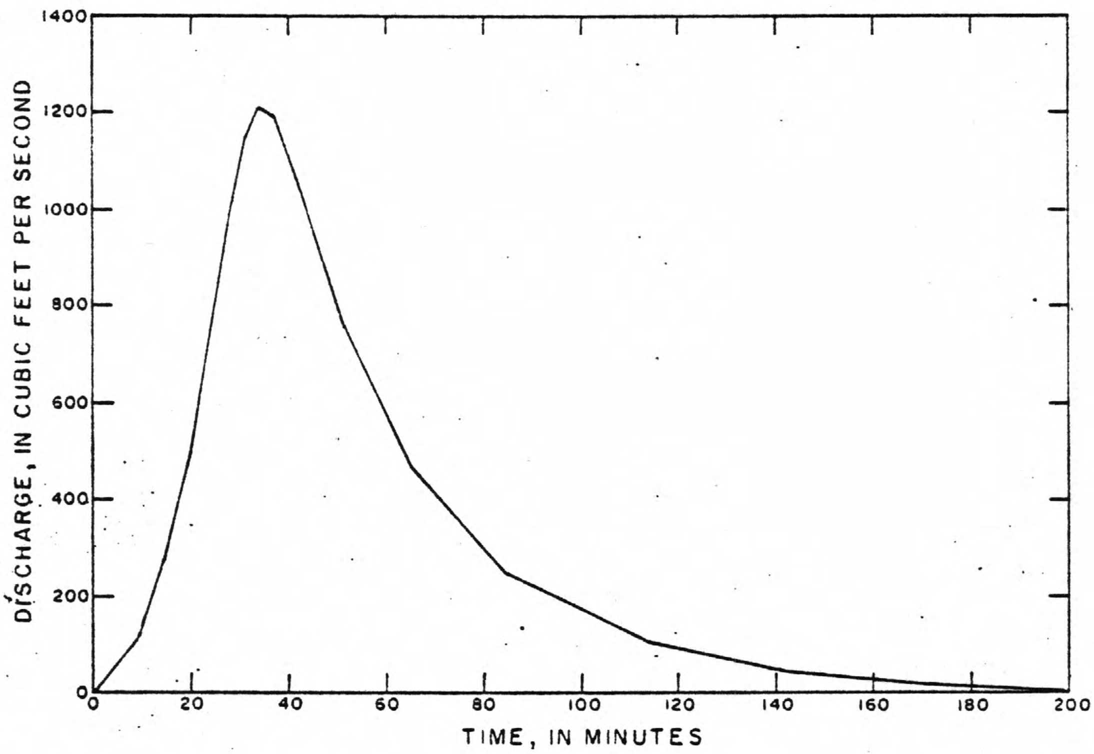


Figure 31.--Computations and resultant hydrograph for Hay Draw near Midwest, Wyo.

The chance of a 25-year peak and a 25-year volume occurring at the same time is somewhat greater than a 1/25 probability of exceedance. There was close agreement between 25-year peaks estimated from basin characteristics and peaks computed from a relationship of peak discharges and runoff volumes, using 25-year volumes.

LIMITATIONS

The defined relations are based on four parameters. Drainage areas ranging from about 0.5 square miles to 11 square miles were tested. Because drainage area invariably was the most significant parameter determined by regression analysis, limitations on the use of the equations should be controlled by drainage area. A test example, using a drainage area of 1.60 square miles (page 103), provided results within 5 percent of the station frequency for Q_2 and to less than 12 percent for other frequencies up to the Q_{25}. The empirical relations are applicable only to unregulated flow sites within the defined range of drainage areas.

The importance of basin slope is apparent within the defined range of drainage areas. The authors believe that the effect of basin slope decreases as drainage area increases, but the size of the area above which basin slope is not significant is not known. The laborious job of determining basin slope for larger basins would be a deterrent to proving this hypothesis. Maximum basin relief, having only a small effect on small drainage areas, might be ineffective on larger ones. Main-channel slope appears to have a minor effect on small drainage basins but apparently becomes more effective on larger basins; the size of area beyond which main-channel slope begins to be effective is not known. Benson (1962b) found main-channel slope to be significant and generally second to drainage area in its effect on peak discharge, for all sizes of drainage areas in New England.

Limitations in the use of the mean dimensionless hydrograph would be only in the ability to obtain a volume for a runoff occurrence. In this study the defined relations for estimating volume are limited to 11 square miles or smaller. The mean dimensionless hydrograph method was developed from hydrographs of runoff events on small drainage basins. The method is similar to Commons' (1942) dimensionless hydrograph which was developed from hydrographs for large drainage basins. The main differences in the two methods is that the recession is reduced for the small basins and, consequently, the area under the hydrograph is smaller for the small basins.

SUMMARY AND CONCLUSIONS

This study has shown that long-term runoff records can be synthesized from long-term rainfall records; that a dimensionless hydrograph can standardize hydrograph shape for use in designing culverts and bridges; and that the potential for temporarily storing flood waters behind highway embankments in undeveloped areas can be economically beneficial.

Methods and techniques were applied or developed as follows to accomplish the objectives that were the basis for this research project.

1. A rainfall-runoff model and a long-term rainfall record (73 years at Cheyenne, Wyo.) were used to synthesize long-term runoff records of annual peak discharges and volumes for 22 small drainage basins in Wyoming. The process involved calibrating a model to each basin from rainfall and runoff observations on each basin. Daily rainfall data from nearby stations of the National Weather Service were used to determine antecedent conditions. Model parameters were developed that best relate the rainfall and runoff. The long-term rainfall record was then used with the model parameters to generate a long-term runoff record on each basin. Variations between Cheyenne and the study basin due to orographic effects were considered and adjustments were applied to the long-term rainfall for transfer to each basin.

2. Volume and peak frequencies were defined at each of the 22 sites through log-Pearson Type III analysis of each synthesized 73-year record.

3. Runoff frequencies of 2, 5, 10, 25, 50, and 100 years were related to basin characteristics, using regression techniques. The basin characteristics most significant in relating volume frequencies were drainage area, maximum basin relief, and basin slope. Those most significant in relating peak frequancies were drainage area, basin slope, maximum basin relief, and channel slope.

4. A relationship between peak discharge and runoff volume was developed for determining a discharge from any volume. The relationship ($Q = 18.66\ V_n^{0.914}$) was defined from 105 runoff occurrences on 35 gaged sites (three hydrographs per site). A correlation coefficient of 0.90 was determined and an average standard error of estimate of 57 percent. The relationship was tested by substituting the volume frequencies (2- to 100-year recurrence intervals) determined from the relationships using basin characteristics. The computed discharges were compared with the peak frequencies determined from relationships using basin characteristics. The equation $Q = 18.66\ V_n^{0.914}$ predicts higher peaks from the 2-, 5-, and 10-year volumes than are estimated from basin characteristics. Peaks predicted from the 25-, 50-, and 100-year volumes are very close to those estimated from basin characteristics.

5. A dimensionless hydrograph was developed to define the characteristic shape of flood hydrographs. A peak discharge and a runoff volume are necessary to produce a synthetic hydrograph that is always a single-peak hydrograph.

6. Analyses of embankment storage indicate that the fast-rising single-peak runoff occurrence is most important in culvert design. Synthetic single-peak hydrographs developed from peaks and volumes of multipeak runoff occurrences and routed through a culvert in an embankment caused higher water-surface elevations behind the embankment than did the natural multipeak flows.

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