EVALUATION OF THE FLOOD HYDROLOGY IN THE COLORADO FRONT RANGE USING PRECIPITATION, STREAMFLOW, AND PALEOFLOOD DATA FOR THE BIG THOMPSON RIVER BASIN

By Robert D. Jarrett and John E. Costa

U.S. GEOLOGICAL SURVEY

Water-Resources Investigations Report 87-4117

Denver, Colorado
1988

DEPARTMENT OF THE INTERIOR

DONALD PAUL HODEL, Secretary

U.S. GEOLOGICAL SURVEY

Dallas L. Peck, Director

For additional information write to:

District Chief
U.S. Geological Survey
Water Resources Division
Box 25046, Mail Stop 415
Federal Center
Denver, CO 80225-0046

Copies of this report can be purchased from:

U.S. Geological Survey
Books and Open-File Reports
Federal Center, Bldg. 810
Box 25425
Denver, CO 80225-0425

CONTENTS

FIGURES

TABLES

CONVERSION FACTORS

The inch-pound units used in this report may be converted to metric (International System) units by use of the following conversion factors:

Multiply inch-pound unit	*By*	*To obtain metric unit*
cubic foot per second (ft^3/s)	0.028317	cubic meters per second
foot (ft)	0.3048	meter
inch (in.)	25.40	millimeter
square mile	2.590	square kilometer

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

EVALUATION OF THE FLOOD HYDROLOGY IN THE COLORADO FRONT RANGE USING PRECIPITATION, STREAMFLOW, AND PALEOFLOOD DATA FOR THE BIG THOMPSON RIVER BASIN

By Robert D. Jarrett and John E. Costa

ABSTRACT

A multidisciplinary study of precipitation and streamflow data and paleoflood studies of channel features was made to analyze the flood hydrology of foothill and mountain streams in the Front Range of Colorado (with emphasis on the Big Thompson River basin) because conventional flood-frequency analyses do not adequately characterize the flood hydrology. In the foothills of Colorado, annual floodflows are derived from snowmelt at higher elevations in the mountain regions, from rainfall at lower elevations in the plains or plateau regions, or from a combination of rain falling on snow. Above approximately 7,500 feet snowmelt dominates; rain does not contribute to the flood potential.

Regression analyses were done to determine flood characteristics at ungaged sites. These study results helped identify a relatively homogeneous hydrologic foothill region in the South Platte River basin. When the drainage area below 8,000 feet was used in the regional flood-prediction equations rather than the total drainage area, the standard error of estimate improved from 142 to 44 percent for the regional flood-prediction equations. These regression relations and study results indicate that methods of computing flood characteristics, based on rainfall-runoff modeling, overestimate flood magnitude in the foothills and mountains of Colorado. Regional flood-frequency relations were compared with rainfall-runoff flood-estimating technique results, which included an evaluation of the magnitude and frequency of the probable maximum flood. The study demonstrated that the concept of storm transposition from lower elevations to higher elevations, that is the basis of the rainfall-runoff method, is not supported by meteorological, hydrological, and paleoflood data. Regional-regression relations were used to compute the recurrence interval of selected large floods in the study area. Regional flood-frequency equations, combined with paleoflood investigations, provide more reliable estimates of both common and rare floods. This technique improved flood estimates beyond the 100-year recurrence interval. These regional analyses, supported by radiocarbon dating, indicate that the 1976 Big Thompson flood, in the area of most intense rainfall, had a recurrence interval of about 10,000 years. Evaluation of streamflow data and paleoflood investigations provide an alternative for evaluating flood hydrology and the safety of dams. The study indicates the need for additional data collection and research to understand the complexities of the flood hydrology in mountainous regions, especially its effects on flood-plain management and design of structures in the flood plain.

INTRODUCTION

Methods of determining flood-frequency relations can be grouped into two general types. One consists of using streamflow-gaging station records; the other uses rainfall-runoff relations. In many parts of the United States, flood-frequency relations from these two methods yield comparable results.

In the method based on streamflow records, the annual flood series is analyzed statistically to obtain flood magnitudes at selected recurrence intervals using guidelines proposed by the Interagency Advisory Committee on Water Data (1982). Because streamflow records are collected at only a few of the many sites where information is needed, streamflow-gaging station information must be transferred to ungaged sites. Regional analysis is concerned with extending records spatially and provides a tool for regionalizing streamflow characteristics (Riggs, 1973). In addition, regional analysis may produce improved estimates of streamflow characteristics at the gaged sites by decreasing time-sampling errors. Multiple regression is used to relate the discharge for a given frequency to climatic, basin, and channel-geometry characteristics, leaving residuals that may be considered due to chance. The regression line averages these residuals. In Colorado, several regional analysis reports are available to estimate flood-frequency relations (McCain and Jarrett, 1976; Livingston, 1981; Kircher and others, 1985; Livingston and Minges, 1987).

In the second method, flood-frequency estimates are calculated using rainfall-runoff relations. Rainfall and runoff data are collected at a site, and the hydrologic response of the basin (in terms of loss rates, unit-hydrograph coefficients, and routing) is established. Then, by using the calibrated model and long-term rainfall and runoff records or design rainfall information, flood-frequency relations can be determined.

Flood-frequency estimates are used for flood-plain management and the design of structures in the flood plain. For example, current practices for the design of high-hazard dams include protection against severe short-term precipitation of approximately 1 to 72 hours in duration, termed probable maximum precipitation (PMP). The basic guideline used in establishing these criteria for design of dams in Colorado is a publication of the U.S. Bureau of Reclamation (1973). The PMP magnitudes are based on the hydrometeorological processes that generate extreme floods. Careful consideration is given to the meteorology of storms that produce these major floods in the United States and include features, such as quantity of rainfall, dew-point temperatures, and depth-area-duration (D-A-D) values, produced by these storms. The D-A-D values for different areas then can be maximized hypothetically by maximizing the factors affecting rainfall to estimate an appropriate PMP value. A recent report establishes revised PMP values in the Front Range of Colorado (Miller and others, 1984).

Probable-maximum-flood (PMF) estimates based on rainfall-runoff relations are determined by identifiying the drainage basin, distributing the PMP by time, maximizing antecedent-moisture conditions and minimizing loss rates, and using a mathematical model (usually the unit-hydrograph method) to translate precipitation excess throughout the entire drainage basin into its resulting flood hydrograph or PMF. The revised PMP values (Miller and others, 1984) indicate that extremely large-magnitude rainfall floods may occur at higher elevations in Colorado.

In Colorado, flood estimates based on streamflow records and rainfall-runoff relations are different. Design hydrology for flood-plain management and hydraulic structures may be questionable because of the large differences in flood estimates in the foothills and mountains of Colorado. Presently (1987), the U.S. Bureau of Reclamation is reevaluating the design of the spillway for Olympus Dam on the Big Thompson River at Estes Park, Colorado. The existing spillway is designed for a flood of 22,500 cubic feet per second. However, a revised PMF (U.S. Bureau of Reclamation, written commun., 1984), based on new PMP estimates, is 84,000 cubic feet per second. This revised design discharge would increase dramatically the size of the spillway. Studies of preliminary streamflow and regional analysis and paleoflood data indicate that the largest natural floodflow in the Big Thompson River at Estes Park is about 5,000 cubic feet per second during the last 10,000 years.

The 1976 Big Thompson River flash flood in the Front Range west of Loveland was the largest natural disaster in Colorado history; 139 people were killed and $35 million in property damages occurred. The subsequent difficulties in interpretation of the magnitude and frequency of this and other catastrophic floods, using conventional hydrologic analyses, indicated a new method, or modifications to existing procedures, are needed.

Purpose and Scope

A multidisciplinary study was conducted to evaluate the flood hydrology of the Big Thompson River basin and to compare the systematic, historic, and paleoflood estimates with PMF results. The primary purpose of this report is to describe the extreme differences in flood-frequency estimates based on systematic streamflow and paleohydrologic data compared to PMF estimates in an area of mixed-population flood hydrology. The second purpose is to describe the lack of intense large-areal-extent rainstorms at high elevations, and to indicate that storm transposition of low elevation storms could lead to erroneously large computed flood discharges.

Approach

This flood-hydrology report supplements the existing report about flood hydrology of foothills and mountains by Jarrett and Costa (1983) with: (1) Onsite paleoflood investigations in the Big Thompson River basin and surrounding river basins, (2) a new index of the contributing drainage to flood runoff that indicates the trends based on elevation, (3) computation of regional rainfall flood-frequency relations, (4) incorporation of paleoflood data into site and regional flood-frequency relations, (5) a comparison of the regional flood-frequency relations to rainfall-runoff estimates for the selected sites, (6) demonstration of the effect of these flood-frequency relations on design of structures and use of the flood plain, and (7) an indication of future research needs.

This report evaluates the flood hydrology in a part of the South Platte River basin (fig. 1), with emphasis on two sites in the Big Thompson River basin: a high elevation mountain site (site 18) and a low elevation site (site 21). The two sites were selected because of their extensive streamflow record and paleohydrologic-data base, and because they indicate the effect of elevation on hydrology.

COLORADO FRONT RANGE STUDY OVERVIEW

The majority of Colorado's population is concentrated in, along, or near the foothills at the base of the Rocky Mountains. Extremely destructive flash floods [such as the 1976 Big Thompson River flood described by McCain and others (1979)] occur in this area. Therefore, a comprehensive, multidisciplinary study was undertaken to evaluate the flood hydrology of foothill and mountain streams in Colorado (Jarrett and Costa, 1983) and is summarized in this section. That study focused on the analysis of available precipitation and streamflow records, the use of paleohydrologic techniques in flood-hydrology studies, and the installation and operation of 18 crest-stage streamflow gages to determine the annual maximum flood on selected foothill stream watersheds. Paleoflood hydrology (the study of botanic, sedimentologic, and geomorphic flood evidence remaining in the valley) can provide important supplemental information about the spatial occurrence, magnitude, and frequency of floods.

In the foothills of Colorado, annual floodflows are derived from snowmelt at higher elevations in the mountain regions, from rainfall at lower elevations in the plains or plateau regions, and/or from a combination of rain falling on snow or mixed-population hydrology. When snowmelt- and rain-generated peaks were examined separately (which improves flood-frequency estimates in mixed-population flood regions) for 69 unregulated streams in the foothills region of Colorado in the South Platte, Arkansas, and Colorado River basins (Elliott and others, 1982), flood-frequency analysis indicated different trends based on elevation. The location of 27 selected study sites in the South Platte River basin are shown in figure 1. Flood-frequency relations for two sites analyzed in the Clear Creek drainage basin just west of Denver indicate that the change from snowmelt- to rainfall-dominated flooding occurs abruptly within a small range in elevation. Clear Creek near Golden (site 11) (figure 2*A*) has a gage elevation of 5,735 feet, is a snowmelt-dominated stream for floods less than the 10-year flood, and a rainfall-dominated stream for floods in excess of the 10-year flood. The flood of record at this site is 5,890 cubic feet per second as a result of an intense thunderstorm over the drainage area at an elevation less than 7,500 feet. In contrast, for Clear Creek near Lawson (site 10) (figure 2*B*) at an elevation of 8,080 feet, the snowmelt-runoff floods predominate to the 500-year flood. The flood of record at this site is 2,240 cubic feet per second resulting from snowmelt, and the largest rainfall flood of record at this site is 1,500 cubic feet per second.

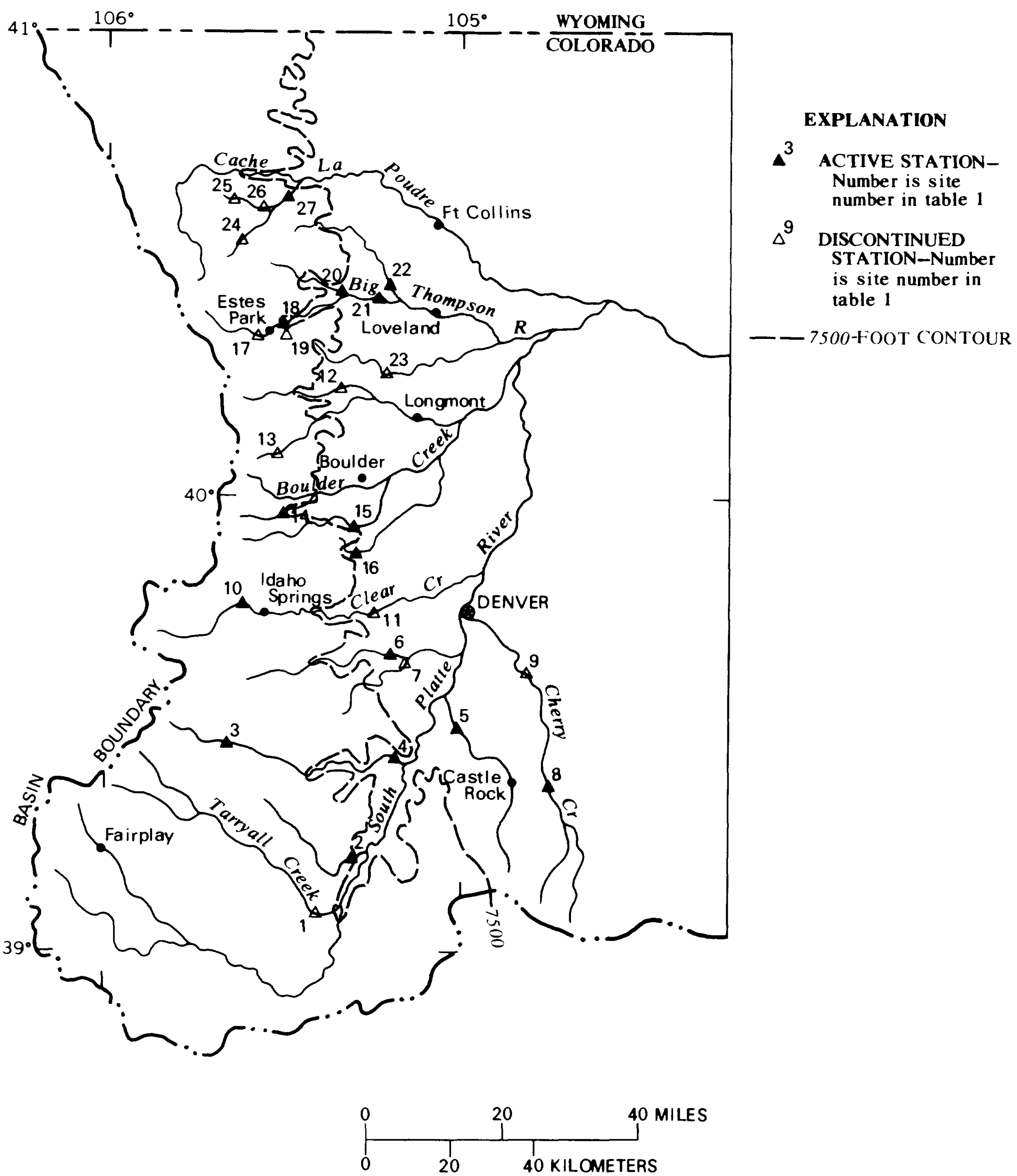

Figure 1.--Selected streamflow-gaging stations for which peak flows were differentiated in the South Platte River basin.

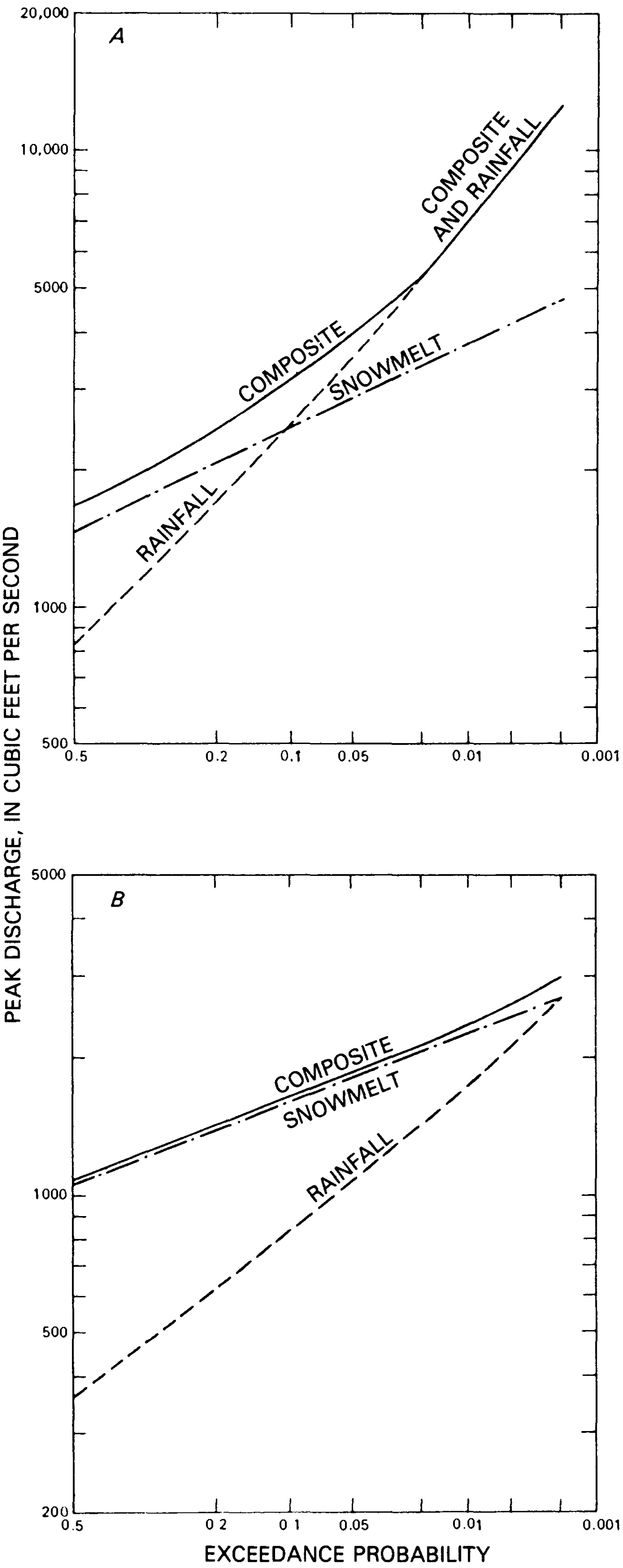

Figure 2.--Flood-frequency curves for Clear Creek near (*A*), Golden, Colorado (site 11), and (*B*), Lawson, Colorado (site 10).

Precipitation, streamflow, and paleoflood data from throughout the foothill region indicate that snowmelt floods predominate above 7,500 feet, and that rainfall floods predominate below 7,500 feet in the South Platte River basin in the Colorado Front Range. Where rainfall does contribute to floods above approximately 7,500 feet, discharges per unit drainage area are extremely small when compared with lower elevation floods resulting from rainfall. In basins above 7,500 feet, large floods attributed to intense rainfall, which were investigated and used in rainfall-runoff-derived flood hydrology studies, were, in fact, debris flows and not waterfloods (Costa and Jarrett, 1981). A debris flow is a gravity-induced rapid mass movement of a body of granular solids, water, and air. Debris typically constitutes 70 to 80 percent or more, by weight, of the flow. Use of debris flow data in flood hydrology studies produces inaccurate and extremely overestimated values of rainfall and flood discharges.

EVALUATION OF PRECIPITATION, STREAMFLOW, AND PALEOFLOOD DATA

Big Thompson River at Estes Park

Estes Park is at an elevation of 7,500 feet. The Big Thompson River has a drainage area of 137 square miles at this point. Olympus Dam, which forms Lake Estes, is located at the downstream limit of Estes Park (and downstream from the streamflow-gaging station).

Precipitation Data

Rainfall that produced the 1976 Big Thompson River flash flood in Larimer County was reported to have occurred at an elevation of 8,000 feet (Miller and others, 1984). This general statement, however, needs clarification. The higher elevations where intense precipitation was reported were associated with isolated mountain peaks above the general topographic elevation of 7,500 feet. The maximum flood runoff occurred below 7,500 feet (McCain and others, 1979).

For the 1976 Big Thompson River flood, geomorphic indicators and lack of flood evidence in the channels indicate precipitation was small above 7,500 feet. At Estes Park (at 7,500 feet) and at higher elevations, 2 inches or less precipitation was recorded. At the Big Thompson River at Estes Park (site 1), the 1976 peak discharge was 457 cubic feet per second, which was predominantly snowmelt runoff.

Miller and others (1978) evaluated reconstructed flood peaks based on rainfall-runoff analyses to estimate the storm precipitation in areas where precipitation data were lacking. These investigators found it difficult or impossible to reconcile slope-area indirect peak discharges with rainfall measurements. Reconstructed peaks based on rainfall-runoff analyses generally were 25 to 50 percent less than slope-area measurements for the higher gradient streams. However, Miller and others (1978) chose to accept that the indirect peak discharges (McCain and others, 1979) were correct and to increase the rainfall (intensities and quantities) accordingly for the storm. This same practice was done for the 1964 Montana Storm (Boner and Stermitz, 1967). Jarrett (1986) has reported that peak discharges calculated using the slope-area method for higher gradient streams (slopes greater than 0.002) consistently are overestimated, typically, by 75 to 100 percent.

Several studies have evaluated higher elevation precipitation in Colorado. Henz (1974) analyzed Limon, Colorado, radar imagery of summer thunderstorms, which includes the Front Range of Colorado. Over time, these radar images show the location, intensity, and path of progression of each storm. Henz reports that thunderstorm hot spots that result in the intense precipitation in eastern Colorado originated at or below about 7,000 feet and generally move easterly into the plains. Hansen and others (1978), in their study of the climatography of the Colorado Front Range, reported that all large rainstorms east of the Continental Divide occurred below an elevation of about 7,500 feet.

Crow (1983) studied the climatology of the Colorado Front Range by analyzing data from six climatological stations, each having a record of 30 years or more. He found that the available moisture in the higher elevations is a small fraction of the available moisture that feeds convective storms at the lower elevations of the plains just east of the mountains. He also found that most precipitation produced by the most intense thunderstorms in the higher mountains of Colorado generally consists of rain and small ice pellets. The more intense storms generally will have a larger fraction of ice pellets. Crow determined that the most typical precipitation quantities produced by isolated thunderstorms are less than 1 inch and that the majority of storms produce less than 0.3 inch.

Payton and Brendecke (1985) analyzed records of two precipitation stations in the Boulder Creek watershed. These two sites are south of Estes Park, at elevations of 9,900 feet and 12,280 feet and have record lengths of 21 and 18 years. They reported that rainfall intensities decreased with elevation. The data were fitted to an exponential probability distribution and, using the PMP value of 10 inches for 6 hours for these sites reported by Miller and others (1984), they estimated the return period to be much greater than 10,000 years. Although this type of extrapolation, based on short-term data, may not be justified, it does demonstrate the controversy surrounding PMP values at this elevation.

Streamflow Data

Streamflow data for the South Platte River basin that were analyzed by Jarrett and Costa (1983) are listed in table 1. Flood-frequency curves have been developed for several streamflow-gaging stations near Estes Park. These curves are shown for two sites in figure 3*A* and 3*B*: The Big Thompson River at Estes Park (site 18) and Little Beaver Creek near Idylwilde (site 25). The separate snowmelt- and rainfall-flood-frequency curves for each

Table 1.--*Selected basin and flood characteristics for the streamflow-gaging stations*

Site number[1]	Station number	Station number	Rainfall-runoff record (years)	Total drainage area (square miles)	Gage datum (feet)	Mean basin elevation (feet)
1	06699500	Tarryall Creek near Lake George	31	434	8,250	9,900
2	06700500	Goose Creek above Cheesman Lake	52	86.6	6,910	10,100
3	06706000	North Fork South Platte River below Geneva Creek,				
4	06707000	North Fork South Platte River at South Platte	38	479	6,091	10,800
5	06709500	Plum Creek near Louviers	26	302	5,585	6,900
6	06710500	Bear Creek at Morrison	58	164	5,780	8,800
7	06711000	Turkey Creek near Morrison	12	50.1	5,718	7,160
8	06712000	Cherry Creek near Franktown	34	169	6,170	7,100
9	06712500	Cherry Creek near Melvin	29	336	5,630	6,600
10	06716500	Clear Creek near Lawson	32	147	8,080	10,800
11	06719500	Clear Creek near Golden	62	399	5,735	9,600
12	06722000	North St. Vrain Creek at Longmont Dam, near Lyons	27	106	6,050	9,100
13	06722500	South St. Vrain Creek near Ward	22	14.4	9,372	10,500
14	06725500	Middle Boulder Creek at Nederland	33	36.2	8,186	10,400
15	06729500	South Boulder Creek near Eldorado Springs	35	109	6,080	8,800
16	06730300	Coal Creek near Plainview	18	15.1	6,540	8,200
17	06732000	Glacier Creek near Estes Park	14	24.4	7,980	10,700
18	06733000	Big Thompson River at Estes Park	27	137	7,492	10,200
19	06734500	Fish Creek near Estes Park	32	16.0	7,476	8,700
20	06736000	North Fork Big Thompson River, at Drake	30	82.8	6,170	9,000
21	06738000	Big Thompson River at mouth of canyon, near Drake	23	305	5,297	9,300
22	06739500	Buckhorn Creek near Masonville	35	131	5,200	7,400
23	06742000	Little Thompson River near Berthoud	13	101	5,220	7,900
24	06748200	Fall Creek near Rustic	13	3.64	9,765	11,100
25	06748510	Little Beaver Creek near Idylwilde	13	.89	10,000	10,900
26	06748530	Little Beaver Creek near Rustic	13	12.3	8,350	9,700
27	06748600	South Fork Cache La Poudre River near Rustic	18	92.4	7,597	9,900

Table 1.--*Selected basin and flood characteristics for the streamflow-gaging stations*--Continued

Site number[1]	Drainage area (square miles), below elevation (feet)							
	13,000	12,000	11,000	10,000	9,000	8,000	7,000	6,000
1	433	425	383	304	38.2	.000	.000	.000
2	86.6	86.6	70.9	33.3	18.4	6.67	.173	.000
3	123	106	66.9	24.8	2.67	.000	.000	.000
4	474	452	383	306	218	94.4	15.3	.000
5	302	302	302	302	296	254	195	27.8
6	162	157	147	127	99.2	61.7	8.69	.492
7	50.1	50.1	50.1	49.8	48.3	30.9	5.61	.902
8	169	169	169	169	169	169	68.4	.000
9	336	336	336	336	336	336	237	34.3
10	145	111	59.1	25.4	8.38	.000	.000	.000
11	396	355	283	208	129	55.5	9.18	1.20
12	106	99.4	86.8	68.7	52.2	21.2	8.48	.000
13	14.4	12.5	7.98	1.09	.000	.000	.000	.000
14	36.2	34.1	26.0	15.5	6.55	.000	.000	.000
15	109	108	101	85.0	60.4	24.6	4.69	.109
16	15.1	15.1	15.1	15.1	13.9	6.30	1.21	.000
17	24.4	21.0	15.2	9.66	3.76	.000	.000	.000
18	135	125	97.1	65.3	37.1	8.22	.000	.000
19	16.0	16.0	16.0	15.4	11.9	3.90	.000	.000
20	82.6	80.2	72.8	60.5	42.2	19.2	3.73	.000
21	303	290	255	210	162	85.1	25.3	3.66
22	131	131	131	128	117	90.3	50.2	18.6
23	101	101	101	100	96.2	60.4	35.7	14.2
24	3.64	3.36	1.64	.251	.000	.000	.000	.000
25	.890	.890	.520	.000	.000	.000	.000	.000
26	12.3	12.3	11.3	7.72	1.33	.000	.000	.000
27	92.4	90.5	77.3	54.9	24.9	2.22	.000	.000

Table 1.--*Selected basin and flood characteristics for the streamflow-gaging stations*--Continued

Site number[1]	Flood discharge (cubic feet per second), for recurrence interval (years)				
	2	10	50	100	500
1	386	682	936	1,040	1,290
2	114	242	406	492	742
3	180	358	558	655	916
4	449	986	1,640	1,980	2,920
5	393	3,580	17,200	31,300	113,000
6	345	2,050	7,210	11,600	32,500
7	122	732	2,380	3,680	9,170
8	531	3,940	13,900	21,800	55,300
9	2,280	9,880	22,400	29,700	51,300
10	353	817	1,420	1,750	2,680
11	832	2,550	5,350	7,030	12,500
12	400	1,070	2,020	2,540	4,090
13	95.0	246	462	584	952
14	242	574	955	1,140	1,630
15	355	1,440	3,320	4,440	8,000
16	40.0	426	1,760	2,900	7,970
17	126	247	377	439	602
18	425	735	1,030	1,160	1,490
19	20.0	120	391	603	1,490
20	185	938	3,090	4,980	13,400
21	1,180	5,390	14,800	21,600	47,600
22	509	4,050	13,900	21,500	51,600
23	856	4,970	14,400	21,000	45,300
24	21.0	37.0	54.0	62.0	82.0
25	2.90	6.90	12.0	14.0	20.0
26	21.0	50.0	90.0	113	182
27	158	339	587	726	1,150

[1]Site number corresponds to those in figure 1.

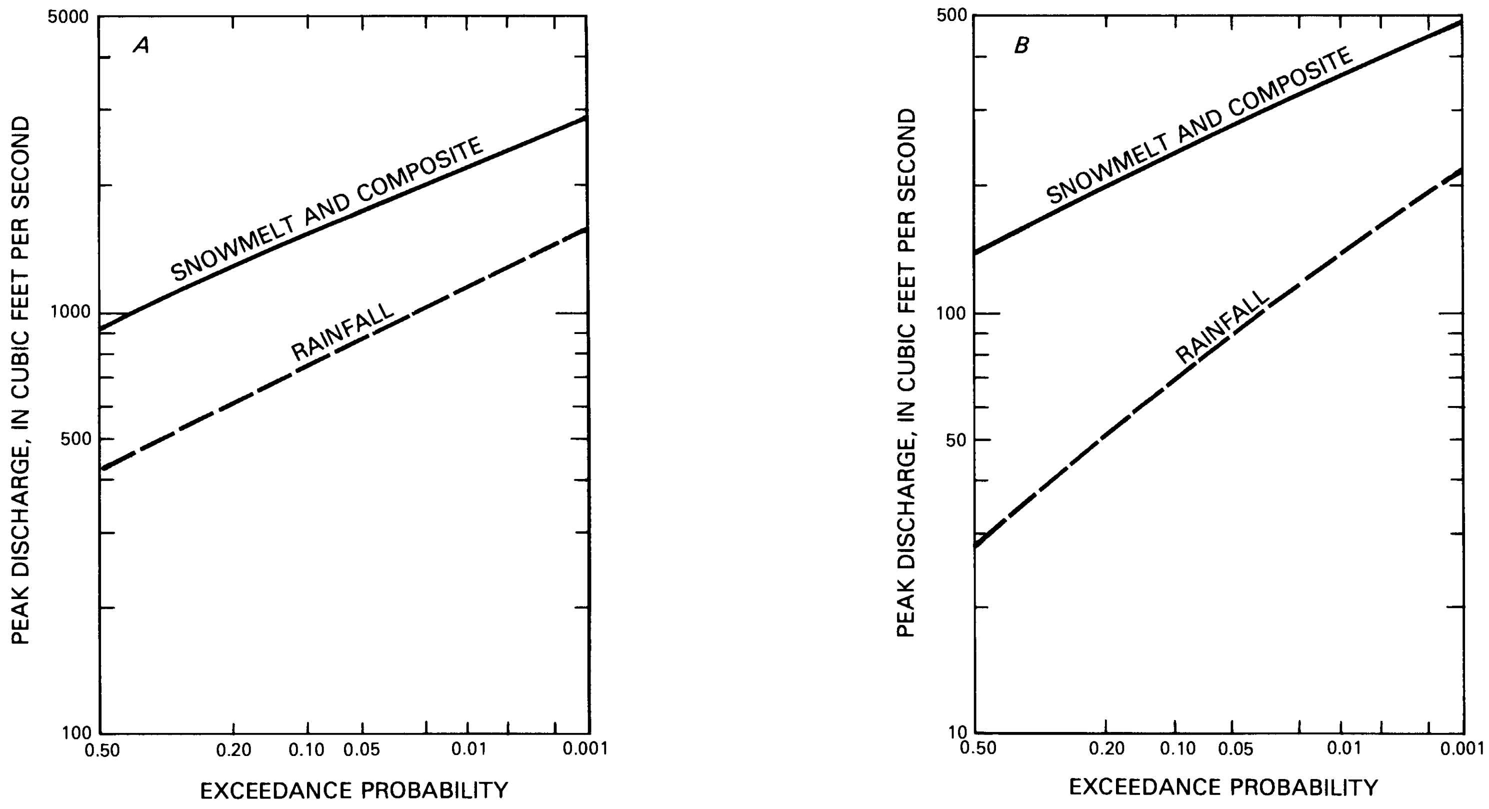

Figure 3.--Flood-frequency curves for: *A*, Big Thompson River at Estes Park, Colorado site 18), and *B*, Little Beaver near Idylwilde, Colorado (site 25).

site can be combined to construct a composite curve, if the populations are independent, by using the equation:

$$P(\text{composite}) = P(\text{snowmelt}) + P(\text{rainfall}) - P(\text{snowmelt}) \times P(\text{rainfall}) \quad (1)$$

where P = the exceedance probability of occurrence (Crippen, 1978).

For both sites, the rainfall curve is much lower than the snowmelt and composite curves, and in neither instance does rainfall contribute to flood hazards. As elevation increases, the difference between the snowmelt and rainfall flood-frequency curves increases. The floods of record at the respective sites are 1,660 cubic feet per second and 28 cubic feet per second. Both floods (highest peak streamflow) resulted from snowmelt runoff. The maximum rainfall floods at these respective sites were 871 and 6.7 cubic feet per second.

Paleoflood Data

Extensive onsite paleoflood research was done in the upper Big Thompson drainage basin upstream from Estes Park. The purpose was to investigate whether there was any stratigraphic or geomorphic evidence of large post-glacial floods in any of the valleys draining into Lake Estes, which is formed by Olympus Dam. Extensive use was made of the sediment and land form evidence left from the flood of the 1982 Lawn Lake Dam failure (Jarrett and Costa, 1986). Although this was not a rainfall-produced flood, the sediments and landforms eroded and deposited by the flood were unique and distinctive. This included huge boulder deposits and an alluvial fan that are so large and distinctive that the occurrence during post-glacial times (approximately 10,000 years ago until 1987) of any other flood of similar magnitude in the other valleys draining to the site should be easy to recognize.

In this type of paleoflood investigation, lack of evidence of the occurrence of extraordinary floods is as important as discovering tangible onsite evidence of such floods. This is true because the geomorphic evidence of extraordinary floods in steep mountain basins, such as the upper Big Thompson River, is unequivocal, easy to recognize and long-lasting because of the volume and size of sediments deposited (Jarrett and Costa, 1986). Knowledge of the nonoccurrence of floods for long periods of time (in this instance, since post-glacial time) has great value in improving flood-frequency estimates (Stedinger and Cohn, 1986) and provides a physical basis for the nonoccurrence of extraordinary floods for very long periods of time.

In the upper Big Thompson River basin, the strategy was to visit the most likely places where evidence of large floods might be preserved, had they occurred. The experience gained from investigating landforms and deposits of the 1976 Big Thompson flood (Costa, 1978b) and the Lawn Lake Dam failure in the upper Big Thompson River basin (Jarrett and Costa, 1986) was used to guide the investigations. Sites studied include: (1) Locations of rapid energy dissipation, where coarse sediment would be deposited, such as tributary junctions or abrupt large valley expansions; (2) locations downstream from moraines across valley floors where large floods would likely deposit sediments eroded from the moraines; and (3) locations along the sides of valleys in wide, expanding reaches where sediment would likely be deposited.

No unequivocal evidence of large floods was found in any stream valley draining into Lake Estes. All of this area is above 7,500 feet, and the results are similar to other studies in similar basins in the Colorado Front Range (Jarrett and Costa, 1983). The kind of paleoflood evidence that was collected during the investigation is shown in the photograph in figure 4. This photograph shows the front of a recessional glacial moraine in Black Creek Valley at an elevation of about 10,800 feet. The moraine is Pinedale (late glacial) in age and is described by Richmond (1960). Black Creek flows over this moraine in a small, narrow channel that has not disturbed the coarse, bouldery material left behind by the glacier. If there had been any floods, greater than about 500 cubic feet per second down this valley since the moraine was deposited, the moraine would have been breached, a wider channel formed, and many of the large glacial boulders would have been strewn across the valley floor downstream. This was not observed here, or in any other valley above 7,500 feet investigated in the upper Big Thompson River basin.

Figure 4.--Front of glacial moraine in tributary to the Big Thompson River at Estes Park. The stream about 3 ft to the left of man has not disturbed the glacial sediments since they were deposited, about 8,000 to 10,000 years ago.

The absence of any paleoflood evidence of large floods in the upper Big Thompson River basin indicates that such floods have not occurred during post-glacial times. The landforms and deposits from such events are sufficiently well-known that, if such evidence existed, it would have been recognized (Helley and La Marche, 1973). The 1982 Lawn Lake Dam-break flood in the Big Thompson River had a peak discharge of 5,500 cubic feet per second at Estes Park and left identifiable flood deposits in the valley. Because similar flood deposits have not been found above 7,500 feet, except for glacial outwash and dam-break floods, there does not seem to have been any floods that had flows greater than 3,000 to 5,000 cubic feet per second during the last 8,000 to 10,000 years.

Big Thompson River at Mouth of Canyon, near Drake

This site is located at the base of the foothills where the river flows out onto the plains of Colorado. The elevation at the site is 5,300 feet. The drainage area of the site is 305 square miles. This site is about 17 miles downstream from Estes Park.

Precipitation Data

At this elevation and in the vicinity of this site, large rainstorms occur frequently. Five extreme storms are listed in the report by Miller and others (1984). These storms include the 1938 Spring Canyon, 1938 Missouri Canyon near Masonville, 1948 Fort Collins, 1948 Tucker Gulch at Golden, and 1976 Big Thompson flood, all resulting from intense thunderstorms.

Streamflow Data

As stated earlier, lower elevation floods result from intense rainstorms. The flood-frequency curves for the Big Thompson River at Mouth of Canyon, near Drake are shown in figure 5. Rainfall controls the frequency curve for floods greater than the 2-year flood. The contribution of snowmelt to the flood frequency is small, because the snowmelt generally only comes from the higher mountains. Although the size of the drainage area at site 21 is 2.23 times larger than at Estes Park (site 18), the 100-year snowmelt flood is only 22 percent larger. The flood of record at site 21 is 31,200 cubic feet per second, which occurred during the 1976 flash flood. Frequency curves for other lower elevation sites have rainfall curves much higher than the snowmelt curves.

Paleoflood Data

The frequency of extraordinary floods can be estimated in a number of ways (Costa, 1978a, 1978b). In the Big Thompson River downstream from Estes Park following the catastrophic flood during 1976 (McCain and others, 1979), radiocarbon dating of truncated and eroded landforms yielded an estimate of the minimum length of time since an event of similar magnitude had occurred in the valley. Radiocarbon dating of older boulder deposits from earlier floods preserved in river terraces and exposed by erosion following the 1976 flood also provided evidence of the length of time since a flood of similar magnitude occurred.

In the lower Big Thompson River basin, three radiocarbon-dated alluvial fans were used to indicate the rare occurrence of floods like the one during 1976. The 1976 flood eroded fans that essentially were

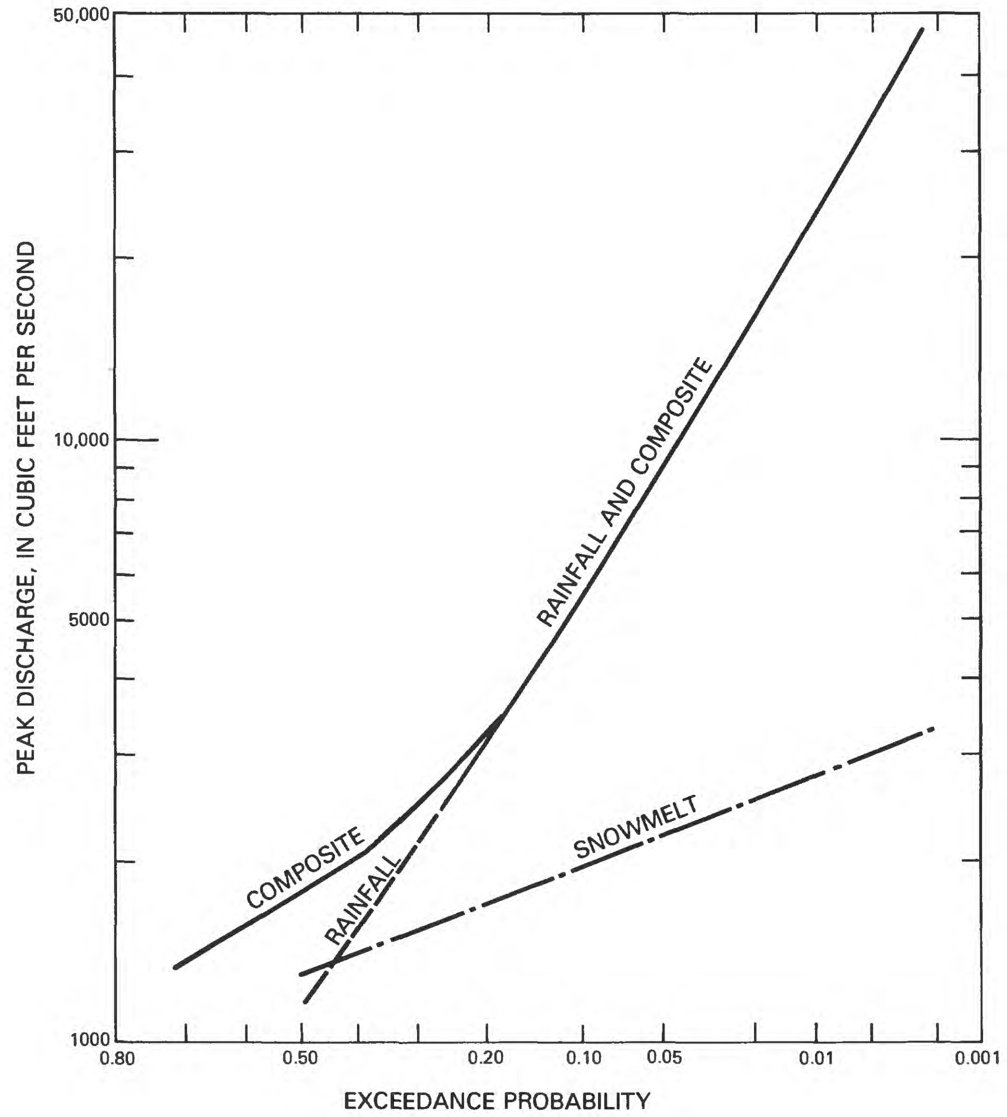

Figure 5.--Flood-frequency curves for Big Thompson River at mouth of canyon, near Drake, Colorado (site 21).

undisturbed for 6,600 to 10,400 years. The flood also eroded old river terraces and exposed some very coarse older flood deposits in one location as shown in figure 6. These are the largest pre-1976 flood sediments known in the valley. A radiocarbon date from the fine-grained deposit on top of the coarse boulders was 10,500 years, which strongly indicates that the flood boulders are glacial outwash and were deposited by large floods during glacial melting. This evidence indicates that the flood in the lower Big Thompson River basin during 1976 was the largest since glacial melting, or during the last 8,000 to 10,000 years.

Figure 6.--Eroded old river terrace and flood deposits on the Big Thompson River downstream from Drake, Colorado.

Historic flood records from the foothills indicate that the foothill region below 7,500 feet in the Colorado Front Range is subject to catastrophic cloudburst rainfalls that may lead to disastrous flooding. Such flooding has occurred numerous times at lower elevations in this area in the past; however, at any given site on a stream draining this area, the frequency of these extraordinary floods is very rare, as indicated by the evidence in the lower Big Thompson River basin.

REGIONAL FLOOD-FREQUENCY RELATIONS

Flood-frequency relations at streamflow-gaging stations are well documented. However, flood characteristics also are needed at ungaged sites. This information can be obtained using the flood-information transfer techniques discussed in the "Introduction". Past applications of these techniques have failed to adequately describe the flood hydrology of foothill streams (McCain and Ebling, 1979). Although there are limited precipitation and streamflow data, investigators have assumed that the total basin area contributes runoff during rainstorms. However, rainfall floods in the foothill region of Colorado are caused by intense short-duration thunderstorms or cloudbursts of very limited areal extent.

Because there is very little rainfall data for such storms for the foothill region, and because transfer of rainfall data from other nonsimilar hydrometeorologic regions may produce inaccurate and overestimated floodflows, transfer techniques at this time need to be based on streamflow and paleoflood data. One of the problems in determining flood-frequency relations in the foothills in Colorado has been that when rainfall-runoff techniques have been applied at long-term gaged sites (50 or more years), the rainfall-runoff estimates are much larger than those based on frequency analysis of the recorded annual peak-flow data. Users of deterministic methods believe that the gaged record is not representative of the flood hydrology of the site (U.S. Federal Emergency Management Agency, 1984). Our belief is that the rainfall-runoff methods have not been calibrated for this region, that rainfall was transposed from a different hydrometeorologic setting, and that the storms are improperly applied over the entire drainage basin above and below 7,500 feet. To illustrate the use of regression techniques, a relatively homogeneous basin in one part of the foothill region, the South Platte River basin, was selected. Streamflow and basin characteristics are listed in table 1 for 27 sites in the study area.

Conceptually in the foothill region, although intense rainstorms can occur above 7,500 feet, rainfall intensities are relatively low and of very limited areal extent so rainfall runoff generally is less than snowmelt runoff. Analysis of flood records indicated that for two basins located in the foothill region--a large basin that has its headwaters at the Continental Divide and a small basin in which all drainage is below 8,000 feet, as hypothetically shown in figure 7--the rainfall flood peak would be approximately the same if the large basin has the same drainage area size below 8,000 feet as the lower elevation basin. An elevation of 8,000 feet was selected because the 7,500-foot contour line is not on the small-scale topographic maps and is more difficult to interpolate. This elevation also is a conservative value, because slightly more drainage area is used for rainfall runoff. Only that part of the large basin below 8,000 feet would contribute significantly to rainfall runoff. In most instances, the rainfall flood characteristics are the same as the composite flood characteristics (Table 1) and therefore can be used to develop regional flood characteristics below 8,000 feet.

To test this hypothesis, the contributing drainage area from each 1,000-foot part of each basin was calculated as shown in figure 7 and results for Clear Creek near Golden, Colorado (site 11) are listed in table 2. Beginning with the 13,000-foot elevation, the contributing drainage areas below this elevation was calculated for all sites and are listed for all 27 sites in table 1. Regression analysis was done between each flood magnitude and drainage areas below each elevation level. The elevation level that defines the contributing drainage area was selected based on a criteria that uses the decrease of standard error of estimate (average) and the increase in the correlation coefficient. The drainage area, mean basin elevation, and gage datum were all significant but were so intercorrelated with each other that mean basin elevation and gage datum were not used. For each decreasing (or increasing) elevation level, fewer sites were included in the regression because the higher (or lower) sites would not have contributing drainage area and were not used in the analysis.

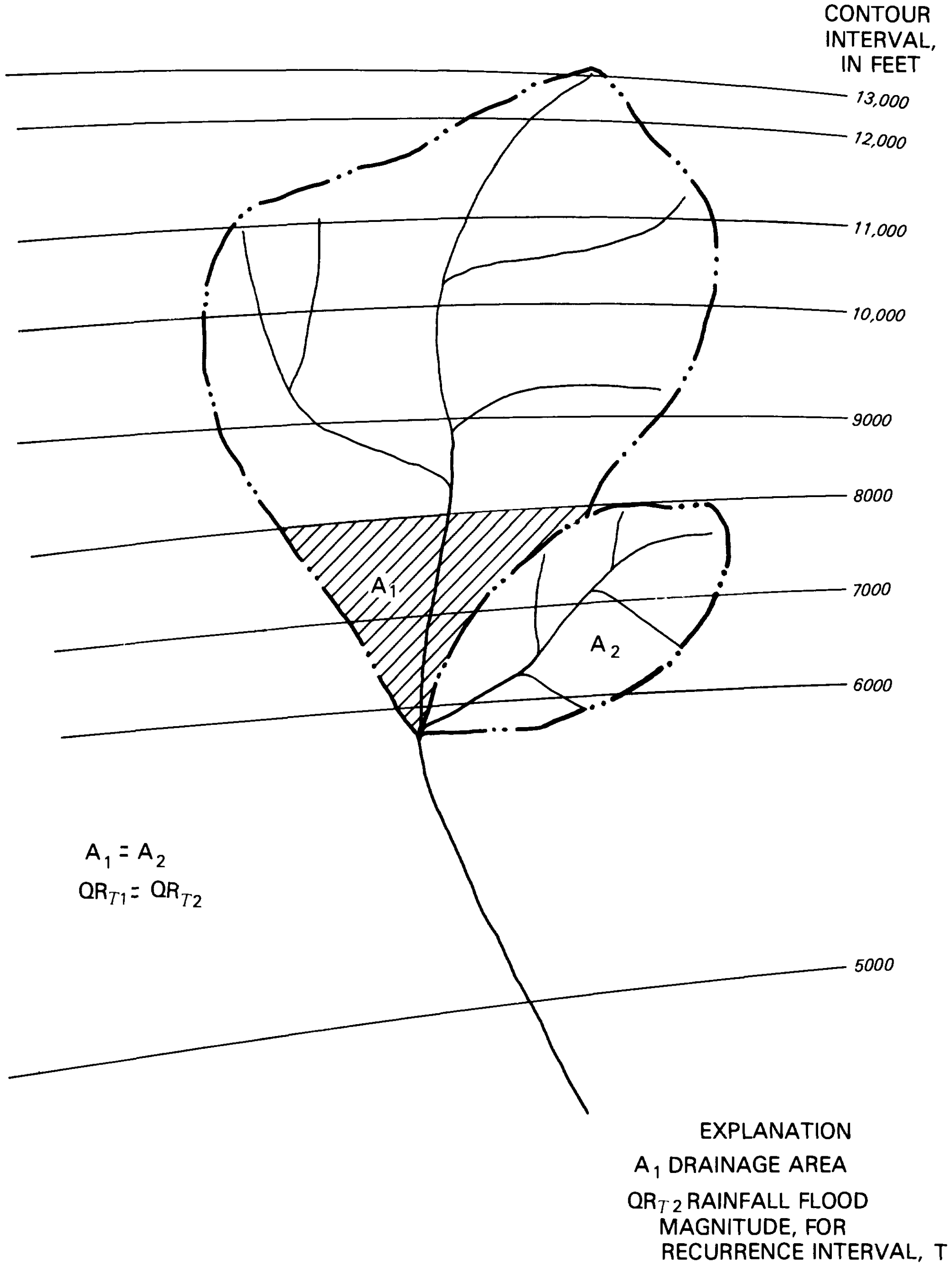

Figure 7.--Plan view of hypothetical drainage basins in the foothills of Colorado.

Regression analyses were made on three drainage-area characteristics: total drainage area, drainage area below a stated elevation level, and drainage area above a stated elevation level. Regression models in the form:

$$QR_T = a(A)^b \quad , \qquad (2)$$

where QR_T = rainfall flood magnitude, in cubic feet per second, for the recurrence interval, *T*, in years;

a = regression constant;

A = drainage-area characteristic, in square miles; and

b = the regression coefficient for the drainage-area characteristic.

Table 2.--*Contributing drainage area, by 1,000-foot elevations, for Clear Creek near Golden, Colorado (site 11)*

Elevation (1,000 feet)	Cumulative Percent area	Drainage area (square miles)
> 12	11.1	44.3
11-12	29.1	71.8
10-11	47.8	74.6
9-10	67.6	79.0
8-9	86.1	73.8
7-8	97.7	46.3
6-7	99.7	8.00
5-6	100	1.20
	Total	399

The standard error of estimate, correlation coefficient, and number of stations included in each regression analyses (for the 100-year recurrence interval) are listed in table 3. For the regression relations that use total drainage area or drainage area above an elevation level, the standard error of estimate is large (184 percent), and the correlation coefficients are relatively small (0.81), indicating poor regression relations. Regression relations that use drainage area above a specified elevation level are not significant. The poor relation between the 100-year rainfall flood and the total drainage area for sites in the South Platte River Basin is shown in figure 8*A*. For the drainage area below a given elevation level, the standard error of estimate is large until the 8,000-foot level where the standard error of estimate decreases. Similarly, the correlation coefficient is maximum at this elevation level; therefore, the drainage area below 8,000 feet was selected as the best area to use to estimate the rainfall flood characteristics in this region. This elevation limit also is supported by the mixed-population, flood-frequency analyses of rainfall data, and paleoflood investigations. The improved relation for the 100-year recurrence-interval rainfall flood and the drainage area below 8,000 feet for the South Platte River Basin is shown in figure 8*B*. The standard error of estimate improved from 142 to 44 percent by using the drainage area below 8,000 feet rather than total drainage area in the 100-year regression model. The standard error of estimate was 207 percent for all 27 stations for the total drainage area in the 100-year regression model. An elevation of 7,500 feet may improve the regression results slightly; however, the 1:250,000-scale topographic maps used do not have this contour line so difficult interpolation would have to be done.

Table 3.--*Standard error of estimate, correlation coefficient, and number of streamflow-gaging stations in the regression analysis of 100-year rainfall flood and selected drainage-area characteristics*

Drainage area below elevation (square miles)			Total drainage area (square miles)		Number of stations in regression analysis[1]
Drainage area below elevation (feet)	Standard error of estimate (percent)	Correlation coefficient	Standard error of estimate (percent)	Correlation coefficient	
13,000	179	0.81	184	0.81	25
12,000	174	.82	184	.81	25
11,000	151	.85	184	.81	25
10,000	147	.80	191	.73	24
9,000	77	.91	204	.62	22
8,000	44	.95	142	.64	16
7,000	44	.90	84	.66	13
6,000	44	.87	84	.54	9

[1]Excluding sites 2 and 4.

Sites 2 and 4 in the upper South Platte River basin were not included in the regression analysis because the rainfall flood characteristics were not considered similar since the sites are in the rain shadow of a large topographic barrier. These sites plot far to the right of the other data and the regressions are shown in figure 8*B*.

The regression equations for estimating flood magnitudes at the 2-, 10-, 50-, 100-, and 500-year recurrence intervals (QR_T) are presented below:

$$QR_2 = 36.9\ (AB8)^{0.61} \qquad SE = 100 \qquad r = 0.74\ , \qquad (3)$$

$$QR_{10} = 111\ (AB8)^{0.75} \qquad SE = 51 \qquad r = 0.92\ , \qquad (4)$$

$$QR_{50} = 231\ (AB8)^{0.83} \qquad SE = 42 \qquad r = 0.95\ , \qquad (5)$$

$$QR_{100} = 302\ (AB8)^{0.86} \qquad SE = 44 \qquad r = 0.95\ , \qquad (6)$$

$$QR_{500} = 533\ (AB8)^{0.92} \qquad SE = 62 \qquad r = 0.92\ , \qquad (7)$$

where *AB*8 = the drainage area below 8,000 feet, in square miles;
(*SE*) = average standard error of estimate, in percent; and
r = the correlation coefficient associated with each equation.

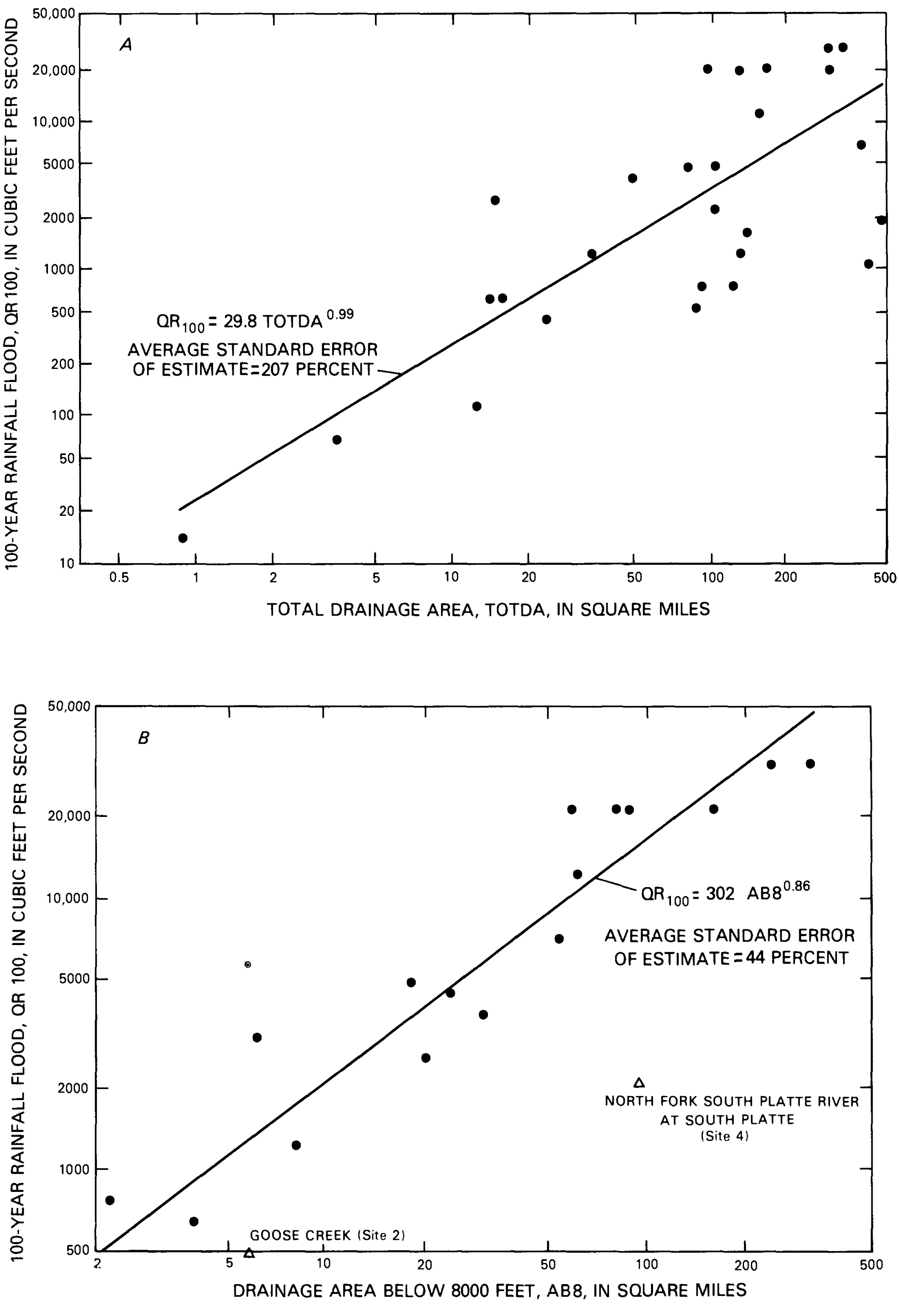

Figure 8.--Relation of 100-year rainfall flood to: *A*, total drainage area for the South Platte River basin, and *B*, drainage area below 8,000 feet for the South Platte River basin.

The residuals of the regression were checked for bias in size of flood, drainage area, gage datum, and mean basin elevation, and no apparent bias was indicated. The regression equations were compared with other regression equations for eastern Colorado (McCain and Jarrett, 1976; Livingston 1981). The regression equations (eq. 3-7) indicated lower flood discharges than the regression equations for the Colorado plains for equivalent recurrence intervals on similarly sized basins, as would be expected. The regression equations can be used in the South Platte River basin (excluding upstream from the South Platte River at South Platte because of the topographic induced rain shadow effects) for sites where elevations are between 5,000 to 8,000 feet and for sites where the drainage area below 8,000 feet ranges from 2 to 250 square miles.

Flood magnitudes at these recurrence intervals can be calculated using only that part of the drainage area below 8,000 feet. The use of the drainage area below 8,000 feet does not imply that it does not rain above this elevation, but rather that rainfall runoff above this elevation does not contribute significantly to flood runoff. To determine the flood characteristics above this elevation requires an evaluation of snowmelt runoff using methods described by Kircher and others (1985). For those sites near the 8,000-foot elevation level, flood characteristics need to be computed by both methods, and the larger values used.

The next step in determining flood characteristics at a site depends on whether the site is ungaged, gaged, or near a gaged site. If the site is ungaged, then use the values from the regression equations. If the site is gaged, then the regression results need to be weighted using the site flood-frequency estimates. The weighting should decrease the time-sampling error that may occur in a site flood-frequency estimate and should improve the flood-frequency estimates. This time-sampling error decreases as the length of record for a site increases. The weighting procedure is described by Sauer (1974). The procedure weights the site flood-frequency estimate and the regression flood-frequency estimate by the years of record at the site and the equivalent years of record of the regression estimate using the following equation:

$$QR_{T(w)} = \frac{QR_{T(s)} \times (N) + QR_{T(r)} \times (E)}{N + E} , \qquad (8)$$

where $QR_{T(w)}$ = weighted flood discharge, in cubic feet per second, for recurrence interval, T, in years;

$QR_{T(s)}$ = site value of the flood discharge, in cubic feet per second, for recurrence interval, T, in years;

N = number of years of site data used to calculate $QR_{T(s)}$;

$QR_{T(r)}$ = regression estimate of the flood discharge, in cubic feet per second, for recurrence interval, T, in years; and

E = equivalent years of record is 10 years for $QR_{T(r)}$ (Interagency Advisory Committee on Water Data 1982, p. 21).

The Interagency Advisory Committee on Water Data (1982) suggestion for equivalent years of record pertains only to the 100-year flood. This assumption is assumed to apply as well to the other recurrence-interval floods. If the site is near a gaged site on the same stream where the ungaged drainage area divided by the gaged drainage area ratio (for the area below 8,000 feet) lies between 0.5 and 2.0, peak discharges for the near gaged site can be computed by the following equation (McCain and Jarrett, 1976):

$$QR_{T(u)} = \left[\frac{A_u}{A_g}\right]^{x} QR_{T(w)} \quad , \tag{9}$$

where $QR_{T(u)}$ = peak discharge at ungaged site for recurrence interval T, in years;

A_u = drainage area at ungaged site;

A_g = drainage area at gaged site, and

x = regression exponent for $AB8$ for selected T (eq. 3-7)

Additional research into the weighting procedures and incorporating other climatic, basin, and geomorphic variables in the regression may improve regional regression results.

RAINFALL-RUNOFF RELATIONS

This section of the report summarizes the flood hydrology resulting from the second approach, rainfall-runoff relations, as applicable in Colorado. This includes calculations of the PMP and PMF.

Probable Maximum Precipitation

The report by Miller and others (1984) provides PMP for durations from 1 to 72 hours for the region between the Continental Divide and the 103rd meridian. The adopted PMP procedure is similar to the procedures used in other PMP studies in the United States. The study region is topographically one of the most complex regions in the conterminous United States. Miller and others (1984) reported that observed extreme storms have not been documented in the mountainous regions of the study area and, to compensate for this, standard storm transposition was employed, assuming the regions were homogeneous meteorologically. Miller and others (1984) attributed the lack of data about large storms in the study area to the fact that the storms were not observed due to a sparse precipitation network and population in the area. The area just to the east of the study area also is sparsely populated, but many extremely intense storms have been recorded (most notably the 1935 Cherry Creek storm, and the 1965 storm over Kiowa, Bijou, and Plum Creek basins) as reported in Miller and others (1984). Reidel and Schreiner (1980) reported that the 1935 Cherry Creek storm actually exceeded the PMP for a 6 hour-10 square mile basin by 4 percent. Several intense storms that occurred in foothill or mountainous regions, included in the report by Miller and others (1984) as major storms, need to be investigated, particularly the effects of storm transposition and elevation.

Precipitation-gage data are subject to various types of errors. The most serious equipment error is the inaccuracy of precipitation measurement because of wind effects; this is especially true for falling snow. Brooks (1938) reported that an unshielded gage may be 75 percent or more deficient in snow catch, or 5 to 10 percent deficient in rain catch. The earliest documented attempt to decrease the adverse effects of wind on precipitation gages was by Thomas Stevenson in Scotland in 1842 (Brooks, 1938). Subsequently, many different devices were attached to the gages prior to the adoption of the Alter shield in 1937.

About 1908 (Warnick, 1956), C.F. Marvin, then Chief of the Instrumentation Division of the U.S. Weather Bureau, fabricated a cone-shaped, solid-metal windshield with a top diameter of about 3 feet that could be attached to the top of a precipitation gage. Unfortunately, this windshield had the effect of "funneling" hail and rainsplash into the precipitation gage. Use of the Marvin windshield resulted in substantially overregistered summer precipitation (when hail is common) in Leadville, Colorado, during 1919-38. Analysis of these precipitation data indicated that the monthly precipitation for these years was overregistered by as much as 157 percent of the long-term monthly precipitation at Leadville (Jarrett and Crow, 1988).

The Marvin windshield was used on the official U.S. Weather Bureau gage in Leadville, Colorado from 1919 to 1938 (Jarrett and Crow, 1988) It is unknown at this time (1987) how many other precipitation gages were equipped with the experimental Marvin windshield; it is unlikely that it was used only on one gage. Analyses of the precipitation records for the gage at Leadville and four nearby precipitation gages, streamflow records, and paleohydrologic investigations were done by Jarrett and Crow (1988).

The precipitation record at Leadville is an unusual and significant data set because it dates back to 1888 and is from a high elevation (10,200 feet). The precipitation record at Leadville has been used in many hydroclimatic investigations because of this long record. Some investigators have interpreted the "increase" in precipitation regime from 1919 to 1938 as an indicator of a climate change.

The precipitation records at Leadville include the largest (and record breaking) higher elevation (7,500 feet) rainstorm (4.25 inches in about 1 hour) recorded in Colorado. This was the only severe storm known to have occurred above 7,500 feet. However, this storm occurred on July 27, 1937, which was during the period the Marvin windshield was used. There was an extraordinary quantity of hail associated with this storm (Jarrett and Crow, 1988); their investigations indicated a more probable storm total of about 1.7 inches. Climatologists and hydrologists have used this storm for the development of design rainfall. Because this storm is the largest and only officially recorded large rainstorm in the mountains of Colorado, it has a large effect on design rainfall. The results of the use of the Leadville data in other hydroclimatic studies are unknown. Because of the importance of the precipitation record at Leadville, a Marvin windshield has been reconstructed, installed on a precipitation gage, and operated next to a standard precipitation gage in Leadville since June 1987.

The most intense longer duration storm at higher elevations was the April 1921 storm just south of Estes Park. This storm had a 24-hour total of 6.40 inches that fell as 87 inches of snow.

One of the major reasons for the extraordinarily large PMP estimates and other design rainfall estimates for the mountains in Colorado when compared with historic records may be the transposition of a severe rainstorm in 1964 in northern Montana to the Colorado mountains. The 1964 floods of northwestern Montana were a result of heavy rain on snow. The Continental Divide at this location averages about 8,000 feet. Boner and Stermitz (1967) indicate that the largest magnitudes of precipitation in mountainous areas were estimated from the indirect estimates of streamflow peak discharge because of lack of precipitation data. Streamflow records from sites at elevations of 4,500 to 5,000 feet had much lower peak runoff than lower elevation sites. Precipitation patterns at higher elevations were erroneously reconstructed from the indirect discharge measurements on the steep small watersheds, resulting in overestimated rainfall quantities. This questionable rainfall data then were transposed to other areas.

The 1972 Rapid Creek flash flood in the Black Hills of South Dakota (Schwarz and others, 1975) was similar in its geographic setting to the 1976 Big Thompson storm. One difference was that the upper elevation limit of precipitation occurred at less than about 4,500 feet, although the Rapid Creek drainage basin reaches elevations of 7,000 feet. This storm and flood occurred just downstream from Pactola Reservoir on Rapid Creek. Maximum peak discharge inflow to the reservoir was 228 cubic feet per second compared with 50,000 cubic feet per second at Rapid City.

PMP values are listed in table 4 (Miller and others, 1984). The values shown are for several durations and for 10 square miles for several locations in the study area.

Table 4.--*Probable maximum precipitation for 10 square miles for selected durations*

Location	Elevation (feet)	Probable maximum precipitation (inches) for selected durations (hours)[1]		
		1	6	24
Continental Divide west of Estes Park---	13,000	7	10	16
Estes Park-------------	7,500	11	17	27
Loveland---------------	5,000	15	26	34

[1]Miller and others, 1984.

The techniques to determine PMP values are for point estimates, whereas in most instances values for larger areas are required to determine PMF values. Depth-area relations are used to determine values for larger areas and seem to be another cause of large rainfall-runoff flood estimates. Miller and others (1984) reported that there are very few storms in the foothills and mountains from which to determine depth-area relations in the study area. Because of the lack of large storms, depth-area relations from other areas were transposed to this study area as shown in figure 9. It is difficult to understand why the 1964 Montana storm with questionable precipitation quantities at high elevations was transposed to this area, and why the 1976 Big Thompson storm was not used to develop depth-area relations. The 1976 storm is the largest storm to occur in the area and was about a 10,000 year recurrence interval flood as discussed

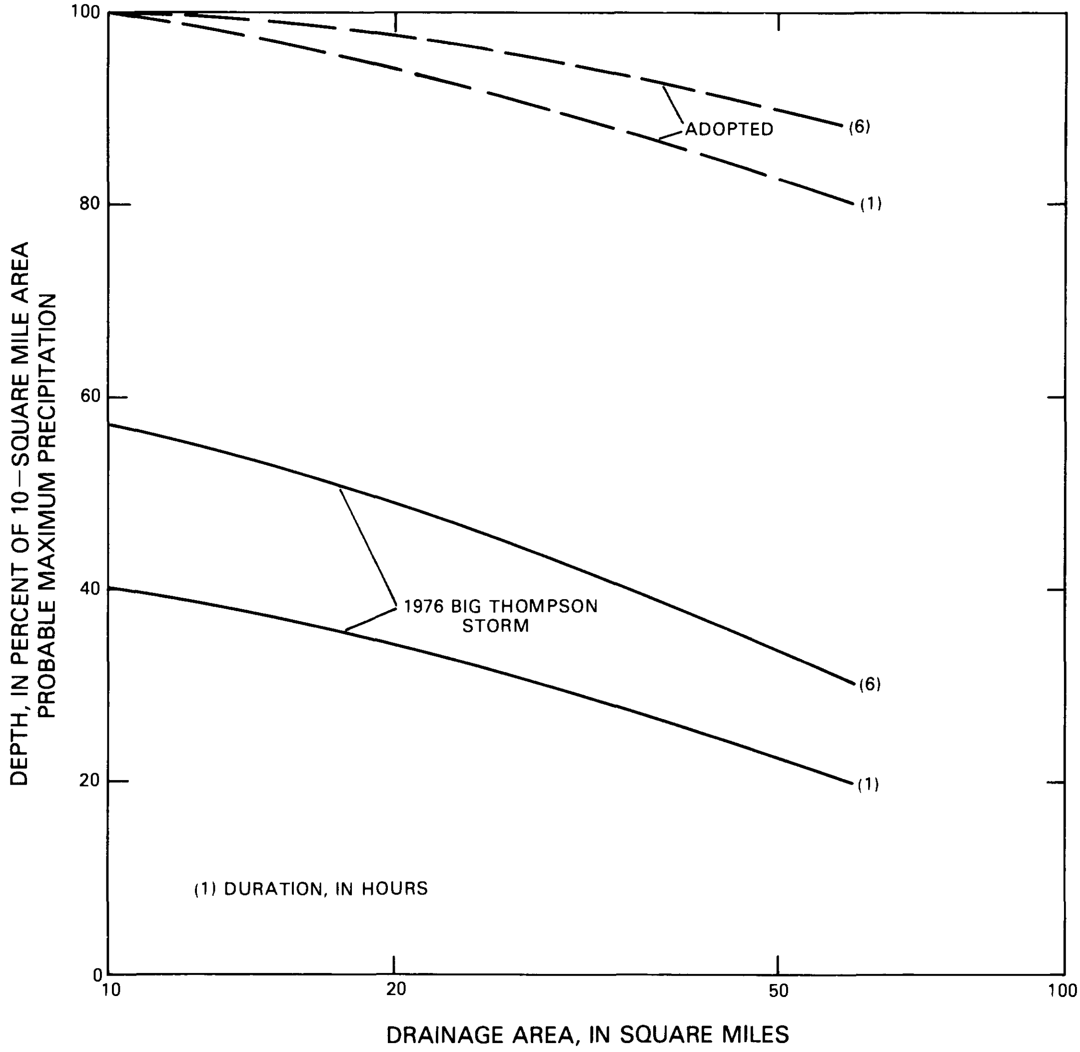

Figure 9.--Depth-area data for the Big Thompson storm and adopted depth-area relations for general-storm probable maximum precipitation for the foothills and mountains east of the Continental Divide, Colorado (from Miller and others, 1978; Miller and others, 1984).

later. The depth-area relations of the Big Thompson storm were determined from the enhanced storm pattern (based on indirect peak-discharge information) in Miller and others (1978) and are shown in figure 9. The Big Thompson relations plot far below the adopted relations that were transposed, indicating that point PMP values would have a much larger reduction factor and smaller PMF values. The other large storms in the foothills and mountains cited by Miller and others (1984) would plot even farther below the adopted curves because their precipitation and area were even smaller than the Big Thompson storm. Overestimated PMP, D-A-D relations, and PMF also would result in overestimated flood volumes resulting in large storage requirements for flood-control dams.

Probable Maximum Flood

The PMF is derived directly from PMP. If PMP values for the Colorado foothill streams are unrealistically large as indicated in this report, then the PMF values also will be unrealistically large. The concept of PMF was developed before paleoflood hydrology was used extensively. Currently (1987), the frequency and magnitude, or just occurrence or nonoccurrence, of extraordinary floods that have return periods of thousands of years in many parts of the United States (Kochel and Baker, 1982) can be estimated. The methods for these estimates are based on the existence of tangible, physical evidence of floods in the drainage basins that can be studied and evaluated. The evidence of the occurrence of extraordinary floods is so diagnostic in some places that well-documented statements can be made about the nonoccurrence of floods of some threshold for many thousands of years in a particular drainage basin.

The concept of PMF is widely used and accepted. The data presented in this investigation indicate some possible modifications in the use of PMF data and their computations. First, because the occurrence of PMF is rare, and extremely variable, the geologic record in the drainage basin being studied might contain some valuable paleoflood data about the occurrence or nonoccurrence of large floods in the geologically distant past. This possibility needs to be investigated. Second, the limitations of the physical environments where large storms are being transposed need to be studied using physiographic and historic records of precipitation and floodflows, and the storms' geographic distributions. And third, regionalization techniques that substitute space for time in flood investigations can add insight and support to situations where PMP and PMF values could be questioned scientifically, as seems to be the situation in the Colorado foothills and mountains.

COMPARISON OF FLOOD-FREQUENCY ESTIMATION METHODS

The problem of defining flood hydrology is not limited only to low probability events but similarly to more frequent events. Methods have been developed to estimate the recurrence intervals of more frequent floods from regionalization of streamflow characteristics and supported by paleoflood evidence. Rainfall-runoff model studies also have been made to determine the flood hydrology for flood hazard studies. Rainfall-runoff analyses were used to calculate flood-discharge values rather than to calculate them for long-term streamflow data because " *** the statistical parameters computed by these methods were not sufficiently reliable to predict the frequency of extreme events *** " (U.S. Federal Emergency Management Agency, 1984, p. 11). A comparison of results from these two methods is important because it demonstrates the range in magnitude-frequency values and may affect results of flood hazard studies for flood-plain management and design of flood-plain structures.

Flood characteristics by the two different methods are computed for Clear Creek for the City of Golden (table 5). Because rainfall was transposed over the entire 399-square-mile basin rather than the 55.4 square miles below 8,000 feet, the flood characteristics determined by rainfall-runoff modeling (U.S. Federal Emergency Management Agency, 1984) are as much as 108 percent larger than estimates from methods in this paper based on long-term streamflow gaging station data, as listed in table 5. We feel that the long-term streamflow data are representative of the flood hydrology. More reasonable rainfall-runoff results probably would be obtained if drainage area above 8,000 feet (where runoff is from snowmelt) were not used as contributing drainage area and representative rainfall and precipitation depth-area reduction data were used for rainfall-runoff calculations.

Table 5.--Comparison of flood magnitudes of selected recurrence intervals for Clear Creek near Golden, Colorado (site 11)

[eq., equation]

Recurrence interval (year) (1)	Flood discharge (cubic feet per second): Foothills analysis: Station (2)	Flood discharge (cubic feet per second): Foothills analysis: Regression (eq. 4 to 7) (3)	Flood discharge (cubic feet per second): Foothills analysis: Weighted (eq. 8) (4)	Flood discharge (cubic feet per second): The city of Golden flood insurance study[1] (5)	Difference column 5-column 4 divided by column 4 (percent) (6)
10	2,550	2,260	2,510	3,470	38
50	5,350	6,480	5,510	8,010	45
100	7,030	9,550	7,380	12,400	68
500	12,500	17,700	13,200	27,400	108

[1]U.S. Federal Emergency Management Agency (1984).

Several extraordinary floods have been described for the study area. The recurrence interval of selected-rainfall floods has been estimated using regionalized regression equations (which are supported with paleoflood studies), and if the flood occurred at a streamflow-gaging station, weighted frequency estimates were developed. The estimated recurrence intervals of the floods listed in table 6 at first might seem improbable; however, the occurrence of floods that have recurrence intervals of thousands of years is entirely possible at some sites in the foothills region. There is extreme variability in the recurrence intervals of the 1976 Big Thompson River flood. The recurrence intervals ranged from less than a 2-year flood at Estes Park to approximately a 10,000-year flood in the areas of most intense precipitation, a 300-year flood at the mouth of the canyon, and about a 10-year flood at the river's confluence with the South Platte River because of attenuation as overbank storage and streamflow diversions.

In Colorado, the historic period dates back to about 1850. Sufficient mining activity in the mountains in the Colorado Front Range at that time make it unlikely that an extraordinary flood would have been unrecorded. Some early floods in the Colorado Front Range were recorded about this time (Follansbee and Sawyer, 1948). The time from 1850 to present (1987) is 136 years. Riggs (1961) and Reich (1973) show the following equation on how frequently floods will occur:

$$P = 1 - (1 - \frac{1}{T})^N \quad , \tag{10}$$

where P = the probability of a specific size flood having a recurrence interval of T-years being exceeded within N years.

During the period from 1850 to the present (1987), the chance of a 5,000-year flood occurring at any single location is 2.7 percent, and the chance of the 10,000-year flood is about 1.3 percent. These percentages are small, but not zero. When all (hundreds) the streams in the Colorado Front Range are considered together, the chance of these rare floods occurring somewhere in the region is much greater.

Recurrence intervals also have been calculated for selected PMF values in the study area. A flood-frequency curve can be constructed using the weighted results for the Big Thompson River at Estes Park site and the PMF. A National Research Council committee recently concluded:

> Clearly, care should be exercised when extending flood-frequency relations to PMF values. Additional research is clearly needed in this area. At present, reasonable and realistic risk investigations can be conducted by linear extension of the frequency curve out through the PMF estimate, which is assigned a return period of 10^6-years, or smaller and more conservative value of 10^4-years (National Research Council, Committee on Safety Criteria for Dams, 1985, p. 244).

Table 6.--*Recurrence intervals from regression analysis and paleoflood data for selected floods*

[--, not applicable]

Site name	Streamflow-gaging station number	Total drainage area (square miles)	Date of flood	Peak discharge (cubic feet per second)	Recurrence interval (years)
Big Thompson River at Estes Park	06733000	137	1976	457	<2
Big Thompson River tributary below Loveland Heights	--	1.37	1976	8,700	>10,000
Rabbit Gulch near Drake	--	3.41	1976	3,540	7,000
Long Gulch near Drake	--	1.99	1976	5,500	>10,000
Big Thompson River above Drake	--	189	1976	28,200	5,000
Big Thompson River at mouth of Canyon, near Drake	06738000	305	1976	31,200	300
Big Thompson River at mouth, near LaSalle	06744000	828	1976	2,470	10
Missouri Canyon near Masonville	--	2.37	1938	2,130	6,000
Tucker Gulch at Golden	--	11.2	1948	11,600	>10,000
Plum Creek near Louviers	06709500	302	1965	154,000	1,500
Cherry Creek near Melvin	06712500	336	1965	39,900	60

Straight-line extrapolations were made from the regional flood-frequency curve (or weighted curve) to the PMF value. The results listed in table 7 indicate that estimates of PMF have recurrence intervals that extend throughout several orders of magnitude. In the study area, these data indicate projects designed for PMF floods do not have the same margins of safety. Dams on the plains and in the foothills are designed for floods that have recurrence intervals generally in the range of 2,000 to 3,000 years, whereas dams above 7,500 feet are designed for floods that have recurrence intervals far in excess of 10,000 years. The present Olympus dam spillway design has a capacity of 22,500 cubic feet per second and has a recurrence interval well in excess of 10,000 years.

Table 7.--Recurrence intervals from regression analysis for selected probable maximum floods
[--, not applicable]

Site name	Streamflow-gaging station number	Total drainage area (square miles)	Probable maximum flood (cubic feet per second)	Recurrence interval (years)
Big Thompson River at Estes Park--------	06733000	137	84,000	>>10,000
Big Thompson River above Drake----------	--	189	[1]116,000	>10,000
Big Thompson River at mouth of canyon, near Drake-----------	06738000	305	[1]180,000	2,200
Plum Creek near Louviers-------------	06709500	302	550,000	2,700
Cherry Creek near Franktown------------	06712000	169	265,000	3,000

[1]Prorated by drainage area from Big Thompson River at Estes Park.

This study has indicated the lack of large floods in areas above 7,500 feet in the mountains of Colorado. In Colorado, there are more than 27,000 dams of which probably several thousand are above 7,500 feet. Since 1890, more than 130 dams have failed (Colorado Water Conservation Board, 1983), but none have failed above 7,500 feet because of overtopping from rainfall runoff. The dams above 7,500 feet have failed as a result of embankment or piping failures, such as the 1982 Lawn Lake Dam failure at an elevation of 11,000 feet (Jarrett and Costa, 1986). Evaluation of streamflow data and paleoflood investigations provide an alternative method for evaluating flood hydrology and the safety of dams.

CONCLUSIONS

The 1976 Big Thompson River flash flood in the Front Range west of Loveland was the largest natural disaster in Colorado history; 139 people were killed and $35 million in property damages occurred. The subsequent difficulties in interpretation of the magnitude and frequency of this and other catastrophic floods, using conventional hydrologic analyses, indicated a new method, or modifications to existing procedures are needed.

A multidisciplinary study of precipitation and streamflow data and paleohydrologic studies of channel features was made to analyze the flood hydrology of foothill and mountain streams in the Front Range of Colorado (with emphasis on the Big Thompson River basin) because conventional hydrologic analyses do not adequately characterize the flood hydrology. In the foothills of Colorado, annual floodflows are derived from snowmelt at high elevations in the mountain regions, from rainfall at low elevations in the plains or plateau regions, or from a combination of rain falling on snow (mixed-population hydrology). Above approximately 7,500 feet, snowmelt dominates; rain does not contribute to the flood potential. Below about 7,500 feet, rainfall-produced floods predominate.

Extensive paleoflood investigations in the Big Thompson River basin support these conclusions. Upstream from Estes Park at an elevation of 7,500 feet, geomorphic indicators and lack of flood evidence in the channels indicate that flooding has been insignificant during the last 10,000 years (since glaciation) including during the 1976 Big Thompson River flood. At the Big Thompson River at the Mouth of Canyon, near Drake, precipitation and streamflow data and paleoflood investigations indicate many large and intense rainfall floods have occurred in the past.

Regression analyses were done to determine flood characteristics at ungaged sites. These study results helped identify a relatively homogeneous hydrologic foothill region in the South Platte River basin. This study indicated that only that part of a basin below 8,000 feet significantly contributes to rainfall-runoff (and total flood runoff). When the drainage area below 8,000 feet rather than the total drainage area, was used in the regional flood-prediction equations, the standard error of estimate improved from 142 to 44 percent for the regional flood-prediction equations. Regional flood-frequency equations, combined with paleoflood investigations, provide more reliable estimates of both common and rare floods. These regression relations and study results indicate that methods of computing flood characteristics, based on rainfall-runoff modeling, overestimate flood magnitude in the foothills and mountains of Colorado. Regional flood-frequency relations were compared with conventional flood-estimating technique results, including an evaluation of the magnitude and frequency of the probable maximum flood. For example, for Clear Creek near Golden, Colorado rainfall-runoff flood estimates are 38 to 108 percent larger than weighted (streamflow gage and regional) flood-frequency estimates. The recurrence interval of probable maximum floods at several sites in Colorado were estimated using the regional relations. These results indicate that for sites at or upstream from 7,500 feet PMF recurrence intervals far exceed 10,000 years. However, at lower elevations, PMF recurrence intervals range from 2,000 to 3,000 years. These regional results, supported by radiocarbon dating, indicate that the 1976 Big Thompson flood, in the area of most intense rainfall, had a recurrence interval of about 10,000 years. The unique quality of the 1976 flood was that it encompassed a large number of tributaries.

The study demonstrated that the concept of storm transposition from lower elevations to higher elevations, that is the basis of the rainfall-runoff method, is not supported by meteorological, hydrological, and paleoflood data. Also, depth-area relations used in the foothills and mountains of Colorado were not developed with data from that area and seem to be another cause of large rainfall-runoff flood estimates. Overestimated design rainfall and depth-area relation result in overestimated flood discharges. Evaluation of streamflow data and paleoflood investigations provide an alternative for evaluating flood hydrology and the safety of dams.

One of the main points of this study is to indicate the dependence of intense precipitation on elevation and its extremely limited areal extent. Precipitation, streamflow, and geomorphic evidence indicates that there is a distinct decrease in floods above about 7,500 feet in the foothills of northern Colorado. The U.S. National Weather Service has started to issue flash-flood watches in the Front Range of Colorado, recognizing the greater flash-flood potential below 7,500 feet (Denver Post, July 24, 1985). The study also indicates one approach to answer the question of how the frequency of extraordinary floods such as the PMF can be assessed. The theories presented also are applicable to mountainous areas in adjoining States, but vary according to elevation.

In the Arkansas River basin in southern Colorado, this decrease in flood magnitude occurs at an elevation of about 8,000 feet. In Wyoming, streamflow records indicate that the elevation is about 6,500 feet. Farther north in South Dakota and Montana, the elevation is less than 6,500 feet. (Studies need to be done to determine the elevations for decreases in floods.) Therefore, the concept of storm transposition from lower elevations to higher elevations is suspect and is not supported by meteorologic, hydrologic, and paleoflood data.

Additional research in flood hydrology needs to be done to: (1) Improve the techniques of indirectly measuring peak discharge on small, steep watersheds, particularly because they are used to reconstruct precipitation; (2) reevaluate the assumptions and conditions for the transposition of large storms from low to high elevations and the associated D-A-D relations in the mountains; (3) identify the different flow processes in the foothills and mountains of Colorado and other mountain areas and to corroborate the results reported here; and, (4) collect additional precipitation (particularly short-duration data) and streamflow data.

REFERENCES

Boner, F.C., and Stermitz, Frank, 1967, Floods of June 1964 in northwestern Montana: U.S. Geological Survey Water-Supply Paper 1840-B, 242 p.

Brooks, C.F., 1938, Need for universal standards for measuring precipitation, snowfall, and snowcover: Bulletin 23, International Association of Hydrology, I.U.G.G. Riga, 1938.

Colorado Water Conservation Board, 1983, Flood hazard mitigation plan for Colorado: Denver, Colorado Water Conservation Board, 135 p.

Costa, J.E., 1978a, Holocene stratigraphy in flood-frequency analysis: Water Resources Research, v. 14, p. 626-632.

_____1978b, Colorado Big Thompson flood: Geologic evidence of a rare hydrologic event: Geology, v. 6, p. 617-620.

Costa, J.E., and Jarrett, R.D., 1981, Debris flows in small mountain stream channels of Colorado and their hydrologic implications, Association of Engineering Geologists Bulletin, v. 14, p. 309-322.

Crippen, J.R., 1978, Composite log-type III frequency-magnitude curve of annual floods: U.S. Geological Survey Open-File Report 78-352, 5 p.

Crow, L.W., 1983, Review of pertinent meteorological factors relating to peak streamflow feeding Comanche Reservoir: McCall-Ellingson & Morrill, Inc., Engineers, Denver, 87 p.

Elliott, J.G., Jarrett, R.D., and Ebling, J.E., 1982, Annual snowmelt and rainfall peak-flow data on selected foothills region streams, South Platte River, Arkansas River, and Colorado River basins, Colorado: U.S. Geological Survey Open-File Report 82-426, 86 p.

Follansbee, Robert, and Sawyer, L.R., 1948, Floods in Colorado: U.S. Geological Survey Water-Supply Paper 997, 151 p.

Hansen, W.R., Chronic, John, and Matelock, John, 1978, Climatography of the Front Range urban corridor and vicinity, Colorado: U.S. Geological Survey Professional Paper 1019, 59 p.

Helley, E.J., and La Marche, V.C., 1973, Historic flood information for northern California streams from geological and botanical evidence: U.S. Geological Survey Professional Paper 485-E, 16 p.

Henz, J.F., 1974, Colorado high plains thunderstorm systems, a descriptive radar-synoptic climatology: Master's thesis, Colorado State University, 66 p.

Interagency Advisory Committee on Water Data, 1981, Guidelines for Determining flood-flow frequency (2nd ed., revised) [editorial corrections made March 1982]: U.S. Geological Survey Office of Water Data Coordination, Reston, Va.

Jarrett, R.D., 1986, Evaluation of the slope-area method of computing peak discharge, *in* Subitzky, Seymour, ed., Selected Papers in the Hydrologic Sciences 1986: U.S. Geological Survey Water-Supply Paper 2310, p. 13-24.

Jarrett, R.D., and Costa, J.E., 1983, Multidisciplinary approach to the flood hydrology of foothills streams in Colorado, International Symposium on Hydrometeorology, *in* Johnson, A.I., and Clark, R.A., eds., Bethesda, Md., American Water Resources Association, p. 565-569.

Jarrett, R.D., and Costa, J.E., 1986, Hydrology, geomorphology, and dam-break modeling of the July 15, 1982, Lawn Lake Dam and Cascade Lake Dam failures, Larimer County, Colorado: U.S. Geological Survey Professional Paper 1369, 78 p.

Jarrett, R.D., and Crow, L.W., 1988, Experimental Marvin windshield effects on precipitation records in Leadville, Colorado: Water Resources Bulletin, v. 24, no. 3, p. 615-626.
Kircher, J.E., Choquette, A.F., and Richter, B.D., 1985, Estimation of natural streamflow characteristics in western Colorado: U.S. Geological Survey Water-Resources Investigations Report 85-4086, 28 p.
Kochel, R.C., and Baker, V.R., 1982, Paleoflood Hydrology: Science, v. 215, p. 353-361.
Livingston, R.K., 1981, Rainfall-runoff modeling and preliminary regional flood characteristics of small rural watersheds in the Arkansas River basin in Colorado: U.S. Geological Survey Water-Resources Investigations 80-112, 43 p. [Available from the National Technical Information Service, Springfield, VA., as PB81 224 321.]
Livingston, R.K., and Minges, D.R., 1987, Techniques for estimating regional flood characteristics of small rural watersheds in the plains region of eastern Colorado: U.S. Geological Survey Water-Resources Investigations Report 87-4094, 72 p.
McCain, J.F., and Jarrett, R.D., 1976, Manual for estimating flood characteristics of natural-flow streams in Colorado: Technical Manual No. 1, Colorado Water Conservation Board, Denver, 68 p.
McCain, J.F., and Ebling, J.L., 1979, A Plan for study of flood hydrology of foothill streams in Colorado: U.S. Geological Survey Open-File Report 79-1276, 29 p.
McCain, J.F., Hoxit, L.R., Maddox, R.A., Chappell, G.F., and Caracena, Fernando, 1979, Storm and Flood of July 31-August 1, 1976, in the Big Thompson River and Cache La Poudre River basins, Larimer and Weld Counties, Colorado: U.S. Geological Survey Professional Paper 1115, 152 p.
Miller, D.L., Everson, C.E., Mumford, J.A., and Bertle, F.A., 1978, Peak discharge estimates used in refinement of the Big Thompson storm analysis, *in* Conference on Flash Floods-Hydrometeorological Aspects, American Meteorological Society, Boston, p. 135-142.
Miller, J.F., Hansen, E.M., Fenn, D.D., Schreiner, L.C., and Jensen, D.T. 1984, Probable maximum precipitation estimates -United States between the Continental Divide and the 103rd meridian: U.S. Department of Commerce Hydrometeorological Report No. 55, National Oceanic and Atmospheric Administration, Silver Springs, Md., 245 p.
National Research Council, Committee on Safety Criteria for Dams, 1985, Safety of dams--Flood and earthquake criteria: Washington, D.C., National Academy Press, 276 p.
Payton, E.A., and Brendecke, C.M., 1985, Rainfall and snowmelt frequency in an alpine watershed, *in* Proceedings of the 53rd Annual Western Snow Conference, Spokane, Wash., p. 25-36,
Reich, B.M., 1973, How frequently will floods occur?: Water Resources Bulletin, v. 9, p. 187-188.
Reidel, J.T., and Schreiner, L.C., 1980, Comparison of generalized estimates of probable maximum precipitation with greatest observed rainfalls: NOAA Technical Report NWS 25, National Weather Service, Washington, D.C. 66 p.
Richmond, G.M., 1960, Glaciation of the east slope of Rocky Mountain National Park, Colorado: Geological Society of American Bulletin, v. 71, p. 1371-1382.

Riggs, H.C., 1961, Frequency of natural events, *in* American Society of Civil Engineering Proceedings, v. 87, No. HY 1, p. 15-26.

_____, H.C., 1973, Regional analysis of streamflow characteristics: U.S. Geological Survey Techniques of Water-Resources Investigations, bk. 4, chap. B3, 15 p.

Sauer, V.B., 1974, Flood characteristics of Oklahoma streams: U.S. Geological Survey Water-Resources Investigations 52-73, 301 p.

Schwarz, F.K., Hughes, L.A., Hansen, E.M., Petersen, M.S., and Kelly, D.B., 1975, The Black Hills-Rapid City flood of June 9-10, 1972--A description of the storm and flood: U.S. Geological Survey Professional Paper 877, 47 p.

Stedinger, J.R. and Cohn, T.A., 1986, Flood frequency analysis with historical and paleoflood information: Water Resources Research, v. 22, p. 785-793.

U.S. Bureau of Reclamation, 1973, Design of small dams: U.S. Government Printing Office, Washington, D. C., 816 p.

U.S. Federal Emergency Management Agency, 1984, Flood insurance study--City of Golden, Jefferson County, Colo., 1 v.

Warnick, C.C., 1956, Influence of wind on precipitation measurements at high altitudes, Bulletin 10, Engineering Experiment Station, University of Idaho, 61 p.

☆ U.S. GOVERNMENT PRINTING OFFICE:1988- 576-382/85203