Hydrologic Aspects of Dam Safety

Report of Workshop held on November 16, 1989

Edited by

Neil S. Grigg

Colorado Water Resources Research Institute

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Colorado State University

HYDROLOGIC ASPECTS OF DAM SAFETY

Report of Workshop held on November 16, 1989
at Colorado State University

Organized by the Colorado Water Resources Research Institute
and the Office of the State Engineer

Edited by

Neil S. Grigg

February 1990

COLORADO WATER RESOURCES RESEARCH INSTITUTE
Colorado State University
Fort Collins, Colorado 80523

Neil S. Grigg, Director

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WORKSHOP ON THE HYDROLOGIC ASPECTS OF DAM SAFETY

Summary of Workshop

A workshop was held on November 16, 1989 at Colorado State University to assess current methods for using PMP estimates and snowmelt data for estimating spillway design floods. Colorado's State Engineer requested the workshop to provide for an independent evaluation of current methods and to elicit suggestions about policies and research needed to improve estimates of spillway design floods (see Attachment 3 for the details of the State Engineer's request). Other states in the Mountain West have similar problems, and representatives of Wyoming's and New Mexico's State Engineer offices attended the workshop. A representative of Montana's dam safety office expressed interest after the workshop and is listed on Attachment 2.

The attached agenda (Attachment 1) shows the order of presentations and discussion. Twenty-five persons as shown on the roster (Attachment 2) attended the workshop.

Overall summary

As expected, there was controversy at the workshop about the adequacy of Hydrometeorological Report 55A (HMR 55A) for use as a guide to develop site-specific PMP estimates in the Colorado mountains where considerable variation of PMP with elevation is expected, but not verified because data is inadequate. Additional research to verify or refute HMR 55A at elevations above about 7500 feet in Colorado is needed. The lack of research results places the State Engineer's Office in a difficult position because the only choices available are: use HMR 55A with full knowledge that the results may be overly conservative and expensive; accept consultant reports on a site-specific basis, but without adequate criteria for evaluating the work of the consultant; or to delay decisions indefinitely in spite of the fact that an adequate program of the needed research in not now ongoing. The question of liability drives much of the conservatism that is observed. To make progress on this issue additional research is needed, both to relate PMP-to-elevation through modeling of the physical processes involved, and also to recommend estimation and review techniques that will consider the state-of-the-knowledge of PMP/PMF phenomena in the mountains while the meteorological research proceeds. The meteorological research might be funded from federal or state sources and could be proposed by participants in the workshop. The research needed to develop site specific estimation and review techniques could be completed by a working group that could be organized through the state engineers' offices or by a WRRI, with some funding to provide for contracting with a consultant to prepare review documents that could be evaluated by a working group such as the one that assembled at this workshop.

Specific conclusions of the workshop

There remains considerable controversy about HMR 55A; the questions could not be resolved in one workshop. The Bureau and NOAA have confidence in the curves in HMR 55A and do not believe them to be overly conservative, but use of the document for estimates at high elevations where data is scarce is difficult to justify. A clear presentation of the Bureau's position and policies is provided by the January 16, 1990 letter from Raymond H. Willms, Attachment 4, and it is recommended to review this letter and its enclosures in detail.

USGS research has not observed floods of the magnitude predicted by application of HMR 55A at elevations above about 7500 feet in Colorado. The research approach of Robert Jarrett was presented at the workshop, and Dr. Jarrett's letter about the workshop and the enclosures he provided should be reviewed in detail, Attachment 5.

Some meteorologists believe that the curves in HMR 55A are too high because in the analysis to develop the curves the extreme value of the impact of each parameter was taken meaning that the maximum final results were obtained. Most, but not all, agree that the use of HMR 55A for elevations below about 7500 feet is not a problem (See letter from Keith Brown, Attachment 10).

Available meteorological research is not adequate to pinpoint the variation of PMP with elevation in Colorado mountain environments above about 7500 feet. The data base is not adequate to fix the variation with elevation and the only research tool available is dynamic modeling that takes into account the physical processes. The state-of-the-art of this modeling is not advanced enough to provide absolute values, but relative values could be determined. Research into this phenomena is needed, and organizing this research was of interest to the participants at the workshop. Colorado's State Climatologist, Tom McKee, attended the workshop and described the nature of the research needed. However, the research plan and the funding sources would have to be determined. USGS does have a small project underway to determine the elevation limit of significant rainfall flooding (see Robert Jarrett's letter, Attachment 5).

There is apparently a big gradient in extreme rainfall effect between about 7000 and 9000 feet of elevation in Colorado. Some believe that floods above this level are primarily caused by snowmelt. Techniques to calculate maximum possible snowmelt are readily available. In spite of some difficulty in applying snowmelt calculations for flood estimation, best estimates are that flood peaks from snowmelt would be an order of magnitude lower than those currently predicted by HMR 55A. For the time being Colorado is using statistical analysis of runoff records rather than snowmelt estimates (see Alan Pearson's letter, Attachment 6).

Little is known about joint probabilities of snowmelt and extreme rainfall. Rainfall is not very effective in increasing snowmelt rates, but research is needed to determine joint probabilities (See Ernie Flack's letter, Attachment 8).

There is little risk in delaying decisions on existing spillways due to the long return periods of concern, but the research needed to improve techniques is not now underway and little progress is expected in the near future unless a working group is formed to recommend improved procedures. The State Engineer has options for program design, but they seem to reduce to two: to assume risk by delaying the application of HMR 55A or by accepting estimates of reduced PMP levels; or to initiate a program of research to lead to recommendations for revised procedures. In the event that the research program is launched it could be in combination with other Rocky Mountain states, as they all have similar problems.

The workshop suggested that a federal interagency working group could be organized to review HMR 55A and to recommend procedures to apply it on a site-specific basis. USBR reported that a Interagency Hydrometeorological Study Team has been meeting for several years, and this group could serve as a sounding board to evaluate state's concerns (See USBR's letter, Attachment 4). USBR could arrange for a hearing before that group for the states.

Keith Brown described an approach to the needed research that would be based on comparing different methods to derive PMP estimates, and refers to a procedure that the Tennessee Valley Authority used to derive their own regional estimates (See Attachment 10).

Research needed should go beyond modeling, and to the development of a manual of practice that can be used by consultants and review agencies. This manual of practice should provide advice on site specific PMF determination for locations where either rainfall or snowmelt may be controlling. The manual of practice should be based on the input of several disciplines, and additional interdisciplinary research should be conducted. Alan Pearson's letter (Attachment 6) describes the need for this manual. See letters from Robert Jarrett and Frank J. Trelease (Attachments 5 and 7) for additional statements about the need for the interdisciplinary approach.

Few consultant's reports have been accepted to date. Review agencies will have difficulty reviewing consultant proposals unless a certified meteorologist in available to review the meteorological work. Alan Pearson's letter (Attachment 6) describes the difficulty the state has in reviewing meteorological reports.

Additional suggestions are made in the attached letters, each of which is worthy to read on its own merit.

Workshop on Hydrological Aspects of Dam Safety

Colorado Water Resources Research Institute and State Engineer
Colorado State University
November 16, 1989

Agenda

11:30 - 1:00 Lunch in Ramboullet Room (Room B), CSU Student Center

1:00 - 4:30 Technical Discussions, Room 203 Lory Student Center

(each person shown is asked to summarize issues as they see them in about 10 minutes)

Moderator: Neil Grigg

Problem from State Engineer's Perspective	- Hal Simpson Bill McIntyre
Current Procedures in Burec	- Lou Schreiner
Studies by USGS	- Bob Jarrett
State Climatologist's Viewpoint	- Tom McKee
Meteorological Viewpoint	- Keith Brown
Snowmelt Research	- James Meiman
Discussion and Issue Identification	- Participants
Wrap-up	- Neil Grigg

Workshop on Hydrologic Aspects of Dam Safety

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Fort Collins, CO 80523

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* Did not attend workshop

ATTACHMENT 3

ROY ROMER
Governor

STATE OF COLORADO
NIL SINE NUMINE
1876

JERIS A. DANIELSON
State Engineer

OFFICE OF THE STATE ENGINEER
DIVISION OF WATER RESOURCES

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Denver, Colorado 80203
(303) 866-3581

June 16, 1989

Dr. Neil Grigg
Director, Colorado Water Resources Research Institute
410 University Services Building
Colorado State University
Fort Collins, Colorado 80523

SUBJECT: Formulation of Workshop to Discuss Snowmelt Runoff and Evaluate Apparent Discrepancies Between HMR 49 and 55A Precipitation Data General Storm

Dear Neil:

As a regulatory agency responsible for reviewing engineering reports for the design and modification of storage reservoirs, I am requesting your assistance concerning apparent discrepancies in recently promulgated precipitation data. My staff in the Dam Safety Branch reviews approximately 30 hydrology studies annually.

Last year, a revised Hydometerological Report (HMR) 55A (Probable Maximum Precipitation Estimates--United States Between the Continental Divide and the 103rd Meridian) was published and distributed. Comparing the procedures outlined in HMR 49 (west of the Continental Divide) and HMR 55A, specifically the general storm computations, we note HMR 49 recommends elevation reduction factors ranging from 30 to 50% while HMR 55A provides a minor adjustment for elevation. HMR 55A indicates no consistent increase or decrease, and precipitation amounts vary with elevation; however, one-half of the traditional adjustments were made and incorporated in the general storm maps. In light of these procedures, a more in-depth analysis of the effect of elevation on maximum precipitation is needed in Colorado, more specifically, above the 7000 foot elevation.

A related topic, on which I also solicit your assistance, is the question of snowmelt runoff. On September 30, 1988, I promulgated the "Rules and Regulations for Dam Safety and Dam Construction." Contained within that document are hydrologic guidelines for spillway sizing. Depending on the hazard classification and physical size, we permit inflow design floods ranging from a 25 year recurrence interval up to a flood caused by the probable maximum precipitation. Many of the structures under my jurisdiction are situated in high elevation areas. I feel a snowmelt hydrology procedure, recommended by this office, is needed to provide guidance to practicing engineers in the state.

June 16, 1989

Neil, this appears to be a topic that fits within the charter of the research institute and would greatly benefit my office in performing its regulatory duty and dam owners in particular.

A few experts I would recommend are Mr. Lou Schreiner (236-3791) of the USBR Denver (co-author of HMR-55A) and Dr. Robert Jerrett (236-6447) of the USGS-Denver who researched streamflow, paleo flood, and precipitation data in Colorado.

I propose the following be the theme of the workshop: "Conversion of Regionalized PMP Estimates from HMR 49 and HMR 55A to Site Specific PMP Estimates; and Determining PMF and More Frequent Snowmelt Floods."

I look forward to the workshop! My staff contact for this endeavor is Bill McIntyre, a five-year member of the Dam Safety branch.

Sincerely,

Jeris A. Danielson
State Engineer

JAD/WCM/rjb/1982I

United States Department of the Interior

BUREAU OF RECLAMATION

DENVER OFFICE

P O BOX 25007
BUILDING 67, DENVER FEDERAL CENTER
DENVER, COLORADO 80225-0007

IN REPLY REFER TO:

D-5751

Dr. Neil Grigg
Colorado Water Resources
Research Institute
Colorado State University
Fort Collins CO 80523

Subject: Review of Draft Summary - Workshop on Hydrologic Aspects of Dam Safety Held November 16, 1989, at Colorado State University, Fort Collins, Colorado (Safety of Dams)

Dear Dr. Grigg:

I appreciated your invitation for the Bureau of Reclamation (Reclamation) to participate at your recent workshop regarding dam safety issues for the State of Colorado. My representative, Mr. L. C. Schreiner, of the Flood Section, reported on a lively yet informative meeting. As you noted in your tentative summary of the workshop, the theory behind the use of probable maximum precipitation (PMP), probable maximum flood (PMF), and their derivation can be quite controversial. I hope that our involvement at the workshop has been beneficial to all concerned.

In responding to your memorandum of November 20, 1989, it is believed your preliminary summary fairly portrays the overall tone of the workshop. From our position, it is inappropriate to comment on what specific policies the State Engineer's Office of Colorado should adopt regarding state dam safety issues. However, it is appropriate for us to provide information regarding policy and technical data/methodologies Reclamation uses in support of its dam safety program. Reclamation's policy for new storage dams is to design them to accommodate safely the PMF unless it can be clearly shown that no serious adverse consequences such as loss of life or extensive property damage would occur as a result of dam failure. For existing dams, a flood less than the PMF may be selected as the inflow design flood where the consequences of failure are acceptable. This is usually where detailed studies conclude that no significant increased damage to downstream areas or loss of life is created by failure under flood conditions exceeding the adopted inflow design flood.

For all PMF determinations, the PMP as described in the appropriate hydrometeorological report issued by the National Weather Service (NWS) is used. Designs where the PMP from these reports are unavailable, hydrometeorologists working in the Flood Section, or those hired by Reclamation, working with Flood Section personnel, are used to derive the PMP estimate. It is the opinion of Reclamation that in general, the hydrometeorological report series provide the best evaluation of an upper limit to design precipitation and fulfills the meteorological requirement of its definition of the PMF, ". . . the maximum runoff condition resulting from the most severe combination of hydrologic and meteorologic conditions considered reasonably possible for the drainage under study."

The above mentioned policy and technical procedures incorporated by Reclamation are fairly in line with the recommendations advocated by the committee on Safety Criteria for Dams, Water Science and Technology Board, and National Research Council in their 1985 publication "Safety of Dams - Flood and Earthquake Criteria." Further support for this policy and technical application are also given in a 1988 report titled, "Evaluation Procedures for Hydrologic Safety of Dams," prepared by the Task Committee on Spillway Design Flood Selection, American Society of Civil Engineers. Similarity between Reclamation's policy and that recommended by these reports is particularly so for dams of the high hazard classification.

Having stated Reclamation's policy and technical sources, at least in regard to estimating PMP (the main issue), we would like to spend the remaining part of this letter commenting on some of the individual technical issues presented at the workshop. In this respect, one noted at the workshop that there is a great deal of misunderstanding as to what PMP represents, why the deterministic approach is taken for its estimation, and what data and procedures are used in the various hydrometeorological reports to define the PMP.

For example, Mr. Brown explained that in reading Hydrometeorological Report No. 43 (HMR No. 43), PMP for the Northwest United States, he understood that the authors adopted winds, used for maximization, at only the 50-year level, and this was contrary to what was done in HMR No. 55A. This statement misrepresents the different procedures used in each report in developing PMP. In the case of HMR No. 43, an orographic model was used to describe the orographic component of PMP which required the use of some level of windspeed taken through atmospheric height. Considering other components of the model that required some level of maximization (moisture, temperature, etc.), the 50-year level windspeed was considered adequate for estimating orographic PMP. In HMR No. 55A, windspeed is not directly used in determining values of PMP--no maximization was considered. Mr. Brown had also indicated that in developing the isohyetal pattern for the June 7-8, 1964, Montana storm, as shown in HMR No. 55A, the analysis consisted of almost a dozen stations or so, and through his efforts (he located a handful of additional stations), he was able to reanalyze a more correct interpretation of spatial distribution of precipitation in this important precipitation event. Mr. Brown was apparently unaware that a supplemental precipitation survey was undertaken shortly after this event occurred. Over 300 additional precipitation measurements were obtained and used in the HMR No. 55A storm analysis. Enclosed are the data collected from this survey (enclosure 1) as provided in the June 1964 issue of "Climatological Data." As one can note, there are a number of stations that recorded total storm precipitation greater than 10 inches, the largest amount Mr. Brown states he found in his review of this storm.

Mr. Crow stated that he is part of a group effort, funded by the Electric Power Research Institute (EPRI), that will attempt to redefine PMP in the Eastern and Central United States. He is sure that his revised PMP will not look like the smooth analysis provided in HMR No. 51. In this case, HMR No. 51 represents a nonorographic evaluation of PMP without the influence of orography indicated in the final results. It is logical that PMP, as indicated in HMR No. 51, should be represented as a smooth analysis. One needs to examine reports such as National Oceanic and Atmospheric Administration Technical Memorandums NWS Hydro-39 or -41 that compliment the information provided in HMR No. 51 for orographic regions.

An additional example of misunderstanding PMP development is from the Colorado State Engineer's Office in their letter requesting the formulation of the workshop. In the letter it is stated "Comparing the procedures outlined in Hydrometeorological Report No. 49 (west of the Continental divide) and HMR No. 55A, specifically the general storm computations, we note HMR No. 49 recommends elevation reduction factors ranging from 30 to 50% while HMR No. 55A provides a minor adjustment for elevation." Here again there appears to be some misinterpretations of the information presented. The 20 to 50 percent reduction for elevation only applies to the nonorographic component of precipitation as shown in HMR No. 49. What one really needs to examine is the relation of how total PMP drops off with increasing elevation among the two reports. In most cases, the relationship of total PMP with change in elevation will be very similar. For some locations and durations, the relation of decreasing PMP with increasing elevation is even greater in HMR No. 55A than for HMR No. 49.

Reclamation would welcome any research that could aid in defining PMP; therefore, work as suggested by Dr. McKee concerning storm modeling or continued investigations performed by Dr. Jarrett are advocated. However, viable results from these endeavors will likely take a longer time period to be evaluated than the rather limited time suggested by the State Engineer's Office of 1 year. As for possible funding of additional research suggested by the workshop participants, you might try contacting Mr. D. I. Morris, who is associated with EPRI. His phone number is (415) 855-2924. EPRI is highly involved in hydroelectronic power generation which is also sensitive to the level of PMP determination. Additionally, enclosed (enclosure 2) is a copy of the November 1989 "Colorado Water" newsletter. Page 12 discusses congressional bills which might be a source of funding. Also note the article concerning "Reauthorization of the Water Resources Research Act."

The State Engineer's Office expressed the thought that a manual could be developed by the workshop participants or others that would provide guidance in the preparation of site-specific PMP estimates. For reasons given in Reclamation's recently published "Flood Hydrology Manual" (enclosure 3, page 41 of text), the regionalized approach is preferred and has been adopted by the major Federal dam building agencies. We would also call your attention to advantage number 5 which states ". . . regionalization serves as a base of severe storm information and criteria to further develop individual drainage study requirements for specific locations when additional information becomes available." It is highly suggested that additional research into what techniques could be applied to present values of PMP provided by the hydrometeorological report series might become an important tool for further adjustments to this type of information. Work along these lines has been reported in HMR No. 52 which provides techniques to additionally adjust the basic PMP indicated in HMR No. 51. Similar application techniques might be a better avenue of research to evaluate for the region covered by HMR No. 55A and would likely perk the interest of the NWS as well as Federal dam building agencies.

The summary mentions the formation of a Federal interagency working group to review HMR No. 55A and other related hydrometeorological reports. Since the early eighties, there has been established an Interagency Hydrometeorological Study Team with representatives from the NWS, Reclamation, Corps of Engineers, and the Soil Conservation Service that reviews current studies of those directly involved in the estimation of PMP as developed and used by the major Federal dam building agencies in the United States. This group meets two or three times a year. It might serve the interests of the State Engineer's Office to directly present their observations and concerns before this group as the need would arise. Having a representative on this team since its inception, we could arrange for such a hearing.

There was a great deal of commentary offered at the workshop as to whether it can rain at high elevations, and if it can, will the amounts be large in magnitude. The cutoff elevation (rain-to-snow) rose from 7,500 to 9,000 feet during the discourse. When our representative indicated that calculated PMP obtained from the hydrometeorological report series would occur as rain at the highest elevations during the summer months, such comments were dismissed as folly. One participant even went as far to say,

> " . . . I guarantee you that it does not rain above 9,000 feet in Colorado . . ."

Enclosed are portions of two articles (enclosures 4 and 5) where during large storm events heavy rainfalls were observed at elevations above 10,000 feet in Colorado. Rainfall of 8.05 inches in a day at an elevation of 3,220 meters is significant.

In consideration of the above, and inferred in the workshop summary regarding PMP estimates such as "overly conservative" or "reasonable values," it is felt that many of the participants have not had the opportunity to become fully aware of the philosophy associated with the PMP/PMF concept. It is with this concern that Reclamation would be willing to offer use of both its facilities and technical staff to conduct a 1- to 2-day course regarding the philosophy and techniques used to derive estimates of PMP. It is contemplated that numerous participants of the workshop, and possibly others, would desire to attend and benefit from such a course. Becoming further informed should only serve to enhance an individual's thoughts and research regarding issues presented at the workshop. More importantly, discussions regarding basic philosophical views and methods of PMP derivation may open ideas among participants as to what areas of further research could be actively pursued to provide a better estimate of PMP or how it might be applied.

Reclamation recommends that the Colorado Water Resources Research Institute solicit the participants at the workshop and of others that they believe may be interested in attending such a course. It is anticipated that the philosophical aspects of the course will be universal in nature. However, most detailed technical issues will be confined to basically those concerned with estimating PMP for the State of Colorado. Therefore, participation might be most beneficial for those interested in Rocky Mountain meteorology, hydrology, and dam safety issues regarding PMP estimation. Mr. Louis C. Schreiner of my staff will serve as the focal point of contact within Reclamation if positive interest in offering such a course is expressed. He can be reached at (303) 236-3791.

We hope that the foregoing discussion presented some thoughts and answers to the various issues raised at the November workshop. Reclamation's comments are offered with the sincerity that they will aid your office and that of the State Engineer's Office regarding formulation of adequate dam safety criteria.

Sincerely,

Raymond H. Willms

Raymond H. Willms
Acting Assistant Commissioner
Resources Management

Enclosure

U. S. DEPARTMENT OF COMMERCE
LUTHER H. HODGES, Secretary
WEATHER BUREAU
ROBERT M. WHITE, Chief

CLIMATOLOGICAL DATA

MONTANA

JUNE 1964

Volume 67 No. 6

ASHEVILLE: 1964

TEMPERATURE AND PRECIPITATION EXTREMES

Highest Temperature:	104° on the 27th at Miles City
Lowest Temperature:	21° on the 1st at Opheim 10 N
Greatest Total Precipitation:	10.34 inches at Gibson Dam
Least Total Precipitation:	0.96 inch at Libby 1 NE Ranger Sta
Greatest One-Day Precipitation:	7.31 inches on the 8th at Summit
Greatest Reported Total Snowfall:	2.0 inches at Wisdom

SPECIAL WEATHER SUMMARY

By far the most significant weather event of the month (and in many ways the most important in many years) was the extensive extremely heavy rainstorm of June 7-8 along both sides of the Continental Divide from north of Helena to north of the Canadian Border. Flooding from these heavy rains, which fell on top of late, heavy snowpack along the mountains, was severe; in fact, resulting floods were in many instances the worst on record. The number of fatalities and total damage are large. The total known dead, and missing and presumed dead, is 34; preliminary damage estimates range from $62 million to $65 million.

Beginning generally about noon on June 7, rain began over the affected area and varied in intensity from light to moderate until near sunset, after which rates of fall increased to moderate to heavy over a large area. By midnight, and during the morning of June 8, intensity of rainfall was very heavy along both sides of the Continental Divide. At Summit, for example, the rate of fall exceeded 0.46 inch per hour for one 8-hour period. After the worst of the flooding had subsided, a cooperative survey of the areas of heaviest rainfall produced several measurements of 10 inches or more (see supplemental table, Pages 124 through 127). Flows in the following rivers, according to the U. S. Geological Survey, exceeded by large and significant amounts the maximum of record: Belly River at Int'l Boundary, Waterton River near Waterton Park, Alta., St. Mary River near Babb, Flathead River near Columbia Falls; Middle Fork, Flathead near West Glacier; South Fork, Flathead at Spotted Bear Ranger Station; Sun River at three points; Marias River near Shelby; Cut Bank Creek at Cut Bank; and many others.

Surface transportation was paralyzed, not only over the affected area, but as extreme flood crests moved downstream on Flathead, Marias, Two Medicine, Teton, Sun, St. Mary, and Dearborn Rivers, as well as on many tributary streams, highway and railroad bridges and embankments suffered seriously, and farms and ranches along the river bottoms were extensively damaged. The Sun River at Great Falls was at or above flood stage for a total of nine days. Failure of irrigation reservoirs (Swift Dam, 30,000 acre-feet; and lower Two Medicine Dam, 16,600 acre-feet, on Birch and Two Medicine Creeks, respectively) was more or less directly responsible for the loss of at least 30 lives. The USGS has said, "A recurrence interval of 100 years or more is indicated for most streams in this area on the basis of provisional peak discharges." The fact that Tiber Reservoir was able to contain the entire Marias flood peak, releasing only 10,000 c. f. s. at the maximum, saved the Loma area, near Marias and Teton confluences, from more serious damage--as well as the Missouri River from Loma to the Fort Peck Reservoir.

The situation was complicated upstream on the Missouri above Canyon Ferry Reservoir, where June rains (heaviest in years) kept all streams relatively high most of the month. The Jefferson River experienced minor flooding twice--for a few days around the 11th and again about a week later. During the earlier (11th) flooding, two lives were lost during an attempted crossing of a flooded slough near the river, and a few bridge approaches and embankments were damaged between Twin Bridges and Three Forks. Minor flooding occurred also on some tributaries from Lewistown westward to Great Falls, but damage here was small.

Complete analysis of the flood of early June, including a study of the atmospheric processes involved in this type of a deluge, is beyond the scope of this summary. It is an important storm, in many aspects it can be estimated to have a recurrence interval of 200 years or even more, and no doubt it will receive the study it appears to warrant. Reports of such studies will be published, in due course, in appropriate journals, water supply papers, etc.

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Weather Bureau State Climatologist
Weather Bureau Airport Station
P. O. Box 1711
Helena, Montana 59601

SUPPLEMENTARY PRECIPITATION DATA

Storm of June 7 - 8, 1964

Data from privately-owned gages, or other receptacles, not otherwise published by the Weather Bureau.

County	Location: Township	Range	Section	June 7	June 8	Total	Type of Gage	Evaluation of Record	Remarks
Cascade	22N	1E	8			4.8	Glass Tube	Fair	
	22N	1E	22			4.9	Glass Tube	Good	
	22N	2E	4			6.0	Glass Tube	Fair	
	22N	2E	20			5.25	Glass Tube	Good	
	22N	2E	24			4.0	Glass Tube	Good	
	22N	3E	28			4.75	Glass Tube	Good	
	22N	4E	6			4.1	Wedge Type	Good	
	22N	4E	23			4.1	Rectangular Gage	Good	
	22N	4E	33			4.0	Glass Tube	Good	
	22N	5E	20			3.6	Glass Tube	Good	
	21N	2W	9			4.3	Glass Tube	Good	
	21N	2W	25			3.8	Glass Tube	Fair	
	21N	1W	1			2.5	Glass Tube	Fair	
	21N	1W	8			4.5	Glass Tube	Fair	
	21N	3E	13			6.3	Glass Tube	Good	
	21N	3E	15			3.5	St. sided bucket	Fair	
	21N	3E	21			4.0	Glass Tube	Good	
	21N	3E	27			4.25	Glass Tube	Fair	
	21N	4E	20			3.65	Glass Tube	Good	
	20N	3W	25			5.5	Glass Tube	Good	
	20N	2W	35			4.0	Glass Tube	Good	
	20N	1W	21			4.5	Coffee Can	Fair	
	20N	2W	7	1.0	3.7	4.7	Glass Tube	Good	
	20N	2W	11			4.1	Glass Tube	Good	
	20N	2W	12			4.2	Glass Tube	Good	
	20N	1E	32			3.85	Wedge Type	Good	
	20N	4E	(In Great Falls)			3.65	Various	Good	
	20N	4E	26	3.0	1.8	4.8	Glass Tube	Good	Average of 6 reports. ±0.20"
	19N	3W	22			3.5	Wedge Type	Fair	
	19N	2E	33			3.5	Co-op	Good	
	19N	4E	21			4.7	Glass Tube	Good	
	19N	4E	26			3.2	-	Fair	
	19N	4E	31	2.1	2.3	4.4	Glass Tube	Good	
	19N	5E	7			3.94	Special Gage	Good	
	19N	7E	29			3.2	Glass Tube	Good	
	18N	2W	19			5.0	Wedge Type	Good	
	18N	1W	8			3.5	Glass Tube	Good	
	18N	1W	(In Cascade)			5.5	Glass Tube	Fair	
	18N	2E	30			3.0	Glass Tube	Fair	
	18N	4E	18			3.25	Glass Tube	Good	
	18N	4E	35			3.5	Glass Tube	Good	
	16N	2W	11			4.00	Wedge Type	Good	
	16N	2E	8	.15	2.05	2.20	Wedge Type	Good	
	16N	5E	-			3.9	Glass Tube	Good	
	15N	7E	-			3.80	Wedge Type	Good	
Chouteau	27N	10E	27	.70	.98	1.68	Glass Tube	Good	
	26N	9E	4			3.5	Glass Tube	Good	
	26N	10E	19			2.75	Glass Tube	Good	
	25N	3E	34			3.75	Glass Tube	Fair	
	25N	6E	12			2.3	Glass Tube	Good	
	25N	7E	35			3.2	Glass Tube	Good	
	25N	8E	30			2.5	Glass Tube	Good	
	25N	14E	31	0.4	0.3	0.7	Glass Tube	Good	
	24N	3E	34			3.90	Glass Tube	Good	
	24N	5E	8			3.0	-	Fair	
	24N	6E	3			3.0 to 3.2	Glass Tube	Fair	
	24N	6E	27			3.4	Glass Tube	Good	
	24N	7E	28			3.0	Glass Tube	Good	
	23N	3E	15			4.25	Wedge Type	Good	
	23N	3E	25			4.4	Glass Tube	Good	
	23N	3E	36			4.35	Commercial	Good	
	23N	5E	30			5.35	Glass Tube	Good	
	23N	6E	5			3.4	Glass Tube	Good	
	23N	6E	30			3.5	Glass Tube	Fair	
	23N	7E	33			4.0	Glass Tube	Good	
	23N	8E	(Ft. Benton)			3.55	Glass Tube	Good	
	23N	10E	9			2.7	Glass Tube	Fair	
	23N	11E	33			1.8	Glass Tube	Good	
	22N	6E	-			3.8	Glass Tube	Good	
	22N	7E	7			4.10	Glass Tube	Good	
	22N	7E	-			3.6	Glass Tube	Good	
	22N	9E	32			5.0	Glass Tube	Good	
	21N	7E	6	1.0	2.80	3.6	Glass Tube	Good	
	21N	9E	15			6.5	Massey-Harris Standard Gage	Good	
	21N	12E	26			3.5	Glass Tube	Good	
	21N	14E	7			3.0	Glass Tube	Good	
	20N	8E	18			3.0	Glass Tube	Good	
	20N	9E	18			4.2	Glass Tube	Good	
	20N	12E	26			4.10	Glass Tube	Good	
Fergus	19N	12E	26			3.5 to 4.0	Glass Tube	Fair	
	19N	13E	22			3.7	Rectangular Gage	Fair	
	19N	15E	7			4.1	Glass Tube	Fair	
	18N	13E	3			3.5	Glass Tube	Good	
	18N	14E	2			3.75	Wedge Type	Fair	
	18N	15E	21			3.5	Glass Tube	Good	
	18N	21E	12			1.9	Glass Tube	Good	
	18N	21E	29	.50	3.60	4.10	Glass Tube	Good	
	18N	23E	3			1.65	Glass Tube	Good	
	17N	15E	27			3.85	Glass Tube	Good	
	17N	18E	23			2.5	Glass Tube	Good	
	16N	16E	31			4.82	Glass Tube	Good	
	16N	18E	28			3.4	Glass Tube	Good	
	16N	23E	15			1.25	Glass Tube	Good	
	15N	16E	17			4.0	Rectangular Gage	Good	
	15N	17E	14			3.8	Glass Tube	Fair	
	15N	19E	18			4.0	Glass Tube	Good	
	15N	21E	29	4.04	3.20	7.25	Plastic	Good	
	15N	22E	21			3.5	Glass Tube	Fair	
	14N	18E	(Moore)			4.32	Wedge Type	Good	Average of several gages in colony.
	14N	19E	11			5.5	Glass Tube	Good	
	14N	21E	11			3.5	Glass Tube	Good	
	14N	21E	17	.09	5.0	5.9			
	12N	24E	13			2.0	Glass Tube	Good	
	11N	16E	(Garneill)			3.5	Glass Tube	Good	
Flathead	37N	22W	6			3.25	Tobac. Can	Fair	
	35N	21W	23	.55	2.63	3.18	8" SRG	Good	
	33N	20W	28		2.25	2.25	8" SRG	Good	
	33N	18W	(Lake McDonald Lodge)			10.0	5 gal. pail	Fair	Depth est. from height of lettering on outside of pail.
	32N	19W	(Apgar)	.53	2.98	3.51	-	-	

See reference notes following Station Index.

SUPPLEMENTARY PRECIPITATION DATA

Storm of June 7 - 8, 1964

County	Location: Township	Range	Section	June 7	June 8	Total	Type of Gage	Evaluation of Record	Remarks
Flathead - Continued	31N	21W	31			2.40	Glass Tube	Good	
	30N	20W	16	.54	2.86	3.40	8" SRG	Good	
	30N	19W	8	.48	2.65	3.13	8" SRG	Good	
	29N	19W	-			4.5	3x8" tall	Good	
	27N	20W	36	.12	2.31	2.42	8" SRG	Good	
	27N	19W	-			4.0	Gallon	Good	
	27N	13W	28	2.48	3.07	5.55	8" SRG	Good	
	26N	20W	12			2.5	Plastic	Good	
	26N	19W	20	.08	1.6	2.4	Glass Tube	Good	
	25N	18W	5			3.0	Glass Tube	Good	
	25N	15W	17	.50	3.99	4.49	8" SRG	Good	
	24N	19W	9			3.6	6" Plastic	Good	
Glacier	37N	18W	3			6.5+	Bucket (sloping sides)	Fair	Furnished by WB observer, West Glacier 11" diam. at top, 9.5" bottom, 9.5" deep. Bucket overflowed.
	37N	14W	1			4.8	11" diam. bucket st. rough sides.	Fair	
	37N	14W	-			6.0	Glass	Good	10 miles north of Babb
	36N	14W	21			7.40	Wedge Type	Good	5.03" 6 am 7 June to 1 pm 8 June. 6A on 7th to 6A on 8th 5.02, 6A on 8th to 1p on 8th 2.27.
	36N	14W	23			7.29	Tru-check rain gage	Good	
	36N	13W	(Duck Lake)			5.0	Barrel	Fair	
	36N	12W	32			6.0	Coffee Can 6" deep	Good	Meas. 5.5 and emptied-caught an additional 0.50".
	33N	9W	14			4.5	5 1/2" Glass Tube	Good	
	33N	7W	3			4.2	5 1/2" Glass Tube	Fair	
	33N	5W	13			5.3	-	-	
	32N	13W	30			14.5	50 gal. drum	Fair to good	2- 5 gal. pails ran over, est. good to +.50.
	32N	12W	8			9.0	5 gal. pail	Good	Located 1 mile from above meas.
	32N	12W	9			10.0+	35 gal. oil dr.	Fair	Less than 2" above first rib, 9" above bottom. Good exposure.
	32N	5W	11			4.9-	6" Glass Tube	Good	
	31N	12W	18			11.0	5 gal.bucket	Fair	Est. good to ± 1.0"
	31N	8W	6			4.5	5" Glass tube	Good	
Granite	6N	15W	30	.80	.85	1.65	Glass Tube	Good	
	5N	14W	15	.10	1.50	1.60	Glass Tube	Good	
Judith Basin	18N	8E	5			3.5	Glass Tube	Fair	
	18N	6E	24			4.8	Glass Tube	Good	
	18N	9E	3			2.9	Glass Tube	Fair	
	18N	9E	12			4.0	Glass Tube	Good	
	18N	10E	1			4.5	2# Coffee Can	Good	
	18N	10E	7			4.0	Glass Tube	Fair	
	18N	11E	35			5.0	Glass Tube	Fair	
	17N	9E	27			5.0	Glass Tube	Fair	
	17N	10E	25	1.2	3.7	4.9	Glass Tube	Fair	
	18N	8E	5			6.0	Glass Tube	Fair	
	16N	9E	17			7.25	Glass Tube	Good-	
	16N	13E	19			4.5	Glass Tube	Fair	
	16N	14E	2			3.6	Glass Tube	Good	
	15N	12E	12			4.5	Glass Tube	Good	
	15N	13E	7	1.2	2.85	4.05	Glass 1"x16"	Good	
	15N	14E	-			4.2	Glass Tube	Good	
	14N	12E	14			5.75	Glass Tube	Good	
	14N	13E	24			4.3	Glass Tube	Good	
	14N	15E	12			6.0	Glass Tube	Good	
	14N	15E	28			7.0	Glass Tube	Fair	
	13N	12E	8			4.5	Glass Tube	Fair	
	13N	14E	19	1.3	3.3	4.6	Glass Tube	Good	
	12N	14E	1			3.5	Glass Tube	Fair	
Lake	26N	19W	20			2.75	Wedge Type	Good	
	25N	20W	30	.52	2.45	2.97	-	-	
	25N	19W	29			2.35	-	-	
	24N	21W	3			3.00	Glass	-	
	24N	21W	19			3.25	-	-	
	24N	19W	2			4.0+	Wedge	Good	
	24N	19W	9			3.6-	Wedge	Good	
	24N	19W	21			4.5+	Wedge	Good	
	24N	19W	33			4.2-	Wedge	Good	
	23N	19W	15			3.5	Wedge	Good	
	22N	19W	4			4.0(about)	-	Fair	
	22N	17W	29			2.2	Pail (sloping sides)	Fair	
Lewis & Clark	22N	8W	31			8.0	5 gal. pail	Fair	Bucket was set out in yard after it had been raining awhile. The amt. meas. is from Mon night to Tues AM. No knowledge of amt prior to Mon. night.
	21N	6W	27			6.47	8" SRG	Good	
	21N	7W	35			5.1	Glass Tube	Fair	
	20N	10W	23			10.0	Unknown	Fair	
	20N	8W	12			6.1	Glass Tube	Fair	
	20N	6W	13	4.0	2.0	6.0	Rectangular	Fair	
	20N	7W	35			5.75	Glass Tube	Good	
	20N	5W	8			5.0	Glass Tube	Good	
	20N	4W	8			7.4	Glass Tube	Fair	Gage emptied Mon with 3.4 & Wed with 4.0.
	19N	8W	20	11A on 7th to 11A on 8th - 8 7/8"	——	12.75	Glass Tube	Good	
	19N	8W	35			8.3	Glass Tube	Good	
	18N	8W	4			10.+	Glass Tube	Fair	
	19N	7W	28			5.8	Glass Tube	Good	
	19N	7W	32			8.0	Glass Tube	Fair	
	18N	8W	13			8.0	Glass Tube	Fair	
	18N	7W	24			5.5	2# coffee can	Fair	
	18N	6W	7			6.0	Glass Tube	Good	
	17N	6W	20			4.5+	Glass Tube	Poor	
	16N	6W	1			6.1	Glass Tube	Good	
	16N	5W	4			4.3	Glass Tube	Fair	
	15N	7W	4			8.0	5 gal. can	Good	Very hard rain noon to mid on the 8th.
	15N	3W	30	.49	1.48	1.97	8" SRG	Good	Ranger Station
	14N	2W	4			3.8	Glass Tube	Good	
Liberty	33N	4E	15			1.4	Funnel Gage	Good	
	33N	5E	22	.55	.30	.85	Wedge	Good	
	33N	5E	25	0.6	0.2	0.8	Glass Tube	Good	
	31N	4E	4	.70	1.10	1.8	5" Glass Tube	Good	
	30N	6E	5			2.0	5" Glass Tube	Good	
	29N	4E	15	2.0	2.4	4.4	Victor Rain Gage	Good	Written Record
	29N	4E	15	1.7	2.3	4.0	Victor Rain Gage	Good	Written Record
	29N	6E	2			2.1	5" Glass Tube	Good	
	28N	7E	29			2.2	5 1/2" Glass Tube	Good	
Lincoln	37N	27W	29	1.00	.27	1.27	Wedge shaped	Good	
Meagher	14N	3E	-			1.90	Wedge	Good	
	13N	5E	26			2.5	Glass Tube	Fair	
	12N	4E	2			2.8	Glass Tube	Good	
	11N	8E	26			1.70	Glass Tube	Fair	
	10N	4E	33			2.4	Glass Tube	Fair	
	10N	6E	14			2.75	Glass Tube	Fair	
	9N	6E	3			2.25	Glass Tube	Fair	
	9N	10E	9			1.90	Glass Tube	Good	
	8N	6E	14	.50	1.55	2.05	Plastic Gage	Fair	

See reference notes following Station Index.

SUPPLEMENTARY PRECIPITATION DATA

Storm of June 7 - 8, 1964

County	Location: Township	Range	Section	June 7	June 8	Total	Type of Gage	Evaluation of Record	Remarks
Meagher - Continued	8N	6E	18			2.25	Glass Tube	Fair	Average of several gages in colony.
	8N	9E	27	.50	1.32	1.82	Can Gage	Good	
	8N	11E	11	1.40	1.70	3.10	Glass Tube	Good	2 others in town received similar amts.
	8N	11E	18			2.00	Glass Tube	Fair	
	8N	9E	35	.50	1.32	1.82	-	Good	
	7N	6E	6			2.05	Glass Tube	Fair	
	7N	8E	1	.24	.75	.99	Plastic Gage	Fair	
	7N	8E	28			2.05	20 gal oil drum	Fair	
	7N	10E	6	.25	2.09	2.34	Can Gage	Good	
	7N	11E	30			3.4	Glass Tube	Fair	
	6N	6E	23			1.70	Glass Tube	Good	
Missoula	16N	14W	28			2.0	1# coffee can	Good	
	16N	16W	15			2.0	Pail	Good	
	21N	17W	11	.12	2.31	2.43	8" SRG	Good	
	15N	20W	24	.70	2.29	2.99	Wedge Type	Good	
	19N	17W	11	.37	1.78	2.5	8" SRG	Good	
Pondera	31N	5W	34			6.0	4" Glass Tube	Good	
	30N	4W	8			6.0	4" Glass Tube	Fair	
	30N	3W	15			5.5	4" Glass Tube	Good	
	30N	2W	23			4.27	4" Glass Tube	Fair	
	29N	6W	3			7.0	4" Glass Tube	Good	
	29N	5W	21			5.9	4" Glass Tube	Fair	
	29N	4W	10			6.5	4" Glass Tube	Good	
	29N	3W	4			5.5	4" Glass Tube	Fair	
	28N	7W	22			6.5	5" Glass Tube	Good	Emptied during storm.
	28N	8W	3	.62	5.40	6.02	Standard 8" Manual	Very Good	Gage is part of a watershed study being conducted by Civil Engineering Department Montana State College.
	29N	5W	33			4.75	Standard 8"	Good	Same as above.
	29N	5W	34	1.52	3.32	4.81*	Friez Recorder	Very Good	Copy of Recorder Record on hand, WBAS, Helena, Montana. Storm Total 4.81 28 hrs.* *Small amounts before noon on 7th not included in storm totals.
	29N	[illegible]W	26	1.42	4.02	5.34*	Friez Recorder	Very Good	Same as above. Copy of Recorder Record on hand, WBAS, Helena, Montana. Storm Total 5.34 29 hrs.* Small amounts before noon on 7th not included in storm totals.
	28N	5W	22	1.00	7.05+	8.05+	Victor	Fair	Gage ran over on 8th.
	28N	4W	28			4.5	5" Glass Tube	Good	
	28N	2W	12			4.1	5" Glass Tube	Fair	
	28N	2W	35			4.3	5" Glass Tube	Fair	
	28N	1W	6			4.80	4" Glass Tube	Fair	
	28N	1E	15			4.20	4" Glass Tube	Good	
	28N	2E	15			3.50	4" Glass Tube	Fair	
	27N	3W	29			5.5	Plastic Gage	Fair	
	26N	2W	21			3.5	5" Glass Tube	Good	
	27N	2W	28			4.7	Gage	Fair	
	27N	1W	32			2.9	-	Fair	
	27N	1E	14			3.5	Gage	Good	
	27N	2E	15			4.0	Victor Gage	Good	
	27N	2E	22			4.6	1 1/4"x 10"	Good	
	26N	1E	23			3.0	5" Glass Tube	Fair	
	Heart Butte					→ 11.0	Wash Tub	Fair	Empty before storm. Observer reports 12" depth; corrected to 11" ±.5" for tub sloping sides.
Powell	15N	13W	4			1.5	-	-	
	15N	12W	21			1.3	-	-	
	15N	11W	22			2.2	-	-	
	15N	11W	31			2.04	-	-	
	15N	10W	18			3.0	-	-	
	15N	10W	28			1.85	-	-	
Sanders	22N	23W	30			3.40	-	-	
Teton	27N	8W	13			7.5	Glass Tube	Fair	
	27N	7W	26			6.4	Glass Tube	Fair	
	27N	5W	22			6.5	Glass Tube	Good	
	27N	4W	21			6.5	Glass Tube	Good	
	26N	8W	23			6.7	Glass Tube	Good	
	26N	6W	3			6.0	Glass Tube	Good	
	26N	5W	12			4.0	Rectangular Gage	Fair	
	26N	5W	19			4.75	-	Good	
	26N	4W	23			4.7	Glass Tube	Good	
	26N	3W	28			4.5	Glass Tube	Good	
	25N	8W	9			9.0	Wedge	Good	
	25N	7W	25			8.0	Wedge	Fair	
	25N	5W	18			4.65	Govt. Issue	Good	
	25N	3W	25			4.0	Glass Tube	Good	
	25N	2W	1			4.85	Glass Tube	Good	
	24N	5W	12			4.73	Glass Tube	Good	
	24N	5W	13			5.5	Glass Tube	Fair	
	24N	5W	25	1.09	4.12	5.21	SRG	Good	
	24N	4W	14			5.0	Glass Tube	Good	
	24N	3W	1			4.05	Glass Tube	Good	
	24N	3W	34			5.5	Glass Tube	Good	
	24N	2W	3			5.5	Glass Tube	Good	
	24N	1W	11			3.3	Glass Tube	Good	
	24N	1W	17			3.25	Glass Tube	Good	
	24N	1E	28			3.8	Glass Tube	Good	
	24N	2E	22			3.5	Glass Tube	Good	
	23N	3W	18			4.1	Glass Tube	Good	
	23N	2W	-			5.5	Glass Tube	Good	
	23N	2W	28			4.8	Glass Tube	Good	
	23N	1W	25			3.5	Glass Tube	Good	
	23N	1E	3			3.8	Glass Tube	Good	
	23N	1E	23			4.15	Glass Tube	Good	
	23N	1E	23			3.75	Glass Tube	Good	
	23N	1E	33	.60	3.20	3.80	Glass Tube	Good	
	23N	2E	5			3.1	Glass Tube	Good	
	23N	2E	18			3.5	Glass Tube	Good	
	22N	9W	32			→ 10.5	Glass Tube	Good	
	22N	7W	9			7.5	2" Diam.	Good	
	22N	6W	27	2.21	4.11	6.32	Funnel top with 1-10 ratio	Good	
	22N	6W	34			6.50	2" Diam.	Good	6p of 7th to 8p of 8th.
	22N	5W	20			7.08	Glass Tube	Good	
	22N	5W	35			7.5	Glass Tube	Good	
	22N	3W	4			4.2	Glass Tube	Good	
	22N	3W	38			4.3	Glass Tube	Good	
	22N	2W	1			5.3	Glass Tube	Good	
	22N	2W	8	.40	6.25	6.65	Victor	Good	
	22N	2W	28			5.01	Glass Tube	Good	
	22N	2W	-			4.2	Glass Tube	Good	
	22N	1W	10			5.3	Glass Tube	Good	
	21N	5W	18			5.25	Glass Tube	Good	

See reference notes following Station Index.

SUPPLEMENTARY PRECIPITATION DATA

Storm of June 7 - 8, 1964

County	Location: Township	Range	Section	June 7	June 8	Total	Type of Gage	Evaluation of Record	Remarks
Teton - Continued	21N	4W	14	1.50	4.00	5.5	Glass Tube	Good	
	21N	4W	15			5.5+	Glass Tube	Good	Overflowed
	30N	3W	1			4.0	Glass Tube	Good	
	25N	9W	27			13.0	Pail & Bucket	Good	First used aluminum pail (8" sides) then a 5 gallon paint pail (straight sides) Time - 5 am 6/7 to 4 pm 6/8.
Toole	Galata					2.0	5" Glass Tube	Good	
	Sunburst					2.0	5" Glass Tube	Fair	
	37N	2W	20			2.1	Glass Tube	Fair	
	38N	4W	2			2.2	Glass Tube	Good	Avg. of several glass tube gages.
	38N	3W	28			2.0	Glass Tube	Fair	
	35N	4W	2			6.4	Glass Tube	Good	
	35N	2W	33			2.5	Glass Tube	Fair	Poor Exposure
	35N	1E	21	.80	.70	1.5	Glass Tube	Good	
	34N	4W	16			4.0	Glass Tube	Fair	
	34N	3W	11			3.0	Glass Tube	Fair	
	34N	1W	2			1.5	Glass Tube	Fair	
	33N	3W	6			3.1	Glass Tube	Good	
	33N	3W	6			3.25	-	-	
	33N	2W	26			3.0	Glass Tube	Fair	
	33N	1W	19			2.5	Glass Tube	Good	
	33N	3E	22			1.7	Glass Tube	Good	
	32N	4W	18			4.6	-	-	
	32N	4W	35			5.3	Glass Tube	Good	
	32N	3W	34			4.0	Glass Tube	Fair	
	32N	2E	4			2.0	Glass Tube	Good	
	32N	3E	34			3.85	Glass Tube	Good	
	31N	2W	16	2.7	2.0	4.7	Glass Tube	Good	
	31N	2W	26			4.1	Glass Tube	Fair	
	31N	1W	4			3.5	Glass Tube	Fair	
	31N	1E	27			2.25	Glass Tube	Good	
	30N	1W	20			3.3	Glass Tube	Good	
	30N	2E	7			2.25	Glass Tube	Good	
	30N	3E	3			2.0	Glass Tube	Good	
	29N	2E	12			3.2	Glass Tube	Good	

Stations for which hourly amounts will be available in the supplemental publication "Hourly Precipitation Data" for June 1964.

County	Station	June 7	June 8	Remarks
Cascade	Kings Hill	.77	1.36	Storm total 2.13 in 41 hours.
	Millegan	.67	.52	-
Choteau	Fort Benton 20N	.65	1.69	Storm total 2.61 in 29 hours.
	Highwood	.69	2.52	Storm total 3.21 in 31 hours.
Fergus	Hilger	.53	1.62	Storm total 2.15 in 36 hours.
	Lewistown FAA AP	1.12	1.62	Storm total 2.74 in 32 hours.
Flathead	Summit	2.41	5.68	Storm total 8.09 in 38 hours.
Glacier	Browning	2.03	5.65	Storm total 7.68 in 35 hours.
	Cut Bank AP	.82	2.29	Storm total 3.11 in 26 hours.
	Grinnell Creek Gaging Stations	2.5	3.0	USGS T Bucket on water storage recorder - total 5.5.
Lake	Swan Lake	.24	3.44	-
Lewis & Clark	Gibson Dam	1.60	6.49	Storm total 8.09 in 37 hours.
Missoula	Seeley Lake RS	.70	.55	-
Pondera	Dupuyer	1.55	4.48	-
Sanders	Lonepine RS	.46	1.69	-
Teton	Choteau	1.14	3.89	Storm period 2 pm 7th - 7 pm 8th. Total 5.03 in 30 hours.
	Dutton 6E	.83	1.88	Storm total 2.71 in 33 hours.

See reference notes following Station Index.

COLORADO WATER

Newsletter of the Colorado Water Resources Research Institute, Fort Collins, Colorado 80523

WATER ITEMS AND ISSUES . . . *November 1989*

copy of a paper by Russell N. Clayshulte, **Denver South Platte Water Quality and Wastewater Management Study**, is ovided as an attachment. The paper was presented at the Colorado Groundwater Engineering and Management Conference.

Colorado State University

CONGRESSIONAL BILLS OF INTEREST IN SUPPORT OF WATER RESOURCES AND WATER RESEARCH

This legislative summary was compiled as a news update for the Universities Council on Water Resources by Jon F. Bartholic, Director, Institute of Water Research, Michigan State, and printed in HYDATA.

A great deal of water legislation has been proposed in the last two sessions of Congress, including two major water resource management and education bills (S203 and HR37). A number of bills involving sections of these two have also been proposed (HR2734, HR978 [Title IV], HR2258 [Title III]; S362 [Title II], S397 [Title IV], and S779 [Title III]. At least a dozen additional water bills are of some interest. Of particular interest are the reauthorization bills for the Water Resources Research Act which will continue the authorization for the water research institutes (HR1101 and S714).

The key water resources research activities bill in the House is HR37, the National Groundwater Research Act of 1989. The bill introduced by Representative Gejdenson is identical to HR791 as it passed during the last session of Congress in December, 1988. HR37 currently has 94 cosponsors. It authorizes a wide variety of activities in the Departments of Interior, Agriculture, and the Environmental Protection Agency. Because of its breadth, HR37 has been referred to several Congressional committees for consideration.

In the Department of the Interior the bill proposes authorization to undertake research investigations, appraisals, surveys and related activities--in cooperation with federal, state and local government agencies, and academic institutions--and to disseminate the results of such research. Further, groundwater contamination risk assessment analysis would be undertaken and programs, training and technology transfer would be established, as well as a national groundwater information clearinghouse.

The Department of Agriculture would be involved in agricultural water quality and use studies, including non-point source management programs and the establishment of an agricultural nitrogen best management practices task force. An additional clause deals with groundwater radium contamination.

EPA would be given additional authority to issue grants to higher learning and research institutions, including consortia, with the establishment of five groundwater institutes in the United States. Cost sharing on a one-to-one basis could apply.

In the Senate a companion bill, S203, "Groundwater Research, Management and Education Act," has been submitted by Senator Burdick with numerous cosponsors. This bill is in the Committee on the Environment and Public Works. S203, in many aspects, is similar to HR37 but leans toward more regulatory and national responsibilities vs. the strong emphasis in the House bill on state level decision making.

Additionally, S203 includes a section (104) which involves the reauthorization of the water resources institutes. HR37 does not include similar language. The "Reauthorization of the Water Resources Research Act," HR1101, deals with the authorization of the water research institutes. This bill was sponsored by Representative George Miller with 40 cosponsors. It was passed in an amended form on June 6, 1989 by a vote of 336 to 74. The cost-sharing on the House side is one-to-one and evaluation of the institutes is required at least every five years. Section 104 was amended to include a new subsection authorizing up to $5 million for work on water problems and issues of a regional or interstate nature. A new section, 107, was added which would authorize the Secretary of the Interior, in consultation with the Secretary of Agriculture and the administration of EPA, to enter into contracts to carry out R and D demonstration projects related to contamination of groundwater and toxicological significance. Section 107 is confined to reclamation states and special reference is made to the Los Alamos National Laboratory.

Senate Bill 714 has also been introduced for the reauthorization of the Water Resources Act. This bill, sponsored by Senator McClure and at least 34 cosponsors, has been referred to the Committee on Environment and Public Works. There appears to be an ongoing impasse within the Environment and Public Works Committee as to whether they are willing to act on Senate Bill 714 (my feeling is that this is unlikely), or whether they will try to push the authorization through as part of Senator Burdick's bill, S203. S203 will probably not move this year.

Additional water bills which may be of some interest include: HR980 - Global Environment Research and Policy Act of 1989 for development of a National Global Change Research program; HR1421 - Marine Research Act of 1989. A bill oriented toward the Sea Grant Program; HR2521 - Reclamation States Groundwater Protection and Management Act, 1989; S57 - National Acid Rain Control Act of 1989; S676 -Global Environmental Protection Act of 1989 (similar to HR980).

Developments of the 1990 Farm Bill represent another area of interest from a water resources standpoint. Numerous conservation-oriented sections will probably be added to the ag bill as it evolves and is ultimately passed next year. Already, numerous bills which could ultimately be incorporated into the Farm Bill are being introduced. Among those are Senator Lugar's bill, S1063, and Senator Lawler's bill, S970. Numerous other bills will likely be introduced, allowing hearings on various aspects that could be incorporated as sections into the Farm Bill. Clearly, the increasing concern for conservation and possible impacts of agriculture on ground and surface waters will lead to policies that will attempt to facilitate a more environmentally benign agricultural system.

Inputs for the above comments were obtained from a variety of sources. Of particular importance was the Policy, Legislative Administrative (PLA) Committee report for the UCOWR Annual Meeting in Minneapolis, August 8-11, 1989.

Flood Hydrology Manual

A Water Resources Technical Publication

by
Arthur G. Cudworth, Jr.

Surface Water Branch
Earth Sciences Division

FIRST EDITION 1989

United States Department of the Interior
Bureau of Reclamation
Denver Office

It is generally accepted, among practicing hydrometeorologists concerned with severe storm precipitation events, that use of such models is the preferred method. It is expected that models will be developed that will eventually simulate the severe storms of record and be adapted to provide more reliable estimates of PMP.

(c) Individual Drainage Estimates and Regionalized Studies.—The approaches to PMS development of storm maximization or modeling techniques can be applied to either an individual basin or to a large region that contains a multitude of drainages of varying size and shape. For the individual basin, the "individual drainage estimate" and the results are to be exclusively applied to the single drainage under study. For a large region, the term "regionalized" or "generalized" approach is used for the PMS evaluation. For the regionalized approach, an area of similar topographical and meteorological features is defined and the procedures of storm maximization and/or model technique are applied to portray the PMS in generic form for the entire region. The final result is obtained using appropriate figures, tables, and equations for which values of the PMS are obtained for any drainage located within the study area and within the limits (durational-areal) of the regionalized report. With few exceptions, the regionalized approach as set forth in the HMR report series is to be used in determining PMP and PMS values for PMF development. Usually, exceptions arise when the drainage basin being studied is larger than that for which criteria are presented in the report series.

Regionalized PMS criteria [18,20,29,31,35,39,40,41] are used because they possess several distinct advantages such as: (1) greatest use of available data can be incorporated, (2) storm maximization or model techniques provide a greater degree of reliability to the PMS if analyzed on a regional basis, (3) consistency among individual basin estimates is obtained, (4) individual estimates of PMS can be readily obtained from completed regional studies by hydrologic engineers, and (5) regionalization serves as a base of severe storm information and criteria to further develop individual drainage study requirements for specific locations when additional information becomes available.

The primary disadvantages of regionalized studies are: (1) time required to complete and document studies often take several years, (2) extensive manpower requirements that include several hydrometeorologists with a specialty in PMS criteria development, and (3) the scale of analysis is such that minor refinements are not incorporated because of the smoothing involved.

The Bureau's development of the PMS, unless obtained from regionalized reports [18,31,35,38,39,40,42,43,44,45], is always conducted by a professional hydrometeorologist in the Flood Section of the Bureau's Denver Office; or through consulting meteorologists in conjunction with

TECHNICAL ATTACHMENT

THE UPPER RIO GRANDE FLOOD OF OCTOBER 1911

INTRODUCTION

Each springtime the melting of snowpacks from the high mountains of southwestern Colorado sends the Upper Rio Grande on a rise with flows cresting sometime between late May and early July. The annual occurrence is routinely expected by all residents of the valley. By late summer, the river flow is generally back down to a minimum, and the river's tranquil state lasts until the following melt season. On very rare occasions, however, this cycle is disrupted. Nineteen eleven was such a year.

THE FLOOD

The greatest flood in recorded history in the uppermost reaches of the Rio Grande Basin in southwestern Colorado occurred October 5-6, 1911. While no flood in the intervening 78 years has eclipsed that autumn inundation, this fact itself speaking strongly of the flood's singularity, the most rare feature yet remains its occurrence in October, an unusual time for high river flows from the stream's source region. Table 1 lists the maximum discharges and their months of occurrence each year for the 50-year period 1900-1949 at Del Norte, Colorado, on the Rio Grande. For that 50-year period, only the 1911 maximum failed to occur during the May-July melt season. Figure 1 is the flood discharge hydrograph for the Rio Grande near Del Norte, Colorado, covering the six-day period October 4-9, 1911 (1).

The Rio Grande trunk stream rises in the central part of Hinsdale County, Colorado, and flows easterly emerging from the mountains at Del Norte and then flowing through the heart of the 7,000-foot high San Luis Valley to Alamosa, and then southward into New Mexico. The character of the region drains a mountainous country ranging in altitude from over 14,000 to 6,000 feet MSL, encompassing some of the highest mountain country in the continental United States. Downpours of rain in that remote high region during the warmer months of the year from local thunderstorms are expected occasionally in the mountains, but the areas affected are usually small. With the coming of autumn, thunderstorms give way to general storms that spread their influence over a wide scope of the country, causing sharp falls in temperature and occasional heavy snowfalls. On October 4 and 5, 1911, instead of these last-named conditions, mild temperatures prevailed as high as or higher than timberline, permitting precipitation in the form of rain rather than snow. Indeed, those rains were widespread, copious, and entirely at fault in producing the worst flood since the settlement of that part of the country.

The widespread heavy rains caused floods also in the Dolores and San Miguel Rivers in western Colorado, the San Juan and its tributaries in Colorado and New Mexico, as well as the Upper Rio Grande in Colorado, and the tributaries of the Rio Grande in northwestern New Mexico on October 5 and 6, 1911. There is no previous record, or even tradition, among the Indians of such severe floods occurring simultaneously in all the streams of that two-state area.

The San Juan Mountains, which are part of the Continental Divide, form the watershed between the upper Rio Grande on the east, the San Juan on the south, and the Gunnison on the north. It was in this region that the storm was most severe, although there were torrential rains throughout the district. In general, the rains began during the forenoon of the 4th, becoming heavy during the night, and continuing heavy until late in the afternoon of the 5th. There is evidence that the rainfall increased with altitude. The effect of rainfalls of 2.50 inches to more than 8 inches on the steep slopes of the San Juan Mountains was to cause quickly forming floods that swept away everything in their path. Five lives were lost; miles of railroad tracks were destroyed; scores of bridges were carried away; and there was a general destruction of crops, of farm lands by immense deposits of silt or by erosion, wagon roads, trails to the mines, irrigating ditches, flumes, and other mining equipment. It was months before normal conditions of travel could be restored.

An account by Mr. E. T. Walker, Weather Bureau cooperative observer at Pagosa Springs, Colorado, on the San Juan River, is revealing of the severity of conditions during the siege (2).

> The precipitation beginning at 1 PM on the 4th, and ending at 11 AM on the 5th, totaling 3.82 inches, resulted in the most disastrous flood known within the memory of the oldest inhabitants -- including Indians. The precipitation of the previous few days, viz, September 29, 0.30, September 30, 0.62, October 1, 0.33 inch, had thoroughly soaked the ground, and much of the water ran off. Owing to the constant changing of the channel of the river at this place, it is difficult to gage the rise of the flow with any degree of accuracy, but it is safe to say that twice as much water passed here on the 5th as has ever flowed in any single 24 hours of the 32 years that I have resided on the banks of the San Juan. The precipitation was general throughout the county and resulted in much damage to ranches, roads, bridges, irrigating ditches, railroads, etc.

News of the flood in the upper parts of the different watersheds was communicated to the downstream points, permitting the taking of steps to minimize as far as possible the damages.

The Rio Grande in flood spread out, and in places was from 2 to 4 miles wide. In Alamosa, the principal damage resulted from the breaking of a dike and the inundation of 30 city blocks. In New Mexico where the river bed is of greater capacity, the damage was not as serious.

Flooding from the heavy rains of October 4-5 was undoubtedly made more severe by the fact that widespread rains of nearly an inch over the three-day period September 29 - October 1 had largely saturated the mountain soil, leaving it ill-prepared to accept the heavier rainfalls which precipitated the flooding. Again, Figure 1 is the hydrograph for the flood as it passed Del Norte Colorado.

EASTERN NORTH PACIFIC TROPICAL STORMS

The unfortunate victims of that unprecedented flood in 1911 had no way of knowing that an eastern North Pacific tropical storm, unnamed of course, was the principal culprit in inflicting such misery on one of the mountain west's most scenically-endowed areas. That the rains for that flood were of tropical origin is now widely believed. A strong case is made in studies by Walter Smith (3) which was presented in his 1986 publication, "The Effects of Eastern North Pacific Tropical Cyclones on the Southwestern United States."

Smith describes the tropical cyclone of October 1-5, 1911, in the following fashion.

> The storm apparently weakened rapidly on October 4 after moving inland over Baja California just west of La Paz. Nevertheless, moist tropical air was drawn northward ahead of a digging short wave which by 1300 GMT on the 4th was located in northern Nevada. A day later the surface low was situated on the Utah-Arizona border producing heavy rains over the eastern half of Arizona, northwestern New Mexico, southeastern Utah, and southwestern Colorado where torrential rains fell causing a major flood in the San Juan River basin and five fatalities. Gladstone, Colorado, (elevation 3,220 M) reported a total of 8.16 inches of rain, 8.05 of it falling on October 5.

Figure 2 is Smith's plot of the storm track and isohyets for that October 1-5, 1911, tropical storm. Table 2 shows rainfall data for a number of precipitation stations in both Colorado and New Mexico that were in or near the Upper Rio Grande basin. The data includes not only the flood producing rainfalls of October 4-6, but also the antecedent rainfalls of October 1-2, 1911. Although missing from the map provided, Gladstone, Colorado, at an altitude of nearly 10,000 ft. MSL and shown receiving the phenomenal 8 inches of rainfall, lies just west of the westernmost extension of the Rio Grande basin.

Smith's work clearly points out the significant role of eastern north Pacific tropical cyclones in bringing heavy precipitation and related floods in late summer and early autumn to much of the southwestern United States. He furthermore states that given the rapid growth and urbanization of many cities in the southwest over recent years, these storms will probably cause many serious floods in the future.

Citing a more recent example, his studies point out the occurrence of Tropical Storm Norma of August 30 - September 5, 1970, which brought devastating floods to Arizona and Utah, causing at least 25 deaths. Rains from Norma reached the basin of the Upper Rio Grande as well, and the September 6, 1970, annual record high discharge at Del Norte, Colorado, of 7380 CFS represents a second case since the great flood of October 1911 when the year's greatest flow occurred from autumn rainfall rather than springtime snowmelt. Fortunately for the modern public, and unlike the hapless residents of the Upper Rio Grande in 1911, or even to a lesser degree those of 1970 and Norma, today's weather surveillance technology furnishes a means by which the developing meteorological conditions can be detected in a much more timely fashion. It will be left up to the interpretive skills of NWS meteorologists and hydrologists working together to discern the rapidly developing flood scenarios and get out the appropriate warnings.

<u>EASTERN NORTH PACIFIC STORM RAYMOND, 1989</u> Eastern North Pacific Tropical Storm Raymond did not bring heavy rainfalls to the southwestern United States. Rainfalls from this storm were instead quite light, falling mainly over Arizona and New Mexico. The storm did occur, however, at exactly the same time of the

year, the first five days of October, as did the storm of 1911. Modern surveillance provided by satellite imagery permits us to watch these storms as they progress from off-shore to inland, as shown by the four-day series of pictures for Tropical Storm Raymond presented by Figure 3. Perhaps added interpretive skills, especially when coupled with anticipated new data sets, provided by NEXRAD especially, will allow accurate pinpointing of the occurrence of outstandingly heavy rainfalls such as occurred in 1911, and adequately warn, with some lead time, of the impending disaster.

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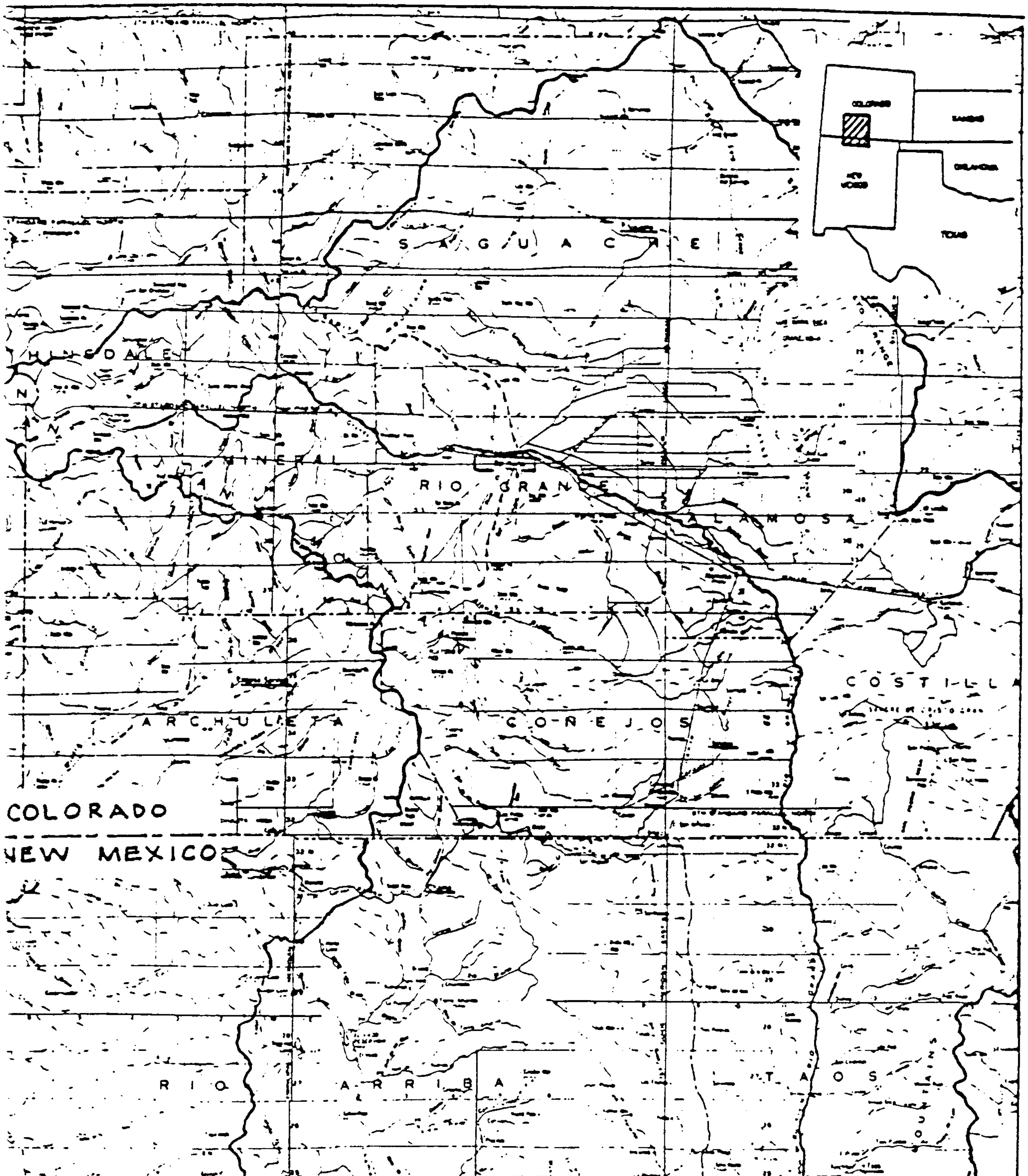
2. U.S. Department of Agriculture, Weather Bureau; Monthly Weather Review, July to December 1911 -- Floods in Southwestern Colorado and Northwestern New Mexico, October 5-6, 1911 (F. H. Brandenburg); pg. 1570.

3. NOAA Technical Memorandum NWS WR-197; The Effects of Eastern North Pacific Tropical Cyclones on the Southwestern United States; Walter Smith; Department of Atmospheric Sciences, University of Arizona, Tucson, Arizona; August 1986.



SAGUACHE
HINSDALE
MINERAL
RIO GRANDE
ALAMOSA
COSTILLA
ARCHULETA
CONEJOS
COLORADO
NEW MEXICO
RIO ARRIBA
TAOS
COLORADO
KANSAS
OKLAHOMA
NEW MEXICO
TEXAS

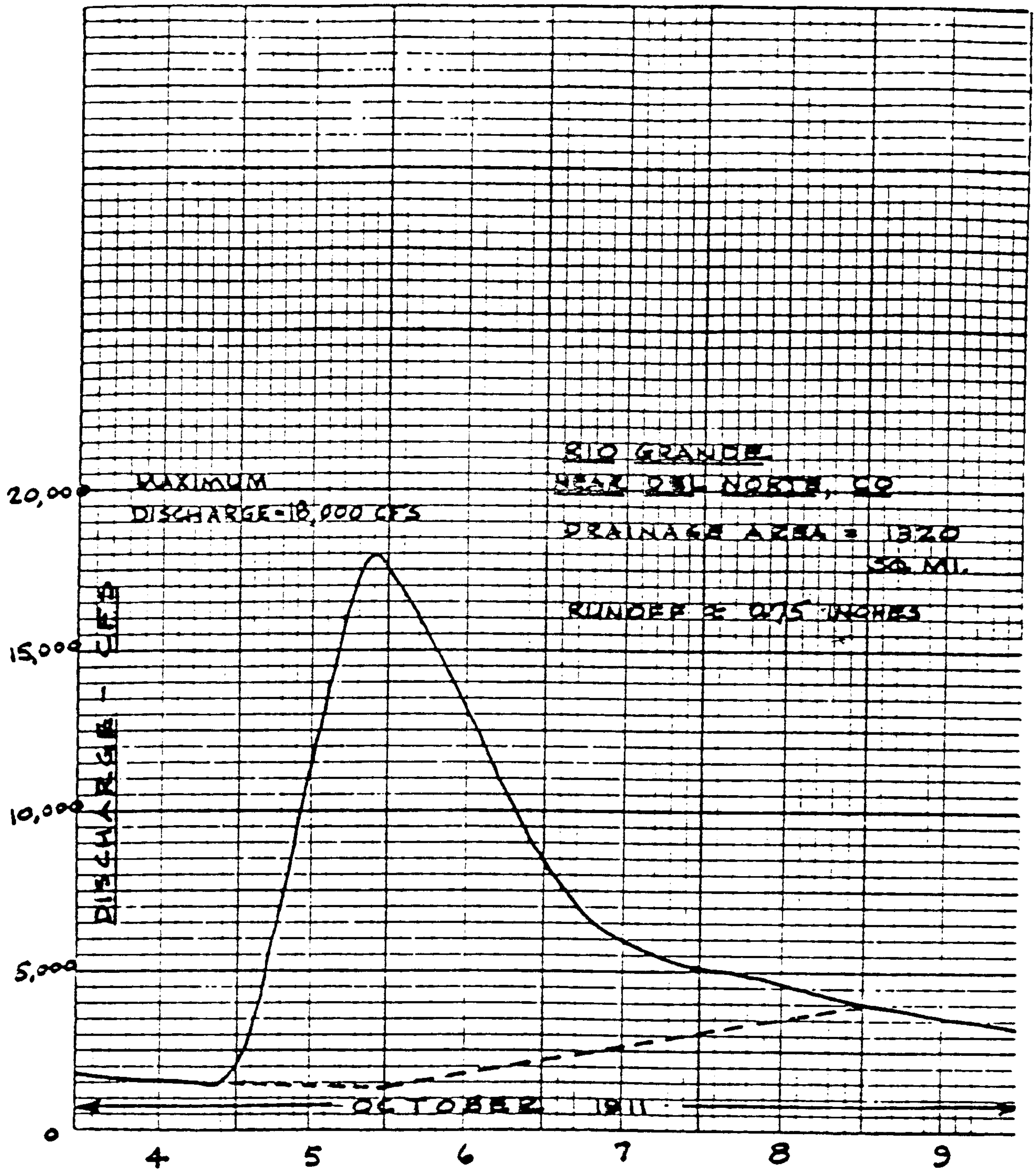


FIGURE 1

Flood Hydrograph for Del Norte, Colorado, October 1911

TROPICAL CYCLONE OF
10/1-5 1911

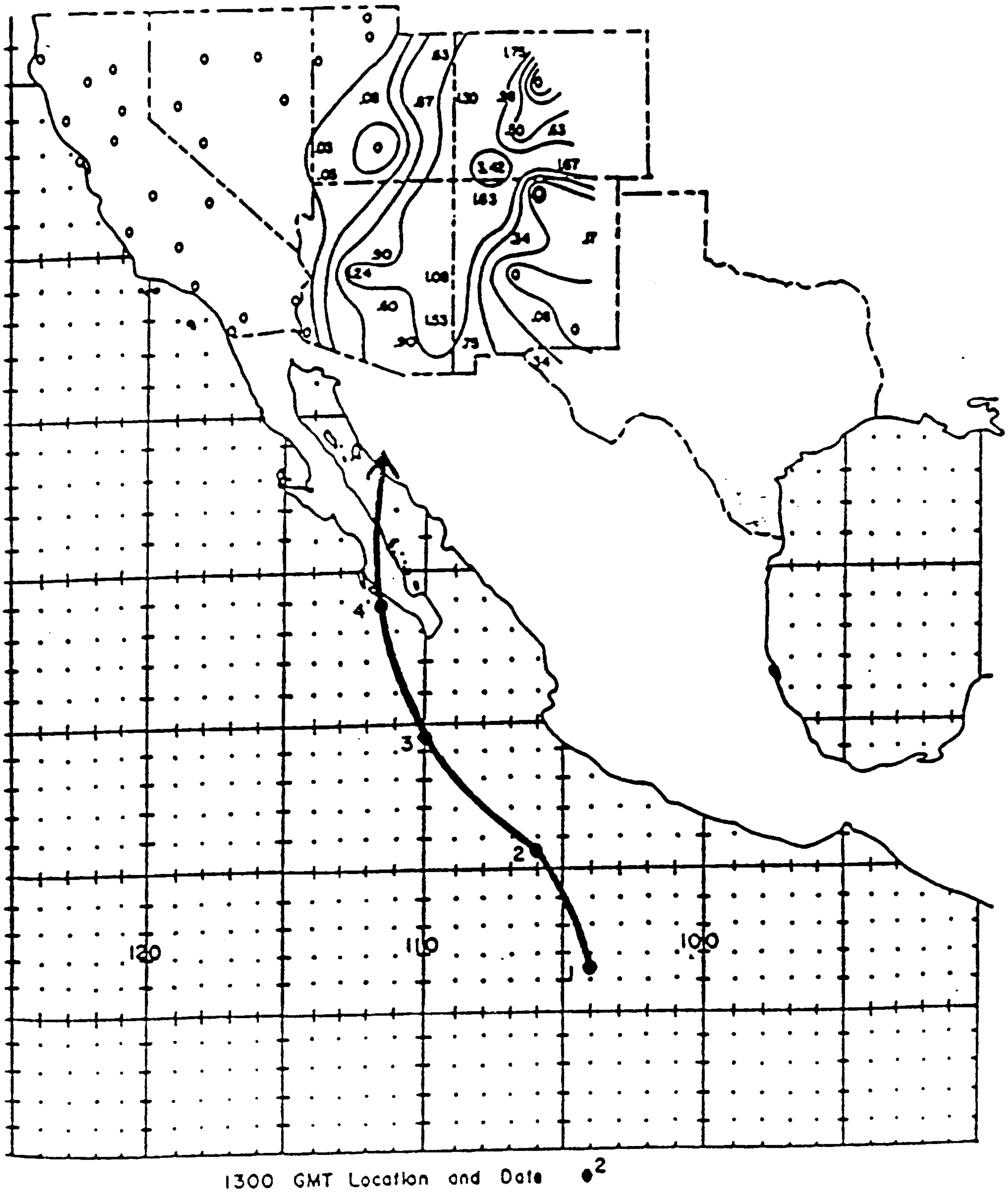


Figure 12. Track of the Tropical Cyclone of October 1-5, 1911 and associated rainfall in the Southwest. Precipitation totals are in inches and the isohyets are drawn at .01, .25, .50, 1.00, and 2.00 inches.

FIGURE 2

From Walter Smith's "The Effects of Eastern North Pacific

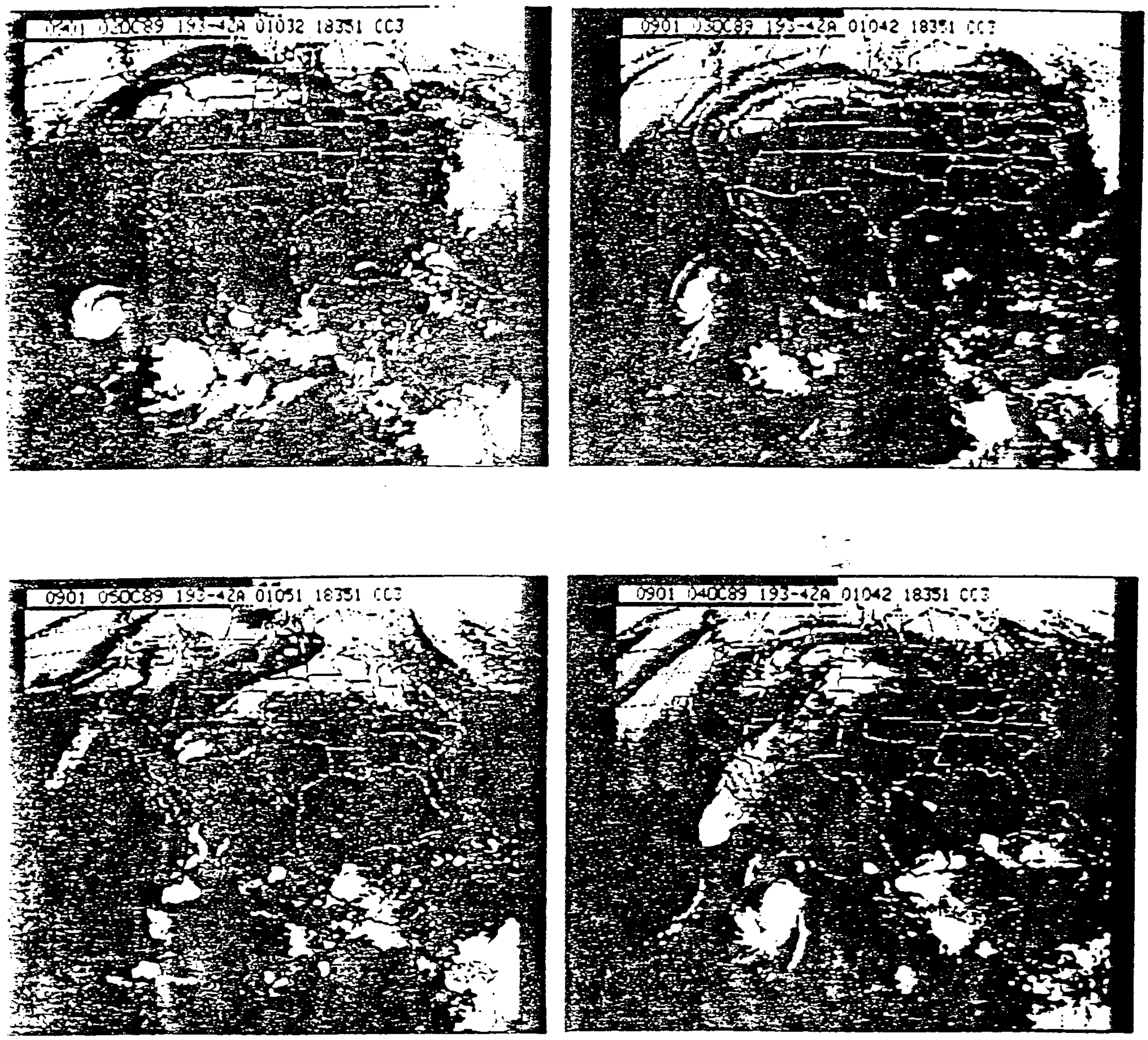


FIGURE 3

Tropical Storm Raymond, October 2-5, 1989

Momentary Maximum Annual Discharge 1900-1949
Rio Grande near Del Norte, Colorado

Year	Month	Discharge	Year	Month	Discharge
1900	May	5,450	1925	June	3,610
1901	May	4,480	1926	June	5,450
1902	May	1,790	1927	June	15,000
1903	June	6,020	1928	June	4,900
1904	May	2,040	1929	June	5,830
1905	June	10,000	1930	May	4,400
1906	June	7,670	1931	June	2,670
1907	July	7,770	1932	June	5,460
1908	June	4,130	1933	June	5,050
1909	June	6,980	1934	May	2,980
1910	May	5,260	1935	June	6,520
1911	October	18,000	1936	May	4,000
1912			1937	May	3,920
1913	May	4,030	1938	June	6,560
1914	June	5,820	1939	May	3,550
1915	June	4,690	1940	May	2,810
1916	May	5,020	1941	June	7,960
1917	June	8,790	1942	May	7,150
1918	June	3,820	1943	June	3,380
1919	May	6,020	1944	May	7,070
1920	June	8,100	1945	June	4,030
1921	June	9,630	1946	June	3,860
1922	May	8,320	1947	June	4,390
1923	May	5,210	1948	May	8,840
1924	June	5,980	1949	June	10,000

TABLE 1

DAILY PRECIPITATION FOR SELECTED STATIONS
IN COLORADO AND NEW MEXICO -- OCTOBER 1911

STATION	STATE	October 1911						
		1	2	Σ(1+2)	4	5	6	Σ(4+5+6)
Chama	NM	0.45		0.45	0.40	2.30	0.05	2.75
Chromo	CO	0.45		0.45	0.50	2.00	0.01	2.51
Cumbres	CO		0.30	0.30	3.08	1.26	0.49	4.83
Dulce	NM	0.28		0.28	0.20	1.75		1.95
Durango	CO	0.05	0.02	0.07	1.16	2.26		3.42
Gladstone	CO	1.62	T	1.62	0.11	8.05	T	8.16
Hesperus	CO			0.00		2.30	0.58	2.88
La Veta Pass	CO			0.00	0.59	1.42		2.01
Manassa	CO	0.15		0.15	1.28	0.15		1.43
Mancos	CO	1.12	T	1.12	0.08	1.54		1.62
Pagosa Springs	CO	0.33	0.01	0.34	0.15	3.67		3.82
Platoro	CO	0.61	0.02	0.63	0.05	3.25	0.04	3.34
Saguache	CO			0.00		1.20	0.10	1.30
San Luis	CO	0.02		0.02	0.40	1.50	0.07	1.97
Silverton	CO	0.90	T	0.90	0.20	4.05		4.25
Taos	NM	0.10		0.10	0.27	1.38	0.20	1.85
Telluride	CO	0.96	0.02	0.98	0.02	1.57	0.20	1.79
Wagon Wheel Gap	CO	0.17	T	0.17	0.71	1.94		2.65

TABLE 2

AMERICAN SOCIETY OF CIVIL ENGINEERS
INSTITUTED 1852

TRANSACTIONS

This Society is not responsible for any statement made or opinion expressed in its publications.

Paper No. 1480

THE FLOOD OF JUNE, 1921, IN THE ARKANSAS RIVER, AT PUEBLO, COLORADO*

By James Munn† and J. L. Savage,‡ Members, Am. Soc. C. E.

With Discussion by Messrs. Arthur O. Ridgway, R. G. Hosea, George G. Anderson, Robert Follansbee, and E. E. Jones.

Synopsis

This paper describes the causes and effects of the flood of June, 1921, in the Arkansas River, at Pueblo, Colo., and discusses general plans and estimates for future flood-control works.

A history of former floods is followed by a description of the recent flood, including a discussion of the causes, the resulting property damage, the estimated peak flow and flood volume, the drainage area and rainfall data, and a presentation of alternative plans and estimates for flood-control works.

History of Former Floods

The first flood in the Arkansas Valley known to white settlers occurred in 1864. At that time, Pueblo was little more than a trading post, and the damage was slight. The next flood of unusual volume occurred in 1894. At the time of this flood, Pueblo had little or no river protection, and the Arkansas River meandered through the city, cutting its banks and changing its course. This flood did considerable damage by covering the railroad yards and flooding the city to Third and Fourth Streets. After the flood of 1894, the river channel was straightened and substantial levees were built, leaving the river in the condition obtaining at the time of the flood of June, 1921.

With the exception of a flood in the Purgatoire River, a tributary of the Arkansas, in 1908, which washed out the Fort Bent Canal diversion dam and the Amity Canal diversion dam, there has been little damage to irrigation or

* Presented at the meeting of October 5th, 1921.

† U. S. Reclamation Service, Denver, Colo.

‡ Designing Engr., U. S. Reclamation Service, Denver, Colo.

other works through floods on the Arkansas River or its tributaries in the past twenty years. The minor damages which have occurred from time to time during this period, have been due more to poor construction or insufficient protection than to unusual flood conditions.

Description of the June, 1921, Flood

On the afternoon of June 2d, 1921, the Arkansas River at Pueblo was carrying 8 100 sec-ft. At 11.30 P. M., the river began to rise rapidly and, at 2.00 A. M., on June 3d, the discharge was about 28 500 sec-ft. At 8.00 A. M., June 3d, the discharge had dropped to 3 500 sec-ft. and, from noon to 5.00 P. M., it again began to rise rapidly, overtopping the levees and beginning to rise very rapidly, reaching a gauge height of 12.7 ft. and a discharge of 24 000 sec-ft. at 6.40 P. M., where it remained stationary until 7.40 P. M. At 7.40 P. M., it again began to rise rapidly, overtopping the levees and beginning to flood the city at 8.45 P. M., with a gauge height of 18.14 ft.

When the river began to overflow its banks, the discharge was probably about 40 000 sec-ft., but from the time of overflow the quantity of water passing through the city cannot be accurately determined, due to the choking of the channel with débris of all kinds. Subsequent levels showed a maximum gauge height of 24.66 ft., and the peak discharge has been roughly estimated at 100 000 sec-ft. The river after overflowing at 8.45 P. M., on June 3d, continued to rise until about 1.30 A. M., of June 4th, when it began to recede. At 4.30 A. M., it had fallen to a gauge height of about 18 ft., with an estimated discharge of about 50 000 sec-ft.

Sometime during the night of June 3d, a flood came down Fountain Creek, a tributary from the north, which joins the Arkansas River at Pueblo. The peak of this flood has been roughly estimated at 50 000 sec-ft. Although this flood receded quickly, it did considerable damage along its own course and added greatly to the damage in the Arkansas Valley below Pueblo.

On Sunday, June 5th, at about 3.00 P. M., another flood in the Arkansas River swept through Pueblo, adding somewhat to the damage and causing renewed alarm. This flood was caused by the destruction of the Schaeffer Dam on Beaver Creek, which released about 3 100 acre-ft. of reservoir storage. Probably no damage would have resulted from this flood if the levees had not already been breached by the greater flood of June 4th. In this connection, it will be noted that the flood of June 5th, resulting from the destruction of the Schaeffer Reservoir, totaled only 3 100 acre-ft., or about one-thirtieth of the whole flood volume.

The flood in the Arkansas River below its junction with Fountain Creek at Pueblo was augmented to a considerable extent by floods in some of the tributaries entering below Pueblo. The St. Charles River added probably 10 000 sec-ft., and this stream did considerable damage along its own course. At La Junta, Colo., the peak in the Arkansas River was probably between 170 000 and 175 000 sec-ft. Below La Junta, the accretions were negligible and near Lamar, at the Amity Canal diversion dam, the peak flow was estimated at 170 000 sec-ft.

TABLE 4.—DAILY AND CUMULATED RAINFALL OVER ARKANSAS DRAINAGE AREA IN COLORADO DURING THE STORM OF MAY, 1894.

(Order of Stations is from West Proceeding East)

Station.	Daily Rainfall, in Inches. Day of month.						Cumulated Rainfall, in Inches. Days of month.					Rainfall to:
	28	29	30	31	1	2	28–29	28–30	28–31	28–1	28–2	
Lake Moraine			5.50	2.00				5.50	7.50			6.00 P. M.
Canon City		0.75	4.31					5.06				
Husted	0.08	0.08	1.15	0.84	0.22		0.11	1.26	2.10	2.32		6.00 A. M.
Glen Eyrie			3.13	1.58	0.15			3.13	4.71	4.86		
Colorado Springs		0.08	2.95	1.44	0.50		0.08	3.03	4.47	4.97		
Divide Exp. Station		0.02	1.65	1.82			0.02	1.67	3.49			12.00 P. M.
Hamps		0.06		2.70			0.06	0.06	2.76			7.00 P. M.
Rocky Ford				3.50					3.50			
Las Animas			0.07	1.09				0.07	1.16			7.00 P. M.
Cheyenne Wells			2.00					2.00				
Springfield		4.00		0.10			4.00	4.00	4.10			
Vilas	0.14	0.62	0.93	0.76			0.76	1.69	2.45			

TABLE 5.—DAILY AND CUMULATED RAINFALL OVER ARKANSAS DRAINAGE AREA IN COLORADO DURING THE STORM OF JUNE, 1921.

(Order of Stations is from West Proceeding East)

Station.	Daily Rainfall, in Inches. Day of month.						Cumulated Rainfall, in Inches. Days of month.					Rainfall to:
	2	3	4	5	6	7	2–3	2–4	2–5	2–6	2–7	
Victor		0.03	2.08	1.56	0.37	0.01	0.03	2.11	3.66	4.03	4.04	4.00 P. M.
Canon City		0.30	2.35	0.75	0.40		0.30	2.65	3.40	3.80		
La Veta Pass		0.98	0.89		0.20		0.98	1.87	1.87	2.07		
Lake Moraine		0.65	3.68	1.40	0.18		0.65	4.33	5.73	5.91	5.91	3.30 P. M.
Florence		0.99	3.31	2.47	0.13		0.99	4.30	6.77	6.90		
Monument	0.06		2.90	0.82		0.40	0.06	2.96	3.78	3.78	4.18	4.00 P. M.
Colorado Springs	0.35	5.00	4.40	1.26	0.42	0.01	5.35	9.75	11.01	11.43	11.44	12.00 M.
Pueblo	1.94	1.64	1.45	1.12	0.09	0.01	3.58	5.03	6.15	6.24	6.25	3.25 P. M.
Huerfano			1.06	0.56	0.04	0.03		1.06	1.62	1.66	1.69	6.30 P. M.
Cuchara Camps			0.86	0.21	0.12	0.48		0.86	1.07	1.19	1.61	12.00 M.
Trinidad		0.20	0.55	0.30		0.27	0.20	0.75	1.05	1.05	1.32	3.15 P. M.
Calhan			3.26	0.83	0.39			3.26	4.09	4.48		7.30 P. M.
Ordway	0.25		0.90	0.75	0.19	0.03	0.25	1.15	1.90	2.09	2.12	
Rocky Ford			1.40	0.80	0.15			1.40	2.20	2.35		
Las Animas		0.27					0.27					8.00 P. M.
Eads		0.03	0.13	0.21			0.03	0.16	0.37			5.00 P. M.
Lamar			0.50		0.65			0.50		1.15		5.00 P. M.
Two Buttes			0.22	0.15	0.30	0.24		0.22	0.37	0.67	0.91	
Holly	5.88		0.05				5.88	5.93				

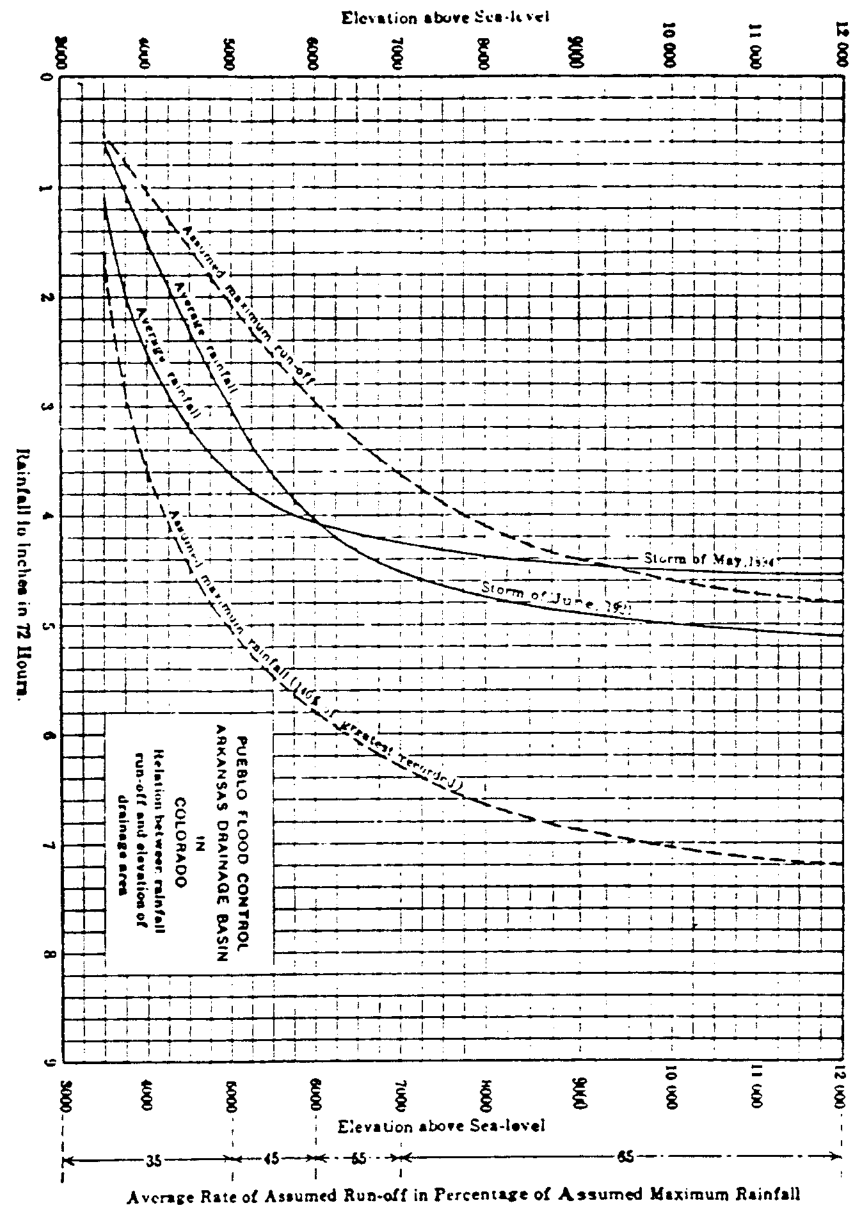

Elevation above Sea-level
3000
4000
5000
6000
7000
8000
9000
10 000
11 000
12 000
Rainfall in Inches in 72 Hours.
0
1
2
3
4
5
6
7
8
9
Assumed maximum run-off
Average rainfall
Average rainfall
Storm of May, 1894
Storm of June, 1921
Assumed maximum rainfall (160% of greatest recorded)
PUEBLO FLOOD CONTROL
ARKANSAS DRAINAGE BASIN
IN
COLORADO
Relation between rainfall run-off and elevation of drainage area
35
45
55
65
Average Rate of Assumed Run-off in Percentage of Assumed Maximum Rainfall

FIG. 10.

Although the total precipitation for June 3d, at Florence, as given in Table 5, is 0.99 in., it is unlikely that this amount was the total for that day of the rainfall which caused the run-off accumulating in the flood at Pueblo during the night of June 3d and the early morning of June 4th. It is much more likely that the quantity given as the total for that day at Florence was the rainfall up to 6.00 P. M., which hour is the beginning and ending of the Weather Service Bureau's day at various stations in Colorado, for instance, as at Colorado Springs and Lake Moraine, while, at Victor, the day begins and ends at 4.00 P. M. It is noticeable that on the following day, Saturday, June 4th at Florence the total rainfall is the maximum quantity, 3.31 in. It is probably correct to state that the greater part of this fell during the evening, after 6.00 P. M., and the night of June 3d, and in all probability thus contributed some volume to the flood at Pueblo and, also, to its peak flow.

Although only a slight run-off was observable in Eight-Mile Creek on the night of June 3d, Brush Hollow Creek, the next creek eastward, discharged a very high run-off. Subsequent measurements indicated more than 6 000 cu. ft per sec. as the peak flow from a drainage area not in excess of 25 sq. miles The next creek eastward is Beaver Creek which is known to have increased its discharge below the Schaeffer Dam before that structure failed, but all evidences of the volume on that night have been obliterated.

The next creek eastward is Turkey Creek. Although it may be correct t state that the Turkey Creek Reservoir retained the stream flow which occurre above it, there were evidences of quite heavy rainfall on that area, with considerable damage to roads and irrigation ditches. If that heavy rainfall di not extend into the area which the Turkey Creek Reservoir does not intercep there is indication that the intensity of the storm varied in different localitie which is quite probable. For instance, on the Dry Creek area, the next eas ward to Turkey Creek, there is every evidence of intense rainfall and a larg run-off.

From the foregoing comments, the writer is of the opinion that, althoug the greater volume of the Arkansas River flood came from the south side o that stream, and largely east of Hardscrabble Creek, considerable volum were added from streams on the north side, and that the tributary area these streams cannot be wholly disregarded in these considerations.

At the Schaeffer Reservoir the heavy rainfall did not commence until abo 7.30 P. M., on June 3d, and the consequent run-off may not have reach Pueblo at the time of peak flow, but, undoubtedly, it did add something to t total volume. The flow of Beaver Creek at and below the Schaeffer Dam d not exceed 90 cu. ft. per sec. until 4.00 A. M., on June 4th, when the wat surface of the reservoir reached the spillway level.

The writer is of opinion that the statement, "in the two largest storn [of the Arkansas Valley], namely, those of May, 1894, and June, 1921, t average rainfall increases quite uniformly with the elevation of the draina area", is apt to be misleading, and to require revision in its application the storm of June, 1921.

As has been stated, the rainfall at the Schaeffer Dam, on Beaver Creek, an elevation of 5 700 ft., during the night of Friday, June 3d, was about 4

The rainfall, at Victor (elevation, 9 775 ft.), from June 3d, 4.00 P. M., to June 4th, 4.00 P. M., was 2.08 in. Victor is on the western slope of Pike's Peak, while Lake Moraine, at an elevation of 10 200 ft., and Colorado Springs, at an elevation of 6 500 ft., are on the eastern slope and in the Fountain Creek drainage. At the two latter points, the precipitation is given, as recorded in Tables 4 and 5, from 6.00 P. M. of one day to 6.00 P. M. of the next. Table 21 shows the comparative rainfall, in inches, at these points.

TABLE 21.

Date.	Victor.	Lake Moraine.	Colorado Springs.
June 3, 1921	0.03	0.65	5.00
June 4, "	2.08	3.68	4.40
June 5, "	1.52	1.40	1.26
June 6, "	0.37	0.18	0.42
June 7, "	0.01	0.00	0.01
Total	4.01	5.91	11.09

At these three stations, the total rainfall for five days shows that the lower elevation actually had more than twice as much precipitation as the average of the higher elevations. By analyzing the daily quantities, keeping in mind the different hour to which the report refers, the record shows that prior to 4.00 P. M., on June 3d, 0.03 in. of rain fell at Victor, prior to 6.00 P. M., 0.65 in. fell at Lake Moraine, and prior to 6.00 P. M., 5.00 in. fell at Colorado Springs.

The detailed record at Colorado Springs is much more illuminating as to the character of the storm, and, between rainfall and altitude, to the relation for this particular storm:

		Rainfall, in inches.
June 3d,	1921, 3.30 P. M. to 6 P. M.	5.00
June 3d,	" 6 P. M. to June 4th, 2 A. M.	4.20
June 4th,	" 2 A. M. to 6 P. M.	0.20
June 4th,	" 6 P. M. to June 5th, 6 P. M.	1.26
June 5th,	" 6 P. M. to June 6th, 6 P. M.	0.42
June 6th,	" 6 P. M. to June 7th, 6 P. M.	0.01
Total		11.09

The total rainfall of 9.2 in. at Colorado Springs from 3.30 P. M., June 3d, to 2.00 A. M., June 4th, is comparable with the rainfall of 2.08 in. reported at Victor for June 4th, which really occurred after 4.00 P. M., on June 3d, and probably continued, as at Colorado Springs, until the early morning of June 4th. A similar comparison applies to Lake Moraine, with the alteration that the daily periods are parallel as previously given.

These three Weather Bureau Stations are fairly comparable, for, apart from being the only stations in the path of that particular storm, they are situated, relatively, in the general line followed by the storm of June 3d, elevation of 7 000 ft., with less rainfall within relatively the same period, the run-off would be less than at the lower elevations. On this occasion, in the region of Victor and Lake Moraine, the precipitation above an elevation of about 10 500 ft. was in the form of snow, and, in one instance at that elevation, the run-off from about 10 sq. miles of drainage area did not exceed 50 acre-ft. per day for 3 days after the storm, while the average precipitation, as previously stated, was 4.86 in.

It may be that because "probably one-half this volume [100 000 acre-ft., which passed Pueblo] came from less than 300 sq. miles of drainage area between Hardscrabble Creek and Pueblo, * * * the storm which caused the flood was far from a maximum". It was a maximum, so far as flood volume of the Arkansas River passing Pueblo during more than 30 years is concerned, and so far as intensity of rainfall in adjacent territory, as at Colorado Springs, is concerned. A greater rainfall was recorded at Canon City during the storm of 1894—5.06 in. as compared with 3.40 in. in 1921. Unfortunately, that is the only station in the Arkansas Valley above Pueblo, at which comparison may be made.

Assuming the accuracy of the judgment that 50 000 acre-ft. came from 300 sq. miles, an equally intense rainfall with an equally great percentage of run-off from 1 000 sq. miles would result in a flood of more than 166 000 acre-ft., not three times the volume of the recent flood. It is conceivable, however, that a rainfall of an intensity equal to that at Colorado Springs (elevation 6 000 ft., 9.2 in. in 10½ hours) could occur over all the drainage area in the Arkansas Valley above Pueblo and below Canon City, all of it below an elevation of 6 000 ft., and from 1 740 sq. miles, in place of 1 000 sq. miles, produce a flood equal to or greater in relative volume than that yielded from 300 sq. miles on June 3d, which would approach a volume "three times that of the recent flood".

Under such conditions, with a total run-off of more than 300 000 acre-ft., it may be reasonable to expect a peak flow of 168 000 sec-ft. in the Arkansas River at Pueblo, and it may be essential to provide for that volume, since it is only 68% in excess of the recent flood, although that is the maximum discharge of record in a period of more than 30 years, following a precipitation which is also the maximum in the same period, with the single exception of the record at Canon City.

The results anticipated from the Fountain Creek drainage area, following on a similar study, are not equally convincing, however. The flood of June 3d in Fountain Creek, at Pueblo, showed a total volume of 50 000 acre-ft. and a peak flow of 50 000 sec-ft., both of which are, apparently, the maximum of which there is any record.

From the whole drainage area of 930 sq. miles, the total discharge of 50 000 acre-ft. is equivalent to an average run-off of practically 1 in. Approximately, one-half of that area is below an elevation of 6 000 ft., and the greatest rainfall occurred at Colorado Springs, practically at that elevation. Therefore, on the basis of the authors' tabulation of assumed percentage of run-off—55%—the volume of the flood would have been due to an average rainfall of 1.8 in. There are four rain-gauge stations within the Fountain Creek area, Lake Moraine, Monument, Colorado Springs, and Pueblo, and the rainfall at these stations, on the night of June 3d-4th, as nearly as it may be established from the reports, was:

Lake Moraine	3.68 in.
Monument	2.90 "
Colorado Springs	9.20 "
Pueblo	3.09 "
Average	4.72 in.

In order to produce a flood of 164 000 acre-ft., on the basis of a run-off of 55%, the average rainfall would have to be in excess of 6 in. Although such anticipated flood might be possible, it does not seem to be probable, in view of the facts that the recent flood in Fountain Creek at Pueblo was a maximum alike in total volume and peak flow, as was the rainfall at Colorado Springs and other stations, with the single exception of Lake Moraine. Such anticipation, at any rate, cannot very well be based on the related data in the recent experience.

As an incidental item in connection with these estimates or forecasts, it may be noted that, on the same basis, the area of approximately 183 sq. miles between the site of the suggested detention reservoir on Rock Creek and Pueblo, might produce a flood greater in peak flow than the capacity of the channel within the levees, which existed in Pueblo prior to June 3d, 1921.

It may be proper, and permissible, to bear testimony to the accuracy of some of the detailed statements made by the authors and by Mr. Hosea. At the time of original construction in 1910, the capacity of the Schaeffer Reservoir, at the spillway level, was approximately, 3 190 acre-ft. Some silting had occurred in the basin, but reduction from that cause was offset by the storage above the spillway level which had occurred prior to the failure. For 12 hours or more preceding the failure on Sunday morning, June 5th, the discharge of Beaver Creek had ranged from 1 500 to 4 000 sec-ft., or more.

The writer passed through the Lower Arkansas Valley, below La Junta, on the morning of June 4th, finding the contributions to the river flow from tributary streams generally as presented. There was some flood flow in Timpas Creek, immediately west of La Junta, estimated at about 1 000 sec-ft., and that was probably all diverted before its junction with the Arkansas River.

In their consideration of "Reconstruction and Flood Control", the authors, very properly, have not attempted to do more than give a general outline of possible alternative and combined methods of improvement that would prevent similar damage in the future, and only in such general terms will comments thereon be submitted.

It would seem to be inevitable, and it certainly would be desirable, to combine any reconstruction work in the City of Pueblo with necessary plans for some improvement of the conditions along the Arkansas River below Pueblo, where very great damage was sustained by irrigation works. The interests of the city and the adjacent farming district are so interdependent that some plan incorporating improvement of mutual benefit should be devised, if at all

United States Department of the Interior

GEOLOGICAL SURVEY
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DENVER, COLORADO 80225

IN REPLY REFER TO:

December 9, 1989

Dr. Neil Grigg
Colorado Water Resources Research Institute
Colorado State University
Fort Collins, Colorado 80523

Dear Dr. Grigg:

Following are my comments on your "Preliminary Summary of Workshop on the Hydrological Aspects of Dam Safety".

Specific comments

1. I believe that the summary document needs to have a well written and concise overview of the problem in addition to the June 16, 1989 letter from the State Engineer. The summary should stand alone on its own merits. Possibly you may want to include a brief overview of the hydrologic research the US Geological Survey did for Olympus Dam where we compare the old and new PMF values to the paleoflood estimate. I have enclosed a copy of this report for your information.

2. Page 1. Although at a relatively low level of funding there is current research related to the elevation limit of significant rainfall flooding that I am conducting for the entire Rocky Mountain region. Analysis of about 100,000 station years of streamflow record in the Rocky Mountains support an elevation limit that is dependent on latitude (the elevation limit decreases with increasing latitude). I am presently preparing a paper on this research and would be happy to send you a draft for your information and possible review. I am currently seeking additional funding for my hydrologic and paleohydrologic research.

General Comments

1. I believe it is essential that we indicate that to paleohydrology complements existing engineering hydrology. Some people believe that paleohydrology is meant to replace engineering hydrology and that certainly is not what I believe. Each approach (engineering hydrology, paleohydrology, and meteorology) has its unique advantages and disadvantages. Hence, interdisciplinary research will best improve our understanding of hydrometeorology, to reduce the uncertainty in flood estimates, and to enable us to develop new methods for assessing flood hazards. For example paleohydrology can provide us with reasonable

estimates of the maximum flood in a basin for a time spanning several thousands of years which is much greater than our present short-term hydrologic records that average about 20 years per gaging station. Also paleohydrologic information at gaging stations will improve the flood-frequency estimates. If studies are done in a number of basins (say 15 to 25) we can develop regional envelope curves of maximum floods. What is presently needed is to decide how such information can be incorporated into the hydrologic aspects of dam safety.

2. I believe that it is imperative that the primary message of our meeting is that additional interdisciplinary research is needed. I believe my research has indicated we have some time (given that the risk of significant rainfall at higher elevations is very low) to conduct such research. The engineering community must be cautious in developing interim solutions because their availability may hinder conducting much needed research.

3. While I recognize the purpose of the meeting was related to the problems associated with assessing extraordinary floods, we must also recognize that there are similar problems defining flood characteristics of more common floods (10 to 500 year recurrence intervals). For example, see Table 5, page 29 of the enclosed report. This comparison and different estimates of flood characteristics computed from gaged records and from rainfall-runoff methods are typical of results from throughout the foothills and mountains of Colorado. I am currently supporting a graduate student at the University of Colorado to work with me to attempt to assess the magnitude and causes of the differences in flood hydrology.

If you have any questions concerning my comments please call me at 236-6447.

Sincerely,

Robert D. Jarrett

Robert D. Jarrett
Hydrologist

encl.

PROCEEDINGS OF THE SECOND INTERNATIONAL SYMPOSIUM ON DESIGN OF HYDRAULIC STRUCTURES / FORT COLLINS, COLORADO / 26-29 JUNE 1989

Design of Hydraulic Structures 89

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Hydrology and paleohydrology used to improve the understanding of flood hydrometeorology in Colorado

Robert D. Jarrett
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ABSTRACT
A multidisciplinary study of streamflow, precipitation, and paleohydrology was conducted to improve the understanding of flood hydrometeorology in Colorado. Conventional flood-frequency analyses do not adequately characterize the flood hydrology in the foothills and mountains of Colorado. Annual peak flows are caused by snowmelt at higher elevations in the mountains and by rainfall at lower elevations. Above 2,300 meters (this elevation is lower in some river basins), snowmelt rather than rainfall contributes to the flood potential. Below 2,300 m, large rainfall-generated floods are common. Regional flood-frequency methods, supported by paleoflood information, were developed that indicate the 1976 Big Thompson River flood has a recurrence interval of approximately 10,000 years. The approach and results may be useful in decreasing the uncertainty in the design of hydraulic structures as discribed for the spillway of Olympus Dam in the Big Thompson River basin or for other hydrologic studies.

1 INTRODUCTION

The design of dams and other flood-control structures, land-use management, and the siting of critical installations such as nuclear powerplants and waste-storage facilities require evaluating risk from floods. Because risk assessment of large floods and their impact are uncertain, there is a need for a better understanding of flood processes. Because the length of precipitation and streamflow records at most sites in the United States generally is much less than 100 years, it is difficult to accurately estimate the magnitude and frequency of large infrequent floods using conventional flood-frequency analysis. When one or more large floods occur within a short record, there is considerable uncertainty in estimating the recurrence intervals. Consequently, conventional flood-frequency analysis may not provide the most accurate representation of flood risk.

The 1976 Big Thompson River flash flood in Colorado resulted from as much as 305 millimeters of rainfall in a few hours and had a peak discharge of 883 cubic meters per second. The flood killed 139 people and caused property damage estimated at $35 million. The flood occurred a short distance downstream from Estes Park, Colorado (elevation 2,300 m), where the U.S. Bureau of Reclamation's Olympus Dam forms Lake Estes on the Big Thompson River. The inflow to Lake Estes during the 1976 flood had a recurrence interval of about 2 years. The existing spillway is designed for a probable maximum flood (PMF) of 637 m^3/s. As a result of the nearby location of the 1976 flood, a reevaluation of the capacity of the Olympus Dam spillway was initiated by the U.S. Bureau of Reclamation. The revised PMF (U.S. Bureau of Reclamation, written commun., 1984), based on new probable maximum precipitation estimates, is 2,380 m^3/s. This revised design discharge would increase dramatically the size of the spillway.

Two basic questions were posed as a result of the 1976 flood: (1) What was the frequency of the flood, and (2) could a flood of this magnitude occur anywhere in Colorado? Conventional flood-frequency analysis indicated that the recurrence interval of the 1976 flood was between 100 and 300 years. It commonly was believed that a flood like the 1976 flood could occur anywhere in Colorado.

A multidisciplinary study of streamflow and precipitation records and paleoflood hydrology was conducted to improve the understanding of flood hydrometeorology in the foothills and mountains of Colorado. The purposes of this paper are (1) to provide an overview of the study and (2) to provide an example to show how the information obtained may be useful in the design of a hydraulic structure specifically the spillway of Olympus Dam on the Big Thompson River.

2 OVERVIEW OF PALEOHYDROLOGY

To extend climatic and hydrologic records, hydrologists have used paleohydrologic techniques (Costa, 1987; Patton, 1987; Stedinger and Baker, 1987; Baker et al., 1988). Paleohydrology is the study of the movement of water and sediment before the time of continuous hydrologic records (Costa, 1987). Evidence of historic or prehistoric floods often are preserved in channels as distinctive sedimentologic deposits or landforms as well as in botanical evidence. These records are relatively easy to recognize and are long lasting, generally for as long as 10,000 years (Jarrett, 1987). Tree-ring data have been used to reconstruct past precipitation, temperature, and average discharge for several hundred to thousands of years (Fritts, 1976). Paleohydrology can provide important supplemental information about the spatial occurrence, magnitude, and frequency of floods, droughts, and hydrologic variability. Paleohydrologic information complements short-term streamflow records and can provide information at ungaged locations. Paleoflood studies can provide information about reasonable upper limits of the maximum size of floods that have occurred in a river basin. The results of paleoflood investigations enhance conventional hydrologic studies and help reduce the uncertainty in the flood hydrology.

3 COLORADO FLOOD STUDY

The multidisciplinary study of streams in the foothills and mountains of Colorado has concentrated on: (1) An analysis of available streamflow and precipitation data, (2) the use of paleohydrologic techniques in flood-hydrology studies, and (3) flood information-transfer techniques (Jarrett, 1987; Jarrett and Costa, 1988). This study answers questions about the flood hydrometeorology that studies limited to a single discipline cannot provide because of limited data.

3.1 Streamflow and precipitation

In the foothills and mountains of Colorado, annual peak flows are derived from snowmelt at higher elevations, from rainfall at lower elevations, and/or from a combination of rain falling on snow (mixed population hydrology). Snowmelt-runoff peaks were distinguished from rainfall-runoff peaks on the basis of daily and seasonal occurrence, hydrograph shape, and local weather conditions for 69 unregulated streams in Colorado in the South Platte, Arkansas, and Colorado River basins (Jarrett, 1987). Snowmelt- and rainfall-generated peaks were used to develop snowmelt, rainfall, and composite flood-frequency curves that improved flood-frequency estimates (Jarrett, 1987).

Evaluation of rainfall and snowmelt flood-frequency curves can indicate which meteorological cause predominates for a stream. Comparisons of flood-frequency curves for two streamflow-gaging stations demonstrate that the change from snowmelt- to rainfall-dominated peak flows occurs abruptly over a 700-meter range of elevation within about 25 kilometers in the Big Thompson River basin (this distance would vary by basin). The flood-frequency curves for the higher elevation (2,290 m) station (Big Thompson River at Estes Park, a drainage area of 355 square kilometers), indicates a snowmelt-dominated stream (Figure 1). In contrast, the flood-frequency curves for the lower elevation (1,615 m) station (Big Thompson River at the mouth of the canyon near Drake, a drainage area of 790 km^2), indicates a rainfall-dominated stream (Figure 2). Similar analyses were made for all 69 stations; these analyses indicate that snowmelt runoff dominates above an elevation of about 2,300 m (the elevation is lower for some river basins). Above this elevation, rainfall did not significantly contribute to peak flows. Below 2,300 m, rainfall produces large floods. These analyses also indicated that rain-on-snowmelt peak flows generally were small and very infrequent and that there is a relation between peak flow and elevation.

The mixed-population analysis was done for 69 representative stations in Colorado; however, a question remained: could rainfall floods have occurred elsewhere above 2,300 m? Therefore, data from all other U.S. Geological Survey streamflow-gaging stations (935 stations) and miscellaneous flood measurement sites (706 flood sites) in Colorado were analyzed to determine if large rainfall-generated floods have occurred at higher elevations in Colorado

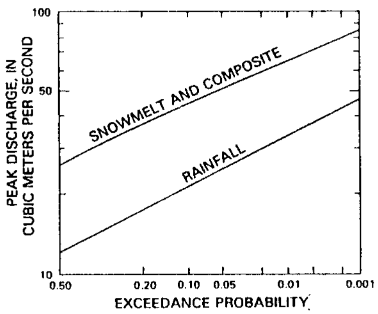

Figure 1. Flood-frequency curves for the Big Thompson River at Estes Park, Colorado; elevation is 2,290 meters.

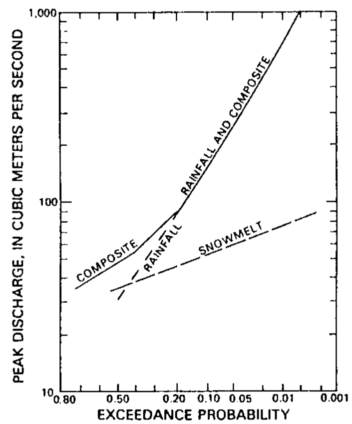

Figure 2. Flood-frequency curves for the Big-Thompson River at mouth of canyon, near Drake, Colorado; elevation is 1,615 meters.

(Jarrett, 1987). The unit discharge (discharge divided by drainage area) for each peak discharge value was computed and ranked for each county. For each major river basin, maximum unit discharge in each county was plotted against elevation. The data and an envelope curve are shown in Figure 3 for the South Platte River basin, which includes the Big Thompson River basin. The magnitude of rainfall-generated floods decreases dramatically as elevation increases. Below 2,100 m, unit discharge has exceeded 40 $m^3/s/km^2$. Above 2,300 m, unit discharge has not exceeded 1.1 $m^3/s/km^2$. Data for the other major river basins above 2,300 m in Colorado show that unit discharge also has not exceeded 1.1 $m^3/s/km^2$.

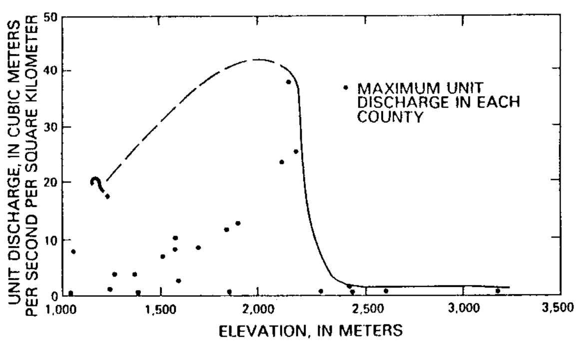

Figure 3. Relation between maximum unit discharge and elevation, including envelope curve, for the South Platte River Basin in Colorado.

To understand runoff processes, the causative factors, particularly precipitation, need to be understood. Since before 1900, the U.S. Bureau of Reclamation has documented and compiled rainfall amounts of large and intense rainstorms in the western United States. Ninety-seven of these storms have occurred in Colorado. The distribution of 6-hour rainfall with elevation is shown in Figure 4 (Jarrett, 1987). Rainfall at lower elevations in the plains of eastern Colorado has exceeded 500 mm. Six-hour rainfall decreases abruptly from about 500 mm to less than 50 mm, at elevations above 2,440 m.

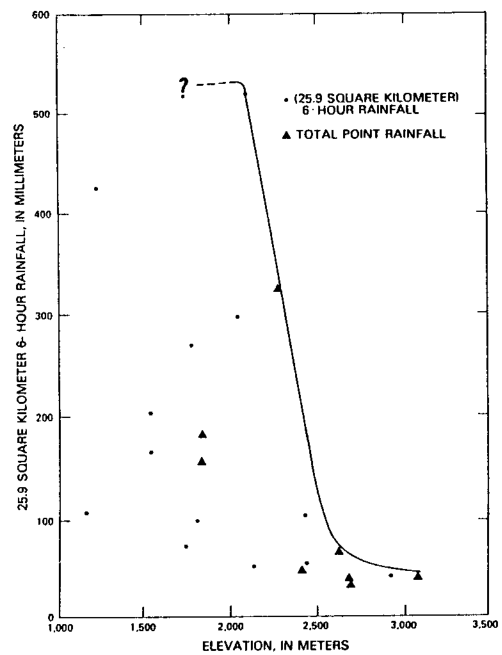

Figure 4. Relation between precipitation and elevation, including envelope curve, for large storms in Colorado.

3.2 Paleohydrologic techniques

Historic and prehistoric floods leave distinctive deposits and landforms in valleys and channels. Geomorphic evidence of large floods in steep mountain basins, such as in the Big Thompson River, is easy to recognize and long-lasting because of the volume and size of sediments deposited. Lack of paleoflood evidence from large floods is as important as tangible onsite evidence of such floods (Jarrett, 1987).

Paleoflood research has been conducted in the South Platte River basin (Jarrett, 1987), particularly in the Big Thompson River basin (Jarrett and Costa, 1988). The strategy of these studies is to examine those sites where evidence of any large floods might be preserved. Sites studied include: (1) Locations of rapid energy dissipation, where coarse sediments would be deposited, such as tributary junctions, abrupt decreases of stream slope, or abrupt valley expansions; (2) locations downstream from glacial moraines across valley floors where floods would deposit sediments eroded from the moraines; and (3) locations along the sides of valleys in wide, expanding reaches where sediments would likely be deposited. These paleoflood investigations indicate that large but infrequent floods have occurred in all basins below 2,300 m. No evidence of water flows much higher than bankfull discharge was found in any stream above 2,300 m in Colorado (Jarrett, 1987).

A paleoflood investigations was conducted in the Big Thompson River basin (Jarrett and Costa, 1988). A principal purpose of that study was to investigate whether there was any evidence of large post-glacial floods in the valleys draining into Lake Estes, which is formed by Olympus Dam. There is an absence of any paleoflood evidence of large floods upstream from 2,300 m in the Big Thompson River basin. Radiocarbon dating of paleoflood deposits in the Big Thompson River basin yielded estimates of relative frequency of the 1976 flood. This dating indicated that the 1976 flood was the largest since the occurrence of glacial melting 8,000 to 10,000 years ago.

3.3 Flood information-transfer techniques

Flood characteristics commonly are needed at ungaged sites; the information also can increase the reliability of estimates of flood characterisitics at short-record gaged sites. Investigations of flood potential based on rainfall-runoff modeling techniques fail to adequately describe the flood hydrology of foothill and mountain streams; generally these techniques significantly overestimate flood magnitudes (Jarrett, 1987). Investigators have assumed that the total basin area contributes runoff during rainstorms. However, in the foothills and mountains of Colorado below 2,300 m floods are caused by rainfall, generally intense short-duration thunderstorms of limited areal extent. Therefore, regional flood estimating procedures need to compute rainfall-generated flood estimates on that part of the basin below about 2,300 m in Colorado.

One component of rainfall-runoff modeling to determine the magnitude of floods is the use of storm transposition. Jarrett and Costa (1988) demonstrated that the concept of storm transposition from lower elevations to higher elevations in Colorado is not supported by meteorological, hydrological, and paleoflood information. Also, depth-area relations, used in rainfall-runoff methods to reduce point rainfall for the size of the watershed, applied to the foothills and mountains of Colorado were not developed with data from that area and result in large rainfall-runoff flood estimates.

Jarrett (1987) developed regional rainfall flood-frequency relations for the foothills area of the South Platte River basin in Colorado. The analysis used only the drainage area of a basin below 2,440 m (believed to be a conservative elevation selection). These regional flood-frequency equations provide more reliable estimates of both common and rare floods (Jarrett, 1987; Jarrett and Costa, 1988). The regional flood-frequency relations, supported by the paleoflood information, indicate that the 1976 Big Thompson River flood, downstream from the center of the rainstorm, had a recurrence interval of approximately 10,000 years.

The recurrence intervals of the probable maximum flood (PMF) at several sites in Colorado were estimated using the regional relations (Jarrett and Costa, 1988). These results indicate that for sites at or upstream from about 2,300 m (including the PMF for Olympus Dam), PMF recurrence intervals far exceed 10,000 years. However, at lower elevations, PMF recurrence intervals range from 2,000 to 3,000 years. The differences in recurrence intervals suggest varying risks associated with the PMF values in different locations.

4 SUMMARY AND DISCUSSION

A multidisciplinary study was conducted to improve the understanding of flood hydrometeorology in Colorado. Interpretation of streamflow (Figures 1, 2, and 3) and precipitation (figure 4) data and paleoflood information indicates that snowmelt flows predominate above 2,300 m, and rainfall generated floods predominate below 2,300 m in Colorado. Above 2,300 m, maximum unit discharge has not exceeded 1.1 $m^3/s/km^2$. Maximum 6-hour rainfall has not exceeded 50 mm above 2,440 m. Paleoflood hydrology provides important supplemental information about the spatial occurrence, magnitude, and frequency of flooding. Paleoflood investigations indicate that large but infrequent floods have occurred in all basins below 2,300 m. No evidence of water floods much higher than bankfull discharge has been found in any stream valley above 2,300 m in Colorado (a paleoflood record of about the last 10,000 years). Together the hydrologic results and the paleoflood information indicate that the 1976 Big Thompson River flood had a recurrence interval of approximately 10,000 years.

The results of this study are useful in assessing flood hazards and in decreasing the uncertainty in the design of hydraulic structures or for other flood-plain studies. These results have important implications for the evaluation of the spillways of dams, such as Olympus Dam located at Estes Park, Colorado (elevation 2,300 m), in the Big Thompson River basin. The absence of any paleoflood evidence of large floods in the upper Big Thompson River basin that drains into Lake Estes indicates that significant floods have not occurred during post-glacial times. Paleoflood investigations in the Big Thompson River basin upstream from Olympus Dam indicate there has not been a natural flow greater than 85 to 140 m^3/s, which is consistent with peak discharges expected from snowmelt runoff, during the last 8,000 to 10,000 years (Jarrett and Costa, 1988). The present capacity for the Olympus Dam spillway is 637 m^3/s.

The methods developed for this study are applicable to other regions. Although many paleohydrologic techniques are available, paleohydrology has not yet reached its full potential; additional paleohydrologic research is needed. Meteorologic research is needed to understand the causes of the elevation limit of 2,300 m on significant rainfall-produced flooding in Colorado.

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

U.S. GEOLOGICAL SURVEY

Water-Resources Investigations Report 87-4117

Cover photo–View upstream from Olympus dam and Lake Estes, Estes Park Colorado.

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Denver, Colorado
1988

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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

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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.

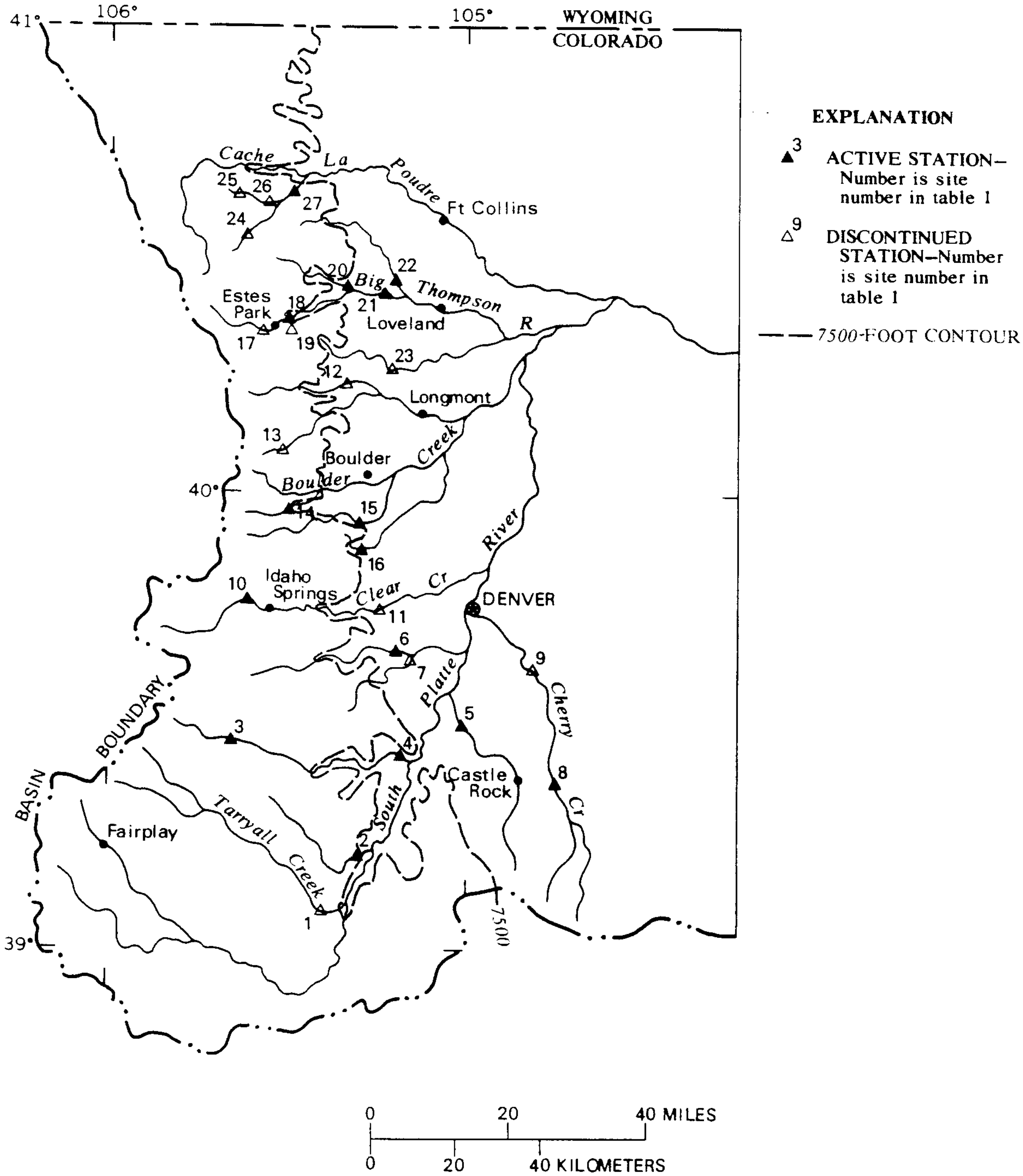

Figure 1.--Selected streamflow-gaging stations for which peak flows were differentiated in the South Platte River basin.

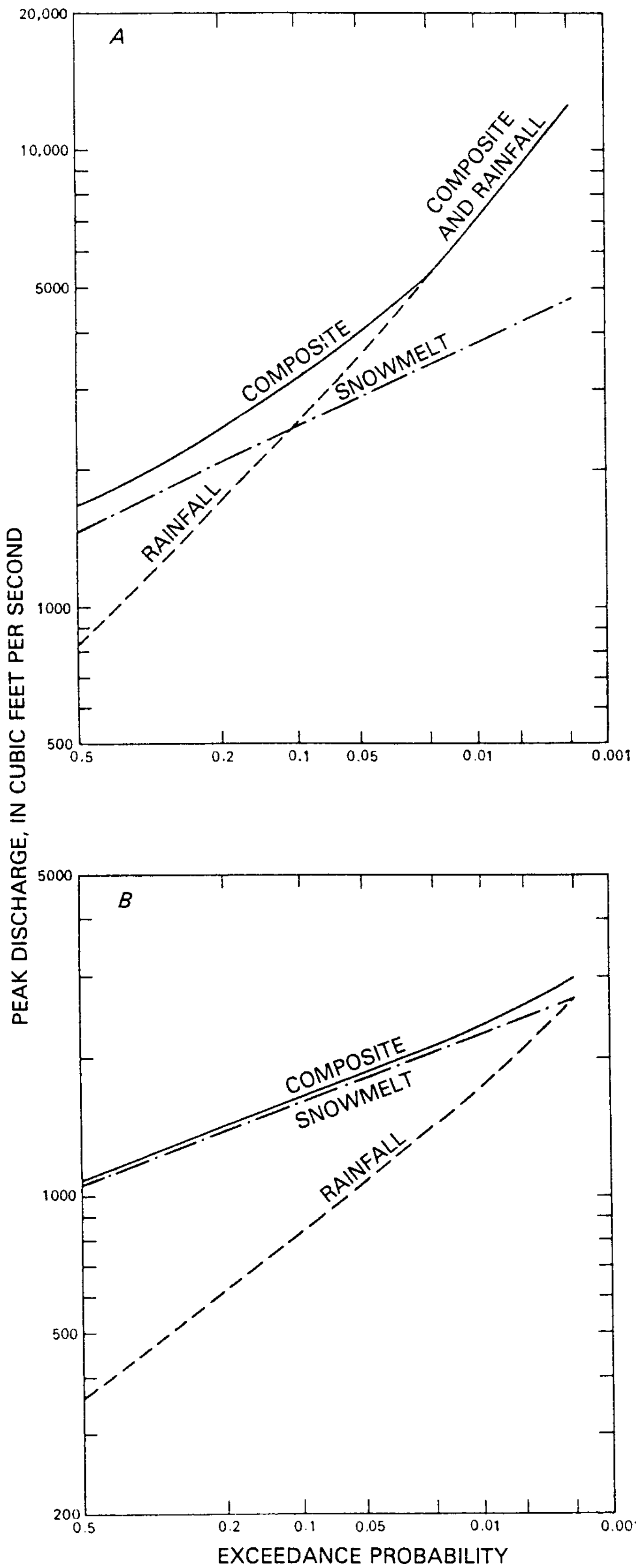

Figure 2.--Flood-frequency curves for Clear Creek near (*A*), Golden, Colorado (site 11), and (*B*), Lawson, Colorado (site 10).

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.

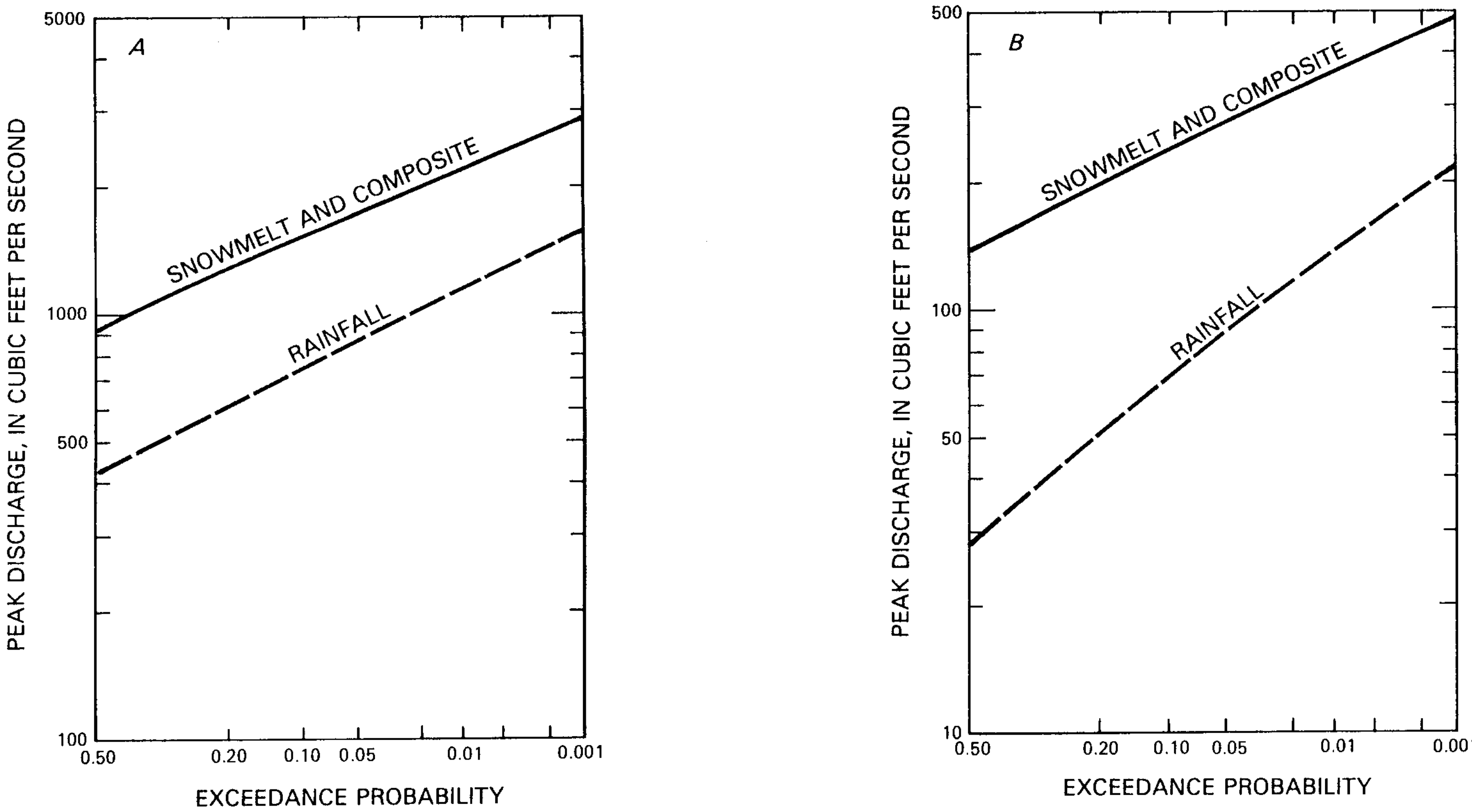

Figure 3.--Flood-frequency curves for: *A*, Big Thompson River at Estes Park, Colorado site 18), and *B*, Little Beaver near Idylwilde, Colorado (site 25).

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, <u>lack</u> 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 <u>nonoccurrence of floods</u> 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.

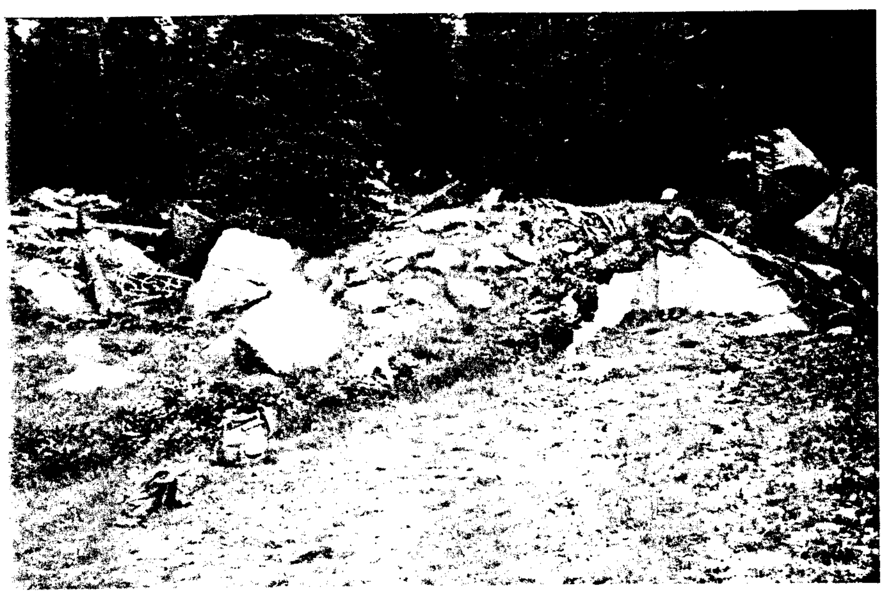

Figure 4.--Front of glacial moraine in tributary to the Big Thompson River at Estes Park. The stream about 3 ft to the left of man has not disturbed the glacial sediments since they were deposited, about 8,000 to 10,000 years ago.

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

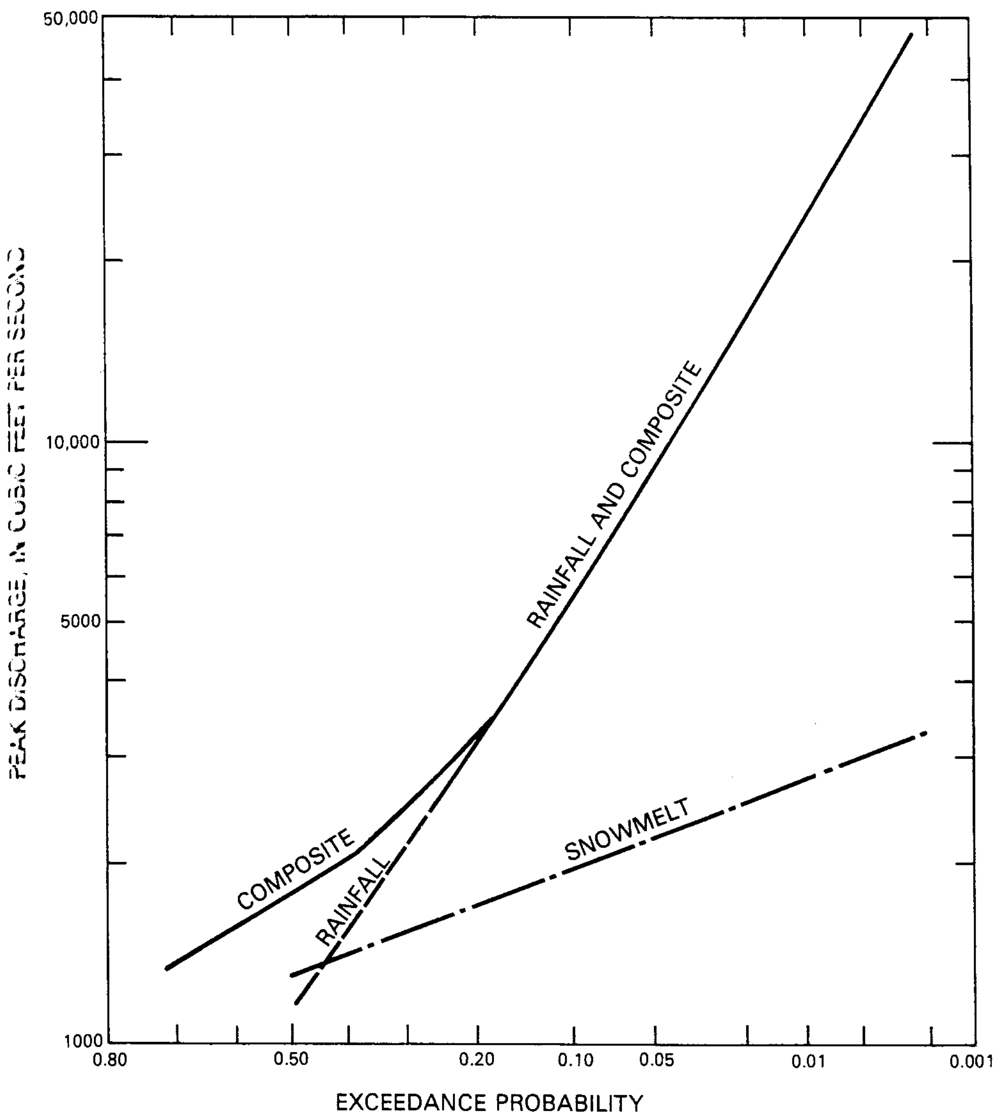

Figure 5.--Flood-frequency curves for Big Thompson River at mouth of canyon, near Drake, Colorado (site 21).

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.

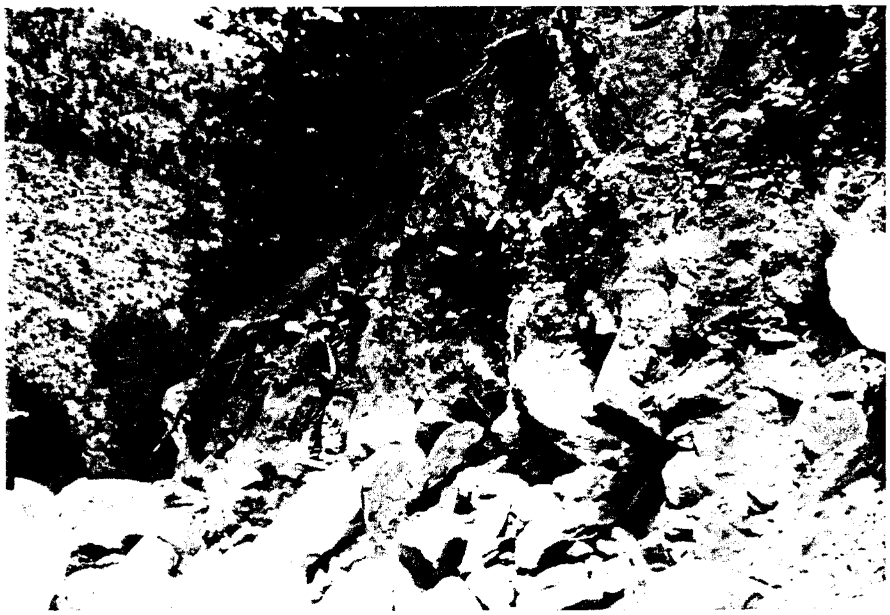

Figure 6.--Eroded old river terrace and flood deposits on the Big Thompson River downstream from Drake, Colorado.

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 non-similar 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.

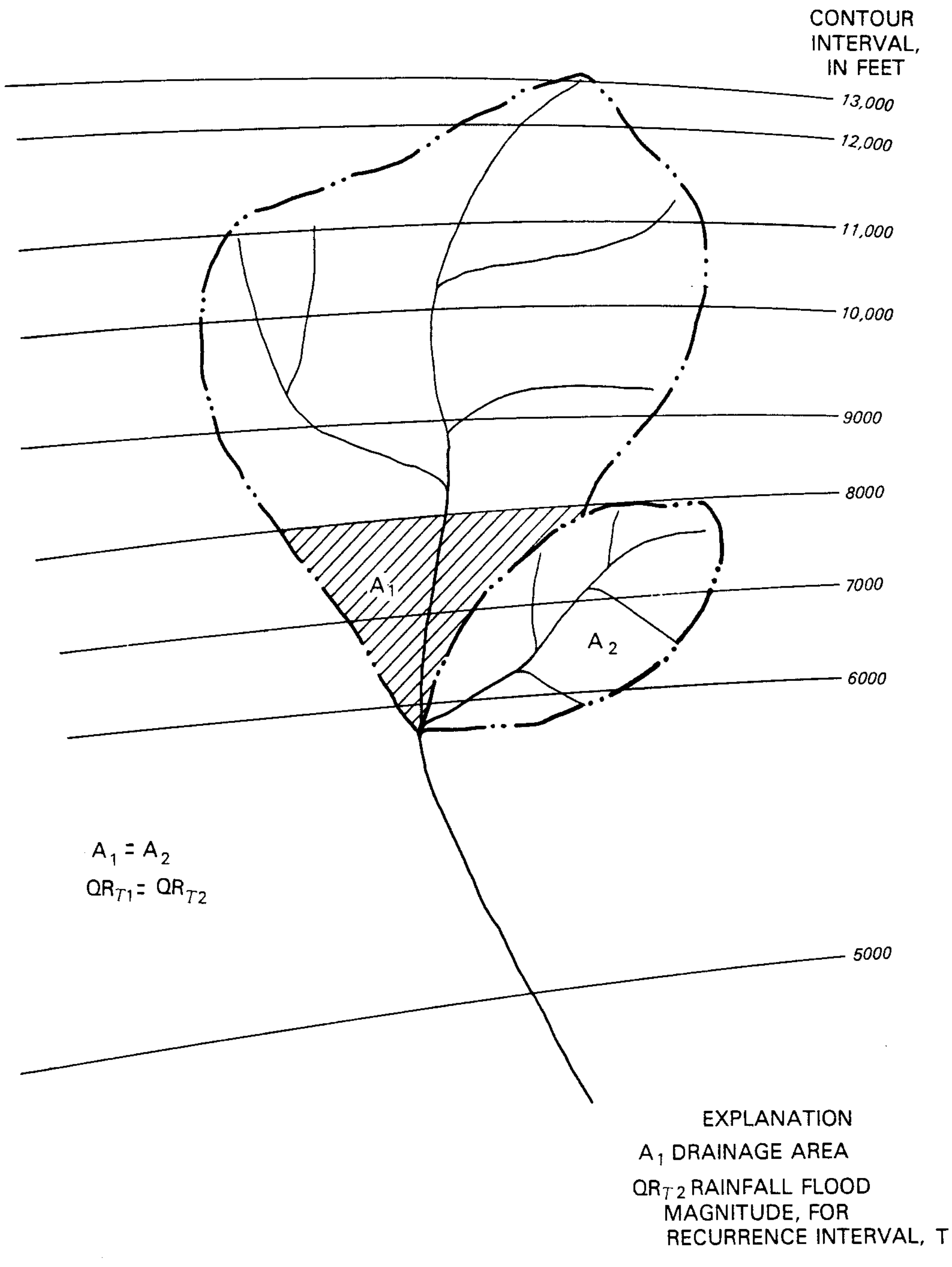

Figure 7.--Plan view of hypothetical drainage basins in the foothills of Colorado.

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:

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

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

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

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

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

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.

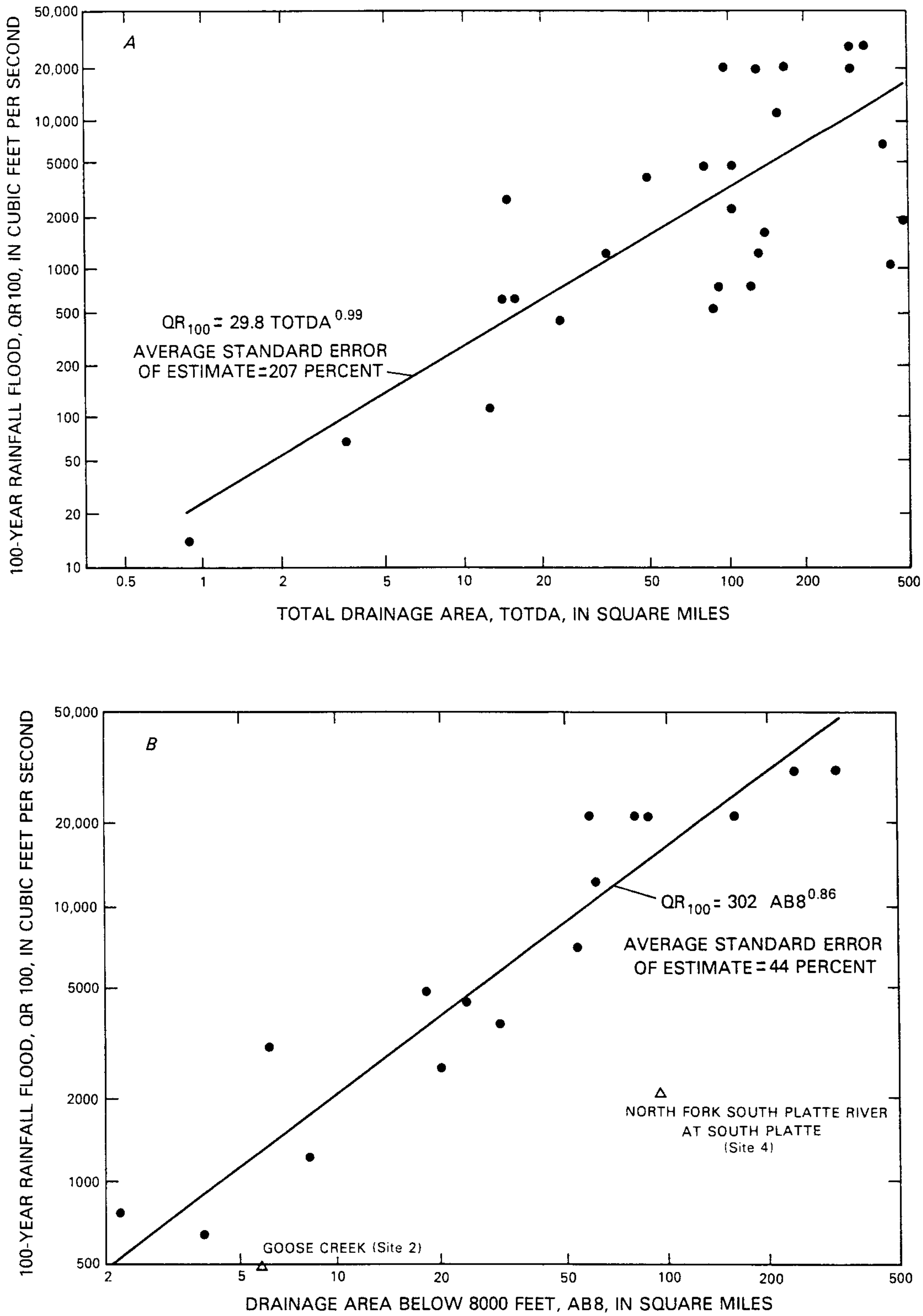

Figure 8.--Relation of 100-year rainfall flood to: *A*, total drainage area for the South Platte River basin, and *B*, drainage area below 8,000 feet for the South Platte River basin.

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):

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

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 *AB*8 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

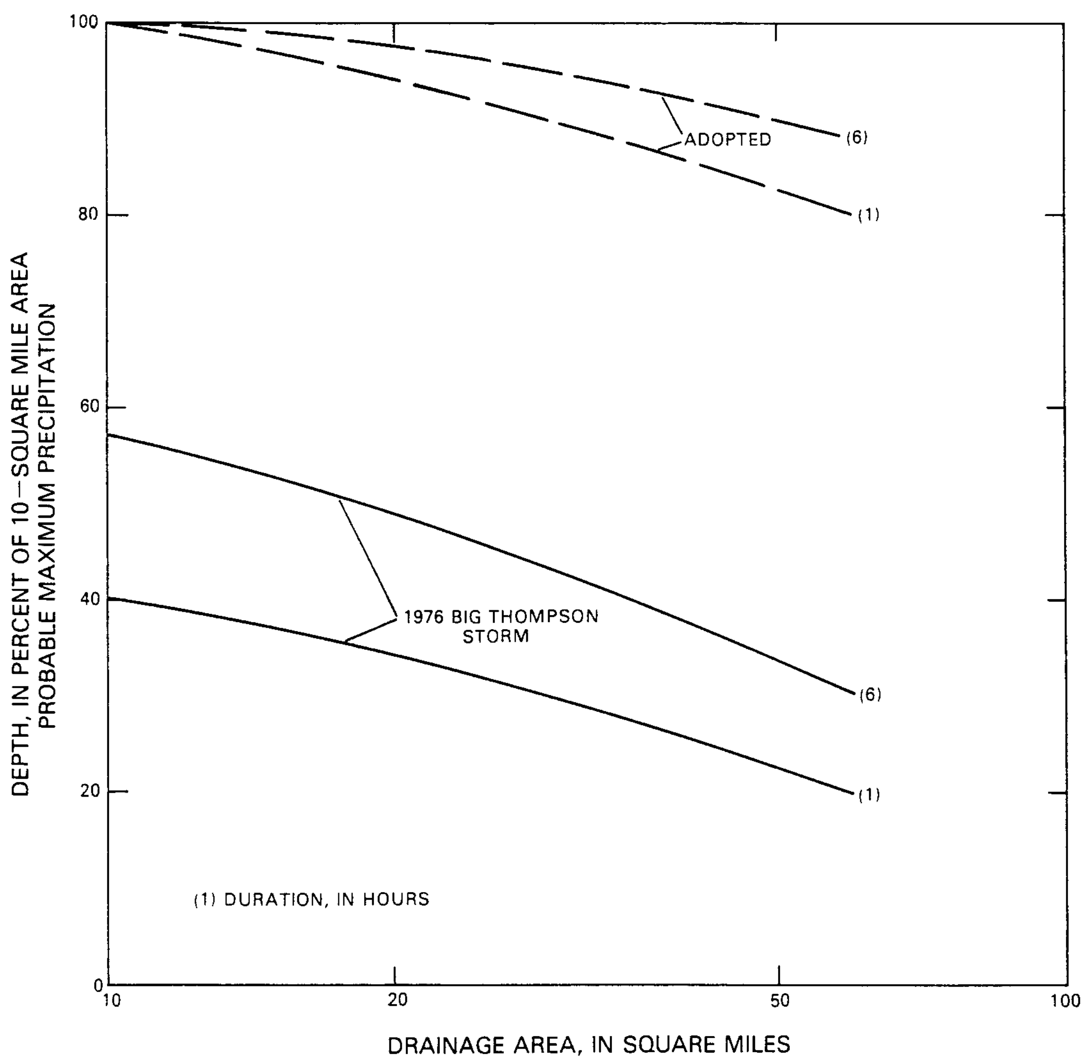

Figure 9.--Depth-area data for the Big Thompson storm and adopted depth-area relations for general-storm probable maximum precipitation for the foothills and mountains east of the Continental Divide, Colorado (from Miller and others, 1978; Miller and others, 1984).

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)				Difference column 5-column 4 divided by column 4 (percent) (6)
	Foothills analysis			The city of Golden flood insurance study[1] (5)	
	Station (2)	Regression (eq. 4 to 7) (3)	Weighted (eq. 8) (4)		
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:

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

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 paleo-flood 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.

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ATTACHMENT 6

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January 5, 1990

Mr. Neil Grigg
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Dear Mr. Grigg: Neil

It appears that you have summarized the meeting very well. Specific comments I have are:

PMP is intended to represent a maximum based on the maximization of the appropriate meteorological parameters. This is its definition. How we use this data is a policy decision of the users. There is doubt though whether these values have/can occur above 7500 feet based on Jarrets work. In this regard, we will need to devise another name for the flood that will be used to evaluate or design spillways that aren't based on PMP. (PMF is based on PMP only, by definition). Others have recommended the use of Inflow Design Flood (IDF) for design; and Safety Evaluation Flood (SEF) for existing dams. (The IDF or the SEF could be the PMF in some cases; the 100 year flood in other cases, either rainfall or snowmelt related).

As the summary suggests, a prescribed site specific hydrologic procedure (manual) is needed that will produce an appropriate level of protection (spillway capacity) for the hazard class of a dam. This could be regional flood-frequency relations as Jarret suggests, with paleohydrological verification; or transposition techniques using large storms. The procedure would need to be developed by/or sanctioned by a recognized group of experts in order to develop its credibility and adoption as a standard for safety of dams. As you point out, the federal government does not have any reason to revise HMR 55A at the present time.

The main reason that site specific meteorological studies (Crow) have not been accepted to date, is because of the large difference in predicted precipitation between the HMR's (55A in this case) and the consultants values. The meteorological record is of relatively short duration for predicting abnormal precipitation, the same problem associated with statistical determination of PMF using runoff data.

In regard to snowmelt, I believe we will depend on the statistical determination of 25, 50, and 100 year floods from runoff records rather than predicting them from snowmelt equations. There still may be a way to predict an IDF/SEF from snowmelt equations based on some reasonable assumptions of abnormal meteorological events affecting the snowpack. This should be addressed by the expert group assembled for the site specific criteria (manual).

It has been a pleasure working with you on this. Thank you for your continued interest.

Sincerely,

Alan Pearson
Chief, Dam Safety Branch

AEP/gla:6745I

cc: Hal Simpson
Dennis Miller
Bill McIntyre

ATTACHMENT 7

THE STATE OF WYOMING

MIKE SULLIVAN
GOVERNOR

GORDON W. FASSETT
STATE ENGINEER

State Engineer's Office

HERSCHLER BUILDING CHEYENNE, WYOMING 82002

December 8, 1989

Dr. Neil Grigg
Colorado Water Resources Research Institute
Colorado State University
Fort Collins, Colorado 80523

Re: Workshop on Hydrology Aspects of Dam Safety

Dear Dr. Grigg:

I have reviewed your draft summary of workshop as requested. You appear to have covered the proceedings very well.

The use of PMP to derive PMF hydrographs results in very large flood peaks and volumes in the mountains east or west of the Continental Divide. The workshop zeroed in on HMR 55A, for use on the east side of the Divide. We find that PMP's for various durations can be 2 to 3 times greater for the east side of the divide (HMR 55A) than for the west side (HMR 49). It would be helpful if the meteorological reasoning could be reconciled for the mountain areas. Presumably there are different moisture sources and physical mechanisms that explain the differences?

Frankly, it appears to me that the real question may be whether in the mountains the dam safety professionals want to abandon PMF-based-on-PMP methodology and adopt some other methodology (paleo hydrology?). I think research to decide on a new methodology will involve several professions, many organizations, and much review and discussion.

Meanwhile, I believe dam safety professionals are driven by the state of science and practice as defined by themselves, with the help of the scientific community and technical societies, and as defined by results of liability lawsuits into the use of PMP to derive probable maximum inflow flood (PMF) hydrographs for dam spillway evaluation. Sizing of spillways, freeboard, and other structures associated with dams can be tempered with damage and/or risk analyses.

Very truly yours,

Frank J. Trelease

FRANK J. TRELEASE
Administrator, Surface Water and
Engineering Division

FJT/dll

UNIVERSITY OF COLORADO, BOULDER

Civil, Environmental, and
Architectural Engineering

MEMORANDUM

November 30, 1989

To: Neil Grigg
From: Ernie Flack EF
Subject: Review of Workshop on Dam Safety

In response to your recent request, I suggest the following:

(1) What policies should the State Engineer adopt? I suggest that he delay decisions on spillway adequacy indefinitely on existing structures unless a clear danger to life or property is present. On new construction, however, I suggest a criteria along the following lines.

Where failure would pose a clear danger to life and/or property the SE should require use of the PMP.

Where failure would pose a moderate danger use 75% of PMP.

Where failure would pose little danger use 50% of PMP.

(2) What research is needed? I suggest the following.
(a) Can hydraulic design incorporate inexpensive emergency features along the line of the duck bill spillway and the plug-type emergency spillway. Run model tests.
(b) Determine the degree to which the isohytals of HMR 55A were increased to reflect actual flood flows, but not taking into account possible bulking effects of mud and debris that make the 100-yr flood look like the 1000-yr flood. Historic floods should be analyzed to see to what degree bulking may have occurred.
(c) Provide the State Engineer with criteria on risk assessment so he can better evaluate consultants' site specific reports. This would be an effort to place a rational decison making format on the suggestions of item 1 above.
(d) Research on joint probabilities of heavy rain occuring during times of rapid snowmelt.

Thanks for the opportunity to participate.

Campus Box 428 • Boulder, Colorado 80309 • (303) 492-7315

December 12, 1989

To: Dr. Neil Grigg

From: Dr. Freeman Smith

Re: PMP

Your summary is accurate and representative. I believe that the following research should be pursued:

1) Uncertainty analysis of the NOAA PMP procedure - to establish the "envelope" of PMP estimates.

2) Maximum snow melt rates: I judge the maximum rates would be much simpler than one might think... because transfer of heat from the atmosphere to the snow probably dominates during maximum melt.

3) PMP MPF? Comparison of PMP to MPF: simulation by agency models would be useful.

4) Data/theoretical study of PMP absorptions above 7000 ft. should be re-visited.

5) Maximum precipitation data-base of bucket surveys would compliment existing precipitation data (also fire - weather stations).

6) High elevation rainfall (only) network above 7000 ft. A good design for a network would be required.

Topics one through four could be set up with an interagency task-force approach through CWRRI. BOR/USGS/CORPS/NOAA/etc. models could be used.

Funding:

- special experiment station appropriation
- state appropriation
- NSF ?
- DOD ?
- etc.

Topics five and six: Five could be funded (for graduate students) through the State Engineer's Office. Six could be accomplished with a voluntary network - science for high school?

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December 5, 1989

Dr. Neil Gregg
Director, Colorado Water Resources
Research Institute
410 University Services Bldg.
Colorado State University
Fort Collins, CO 80523

Dear Neil:

I would like to thank you for the opportunity to meet with the distinguished panelists at the Workshop on Hydrologic Aspects of Dam Safety. It was an interesting and enjoyable experience. I do not envy your job of trying to summarize the diverse viewpoints expressed at the conference nor the State Engineer's job of deciding on the methodology to be used for calculating Probable Maximum Precipitation (PMP). The line between adequate protection for the public and the imposition of unnecessary economic hardship on the dam owners and operators is very difficult to define.

I think that your summary of the workshop agrees quite closely with my recollection of the views expressed by the participants. I might nitpick one statement on page two that states that HMR-55A is "difficult to use at high elevations". I don't think it is difficult to use but I do think its use is difficult to justify at high elevations.

The questions of what policies the State Engineer should adopt and what type of research is needed are difficult ones given the fact that politics play as large a role as science in many of these decisions. I do believe that additional research is needed in order to formulate a reasonable policy. Clearly, the authors of HMR-55A are not inclined to make further changes in their procedures and as long as their estimates are high enough they can never be proven wrong. One approach, which might be useful and not cost very much, would be to compare various methods of calculating PMP for one or two selected watersheds in Colorado. The watersheds selected should have a range of elevations and as many long-term precipitation gauges and streamflow measurements as possible. It would then be possible to calculate PMP and PMF at various elevations using HMR-55A; the statistical methods suggested by the World Meteorological

Organization (WMO), National Weather Service(NWS), and others; the paleohydrology approach described by Bob Jarrett; and the HMR-55A method but with more reasonable, and scientifically defendable, adjustment curves. It would also be interesting to try some of the atmospheric models but that would probably double the cost of the other research. It seems reasonable to me that if all the other methods of calculating PMP produce estimates that are clustered near one value and HMR-55A produces an estimate that is significantly higher (my hunch is that this is probably the case), then the State Engineer would have the scientific backing to adopt a "Colorado PMP" in the same manner that the Tennessee Valley Authority did in adopting a "TVA PMP" that was lower than the HMR estimates for that area. Most of the methods mentioned above could be either done in-house or by contractors for a relatively small expenditure of funds.

Since my presentation at the workshop was primarily concerned with, what I consider unreasonable, adjustment curves used in HMR-55, I would like to provide three examples to make my point. The first area which I questioned, and which I discussed at the workshop, was the construction of the isohyetal maps used to determine Depth-Area-Duration (DAD) curves in HMR-55A. I have enclosed a copy (Figure 3.8) of the HMR-55A analysis and our analysis of the Gibson Dam storm of June 7-8, 1964. Our analysis of this storm used all the available published data we could find plus meteorological judgement of the terrain effects on precipitation. In contrast, the HMR-55A analysis ignored some of the published data, presumably included some unpublished "bucket surveys" and, wherever there were areas of no data, expanded the centers of high precipitation amounts as much as possible even though they extended them west of the Continental Divide (the downwind side).

The second example (Figure 4.1) is the elevation adjustment curve used in HMR-55A when transposing a storm from one area to a higher or lower elevation. The HMR-55A curve (marked by triangles) is a significant departure from the curve used in previous HMR studies (marked by squares) and which fits more closely the depletion of precipitable water with elevation. The effect of this change is to overestimate precipitation in areas above about 7000 feet MSL and underestimate precipitation below about 3000 feet MSL.

The final example (Figure 4.2) deals with the adjustment for distance from a tropical moisture source. HMR-55A uses a curve that suggests that there is no change in tropical moisture after you reach about 700 km from the source. Therefore an area 1300 km from the Gulf coast has the same tropical moisture as an area 700 km from the coast. This does not appear to be consistent with our knowledge of meteorology.

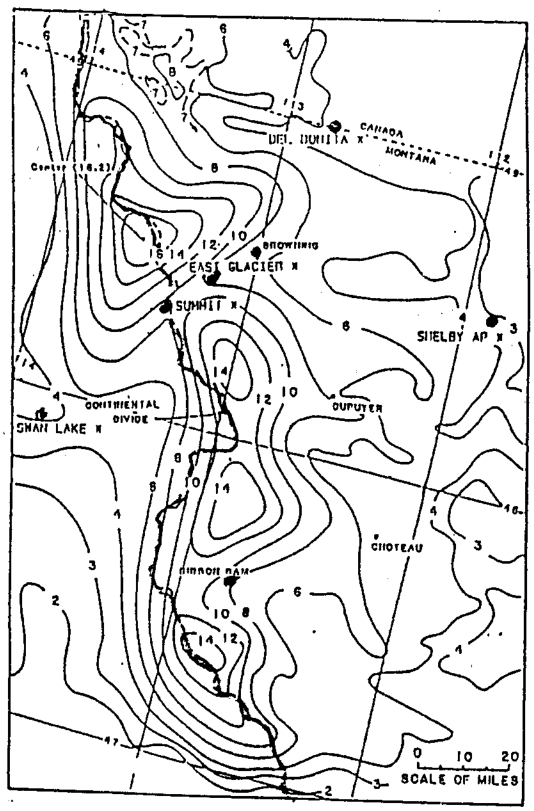
The effect of using more realistic adjustment curves, or of using curves that were used in earlier HMR studies, would reduce the HMR-55A PMP estimates by at least 50% at high elevations. We have found that these modified estimates would be very close to the PMP estimates obtained by using the standard statistical tests used by the WMO, NWS and others.

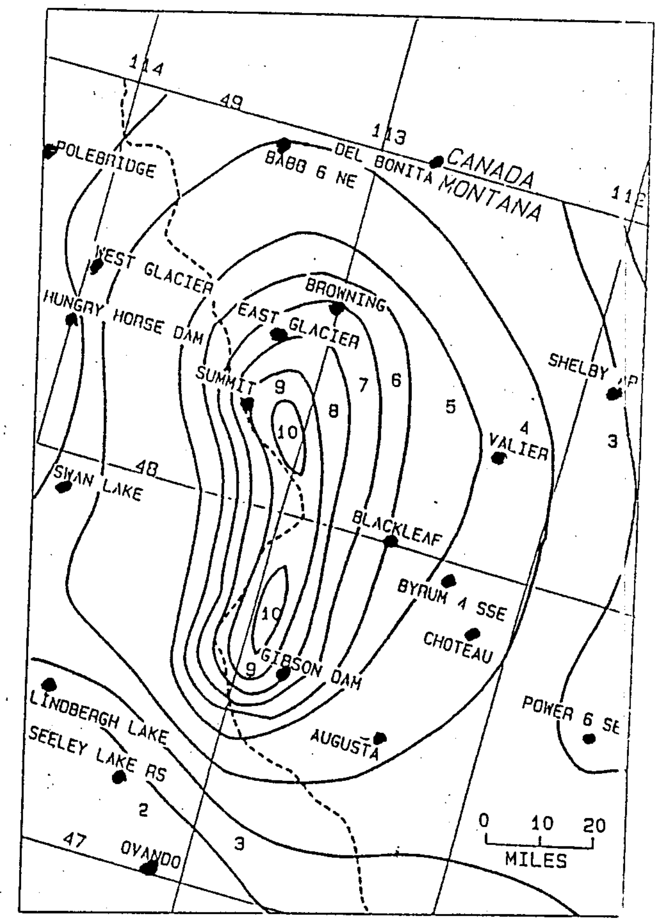
We would be pleased to assist the State Engineer in this study if he wishes. Thanks again for allowing me to participate.

Sincerely,

Keith J. Brown
President
Certified Consulting Meteorologist

KJB:k/782





Isohyetal map of Gibson Dam storm as shown in HMR-55.

Isohyetal map of Gibson Dam storm incorporating precipitation measurements and topography.

Figure 3.8

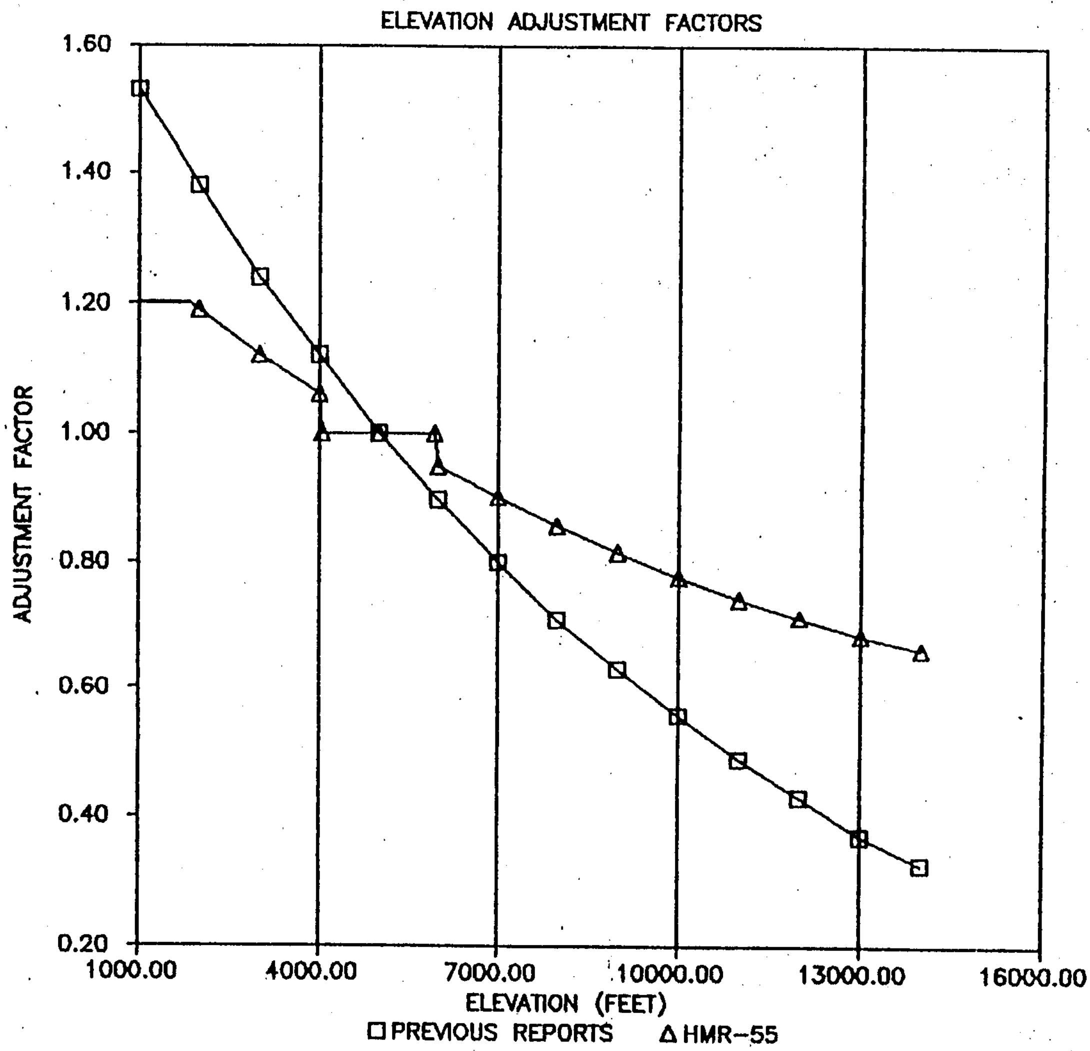


Figure 4.1 Elevation adjustment factors using HMR-55's equation and simple ratio of precipitable water.

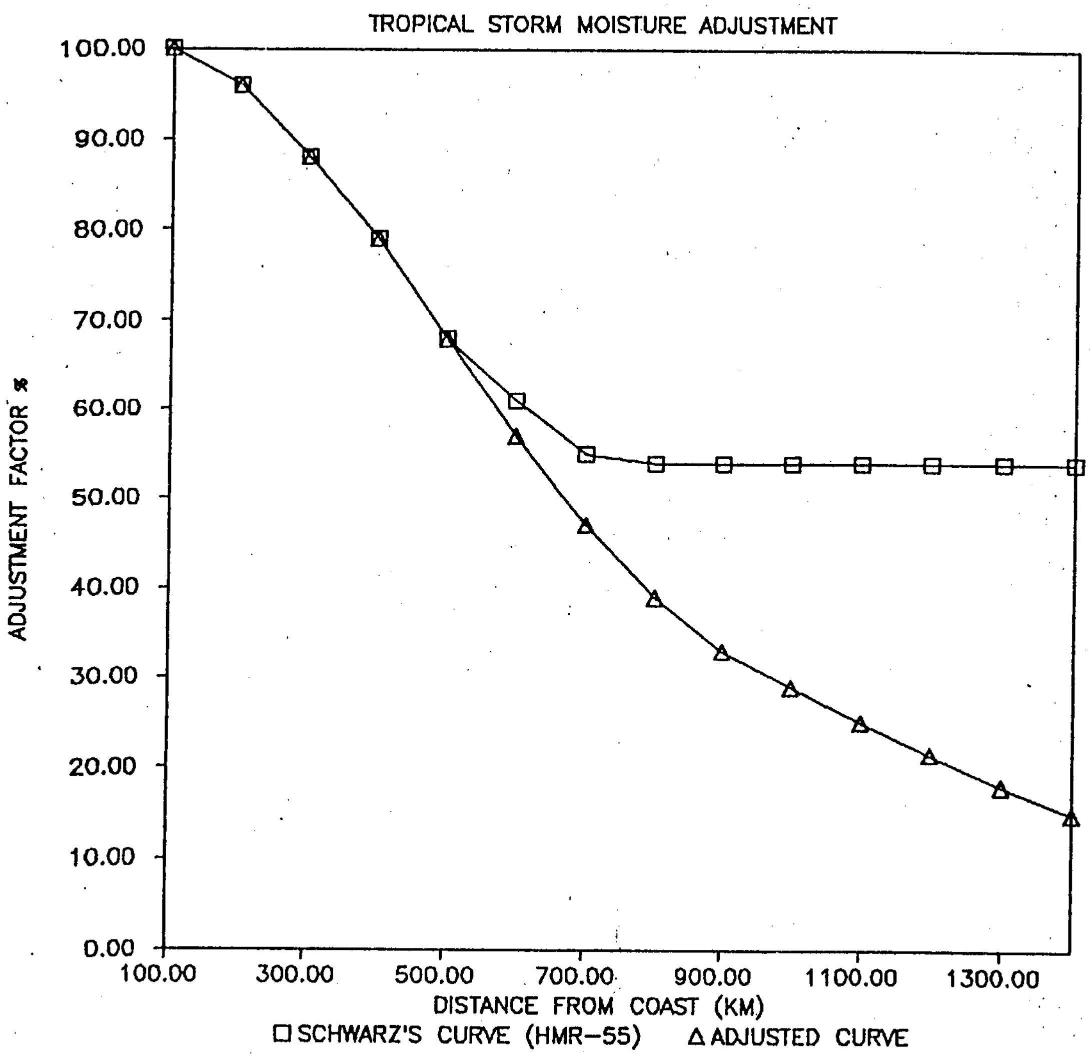


Figure 4.2 **Tropical storm inland moisture adjustment as used in HMR-55 and adjusted non-orographic influence curve.**