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# Economic Impacts and Analysis Methods of Extreme Precipitation Estimates for Eastern Colorado



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# ECONOMIC IMPACTS AND ANALYSIS METHODS OF EXTREME PRECIPITATION ESTIMATES FOR EASTERN COLORADO

by

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ABSTRACT

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PRECIPITATION ESTIMATES FOR EASTERN COLORADO

Dams are designed to store water and to insure human safety and as such they must withstand, in their lifetimes, any extreme precipitation event in their drainage basin. Correct estimation of this event is critical because on one hand it must provide an adequate level of safety to not occur, but it must not be any greater than needed since the high costs of dam construction and modifications are directly related to the magnitude of the estimated extreme event. Most frequently the extreme precipitation event is labeled as the Probable Maximum Precipitation, or PMP.

National and state concerns over the adequacy of existing dams in the United States as well as increased development of the Front Range led to state dam risk reclassification and federal redefinition of new PMP values issued for Colorado in 1984. The study area included the region from the Continental Divide to the 103rd Meridian. Study of the implementation of PMP values and their potential economic impacts in Colorado reveals that an enormous cost will result in Colorado.

Techniques for estimating cost of modifications for spillways were developed. Among 162 high risk dams, the estimated total cost for modification was approximately $184 million. The economic value of this precipitation estimate is $9.45 million per inch change of rainfall in this limited study area. In one elevation region, 7000 to 9000 feet,

the costs is approximately $15.76 million per inch change of rainfall. Regional cost analyses revealed the South Platte River Division had the greatest costs.

Inherent limitations in the PMP procedure and the cost of spillway modifications have made evaluating other alternatives necessary. Special aspects of estimates for extreme precipitation, such as snowmelt runoff versus extreme precipitation events and climate variations were examined. Four methods for estimating extreme precipitation events were evaluated; the traditional PMP, the paleogeological, the cloud/mesoscale dynamic model, and the statistical approaches. A collection of approaches were recommended for Colorado dam design in three elevation regions: the plains, the foothills, and the mountains.

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# CHAPTER I

# INTRODUCTION

With the completion of every weather observation data is added to the climate history for that station. Every component of that data has some value, no matter how minute. However, as time passes the accumulated amount of data increases in value. From climate data one can find averages, means, extremes, etc. Climatological information is used quite often to make many operational and design decisions, (Changnon et al., 1980).

Climate event estimates are also used to help in major design decisions wherein the historical data record is insufficient to have sampled, in most cases, the extreme events under consideration. Design decisions have varying economic value. Some are of great value, or cost, such as sites of power plants and pipelines, as well as design of airports, roads, bridges, and large buildings. Dams are another costly structure in which climate estimates are used in the design.

## A. Statement of Problem

Dams serve several purposes, two of which are water storage and prevention of floods. Decisions relating to dam design include an important concern over human and property safety. Caution in design pertains to dams located where a sudden release of water due to dam failure could endanger human lives and valuable property below the dam. Because of safety concerns, estimates of extreme precipitation events which could fall in the drainage basin of the dam needed to be developed.

The estimation of such extreme events that are far outside the normal sample of observations becomes a critical issue relating to dam design. Beginning in 1940, the Federal Government started publishing a series of hydrometeorology reports in which estimates of the Maximum Possible Precipitation, or MPP, were calculated. These MPP numbers represented a estimate of extreme precipitation events. In the early 1950's MPP was changed to Probable Maximum Precipitation, or PMP, due to the uncertainities, limitation of data and knowledge of the precipitation process.

Probable Maximum Precipitation has been defined several ways. An early definition, (Weather Bureau, 1956), expressess PMP by saying, "The probable maximum precipitation represents the critical depth-duration-area rainfall relations for a particular area during various seasons of the year that would result if conditions during an actual storm in the region were increased to represent the most critical meteorological conditions that are considered probable of occurrence." The Glossary of the American Meteorological Society defined PMP in 1959 as, "The theoretical greatest depth of precipitation for a given duration that is physically possible over a particular drainage area at a certain time of year. In practice this is derived over flat terrain by storm transposition and moisture adjustment to observed storm patterns." Finally, in HMR-55, (Miller et al., 1984), PMP is described as, "Theoretically the greatest depth of precipitation for a given duration that is physically possible over a given size storm area at a particular geographical location at a certain time of the year."

Hence, the definition of PMP has varied with time, however, the critical issue is that the PMP estimate has changed drastically over the last 40 years for areas in Eastern Colorado. Does the PMP estimate define with much accuracy an extreme precipitation value of nature or rather is it just dependent upon the climatological data that is used in its calculations? The controversy just described has become a major issue when considering the latest PMP values in HMR-55, (Miller et al., 1984). The decision to develop new PMP estimates was based on two concerns. First, the increased development of the region has necessitated more water projects and increased flood control. The second concern focusses on the hydrologic adequacy of many existing structures (Miller et al., 1984).

The potential effects from implementation of HMR-55's PMP estimates on Colorado are enormous. The economic impact, relating to modification of existing high risk dams to the new extreme precipitation standards, is estimated in this study.

Questions relating to the current PMP estimation methods and resulting estimates arise because of the high costs and because the PMP predicts an event with no probability of occurrence. Could and should a more realistic climate estimate be developed?

In this study other estimates of extreme precipitation events were analyzed and alternatives were developed by combining data and information from different fields. The high costs involved in dams certainly justified an examination of this issue. The alternative approaches included the traditional approach of PMP as used in HMR-55, a paleogeological analysis of streambeds; a cloud/mesoscale dynamic model; and a statistical estimate.

## B. Research Nature And Scope

The scope of the study is broken down into three objectives which are summarized below.

### 1. Objectives

1) Review the approach to PMP determination from 1940 to present,
2) Analyze an economic impact of the PMP estimate found in HMR-55 for Colorado, and
3) Evaluate a collection of approaches to estimation of extreme precipitation events for use in Colorado dam design.

### 2. Background

The area of interest is that from the Continental Divide east to the 103rd Meridian in Colorado. This region is considered in (Miller et al., 1984).

In this study the focus is on the 24-hour period and 10 square mile area. The fact that climatological data is much more prevalent for durations of 24 hours is why it was preferred over any other time period. Moreover, most precipitation data is observed and recorded for this time period. The use of a 10 square mile area was based on two reasons. First, this area is the smallest used by the hydrometeorologists in their PMP studies. Second, they assumed the areal value is approximately equal to a point value.

## CHAPTER II

## HISTORICAL REVIEW OF PMP INFORMATION

The first objective of this paper was accomplished by reviewing selected hydrometeorological reports for the nation, and then those pertaining to Colorado. Changes in climate data and methods for computing the climate estimate were characterized for several reports beginning with the first one published in 1940 up through the latest, HMR-55.

### A. General

Climate estimates of events such as PMP originated in the middle of this century after enough climate data had been accumulated to form an informational base from which estimates could be made.

The first hydrometeorology report was published in 1940 and provided estimates for the Ompompanoosuc Basin in Vermont (U.S. Weather Bureau). The PMP in this report was calculated simply by multiplying the area-depth curves for the maximum actual precipitation events by a "reliability factor". This factor, which was generally 1.3, was considered a best guess when calculating the maximum possible rainfall.

The next two reports issued (HMR-2 and HMR-3), also concentrated on basins; however, the calculations of the PMP values became more complex. An adjustment for transposition of a storm into a region and a factor for orography were added. The factor for orography defined the maximum zone of rainfall intensity 4000 feet above the ground. Also, dew points and wind velocities used in the calculations were maximized. The equation developed to get the maximum 24-hour precipitation event was:

$$D_{24} = 24VbWe/M \qquad (1)$$

where

b = width of moist column

$D_{24}$ = largest 24-hour precipitation event

M = area

V = mean inflow velocity

We = effective precipitable water

Finally, the reliability factor used in the first set of calculations was discontinued.

The next report considered was Hydrometeorology Report #36 (1961), a generalized report that presented values for all of California, not just a basin. It should be noted that in the early 1950's the name was changed from maximum possible precipitation to probable maximum precipitation due to the uncertainities, limitation of data and knowledge of the precipitation process. Hydrometeorology Report #36 was concerned with "how much" a storm model could relate precipitation to measurable variables such as wind, moisture, etc., as well as "how far" one could extend the maximum values of the variables in the calculations. When HMR-36 was published, precipitation values were divided into two categories, convergent and orographic. Each component had its own complex factors that contributed to higher values for PMP. Furthermore, a model coefficient had been developed from the largest storm on record from areas within or close to California. The largest storm was not necessarily located in the study region and was assumed to be transposable to any location within the study region. Area-depth curves which were used extensively in the early reports did not play such a significant role in defining the PMP estimate. Finally, the reports started presenting the PMP for durations of 6-hour, 12-hour, 24-hour, etc, so that users could further understand and design for the nature of the storm.

More recently in HMR-40, (U.S. Weather Bureau, 1965), a basin PMP study which dealt with the Susquehanna River in Pennsylvania, procedures for calculating PMP were significantly dissimilar from those in the 1940's. The procedure in HMR-40 developed enveloping curves for different storm durations. The curves were obtained by transposing storms of record into the study basin and then adjusting them for maximum moisture at the transposed location. Also included in this report was an adjustment for elevation. This adjustment was an increase of 0.5 inches of precipitation per 1000 feet increase in elevation for a 24 hour period. Gone from the earlier more statistical methods were the calculations of wind, area-depth curves, reliability factors, etc.

Hydrometeorological Report #51, (Schreiner et al., 1978), produced generalized PMP amounts for the continental United States east of the 105th Meridian. This report dealt again with the "how much" and "how far" questions which were considered in earlier reports. Here the issue of moisture maximization, transposition of storms, and envelopment of depths over specific areas for specific durations were considered. The model coefficient was no longer used in computing PMP.

Three things appear after reviewing the history of the hydrometeorological studies in the Weather Bureau reports: 1) The methods and procedures for calculating a PMP estimate grew more complex with time, 2) basin reports were much more detailed in their methodology than generalized reports, 3) basic factors used in the computing of PMP such as topography were modified from time to time in some way. The value offered in an individual report would become obsolete when a value in a new report replaced it. The shift is obvious when one considers reports that deal with the Colorado PMP values.

### B. Colorado Specific Information

Three reports have values that relate to all or part of the Colorado region under study, which is from the Continental Divide east to the 103rd Meridian, see Figure 1. The first report was published in 1947 (U.S. Weather Bureau), the second in 1960 (U.S. Weather Bureau) and the third in 1984 (Miller et al.). In this span of 37 years the methods to compute the climate estimate of PMP for this area of Colorado became very complex. Even though there were major changes in the methodology for computing the estimate, the major influence on the estimate came from the use, or non-use, of "bucket surveys" in the Cherry Creek storm of 1935. Bucket surveys are made by trained scientists in the area of a known major rainstorm to seek accidental collections of rain in cans, buckets, or other containers; as such they usually find rainfall amounts much heavier than measured in the sparse weather service network of rain guages (U.S. Weather Bureau, 1960).

The first report, HMR-23, computed generalized estimates of Maximum Possible Precipitation over the United States east of the 105th Meridian. Storm precipitation was adjusted for maximum moisture influx defined by

$$Wp_1 - (p_1/p_2)Wp_2 \qquad (2)$$

where

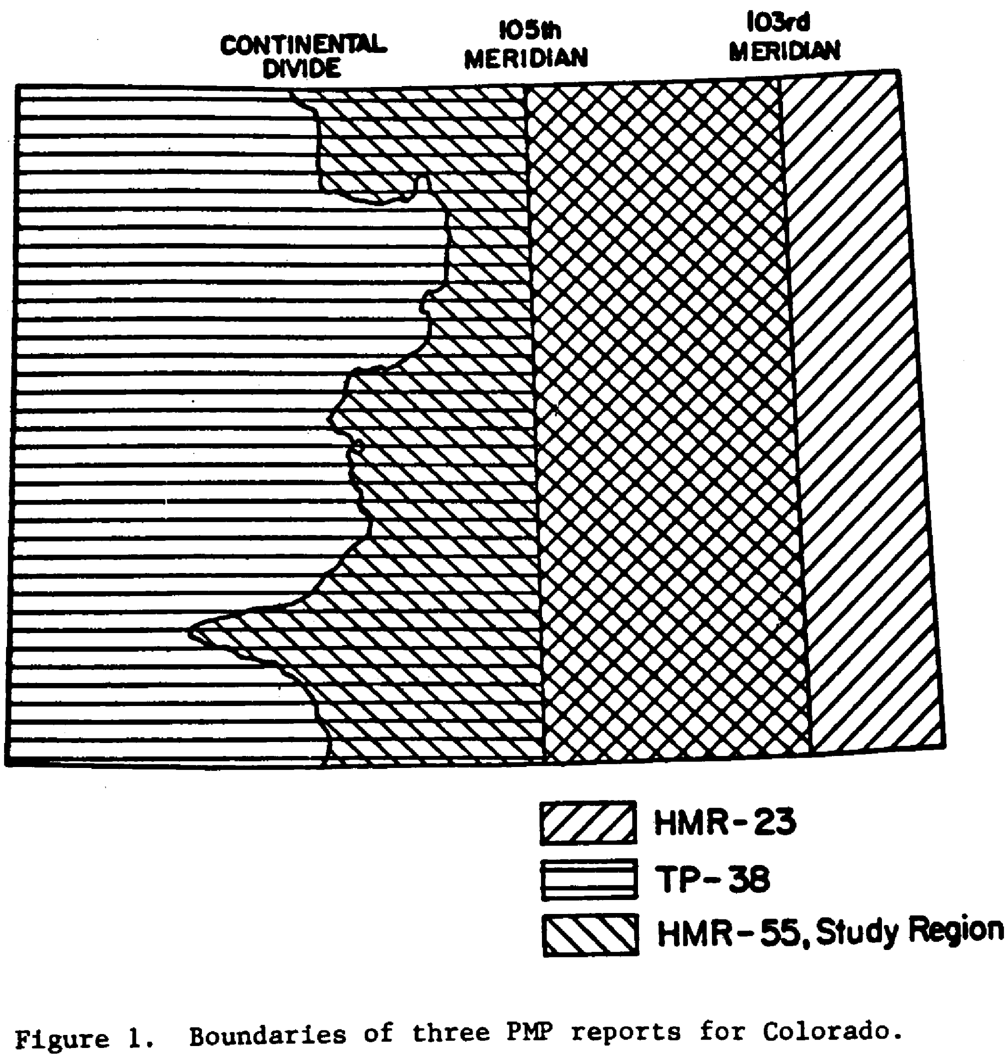


Figure 1. Boundaries of three PMP reports for Colorado.

$p_1$ = pressure difference entering,

$p_2$ = pressure difference leaving,

$Wp_1$ = effective precipitable water in,

$Wp_2$ = effective precipitable water out,

and elevation. The precipitation was then transposed to localities which had similar terrain and synoptic features. In this report, the values from the Cherry Creek "bucket survey" of 1935 were not included as a data source because it was believed by those who wrote HMR-23 that the storm rainfall could have been influenced greatly by the nearby orographic effects. The estimated PMP for a 10 square mile area at Denver in this report was 25.4 inches for a 24-hour period.

The second report was Technical Report #38. This report produced generalized estimates of PMP for the United States west of the 105th Meridian. Once again basic storm precipitation data from climatological records was used as well as data from any "bucket surveys" that were considered reliable and available. The Cherry Creek storm "bucket survey" values, were recorded 20 miles east of the 105th Meridian. Although they were found to be reliable, the storm was not transposed or used in this report. The storm precipitation used in TR-38 was maximized and adjusted for elevation then transposed into homogeneous areas as defined by terrain and synoptic conditions in the same way as in the previous report. It should be noted that even though this report dealt with values for very mountainous terrain, no complex orographic factors were developed for use in the computations. The estimated 24-hour PMP for Denver (10 square mile area) increased to 27.1 inches.

The final report, HMR-55, included the entire region of interest from the Continental Divide to the 103rd Meridian. The values in this report and their potential economic impact prompted this study. Probable Maximum Precipitation estimates in this report were much higher than prior values along the Colorado foothills. Denver's 24-hour, 10 square mile value estimated at 34.7 inches, is 36 percent more than the value presented in 1947.

The method for computing the PMP estimate for HMR-55 was quite complex. Besides classifying the type of storm, the procedure classified the terrain effect, separating the orographic and non-orographic regions. Along the same lines as earlier procedures, the method maximized moisture which could be advected into the region. The atmospheric moisture was adjusted seasonally, being 15 days closer to a higher value. The elevation adjustment used in earlier reports was increased in this study. The free atmospheric forced precipitation (due to convergence) was determined using a numerical model to separate storms and then transposed anywhere +/- 1500 feet in elevation from the location of the storm. However, once transposed, this number was then multiplied by horizontal and vertical adjustments, an orographic factor, and a storm intensity factor.

Although procedures to compute an estimate of PMP became more complex, analyses of storm data used in the hydrometeorological reports reveal that the main reason that the PMP numbers in HMR-55 changed so dramatically from earlier ones is the addition of data from two large "bucket surveys" of storm precipitation. The Cherry Creek storm discussed earlier but never included until this study, as well as the June 1964 storm at Gibson Dam, Montana storm were now considered. The heavy rains in these two storms drastically affected the PMP estimates for the region in Colorado for elevations from 5000 to 7500 feet. Thus, the earlier reports which ended their analyses at the 105th Meridian divided this important region into two parts and made it difficult to develop an accurate PMP estimate.

### C. Importance of Climate Data to PMP Estimates

Although means for producing the climate estimate of PMP were modified over the years, the addition of new storm data into the calculations had the greatest impact on the final PMP numbers. Atmospheric conditions such as temperature, dew point, wind speed and direction have important roles in maximizing precipitation. These meteorological parameters were consistently maintained throughout the three studies. Thus, storm precipitation data greatly influenced the final PMP estimates.

As can be seen in the historic review of the PMP studies that included Colorado, the decision on whether or not to include the "bucket surveys" was a most difficult and relevant one. Each hydro-meteorological report concluded with the statement that if the data was considered to be reliable, then it should not be discarded. Hydrometeorology Report #55 includes all "bucket surveys" which could influence a PMP estimate for the region. Other reports did not utilize all of them because earlier investigators believed that the values from the "bucket surveys" conducted in the western part of the United States had too few reports to make them reliable.

It would appear that because new PMP estimates are largely based on bucket surveys and weather service climate data, every time a new item of information is added to the record, a new analysis can be performed and written. Unfortunately, the historical review of PMP reports reveals certain limitations:

1) estimates are quite sensitive to data,
2) some of the data is questionable,
3) accuracy of the reports and PMP estimates is unspecified,
4) dependence on one method, and
5) the effects of elevation are not well understood.

When considering these limitations, two broad questions arise. The first asks, "What is the economic value of a PMP estimate." The second question asks, "Is there a way to approach the problem which gives less sensitivity to the data and provides more confidence in an estimate."

## CHAPTER III

## A POSSIBLE ECONOMIC IMPACT OF USING AN ESTIMATE OF PMP IN COLORADO

The second objective of this work was fulfilled by developing a method to estimate costs for modification of existing dams to satisfy the implementation of HMR-55 PMP values. The method used five known dam estimates to predict costs for 162 high risk dams affected by HMR-55 values. A total cost of modification was found for Colorado. The total cost of dam modifications was then compared to costs of other alternatives available to dam owners.

The economic value of using climate data and information can range from small to large depending on the issue under consideration. In the case of dam design and modification of existing dams, the costs can be enormous. The designs are partly derived from the use of an estimate of extreme precipitation events. A majority of the estimates of large precipitation events have been computed in a traditional manner and published in the hydrometeorological reports of the United States Government.

When HMR-55 was published in 1984, the report caused concern among those affected by PMP values. In Colorado, all areas between the Continental Divide and the 103rd Meridian (Fig. 1) had changes in their PMP estimates. As seen in Figure 2, most areas above 7500 feet elevation had their PMP values decrease, whereas those below this elevation increased. The areas that showed the most dramatic increases

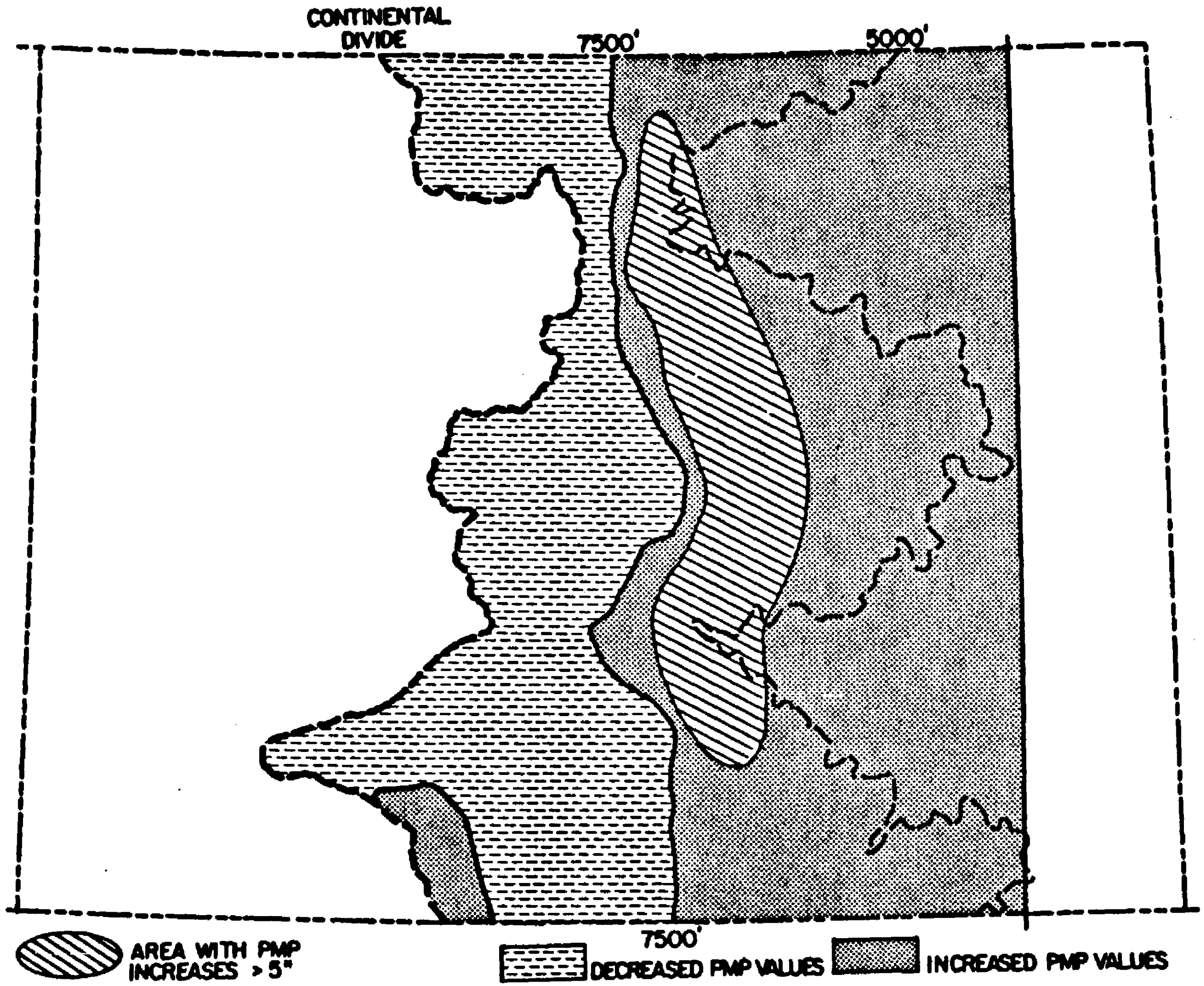


Figure 2. Change in PMP values for HMR-55 region.

were those in the 5000 to 7500 foot range. Increases in the PMP over those in the previous reports were as much as 10 inches.

A. Economic Impacts to Existing Dam Spillways

In the study region (Figure 1) there are more than 1500 dams with a majority of these located in or near the foothills of the Rocky Mountains. However, not all these dams are of major concern because some store small amounts of water or are located in sparsely populated areas where their failure could do little damage downstream. Since not all these dams posed the same threat, the State Engineer's Office of Colorado developed a risk value for each dam. The classification for the dams range from low to high. Also, soon after the release of HMR-55, the "high risk" dams were designated to meet the new PMP estimates (Committee on Safety Criteria for Dams et al., 1985).

High risk dams were those defined as providing risk of loss of life and property damage greater than $200,000 downstream of the dam after a collapse due to heavy rain (Committe on Safety Criteria for Dams et al., 1985). The number of high risk dams located in the study region affected by HMR-55 is 162. This number of dams would be expected to meet the new PMP requirements. Of this total, 14 do not have conventional spillways that allow water to flow over the dam. These 14 dams were considered separately.

To assess the economic impacts of adjustment to the new PMP values, it was necessary to have as many dam modification cost estimates as possible from the HMR-55 region. One year after HMR-55 was issued only five dams could be identified which had been or were in the process of being estimated for modifications. The five completed estimates were assembled, as listed in Table 1 along with their cost estimates. The estimated cost for dams were; Beaver Creek Dam, $600,000 (Erthal, 1985), Boulder Reservoir, $1.3 million (Kuiken, 1985), Commanche Reservoir, $1.2 million (Flook, 1986), Pueblo Reservoir, $10.0 million (Thompson, 1985), and Trinidad Reservoir, $6.0 million (Flook, 1986).

## B. Method For Estimating Costs

The process of estimating impacts required cost estimates for dam modifications. Since the cost estimates were not available for most Colorado high risk dams, a process for estimating the PMP effects on such basins and ensuing costs for modifications had to be developed. To develop the process by which dam modification cost estimates could be made, it was necessary to define what exactly would be affected, given the new PMP estimate. The process began by placing the new PMP value over the drainage area for a given lake. In the areas that the new PMP estimate is larger than the previous one, more water can be expected to flow out of the drainage area into the lake. The dam must be capable of releasing the increased amount of water through its spillway or it will flow over the dam and possibly cause the dam to fail. Thus, a key aspect is the spillway capacity for a certain maximum flow to be released from the lake. If this is adequate to address the new PMP generated flow values, spillway modifications can then be estimated and then the economic costs related to HMR-55 for existing dams.

It is important to note that for those dams that had a PMP value decrease since the last estimate may also need spillway modifications. This is due to two reasons, 1) some dams did not meet earlier PMP values and 2) other dams have been recently reclassified as high risk dams.

Thus, when considering the implementation of HMR-55, all high risk dams were included in the cost estimates.

## C. Dam Characteristics

The design of spillways involves several factors. The four main factors in the design of most spillways are:

1) drainage area for a given lake,
2) reservoir capacity at time of large precipitation event,
3) the PMP that falls on the drainage area, and
4) rate and amount of runoff from drainage area.

Values for the first three factors were assembled for the five dams which had modification cost estimates. The fourth factor was not available in this study due to lack of information. However, this element is estimated through a volume in a later section. Table 1 lists the information relating to spillway capacity, drainage area, reservoir capacity, and PMP levels over each given basin for the five available estimates.

Table 1. Reservoir Information.

| Reservoir/ Dam | Estimated Cost $Mil | Spillway Capacity cfs | Reservoir Capacity a-f | Drainage Area $mi^2$ | PMP inches |
|---|---|---|---|---|---|
| Pueblo Resvr | 10.0 | 191,500 | 357,000 | 1,545.0 | 34 |
| Trinidad Resvr | 6.0 | 55,400 | 119,877 | 671.0 | 32 |
| Commanche Resvr | 1.2 | 2,080 | 2,629 | 11.9 | 21 |
| Boulder Resvr | 1.3 | 6,700 | 13,300 | 12.9 | 33 |
| Beaver Crk Resvr | 0.6 | 2,800 | 2,161 | 7.4 | 24 |

The next step in the spillway modification estimation process was study of the distribution of sizes of drainage areas for all the Colorado high risk dams, (see Appendix A for classification). The distribution of drainage areas is depicted in Figure 3, revealing that the values are quite skewed with 85 dams having drainage areas of 5 square miles or less. As the drainage area size increases above 25 square miles, the number of dams greatly decreases. The largest drainage area for a high risk dam in the study region was 1,545 square miles. With no available estimates for dams with drainage areas smaller than five square miles, the group of 85 dams was not analyzed in the same manner as the remaining dams. The number of dams remaining for study was 63. The group of 63 high risk dams used in this section of the economic study are shown in Figure 4 and listed in Appendix A.

The spatial distribution of the 63 high risk dams in the region defined by HMR-55 was weighted to certain areas. In the Rio Grande River Division there were eight dams (Fig. 4); in the Arkansas River Division 13; and in the South Platte River Division there are 42 high risk dams. The elevations of the dams by intervals are listed in Table 2.

Table 2. The elevation of the 63 high risk dams analyzed.

| Elevation (feet msl) | Number of Dams |
|---|---|
| 3000-5000 | 10 |
| 5000-7000 | 25 |
| 7000-9000 | 19 |
| 9000-12,000 | 9 |

The characteristics of the dams are quite different. A majority, 79%, are earthfill dams; however, 8% are rockfill, 6% are concrete gravity, 5% are concrete arch, and 2% are masonry arch. Several of the high risk dams had more than one spillway with extras to be used only for emergency purposes. Finally, a few dams had excessively large

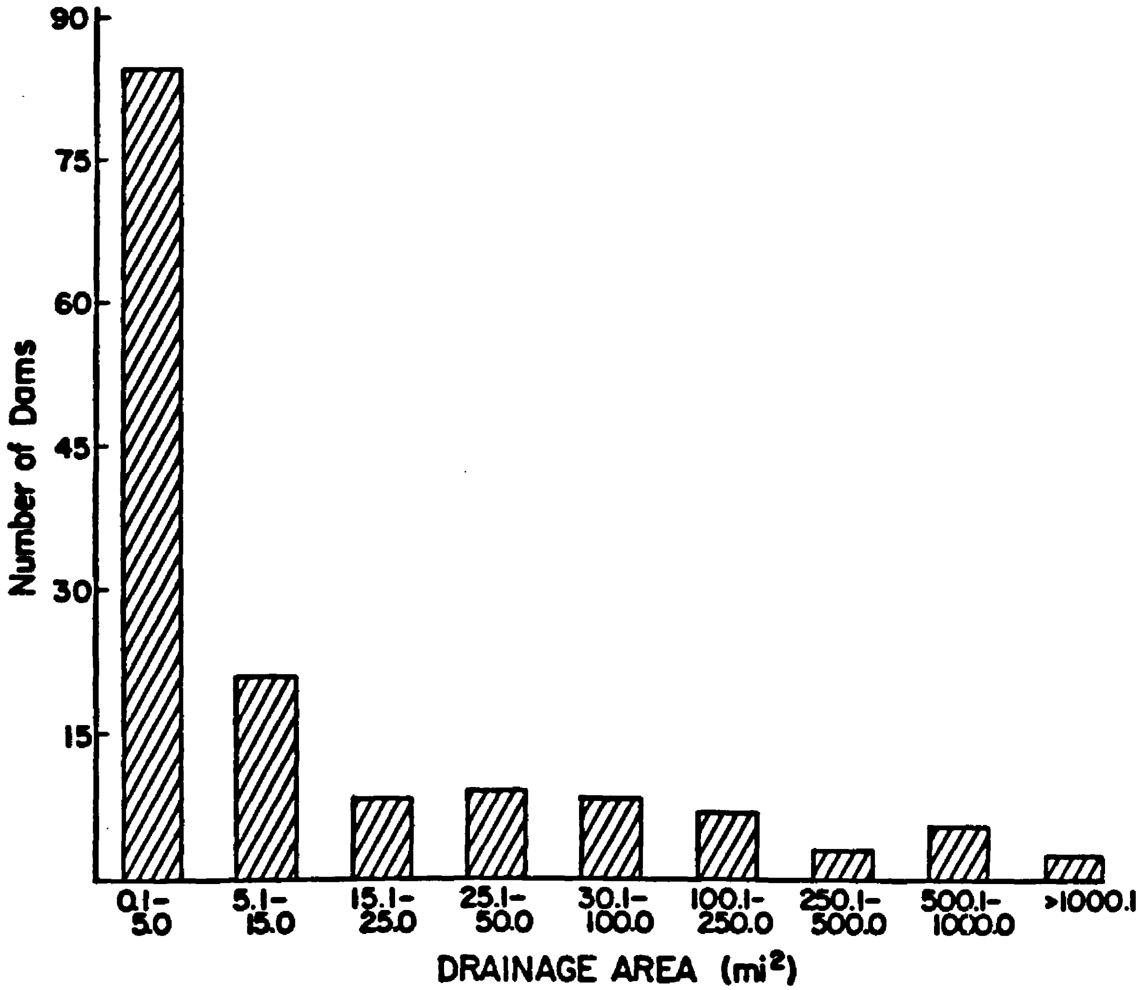


Figure 3. Distribution of dams by the size of their drainage areas.

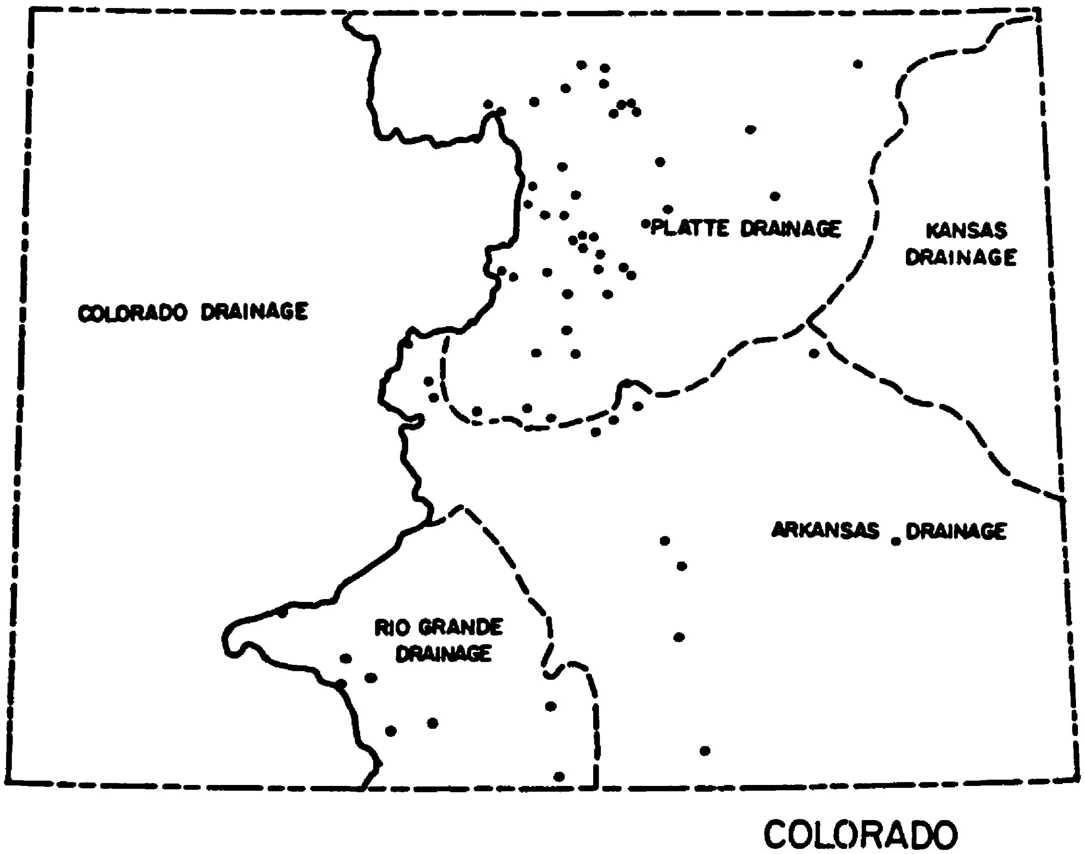


Figure 4. Location of 63 high risk dams.

reservoir capacities when compared with their spillway capacity. These differences made it difficult to estimate costs from one design type. The five dams with cost estimates (Table 1) had earthen dams.

An effort was made to divide the 63 high risk dams into three groups based on the size of their drainage areas. The largest group included 28 dams that had drainage areas ranging from 5 to 25 square miles. The second group consisted of 25 dams and its drainage area ranged from 25 to 250 square miles. The third and smallest group which included 10 dams had drainage areas greater than 250 square miles. The 14 high risk dams without spillways were not considered in this part of the study.

## D. Rationale For Cost Estimates

To determine the estimated costs for the 63 high risk dams, a procedure was developed in which:

1) the largest category related to cost is to modify spillways,
2) the basic quantity is a volume of water generated by an extreme rainstorm,
3) the number of available estimates is limited to 5,
4) how to use the 5 estimates, and
5) the approach is to interrelate 3 variables:
    a) spillway capacity,
    b) cost of spillway modifications, and
    c) potential water volume.

Figure 5 depicts this 3-way interrelationship.

### 1. Defining a potential water volume

Several parameters were explored to use as the measure of water

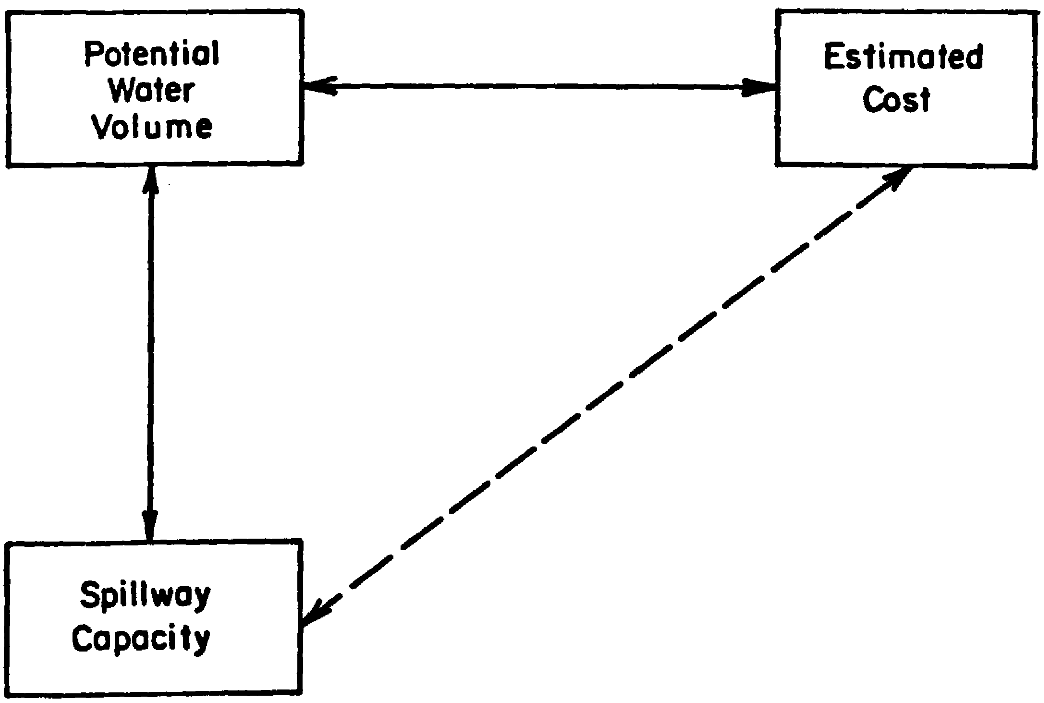


Figure 5. Relationships used to make cost estimates for 63 high risk dams.

volume. The one selected is

$$V = (D - R)PMP \qquad (3)$$

where

D = Drainage Area,

R = High Water Line Area of the Reservoir at time of a flood,

PMP = Probable Maximum Precipitation,

V = Potential Water Volume,

The product (D)PMP is the volume of water falling on the drainage area. By definition of drainage area, this includes the area of the reservoir/lake. For drainages in which $D >> R$ this parameter would be a sufficient estimate of water volume. However, for the 63 high risk dams, the (D)PMP was correlated with spillway capacity, S. The resulting $r = 0.61$, which is not particularly high.

Equation 3 which related to total water volume in the drainage area without the water falling in the lake seems be better correlated to spillway capacity with an $r = 0.733$ for the 63 high risk dams. It should be noted that the value of R includes the multiplication of 0.75 times the high water line area of a reservoir. This value was arbitrarily chosen as the best estimate of a water level area in a reservoir at time of a flood.

2. Relating spillway capacity to potential water volume

From Figure 5, an important relationship was that of spillway capacity to potential water volume. Calculations using bivariate linear regression analysis produced a correlation between the spillway capacity and potential water volume for the five estimated dams, see Figure 6.

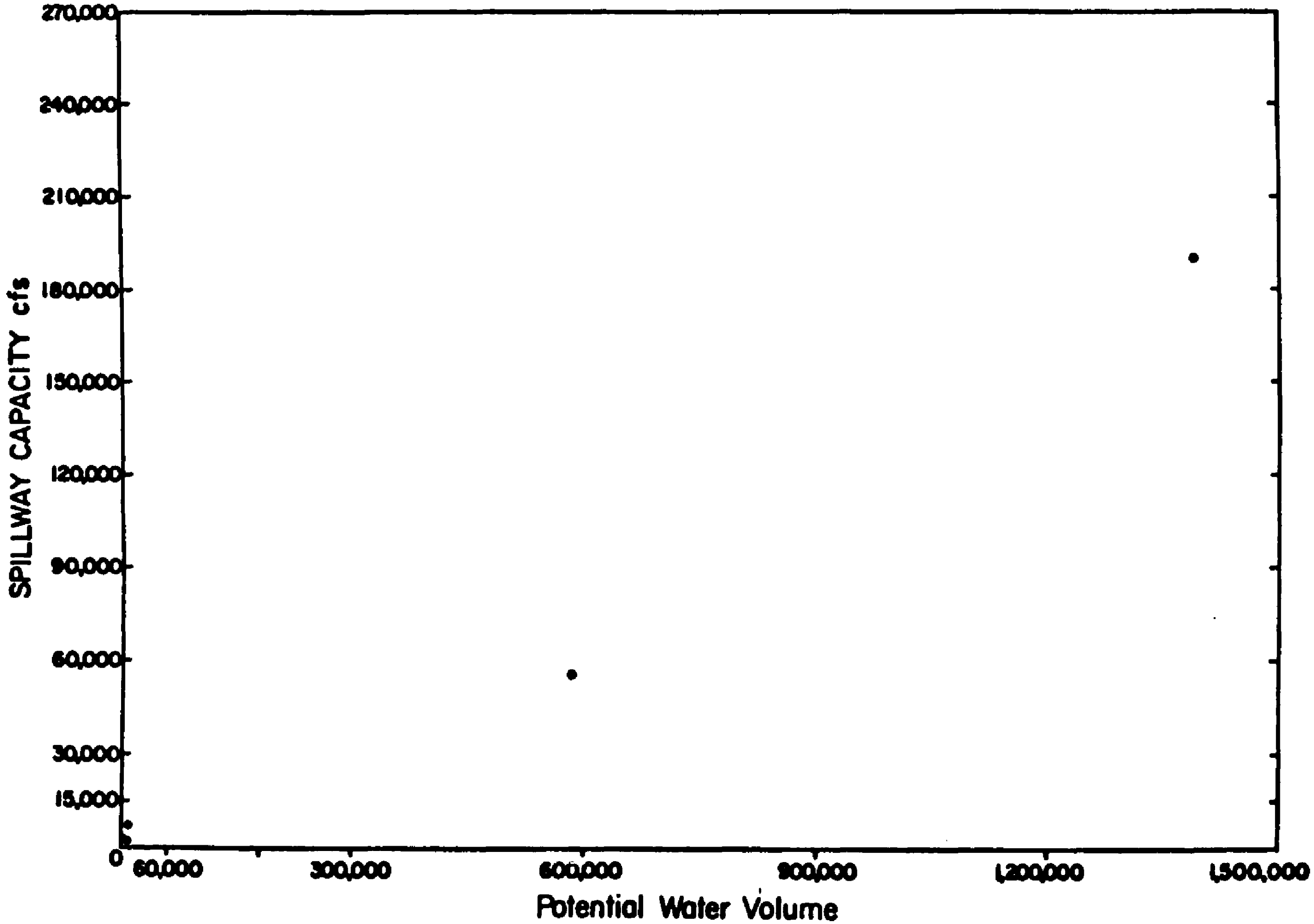


Figure 6. Spillway capacity vs. potential water volume for 5 dams with available estimates.

The equation developed from the regression is:

$$S = a + b(V) \qquad r = 0.99 \qquad (4)$$

The correlation coefficient values reveal a strong correlation between the cost and potential water volume and that 98% of the changes in spillway capacity are due to changes in potential water volume.

Next, spillway capacity was related to potential water volume for the entire group of 63 dams. Correlations displayed a relationship with an r=0.733, see Figure 7. More than 50% of the changes in spillway capacity could be attributed to changes in potential water volume.

A homogeneous group of dams, defined as all the earthfill dams with only one spillway and no excessive reservoir capacity, yielded a sample of 33 dams. This group has a much better relationship, see Figure 8. Based on log/log correlations,

$$\ln(S) = a + b\ln(V) \qquad r = 0.85 \qquad (5)$$

Comparisons of the three groups defined earlier by drainage area size, one can notice in Table 4 how the linear correlations vary depending on size of drainage area.

Table 4. Variations of correlation with Drainage Areas for Different Sizes.

| Basin Area | Equation | Correlations | |
|---|---|---|---|
| 5-25 $mi^2$ | $S = a + b(V)$ | $r = 0.77$ | (6) |
| 25-250 $mi^2$ | " " | $r = 0.93$ | (7) |
| >250 $mi^2$ | " " | $r = 0.94$ | (8) |

The results in this table suggest that as the size of drainage area increases, the relationship between spillway capacity and potential flood volume increases (see Appendix B for figures). No statistical

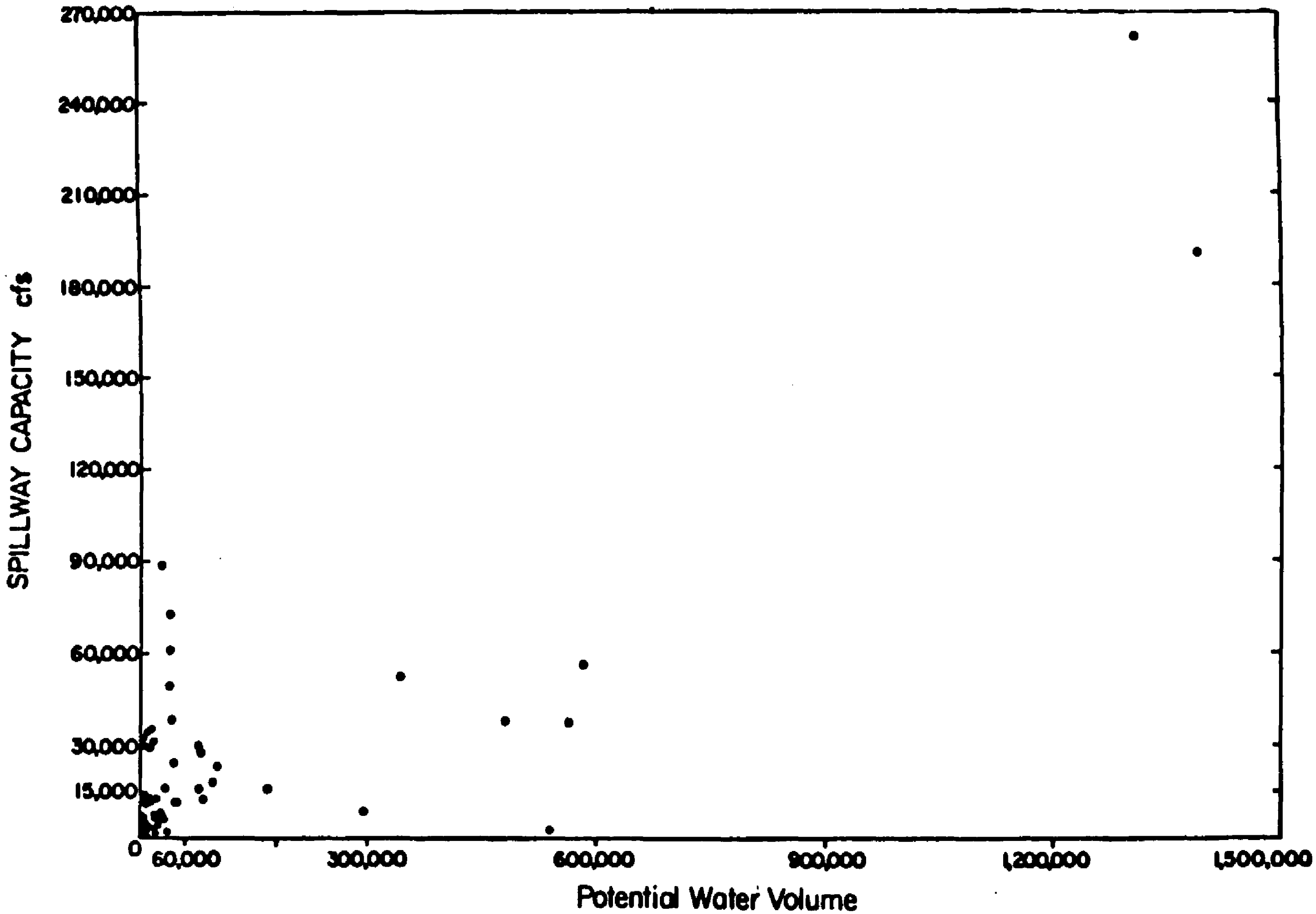


Figure 7. Spillway capacity vs. potential water volume for 63 high risk dams.

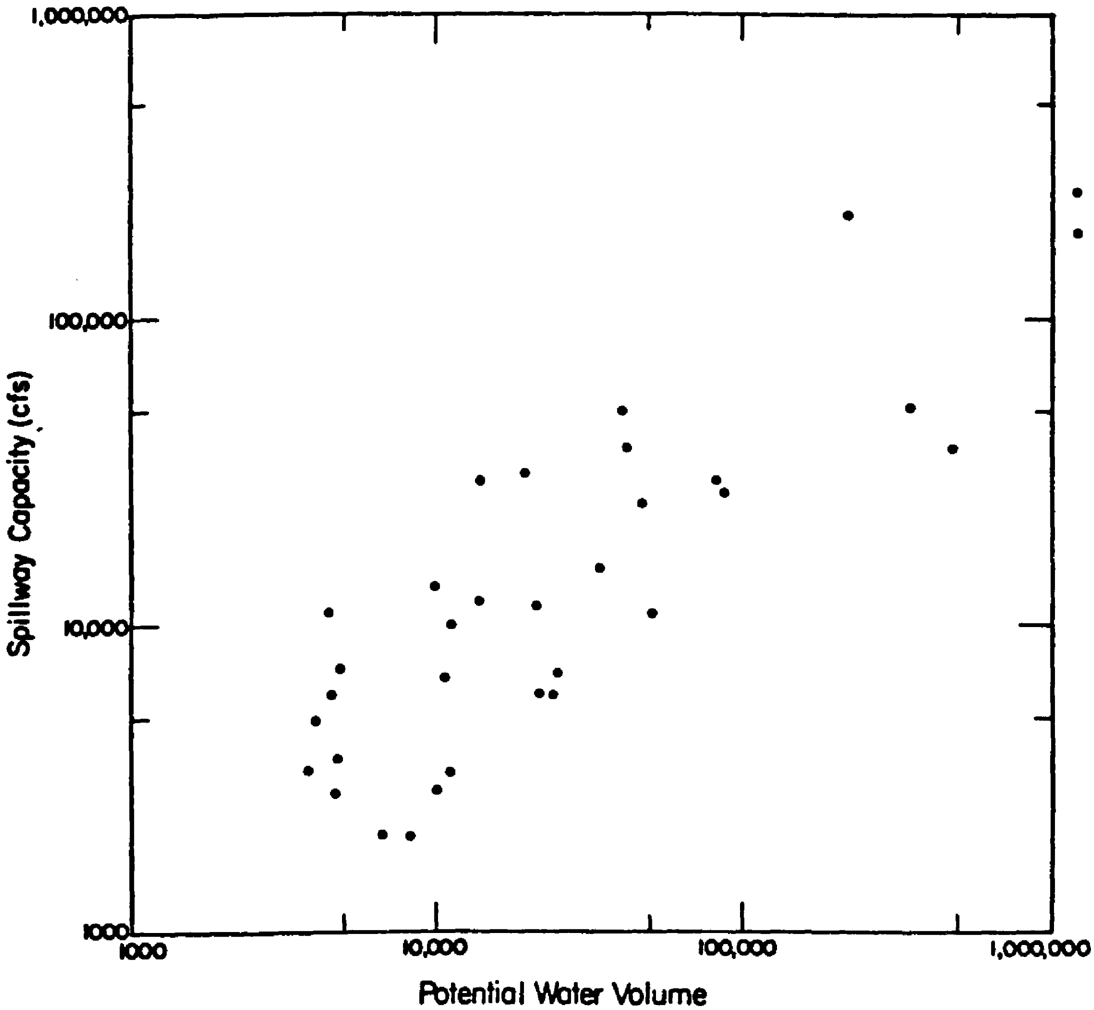


Figure 8. Spillway capacity vs. potential water volume for 33 homogeneous high risk dams.

test for similarity of sample was conducted in this study.

3. Relating cost of spillway modifications to potential water volume

Two views of cost appear in Figure 5. The relationship between potential water volume, spillway capacity and spillway modification costs, and their correlations are shown in Table 3.

Table 3. Regression Equations and Related Correlations for Costs of Spillway Modifications

| | | |
|---|---|---|
| $C = a_1 + b_1(S)$ | $r = 0.96$ | (9) |
| $C = a_2 + b_2(V)$ | $r = 0.99$ | (10) |

where

C = Estimated Cost,

PMP = Probable Maximum Precipitation,

r = Correlation,

S = Spillway Capacity,

V = Potential Water Volume,

The high correlation values give some confidence of the relationship even if the number of available estimates is small.

The cost of the 63 high risk dams estimated using $C = a + b(V)$ is \$124.56 million and using $C = a + b(S)$ is \$168.83 million. The lower estimate was adopted to be conservative. Also, the $C = a + b(V)$ relationship can be used on dams without spillways.

## E. Cost Estimates

1. Estimated costs for 63 high risk dams

The above findings suggest that whether 5 dams, 33 dams, or all 63 dams are considered, there is a sufficiently strong relationship to justify their use in an effort to estimate modification costs. The flow diagram in Figure 5, presents these relationships used to estimate costs in all 63 dams.

First, using linear regression, an equation was developed for the estimated cost versus potential water volume for the five dams with estimates, (Table 3). Next, the computed potential water volume value for each dam was inserted in this equation to produce a cost estimate for each of the other 58 dams. For the 33 homogeneous earthfilled dams, the estimate was $66.73 million; however, when considering the entire group of 63 dams the number increased to $124.56 million. See breakdown in cost per dam in Appendix C. Table 5 describes the impact as related to PMP values for the 63 dams in the Colorado study region.

Table 5. Relation of Costs of No Action and Adaptation of New PMP Values.

| Total Cost | Status |
|---|---|
| 0 | current PMP (20-27 inches) |
| $124.56 Million | new PMP (16-36 inches) |

As noted earlier, dams were classified into four elevation groups. For each one of these groups, an average PMP change was calculated for the 63 high risk dams, see Table 6.

Table 6. Relationship of Basin Elevation and New PMP Values.

| Elevation (feet msl) | Average Change in PMP (inches) |
|---|---|
| 3000-5000 | +5.00 |
| 5000-7000 | +6.24 |
| 7000-9000 | -2.06 |
| 9000-12,000 | -5.00 |

The results above suggest that the previous reports underestimated PMP below 7000 feet and overestimated those above 7000 feet. It should be noted that although the high risk dams in the range of 7000-9000 feet had an average decrease, some dams showed an increase in their PMP from the previous report.

Even though PMP values declined for most of the high elevation dams, all are included in future modifications to meet the implementation of HMR-55 because they either did not meet earlier PMP reports or were just recently classified as a high risk dam.

To better understand how important it was to have the PMP estimates as accurate as possible, an average cost per inch change in the average PMP for the high risk dams was calculated; see Table 7. The average value of the cost is $9.45 million per inch change of PMP.

Table 7. Relationship of Spillway Modification Costs in High Risk Dams to Changes in Basic PMP Values

| Elevation (feet msl) | Average Cost/Inch Change in PMP, ($Mil.) |
|---|---|
| 3000-5000 | 4.76 |
| 5000-7000 | 9.05 |
| 7000-9000 | 15.76 |
| 9000-12,000 | 2.40 |

It is important to note that the foothills region, 5000-9000 feet, is the area most greatly affected by the new PMP estimates in HMR-55. With the average costs so high, it raises important questions about the absolute accuracy of the PMP values. An estimate which is incorrect by one inch for the dams in the 7000 to 9000 foot elevation range could mean a difference of as much as nearly $16 million in costs for modification of existing dams. The history of change in PMP values since 1940 with five to ten inch increases further provides uncertainty in the potential accuracy. A summary of information relating to the 63 high risk dams is located in Table 8.

Table 8. Summary of Information for the 63 High Risk Dams.

| Elevation feet msl | Number of Dams | Average Change in PMP, inches | Total Cost for Dams $M. | Average Cost/Inch Change in PMP $Mil. |
|---|---|---|---|---|
| 3000-5000 | 10 | +5.00 | 23.8 | 4.76 |
| 5000-7000 | 25 | +6.24 | 56.5 | 9.05 |
| 7000-9000 | 19 | -2.06 | 32.5 | 15.76 |
| 9000-12,000 | 9 | -5.00 | 12.0 | 2.40 |

The spatial distribution of the costs for the 63 high risk dams was analyzed for different drainage sections. The Rio Grande River Division total cost for dam modifications would be about $10.97 million, while the total cost for all dams to be modified in the Arkansas River Division would be approximately $33.66 million. The greatest expense is seen in the South Platte River Division where the total comes to $79.93 million. These large costs justifiably have dam owners weighing other alternatives.

2. Cost estimates for 85 dams with drainage areas equal to or less than 5 Square Miles.

The 85 dams that have drainage areas 5 square miles or less were not included in the previous analysis because there were no cost estimates available. Hence, C = a + b(D) was used to approximate costs for the group of 85 small drainage area dams. Of the estimates available, the dam with the smallest drainage area was Beaver Creek, which was 7.4 square miles. The Beaver Creek point fell 50 percent below the regression line that had been established using all five available estimates. Thus when the 85 drainages areas were substituted into C = a + b(D), the cost for each dam was multiplied by 0.50 to get a more accurate cost estimate. The total estimated cost for the 85 dams is $47.88 million, however, the level of confidence in this estimate is not as high as that for the 63 high risk dams previously analyzed.

### 3. Cost estimates for 14 dams which do not have conventional spillways

The group of 14 dams without conventional spillways varied in their characteristics. For example, drainage areas ranged from 0.4 square miles to 17.5 square miles and the reservoir capacities for the dams varied between 3 acre-feet to 152,000 acre-feet. In an effort to develop an estimate for dams with such variability, several different procedures were examined. The procedure that was developed for 63 dams analyzed earlier was found to be most appropriate for the group of 14 dams with no spillways. The total estimated cost for the 14 dams was $11.96 million. In the same way as with the group of 85 dams, the level of confidence in this estimate is much lower than that in the group of 63 high risk dams.

### 4. Summary of estimated costs

The total cost for the 162 high risk dams located in the region from the Continental Divide to the 103rd Meridian in Colorado is $184.40 million. As discussed earlier, due to differences in design and characteristics of dams, not every cost estimate has the same level of confidence.

## F. Comments On The Cost Of Water

A possible alternative to modifying the existing dams is to maintain less water in the reservoirs. Hence, the cost of this alternative was determined and compared to the spillway costs. First, a value was derived for all the water held in the 63 high risk dams. A conservative price of $4.00 per acre-ft was used in the study's calculations (Northern Colorado Water Conservancy District, 1986). Other references, (Young and Gray, 1972) used values as high as $10.00 per acre-ft.

It was further assumed that in a given year the entire amount of water which is held in a lake would be used. Thus, for the 63 high risk dams the value of the water consumed is approximately $9,136,196 per year.

If dam owners decided not to modify their existing spillways, they would be forced to lower their water level an average of 25% to handle the new PMP events as defined by HMR-55. The cost of not having 25% of the available water would be approximately $2,284,049 the first year and a portion, if not all, of that value every succeeding year.

Assuming an economy with an inflation rate of 12% and a stable water price, a length of time was calculated in which the total cost from lost water holdings would equal the estimated costs of modifications. It should be noted that this assessment of the impacts of reacting to the new PMP was of direct economic costs. Other social and environmental impacts were not assessed. The calculations suggest it would take 36 years on the average before the losses due to 25% less water would equal the cost of spillway modifications. Note that every year after the 36th year, the decision to decrease water holdings by 25%

would be more costly than to proceed with the modifications.

No matter what decision the dam owners make, increased costs for the use of water would occur and be passed on to those buying the water, largely communities, industries, and agriculture interests in Colorado. This increase might exceed the ability of one water using group to pay. Agriculture, with its already thin profit margin, could be forced to stop or limit irrigation. Dry land farming might ensue.

Another possibility for addressing the problem is that dam owners may breach their dams rather than go into debt trying to improve their spillways. If this were to occur it would mean a permanent loss of water storage in part of Colorado. The cost of this alternative was not calculated.

Another option to consider is that more lakes will be built to store more water to compensate for water loss due to less storage or breaching of existing dams. These new dams would cost vast amounts of money, much more than previous dams because they would have to meet requirements established by HMR-55.

## G. Summary

From the techniques developed in this study the estimated cost for modification of the 162 high risk dams were computed to be approximately $184.40 million for the state of Colorado. Another important outcome of the economic study relates to the average cost per inch change in PMP. The average cost is $9.45 million per inch change in PMP. In one elevation region, 7000 to 9000 feet, the cost is approximately $15.76 million per inch change in PMP. These extreme high cost values indicate that the most accurate estimates possible are needed.

# CHAPTER IV

# APPROACHES TO ESTIMATION OF EXTREME PRECIPITATION EVENTS FOR DAM DESIGN

The third objective of this research deals with evaluating alternative approaches which can estimate extreme precipitation events. Several methods including PMP were considered. A collection of these approaches which could be used for dam design was recommended for the orographically dissimilar region in Eastern Colorado.

## A. The Need For Alternative Views Of An Estimate of Extreme Precipitation Events

Inherent limitations in the PMP procedure such as data dependency, uncertainty in the accuracy, and effects of elevation as well as climate variations have made evaluating other alternatives necessary. As shown in the previous chapter, the economic impacts from the implementation of the latest Probable Maximum Precipitation estimates are enormous in Colorado. Also, since the values in the hydrometeorological reports are based on climate data, it appears rational to consider other forms of estimation which can predict large precipitation events.

This chapter examines alternative methods for developing an estimate of extreme precipitation events. Evaluating special aspects of estimates for extreme precipitation, snowmelt runoff versus extreme precipitation events and climate variations, is necessary when considering the different approaches. The advantages and disadvantages of each method are assessed. A collection of approaches might provide a more accurate range of estimates from which dam designers can choose for the dissimilar topographical region from the Continental Divide to the 103rd Meridian. Here a proposed collection of methods is evaluated for the plains, the foothills, and the mountains.

### B. Special Aspects Of Estimates For Extreme Precipitation

#### 1. Snomelt runoff versus extreme precipitation events

When evaluating regions which have elevations that vary from 4,000 to 14,000 feet, as defined in HMR-55, two types of floods must be considered. One type of flood consists of runoff from rainfall. The second flood type is related to snowmelt runoff. The results of Jarrett and Costa (1986) indicate that higher elevations have maximum streamflow from snowmelt. This raises an obvious question. Should large rainstorms be the primary element in dam design at higher elevations in Colorado. In this study the critical snowmelt/rain elevation division separates the foothills region from the mountains. In the design of dams this information is particularly important.

#### 2. Climate variations

Before any collection of methods can be evaluated for use in dam design, time scales must be assessed. The study revealed that as time scales increase, the magnitude of the climate variations becomes greater (Griffiths and Driscoll, 1982).

In the traditional PMP approach, an estimated value with a zero risk of occurrence is produced. However, scientists have suggested with the use of different statistcal distributions that precipitation events near those predicted by PMP have return periods which range from $10^9$ to $10^{12}$ years (Evans, 1986).

Paleoclimatological records suggest that the past one million years can be broken down climatologically into four time scales (Griffiths and Driscoll,1982). Figure 9 shows the magnitude of temperature change over differing time scales for the past. These time scales are listed below along with the temperature departure for each scale.

Table 13. Temperature ranges for different climate time scales.

| Temperature Range, C | Past time scale (years) |
|---|---|
| 0.4 | 100 |
| 1.5 | 1,500 |
| 5.0 | 10,000 |
| 10.0 | ice age |

First, long records reveal that the earth has experienced an ice age about every 100,000 years in the past 300,000 years (Griffiths and Driscoll, 1982). Second, changes of temperature as large as 1.5 C can have dramatic effects on the climate of earth. For example, a decrease in average temperature of 1.5 C from today's global average would put the world into a "little ice age" such as was experienced from 1430 to 1850 (Griffiths and Driscoll, 1982).

The speculation that increased concentrations of carbon dioxide, $CO_2$, could influence the global climate in a very short period of time has to be assessed when developing an estimate of extreme precipitation events. A doubling of $CO_2$ concentrations could increase surface temperatures 1.5 C to 3.5 C and cause a reduction in precipitation in areas such as Colorado (U.S. Department of Energy Report-0237, 1985). Further research is needed in this area before a clear conclusion can be drawn to the direct effects of $CO_2$ increases on the climate and extreme precipitation events. However, because the effects of $CO_2$ may be felt

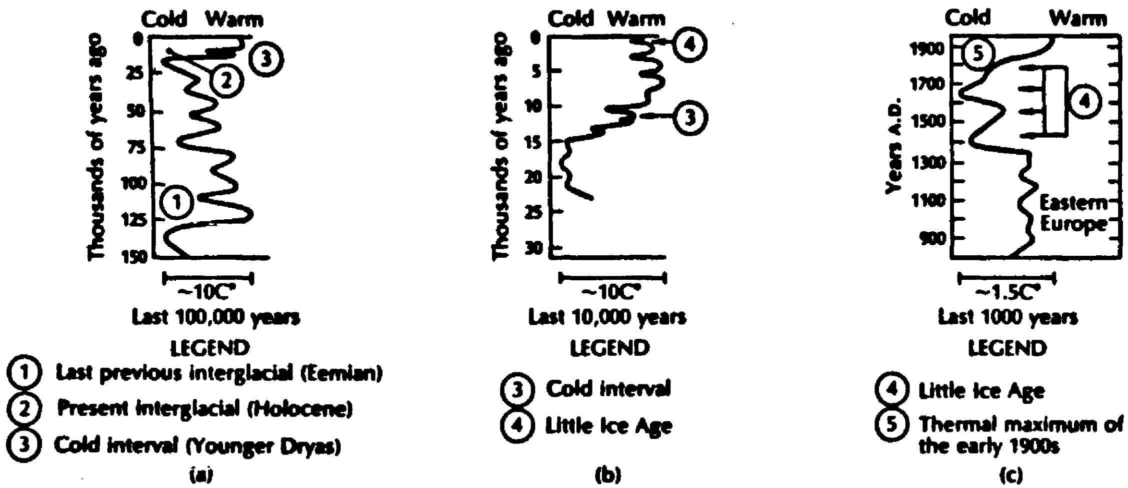


Figure 9. Mid-latitude temperature changes during the last (a) 100,000 years; (b) 10,000 years; and (c) 1,000 years. (From Griffiths and Driscoll, 1982.)

in the next 50 years, any information relating to $CO_2$ should be carefully examined and considered before an estimate of an extreme precipitation event is developed.

Regardless of the climate shift, what is important is that climate variations for time scales of 1,000 years and shorter should be considered when designing a dam. The extreme precipitation event estimate currently used is a fixed and stable number.

It is important to realize that although it can be seen how temperatures have fluctuated for different time scales, it is not exactly known how extreme precipitation events are influenced by climate variations. Further research needs to be done in this area.

### C. Methods For Estimating Extreme Precipitation Events

A method is needed which results in the most reliable estimate available for science at the present time. It would be helpful for a method to have two traits, an estimate of probability and be checked in part by independent methods. This leads to the attempt to assemble a collection of analyses that can be done as a guide to selecting an appropriate estimate. This section will evaluate the advantages and disadvantages of the methods available as well as recommend future research.

#### 1. Traditional PMP approach

The first approach analyzed is the traditional one used in HMR-55 (1984). Figure 10 shows how PMP values vary with elevation along the 40th parallel from the Continental Divide to the 103rd Meridian. Table 9 identifies the advantages and disadvantages of this method which has been in use since 1940.

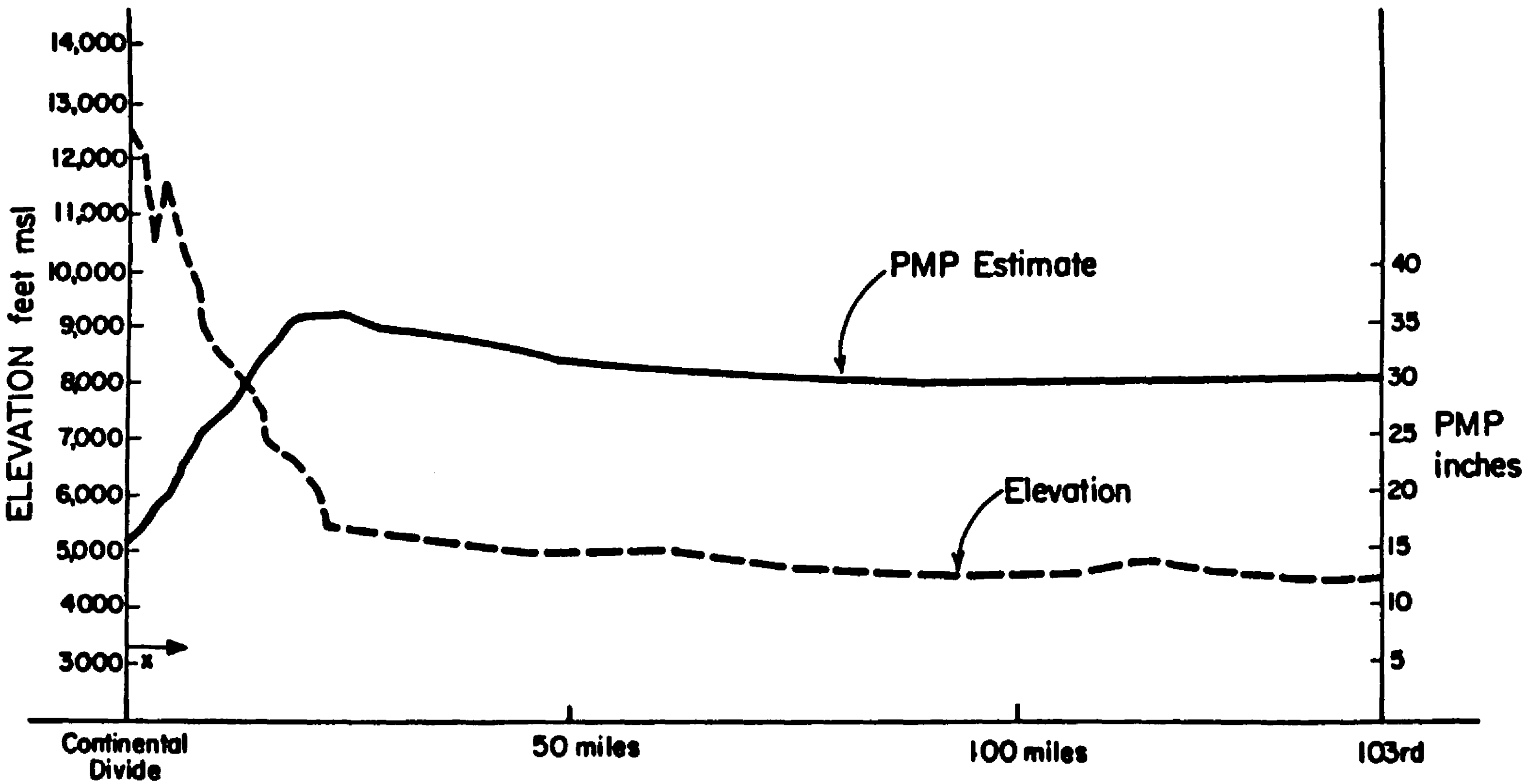


Figure 10. PMP estimate vs elevation along the 40th parallel from the Continental Divide to the 103rd meridian.

Over estimation from this traditional approach is very great in certain geographical areas. Figure 11 shows the ratio of the 24-hour, 10 square mile PMP to the 24-hour maximum precipitation amounts recorded over the past 100 years at weather stations in the study region. The ratios range from 4 to 14 whereas over most of the eastern United States ratios range from 2 to 4. The large ratios suggest an unrealistic assessment of PMP in the foothills and mountains of Colorado.

The traditional PMP approach appears to be a more consistent estimate of extreme precipitation events out on the plains where the topography is rather flat and there is a larger number of observing weather stations. However, in the foothills and the mountains where the topography is very different and there is little and often questionable data, the PMP values are more questionable when considering an estimate of extreme precipitation events.

Table 9. Comparisons of Major Advantages and Disadvantages of Using the Traditional PMP Approach.

| Advantages | Disadvantages |
| --- | --- |
| + uses meteorological factors such as temperature, moisture, wind, etc. | - data dependent |
| + provides estimate with near zero risk | - does not separate areas with potential orographic effects |
| + consistent in flat terrain | - does not analyze individual basins |
| | - does not consider temporal climate variations |
| | - maximizes all meteorological factors in determining PMP |
| | - transposes storms +/-1500 feet from original location of the storm |

## 2. Paleogeological approach

Another estimate of extreme precipitation events can be derived from paleogeological studies. Several of these studies were conducted in

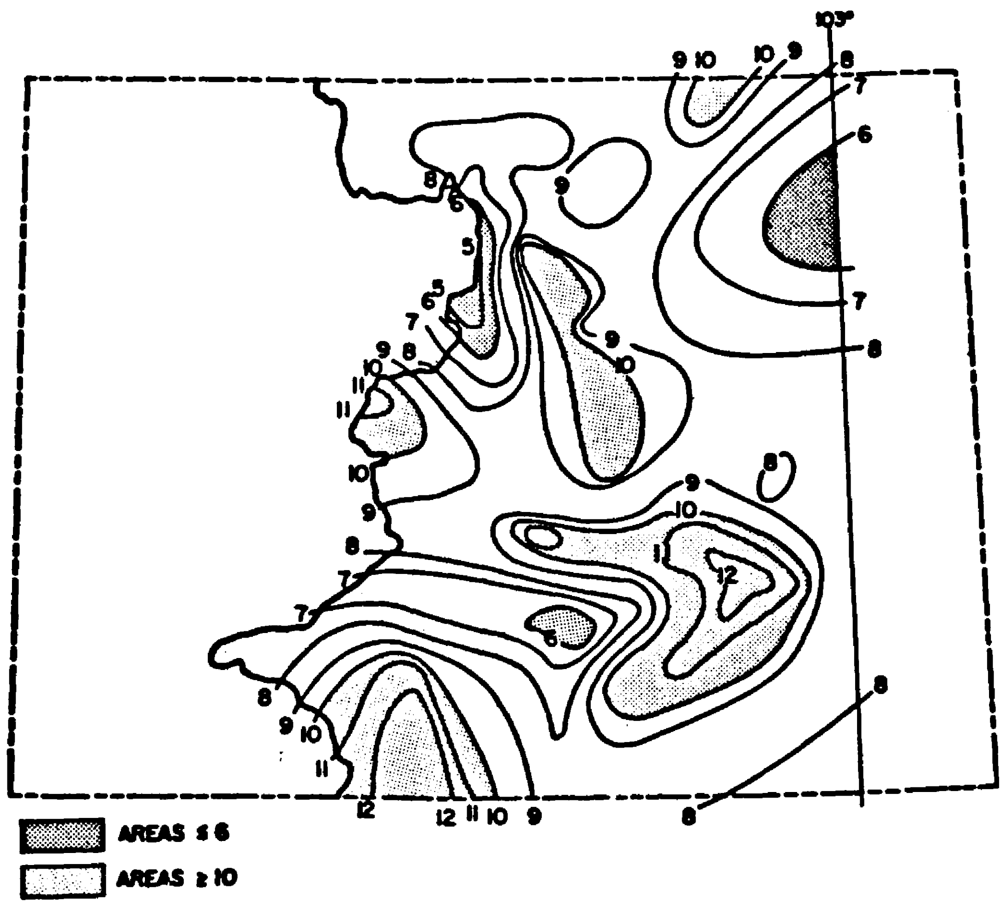


Figure 11. Ratio of 24-hour PMP to 24-hour maximum precipitation.

the foothill streambeds (Jarrett and Costa, 1986). The advantages and disadvantages are listed in Table 10. The paleogeological estimation is entirely different from the traditional PMP approach to predict large precipitation events. This method uses a longer record of data, dating back to the last ice age in some areas. Paleohydrologic reconstruction has shown that there have been only a few large events such the Big Thompson rainstorm of 1976, anywhere in the foothills or mountains above 5000 feet since the latest ice age.

The paleogeological approach also suggests that several of the floods used in previous reports for the high mountains were not all due to a large precipitation event, but rather a result of excessive debris being transported in a stream course. This conclusion weakens the idea that large precipitation events can occur at high elevations above 9000 feet.

The paleogeological method was also able to define an elevation above which most floods were due to snowmelt and below which they were due to excessive precipitation events. This elevation was estimated at 7500 feet in Northern Colorado and 9000 feet in Southern Colorado.

The disadvantages of the paleogeological approach appear to be few. One disadvantage is that below 5000 foot elevation, study of streambed records cannot easily detect past major floods because they spread out on the plains. The other problem is that of limited data. Not all streams in the foothills have yet been investigated; however, with the amount of data now available, the probability of occurrence for the entire region above 5000 feet can be estimated.

Table 10. Comparison of Major Advantages and Disadvantages of Using the Paleogeological Approach.

| Advantages | Disadvantages |
|---|---|
| + defines history of streambed back to ice age | - can only be used for areas above 5000 feet |
| + Does include climate variations | - limited data |
| + identifies debris floods | |
| + separates snowmelt floods from precipitation floods | |
| + includes estimate of probability | |

3. Cloud/mesoscale dynamic model approach

Improvements in mesoscale dynamic models have been significant in the past decade. At the present time the models such as the one described by Cotton et al. (1982) and Tripoli et al. (1982) appear attractive to apply to the problem of estimates of extreme precipitation events. These models have the potential to be an excellent tool to use in estimates of extreme events. They could take advantage of recent studies by Henz (1974) and Klitch et al. (1984) which use radar and satellite analyses respectively to locate "hot spots" for thunderstorm development along the Colorado foothills. Using this information, the model could predict to what extent these thunderstorms can grow with a non-linear combination of meteorological variables. However, a current problem with this model is that it is extremely expensive to run. The other advantages and disadvantages are listed in Table 11. This method may be the best in predicting extreme precipitation in most areas of the study region.

Table 11. Comparison of Major Advantages and Disadvantages of Using the Cloud/Mesoscale Dynamic Model.

| Advantages | Disadvantages |
|---|---|
| + can input any amount of data | - untested at present time |
| + can place storm at any location | - expensive to apply throughout all basins |
| + non-linear combination of meteorological variables | |

4. Statistical approach

Statistical approaches have been considered when defining an estimate of extreme precipitation events. It has been suggested that with 100 years of historical weather service records estimation out to 10,000 years is possible, (World Meteorological Organization, 1973). This approach was assessed in Table 12.

Table 12. Comparison of Major Advantages and Disadvantages of Using the Statistical Approach.

| Advantages | Disadvantages |
|---|---|
| + can estimate 1,000-10,000 year return event | - does not provide zero risk |
| | - does not include climatic variations for >100 years |
| | - bucket surveys not used |

The statistical method can only be used for those Colorado stations with very long records such as that at Fort Collins, ( 100 years). While the data does include variations in the climate over the past 100 years, the 10,000 year return event cannot address climate variations which could be expected for a 10,000 year period. Data from a study of Fort Collins data by McKee et al., (1976), is depicted in Figure 12. This figure suggests that on the tail of a distribution curve the probability of an event occurring in 100 years is 100 times the probability of it occurring in one year.

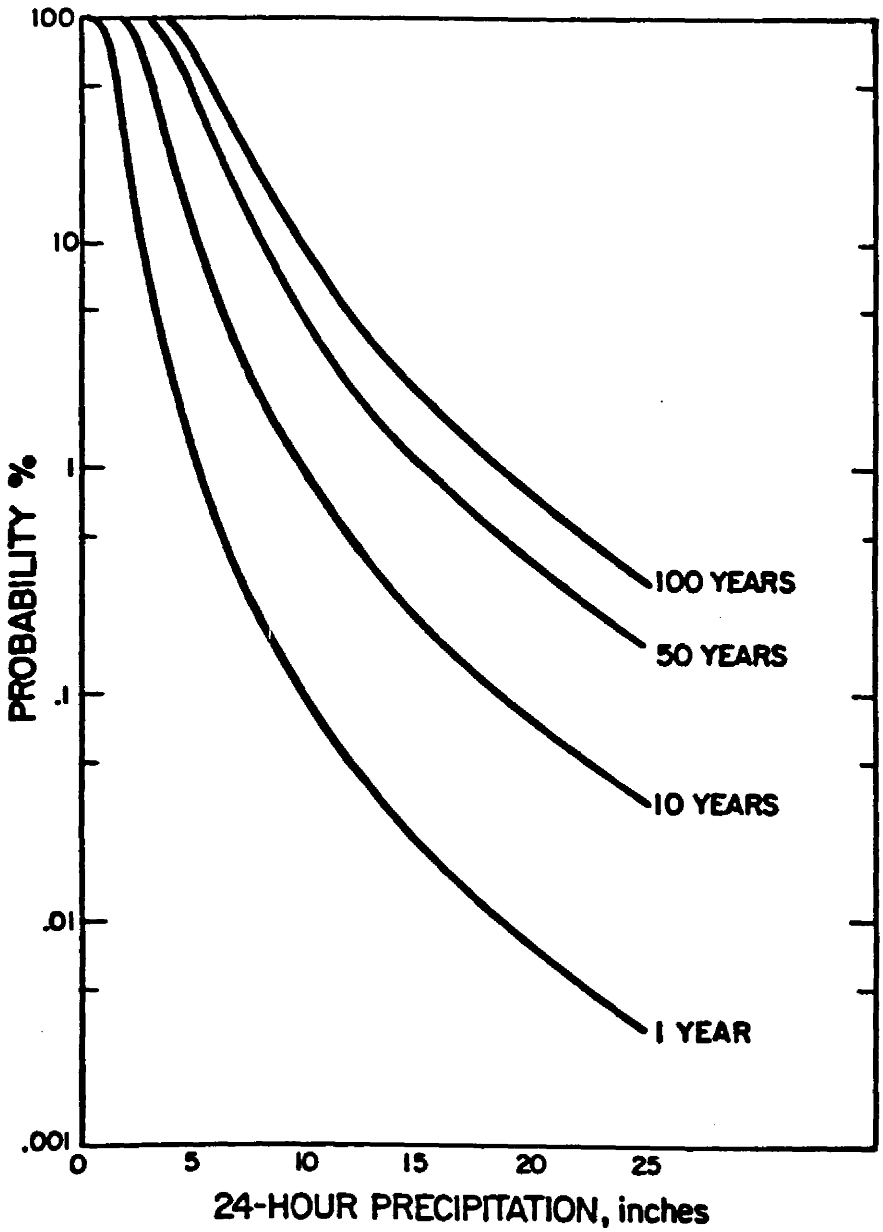


Figure 12. Precipitation probability for Fort Collins.

In the HMR-55 study region a statistical approach which can detect large precipitation events is streamflow records. Although streamflow records are relatively short, less than 50 years, they do suggest the magnitude of floods which are due to extreme precipitation events. Typical peak flows decline with elevation, (Jarrett and Costa, 1986). This helps to support the theory that extreme precipitation events decline in magnitude with elevation. Streamflow records define the elevation at which above the flow consists of only snowmelt and below the flows are mainly due to rainfall. This elevation is approximately 7500 feet in Northern Colorado and 9000 feet in Southern Colorado, (Jarrett and Costa, 1986). Streamflow data also indicates that snowmelt runoff produces the entire flow above the critical elevation and becomes an ever smaller part of the composite flow as it extends farther below the critical elevation (Jarrett and Costa, 1986).

5. Other approaches

The list of approaches to define extreme precipitation events does not end with the four discussed. Options for consideration will continue to expand with further interest in the subject. When considereing the vast differences in terrain located in the study region the goal of producing the best estimate might have to include several different approaches. A great deal of research remains.

D. Proposed Collection Of Methods For Different Elevation Regions

Due to large variations in the orography of Eastern Colorado, no single estimate of extreme precipitation events was thought to be adequate in the design of dams, see Figure 13. The differences between values determined from the paleohydrological reconstruction (Jarrett and

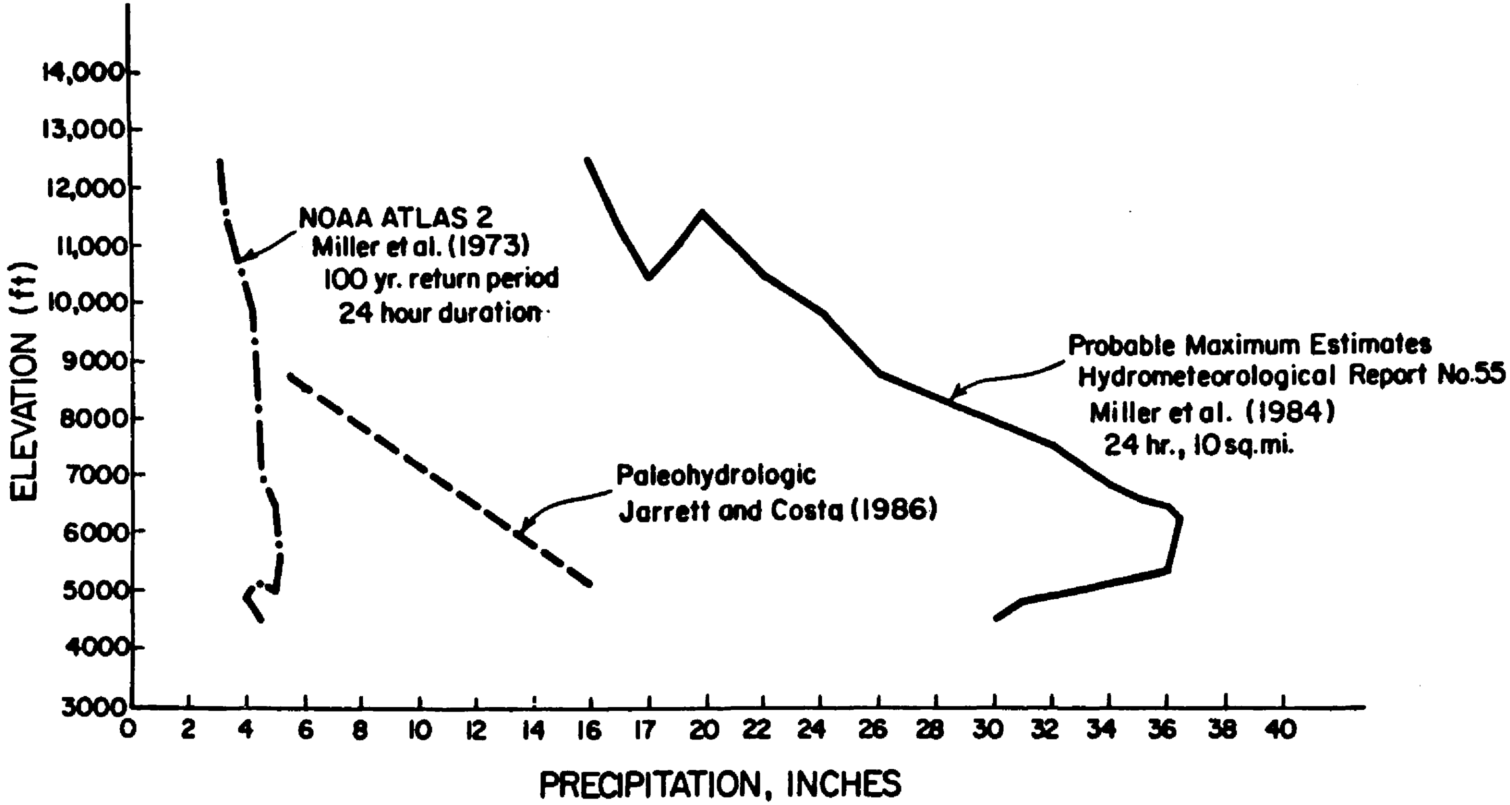


Figure 13. Estimates of large precipitation events versus elevation from the Continental Divide to 103° longitude at 40° latitude in Colorado.

Costa, 1986), NOAA Atlas 2's 100-year return values (Miller et al., 1973), and the latest PMP values (Miller et al., 1984) are shown versus changes in elevation. It is obvious from the figure that the three estimates do not agree. The 100-year return values show essentially no variations with elevation. Paleogeological shows that these events decrease with elevation, and the PMP estimate appears to have its maximum event occurring in the elevations between 5200 and 6500 feet. The conclusion is that elevation effects are not understood at this time. These differences advocate the need for a collection of approaches for varying elevation regions in Eastern Colorado.

Thus, the study area was divided into three main regions: plains, foothills, and mountains. The plains region was defined as the relatively flat area east of the 5000 foot elevation boundary. The foothills region included those areas between 5000 and the critical snowmelt/rain elevation defined in the paleogeological approach. Finally, the mountainous region was considered as the elevated area above the critical snowmelt/rain elevation. Each approach was evaluated in all three regions. Potentially the best method to estimate extreme precipitation events for all elevation regions is the cloud/mesoscale dynamic model; however, this study did not have the means to address this approach.

1. Plains

Three methods provided useful estimates of extreme precipitation events for this region, none of which included climate variations greater than 100 years. The three approaches included, the statistical method, the traditional PMP method, and the cloud/mesoscale dynamic model.

The cloud/mesoscale dynamic model appears to be an excellent approach for the plains. Although no estimate of extreme precipitaion events has been developed from this method, it is reasonable to assume that the model could predict a large rainfall amount with a non-linear combination of meteorological variables.

It should be noted that the paleogeological approach was found to be of little use when considering this region. Floods due to large precipitation events tend to spread out over the plains making it more difficult to detect an accurate frequency.

2. Foothills

The foothills orography varies greatly. Some areas have a quick ascent from 5000 to 9000 feet, such as west of Boulder, while others have a rather gentle slope. Four approaches; the traditional PMP, the paleogeological, the cloud/mesoscale dynamic model, and the statistical, give valuable estimates in this region.

The limitations in this elevation region, which effect estimates, include fewer stations, less data and dissimilar topography. Both the statistical and the paleogeological define a critical snowmelt/rain elevation which separates the foothills from the mountains.

The cloud/mesoscale dynamic model would be most valuable in this region. It would propose an area where maximum extreme precipitation events could occur. Also, the model could define an elevation in which most precipitation that falls above this elevation would be frozen in the form of hail, graupel or ice pellets.

3. Mountains

There are four estimates; the traditional PMP, the paleogeological, the cloud/mesoscale dynamic model, and the statistical calculated for areas above the critical snowmelt/rain elevation. The level of confidence for estimates in this region is lower due to few stations located at this elevation and the dissimilar topography. Both the paleogeological and the statistical approach suggest that runoff from snowmelt is an important component of the peak flows in streams for this region.

The cloud/mesoscale dynamic model could give an accurate estimate of precipitation for these high elevation areas. The interesting question that relates to this model for high elevation regions is whether it would predict only frozen precipitation to fall.

## E. Summary

In summary, due to inherent problems with the PMP procedure and the enormous economic costs relating to the latest PMP estimate, alternative views to estimate extreme precipitation events needed to be considered. Not only are alternative views of extreme precipitation event estimates available, they appear to be applicable when considering the design and modification of dams. Special aspects of estimates of extreme precipitation, such as snowmelt runoff versus extreme precipitation events and climate variations are important to assess before any collection of approaches can be done. The advantages and disadvantages for each method were assessed.

The complex terrain located in the Colorado study region leads to the recommendation that several methods need to be included in each elevation region (plains, foothills, and mountains) to derive a collection of approaches which would provide meaningful estimates of extreme precipitation events for Colorado dam design. Other regions of the country likely will have other methods which would appear more applicable.

# CHAPTER V

# CONCLUSIONS

Dams are designed to store water and to insure human safety and as such they must withstand, in their lifetimes, any extreme precipitation event in their drainage basin. Correct estimation of this event is critical because on one hand it must provide an adequate level of safety to not occur, but it must not be any greater than needed since the high costs of dam construction and modifications are directly related to the magnitude of the estimated extreme event. Most frequently the extreme precipitation event is labeled as the Probable Maximum Precipitation, or PMP.

National and state concerns over the adequacy of existing dams in the United States as well as increased development of the Front Range led to state dam risk reclassification and federal redefinition of new PMP values issued for Colorado in 1984. The study area included the region from the Continental Divide to the 103rd Meridian. Study of the implementation of PMP values and their potential economic impacts in Colorado reveals that an enormous cost will result in Colorado.

Techniques for estimating cost of modifications for spillways were developed. Among 162 high risk dams, the estimated total cost for modification was approximately $184 million. The economic value of this precipitation estimate is $9.45 million per inch change of rainfall in this limited study area. In one elevation region, 7000 to 9000 feet, the costs is approximately $15.76 million per inch change of rainfall.

Regional cost analyses revealed the South Platte River Division had the greatest costs.

Inherent limitations in the PMP procedure and the cost of spillway modifications have made evaluating other alternatives necessary. Special aspects of estimates for extreme precipitation, such as snowmelt runoff versus extreme precipitation events and climate variations were examined. Four methods for estimating extreme precipitation events were evaluated; the traditional PMP, the paleogeological, the cloud/mesoscale dynamic model, and the statistical approaches. A collection of approaches were recommended for Colorado dam design in three elevation regions: the plains, the foothills, and the mountains.

# CHAPTER VI

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# APPENDIX A

## CHARACTERISTICS OF THE 63 HIGH RISK DAMS

The HMR-55 region includes nearly 1500 dams. However, only 162 of those were found to be high risk dams. Fourteen of these did not have conventional spillways located on top of the dam. The 85 dams which had drainage areas less than 5 square miles were not included in this part of the analysis because there were no cost estimates available.

Thus, 63 dams were considered. These dams were located most anywhere in Colorado defined by the boundaries of the Continental Divide and the 103rd Meridian. In the table that follows the 63 dams are listed by name followed by their reservoir capacity, drainage area, type of structure, spillway capacity, and PMP.

Table 14. Characteristics of 63 High Risk Dams

| Reservoir/Dam Name | Reservoir Capacity,a-f | Drainage Area,$mi^2$ | Type | Spillway Capacity,cfs | PMP inches | |
|---|---|---|---|---|---|---|
| SOUTH PLATTE DIVISION | | | | | | |
| Horse Creek | 18,747 | 26.6 | E | 11,400 | 33 | |
| Jackson Lake | 35,629 | 16.8 | E | 10,000 | 30 | |
| Williams/ McCreery | 948 | 69.7 | E | 49,900 | 30 | |
| Barr Lake | 32,100 | 14.6 | E | 1,911 | 33 | ** |
| Milton Lake | 29,732 | 120.0 | E | 17,350 | 32 | * |
| Standley Lake | 42,380 | 16.0 | E | 12,000 | 36 | |
| Black Hollow | 8,058 | 21.4 | E | 6,810 | 33 | * |
| Cache la Poudre/ Tinmath Res. | 10,027 | 20.7 | E | 34,441 | 33 | * |
| Commanche Lake | 2,629 | 11.9 | E | 2,080 | 21 | |
| Douglas | 580 | 46.4 | E | 2,175 | 32 | * |
| Fossil Creek | 11,100 | 28.2 | E | 88,100 | 35 | * |
| Indian Creek/ Cowan Lake | 1,906 | 16.6 | E | 29,100 | 32 | |
| Joe Wright/ Cameron Pass | 7,161 | 5.4 | E | 3,875 | 18 | * |
| Long Draw | 10,900 | 8.4 | E | 3,400 | 18 | |
| Milton Seaman | 5,008 | 541.0 | E | 37,500 | 33 | |
| N. Poudre #5 | 8,050 | 8.4 | E | 10,600 | 33 | * |
| Windsor | 17,538 | 5.6 | E | 4,940 | 33 | |
| Beaver Creek | 2,161 | 7.4 | E | 2,800 | 24 | |
| Button Rock | 16,080 | 103.0 | E | 29,000 | 30 | |
| Barker Meadow | 11,500 | 36.2 | CG | 6,719 | 30 | |
| Boulder Res. | 13,300 | 12.9 | E | 6,700 | 33 | |
| Gross Lake | 41,811 | 92.8 | CG | 15,680 | 33 | |
| Silver Lake | 3,987 | 8.7 | E | 7,160 | 21 | |
| Beaver Brook #2 | 30 | 6.4 | R | 313 | 27 | |
| Blunn | 5,800 | 48.0 | E | 60,000 | 33 | * |
| Clear Creek/Lake | 700 | 15.0 | R | 320 | 24 | |
| Leyden | 1,152 | 8.5 | E | 2,080 | 36 | |
| Lower Cabin Creek | 1,905 | 14.0 | R | 2,778 | 24 | |
| Maple Grove | 655 | 10.9 | E | 13,365 | 35 | |
| Ralston | 11,272 | 46.0 | E | 37,500 | 35 | |
| Chatfield | 235,000 | 1,455.5 | E | 262,000 | 34 | |
| Cherry Creek | 79,960 | 386.0 | E | 52,000 | 34 | |
| Englewood/ Little Dry Creek | 1,850 | 9.0 | E | 32,000 | 34 | * |
| Bear Creek | 55,290 | 236.0 | E | 223,700 | 35 | |
| Evergreen | 669 | 101.0 | CG | 12,000 | 33 | |
| Antero | 85,564 | 185.0 | E | 27,400 | 18 | |
| Eleven Mile | 97,800 | 963.0 | CA | 2,140 | 21 | |
| Montgomery | 5,088 | 8.5 | R | 7,223 | 18 | |
| Spinney Mtn. | 53,873 | 772.0 | E | 135,740 | 18 | * |
| Tarryall | 2,617 | 355.2 | CG | 15,000 | 18 | * |
| N. Sterling | 74,010 | 370.4 | E | 8,000 | 30 | * |
| Cheeseman | 79,064 | 187.5 | MA | 22,368 | 21 | |

Table 14 continued.

| Reservoir/Dam Name | Reservoir Capacity,a-f | Drainage Area,$mi^2$ | Type | Spillway Capacity,cfs | PMP inches | |
|---|---|---|---|---|---|---|
| ARKANSAS DIVISION | | | | | | |
| North Catamount | 12,300 | 6.5 | E | 5,854 | 27 | |
| Palmer Lake/ #2 Glen Park | 147 | 11.6 | CA | 500 | 34 | |
| Rampart/ Northfield #5 | 38,783 | 5.6 | E | 11,145 | 33 | |
| South Catamount | 2,604 | 6.0 | E | 3,670 | 30 | |
| Clear Creek/ Otero Res. | 11,500 | 69.0 | E | 5,380 | 18 | * |
| Sugarloaf | 129,432 | 26.0 | E | 2,920 | 16 | |
| Twin Lakes | 141,000 | 50.0 | E | 1,400 | 18 | ** |
| Peublo Res. | 357,000 | 1,545.0 | E | 191,500 | 34 | |
| St. Charles #3 | 8,638 | 22.4 | E | 30,726 | 33 | |
| Cucharas | 40,960 | 660.0 | R | 44,000 | 32 | |
| Adobe C./ Blue Lakes | 71,000 | 53.3 | E | 72,000 | 31 | * |
| Trinidad Res. | 119,877 | 671.0 | E | 55,400 | 32 | * |
| Limon Watershed | 1,200 | 8.2 | E | 11,317 | 31 | * |
| RIO GRANDE DIVISION | | | | | | |
| Beaver Park | 4,758 | 47.0 | E | 5,900 | 18 | |
| Big Meadows | 2,436 | 17.2 | E | 3,333 | 24 | |
| Continental | 22,679 | 50.9 | E | 5,950 | 18 | |
| Humphrey/ Goose Creek | 842 | 53.0 | CA | 3,225 | 18 | |
| Terrace/ Alamosa River | 15,182 | 108.8 | E | 10,900 | 18 | |
| Platora | 59,571 | 40.0 | E | 6,900 | 24 | |
| Sanchez | 103,114 | 86.9 | E | 24,500 | 21 | |
| Mountain Home | 17,374 | 71.5 | E | 15,000 | 18 | |

* Dams with two or more spillways

** Dams with extremely large reservoir capacity in comparison to spillway capacity

Dam classifications:
E = Earthfill
R = Rockfill
CG = Concrete Gravity
CA = Concrete Arch
M = Masonry

## APPENDIX B

## RELATING SPILLWAY CAPACITY TO POTENTIAL WATER VOLUME FOR THE 63 HIGH RISK DAMS

In chapter 3, reservoir capacity at time of flood, drainage area, and the PMP, were identified as functions of spillway capacity at a time of a flood. This relationship was first analyzed for the five dams which had been previously estimated, then for the 33 earthfilled dams and finally for all 63 dams. Although the correlations became poorer with the larger groups, they were thought to be applicable in estimating a total cost for dam modification. Table 15 shows the spillway capacity as well as the numbers which were calculated for potential water volume.

For the 63 high risk dam estimates, see Figure 7.

$S = a + b(V)$,
a = y-intercept = 11,162,
b = slope = 0.140,
bivariate linear regression analysis,
r = .733.

For earthfilled dams with Drainage Areas 5 to 25 square miles, see Figure 14 for the scatter diagram of spillway capacity versus potential water volume.

a = -3338,
b = 1.46,
bivariate linear regression analysis,
r = 0.77.

For earthfilled dams with Drainage Areas 25 to 250 square miles, see Figure 15 for the scatter diagram of spillway capacity versus potential water volume.

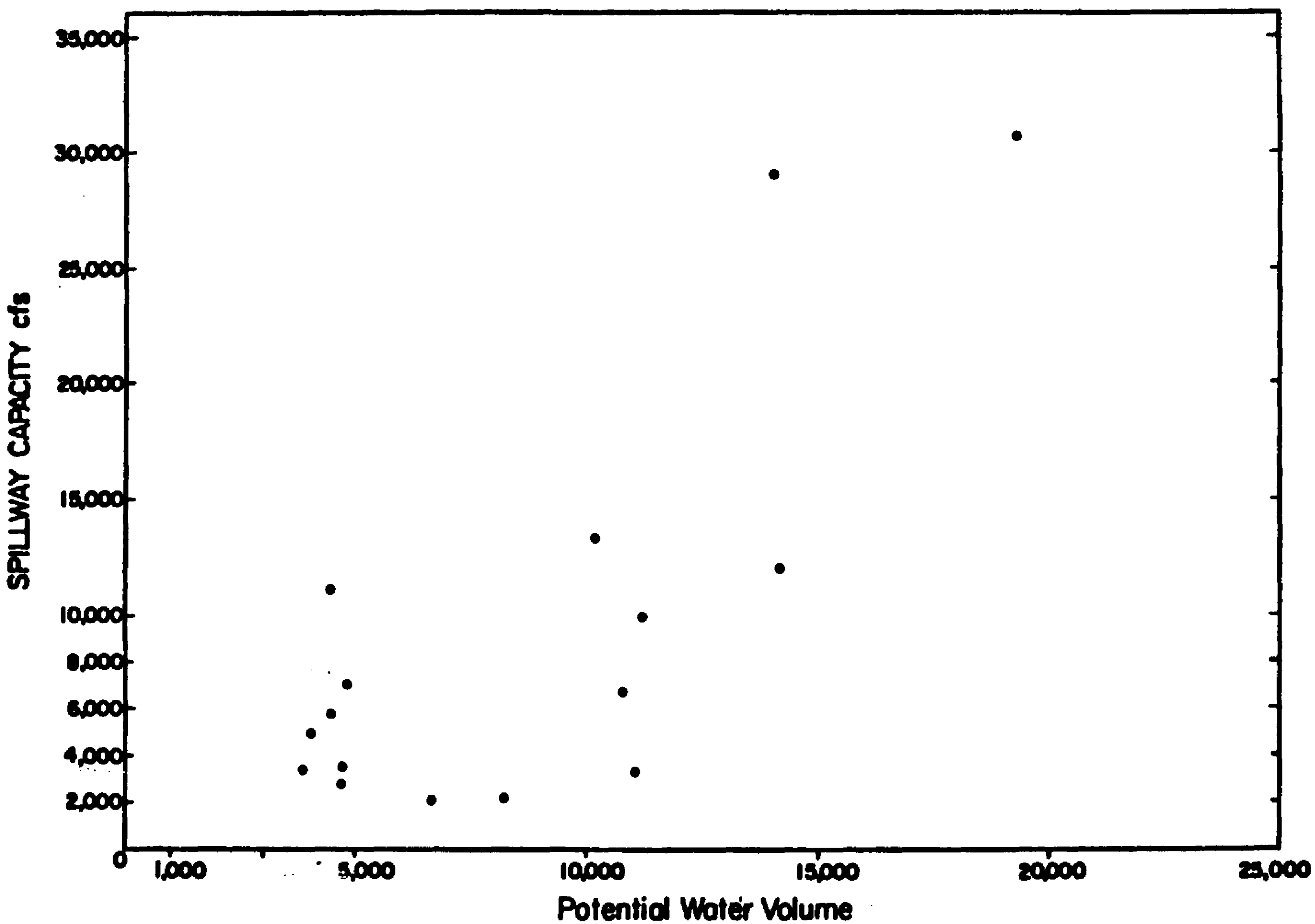


Figure 14. Spillway capacity vs. potential water volume for homogeneous high risk dams with drainage areas 5-25 mi$^2$.

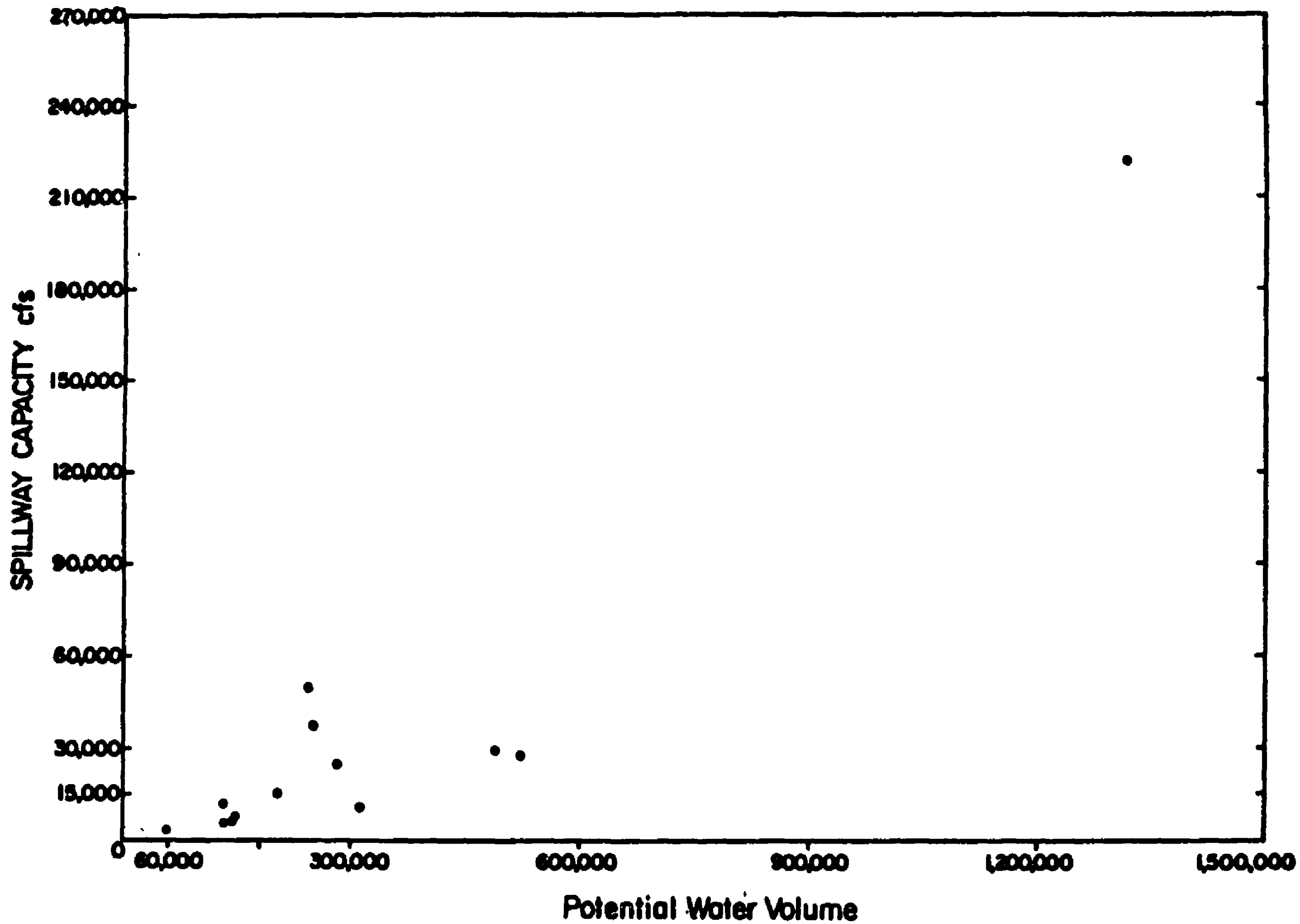


Figure 15. Spillway capacity vs. potential water volume for homogeneous high risk dams with drainage areas 25-250 mi$^2$.

a = −19,304,
b = 0.98,
bivariate linear regression analysis,
r = 0.93.

For earthfilled dams with Drainage Areas greater than 250 square miles, see Figure 16 for the scatter diagram of spillway capacity versus potential water volume.

a = −29,433,
b = 0.19,
bivariate linear regression analysis,
r = 0.94.

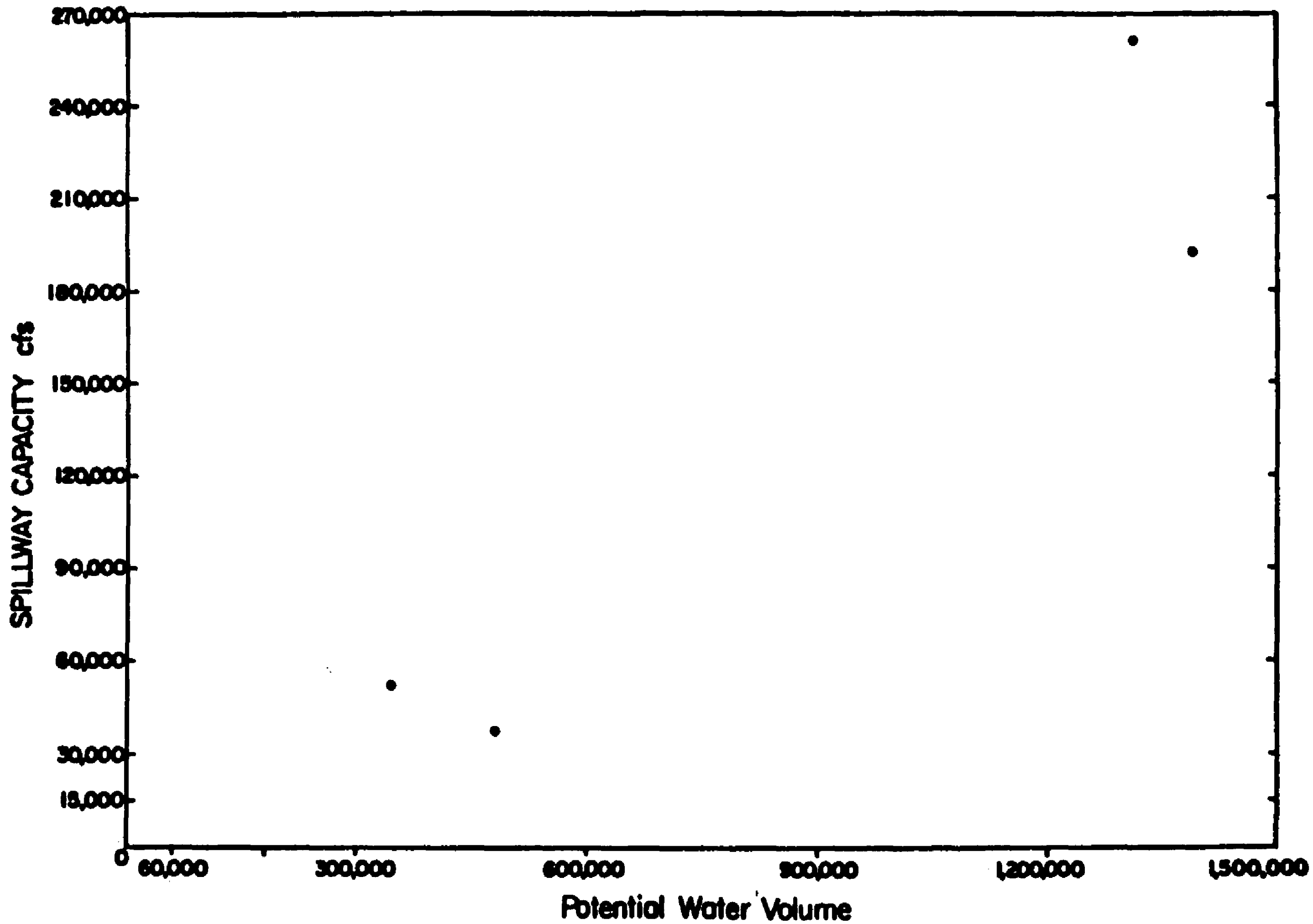


Figure 16. Spillway capacity vs. potential water volume for homogeneous high risk dams with drainage areas greater than 250 $mi^2$.

Table 15. Spillway Capacity and Potential Water Volume

| Reservoir/Dam Name | Spillway Capacity,cfs | Potential Water Volume,cfs | |
|---|---|---|---|
| SOUTH PLATTE DIVISION | | | |
| Horse Creek | 11,400 | 22,651 | |
| Jackson Lake | 10,000 | 11,189 | |
| Williams/ McCreery | 49,900 | 40,816 | |
| Barr Lake | 1,911 | 11,300 | * |
| Milton Lake | 17,350 | 100,002 | * |
| Standley Lake | 12,000 | 14,168 | |
| Black Hollow | 6,810 | 18,603 | * |
| Cache la Poudre/ Tinmath Res. | 34,441 | 17,731 | * |
| Commanche Lake | 2,080 | 6,645 | |
| Douglas | 2,175 | 39,109 | * |
| Fossil Creek | 88,100 | 25,499 | * |
| Indian Creek/ Cowan Lake | 29,100 | 14,005 | |
| Joe Wright/ Cameron Pass | 3,875 | 2,614 | * |
| Long Draw | 3,400 | 3,876 | |
| Milton Seaman | 37,500 | 479,895 | |
| N. Poudre #5 | 10,600 | 6,972 | * |
| Windsor | 4,940 | 4,094 | |
| Beaver Creek | 2,800 | 4,696 | |
| Button Rock | 29,000 | 82,852 | |
| Barker Meadow | 6,719 | 29,012 | * |
| Boulder Res. | 6,700 | 10,735 | |
| Gross Lake | 15,680 | 81,915 | * |
| Silver Lake | 7,160 | 4,844 | |
| Beaver Brook #2 | 313 | 4,645 | * |
| Blunn | 60,000 | 42,407 | * |
| Clear Creek/Lake | 320 | 9,657 | * |
| Leyden | 2,080 | 8,149 | |
| Lower Cabin Creek | 2,778 | 8,989 | * |
| Maple Grove | 13,365 | 10,151 | |
| Ralston | 37,500 | 42,868 | |
| Chatfield | 262,000 | 1,309,967 | |
| Cherry Creek | 52,000 | 345,954 | |
| Englewood/ Little Dry Creek | 32,000 | 7,999 | * |
| Bear Creek | 223,700 | 219,758 | |
| Evergreen | 12,000 | 89,579 | * |
| Antero | 27,400 | 87,271 | |
| Eleven Mile | 2,140 | 541,458 | * |
| Montgomery | 7,223 | 4,060 | * |
| Spinney Mtn. | 135,740 | 372,258 | * |
| Tarryall | 15,000 | 171,823 | * |
| N. Sterling | 8,000 | 296,053 | * |
| Cheeseman | 22,368 | 105,296 | * |

Table 15 continued.

| Reservoir/Dam Name | Spillway Capacity,cfs | Potential Water Volume,cfs | |
|---|---|---|---|
| ARKANSAS DIVISION | | | |
| North Catamount | 5,854 | 4,490 | |
| Palmer Lake/ #2 Glen Park | 500 | 10,321 | * |
| Rampart/ Northfield #5 | 11,145 | 4,439 | |
| South Catamount | 3,670 | 4,728 | |
| Clear Creek/ Otero Res. | 5,380 | 33,155 | * |
| Sugarloaf | 2,920 | 10,027 | |
| Twin Lakes | 1,400 | 22,609 | * |
| Peublo Res. | 191,500 | 1 390,937 | |
| St. Charles #3 | 30,726 | 19,218 | |
| Cucharas | 44,000 | 563,049 | * |
| Adobe C./ Blue Lakes | 72,000 | 40,697 | * |
| Trinidad Res. | 55,400 | 582,515 | * |
| Limon Watershed | 11,317 | 6,738 | * |
| RIO GRANDE DIVISION | | | |
| Beaver Park | 5,900 | 22,694 | |
| Big Meadows | 3,333 | 11,012 | |
| Continental | 5,950 | 24,219 | |
| Humphrey/ Goose Creek | 3,225 | 25,627 | * |
| Terrace/ Alamosa River | 10,900 | 52,489 | |
| Platora | 6,900 | 25,097 | |
| Sanchez | 24,500 | 46,988 | |
| Mountain Home | 15,000 | 34,256 | |

* 30 Dams that are not earthfilled; more than one splillway; or have excessive reservoir capacities

## APPENDIX C

## COST ESTIMATES FOR THE 63 HIGH RISK DAMS

Once the relationship between spillway capacity and potential water volume was determined the next step, as described in chapter 3, was to see what kind of relationship potential water volume had to cost of modification. The relationship was calculated to have a correlation of 0.99. Knowing this, potential water volume values of each dam were substituted into equation (9). The total cost for the 33 earthfilled high risk dams was $66.73 million and the cost for all 63 high risk dams was found to be $124.56 million (see Table 16 for individual dam modification cost estimates).

Table 16. Estimated costs for 63 high risk dams

| Reservoir/Dam Name | Potential Water Volume,cfs | Estimated Cost, $ mil. | |
|---|---|---|---|
| SOUTH PLATTE DIVISION | | | |
| Horse Creek | 22,651 | 1.32 | |
| Jackson Lake | 11,189 | 1.25 | |
| Williams/ McCreery | 40,816 | 1.44 | |
| Barr Lake | 11,300 | 1.25 | * |
| Milton Lake | 100,002 | 1.84 | * |
| Standley Lake | 14,168 | 1.27 | |
| Black Hollow | 18,603 | 1.30 | * |
| Cache la Poudre/ Tinmath Res. | 17,731 | 1.29 | * |
| Commanche Lake | 6,645 | 1.20 | |
| Douglas | 39,109 | 1.43 | * |
| Fossil Creek | 25,499 | 1.34 | * |
| Indian Creek/ Cowan Lake | 14,005 | 1.26 | |
| Joe Wright/ Cameron Pass | 2,614 | 1.19 | * |
| Long Draw | 3,876 | 1.20 | |
| Milton Seaman | 479,895 | 4.36 | |
| N. Poudre #5 | 6,972 | 1.22 | * |
| Windsor | 4,094 | 1.20 | |
| Beaver Creek | 4,696 | 0.60 | |
| Button Rock | 82,852 | 1.72 | |
| Barker Meadow | 29,012 | 1.36 | * |
| Boulder Res. | 10,735 | 1.30 | |
| Gross Lake | 81,915 | 1.72 | * |
| Silver Lake | 4,844 | 1.20 | |
| Beaver Brook #2 | 4,645 | 1.20 | * |
| Blunn | 42,407 | 1.45 | * |
| Clear Creek/Lake | 9,657 | 1.24 | * |
| Leyden | 8,149 | 1.23 | |
| Lower Cabin Creek | 8,989 | 1.23 | * |
| Maple Grove | 10,151 | 1.24 | |
| Ralston | 42,868 | 1.46 | |
| Chatfield | 1,309,967 | 9.86 | |
| Cherry Creek | 345,954 | 3.47 | |
| Englewood/ Little Dry Creek | 7,999 | 1.22 | * |
| Bear Creek | 219,758 | 2.63 | |
| Evergreen | 89,579 | 1.77 | * |
| Antero | 87,271 | 1.75 | |
| Eleven Mile | 541,458 | 4.76 | * |
| Montgomery | 4,060 | 1.20 | * |
| Spinney Mtn. | 372,258 | 3.64 | * |
| Tarryall | 171,823 | 2.31 | * |
| N. Sterling | 296,053 | 3.14 | * |
| Cheeseman | 105,296 | 1.87 | * |

Table 16 continued.

| Reservoir/Dam Name | Potential Water Volume,cfs | Estimated Cost, $ mil. | |
|---|---|---|---|
| ARKANSAS DIVISION | | | |
| North Catamount | 4,490 | 1.20 | |
| Palmer Lake/ #2 Glen Park | 10,321 | 1.24 | * |
| Rampart/ Northfield #5 | 4,439 | 1.20 | |
| South Catamount | 4,728 | 1.20 | |
| Clear Creek/ Otero Res. | 33,155 | 1.39 | * |
| Sugarloaf | 10,027 | 1.24 | |
| Twin Lakes | 22,609 | 1.32 | * |
| Peublo Res. | 1,390,937 | 10.00 | |
| St. Charles #3 | 19,218 | 1.30 | |
| Cucharas | 563,049 | 4.91 | * |
| Adobe C./ Blue Lakes | 40,697 | 1.44 | * |
| Trinidad Res. | 582,515 | 6.00 | * |
| Limon Watershed | 6,738 | 1.22 | * |
| RIO GRANDE DIVISION | | | |
| Beaver Park | 22,694 | 1.32 | |
| Big Meadows | 11,012 | 1.24 | |
| Continental | 24,219 | 1.33 | |
| Humphrey/ Goose Creek | 25,627 | 1.34 | * |
| Terrace/ Alamosa River | 52,489 | 1.52 | |
| Platora | 25,097 | 1.34 | |
| Sanchez | 46,988 | 1.48 | |
| Mountain Home | 34,256 | 1.40 | |

* 30 Dams that are not earthfilled; more than one spillway; or have excessive reservoir capacities

## APPENDIX D

### GEOMORPHIC AND STRATIGRAPHIC RESEARCH OF COLORADO FOOTHILL STREAMBEDS

Conventional methods poorly defined peak floods for foothill streambeds beyond 100 years, (Costa, 1978) and (Jarrett and Costa, 1982). These scientists suggested that paleohydraulic reconstruction of streambeds might provide a more accurate history of streambeds which could perhaps define return flood intervals.

This method was considered in the Big Thompson flood of 1976. At the time of the flood, many scientists felt that it was a once in a hundred year flood. However, with radiocarbon dating of landforms and deposits it was discovered that the Big Thompson flood event would have a recurrence interval greater than 5,000 years. This fact can be detected in Figure 17a and Figure 17b from Jarrett and Costa (1982).

Further research by Jarrett and Costa (1986) into the entire basin of the South Platte River suggests that a few floods in the foothills above 5000 feet have had a magnitude near that of the Big Thompson flood. Using only the Big Thompson flood, the regional probability of an event of this magnitude occurring anywhere in the Colorado foothills is 1.96 percent. However, most of the studies done by Jarrett and Costa (1982) for the various streambeds in the foothills show a return period in each basin of 5000 to 10,000 years. If one were to use a conservative estimate that half the streambeds had return intervals like that of the Big Thompson then the regional probability of another Big Thompson flood increases.

Figure 17a. Regional flood-frequency curve computed for ungaged cross section on Big Thompson River at alluvial fan shown in Figure 18b. Curve developed from multiple regression techniques of McCain and Jarrett (1976). Relation was extended to the estimated flood peak at this location (28,200 cubic feet per second). (From Jarrett and Costa, 1982.)

Figure 17b. Schematic stratigraphy and radiocarbon dates for truncated alluvial fan at Waltonia, Colorado. Fan is located just below area of maximum runoff. Peak discharge at this location is estimated to be 28,200 cubic feet per second. Radiocarbon dates from the Radiocarbon Laboratory, University of Texas, Austin, Texas. (From Jarrett and Costa, 1982).

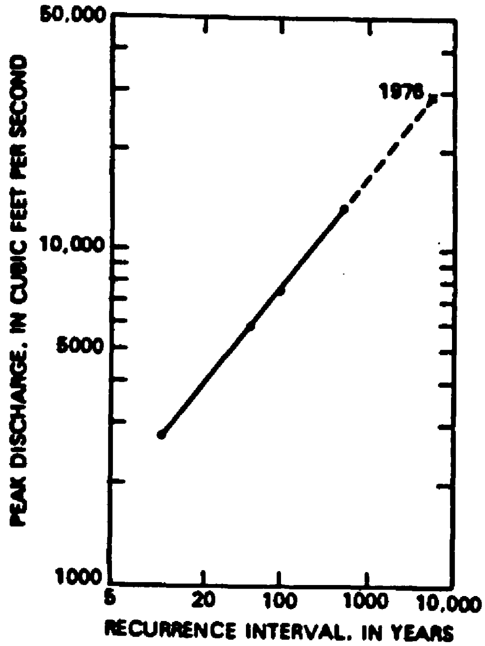


Figure 17a.

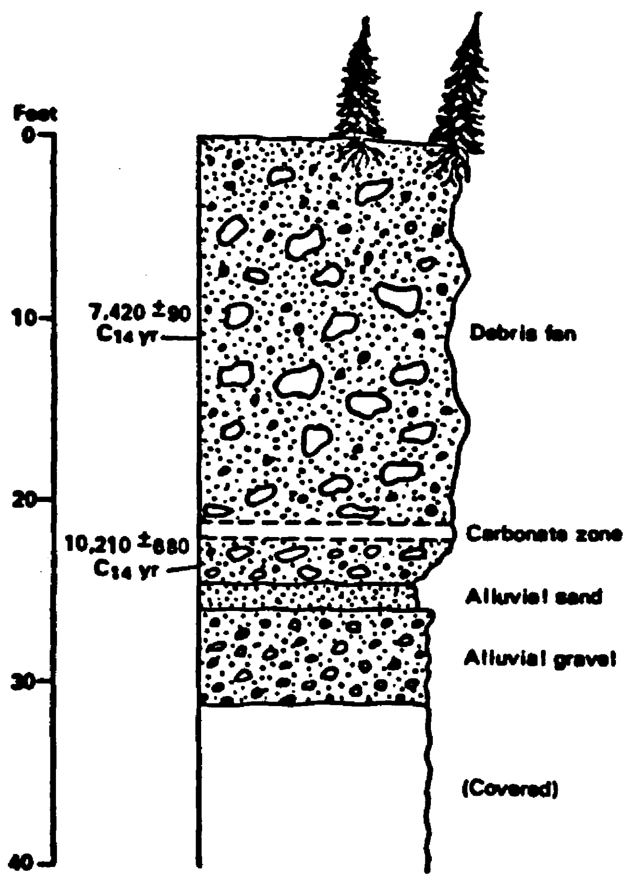


Figure 17b.