US Army Corps of Engineers ®
Omaha District

CHATFIELD DAM & LAKE
DENVER, COLORADO

ANTECEDENT FLOOD STUDY
FINAL REPORT

TRI-LAKES REALLOCATION FEASIBILITY STUDY
DECEMBER 2005

Chatfield Antecedent Flood Study

December 2005

INTRODUCTION

The purpose of this study was to evaluate the criteria for the antecedent flood to be used in the Inflow Design Flood (IDF) routing for Chatfield Reservoir near Denver, Colorado. As documented in ER1110-8-2 (FR), Corps of Engineers regulations for routing the Inflow Design Flood requires consideration of an antecedent flood of a magnitude of 50 percent of the IDF assumed to occur 5 days prior to the occurrence of the IDF. For Chatfield Dam, which is considered a high hazard dam, the IDF is based on the Probable Maximum Precipitation occurring over the upstream watershed. Specifically, this study evaluated the 50 percent criteria to see if it was appropriate or if some other value would be more appropriate for use in the Chatfield IDF routings. Statistical analysis of streamflow and meteorological data were used to evaluate the appropriate criteria for the antecedent flood.

This study was conducted by Hydrologic Engineering Branch of the Omaha District, US Army Corps of Engineers and was cost shared with the Colorado Water Conservation Board as part of the Tri-Lakes Reallocation Feasibility Study. Results of this study were reviewed by the Corps Hydrology Committee in July 2005. An Independent Technical Review (ITR) of this study was performed by the US Bureau of Reclamation in November 2005. Comments and responses from the ITR are contained in the Appendix to this report.

BACKGROUND INFORMATION

Chatfield Dam is located on the South Platte River at the southern edge of Denver, Colorado immediately downstream from the Plum Creek confluence. Chatfield Dam and Lake and downstream channel improvements were authorized by the Flood Control Act of 1950, substantially in accordance with the recommendation of the Chief of Engineers in House Document No. 669, 80^{th} Congress, 2^{nd} Session. The authorized purposes of the project were flood control and recreation.

The Chatfield Dam and Lake Project was funded for construction following the historic flood of record which occurred in June 1965. The Omaha District recommended and received approval to construct that portion of the authorized project between Chatfield Dam and Denver as a part of the Chatfield Project. The State of Colorado provided assurances of local cooperation required the authorizing legislation for that portion of the project downstream of the dam.

The proposed downstream portion of the project included flood and erosion protection between the Federal acquisition line for the Chatfield Dam and the south edge of Denver (Hampden Avenue). A plan for the channel capacity improvement was approved in May 1968. That plan provided protection for flows having a 1 percent chance of annual exceedence with a minimum channel sized to carry the maximum operational release from Chatfield Lake.

Chatfield Dam is a rolled earth fill structure, which has a crest length of 13,136 feet at elevation 5527 feet mean sea level (msl). Part of the upstream face is protected by riprap to prevent erosion from wave action. The downstream face and upper portion of the upstream face are grassed with adapted native species to prevent erosion from wind and precipitation.

A concrete lined ungated chute spillway was constructed in the left abutment of the dam. It has an ogee crest with a length is 500 feet at elevation 5500 feet msl. From the crest, the spillway transitions into a rectangular chute with a bottom width 390 feet. At maximum pool elevation of 5521.6, the design capacity of the spillway is 188,000 cfs.

The outlet works consists of an intake tower with two gated 11 x 16 feet oval conduits with a length of 1,280 feet. Design discharge capacity of the outlet works is 8,400 cfs with the pool at top of the flood control pool (elevation 5500 feet msl) and 5,350 cfs with the pool at elevation at the bottom of the flood control pool (elevation 5432 feet msl).

Table 1
Chatfield Pool Elevations and Capacities

Pool	Original Design (1972 Survey)		Current (1998 Survey)	
	Elevation (ft msl)	Capacity (acre-feet)	Elevation (ft msl)	Capacity (acre-feet)
Maximum	5521.6	354,900	5521.6	351,400
Flood Control	5500	235,000	5500	234,200
Multi-Purpose	5430	23,800	5432	27,400
Sediment	5426	18,900	5426	19,600

Note: Multi-Purpose pool raised in 1979

Originally, in the feasibility study published in 1965, the planning of the Chatfield Dam and Lake Project did not provide for water supply storage and included a multi-purpose storage pool at elevation 5426 to accommodate 100-year sediment inflow of about 20,000 acre-feet. In 1967, the State of Colorado requested permission to store water up to elevation 5,430 feet msl. The request was granted and the State of Colorado agreed to furnish necessary water to fill the minimum pool and to replace annual evaporation losses.

In 1979, as part of litigation settlement between the Denver Water Board and Department of the Interior, regarding the permits for construction of the Strontia Springs Dam and Foothills Treatment plant (referred to as the Foothills Agreement), The Denver Water Board was granted 10,785 acre-feet of storage in Chatfield Reservoir. This amount of storage (between elevations 5423 and 5432) was provided to allow Denver to recover a portion of instream flows released from Strontia Springs Dam for stream and fishery habitat purposes which were mandated as part of the Foothills Agreement.

In March 1979, following the Foothills Agreement, the Corps of Engineers entered into a new contract with the State of Colorado, that raised the Multi-purpose pool to elevation 5432 feet msl. It also specified that the State of Colorado would provide the water to fill the pool to elevation 5432 and thereafter maintain the pool elevation between elevation 5423 and 5432 feet msl except during extreme periods of protracted drought when the pool would be allowed to fall below elevation 5423 feet msl. The existing storage zones at Chatfield Reservoir are illustrated on Figure 1.

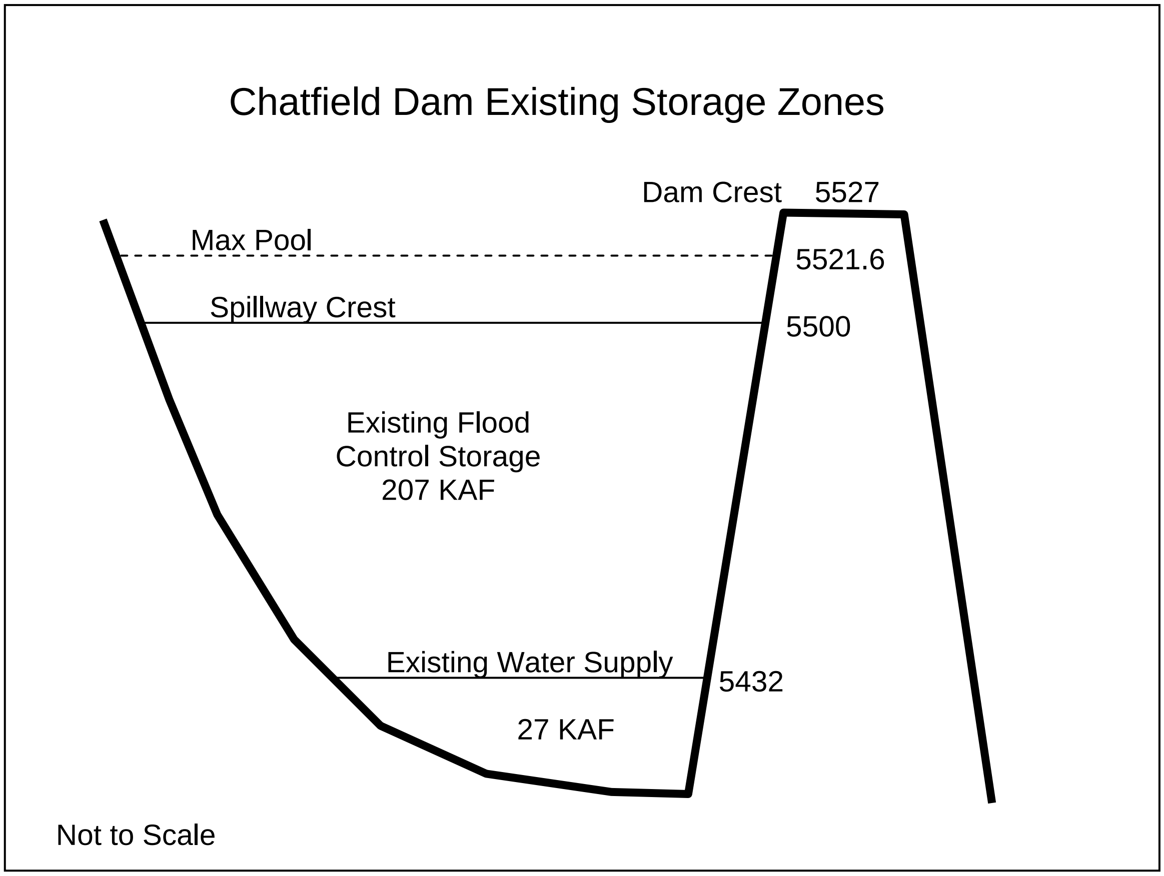

Figure 1 Chatfield Dam Existing Storage Zones

Because of growing demands for municipal water supplies in the Denver Metro area, in 1997, the Colorado Water Conservation Board requested the Corps undertake a study of Chatfield Reservoir to reallocate a portion of the flood control storage for municipal water supply. After several scoping meetings with State and Local officials, the Tri-Lakes feasibility study was initiated in 1998 to evaluate the impacts of reallocating up to 20,600 acre-feet of flood control storage for water supply purposes. Reallocating 20,600 acre-feet of flood control storage to water supply would raise the existing multi-purpose pool at Chatfield by 12 feet, from elevation 5432 feet msl to 5444 feet msl and decrease total flood control storage by about 10 percent. Reallocating 20,600 acre-feet of storage to water supply would result in the storage allocation zones as shown on Figure 2.

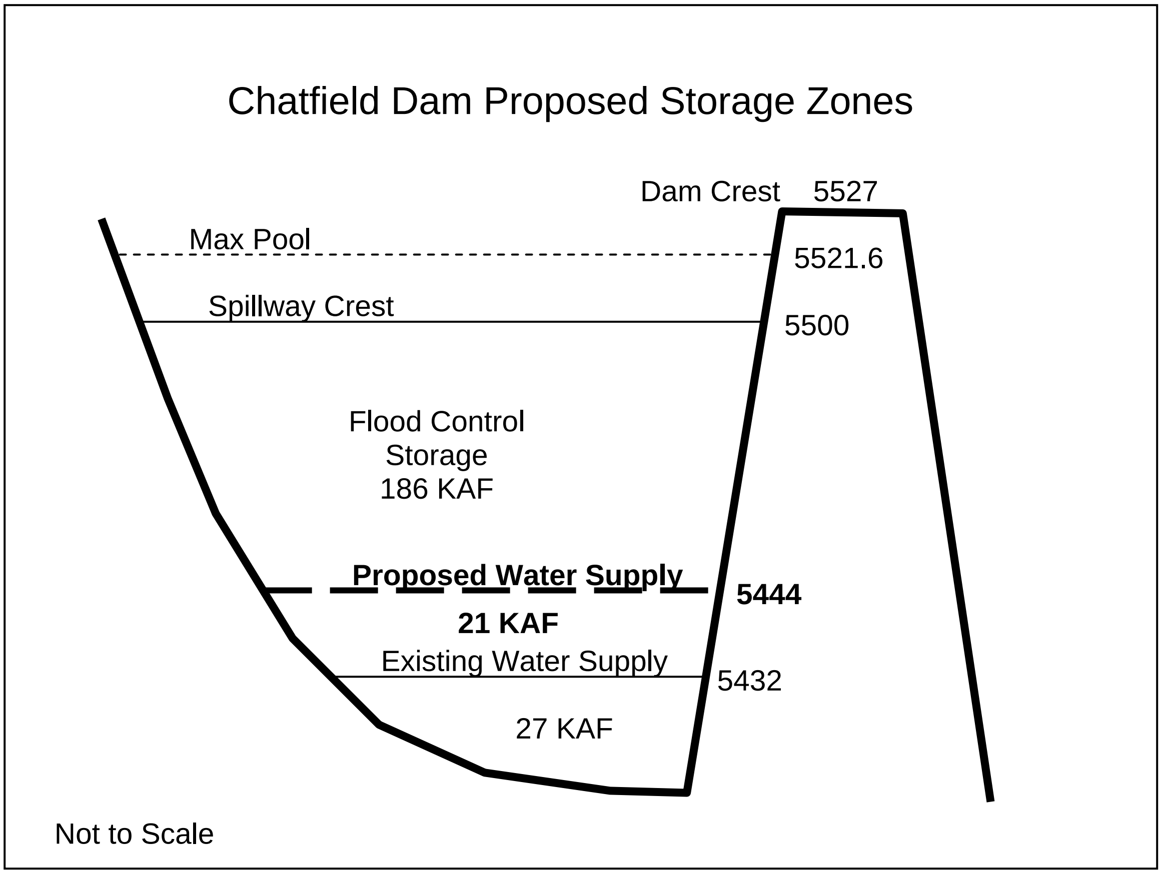

Figure 2 Chatfield Dam Proposed Storage Zones

As part of the Tri-Lakes Reallocation Study, the impacts of raising the multiple purpose pool on Dam Safety was evaluated. Corps of Engineers regulations require Chatfield Dam to safely pass the Inflow Design Flood (IDF) as specified in ER 1110-8-2 (FR) "Inflow Design Floods for Dams and Reservoirs" dated 1 March 1991. According to ER 1110-8-2, the IDF for Chatfield Dam is based on Probable Maximum Precipitation (PMP) occurring over the upstream watershed. The PMP for Chatfield Dam is based on a site specific study completed by the National Weather Service and published in 1969 as HMR44. Application of the PMP results in a Probable Maximum Flood (PMF) for Chatfield with a peak discharge of 548,000 cfs and a volume of 317,000 acre-feet. ER 1110-8-2 (FR), paragraph 8f also requires that an antecedent flood be assumed to occur 5 days prior to the PMF. Paragraph 8f of ER 1110-8-2 (FR) is as follows:

> "An antecedent flood will be assumed to occur prior to the IDF and will be developed using sound hydrologic engineering principles. Reallocations of flood control storage to some other use in the future that may result in higher pool levels at the beginning of the IDF should be considered. Experience has demonstrated that an unusual sequence of floods can result in filling all or a major portion of the flood control storage in a reservoir immediately before the

> beginning of the IDF. In view of the uncertainties involved in estimating reservoir levels that might reasonably be expected to prevail at the beginning of the IDF, the minimum starting elevation for routing the IDF will be assumed as the full flood control pool level or the elevation prevailing five days after the last significant rainfall of a storm that produces one-half the IDF, whichever is most appropriate. If the IDF estimate is associated with a particular season, the determination of initial pool level will consider flood conditions during comparable times of the year. A comparison of surcharge elevations computed under alternative starting elevation assumptions is required to the sensitivity of the maximum pool to the starting elevation."

In the absence of better data, the antecedent flood is assumed to result from a storm that produces 50 percent of the PMF hydrograph. When applying the criteria in ER 1110-8-2 to Chatfield the Antecedent Pool elevation resulting from routing 50 percent of the PMF hydrograph is 5476 feet msl. This assumes maximum releases of 5,000 cfs during the five day draw down period. The starting pool for routing the Antecedent flood is the bottom of flood control pool or top of multi-purpose pool, elevation 5432 feet msl. If the multi-purpose pool is raised to elevation 5444 feet msl, the resulting antecedent pool increases to elevation 5481.7 feet msl as shown on Figure 3.

For the IDF routing, the antecedent pool is used as the starting pool elevation for routing the PMF hydrograph. Based on this analysis the maximum pool elevation reached during the IDF routing would increase by 2 feet, from elevation 5521.6 feet msl to 5523.6 feet msl. Since Chatfield Dam requires 5 feet of freeboard above the Maximum Pool elevation, the freeboard requirement would no longer be met if the multi-purpose pool is raised to elevation 5444 feet msl for water supply purposes as there would only be 3.4 feet of freeboard based on the criteria in ER 1110-8-2. Results of this analysis are illustrated on Figure 3.

A preliminary evaluation of alternatives to mitigate the loss of freeboard included increasing spillway capacity and raising the dam. Results of these analyses indicated that the spillway would have to be widened by 100 feet to increase capacity and provide 5 feet of freeboard. The cost to widen the spillway by 100 feet is estimated to be about $18 million. Another alternative was evaluated to raise the dam crest by constructing a 3-feet high parapet wall along the existing dam crest to increase the freeboard. The cost to construct the parapet wall was estimated to exceed $2 million. Because of the high cost required for structural modifications to mitigate 2 feet of freeboard, it was decided to do a detailed study of antecedent flood conditions to determine if the assumption of using 50 percent of the PMF was appropriate.

In order to evaluate the antecedent flood criteria, analyses were made of historic precipitation records along the Front Range and historic streamflows above Chatfield. These studies are described in the following sections.

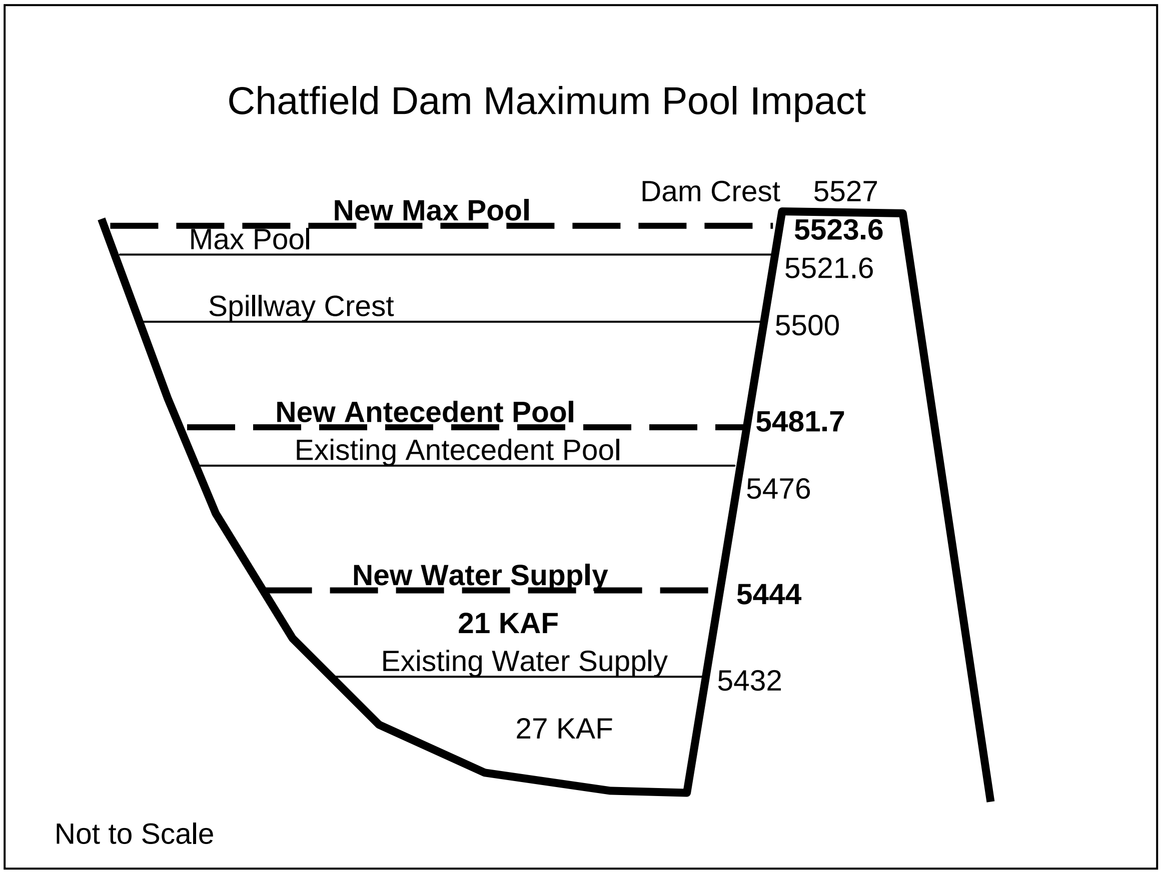

Figure 3 Chatfield Dam Maximum Pool Impact

PRECIPITATION

Historical precipitation data from 114 National Weather Service (NWS) gages located along the Front Range were used to evaluate antecedent precipitation. Locations of the precipitation gages used are shown on Figure 4. An analysis was made to evaluate amount of precipitation occurring 5 and 10 consecutive days prior to all precipitation events exceeding 1 inch in 24 hours for all NWS stations. Next, the ratios of total antecedent precipitation to main event precipitation were computed. Graphs were prepared to plot the ratios against the main event values. In addition to the data recorded at NWS stations, precipitation records from 18 extreme storms that have occurred along the Front Range listed in Table 2 were obtained from the Colorado Extreme Storms database and were added to graphs. Antecedent precipitation for the extreme storms was based on NWS gages in proximity to the center of storm as listed in Table 2. Results of this analysis indicated that the 10 day antecedent ratios were slightly larger than the 5 day values. Therefore, the results of the 10-day antecedent values were adopted for use in this study. As shown on figure 5, there is a definite trend for ratios to decrease as the precipitation amounts increase. An envelope curve was used to define the upper limit of antecedent ratios for each main event precipitation amount. Based on the envelope curve, the maximum 10-day antecedent precipitation ratio for a 24 hour PMP event of 17 inches would be 0.3 or 30 percent. The 24-hour

PMP value of 17 inches was the largest amount that would occur over the watershed upstream from Chatfield based on the pattern ‘B’ PMP storm developed in HMR44.

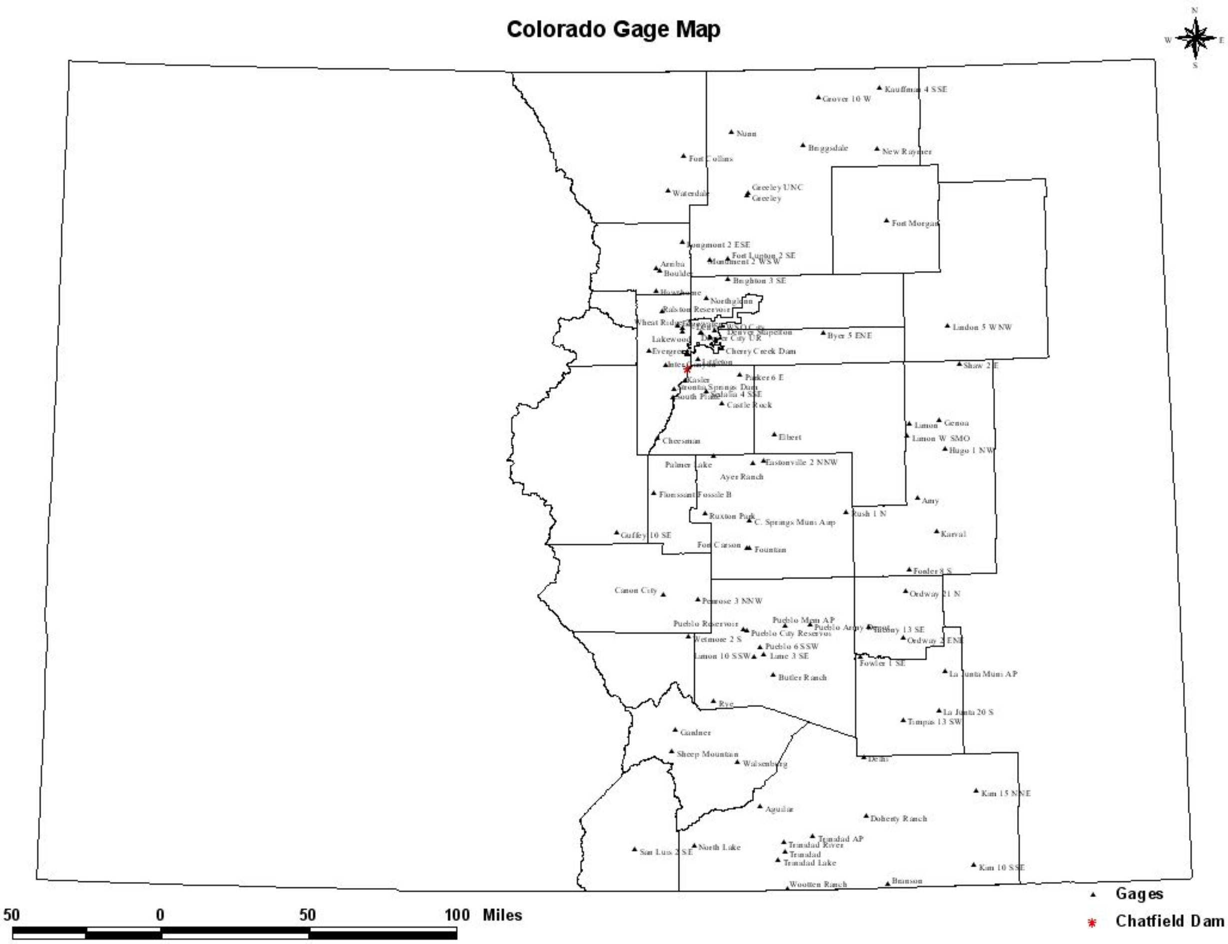

Figure 4 Location Map of NWS Precipitation Gages

Table 2
Historic Storms from Colorado Extreme Storms Database

Date	Storm Location	Antecedent Precipitation Gage	Precip (in)	Antecedent 5 Day		Antecedent 10 Day	
				(in)	Ratio	(in)	Ratio
May 20, 1908	Boulder CO	Boulder	8	0	0.000	0.12	0.015
Jun 31, 1921	Penrose (Pueblo) CO	Pueblo	15	1.94	0.129	1.94	0.129
Sep 27, 1923	Savageton WY	Gillette	17	0.92	0.054	1.28	0.075
May 30, 1935	Cherry Creek CO	Denver	24	1.27	0.053	1.66	0.069
May 30, 1935	Hale CO	Cope	24	0.55	0.023	1.04	0.043
Sep 1, 1938	Masonvile CO	Estes Park	10	1.04	0.104	2.02	0.202
May 18, 1955	Rye CO	Rye	13	0	0.000	1.12	0.086
Jun 6, 1964	Gibson Dam MT	Gibson Dam	16	0	0.000	3.29	0.206
Jun 16, 1965	Plum Creek CO	Parker 9 E	14	0.68	0.049	0.68	0.049
Jun 17, 1965	Falcon CO	Colorado Springs	16	3.15	0.197	4.89	0.306
Jun 17, 1965	Holly CO	Holly	15.2	1.05	0.069	1.44	0.095
May 4, 1969	Big Elk Meadow CO	Boulder	16	0.07	0.004	0.07	0.004
Jun 9, 1972	Rapid City SD	Rapid City	12	0.16	0.013	0.34	0.029
Jul 31, 1976	Big Thompson CO	Estes Park	14.5	0.95	0.066	2.00	0.138
Jul 3, 1981	Frijole Creek CO	Trinidad FAA AP	14	0.25	0.018	1.52	0.109
Aug 1, 1985	Cheyenne WY	Cheyenne Wsfo	8	0	0.000	0.02	0.003
Jul 27, 1997	Ft. Collins CO	Fort Collins 4 E	14.5	0.09	0.006	0.12	0.008
Jul 28, 1997	Pawnee Creek CO	Sterling	15.1	0	0.000	0.14	0.009

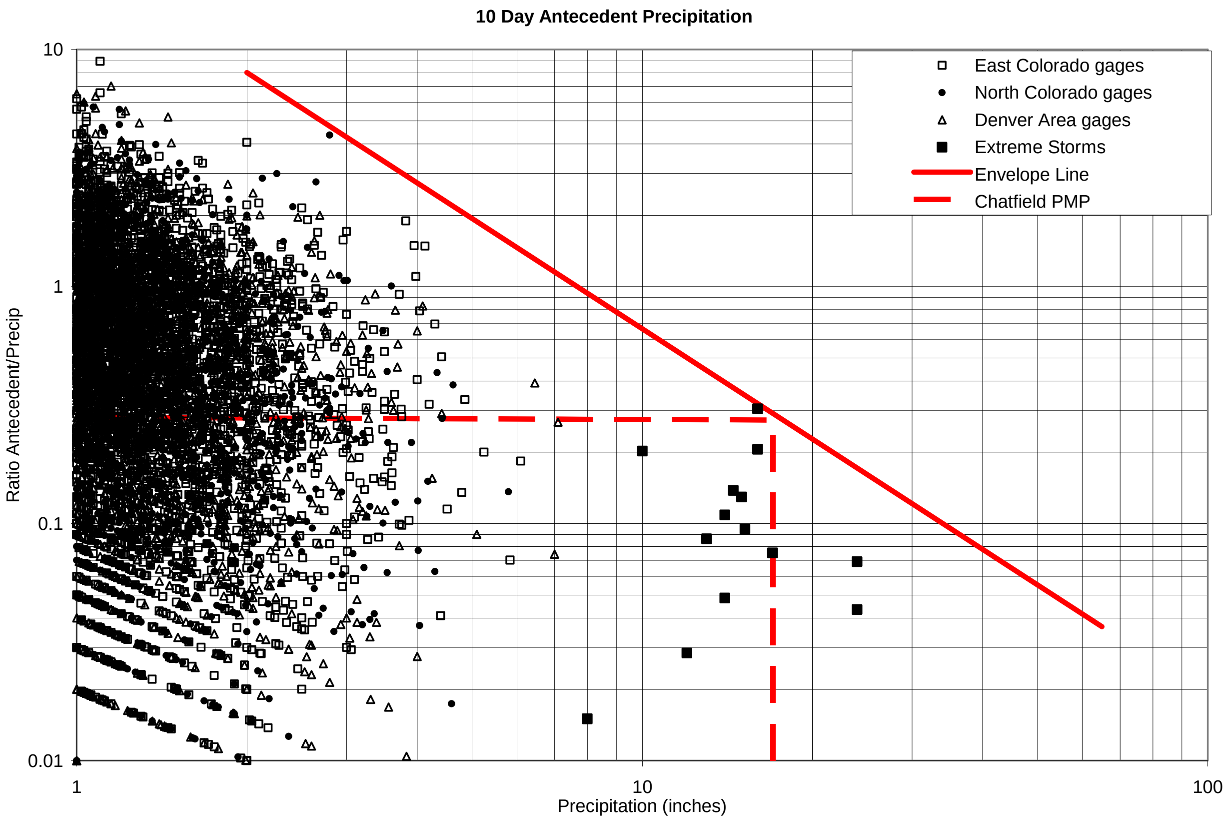

Figure 5 Antecedent Precipitation Ratios

COMPARISON WITH OTHER STUDIES

Based on the analysis of historical precipitation, it appears that the ratio to be used for the antecedent flood at Chatfield should be much less than 50 percent with the maximum value of about 30 percent of the PMP preceding the PMF event. This value compares favorably to previous studies by the National Weather Service. A regional study of Kansas, Oklahoma and Eastern Colorado was prepared by the NWS in 1995 and published in HYDRO-45. That study recommended a value of 10 to 20 percent be used for precipitation antecedent to PMP events in that region. In 1996, the NWS completed a study for the Cherry Creek project and recommended a value of 32 percent be used for precipitation antecedent to the PMF. A comparison of these studies is presented in Table 3.

Table 3
Comparison of Results of Antecedent Studies

Study	Year	Antecedent Precip (% of PMP)
Historic Envelope	2005	30
NWS (Cherry Creek)	1997	32
NWS (Chatfield)	1997	36
NWS (Hydro 45)	1995	10 - 20

SNOWMELT

Since Chatfield antecedent pools could also be high due to snowmelt runoff and combinations of snowmelt and precipitation runoff, another analysis was made to look at historical streamflow records. Volume probability curves were derived for historical Chatfield inflows for the 60 year period 1942-2002. Chatfield inflows were based on flows recorded at the USGS streamgage at Littleton for the period prior to closure of Chatfield Dam. Annual maximum values for the 1-Day through 90-Day events were plotted on logarithmic-normal probability grids using the Weibull plotting position formula. Eye-fit curves were drawn through the plotted points to estimate the preliminary flow frequency relationships for all durations. Log Pearson type III distribution statistics including the mean logarithm, standard deviation, and skew coefficient were computed from the eye-fit curves. These statistics were smoothed by plotting the mean versus standard deviation and mean versus skew for all durations according to the guidance in EM 1110-2-1415. Final flow frequency relationships were computed from the smoothed statistics and are shown on Figure 6 along with the annual maximum events for durations of 1 through 90 days.

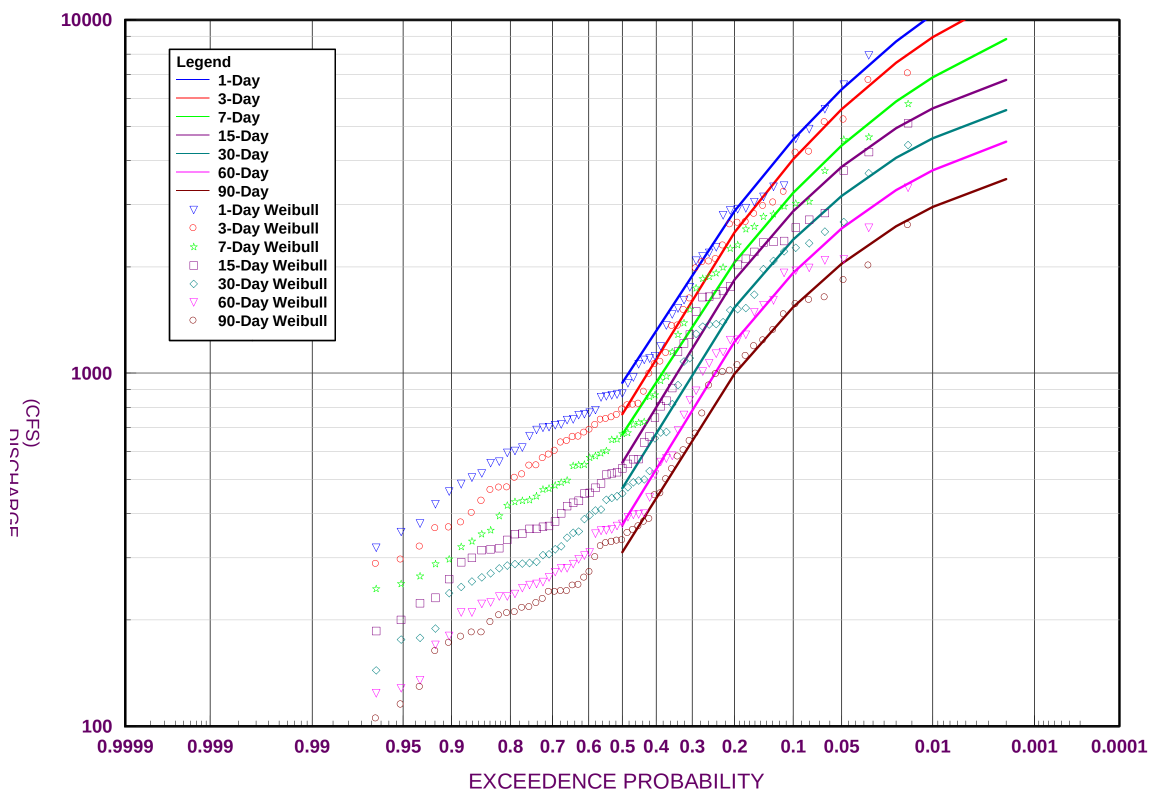

Figure 6 Chatfield Inflow Volume Probability Relationships

From the volume probability relationships, volume duration curves were developed for the 2-year through 500-year events. Results of this analysis are shown in table 4.

Table 4
Chatfield Volume Duration Frequency Relationships

Exceedence Probability	Return Period (years)	Discharge in CFS for Given Duration in Days				
		1	3	7	15	30
0.5	2	938	764	671	557	472
0.2	5	2880	2504	2063	1841	1536
0.1	10	4587	4034	3240	2877	2388
0.05	20	6362	5593	4415	3842	3177
0.02	50	8684	7567	5878	4937	4070
0.01	100	10361	8939	6883	5617	4624
0.002	500	13845	11627	8828	6763	5554

Next, a range of Chatfield releases were subtracted from the volume duration relationships to determine the flood control storage required for the 50-, 100-, and 500-year events. For the maximum required storage to control each event, it was assumed that there would be no release for 5 days followed by gradually increasing the releases by 500 cfs per day until the release reached a maximum of 5,000 cfs. This is consistent with the operating criteria used in developing the Reservoir Design Flood for Chatfield. To determine the minimum storage required for each event, it was assumed that a constant release of 5,000 cfs would occur. Results of this analysis are shown in Table 5.

Table 5
Chatfield Flood Storage Required

Exceedence Probability	Return Period (years)	Flood Storage Required to Control Specified Event (Acre-Feet)	
		Release 0 – 5,000	Release 5,000 cfs
0.02	50	92,330	15,273
0.01	100	112,584	26,138
0.002	500	146,662	53,143

As shown in Table 5, the amount of storage required to control the specific flood events varies substantially depending on the release criteria utilized. These two release conditions analyzed provide the upper and lower bounds of actual storage amounts needed to control each flood event as the actual value would likely fall in between these two conditions. In order to determine the maximum pool level resulting from these flood events, the amount of storage in the multipurpose pool was added to the required storage for each event and converted to elevation using the elevation capacity curve for Chatfield. For existing conditions, the amount of storage added to flood storage was 27,400 acre-feet while for the new Water Supply conditions a total of 48,000 acre-feet was added to reflect the additional 20,600 acre-feet of storage reallocation. The resulting peak elevations were plotted graphically to obtain the peak pool probability relationship for Chatfield as shown on Figure 7. Also shown on Figure 7 for comparison purposes are the 3 highest pool elevations recorded at Chatfield during the period of operation 1974-2005 and the six highest pool elevations simulated with the HEC5 model of the Tri-Lakes system over the study period of record 1942-2002.

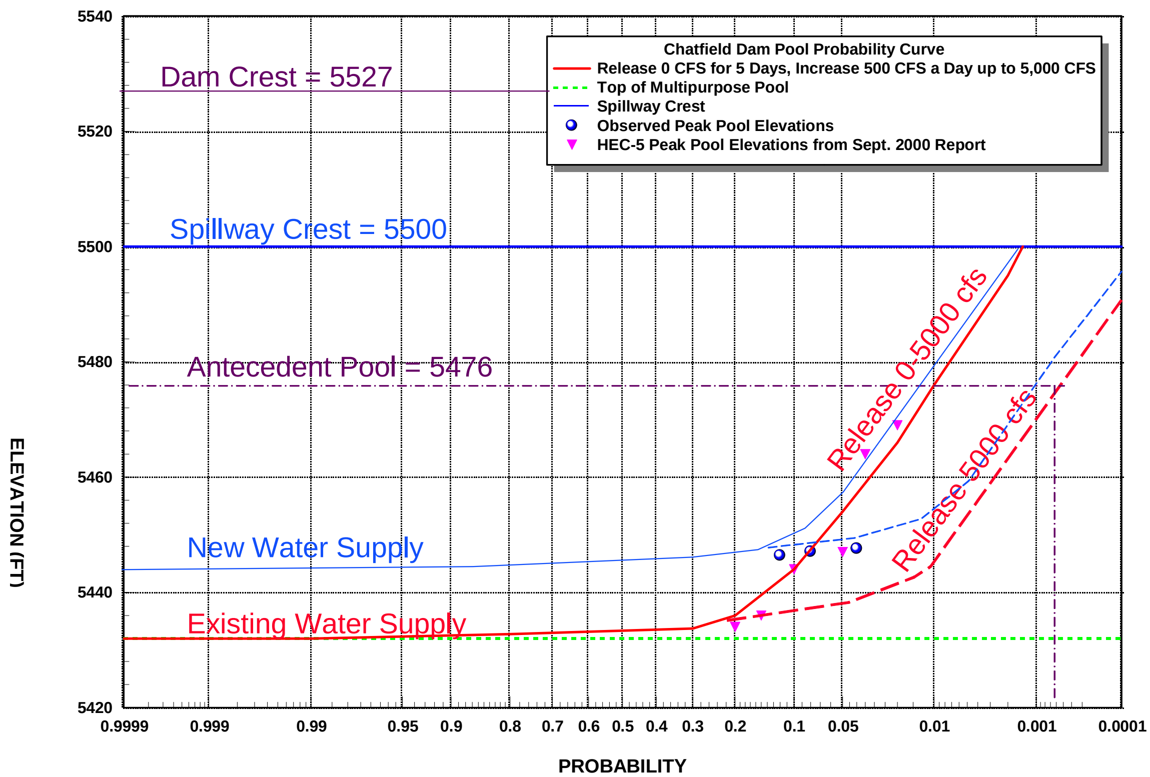

Figure 7 Chatfield Reservoir Pool Probability

Results of the pool probability analysis, as shown in Table 6, indicate that the annual frequency of Chatfield pool levels exceeding the antecedent pool elevation of 5476 feet msl are quite remote, especially if the maximum flood control release of 5,000 cfs can be maintained. Under the most conservation operating criteria the frequency of Chatfield pool levels exceeding the antecedent flood pool would increase from once in 100 years to once in 50 years due to raising the multipurpose pool by 12 feet. This assumes that the water supply pool would remain full each year and not fluctuate, which is also a conservative assumption. In either case, it would be quite rare for the Chatfield pool to exceed the antecedent flood pool prior to the IDF occurring. Additionally, the effects of raising the water supply pool by 12 feet could be offset by changing the criteria for the shut down period from 5 days to 3 days.

Table 6
Frequency of Exceeding Antecedent Pool Elevation 5476

Condition	Release	Annual Exceedence Probability	Return Period (years)
Existing	0 – 5,000 cfs	0.01	100
With Reallocated Storage 21 KAF	0 – 5,000 cfs	0.02	50
Existing	5,000 cfs	.0005	2,000
With Reallocated Storage 21 KAF	5,000 cfs	.001	1,000

CONCLUSIONS AND RECOMMENDATIONS

Based on the analysis of historical precipitation, it appears that the ratio to be used for the antecedent flood at Chatfield should be much less than 50 percent with the maximum value of 30 percent of the PMP preceding the PMF event. This value compares favorably to previous studies by the National Weather Service in the vicinity of Chatfield which recommend using values in the range from 10 - 36 percent.

In order to provide some conservatism and account for the fact that the historical record may not include all possible extreme sequences of antecedent events, it is recommended that a value of 40 percent of the PMF be used to define the antecedent flood for Chatfield Dam and Lake. Using 40 percent of the PMF for the antecedent flood with the multi-purpose pool raised 12 feet for water supply would result in a starting pool for the IDF routing of elevation 5476 feet msl and a maximum pool elevation during the IDF routing of 5521.6 feet msl. This would provide adequate freeboard without any structural modifications.

To offset the impacts of increasing the frequency in which Chatfield pool levels would exceed the antecedent flood pool elevation of 5476 feet msl, it is recommended that if 20,600 acre-feet of flood storage is reallocated to water supply, the operation criteria be changed to shut down no more than 3 days following a significant rain storm event instead of the current 5 days. The effects of this change in operation should be tested on historical flood events using the HEC5 Tri-Lakes system model that is currently being used for impact analysis as part of the Tri-Lakes Reallocation Study.

APPENDIX

Independent Technical Review
Comments and Responses

(Note: The ITR comments and responses included here are reproduced from an electronic copy of the letter from the USBR to the COE sent in an email from Bob Swain to Doug Clemetson on 11/21/2005. COE Responses to the review comments are annotated in this copy using an Arial Font)

Douglas J. Clemetson
Chief, Hydrology Section
U.S. Army Corps of Engineers
106 S. 15th Street
Omaha, NE 68102

Subject: Review of "Chatfield Dam and Lake, Denver, Colorado, Antecedent Flood Study, Draft Report, Tri-Lakes Reallocation Feasibility Study, September, 2005" prepared by the US Army Corps of Engineers (COE), Omaha District

Reclamation has reviewed the subject report in order to fulfill the requirements set forth in the Military Interdepartmental Purchase Request No. W59XQGS2987856, dated October 28, 2005. The purpose of the review is comment on the approaches used to determine the magnitude of the antecedent storm precipitation that would occur ahead of the Probable Maximum Precipitation (PMP) for the watershed located above Chatfield Dam, Colorado. The COE draft report indicates that the goal is not necessarily to derive an absolute value of the antecedent storm event but to provide enough evidence that the relationship between the of the antecedent precipitation event to the PMP would form a ratio of < 40 percent.

The report was reviewed by Lou Schreiner, Flood Hydrology Group Manager, and Bob Swain, Flood Hydrology Technical Specialist. The review will discuss three possible approaches to solving the problem, and then provide minor specific comments to portions of the draft report.

Background

The National Weather Service (NWS) has made site-specific antecedent storm calculations for several locations across the United States over the last 40-50 years. A summary of the techniques applied to these areas is found in Hydrometeorological Report No. 56 (HMR56). However, during the last several years, a number of individuals have criticized parts of the general approach taken by the NWS. This review will concentrate on presenting three methodologies that could be developed by the COE in hope that all three would lead to the conclusion that the ratio of the magnitude of the antecedent precipitation to the PMP would be < 40 percent. For this review, the three approaches are labeled: (1) National Weather Service Approach, (2) Precipitation Frequency Approach, and (3) Independent Antecedent Storm Approach.

Approaches

(1) National Weather Service Approach:
The approach initiated by the COE using historical precipitation data with tentative results shown in table 2 and displayed on figure 5 of the draft report basically follows the initial standard methodology used in all reports that are developed by the NWS in the determination of the magnitude of the antecedent precipitation in relation to the PMP. However, there are several questions that need to be addressed to ensure the completeness/accuracy of the final results. These are:

a. The 114 precipitation stations used in the basic analysis do not include gage data from many of the precipitation stations found along the Colorado Rockies located immediately east of the Continental Divide at elevations greater than Chatfield Dam. Some of these gages are located in the Chatfield Dam watershed. These stations should not only be analyzed in combination with your described data set but should be analyzed separately from those stations located on the plains (figure 4) to see if there is any significant difference in the antecedent to main storm precipitation ratio due to orographic/elevation effects.

RESPONSE: There are eleven additional NWS precipitation stations located in the watershed upstream from Chatfield Dam. Records from those stations were not included in the original analysis since they are located in the mountainous region. PMP amounts are greater in the foothills and plains areas of Colorado so the original analysis focused on precipitation stations in those areas. An analysis was made of the 10-day precipitation antecedent to the maximum 24-hour values recorded at the eleven stations located in the mountainous region above Chatfield. Results of this analysis indicate that the antecedent ratios would all plot well below the envelope curve shown on Figure 5. It should also be noted that the maximum 24-hour value recorded at the mountain precipitation stations was 2.85 inches at the Bailey station on May 7, 1969. Therefore, even if the ratios for these stations exceeded those from the plains stations, the envelope curve would not be impacted for large precipitation events in the magnitude of PMP.

b. The relationship described on figure 5 is basically derived using point precipitation data. The drainage area above Chatfield Dam is 3018 square miles. Studies that involve drainage sizes larger than 100 square miles should evaluate the effect of large area storms. This is accomplished by studying clusters of precipitation stations, both antecedent and during the main precipitation event for storm area sizes similar to that of the drainage area size of interest. Major storms of record, as found in "Storm Rainfall of the United States," are useful to describe average precipitation depths for area sizes of interest in the main storm event. Typically, there is not an observed change in the ratio of the antecedent storm magnitude to the main storm for small area sizes (< 100 sq. mi.) but as storm area size increases the ratio usually increases somewhat.

RESPONSE: Concur that a cluster analysis would likely result in the main event values being smaller than those from a single station value since more than 1 station values would be averaged. Consequently, this type of analysis would likely result in higher ratios since the main event values would be smaller. It would however depend on if and how much the antecedent values decreased. Evaluation of the Depth-Area-Duration relationships for the four Colorado storms in "Storm Rainfall of the United States" indicates that the ratio of storm total precipitation to maximum 24-hour precipitation increased in 2 of the events as the storm area increased from 100 to 1000 square miles and decreased in 3 of the events as the storm area increased from 1000 to 3000 square miles. Based on these storms, it is inconclusive that a larger ratio should be used for drainage areas greater than 100 square miles. It should also be noted that the maximum increase in ratios for these storms is 6 percent based on the 1938 storm.

Storm	Area (sq.mi.)	24-Hr Precip (in)	Total Precip (in)	Ratio
May 29-31, 1894	100	5.2	7.5	1.44
	1000	4.6	6.5	1.41
	3000	4.2	5.9	1.40
May 1-3, 1904	100	3.9	6.1	1.56
	1000	3.4	5.0	1.47
	3000	2.9	4.3	1.48
Apr 14-16, 1921	100	6.9	7.2	1.04
	1000	4.8	5.2	1.08
	3000	4.1	4.3	1.05
Aug30-Sep4, 1938	100	5.2	9.4	1.81
	1000	3.1	5.8	1.87
	3000	2.5	4.6	1.84

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c. The draft study presently derives ratios of 5-day or 10-day antecedent precipitation to a 1-day main storm or PMP type event. The magnitude of the PMP is based on that calculated by use of <u>Hydrometeorological Report No. 44</u> (HMR44) – pattern "B." Since the study references PMP values from HMR 44 being used for guidance to set the magnitude of the main storm event, it appears reasonable to use the entire 4-day PMP as determined from that report for setting the magnitude of the main event. If the COE standard is a 5-day dry period between the end of the antecedent event and the beginning of the PMP, then one should look at an antecedent event magnitude taken over a 9-day period prior to the beginning of the main event (4-day antecedent precipitation plus 5-day dry period). This 9-day antecedent precipitation total would be divided by the PMP (4-day total) to form the antecedent to main storm ratio. Whatever the result using this recommendation, the antecedent to main storm ratio should be considered conservative due to the inclusion of precipitation occurring over the 5-day dry interval. This analysis would probably produce lower ratios than obtained from the COE draft report because looking at the 5 and 10 day periods prior to the daily maximum probably contains rainfall from the same storm as that of the main event.

RESPONSE: Comment noted, no changes required.

d. Since the PMP is derived from use of the procedures in HMR 44 (pattern "B" with the storm centered in sub-basin 6), it is interesting to note that based on the 24-hour total PMP of 16.6

inches for this pattern and storm centering in sub-basin 6, that the 2-day two day adjacent PMP totals 5.3 inches (no dry-day period) already provides a ratio of 32 percent. Additionally, making the same type of calculation for the total area size (3018 sq. mi.) of the Chatfield drainage, the 2-day adjacent PMP to the 24-hour PMP is 3.3 inches and dividing this amount by 8.2 inches produces a ratio of 40 percent. This increase in the ratio (32 to 40 percent) is expected in evaluating the impact of increasing storm area sizes as addressed in item b. above.

RESPONSE: Comment noted, no changes required.

e. In table 2 of the draft report, the June17, 1965, Holly, Colorado precipitation is shown as 26 inches. We are not aware of a 24-hour precipitation amount of that magnitude occurring at that location on that date. McKee and Doesken ("Colorado Extreme Storm Precipitation Data Study", May1997) reported only 15.17 inches in 48-hours at Holly on that date.

RESPONSE: Concur with comment. Holly precipitation revised in table 2 and on Figure 5.

f. In table 2 of the draft report, the ratio for the June 17, 1965, Falcon, Colorado storm is given as 0.306. This data does not appear to be plotted on figure 5. Doing so would raise the ratio value stated at the bottom of page 7 to near 30 percent and change the "Historic Envelope - Antecedent Precipitation" value shown in table 3 to near 30 percent.

RESPONSE: Concur with comment; value plotted on Figure 5 was based on antecedent precipitation at the Ayers Ranch gage. This was later changed to Colorado Springs which was slightly higher. This has been revised and the envelope curve has been modified.

g. In table 3 of the draft report, the "Antecedent Precipitation" ratio from "NWS (Cherry Creek) – 1996" is provided as 32 percent of PMP. Not being aware of that study but of a study done in 1997 by the NWS, specifically addressing the antecedent storm issue for Chatfield, that provided an antecedent ratio of 36 percent. The 1997 NWS antecedent study also provided ratios for both Cherry Creek and Bear Creek drainages in Colorado of 32 percent.

RESPONSE: Concur with comment, date of report revised and Chatfield ratio added to table 3.

<u>(2) Precipitation Frequency Approach:</u>
<u>Technical Paper No. 49</u> (TP49) "Two- to 10- Day Precipitation for Return Periods of 2 to 100 Years in the Contiguous United States" provides the opportunity to quickly examine precipitation ratios formed between durations of intense precipitation (main event) and remaining precipitation (antecedent) derived from a precipitation frequency analysis. In this case, one can quickly find the average 4-day, 100-year precipitation and a similar value for a 10-day, 100-year amount for the Chatfield drainage. For example, in the Chatfield drainage (eye-ball estimate) the 4-day, 100-year precipitation equals 4.9 inches, whereas the 10-day, 100-year precipitation equals 5.9 inches. The difference between these values is 1.0 inch, resulting in a ratio of 0.20 (1.0/4.9). Using a 2-day, 100-year value (4.5 inches) with the10-day, 100year value

(5.9 inches) yields a ratio of 0.31 (1.4/4.5). Various other ratios can be formed through interpolation/extrapolation to test extremes using this information. Justifications/reasoning would have to be employed to evaluate results. Ideally, one would like to have such precipitation frequency analysis carried out to additional days and longer return periods similar to what is available for the Southwestern States and the Ohio River Region (NOAA Atlas 14). One needs to evaluate the limitations of forming ratios in this manner. Is the evaluation of 100-year precipitation applicable to events at the level of PMP? It is unlikely that the many main events (2- or 4-days) are part of the 10-day event. Also these ratios are from point precipitation (station) analysis and do not include storm area analysis [guidance on adjustments for spatial considerations could be applied from results from methodologies (1) and (3) noted in this review]. The reasonableness of the selected durations of main and antecedent storm lengths needs to be evaluated. The purpose of the draft study is not necessarily to derive an absolute value of the antecedent storm event but to provide enough evidence that the relationship between the antecedent precipitation event and the PMP would form a ratio of < 40 percent. If reasonable combinations cannot exceed a ratio greater than 40 percent, then the COE goal criteria have been satisfied.

RESPONSE: As suggested in this comment, an additional analysis was performed using 24-hour precipitation frequency obtained from NOAA Atlas 2 – Volume III Colorado and 10-day precipitation from Technical Paper No. 49. The largest point precipitation values in the vicinity of Chatfield Dam were used in this analysis. Precipitation values for 500-year frequency events were extrapolated using a normal-probability distribution. Ratios were computed by subtracting the 24-hour precipitation from the 10-Day precipitation and then dividing by the 24-hour precipitation. This represents a statistically based analysis with the 24-hour value as the main event and the difference between the 10-Day and 24-hour value as the antecedent precipitation. Results of this analysis indicated that the Ratio is always less than 40 percent throughout the entire range of frequencies as shown in the following table:

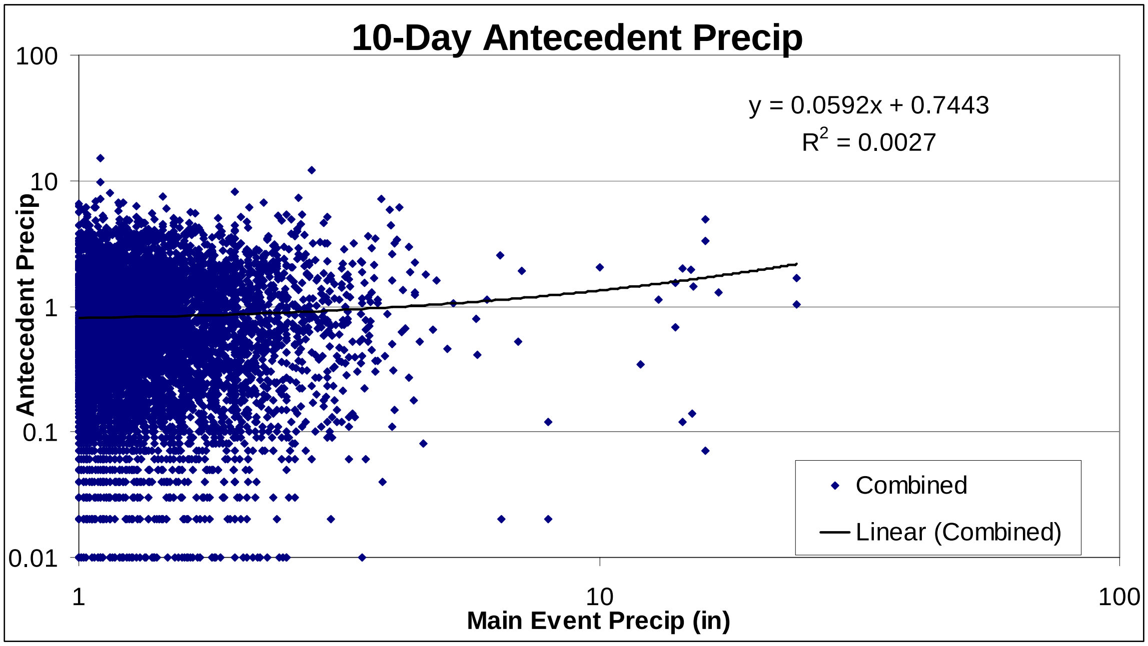
Frequency (years)	24-hr Precip (in)	10-Day Precip (in)	Ratio
2	2.0	2.7	.35
5	2.9	3.8	.31
10	3.3	4.4	.33
25	3.9	5.1	.31
50	4.2	5.5	.31
100	4.5	5.9	.31
500	5.4	6.9	.28

<u>(3) Independent Antecedent Storm Approach:</u>

In this approach (communication – M. Schaefer), the antecedent to main storm data sets are examined from a cause and effect relationship. The various data sets established using the NWS methodology in item (1) above should be examined statistically to determine the correlation between the antecedent and main storm precipitation amounts. If a minimal correlation exists between the antecedent and main storms, then the antecedent storm and main storm are independent events. In this case, if "x" represents the precipitation in the main storm event and “y” represents precipitation for the antecedent portion of the total analyzed event, then a simple plot of y vs. x or a statistical correlation can be established to both visualize and/or compute the relationship. If the data is viewed as being independent, then plotting the data as (y/x vs. x), as the COE has indicated in figure 5 of the draft report, could lead to spurious conclusions as to the relationship of antecedent to main event precipitation.

If independence of the antecedent to main event precipitation is verified, antecedent precipitation values should be examined separately. The mean value of the antecedent precipitation data set would represent antecedent conditions typical of large storms which could center over the Chatfield watershed. In keeping with the concept of developing a storm sequence that is reasonably possible for developing the Probable Maximum Flood, one could select an antecedent precipitation magnitude from the upper end of the antecedent data set (i.e. 90th percentile) to be representative of the magnitude of the antecedent precipitation to be placed ahead of the PMP event. A ratio of this antecedent precipitation to PMP can than be calculated and evaluated. If the ratio is less than 40 percent, the COE draft study requirements have been verified.

RESPONSE: Statistical analysis of all the precipitation data indicates that there is essentially no correlation between 10-day antecedent precipitation and main event 24-hour precipitation with coefficient of determination (R-squared) values ranging from 0.0024 - .0031 depending on the distribution used to fit the data. Therefore, the events can be considered to be independent. The mean value of the 10-day antecedent precipitation values of 0.83 inches, while the 90th percentile value is 2.06 inches and the 99th percentile is 4.50 inches. Therefore, even if the 99th percentile value is used for the antecedent precipitation, the ratio of antecedent precipitation to PMP would be 26 percent. If a simple linear regression curve is used, as shown in the following figure, the antecedent precipitation would be 1.75 inches and the ratio would be 10 percent. Adding 2 standard errors would increase the antecedent precipitation to 3.73 inches or a ratio of 22 percent. Developing an envelope curve to define the upper limit would result in an antecedent precipitation of 5 inches and a ratio of 29 percent.



10-Day Antecedent Precip
y = 0.0592x + 0.7443
R2 = 0.0027
100
10
1
0.1
0.01
Antecedent Precip
1
10
100
Main Event Precip (in)
Combined
Linear (Combined)

Specific Minor Comments

1. Page 2, last full paragraph, second sentence. Capitalize the "P" in "Chatfield project."

   RESPONSE: Concur. Change made.

2. Page 6, second paragraph. Information is presented about the Antecedent Pool elevation that results from routing the antecedent flood through the reservoir. Based on the criteria in ER 1110-8-2, this elevation occurs "five days after the last significant rainfall of a storm that produces one-half the IDF." Two reservoir operating rules are presented later in the report. Indicate which operating rule was used to determine the Antecedent Pool elevations presented in this paragraph. It appears that the elevation was determined using the rule that assumes no releases for five days after the rainfall event.

   RESPONSE: The Antecedent Pool Elevations were determined by adding one-half of the PMF volume to the Multi-purpose Pool volume and subtracting maximum releases of 5,000 cfs during the five day draw down period. Clarification was added to the referenced paragraph.

3. Page 7, second sentence. The phrase "precipitations gages" should read "precipitation gages."

   RESPONSE: Concur, Change made.

4. Page 13, first paragraph, seventh line. The phrase "…reflect the additional 21,600 acre-feet of storage…" should read "…reflect the additional 20,600 acre-feet of storage…."

   RESPONSE: Concur. Change made.

5. Page 13, first paragraph and Figure 7. The text indicates that the six highest pool elevations simulated with the HEC5 model of the Tri-Lakes system are shown on Figure 7. What operating rules were used to determine the highest pool elevations? It is not stated in the text, but I assume that the pool elevations were determined by using zero releases for five days, followed by increases of 500 cfs a day up to a maximum of 5000 cfs.

   RESPONSE: The HEC5 model study utilized operating criteria from the Water Control Manual which included a target flow at Denver of 5,000 cfs and a maximum increase in release of 500 cfs per day. It also included balancing storage at Bear Creek and Cherry Creek reservoirs. Therefore, the operating criteria in the HEC5 model would generally follow the zero to 5,000 cfs release schedule used for developing the pool probability relationships. These values were used for comparison to validate the pool probability relationship based on simulation of historical flows.

6. Page 13, last paragraph, last full sentence. Place a comma after the word "fluctuate."

   RESPONSE: Concur, Change made.

7. Page 14, last paragraph, first sentence. The word "increase" should be replaced with "increasing."

   RESPONSE: Concur. Change made.

Conclusions

It is recommended that all three methodologies indicated above be pursued to varying degrees and results and compared to the requirements set forth by the COE in their draft report. If none of the methodologies (reasonably evaluated) reveal an antecedent to PMP ratio > 40 percent, than there is very good evidence that a refinement to the standard COE antecedent flood policy could be established for the case of Chatfield Dam.

As a point of comparison between Reclamation and COE approaches, in the absence of an antecedent flood study, Reclamation has adopted criteria for developing an antecedent flood by either converting 100-year precipitation to a flood hydrograph or using a balanced 100-year flood hydrograph using statistical analysis of streamflow data. When 100-year precipitation data are used, three dry days are used between the end of antecedent rainfall and the beginning of the probable maximum storm. When the balanced 100-year flood hydrograph is used, a time interval of three days is used between the peak of the antecedent flood hydrograph and the beginning of the probable maximum storm.

Thank you for the opportunity to review this report. It was written in a very clear and concise manner which made the review go very smoothly. A list of references is attached to this letter. If you have any questions about the review, please contact either Lou Schreiner (303-445-2546 email: lschrein@do.usbr.gov) or Bob Swain (303-445-2547 email: rswain@do.usbr.gov).

Sincerely,

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Louis C. Schreiner
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