

# Colorado - New Mexico Regional Extreme Precipitation Study

## Summary Report

### Volume I

Project Background and Overview

November 30, 2018

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# Colorado – New Mexico Regional Extreme Precipitation Study

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## Summary Report

### Volume I

#### Project Background and Overview

Prepared by:

*The Colorado Division of Water Resources, Dam Safety Branch  
and*

*The New Mexico Office of the State Engineer, Dam Safety Bureau*

November 30, 2018



**COLORADO**  
Division of Water Resources  
Department of Natural Resources



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## Acknowledgments and Appreciation

There are many entities and individuals to thank for the successful planning, execution, and results obtained from the Colorado-New Mexico Regional Extreme Precipitation Study (CO-NM REPS). The Colorado Division of Water Resources, Dam Safety Branch and the New Mexico Office of the State Engineer (OSE), Dam Safety Bureau wish to acknowledge and thank the leadership of our respective organizations for their advocacy and encouragement. Colorado Dam Safety could not have conducted the project without the generous support and funding from the Colorado Water Conservation Board (CWCB). The New Mexico Dam Safety Bureau could not have completed the project without the support of the OSE and other state entities, the New Mexico Watershed and Dam Owners Coalition, and the Albuquerque Metropolitan Arroyo Flood Control Authority. Staff from each dam safety agency were instrumental in the successful execution of the technical aspects of the project.

The consultants for the project worked tirelessly and successfully met the challenge to work collaboratively. The sponsors appreciate how each of the teams showed professionalism and scientific curiosity.

The goals of the project could not have been achieved without the encouragement and support of the Federal agencies who provided subject matter experts for our Project Review Board. Representatives of the U.S. Army Corps of Engineers (USACE) and the Federal Energy Regulatory Commission (FERC) are acknowledged for their review board leadership as co-chairs of the Project Review Board.

A number of dam owner representatives participated throughout the process at workshops in Colorado and New Mexico. Their willingness to share their perspectives of our project process and results will be invaluable as we transition from results to Rules and dam safety improvements.

Table 1 below lists the participants in the study and their various capacities.

*Table 1. Colorado-New Mexico Regional Extreme Precipitation Study Participants*

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# 1. Executive Summary

## 1.1. History

The states of Colorado and New Mexico require that the owners of state-regulated dams construct and operate facilities that will safely accommodate runoff from extreme rainfall events. Because dams have the potential to impact life and property, there is a clear public safety need to develop safe hydraulic features at these dams. The construction of features to safely convey these events often require owners to bear significant costs. There has been a growing need to evaluate and update the methodology to estimate both the magnitude and frequency of rare storm events in general, and to specifically update the estimate of Probable Maximum Precipitation (PMP). In response to this need, the Colorado and New Mexico state dam safety programs carried out the Colorado-New Mexico Regional Extreme Precipitation Study.

The sponsors of this study developed three project goals: (1) To create updated tools that are broadly accepted as representing the state-of-the-practice in estimating the magnitude of PMP and calculating its equivalent precipitation frequency annual exceedance probability (AEP). (2) To use the results of the study to develop a recommendation for a draft standard of practice for use as a model nationally, and (3) To identify areas for future research toward improving estimates of extreme precipitation. To estimate the magnitude of PMP, storm-based deterministic methods are used. The existing tools to do this are dated and use only storms that occurred before about 1980. This study utilized the list of historic and also added analysis of more recent extreme storm events, such as the September 2013 event that occurred in both Colorado and New Mexico. Additional advances in the deterministic methodologies were also utilized. Probabilistic Precipitation Frequency analysis has not been previously done as part of state-wide PMP studies. This analysis was added to this study to provide an independent check of the rarity of deterministic PMP estimates, and to also provide the states with tools for probabilistic risk analyses. Although the NOAA Hydrometeorological Design Studies Center (HDSC) has not done research in deterministic PMP analysis since 1999, the NOAA Earth Systems Research Laboratory (ESRL) Physical Sciences Division (PSD) has been conducting research in physically-based dynamical weather modeling. This study contracted with the NOAA ESRL PSD to test application of their High Resolution Rapid Refresh (HRRR) and Weather Research and Forecasting (WRF) models in PMP magnitude and frequency estimating.

The CO-NM REPS was performed from June 2016 to August 2018, and encompassed three critical technical components:

- Task 1: Estimation of Deterministic Probable Maximum Precipitation
- Task 2: Preparation of Probabilistic Precipitation-Frequency Estimates

- Task 3: Applications of Physically-based Dynamical Weather Modeling for PMP and Precipitation Frequency analyses

## 1.2. Task 1—Deterministic PMP Estimation

Until now, PMP estimates for use in spillway design at high and significant hazard dams in Colorado and New Mexico have been estimated using National Oceanic and Atmospheric Administration (NOAA) Hydrometeorological Reports (HMRs) written in 1970s and 1980s. Since the publication of the HMRs, numerous extreme storm events have occurred and private sector research has improved upon the methodology. Due to the dated nature of HMRs, and absence of updates from NOAA HDSC, an updated analysis of PMP methods and estimation was prepared for the Colorado-New Mexico region by Applied Weather Associates, Inc. (AWA) as Task 1 of the REPS.

The updated PMP analysis applied a storm-based approach as was used to develop the original HMR series of documents. AWA employed many updates to these processes to make use of new storm data, increased understanding of storm behaviors, and new technologies (HRRR and WRF) that were not available to the authors of the HMR work. As part of the PMP reanalysis, AWA developed a tool that dam owners and regulators can use to calculate PMP for watersheds within Colorado and New Mexico. The REPS PMP tool operates in a geographical information system (GIS) environment. The GIS based tool produces estimates for local-scale convective storms, larger-scale frontal storms and, in some parts of the region, for storms that potentially have tropical storm influence. The outcome of the PMP reanalysis is a set of appropriately rare extreme rainfall estimates to be used for spillway design where a deterministic standard is appropriate.

In many cases the PMP reanalysis produced rainfall depths for the larger-scale frontal storms that were less than previous estimates. In the case of local-scale convective thunderstorm rainfall, the new estimates often exceed prior values. These differences from prior estimates point to a need for continuous improvement, which the CO-NM REPS accomplishes. The Project Review Board (PRB) provides a discussion of the differences between the REPS PMP tool results and the HMR PMP results. The PRB discussion is very helpful for those comparing the level of conservatism of the old versus the updated methods.

Volume 2 of the report describes the process used to develop PMP for the region. Process updates, improvements, comparisons to prior studies, uncertainties, and the application of information from the other REPS tasks are discussed in detail.

## 1.3. Task 2—Probabilistic Precipitation-Frequency Extreme Rainfall Estimates

Federal dam owners have moved away from a singular application of deterministic PMP for spillway design and are applying a probabilistic approach that examines hydrologic risk and uncertainty in context of the overall safety (risk) profile for their dams. This probabilistic approach requires rainfall event frequency estimates that

have not been available at the state level without site specific precipitation-frequency analysis. The Colorado and New Mexico dam safety programs recognized the present and future need to implement a risk-informed examination of dams. This study developed tools to estimate precipitation-frequency as a step toward probabilistic risk analysis approaches. The development of regional precipitation-frequency estimates was the work of Task 2 in the CO-NM REPS. MetStat, Inc along with MGS Engineering Consultants, Inc. (MGS) conducted the regional precipitation-frequency (PF) analysis portion of the REPS project. MetStat and MGS produced products that can be applied to a standards-based regulatory approach and also within a Risk-Informed Decision-Making framework. The PF rainfall values and other output can be applied to detailed analysis of spillways and other conveyances in the region.

Meteorologists have long known that local, mesoscale, mid-latitude cyclone and tropical storms can produce floods in the Colorado-New Mexico study region. MetStat and MGS performed detailed storm typing of all rain events contained in the historical record to account for different storm processes within each of these distinct events. By conducting separate PF analyses for each storm type, the data are more likely to belong to the population, resulting in better probability distribution model fit and lower uncertainty, when compared to traditional mixed storm type/mixed population analysis. Using regional analyses and spatial mapping of L-Moment statistics, MetStat and MGS developed point PF relationships for locations throughout the study area. Task 2 work utilized advanced statistical analysis methods including spatial mapping of gridded datasets of the at-site means, regional L-moment ratio statistics L-Cv and L-Skewness, and identification of the regional probability distribution. Isopluvial grids were prepared for point precipitation depths with annual exceedance probabilities (AEPs) of  $10^{-1}$ ,  $10^{-2}$ ,  $10^{-3}$ ,  $10^{-4}$ ,  $10^{-5}$ ,  $10^{-6}$ , and  $10^{-7}$ .

The gridded point precipitation depths were used along with spatial patterns from historical storms to develop Precipitation-Frequency Areal Reduction Factors (PF-ARFs). These PF-ARFs are used to apply calculated point PF information to watershed-scale analysis where appropriate. Watershed-average precipitation-frequency relationships are used in combination with dimensionless spatial and temporal patterns to allow sophisticated hydrological modeling of variable natural processes. MetStat and MGS developed a web-based tool, called the MetPortal that dam owners and regulators can use to obtain precipitation-frequency analysis results. The PF tool provides rainfall depths and ARFs for various AEPs at point locations or for specific watersheds. The 5 percent and 95 percent confidence bounds on these estimates are provided to inform the user. In addition to PF depths the MetPortal tool produces area-specific temporal distribution information, watershed spatial data when appropriate, and freezing-level data for more detailed hydrologic modeling.

Volume 3 of the report describes the analysis, advanced methods, uncertainties, comparisons to other studies, and the outputs from the Task 2 portion of the study.

### 1.4. Task 3—Dynamical Modeling

The National Oceanic and Atmospheric Administration (NOAA) applied physically-based dynamical weather modeling techniques to the CO-NM REPS. This was a proof of concept effort to examine the potential and viability of applying these state-of-the-science tools to the PMP development process.

Within the context of the CO-NM REPS, scientists from NOAA applied state-of-the-art numerical weather prediction modeling methods to help clarify decision-making for PMP estimation, inform the PF process, and research application of these techniques for use in the estimation of extreme rainfall. The NOAA used the Earth System Research Laboratory Global Systems Division's High Resolution Rapid Refresh (HRRR) model and Weather Research and Forecasting (WRF) tools to perform the Task 3 analyses.

The HRRR model has been operational since September 2014 and has demonstrated success in forecasting extreme rainfall events. NOAA Task 3 scientists utilized an extensive set of archived data from multiple versions of the HRRR model to examine various topics related to extreme precipitation in the region.

This grid-based forecasting model uses real time data assimilation to develop its forecast estimates. Use of real time data and analysis based on the laws of physics provides advantages to subjective assumptions utilized in deterministic PMP analysis. In the REPS project the HRRR and WRF models provided alternative information and augmented observations in remote and high altitude regions not well covered by conventional data recording. HRRR model results were applied by both Task 1 and 2 to improve the scientific accuracy and reduce the uncertainty of their processes.

The NOAA also used the Weather Research and Forecasting (WRF) model to perform reanalysis of a number of historical storms that are important to PMP development in this and other studies. This work was done to fill in gaps where precipitation data were unavailable and to address the general uncertainty that arises for data from older storms with limited historical information.

Specific applications of Task 3 products by Task 1 and 2 participants are described in Volumes II and III. The Task 3 NOAA numerical modeling components are described in Volume IV of the report. Suggestions for future research specific to dynamical modeling are provided both in Volume IV and Volume VII.

The understanding of physical processes associated with extreme precipitation has improved since the HMR series was last updated for the Colorado and New Mexico region in 1988. By combining the latest technology and science from both deterministic and probabilistic approaches and in addition, utilizing the latest in physical-based weather prediction methods this study benefits from this ensemble approach.

## 1.5. Climate Change White Paper

The climate change white paper contained in Volume VI of the project reports originated as a suggestion from the PRB at Workshop #1. At workshop #1 subject matter experts from the federal agencies involved described what their agencies were doing to consider climate change in their work. After some deliberation, the sponsors agreed that the subject should be included in the CO-NM REPS project. The degree to which it could be considered, since it had not been part of the original scope was further discussed. The discussion quickly led to a research partnership initiated in October 2014 by the Western Water Assessment (WWA), well before the CO-NM REPS project started. By August 2016, WWA had secured funding for that research partnership, the proposal for which is shown in Appendix E of the Volume I report.

What started as a simple research effort to utilize WWA partnership funding to catalog the research applied to consideration of climate change in extreme precipitation estimates turned into a significant effort on climate change trends and potential climate change impacts on the estimation of extreme precipitation. Volume VI also includes recommendations for different “families” of approaches for incorporating climate change, depending on the type of decision framework that is currently operating or desired.

## 1.6. Task 4—Project Management and Facilitation

The Colorado and New Mexico dam safety programs recognized the significant effort required to successfully carry out a regional study with multiple tasks, participants, and agencies. Acclivity Associates, Inc., with its project management consultants and facilitators, provided project management of the overall execution and day-to-day coordination of the REPS. In this project administrator capacity, Acclivity provided structure and coordination that allowed the dam safety programs and technical consultants to focus on technical issues and tasks.

### **Three project goals:**

Past efforts by numerous states and agencies to update extreme precipitation have been marginally successful and have even produced controversial results. Site-Specific PMP estimates are commonly used in lieu of HMR estimates in many states for significant spillway projects. However, no national standards of practice are in place that allow for consistent application of methodologies. These broader questions motivated the project sponsors to explore the potential for resolution of larger issues associated with estimation of extreme precipitation.

The three primary goals of the CO-NM REPS project were designed to benefit regional dam owners, regulators, dam safety practitioners, and the dam safety community as a whole.

Goal 1--Widely Accepted State of the Practice Tools. CO-NM REPS was undertaken to develop new tools that apply the best science to estimation of rare storm rainfall for design of hydraulic appurtenances. These tools will be made available to dam owners,

engineers, researchers and others in the dam safety community who have a need to develop estimates of rare event precipitation. The project sponsors set out to consult with subject matter experts from many different agencies as the study was developed and carried out. The intent was to apply the experience and knowledge of others to develop results that users will accept and can apply with confidence. This goal motivated the establishment of a Project Review Board (PRB) to provide outside guidance and oversight to the study participants.

Goal 2--Draft Standard of Practice Document. There is a nation-wide need to use the best available science for estimation of rare storm events for dam safety. This goal was set to apply the knowledge that was acquired during the REPS to develop documentation of standardized methodology.

Goal 3--Document Research Needs. The science of extreme precipitation is evolving as more data is collected and as the science of meteorological understanding and modeling is improved. The REPS project applied the best available science. There was an understanding that the potential existed to learn more through the REPS process that could reduce uncertainties and create more standardized processes as the science changes with time. This third goal was set to identify topics that can be explored by others to advance the science of estimating rare event precipitation.

### 1.6.1. Funding and Schedule

Funding for the project was secured from a number of sources, including the Colorado Water Conservation Board and Colorado Division of Water Resources for \$1.275 million, the state of New Mexico, the Albuquerque Metropolitan Arroyo Flood Control Authority and the New Mexico Watershed and Dam Owners Coalition for \$375 thousand. The project was begun in June 2016 and completed in August 2018.

## 2. Report Structure

This summary report for the CO-NM REPS project is comprised of seven volumes. The documentation of the project was broken into volumes to enable readers of the volumes and users of the tools and project to focus on the part of the study they are most interested in. Each volume presents a detailed description of the work performed and provides documentation of each of the elements of the CO-NM REPS project within appendices.

### Volume I: Background and Need

Volume 1 was written by the project sponsors and describes how the project came to be, the project goals, overview of the technical tasks, overall management for the successful completion of the study and a brief look at next steps toward implementation of the results and additional work to build on the lessons learned from this study.

### Volume II: Deterministic Regional Probable Maximum Precipitation Estimation

This volume was written by Applied Weather Associates, Inc., and describes in detail how they performed their work on the study. The Volume II Appendices provide thorough documentation of the storm data contained within the CO-NM REPS Tool which was their primary deliverable. The Tool and users guide can be accessed via this Google Drive folder link:

[https://drive.google.com/drive/folders/1BwS5VLnQ6\\_5N\\_NWjfgbLUPV42Ietex4n?usp=sharing](https://drive.google.com/drive/folders/1BwS5VLnQ6_5N_NWjfgbLUPV42Ietex4n?usp=sharing)

### **Volume III: Regional Precipitation-Frequency Estimation**

Volume III was written by the Extreme Precipitation Group (i.e. MetStat, Inc, MGS Engineering Consultants, Inc, and Applied Climate Services) and describes and documents in detail their work on the study developing Extreme Precipitation Frequency estimates. The Volume III report and appendices contain detailed information regarding all aspects of their work on the study. Their MetPortal web-based precipitation frequency tool can be accessed via this link:

<https://conm-reps-gui.shinyapps.io/metportal/>

### **Volume IV: Application of Dynamical Model Approaches Using the NOAA High Resolution Rapid Refresh and Weather Research and Forecast Models**

NOAA ESRL Physical Science Division personnel authored the Volume IV report detailing the proof-of-concept research into the uses of dynamical models in the estimation of extreme precipitation and precipitation frequency. The report also describes where Task 1 and 2 consultants were able to apply information from numerical models to increase the accuracy and reduce the uncertainty in their results. Volume IV also includes a section on future research specific to use of numerical modeling in extreme precipitation estimation.

### **Volume V: Draft Standard of Practice**

Volume V was written by the sponsors and reviewed by the task consultants. This volume contains “draft” in the title since this document is considered a starting point for additional review and work toward a standard of practice. This volume contains an outline and discussion of the essential components to include in a state of the practice study of extreme precipitation at either a site specific or regional scale. Recommendations for scoping and management of such studies are also provided.

### **Volume VI: Climate Change White Paper**

Volume VI was co-authored by Western Water Assessment and NOAA ESRL PSD with significant contributions by PRB members. This volume provides an overview of global climate trends, global climate modeling, climate change factors that influence extreme precipitation, current methods and practices for considering climate change in extreme precipitation and analysis, and recommendations for Colorado and New Mexico to include consideration of climate change in implementation of the results. An extensive bibliography of references on the topic of climate change related to extreme precipitation is also provided.

### **Volume VII: Topics for Future Research**

Volume VII is a compilation of potential research topics suggested by members of the project team through the course of the project. Each item on the list of topics includes the following information to assist future research activities: Description, Value added, What entity might address each topic, Source of the recommendation and Comments.

## 3. Background and Need

### 3.1. History

#### 3.1.1. Deterministic PMP Methods

Since the 1970s, rainfall depths for use in spillway design at high and significant hazard dams have been estimated in the Colorado /New Mexico region using *Hydrometeorological Reports* (HMRs) provided by the National Oceanic and Atmospheric Administration (NOAA). Those reports and associated methods were developed in conjunction with the U.S. Army Corps of Engineers (USACE) and the U.S. Bureau of Reclamation (USBR). Entities in Colorado and New Mexico have each used HMRs 49, 51/52 and 55A since their releases in 1970s and 1980s. Since the release of HMR55 in 1984 the Dam Safety Community has questioned the accuracy of the rainfall estimates produced, especially at high elevations such as we have in the Rocky Mountains. The rainfall depths produced by HMR 55A seemed unrealistically large. The skepticism was corroborated by USGS paleohydrology research in the 1990s that suggested no paleo-record of rain-driven flooding above about elevation 7500 feet in the Colorado's Front Range Mountains (Jarrett and Costa 1986). Dam safety workshops, forums and investigations in Colorado the 1990s attempted to quantify the impacts of elevation and terrain change on rainfall estimates, with few outcomes.

Starting in 2006, agencies in Colorado and New Mexico each endeavored to develop and utilize "statewide" extreme precipitation estimation tools to apply *Site Specific Probable Maximum Precipitation* (SSPMP) methods as a means to improve the methods utilized in the HMRs. These tools were configured within a modern geographic information system (GIS) framework to provide engineers and dam owners with efficient and economical access to those techniques. Those attempts ultimately proved unsuccessful for both Colorado and New Mexico, and the need to answer longstanding questions as to the accuracy of the HMRs remained.

In July 2008, the Extreme Storm Event Working Group (ESEWG) was chartered by the federal Advisory Committee on Water Information, Subcommittee on Hydrology. The ESEWG consists of representatives from federal agencies with connections to the dam safety and nuclear industries including the USBR, USACE, NOAA, Federal Emergency Management Agency (FEMA), Federal Energy Regulatory Commission (FERC) and Nuclear Regulatory Commission (NRC). Their purpose is to coordinate studies and improve methods used to develop extreme precipitation estimates including PMP and to develop a detailed scope of work and funding requirements to update the NOAA

HMRs. The ESEWG identified the need for updating the HMRs to include extreme storms that had occurred since their initial publications, and to modernize methods of analysis. In December 2011, a report titled “Review of Probable Maximum Precipitation Procedures and Databases Used to Develop Hydrometeorological Reports” was written by the USBR for the NRC’s Office of Nuclear Regulatory Research. The report concluded that much research had been conducted on this topic but that little had yet to be assimilated into “operational estimates of PMP,” i.e., none had yet been put to use. Recommended research topics for future updating and use included: numerical modeling, estimation of uncertainty, finer spatial discretization, incorporation of local climate effects, use of climate variability/change information, and probabilistic precipitation estimates.

Since the early 1990’s, SSPMP studies have been conducted around the United States as a substitute for the NOAA HMR estimates. To date there are no national standards of practice for such studies, and some studies with conflicting or contradictory results have been contentious. The dam safety programs in six states, Nebraska, Ohio, Arizona, Wyoming, Virginia, and Texas have employed private sector meteorological consultants to update the HMR procedures in their states using the “Statewide PMP” processes developed by those consultants. These studies were performed with oversight from three-member peer review panels as required by the Federal Energy Regulatory Commission (FERC). However, no federal agency or dam safety community sanctioned standards of practice, guidelines or recommended procedures have been developed through the course of these studies, thereby leaving the states that develop them vulnerable to uncertainty. At the time this report was written, Pennsylvania, Louisiana, Mississippi, Arkansas and Oklahoma are moving ahead with their own Statewide PMP studies.

Through Colorado Dam Safety’s participation in the ESEWG, which includes NOAA representation, we have learned that NOAA does not currently have a plan, or mandate to update the HMR products, documents, or processes. Other federal extreme precipitation estimation efforts are disparate. NOAA Hydrological Design Studies Center (HDSC) publishes its Atlas 14 precipitation frequency estimates for more frequent storms, but not suitably rare for dam safety purposes. Research within NOAA is on-going in regard to extreme climate forecasting using physical-based numerical models, and the USACE and USBR continue to work with probabilistic methods for flood hazard risk assessments.

In 2014, the ESEWG conducted a survey of state dam safety program PMP needs (ESEWG 2014). A significant survey response was the urgent need for updating HMR-like estimates of PMP. The dam safety community at the state level is increasingly viewing the HMRs as outdated and their use in dam safety regulation is becoming increasingly difficult to defend to dam owners and elected officials. Yet in some states, statutes require the use of NOAA HMR PMP as the de-facto standard. The lack of current NOAA PMP estimates along with the lack of federal or industry-sanctioned alternatives leaves those states in limbo with regard to updating spillway design methodologies.

### 3.1.2. Precipitation Frequency Analysis

Using a probabilistic approach to quantify extreme precipitation allows for an entire suite of storm events, from the common to the very rare, to be identified. This ensemble of events may then be used as input into a hydrologic model to determine a flood-frequency relationship, or a full range of flood possibilities. The probabilistic approach also allows for the quantification of flood risk, a measure of the probability and severity of undesirable consequences associated with the full range of flood possibilities (Micovic 2015).

In 1979, the Federal Guidelines for Dam Safety were developed by a committee of federal agency representatives. At that time, *Risk-Informed Decision-Making* (RIDM) was a new concept and was not promoted for implementation until additional research could be completed. Additional steps were taken by the USBR to refine and improve risk-based analyses, and a risk-based framework was adopted to meet the Federal Guidelines to assess high or significant hazard USBR structures in the mid-1990s (USBR 2011). Following the catastrophic flooding in New Orleans from Hurricane Katrina in August 2005, the USACE created the Risk Management Center (RMC) in Lakewood, Colorado. The RMC uses risk analyses to evaluate dam safety risks from all hazard sources, primarily: hydrologic; seismic; geotechnical; and structural. The FERC is in the process of implementing a RIDM process for identifying, analyzing, assessing, and managing the risks associated with FERC-regulated dams. In the FERC process a Probabilistic Flood Hazard Analysis (PFHA) is used to estimate the frequency of flooding hazards. Often these hazard curves are presented as graphs or tables of peak flow and volume versus annual exceedance probability (AEP); the AEPs offer sufficient support to FERC for ascertaining acceptable risk. At present, this is an option as an alternative to using a deterministic PMF approach (FERC 2014). The Tennessee Valley Authority (TVA) has become a leader in the dam safety community for development of analytical tools for conducting probabilistic flood analyses, implementing risk concepts on complex systems of dams and for RIDM. At the state level, Washington and Montana are among the first states to utilize risk-based hydrologic study findings for ascertaining spillway adequacy. The CO-NM REPS will provide Colorado and New Mexico the hydrometeorological tools to move in this direction as well.

Historically, deterministic PMP estimates were not given a probability of occurring, such as 1:1,000 or 1:10,000 chance of happening. By combining both deterministic and probabilistic approaches in the same study probabilistic estimates of annual exceedance probability (AEP) will be available to inform both the deterministic PMP values and as a part of risk-based studies.

### 3.2. Project Development, Funding, and Scoping

Following workshops and additional meetings and discussions with industry experts, a novel, ensemble approach to the project was developed. Throughout the summer of 2014 efforts were made to secure funding for the project. An estimated project cost was developed and presentations were made to the Colorado Water Conservation Board (CWCB) leadership, culminating in a \$1.2 million grant approved in November

2014, for use in July, 2015. New Mexico dam safety also worked during this time to secure their sources of funding for a regional study. New Mexico Dam Safety made presentations to New Mexico legislators, engineers, and dam owner stakeholders, and coordinated with New Mexico Legislative Finance Committee staff. New Mexico received funding for their portion through a combination of funds from the New Mexico Office of the State Engineer (provided by state appropriation), the New Mexico Watershed and Dam Owners Coalition and the Albuquerque Metropolitan Arroyo Flood Control Authority. The Colorado Division of Water Resources (CDWR) also provided funding that allowed a 2-month extension to the project schedule. The Climate Change white paper (Volume VI) was partially funded by a cooperative grant from the Western Water Assessment. A total combined project budget of \$1.65 million was ultimately provided for this study.

The following project tasks were identified and included in the project scope:

- Conduct a deterministic PMP study using state of the practice methods with input from a Project Review Board, and other meteorological expertise assembled for the other tasks.
- Conduct a Regional Precipitation Frequency study to enable independent calculation of the annual exceedance probability (AEP) of deterministically derived PMP and provide the tools necessary for Colorado and New Mexico dam safety to incorporate risk-based probabilistic approaches into their programs,
- Conduct a proof of concept study utilizing the NOAA ESRL dynamical weather model and prediction tools--the HRRR and WRF models, to inform the other technical tasks (1 and 2) and evaluate the potential for utilization of dynamical weather models for prediction of PMP events
- Add project management and workshop facilitation experts to assure efficient management and skilled facilitation and to also allow the technical experts to focus solely on their areas of expertise.

As previously described, some past deterministic statewide PMP studies have been completed and the results were used by the states, only to have Federal regulatory agencies, the FERC and the NRC, indicate they would not accept the results of those studies at dams or facilities they co-regulate. Colorado and New Mexico had similar experiences with the lack of acceptance of the EPAT results. Given this past experience, the project sponsors desired to have full acceptance of this work when it was completed. To accomplish this, the study planning team set out to establish a robust Project Review Board (PRB) comprised of subject matter experts from federal and state agencies with expertise in meteorology and extreme rain events. On four occasions, beginning in April 2015, and extending through September 2015, sponsors presented the project scope and goals to the Association of State Dam Safety Officials (ASDSO), Interagency Committee on Dam Safety (ICODS) and the ESEWG. As a testament to the widespread need for this project, nearly all federal agencies contacted responded positively to requests to participate on the PRB for the project. Additional details on the final makeup of the PRB are included later in this report.

### 3.3. Validation of Project Need—Concurrent Events

Hurricane Harvey made landfall in Texas on August 25th, 2017, and brought heavy rain to an area of over 20,000 square miles for over 144 hours. Point rainfall measurements for the event were on the order of 50 inches over the storm period. All three CO-NM REPS project task consultants applied their expertise to analyze this storm from their various perspectives. Hurricane Harvey showed the record setting extreme events do happen and therefore need to be planned for. The event also showed that extreme precipitation estimating tools need to have the means to accommodate new data when it becomes available.

Applied Weather Associates, LLC (AWA), analysis compared Hurricane Harvey rainfall depths to their recently completed Texas Statewide PMP study and HMR51. AWA found reported storm total depths to be near PMP (in terms of moisture maximization) and close to their recent PMP estimates at many area sizes and durations. At the longest durations and largest area sizes, the storm exceeded PMP values by about 4 percent, which seems well within the confidence bounds. Overall, the state-of-practice PMP methodology seemed to be validated.

MetStat, Inc., also conducted a rainfall and probability analysis of Hurricane Harvey and found point rainfall depths exceeding annual exceedance probabilities of 1-in-1000 across a wide range of durations. For the longest durations (120 hours) and largest basin areas (20,000 square miles) their analysis estimated AEPs on the order of  $2 \times 10^{-6}$  (1-in-500,000).

NOAA ESRL PSD and the HRRR team predicted the events in real time and supported efforts to inform decision makers and first responders through their interaction with the National Water Center (NWC) National Water Model (NWM) hydrologic guidance and interpretation. This experimental guidance complemented the official river forecasts produced by the West Gulf River Forecast Center (WGRFC). Several daily coordination calls were held involving WGRFC, TDEM, and the National Weather Service.

The above discussion demonstrates the benefits of an ensemble approach to the prediction and analysis of extreme rainfall events. The response of the members of this project team show that the CO-NM REPS project has the highest quality experts in these important fields informing the project to ensure the results are truly based on the best available science.

## 4. Project Goals

### 4.1. Broadly Accepted State-of-the-Practice Tools

Due to the outdated nature of existing tools to determine basin rainfall depths for spillway design, one of the goals of the project was to develop state-of-the-practice tools for the Colorado and New Mexico. The newer methods will allow the most up-to-

date storms to be used. Collaboration between the tasks and PRB have allowed some historic storm re-analysis to be included in the results in a way that has not been examined previously. For example, the team looked deeply into the question of orographic influences and physical limits of rainfall at high elevations and the knowledge gained is included in the end products.

Including Precipitation Frequency analysis in this study will allow Colorado and New Mexico to provide independent cross-checks of our deterministic PMP estimates. In addition, having Precipitation Frequency tools will allow the use of risk-based probabilistic analyses in regulatory rules for spillway design.

The project included an experimental approach utilizing NOAA's state-of-the-art High Resolution Rapid Refresh (HRRR) physically-based dynamical weather prediction model. The NOAA research and NOAA's role in the project support the overarching goal to better understand and characterize extreme precipitation estimation uncertainty. The research led by NOAA explored a novel high-resolution dataset and post-processing techniques using a super-ensemble of hourly forecasts from the HRRR model. They also investigated how this rich dataset may be combined with statistical methods to optimally cast the data in probabilistic frameworks. NOAA expertise in the physical processes that drive extreme precipitation was further employed to develop careful testing and improved understanding of the limitations of older estimation methods and assumptions in prior studies.

Peer review by subject matter experts is a typical part of the process as outside consultants and state dam safety programs around the country work to update and modernize the methods of predicting extreme rainfall for spillway adequacy and design. Although review boards are helpful in providing confidence to the participants in the results of their individual studies, past participation by various federal agencies has not resulted in official federal or industry-wide acceptance of the products or methods developed. The Colorado-New Mexico regional study planning team worked to establish a robust Project Review Board (PRB) to ensure that the best available science was used, and to reduce obstacles to industry-wide acceptance of the final results of the study. Acceptance of the methods and tools provides certainty to the sponsors of this study and other statewide studies that have used similar methodologies, and it will also benefit future studies nationwide.

#### 4.2. Draft Standard of Practice

In 1979, FEMA, in conjunction with the ICODS developed the first *Federal Guidelines for Dam Safety* to establish standards of practice in dam safety for federal agencies. Since that time that guideline has been supplemented with guidelines on various design, construction, operations and maintenance topics. Over the past 30 years, the FEMA administered National Dam Safety Program (NDSP) has been a partnership of the states, federal agencies, and other stakeholders that encourage and promote the establishment and maintenance of effective federal and state dam safety programs to reduce the risks to human life, property, and the environment from dam related hazards (FEMA 2012).

One of the goals of this project is to produce a draft standard of practice document suitable to be completed by FEMA, NDSRB/ICODS as a Federal Dam Safety Guideline on the topic of Extreme Precipitation Estimation. The processes developed during this study will be outlined and described to a general degree, such that entities engaged in dam safety activities will be able to execute similar projects anywhere across the country in a consistent way to produce scientifically valid results. A companion document titled *Draft Standard of Practice for Extreme Precipitation Estimation* was developed and is included as Volume V of this study. Additional collaboration with FEMA, ICODS and others is anticipated to further refine this document so that it can eventually be published by FEMA as a Federal Dam Safety Guideline. The Advisory Committee on Water Information (ACWI), Subcommittee on Hydrology (SOH), Extreme Storm Event Work Group (ESEWG) has recommended the Colorado-New Mexico REPS standard-of-practice document should serve as a draft of a national guideline.

### 4.3. Documented Research Needs

Through the course of the study some topics and methodologies were discussed but could not be fully implemented due to schedule and budget constraints. Although those topics could not be utilized in this study, they were identified as important for future research and possible application to the next generation of updates to this methodology. Volume VII of this study report contains a list of those topics identified and a description of the benefits envisioned from additional research.

## 5. Project Organization

### 5.1. Project Philosophy

CO-NM REPS was undertaken to meet the previously stated project goals. The ensemble project scope also provided an opportunity to examine long-standing questions that have been discussed by dam safety and meteorological professionals since the HMRs were published. The sponsors recognized the opportunity and worked to capitalize on the varied and extensive experience of the sponsor agencies, task consultants, PRB members, and study observers. They worked intentionally to create a project environment where team members could work collaboratively to define and reduce the uncertainties inherent to current extreme precipitation estimation processes while developing state of the practice, 21<sup>st</sup> century tools.

### 5.2. A Team of Teams

The broad range of experience of the project participants necessitated a strategy that could make the best use of the expertise that had been assembled. The project sponsors applied a Team of Teams concept to incorporate the strengths of the various groups or "Teams". The Team of Teams concept, adapted from General Stanley McChrystal's *Team of Teams: New Rules of Engagement for a Complex World* (McChrystal 2015), was introduced at the first workshop to provide a framework for

the “teams” to work independently on their assigned tasks but communicate freely and share a common goal. The sponsors and project managers encouraged a shared consciousness of project direction and monitored progress, mitigated conflicts, and ensured accountability.

The sponsors and project managers worked to create a space where participants could apply scientific principles with which they were comfortable while allowing change to be incorporated as the participants communicated and worked together on the project goals. It was important to secure buy-in to the overall project purpose as the team of teams was guided through the process of learning where collaboration could be most effective. The need to identify areas that could be evaluated with the best science were separated from policy decisions that would ultimately be made by the project sponsors.

The PRB was established as an independent team to allow for frank and important discussion of the technical aspects of the project. The project sponsors encouraged focused questioning and input from PRB participants with the idea that the subject matter experts would help the group to answer as many questions as possible regarding the current state of practice.

Participants were encouraged to develop trust, and commitment grew as the team worked together. The project sponsors made it clear they intended for the group to have a sense of accomplishment at the end of the project.

### 5.3. Task Concept—Applied to Meet Project Goals

The project applied three technical practice “tasks” to examine meteorological and statistical aspects of extreme precipitation and precipitation frequency estimation and one project management task to organize and manage the complex activities of the study. The Team of Teams concept allowed these discrete practice specialists to collaborate to improve processes and technical understanding.

#### 5.3.1. Task 1. Deterministic PMP Development

Spillways for dams in Colorado and New Mexico have historically been evaluated for regulatory compliance based on their ability to safely pass the PMP flood (or near PMP). Extreme rainfall depths for the PMP have typically been estimated by the HMR series of publications as mentioned above. Deterministic storm-based PMP is developed through the examination, maximization, and transposition of historic extreme storms. Basin-specific rainfall depths are estimated for dam safety use. Applied Weather Associates, Inc. was selected by the sponsors to develop updated storm-based PMP values across the study region. The work of the Task 1 team provides updated PMP depths that increase confidence in spillway designs through the incorporation of new storm data and improved meteorological analysis applied with geographic information system (GIS) methodologies.

#### 5.3.1.1. Applied Weather Associates, Inc.

Applied Weather Associates (AWA), incorporated in 1996, is a small business located in Colorado specializing in regional and site-specific PMP studies. AWA provides quality high-resolution meteorological analysis and datasets for use in PMP analyses, as well as hydrologic model calibration and validation. The AWA team employs expert analysis, has developed innovative approaches, and uses state-of-the-science technology to provide clients with consistently reliable products accepted by appropriate regulators. AWA was selected for Task 1 because they have largely defined the state-of-practice in PMP studies since NOAA withdrew in 1999.

AWA personnel have completed more than 100 SSPMP studies and similar meteorological analyses since 2003. Several of these studies include the same or similar meteorological and topographical characteristics as are found in Colorado and New Mexico.

#### 5.3.2. Task 2. Regional Precipitation Frequency Analysis

Federal dam owners have been applying risk informed decision making to spillway design for a number of years as described above. The estimation of extreme precipitation at varying and rare probabilities of occurrence (in addition to PMP) is seen as a necessary step in the evolution of state dam safety programs. Spillway designs have been made using deterministic thresholds for many years and the PMP values generated from HMRs do not have an associated Average Recurrence Interval (ARI) or AEP. Precipitation frequency analysis of extreme storms produced for this study will be applied by dam safety programs and practitioners within the study area to understand the probabilistic level of protection that existing and proposed spillway designs provide.

##### 5.3.2.1. MetStat, Inc./Extreme Precipitation Group

MetStat, Inc, is a specialized meteorological consulting company based in Fort Collins, Colorado. MetStat, MGS Engineering Consultants, and Applied Climate Services, formed a team, the Extreme Precipitation Group (EPG), to conduct extreme precipitation analyses for a variety of engineering applications. The MetStat/EPG team were selected by the sponsors to develop Task 2 regional precipitation frequency precipitation depths and AEPs. The MetStat/EPG task 2 team consists of nationally-recognized experts in precipitation analyses, development of PMP estimates, regional precipitation-frequency (PF), probabilistic flood hazard analysis (PFHA) using stochastic flood modeling, and storm analyses using geographic information systems.

The methodology applied by MetStat and MGS is similar to NOAA's approach for its Atlas 14 Precipitation Frequency publications. However, for this study MetStat and MGS utilized storm typing, statistical regionalization, and spatial mapping methodologies different than NOAA Atlas 14. NOAA Atlas 14 provides precipitation frequency estimates as low as 0.1 percent AEP, which is not suitably rare for dam safety purposes. The MetStat and MGS methods were developed to provide very

extreme precipitation frequency estimates (out to  $1 \times 10^{-7}$  AEP) for dam safety purposes, while minimizing statistical uncertainty.

The hydrologic risk for a given facility has typically been established by a site-specific precipitation-frequency analysis. Task 2 developed these estimates on a consistent regional basis and it is anticipated that this work will have an impact on spillway design and policy-making decisions in years to come. The Task 2 work also allows the state programs to compare the estimated average recurrence interval for PMP storms. This comparison will add to the overall understanding of risk at a particular dam and for comparison and prioritization across the portfolio of dams within each state.

### 5.3.3. Task 3. Dynamical Weather Modeling

As part of the project scoping activities, the project sponsors were introduced to the concepts of physically-based dynamical weather modeling. Discussions with NOAA ESRL PSD scientists engaged in these activities revealed that an existing model (HRRR) was currently working on a 3-km grid across the continental U.S. The same scientists were interested in investigating potential uses of the HRRR and WRF models in the extreme precipitation space.

The NOAA ESRL PSD in Boulder, Colorado was contracted to apply the HRRR and WRF model tools to study tasks. The scope of the Task 3 work included carrying out a preliminary proof-of-concept study to investigate how the existing data set from a high-resolution, rapidly-updating numerical weather prediction (NWP) model might inform various aspects of extreme precipitation estimation. A numerical modeling framework such as this one, leveraging high-resolution model data, has not been employed in previous PMP studies, and its potential benefits and limitations are examined here.

The HRRR model was applied to examine a number of questions identified by Task 1 and 2 participants and by the PRB. Task 3 researched many of the assumptions that have been commonly applied to extreme precipitation estimation for dam safety design in prior studies. Questions of seasonality, precipitation in the form of rain versus snow, physical limits on rainfall at high elevations, regional spatial patterns and other ideas were analyzed. HRRR model output was applied in data-sparse regions to fill in gaps where appropriate in both Task 1 and 2 portions of the study.

While the HRRR-based analyses and precipitation estimation prototypes comprised the central activity in Task 3's primary goal to demonstrate the use of dynamical numerical weather models for the CO-NM REPS project, some additional work was performed using a more general instance of the WRF model (the same model core used by the HRRR model). This additional work was largely done in collaboration with Task 1, with the overarching goal to supplement the existing analyses of historical storms. Specific storms of interest for WRF analysis were initially selected by Task 1's assessment of storm importance to PMP and reliability of storm data.

#### 5.3.4. Task 3 - Climate Change White Paper

The Climate Change White Paper is included as Volume VI of the reports for this project. What started as a relatively small research effort turned into a significant document on climate change and potential climate change impacts on the estimation of extreme precipitation. The major findings include the conclusion that as of this report writing, there are no operational methods in use to account for non-stationarity of climate on the processes used to estimate extreme precipitation for design of spillways. Additionally, it is clear that in Colorado and New Mexico, average temperatures have increased in recent times and those trends are expected to continue. Based on the fundamental laws of physics and the atmosphere, with increased temperature comes increased moisture availability to fuel extreme storms. The white paper contains thought provoking discussion and several recommendations for ways the consideration of climate change might be included in operational estimates of PMP.

#### 5.3.5. Task 4. Project Management

The fourth study task involved the participation of a project management team to assist the Colorado and New Mexico dam safety program staff with all aspects of managing a successful project. Acclivity Associates, Inc. (Acclivity) was contracted for this task and provided professionals with specialized experience to the important work of managing time, communication and to provide structure and an external view of the work. The large number of participants in the technical task groups, dam safety staff, observers, and the PRB created challenges for coordination and information sharing. The use of an external project management group was important to maintenance of the team concept, and it was key to the need to collaborate within and among the technical tasks.

The participation of the project management team allowed Colorado and New Mexico dam safety engineers to focus on technical aspects of the study. The Acclivity project management professionals provided external and unbiased direction to the participants for workshops, interim conference calls, monthly technical meetings, work product development and other important study activities. This external voice helped all participants to better maintain the overall direction of the work and to stay on track.

##### 5.3.5.1. Acclivity Associates, Inc.

Acclivity is a team of proven project managers and process facilitators specializing in resiliency planning and hazard mitigation. Acclivity's approach to the management of the CO-NM REPS project builds upon experiences managing similar projects (e.g. precipitation frequency analysis managed for Harris County, Texas), past facilitation assignments for state agencies and includes the use of efficient project management tools. Approaches utilized were cost efficient, inclusive, transparent and effectively allowed the technical experts to focus on advancing tools, procedures, and standards of practice.

## 5.4. Project Sponsors

### 5.4.1. Colorado Dam Safety

The Colorado Dam Safety program is administered within the Division of Water Resources, Department of Natural Resources. Eleven Dam Safety Engineers, managed by a Chief Engineer, carry out two principal duties of the State Engineer: to determine the safe storage level of the reservoir dams in the state and to approve the plans and specifications for the construction and repair of Jurisdictional dams. These broad duties are further defined by the “Rules and Regulations for Dam Safety and Dam Construction (2007)” (Rules). Among other things, the Rules identify specific design and construction details with which all dams must comply, including the design requirements for spillways to safely route the Inflow Design Flood (IDF). Colorado Dam Safety prioritizes regulatory activities among the approximately 1,750 regulated dams according to each dam's Hazard Classification. The hazard classification of a given dam is based on the consequences of unanticipated failure and sudden release of the reservoir contents. The consequences for High Hazard dam failure or mis-operation include the anticipated loss of life within the downstream dam failure inundation zone. The consequences of sudden failure of significant hazard dams include extensive property damage and disruption daily activities, i.e. roads, utilities, etc. Colorado's portfolio of regulated (non-federal) dams includes 378 high hazard dams and 309 significant hazard dams. The elevation of dams ranges from about 3500 feet to over 12,000 feet. Basin size above dams ranges from less than 1 square mile to slightly less than 5,000 square miles.

Spillway design rules for high and significant hazard dams in Colorado currently include consideration of some percentage of the PMP depending on the location and elevation of the basin. The percentage of PMP based on elevation was derived from analysis of approximately 22 SSPMP studies conducted between 1992 and 2006. Those studies were performed by dam owners due to lack of confidence in HMRs, particularly at high elevations. Although the SSPMP studies were a start, the percentage reduction method based on such a small dataset did not provide reliable PMP estimates. Colorado Dam Safety instigated the CO-NM REPS study as a means to provide confidence to staff, dam owners, engineers and others with a vested interest in public safety and safe storage of water. The CO-NM REPS tools developed in this project will replace the HMRs. New dam safety Rules will be written that include consideration of both the PMP derived from the deterministic Task 1 methods and the probabilistic, precipitation frequency estimates based on Task 2 methods.

### 5.4.2. Colorado Water Conservation Board

The mission of the CWCB is to conserve, develop, protect and manage Colorado's water for present and future generations. To accomplish their mission goals the CWCB offers numerous loans and grants to water providers and other entities statewide for a variety of water-related projects, studies, planning documents, awareness campaigns and other activities. The Finance section of the CWCB regularly works with Colorado Dam Safety on dam repair projects they fund. The CWCB Board of Directors supported

the Colorado Dam Safety request and application for a \$1.2 million grant to fund the Colorado obligations for the CO-NM REPS project.

#### 5.4.3. New Mexico Office of the State Engineer Dam Safety Bureau

Included in the responsibilities of the New Mexico State Engineer are the administration of a statewide dam safety program and regulation of certain activities related to water infrastructure. The Dam Safety Bureau in the Water Resources Allocation Program of the New Mexico Office of the State Engineer (NMOSE) provides the New Mexico statewide dam safety program. There are over 500 dams in New Mexico and 298 of those dams are under NMOSE regulation based on their size and storage capacity. The dam safety bureau is staffed with five engineer positions, a staff assistant and a bureau chief.

Jurisdictional dams are located in 29 of 33 counties in New Mexico. The dam safety bureau operates on a statewide basis, and it serves residents who are affected by dams in nearly every part of the state. Some larger dams also potentially affect residents in portions of surrounding states. The New Mexico State Engineer does not regulate federally-owned dams or dams located on tribal lands.

New Mexico jurisdictional dams are required to meet design standards that are set by the rules and regulations found in New Mexico code. Spillway capacity requirements are spelled out in the rules and regulations. High hazard potential dams are required to safely pass a deterministic flood that results from the PMP. Significant hazard potential dams are required to safely pass the flood from a portion of the PMP based on the size of the dam. Since the development of the HMR publications the experience of the dam safety community in New Mexico has mirrored that of Colorado professionals. The need to re-evaluate and update spillway design inputs was identified to ensure that the most appropriate and efficient spillway design can be provided.

The dam safety program in New Mexico has recognized a need for evaluation of the performance of existing and future dams based on relative risk and potential failure modes. This concept is in the beginning stages of implementation. The introduction of precipitation frequency estimates for extreme storms will assist this effort by providing an understanding of the relative hydrologic risk at specific dams.

#### 5.5. Project Review Board

To provide the highest level of project review, the project sponsors engaged those agencies originally responsible for the HMR procedures and guidance documents. The PRB assembled included subject matter experts from the following federal agencies: NOAA ESRL PSD, NOAA NWS, USACE, USBR, FERC, FEMA, USGS, and NRC. A noted expert on climate change and dynamical modeling from North Carolina State University (NCSU) also participated on the PRB. In addition, the State climatologists from each state agreed to participate. It is significant that one of the participating Colorado State climatologists has been involved in the study of extreme precipitation in Colorado for nearly 30 years.

### 5.5.1. PRB Goals and Objectives

The PRB was assembled to ensure the best available science was applied to the technical tasks of the project, within the defined scope and budget. Technical oversight was seen as a key component of the work so the sponsors could confidently apply the results for policy-making, regulatory rule making and safe and efficient spillway designs.

Following the first workshop in August, 2016, a PRB Charter was drafted and completed in October, 2016. The PRB Charter outlined the PRB purpose, goals and objectives, scope of work, roles and responsibilities, schedule, deliverables, estimated level of effort, communication protocols and contacts. PRB objectives found in the Charter are as follows:

#### Primary Objectives

- Provide guidance for the project plan and goals.
- Help to identify the best available science, data, methods and practices that can be reasonably utilized at this time and help identify the uncertainties and limitations of current practice.
- Assist the state sponsors to develop scientifically and technically defensible work products.
- Assist in identifying issues or topics for future research or study by others to continue to advance this science.
- Review project data, and documentation and provide written comments.

#### Secondary Objectives

- Share best practices.
- Engage managers and colleagues in honest scientific debate.
- Advocate for program value and goals.
- Promote cross coordination within and between agencies who could benefit from the results of this study.

### 5.5.2. Leadership and Participation

At the first project workshop it was decided that the PRB needed co-chairpersons to provide leadership of the group, and that a charter was needed to outline PRB processes and activities. A representative of USACE (Chuck McWilliams) and a representative of FERC (Ken Fearon) volunteered to take on the role of PRB Co-chairs. In addition to the co-chairs, PRB Members volunteered as Task review leads for each of the three technical tasks. Kevin Griebenow (FERC) lead the Task 1 PRB effort, Will Asquith (USGS) lead Task 2 PRB efforts and Ken Kunkel (NCSU) lead Task 3 and climate change PRB review efforts.

Subject Matter Experts (SMEs) of the following organizations assumed review roles for various parts of the study. For efficient review of the multiple tasks, the PRB divided themselves into areas of expertise and/or interest as applied to the technical tasks.

This division of review responsibilities ensured PRB input into each of the three technical task activities.

- FERC - 3 SMEs
- USACE - 2 SMEs
- USBR - 4 SMEs
- NRC - 2 SMEs
- USGS - 1 SME
- NCSU - 1 SME
- NOAA ESRL PSD - 1 SME
- NOAA NWS - 2 SMEs (Boulder & Albuquerque)
- FEMA - 2 SMEs
- Colorado State Climatologist - 2 SMEs
- New Mexico State Climatologist - 1 SME

Not all SMEs from each agency were able to participate in all of the face-to-face workshops or all of the monthly PRB webinars. As a result it was beneficial to have multiple SMEs from the various agencies. PRB members reviewed materials provided by the consultants in advance of the workshops. PRB members were assigned as lead reviewers for each task, assembled and presented PRB member review comments at the end of each workshop (See Appendix C3). Consultants addressed each comment with modification in process, additional analysis or justification. Appendices C3 and D provide documentation of resolution of all PRB comments. The PRB proved to be an effective group who were highly active and attentive to the project components and meteorological and statistical details of the project.

## 5.6. Other Participants

### 5.6.1. Dam Owners

Because the project results will be used by the sponsors in dam safety rulemaking, a number of dam owners from Colorado and New Mexico were invited to observe and provide their perspective at the seven face-to-face workshops. Representatives of the following dam owners participated in the workshops: (Colorado) Denver Water, Colorado River District, Colorado Springs Utilities, Colorado Parks & Wildlife, Northern Water, Board of Water Works of Pueblo, (New Mexico) Albuquerque Metropolitan Arroyo Flood Control Authority (AMAFCA), Elephant Butte Irrigation District (EBID), USACE (Albuquerque District), SF-Pojoaque Soil & Water District; U.S. Forest Service, and U.S. Department of the Interior, Bureau of Indian Affairs (BIA).

The project sponsors also encouraged participation by various stakeholders who provided representatives to attend the technical workshops and to provide comments. The entities who provided "observers" included: Western Water Assessment/University of Colorado at Boulder, Colorado State University, NOAA National Weather Service (Albuquerque), Conley Engineering, Wilson & Company, OCCAM, Bohannon-Huston, Inc., Stantec, and AECOM.

## 5.7. Collaboration

The sponsors, PRB, private and NOAA contractors, and dam owners and observers worked together through a series of six multi-day technical workshops to seek consensus on all aspects of the project from goals to final outcomes. A goal of collaboration between all project participants was set by the sponsors from the outset. Sponsor presentations at the kick-off workshop (for consultants) and Workshop #1 (all participants) highlighted teaming and collaborative concepts the project was striving to create. Collaboration and free exchange of ideas across the tasks was slow at the start of the project. However, the consultants, PRB members and sponsors developed a level of trust with one another over the course of the study. As the participants became more comfortable with one another and while working together toward the goals of the project, they became receptive to the idea of collaboration, and innovation occurred between the tasks. Task 3 was at a slight disadvantage since their work was more “proof of concept” and it took some time for everyone to see how the HRRR and WRF tools might be applied to positively impact the study. Collaboration between Tasks 1 and 2, each with Task 3 proved to be the most innovative and productive as those shared understandings developed. Tasks 1 and 2 also found areas for joint collaboration, especially around the concept of determining AEP of PMP.

The PRB members also became more comfortable with the collaborative process as time went on. PRBs are traditionally thought of as “independent” and that thinking can hinder collaboration and exploitation of the knowledge of those experts to the good of the project. The CO-NM REPS projects strived for “independent thinking,” but also collaboration to capitalize on the expertise of the team. The PRB provided good comments and participation throughout the project, and their work product and comfort with sharing their expertise and knowledge generally improved as the project went on.

The project sponsors also worked on collaboration between the two programs through the course of the study. Although the two programs are similar in some ways, there are differences in how each currently apply extreme precipitation results within their programs. In order to derive the greatest benefit from the study, the two programs plan to work together on implementation of the results from the deterministic PMP and precipitation frequency tasks. Collaboration will also occur as the programs work to assess the application of the various temporal distributions provided by each task.

An important lesson was learned regarding managing collaboration and time efficiency in multi-task projects. To get through the efficient review of the work of multiple tasks during each periodic workshop, after Workshop #1, the workshops were split into parallel working sessions. Task 1 and 2 consultants would each review their work in separate rooms with separate PRB members, Sponsor and dam owner reviewers/observers. This separation for necessity and efficient use of workshop time inadvertently limited collaboration. The consultants each presented their individual tasks and did not get to provide input into the other tasks presentations. Similarly, the PRB, sponsors and dam owner/observers also had to split their ranks to cover the

parallel tract working sessions, thereby limiting their exposure to the details of the other tasks.

## 5.8. State Partnership

### 5.8.1. Memorandum of Agreement

Early in the planning SME process for the project, representatives of Colorado and New Mexico Dam Safety recognized the need to formalize an agreement to share resources and benefits of the study. To facilitate this the New Mexico Office of the State Engineer provided a draft Memorandum of Agreement (MOA) which was tailored to the project. The MOA detailed the mutual benefits of a two-state regional study as well as the shared responsibilities and individual responsibilities of the two states. The MOA was signed by the New Mexico State Engineer and OSE representatives and the CWCB Director and Department of Natural Resources purchasing director. Prior to initiating the MOA, the CWCB provided a defined budget for the Colorado portion of the study. In order to determine the cost of a New Mexico share of the study an analysis was conducted of the high and significant hazard dams in each state. Spillway design for high and significant hazard dams is impacted by PMP so that was a common element. The numbers of high and significant hazard dams for each state were determined, and the relative percentage was allocated to each state. Based on that calculation the Colorado share was determined to be 77 percent of the project costs while New Mexico was responsible for the remaining 23 percent.

## 6. Project Management & Facilitation

### 6.1. Approach

The team approach to project management and facilitation provided the framework, processes, guidelines, and techniques to manage the people and the work of the CO-NM REPS. With the REPS having two sponsors, multiple consultant teams, and a large Project Review Board, the project demanded a clearly articulated vision, close collaboration, and an approach that kept the focus on the technical components of the program. To achieve these critical elements, an independent consulting firm performed project management and facilitation, while hydrometeorology consultants and experts delivered the technical tasks. This strategic division of project roles enabled the technical teams to focus their expertise on solving the tough scientific issues while the project management team navigated project management elements throughout the project lifecycle and facilitated open collaboration and targeted inputs from the PRB.

The project management team was comprised of leads from the two sponsors who provided program vision and overall program management, and dedicated project management consultants who provided day-to-day project management and meeting coordination and facilitation. Each technical consultant team had internal project management approaches that fed into the larger project execution. Working in

tandem and with clear roles and responsibilities, the whole team worked together following defined processes and protocols to collaboratively produce the technical deliverables.

Because the three distinct technical tasks were inter-dependent, strong coordination was required among and between the separate technical consultant teams. The project management team developed approaches that encouraged the open interchange of knowledge, data, products, and status to assure that the project stayed on schedule and project deliverables were consistent. With a large and diverse group of producers and reviewers located across the United States, it was critical that the team understood the objectives, adhered to project protocols and processes, and engaged in healthy dialogue and debate over complex issues. Project success was largely due to the commitment and collegiality that were fostered through facilitative methodologies.

### 6.1.1. Documents

Key project management activities included mapping out the project tasks, charting progress against that map, and periodically making course adjustments to optimize resources and achieve goals within time and budget constraints. The project management team planned and executed project management elements including scope, schedule, budget, quality, risk, human resources, and communications. The primary documents used during the study are listed below.

- **Project management plan** - A description of the roles and responsibilities of the project management team, with a focus on the project management consultants.
- **Project schedule** - A high-level project schedule reflective of scope tasks.
- **PRB charter** - A description of how the PRB supports the state agency sponsors to work toward project goals, and lays out the roles and responsibilities, work products, and associated timelines through the course of the project.
- **Status reports** - Monthly updates provided by each of the technical consultant teams to report on performed and planned work, reviewed on the monthly progress conference call.
- **Deliverables** - Iterative versions of the project deliverables, with a designed template and style guide for documents, and agreed upon functionality, design, and maintenance plans for tools.

### 6.1.2. Tools and Technologies

The project management team leveraged a group of tools and technologies to support efficient and transparent processes and work towards end deliverables, as listed in Table 2.

*Table 2. Tools and Technology*

Use Type	What and How Technology was Used
Verbal Communication & Conferencing	<ul style="list-style-type: none"> <li>• Telephone for direct calling</li> <li>• Conference call platform to schedule, run, and record audio conference, and to share screens and documents visually (e.g., UberConference)</li> <li>• Audio-visual capability for in-person meetings to enable people to participate remotely if necessary</li> </ul>
Written Communication	<ul style="list-style-type: none"> <li>• E-mail for formal and informal written communications</li> <li>• Team messaging system for internal communications between individuals, working groups, and entire team (e.g., Slack)</li> </ul>
Meeting Scheduling	<ul style="list-style-type: none"> <li>• Software to inform meeting dates on times (e.g., Doodle Poll)</li> <li>• E-Meeting invitations to calendar events and provide up-to-date information</li> </ul>
Document Management	<ul style="list-style-type: none"> <li>• Documents with widely used software (e.g., Microsoft)</li> <li>• Shared drives and workspaces to store and organize project documents (e.g., Google Drive)</li> <li>• Shared documents to allow multiple users to view and edit documents (e.g., Google Documents)</li> </ul>

### 6.1.3. Meetings

Throughout the project, the group had effective and efficient meetings, which served as touchpoints to connect, collaborate, solve problems, exchange feedback, and assure project initiatives were being met. Specifically, the team deployed four primary types of meetings throughout the project as described in Table 3.

*Table 3. Meeting Types*

Meeting Type	Description	Frequency & Duration	Participants	Inputs	Outputs
Workshops	Large, in-person meetings with presentations and working sessions to review progress, problem-solve, and plan the paths forward	Quarterly (7 meetings in total) 2-3 days in length, depending on need	Sponsors, PRB, consultants, observers (dam owners and other interested parties)	Agenda, technical materials, presentations, project trackers, other documents, list of technical items decisions, logistics	Decisions, meeting documentation, next steps and actions, PRB report
Technical Meetings	Conference calls and webinars to provide status updates, discuss project business, and identify next steps	Monthly, 2 hours in duration; and ad hoc based on need	Sponsors, technical and project management consultants	Agenda, technical materials, project trackers, documents, logistics	Meeting notes, next steps and actions

Meeting Type	Description	Frequency & Duration	Participants	Inputs	Outputs
PRB Meetings	Conference calls and webinars to discuss PRB technical issues and recommendations	Monthly or as needed, with particular emphasis before and after workshops	PRB	Agenda, logistics	Meeting notes, next steps and actions
Ad hoc Meetings	In person or virtual meetings and presentations between 2 or more people for a specified purpose	Varied	Varied	Varied	Varied

The workshops and technical meetings were facilitated or co-facilitated by the project management consultant and the sponsors. (The PRB facilitated its own internal meetings independent of technical consultants to facilitate candid and robust dialogue and debate on complex issues between PRB members). For the project as a whole, facilitation had the following objectives and outcomes:

- Developed an efficient, transparent, and respectful culture of open coordination and collaboration between all team members;
- Invited and honored different opinions and viewpoints between team members;
- Kept the group on task to meet objectives within time and budget constraints; and
- Mediated and resolved conflicts and technical disagreements.

## 7. Project Accomplishments

### 7.1. Updated Tools

#### 7.1.1. REPS PMP Tool

Based on the work performed during this study Task 1 developed the REPS PMP Tool for estimating deterministic PMP rainfall depths and temporal distributions. The REPS PMP tool

([https://drive.google.com/drive/folders/1BwS5VLnQ6\\_5N\\_NWjfgbLUPV42letex4n?usp=sharing](https://drive.google.com/drive/folders/1BwS5VLnQ6_5N_NWjfgbLUPV42letex4n?usp=sharing)) is a GIS-based PMP calculation tool developed to automate the basin-specific PMP calculation process. The REPS PMP tool is Python scripted and runs from a Toolbox in the ArcGIS desktop environment. The tool accepts a basin polygon feature as input and provides gridded, basin average, and temporally distributed PMP depths as output. These PMP output elements can be used with hydrologic runoff modeling simulations for PMF calculations. Full documentation of the PMP tool usage

and structure is found in Appendix G of Volume II. The PMP tool can be used to calculate PMP depths for the following storm types and durations:

● **Local Storm PMP Durations:**

1-, 2-, 3-, 4-, 5-, 6-, 12-, and 24-hour

● **General and Tropical Storm (below 38.5° latitude only) PMP Durations:**

1-, 6-, 12-, 24-, 48-, and 72-hour

The REPS PMP tool provides PMP depths (areal average and gridded) for the drainage basin area size; therefore, no areal reduction factors are needed. Output from the tool allows the user to see detailed information about the storm or storms driving the PMP values calculated. Information of the PMP driving storm(s) including original storm characteristics, IPMF, transposition limits, and all storm adjustment factors (e.g. MTF, GTF, TAF) are provided as part of the output so the user is fully informed and can assess the validity of the results. This tool documentation is a significant advancement over the HMR derived results.

In addition to the PMP rainfall depth estimates, the REPS PMP Tool also provides a range of temporal distributions to utilize in hydrologic rainfall-runoff modeling. The user can research which temporal distribution provided is most applicable to their basin to estimate the runoff for spillway adequacy analysis and design.

### 7.1.2. MetPortal PF Tool

The Task 2 Regional Precipitation Frequency results provide rainfall and AEP estimates via the cloud-based MetPortal tool (<https://conm-reps-gui.shinyapps.io/metportal/>). This is an interactive, public-facing on-line Graphical User Interface (GUI) for data delivery and includes a downloadable User Guide. Output includes precipitation-frequency estimates and 90 percent confidence bounds for a point or for an uploaded watershed for each storm type. Precipitation Frequency estimates are provided for annual exceedance probabilities (AEPs) ranging from  $10^{-1}$  to  $10^{-7}$ . Spatial and temporal precipitation patterns and freezing height climatologies are also available via the MetPortal for integration into watershed models.

For users with the capabilities and need, the MetPortal Tool provides the necessary input to perform full probabilistic Hydrologic Hazard Assessments for the basins and dams of interest. The most basic application of the MetPortal PF tool results is to calculate the equivalent precipitation frequency AEP of REPS PMP estimates, to serve as a fully independent check. This application allows the user to build confidence in the results and also develop an understanding of what uncertainties might exist.

## 7.2. Beta Testing and Quality Assurance Review

Beta testing of the draft REPS PMP and MetPortal precipitation frequency (PF) tools began in March 2018 after preliminary PMP and PF tools were released by the Task 1

and 2 consultants. Beta testing of the PMP and PF tools was performed by the sponsors, dam owners, and engineering consultants on a representative sample of test basins. Test basins were selected to cover all PMP transposition zones and PF climate regions and to represent a variety of basin area sizes. Figure 1 below shows Colorado test basins used in the beta testing.

Early basin-specific testing of the draft tools allowed focused comparison of results versus generalized comparison maps; in some cases basin-specific results revealed unusual results when compared with previous studies or compared to regional knowledge of climate conditions. The nature of a large regional study is such that decisions are applied liberally at first; beta testing results helped the consultants make refinements. Refinements included storm transposition limits and reanalysis of controlling historical storms where results seemed suspect.

Beta testing of the PF tool provided consideration of the effects of climate regions, storm typing, differences between NOAA Atlas 14 methods, and the advanced statistical basis of the results.

Comparing the draft results from the tools to each other also provided a valuable consistency check. Summary results of beta testing were reported to the task consultants and to the PRB at Workshop #6. All parties agreed that the beta testing results were very useful.

The beta testing led into a more general quality assurance (QA) review by the sponsors during the last three months of the study. QA review for PMP included detailed checks of controlling historical storms, storm transposition limits, and elevation reduction factors. QA review for PF estimates included consistency checks between frequency curves for various durations, comparisons to spatial variation in PMP, and statistical checks of AEPs of observed events.

Beta testing and QA review procedures and results are discussed in greater detail in Appendix F.

CO-NM Regional Extreme Precipitation Study

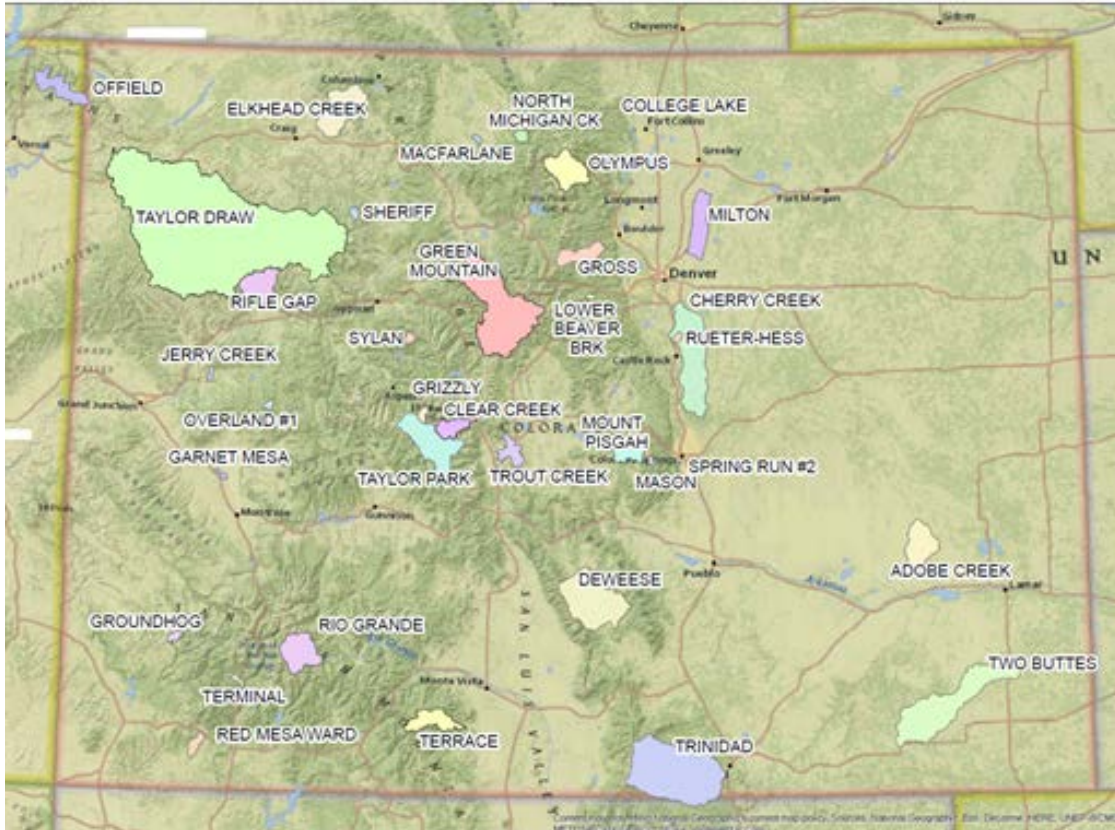


Figure 1. Colorado REPS test basins for beta testing PMP and PF Tools.

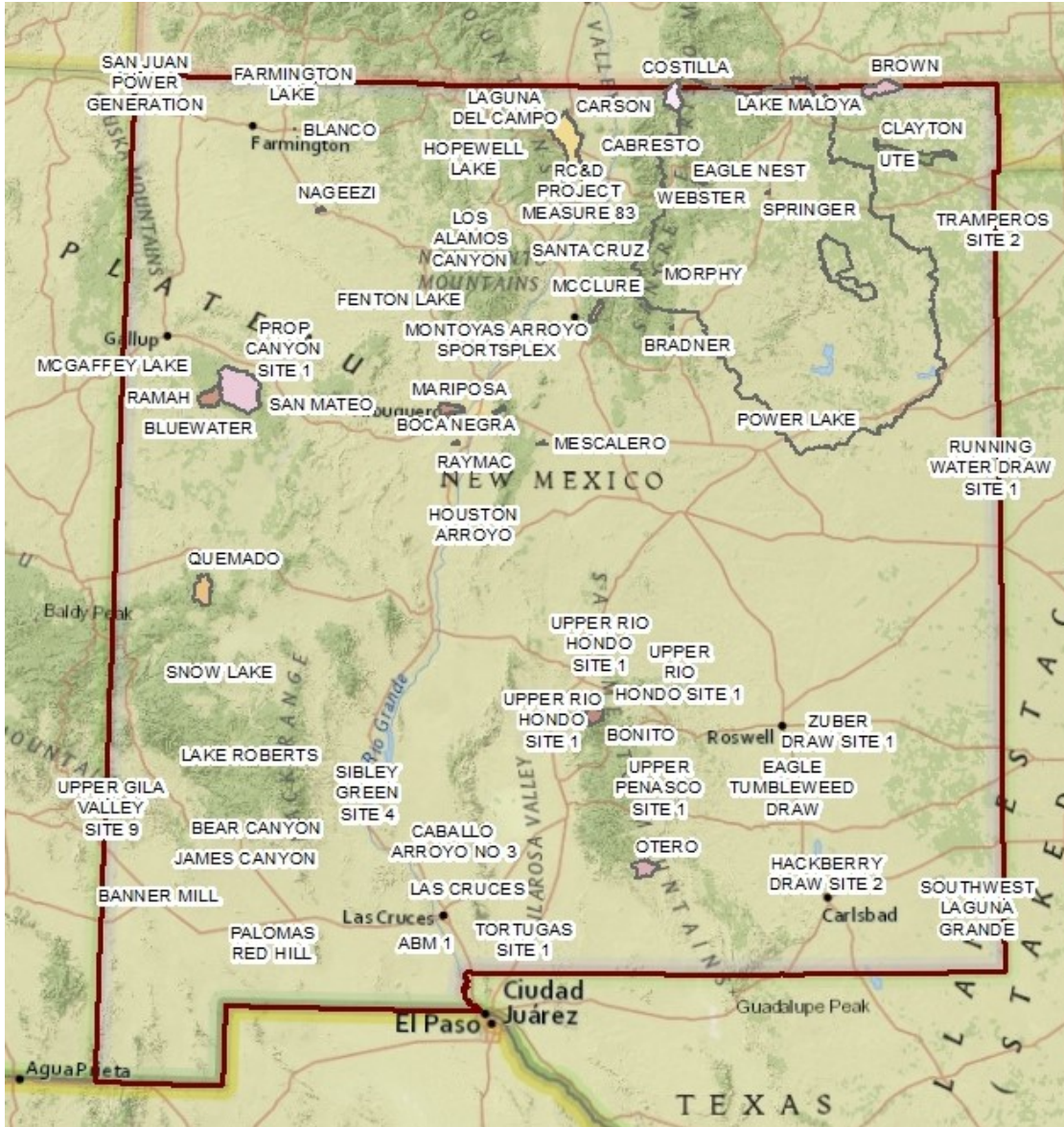


Figure 2. New Mexico REPS test basins for beta testing PMP and PF Tools.

### 7.3. PRB Input

As discussed above, the PRB participated in review and discussion as the consultants described their processes in the workshops and worked on reporting of how they developed the project deliverables (Tools). The PRB provided reports to the project team at the end of each workshop. All PRB project review reports are documented in Appendix C. Near the end of the project the PRB spent considerable time thinking about the differences between the CO-NM PMP and PF tools as compared to the HMRs. Appendix G contains a report presented to the sponsors by the PRB chairman. This report documents PRB member observations and thoughts regarding differences in methodology between the old HMR PMP standard and the new 21st century PMP standard developed by the CO-NM REPS project.

## 7.4. Updates and Improvements in Standard of Practice

The availability of updated climate and storm data since the HMR 49 (1977) and HMR 55a (1988) is a key factor, along with advances in scientific knowledge and computing capabilities that lends credence to and builds confidence in the methods and results of the CO-NM REPS project. The project technical consultants and PRB members each brought knowledge of how to obtain and apply the data and analysis method updates to their portions of the study. The following are highlights of updates and improvements accomplished that establish this project as defining the 21<sup>st</sup> century PMP.

### 7.4.1. Deterministic PMP Analysis

Selected key advances that lead to confidence in the results of the CO-NM REPS Deterministic PMP analysis include the following:

**Improved storm coverage** - Years of research resulted in identification of historical extreme storms for the Rocky Mountain region beyond those used in the HMRs. Additionally, NEXRAD radar has provided more complete coverage of the area and more accurate re-construction of storms that occurred since the 1990s. Finally, the REPS study updated the storm list to include extreme storms that have occurred since the HMRs were published in the 1970s and 1980s.

**Transposition Limits** - As a result of having more complete extreme storm coverage, the REPS study was able to use more reasonable transposition limits. Faced with a limited number of storms, the HMRs often applied broad transposition limits that may have smoothed over important topographic and elevation variations. In the REPS study, the large storm set allowed storm transposition to be more local and preserved regional variation. Numerous modern tools like the geographic transposition factor Task 2's precipitation frequency estimates provided objective checks of storm transposition limits.

**Storm Representative Dew Points** - More accurate storm representative dew points (used for storm maximization) were developed by refining representative storm durations, using NOAA's HYSPLIT moisture trajectory model, and calculating moisture travel times from source to storm location.

**Dew Point frequency climatology** - Task 1 has developed modern dew point frequency climatology at various durations using modern data sets. The calculation of various durations allows the maximization to occur for the duration of a storm's core rainfall, whereas HMRs used maximum persisting 12-hour dew point data regardless of storm duration.

**Depth-Area-Duration (D-A-D) Analysis** - The SPAS processes to develop D-A-D tables for historical storms include; GIS-based gage-weighting and interpolation, quality-control consistency checks, and use of climatological basemaps for storm pattern interpolation. SPAS can also incorporate NEXRAD data for storms that occurred since the mid-1990s. Use of climatological basemaps more accurately represents what

occurs between known rain gauge observations. Separation of different storm centers, within a single weather event, into separate D-A-D zones results in more accurate and realistic time and space depictions of those storms. In past analyses, dis-contiguous storm centers may have been combined into a physically unrealistic D-A-D table.

**Gibson Dam Storm** - Based on the results of the PRB analysis of the Gibson Dam storm and the recommendations they provided (Appendix G), the sponsors performed a sensitivity analysis comparing PMP with and without the Gibson Dam storm (see Volume I, Appendix F). The sponsors then directed the Task 1 consultant to include the Gibson Dam storm in the final short list of storms and the REPS PMP Tool.

These and other state-of-the-science advancements in deterministic PMP analysis utilized in this study are more fully described in the Task 1 - Volume II report.

#### 7.4.2. Regional Precipitation Frequency Analysis

The inclusion of precipitation frequency in a PMP study was in itself an advancement in the state-of-practice. Further, key advances that lead to confidence in the results of the CO-NM REPS Regional Precipitation Frequency analysis include the following:

**Storm Typing** - The automated storm-typing methodology established by the Task 2 consultant was a key advancement in the regional precipitation frequency analysis portion of the study. As described in greater detail in the Volume III report, this resulted in better fit by probability distribution models and reduced uncertainty when extending statistical estimates of extreme rainfall to AEP's smaller than  $10^{-3}$ .

**Synthetic Temporal Distribution Curves** - Development of synthetic temporal distribution curves for each of the storm types and based on observed extreme storms from the study region allows more realistic rainfall-runoff modeling.

**Areal Reduction Factors** - Geographically-fixed Stochastically generated ARFs for use with precipitation frequency estimates were developed each storm type. No precipitation frequency ARFs were previously available for the study region.

**Web Based Tools** - The development of the web-based MetPortal PF application will enable users to efficiently study their basins of interest. This platform will allow seamless periodic updates and error corrections and will also be expandable to include additional regions as interest grows in utilizing these state of the practice tools.

#### 7.4.3. Application of Dynamical Models

The application of dynamical models for the estimation of extreme precipitation was a proof-of-concept effort that proved fruitful in several areas including:

**Historic Storm Re-analysis** - As detailed in the Task 1 (Volume II) and Task 3 (Volume IV) reports, the WRF model reanalysis of key historic storms provided valuable

information that improved confidence in deterministic PMP estimation results. This is truly ground breaking work that reduced uncertainty in CO-NM REPS results and holds promise for future projects.

**Rain vs Snow** - Inflow design flood analysis pertinent to spillway design is generally based on warm-season liquid precipitation (rain) as the forcing variable. But PMP estimation currently relies on climatology data that is sometimes contaminated by frozen precipitation (snow). Task 3 scientists were able to use the HRRR model to calculate gridded ratios of rain to total precipitation (rain and snow) in the high elevation areas of the CO-NM region and incorporate that knowledge into the study results.

**Spatial Patterns** - The HRRR model provides high-resolution spatial output, and therefore captures entire storm spatial patterns. Task 2 utilized storm spatial patterns from the HRRR dataset (along with historical storm patterns from Task 1) for their stochastically generated ARFs.

**Data Gap Filling** - Task 1 and 2 methods each rely on recorded observations of weather and storms. In remote areas across the CO-NM REPS region and elsewhere weather records are nonexistent resulting in gaps between spatially distant recording stations. Task 3 use of the HRRR model was able to provide scientifically valid weather and climate data to improve upon traditional assumptions and/or interpolation methods used to fill those gaps and improved the results from both the Task 1 and Task 2 analyses.

#### 7.4.4. Comparison of Independently Derived Results

One of the most significant aspects of this ensemble approach using two distinct methods to derive extreme precipitation estimates is the ability for independent comparison. Deterministic PMP process is based on transposition of the most extreme historical storms. Regional precipitation frequency analysis is a regional L-moment statistical analysis of historical weather station data. The two methods can be used as a cross check of the results. The Task 1 and 2 reports and appendices contain data that forms the foundation of the methods. Appendix F shows how the QA/beta testing processes utilized this information to verify the results.

## 8. Lessons Learned

Lessons were learned in all phases of the study. The following is a list of some of those lessons, organized by the phase of the project.

### **Project Development/Scoping/Financing**

- The regional approach combining states was easier than initially thought, but still took time and had to consider the bureaucracies involved.
- Leadership is key to a regional study and a lead state or agency should be identified early in the process.

- The ensemble approach was considered novel during scoping and was admittedly complex. However, those involved were enthusiastic about the potential benefits which enabled logistical obstacles to be overcome.
- The project management task was invaluable. The project would not have been completed without a dedicated outside project manager.
- Assembling a Project Review Board and also a time consuming and difficult task but also worth the effort. Future projects should focus on assembling smaller PRBs, with expertise aligned with the tasks included in the project.
- PRB members and their agencies should be contracted and compensated to ensure appropriate time and dedication is provided for their review.
- The project schedule should include defined periods of time after delivery of working tools to allow for several periods or iterations of beta testing and tool revision.
- All entities responsible for financing regional projects should engage in fund raising activities concurrently to ensure smooth project delivery.
- Informal discussions with technical consultants should be conducted to establish the likely “domain” for the project with consideration being given to the storm search limits of the deterministic PMP task, such that those can be used to establish the limits of the Regional Precipitation Frequency domain to enable project specific PF climatologies to be utilized.

### Project Execution

- Time should be explicitly allocated in the schedule for early work sessions involving project participants to discuss the technical aspects of each other’s work. Sufficient time should be allocated and facilitation provided for all tasks to fully discuss and identify potential areas of collaboration, conflict and opportunities for innovation.
- Workshop agendas for the recommended multi-task projects should consider a serial track for presentation and discussion of the topics. Although this will require longer workshops, it will enable all project members to participate in discussion of each topic and become knowledgeable about all technical aspects which will increase the potential for identification of opportunities for collaboration and innovation.
- The project tools are the heart of the project and arguably the most critical deliverable. Tool development is an iterative process and at least three iterations of review should be planned for. This will enable all team members, especially the PRB to be familiar with decisions being made from beginning to end of tool development.
- Beta and QA/QC testing of the tools and the results they generate for a wide range of basin sizes and locations within the project domain should be a defined part of the project. This activity can be executed by the sponsors’ staff or by engineers familiar with the study area. Evaluation of transposition zones, controlling storms, areal reduction factors, statistical anomalies and comparison of AEP of PMP should be included.

- PMP and RPF tools delivered via web-based platforms offer advantages with respect to periodic updating, enhancements and standardization and should be pursued on future projects.

### Project Implementation

- Implementation of the results of the project should be considered in advance of project completion.
- Attempts should be made to implement the results of PMP and PF studies as soon as practical after studies are completed.
- Implementation should include development of standard comparisons with existing or replaced methods. Skepticism will exist regarding the validity of the new method results versus old methods results and standardizing comparisons that provide transparency can be used to build confidence in the newer state-of the practice methods.

## 9. Next Steps

### 9.1. Implementation

Several significant new dam and dam rehabilitation projects in Colorado have been waiting for the results of the CO-NM REPS study to complete spillway design aspects. There is therefore a need for immediate implementation of the project results. Revisions to the Colorado Rules and Regulations for Dam Safety and Dam Construction are in the process of being finalized now that the REPS project is finished. Use of results from both the REPS Tool and MetPortal tool results will be incorporated in the new Rules and promulgation of those Rules is anticipated in summer of 2019. To satisfy the immediate projects needs and keep on-going projects moving forward, Colorado Dam Safety has developed a set of interim Rules and requirements and is working with selected engineering firms to utilize and evaluate these interim rules. Lessons learned from this “soft roll out” will be incorporated into final Rules.

The New Mexico Dam Safety Bureau also has plans to implement the CO-NM REPS PMP Tool and MetPortal Tool into their program. New Mexico dam owners can immediately apply the revised PMP rainfall data under current regulations for design of high and significant hazard dams. The AEP rainfall values can be applied to the design of low hazard potential dams as well. Application of AEP values for risk-based analysis can be applied in New Mexico following consultation with the Dam Safety Bureau. The practice of risk-informed decision making has not been implemented at the state level in New Mexico but it will become a part of dam safety practice in the near future. Under current New Mexico regulations a full risk-based analysis for spillway modification would likely require a waiver from the State Engineer so it will be important to create a process that can be applied consistently. That process must be examined and implemented by the bureau as soon as practical.

Task 1 and Task 2 provided new temporal distribution inputs that can be used for hydrologic modeling of runoff response. At this writing the need remains to evaluate these distributions so that future modeling efforts can be focused toward cost-effective evaluations. The New Mexico Dam Safety Bureau plans to continue to test these and other hydrologic elements and will continue to work with interested parties to that end. The Bureau will be updating its guidance document for hydrologic modeling to include the new REPS tools and their application in 2019.

## 9.2. Outreach and Awareness

As of this report writing, Colorado Dam Safety has begun to utilize the CO-NM REPS PMP and MetPortal tools. Additional testing is being completed by staff within the program and also by consulting engineers at the request of dam owners for on-going design projects. Based on the limited engagement with the consulting community, and staff engineers who did not follow this project and are using the tools for the first time, it is obvious that some form of education, outreach and awareness is necessary. Engineers have obtained results from the new tools and have expressed skepticism and uncertainty, questioning both decreases and increases observed in rainfall depths as compared to the outdated HMR methods and previous Rules (that utilized arbitrary reduction factors) with which they are familiar.

To address this obvious need, Colorado Dam Safety has begun to establish standard reports and comparisons. The goal is for transparency and education and this will be delivered by showing users the results of the tools and providing the extensive background information available both in the tools and the technical reports. We plan to provide step by step methods to enable users to extract key information from the tools and documentation so they can understand how the results were derived. Information is readily available and easily accessible regarding controlling storms, all adjustment factors, depth-duration information for all storms considered and also recommended temporal distributions. The sponsors will demonstrate the validity and accuracy of the CO-NM REPS tool results. In doing so, it is hoped that this will highlight the dated nature of HMR methods and the relative lack of documentation in HMRs available to the user.

Sponsors staff plan to develop multiple presentations to show various aspects of this complex project for different audiences and purposes. The sponsors have identified the need for presentations showing a project overview, presentations detailing each technical task, and presentations demonstrating how to review the results and provide objective comparisons with the existing established methods. The sponsors recognize the need for “marketing and education” to enable users to understand the advances made by the CO-NM REPS project and confidently see the advantages of utilizing the new tool in the interest of safety and engineering efficiency.

## 9.3. Standard of Practice Development

Sponsors will finalize the “draft Standard of Practice” document in 2018 and then begin work with federal agencies with interests in dam safety and standardization of

dam safety practices. As described in Section 4.2, FEMA's National Dam Safety Program (NDSP) and the National Dam Safety Review Board (NDSRB) have expressed interest in working toward a Federal Dam Safety Guideline document for extreme precipitation estimation.

The sponsors plan to leverage the momentum and achievements of the CO-NM REPS project to make advances on this project goal. The sponsors are also committed to continuing to lead efforts toward consistent 21<sup>st</sup> Century PMP and PF tools for state dam safety programs nationally.

#### 9.4. Future Research

The Volume VII - Topics for Future Research outlines possible topics for extreme precipitation researchers to pursue. The sponsors are also committed to supporting those efforts as they can. We hope to continue to work with partner agencies at NOAA ESRL PSD on WRF and HRRR dynamical model applications and the Western Water Assessment on climate change aspects for extreme precipitation. We also look forward to working with researchers like Dr. Ken Kunkel toward exploring other aspects of extreme rainfall estimation. Funding is needed for research to advance extreme precipitation estimation. Although the REPS study made many advancements, it is clear that there is much left to learn. ACWI's Extreme Event Work Group proposal has recommended a federal role in funding extreme precipitation research, as part of updating and maintaining national products, such that the problem of the outdated HMRs is not repeated.

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## Appendices

APPENDIX A - PRB Charter

APPENDIX B - PRB Invitation Letters, PRB Acceptance Letters

APPENDIX C-1 - Workshop Agendas

APPENDIX C-2 - Workshop Presentations

APPENDIX C-3 - PRB Workshop Reports and Consultant Responses

APPENDIX D - Monthly Technical Meetings

APPENDIX E - WWA/DWR/AWA Partnership Research Proposal

APPENDIX F - Beta Testing and Quality Assurance Review APPENDIX

G - PRB Report to Sponsors

APPENDIX H - Project Outreach Handouts