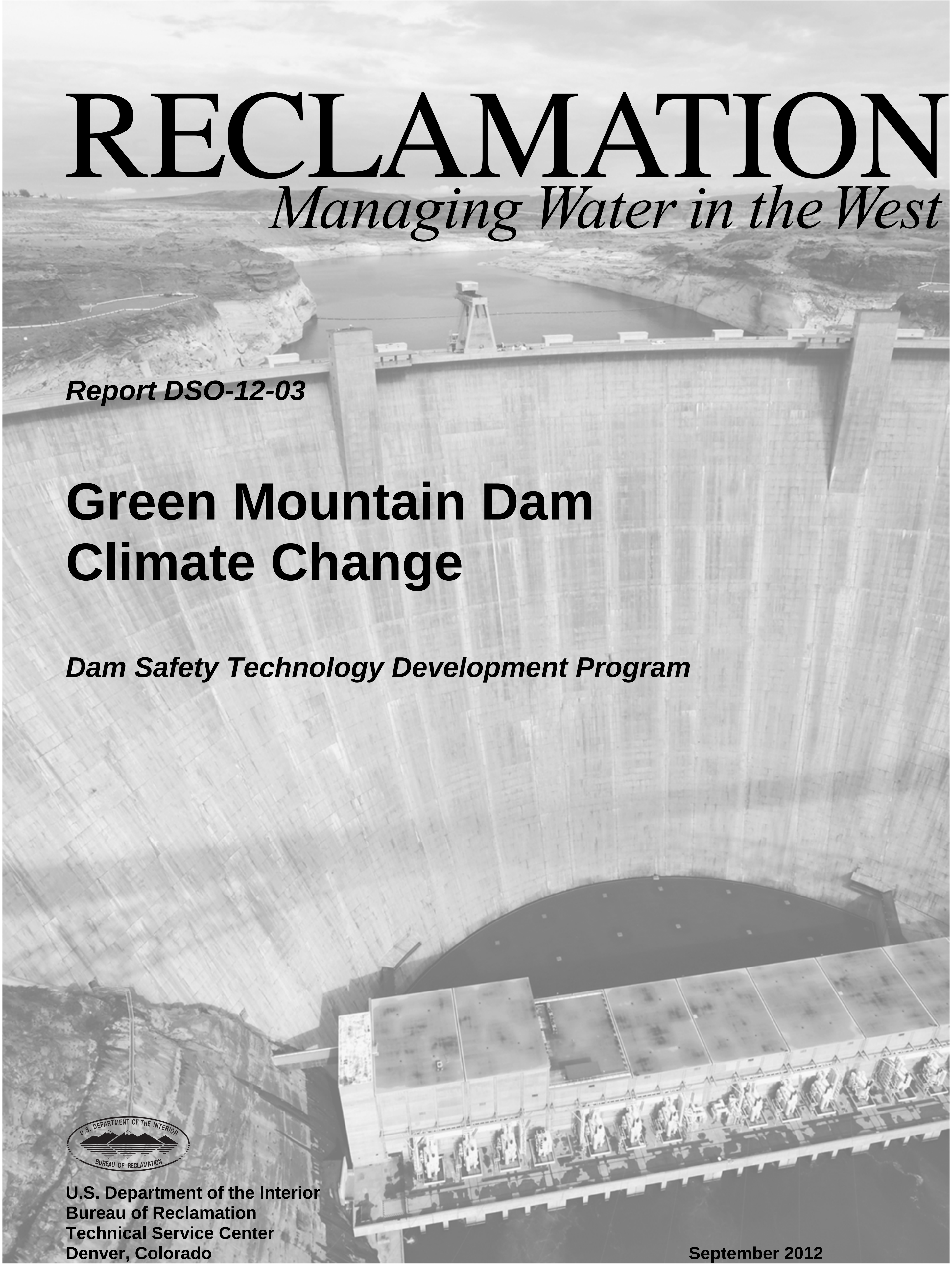

RECLAMATION

Managing Water in the West

Report DSO-12-03

Green Mountain Dam Climate Change

Dam Safety Technology Development Program

U.S. Department of the Interior
Bureau of Reclamation
Technical Service Center
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14. ABSTRACT

The Weather Research and Forecasting (WRF; Skamarock et al., 2007) model was investigated to understand its capabilities concerning its ability to model historic, large precipitation events; allow model users to maximize storm parameters; and allow model users to perturb storm parameters for climate change scenarios. Extreme storms in the vicinity of the Green Mountain Dam watershed were examined due to the orographic nature of the region and as a result of ongoing questions concerning high-elevation precipitation estimates originating from the *Hydrologic Hazard Study for Green Mountain Dam*. Two historical storm events that occurred in the vicinity of the Green Mountain watershed were modeled using the WRF model. The 4-6 Sept. 1970 storm event was deemed sufficient to serve as the basis for experiments for moisture maximization and climate perturbation simulations. This proof-of-concept study demonstrates that the WRF model is capable of simulating extreme storms in orographic locations within the vicinity of Green Mountain Dam. This modeling approach offers potential utility for use in model-based storm-maximization and climate-change assessment studies. The results presented in this study are considered preliminary and exploratory in nature. Running a high resolution model requires significant resources and, for the results to be robust, further improvements to the research methodology and additional applications are required. Based on the preliminary results, the WRF model is beneficial to the extreme storm analysis process needed for Dam Safety Hydrologic Hazard Analyses.

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Green Mountain Dam
Climate Change

Dam Safety Technology Development Program

prepared by

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Dam Safety Technology Development Program
Flood Hydrology and Consequences Group, 86-68250

DSO-12-03

Green Mountain Dam Climate Change

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Abstract

The Weather Research and Forecasting (WRF; Skamarock et al., 2007) model was investigated to understand its capabilities concerning its ability to model historic, large precipitation events; allow model users to maximize storm parameters; and allow model users to perturb storm parameters for climate change scenarios. Extreme storms in the vicinity of the Green Mountain Dam watershed were examined due to the orographic nature of the region and as a result of ongoing questions concerning high-elevation precipitation estimates originating from the *Hydrologic Hazard Study for Green Mountain Dam*. Two historical storm events that occurred in the vicinity of the Green Mountain watershed were modeled using the WRF model. The 4-6 Sept. 1970 storm event was deemed sufficient to serve as the basis for experiments for moisture maximization and climate perturbation simulations. This proof-of-concept study demonstrates that the WRF model is capable of simulating extreme storms in orographic locations within the vicinity of Green Mountain Dam. This modeling approach offers potential utility for use in model-based storm-maximization and climate-change assessment studies. The results presented in this study are considered preliminary and exploratory in nature. Running a high resolution model requires significant resources and, for the results to be robust, further improvements to the research methodology and additional applications are required. Based on the preliminary results, the WRF model is beneficial to the extreme storm analysis process needed for Dam Safety Hydrologic Hazard Analyses.

1. Introduction

This research was completed for the Reclamation Dam Safety Office to understand the capabilities of the WRF model for storm analysis in highly orographic regions, relevant for dam safety applications. The focus is on the Green Mountain Dam watershed. Specifically, this research attempts to model a historical storm event that occurred in the vicinity of the watershed. It is then anticipated that perturbations can be made to the storm to 1) maximize moisture and 2) simulate the storm under climate change conditions.

The first section of the report further discusses the background and research objective. Section 2 provides an overview of the previous studies that have been completed for Green Mountain Dam and their relevance to this research. Section 3 describes the storms selected for analysis in the model. Section 4 briefly highlights the Weather and Forecasting Research Model, followed by Section 5 which describes the methodology that was used to analyze the storms using the model. Section 6 discusses the preliminary model results. Section 7 summarizes the research and comments upon the feasibility of the model in future Dam Safety Hydrologic Hazard studies. This report concludes with Section 7, a description of anticipated future work.

1.1. Research Background

A *Hydrologic Hazard Analysis for Issue Evaluation for Green Mountain Dam* was finalized in early 2011 (Dworak et al.). A companion paleoflood study was also completed (Godaire and Bauer, 2011). While working on the report, questions arose concerning the validity of the Probable Maximum Precipitation (PMP) estimates found in *Hydrometeorological Report No. 49* (HMR 49; Hansen et al., 1977), which hasn't been updated since 1977. Specifically, is a storm of PMP magnitude (18.58 inches in 72 hours for the Green Mountain Dam watershed) physically able to develop in the highly orographic region where Green Mountain Dam is located or is HMR 49 providing unrealistically high PMP estimates? Current paleoflood data suggest that floods of this magnitude (and the storms that would have resulted in these large floods) have not occurred in the last 2,000 years (Godaire and Bauer, 2011). Due to time and budge limitations, this question was considered in the Dam Safety Issue Evaluation report but additional research could not be completed.

The question of the validity of PMP estimates in highly orographic areas is not limited to Green Mountain Dam. The same issue arises at all dams in mountainous regions, including, but not limited to: Anderson Ranch, Arrowrock, Granby, Twin Lakes, Rifle Gap, Ruedi, and Olympus. Furthermore, are PMP estimates in orographic areas valid in a changing climate? Dr. Kelly Mahoney has recently completed climate change research that was jointly funded by the Reclamation Science and Technology Program and the National Oceanic and Atmospheric Administration (NOAA) through the Postdocs Applying Climate Expertise (PACE) post-doctoral program. Her research on climate change suggests that precipitation in higher elevations of the Colorado Front Range may fall as rain as opposed to its current form of hail (Mahoney et al., 2010; Mahoney et al., 2012). If higher elevations experience additional rain and runoff, then the flows of large floods could potentially be greater under climate change scenarios, but additional investigations would need to be done to evaluate any increases.

Dr. Mahoney has modeled past and future extreme precipitation events using the WRF model. Her focus region has been the Colorado Front Range. Since Green Mountain Dam is located within the study region, it is thought that Dr. Mahoney's research will be able to provide insight into the possibility and reasonableness of a storm with PMP magnitude to occur in this and similar highly orographic watersheds, now or in the future.

1.2. Research Objective

The objective of this research is two-fold: 1) to examine the atmospheric conditions in which a storm with extreme rainfall magnitudes (i.e. a storm approaching PMP) could occur in the highly orographic Green Mountain Dam watershed, and 2) to examine the precipitation field in a future climate change environment. To do so, an observed, historical large precipitation event that occurred previously in the area will be identified. The characteristics of this storm will be studied, and the storm will be modeled using WRF. Once successfully modeled in WRF, relevant weather variables of the storm (e.g. moisture, temperature, etc) would be maximized in the model to ascertain how the precipitation field responds. The resulting, maximized storm will then be compared to HMR 49 PMP estimates, as well as to the precipitation values and paleoflood data provided in the Green Mountain Dam Issue Evaluation.

This project is a proof of concept study. It is an initial investigation examining an advanced methodology. Eventually, simulations of storms utilizing the WRF model may be integrated into the storm analyses for hydrologic hazard studies. This study provides the initial step of examining the capabilities of the WRF model.

The WRF model is investigated to understand its capabilities concerning its ability to:

1. model historic, large precipitation events;
2. allow meteorologists to maximize storm parameters;
3. allow meteorologists to examine how storms may change with climate change;
4. help meteorologists to understand the dynamics of an extreme event; and
5. show how the meteorological aspect of Dam Safety projects could benefit and be improved by the latest extreme storm data and modeling technologies.

2. Previous Storm Rainfall and Flood Studies

Previous storm rainfall and flood studies were reviewed to aid in the identification of an observed, historical large precipitation event that occurred in the vicinity of the Green Mountain watershed. They are also presented as background information that motivates this extreme storm research study.

2.1. Design Storm for Dillon Dam

Dillon Dam is located 25 miles upstream of Green Mountain Dam (Figure 1) and is owned and operated by Denver Water. All flood studies for Green Mountain Dam include the Dillon Dam drainage basin as part of the Green Mountain Dam watershed; specifically, Dillon Dam controls 56% of the Green Mountain watershed (Bureau of Reclamation, 1987). The dams may not be operated directly in sequence (due to the difference in dam operators), but the meteorology should be consistent over this area. We considered the data and analyses from the *Design Storm for Dillon Dam* study prepared for Denver Water (Bertle, 1982) in this storm research.

The Bertle study considered four types of storms, defined by the source of moisture: northwest Pacific, southwest Pacific, Gulf of Mexico, and summer thunderstorms with moisture originating from the Gulf of Mexico. In the formulation of the design storm, 40 major storms were reviewed. Of those 40 storms, 11 storms were considered critical to the Dillon Dam watershed.

The 11 critical storms were reviewed in great depth and transposed to the Dillon Dam watershed (Table 1). After transposition, the moisture associated with each storm was adjusted to the elevation of the watershed.

Figure 1 – Location map of Green Mountain Dam and Dillon Dam

Table 1 – Critical storms used in the derivation of the Dillon Design storm (Bertle, 1982)

Date	Center
1-3 June 1943	Glenwood Springs, CO
17-18 May 1944	East of Steamboat Springs, CO
7-8 June 1964	Spillover from Glacier Park, MT
5-7 Oct. 1970	Northeast of Steamboat Spring, CO
4-6 Oct. 1911	Gladstone, CO
1 Aug. 1968	Blanding-Monticello, UT
4-6 Sept. 1970	Bug Point, UT
4-6 Sept. 1970	South of Silverton, CO
3 Aug. 1924	Mesa Verde National Park, CO
27 July 1937	Leadville, CO
16 Aug. 1968	Morgan, UT

Depth-duration data from all storms were plotted on a single graph, and the results were enveloped to determine the design storm. The final design storm for Dillon Dam had a duration of 48 hours with an accumulated rainfall of 7.97 inches (for the 335 mi^2 basin; see Table 2). The temporal pattern of the storm was front-loaded (i.e., decreasing incremental rainfall in time), but a caveat was provided stating that rearrangement of the incremental precipitation estimates is acceptable. The seasonality of the design storm was both the spring and fall seasons. A storm spatial pattern was not provided (Bertle, 1982).

The *Design Storm for Dillon Dam* study (Bertle, 1982) did not incorporate general storm precipitation estimates provided by HMR 49 (Hansen et al., 1977) in their derivation of the design storm. In the report, it was noted that ‘none of the storms analyzed support the severity of the HMR 49 curve’ (Bertle, 1982). It was further suggested that the PMP estimates for Dillon Dam, as derived by the methodology outlined in HMR 49, were not appropriate for this remote, high-elevation, orographic watershed.

Table 2 – Accumulated rainfall in inches for the Dillon Dam Design Storm (Bertle, 1982)

Duration (hrs)	Accumulated Rainfall (in)
1	1.05
2	1.83
3	2.26
4	2.63
5	2.98
6	3.31
8	3.91
10	4.50
12	5.06
14	5.49
16	5.86
18	6.19
20	6.46
22	6.72
24	6.95
30	7.54
36	7.87
42	7.94
48	7.97

2.2. Green Mountain Dam Probable Maximum Flood Study

A probable maximum flood study was completed for Green Mountain Dam by the Reclamation Missouri Basin Region Hydrology branch in conjunction with the Reclamation Flood Hydrology section (Bureau of Reclamation, 1987). Methods outlined in HMR 49 (Hansen et al., 1977) were used to compute PMP. Both a general storm PMP and a local storm PMP were considered.

The general storm PMP was estimated for the months of May, June and July, but maximum precipitation was thought to occur in June. The storm was centered on the area below Dillon Dam (lower sub-basin), and the concurrent precipitation for the area above Dillon Dam (upper sub-basin) was computed using successive subtraction. Incremental rainfall for the 72-hour general storm for the entire Green Mountain Dam watershed, and the upper and lower sub-basins is provided in Table 3.

Table 3 – Accumulated rainfall in inches for the general storm (Bureau of Reclamation, 1987)

	6	**12**	**18**	**24**	**48**	**72**
Entire Watershed	4.20	6.99	9.09	10.91	16.11	18.58
Lower Sub-basin	4.58	7.49	9.69	11.57	16.98	19.54
Upper Sub-basin	3.90	6.60	8.62	10.39	15.43	17.83

Following HMR 49 methods (Hansen et al., 1977), the idealized elliptical storm pattern was overlaid on the Green Mountain watershed to estimate the local storm PMP. The elliptical pattern was centered on the lower sub-basin to produce the greatest peak and volume for the thunderstorm event. Incremental rainfall for the 6-hour local storm is provided in Table 4 for the entire Green Mountain Dam watershed, and the upper and lower sub-basins.

The precipitation increments shown in Table 4 were rearranged in the following hourly sequence: 3, 4, 2, 5, 1, and 6 where 1 is the hour of greatest precipitation and 6 is the hour of least precipitation. This sequence is provided in HMR 49 (Hansen et al., 1977).

The probable maximum flood study (Bureau of Reclamation, 1987) did not consider actual storm events within their study. The PMF was a direct result of the PMP, calculated via HMR 49 methodology (Hansen et al., 1977).

Table 4 – Accumulated rainfall in inches in 15-minute increments for the local storm (Bureau of Reclamation, 1987)

Duration (hrs)	Entire Watershed Depth (in)	Lower Sub-basin Depth (in)	Upper Sub-basin Depth (in)
0.00	0.000	0.000	0.000
0.25	0.730	1.260	0.330
0.50	1.130	1.900	0.560
0.75	1.390	2.260	0.730
1.00	1.600	2.550	0.880
1.25	1.761	2.771	0.996
1.50	1.907	2.975	1.102
1.75	2.040	3.153	1.201
2.00	2.160	3.300	1.300
2.25	2.267	3.417	1.399
2.50	2.364	3.516	1.497
2.75	2.454	3.605	1.591
3.00	2.540	3.690	1.680
3.25	2.624	3.775	1.764
3.50	2.705	3.855	1.845
3.75	2.780	3.931	1.920
4.00	2.850	4.000	1.990
4.25	2.914	4.064	2.054
4.50	2.974	4.124	2.114
4.75	3.030	4.180	2.170
5.00	3.080	4.230	2.220
5.25	3.125	4.275	2.265
5.50	3.166	4.316	2.306
5.75	3.204	4.354	2.344
6.00	3.240	4.390	2.380

2.3. Reanalysis: Probable Maximum Floods

The purpose of the *Probable Maximum Floods, General Storm and Thunderstorm* study (Pick, 1996) was to re-calculate the general storm PMF and thunderstorm PMF as part of an Early Warning System reliability study. Since the previous study (Bureau of Reclamation, 1987), there was a change to basic study assumptions.

The precipitation depths for the general storm and thunderstorm that were calculated in the PMF study (Bureau of Reclamation, 1987) were not revised. However, the temporal patterns for the two storm events were rearranged: both events were rearranged so that the peak rainfall occurred at the two-thirds position (hour 48 for the general storm and hour 4 for the thunderstorm). According to the *Flood Hydrology Manual* (Cudworth, 1989), this temporal pattern will produce critical flood conditions.

For the Early Warning System reliability aspect of the study, the temporal pattern for both storm events were again rearranged: the thunderstorm was front-loaded (maximum precipitation at the first hour, then decreasing rainfall depths for subsequent hours), and the general storm was rearranged to place the maximum precipitation at the end of the second hour.

2.4. Green Mountain Dam Hydrologic Hazard for Issue Evaluation

A recommendation to reevaluate the hydrologic hazard at Green Mountain Dam for a potential spillway modification was requested by the Dam Safety Office. The *Green Mountain Dam Hydrologic Hazard for Issue Evaluation* was completed in response to this request (Dworak et al., 2011). As part of this study, a rainfall frequency curve and a storm temporal pattern were produced. A companion paleoflood study (Godaire and Bauer, 2011) provided paleoflood data for streamflow-based frequency analysis in Dworak et al. (2011).

The Australian Rainfall Runoff method (ARR; Nathan and Wienmann, 2000) was used to estimate the precipitation-frequency curve. According to ARR methods, the upper tail of the frequency curve ends at PMP. Here, there was much debate on the estimate for PMP: should PMP be derived using HMR 49 methods (Hansen et al., 1977), or should the estimates calculated in the *Dillon Dam Design Storm* (Bertle, 1982) study be used? The *Dillon Dam Design Storm* study noted that ‘none of the storm analyzed support the severity of the HMR 49 curve’ (Bertle, 1982). The design storm for the Dillon Dam watershed estimated that the greatest storm would have a duration of 48 hours and produce 7.97 inches of rain (Table 2). The 48-hour estimate, as derived from HMR 49 for the upper Green Mountain Dam sub-basin (upstream of Dillon Dam), is 15.43 inches (Table 3). Paleoflood data for the Blue River near Dillon and Green Mountain Dams (Godaire and Bauer, 2011) also support lower floods and rainfalls in this vicinity. These questions are the impetus for this research project. Since storms of PMP magnitude, as defined by HMR 49, have not been observed in this highly orographic region, are they still physically possible? For the *Green Mountain Dam Issue Evaluation* (Dworak et al., 2011), the lower value design storm estimates as calculated in the *Dillon Dam Design Storm* study (Bertle, 1982) were used to define PMP.

For the temporal pattern, an observed storm event (21-24 September 1961) was considered. Overall, 3.15 inches of rain were recorded in the 1961 storm event at the Green Mountain rain gauge in 96 hours. The temporal pattern for this event was consistent with the temporal patterns of storm events throughout the period of record: periods of drizzle followed by a break in precipitation, then a heavy downpour and another break. The heavy downpours produced the highest magnitudes of precipitation within the storm event (Dworak et al., 2011).

3. Storm Selection

From the above presentation and discussion regarding previous studies, few historical extreme precipitation events have been analyzed in the area surrounding Green Mountain Dam. Most storm events that have been considered did not occur directly over the watershed, but nearby, and then transposed to the Green Mountain watershed. Nonetheless, the storms that were discussed in the previous studies were reviewed. The rationale for selecting a historical storm event was:

- to evaluate WRF's ability to model an actual event deemed significant to the Green Mountain Dam watershed;
- to use WRF to simulate more severe initial conditions of a known event;
- to use WRF to simulate a historical storm under potential climate change conditions; and
- to evaluate the effectiveness of transposition and moisture maximization techniques as outlined in HMR 49.

For this research project, there were two criteria for selecting a historical storm event:

1. the date of the storm event must be post-1948, and
2. the location of the event must be within a region representative of the Green Mountain Dam watershed in Colorado.

The first criterion is the result of the input data limitations of the currently-implemented WRF model. The initial and boundary conditions of the storm event were obtained from the NCAR/NCEP reanalysis data (Kalnay et al. 1996), which is available from 1948 – present. The spatial constraint is due to the orography of the watershed. Additionally, Dr. Mahoney's previous work on climate change was for the Colorado Front Range (Mahoney et al., 2012); this research leverages her previous work. Therefore, of all the storms that were discussed in the previous studies, two storms met the two criteria and were selected for analysis: Sept. 1970 (south of Silverton center) and Oct. 1970.

3.1. 4-6 September 1970 Storm

There were two centers associated with this storm in the Four Corners region of Colorado, Utah, New Mexico, and Arizona: Bug Point, UT, and south of Silverton, CO (Roeske et al., 1978). As mentioned above, storms that occurred in Colorado were considered; the focus of the storm analysis was on the center located south of Silverton, CO (Figure 2). The storm isohyetal pattern, after transposition, may be found in Figure 3. The highest precipitation estimate at this center is 8 inches, and the basin-average (for 335 mi^2, that of Dillon Dam watershed) is 6.15 inches (Bertle, 1982).

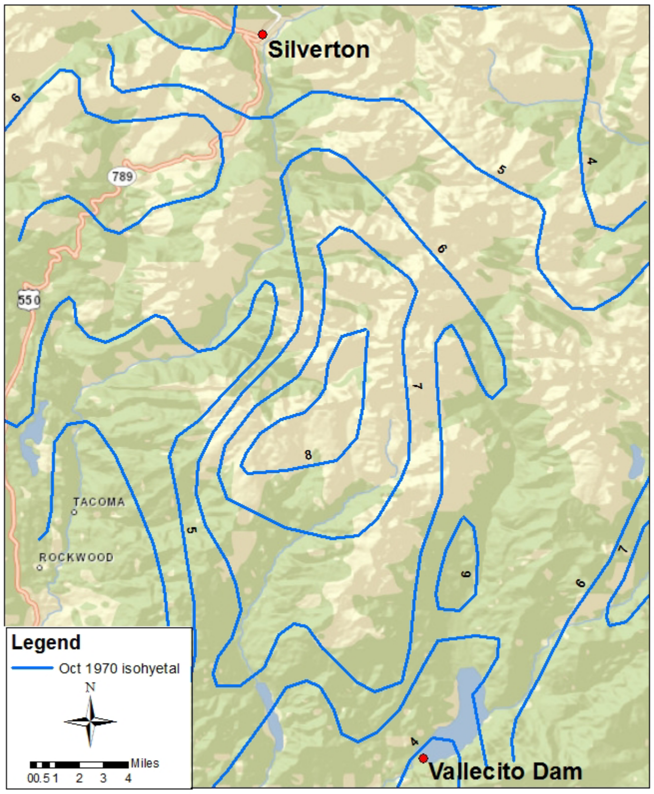


Figure 2 – The Sept. 1970 storm isohyetal pattern, in place near Silverton, CO (Isohyets from Bertle, 1982).

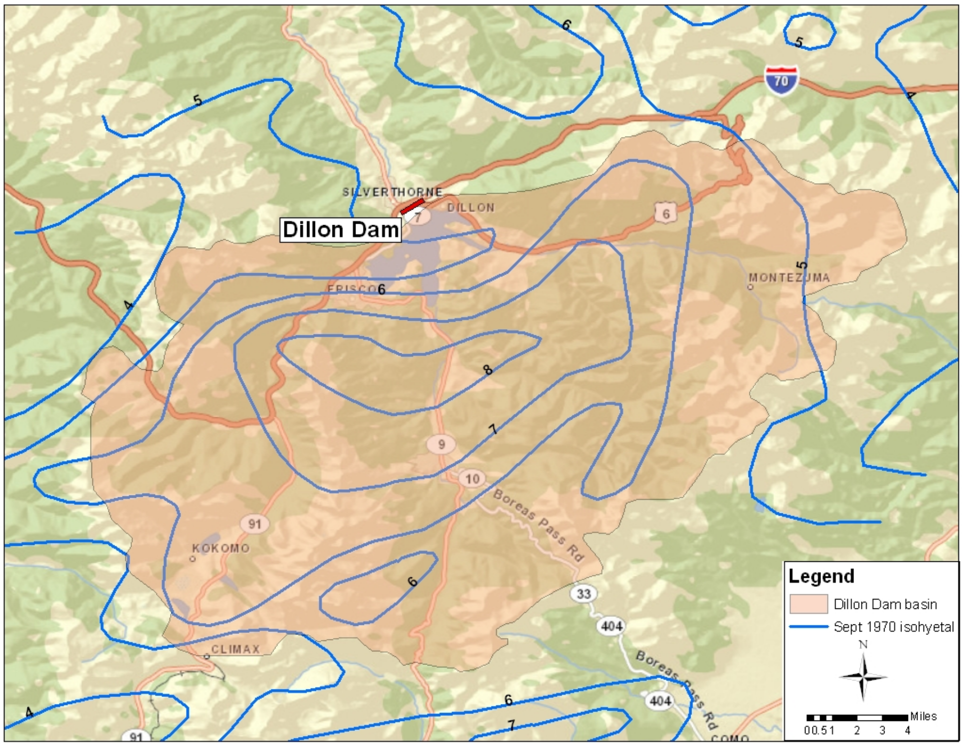


Figure 3 – The Sept. 1970 storm isohyetal pattern, after transposition to the Dillon Dam watershed (isohyets from Bertle, 1982, Figure 18).

The details of storm transposition and adjustment from Bertle (1982) may be found in Appendix A. The storm pattern was moved from south of Silverton to Dillon Dam with a 45 degree counterclockwise rotation. Incremental precipitation estimates for the storm were from Vallecito Dam, which would be located at the southwest corner of the isohyetal pattern (within the 4 inch isohyetal), before transposition (therefore not seen on Figure 3). The point-to-basin-area ratio, a ratio between the observations at Vallecito Dam (total = 3.97 inches) and the average precipitation that fell over an area the size of the Dillon Dam watershed (total = 6.15 inches), was calculated to be 1.549. A moisture adjustment factor, to account for elevation differences between the observed storm location (8,000 feet) and the transposed storm location (11,500 feet), was also applied: 0.900. The incremental precipitation observations at Vallecito Dam were adjusted by the point-to-area ratio and the moisture adjustment factor to determine the basin-average incremental precipitation for the duration of the storm (see Appendix A).

3.2. 5-7 October 1970 Storm

The 5-7 October 1970 storm occurred northeast of Steamboat Springs. Figure 4 depicts the storm isohyetal pattern as it occurred in the Steamboat Springs area. The highest precipitation estimate at the center is 7.00 inches, located in the northeast corner of the storm area analyzed (Bertle, 1982).

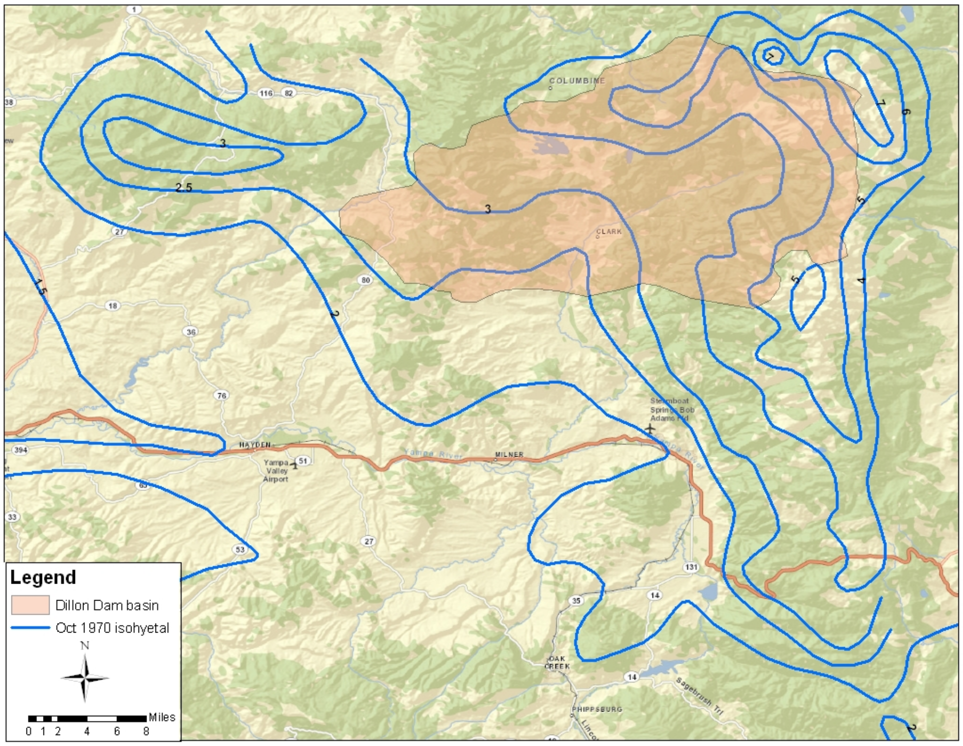


Figure 4 – Isohyetal pattern of the Oct. 1970 event, as it occurred. The Dillon Dam watershed has been transposed and rotated to the location of the storm (Bertle, 1982, Figure 11).

Isopercentile analysis was used to analyze this storm (Bertle, 1982). To do such an analysis, the Dillon Dam watershed was drawn on the storm isohyetal map (seen as the orange polygon on Figure 4). The high elevation ridge of the watershed was set to align with the high-elevation ridge located east of Steamboat Springs, thus rotating the watershed. A map of mean annual precipitation (not shown) was then overlain on the storm isohyetal map. Using graphical division, the percent of mean annual precipitation was found for numerous points around and within the transposed watershed. The average of these points was computed and found to be 10.5%. The average percent of mean annual precipitation was then multiplied by the average mean annual precipitation of the Dillon Dam watershed (28.83 inches) to compute the total basin-average precipitation for the storm event (3.03 inches; Bertle, 1982).

Details of the storm transposition and adjustment from Bertle (1982) may be found in Appendix B. The incremental precipitation observations for the storm event came from Craig, CO, unfortunately not seen on Figure 4 due to the map boundaries, but located west of Hayden. The point-to-basin-area ratio, a ratio between the observations at Craig (total = 0.99 inches) and the average precipitation that fell over the transposed Dillon Dam watershed (calculated above to be 3.03 inches), is 3.061. A moisture adjustment factor, to account for elevation differences between the observed storm location and the transposed storm location) was also calculated: 1.779. The incremental precipitation observations at Craig were adjusted by the point-to-area ratio and the moisture factor to determine the basin-average incremental precipitation for the duration of the storm (see Appendix B).

4. WRF Model Overview

The Weather Research and Forecasting (Skamarock et al., 2007) model is used to generate high-resolution (1.3-km grid spacing) simulations of extreme precipitation events in the Green Mountain Dam watershed. WRF is considered to be a next-generation mesocale numerical weather prediction system, and it is well-suited to serve both operational forecasting and research needs. It features multiple dynamical cores and a software architecture that allows computational parallelism and system flexibility. WRF is appropriate for a broad spectrum of applications across scales ranging from meters to thousands of kilometers.

WRF can be used to produce simulations using either real data or idealized initial configurations. WRF provides a framework that is flexible and efficient computationally, and the modeling system is frequently updated and improved to reflect the latest advances in physics, numerics, and data assimilation contributed by the research community. This very active community consists largely of the National Center for Atmospheric Research's (NCAR) Mesoscale & Microscale Meteorology Division, the National Centers for Environmental Prediction (NCEP) and the Forecast Systems Laboratory (FSL) of NOAA, the Air Force Weather Agency (AFWA), the Naval Research Laboratory, Oklahoma University, and the Federal Aviation Administration

(FAA). Details on the community and model are at: www.wrf-model.org/. WRF provides a fully compressible, non-hydrostatic modeling framework and uses a terrain-following hydrostatic pressure vertical coordinate. WRF model version 3.3.1 was utilized for all of the high-resolution simulations in this study.

5. WRF Methodology

Several methods of producing high-resolution WRF model simulations of heavy precipitation events are explored in order to better understand the potential utility and limitations of each.

5.1 Control simulations

Control simulations of the September and October 1970 storms were obtained using the NCEP/NCAR Reanalysis Project (NNRP) dataset (Kalnay et al. 1996) as initial conditions. The NNRP uses a state-of-the-art analysis/forecast system to perform data assimilation in order to produce analyses of past global data from 1948 to the present. The resolution of the dataset is T62 (~209 km) with 28 vertical sigma levels. Results are available at 6-hour intervals. Initial conditions and boundary conditions are provided to a WRF domain that includes an outer nest with 4-km grid spacing, and an inner nest with 1.3-km grid spacing (Figure 4).

Each WRF simulation was initialized approximately 12 hours prior to the onset of heavy precipitation (as surmised by the limited available observations), and each WRF simulation lasts 72 hours in duration. Experiments were conducted to evaluate sensitivity of simulation results to both model physical parameterizations (particularly to cloud microphysics and planetary boundary layer parameterization) and to model initialization time. Results were not qualitatively affected. Model output for each case is produced hourly, the internal model time-step is 12 seconds, and all physical parameterizations are listed in Table 5.

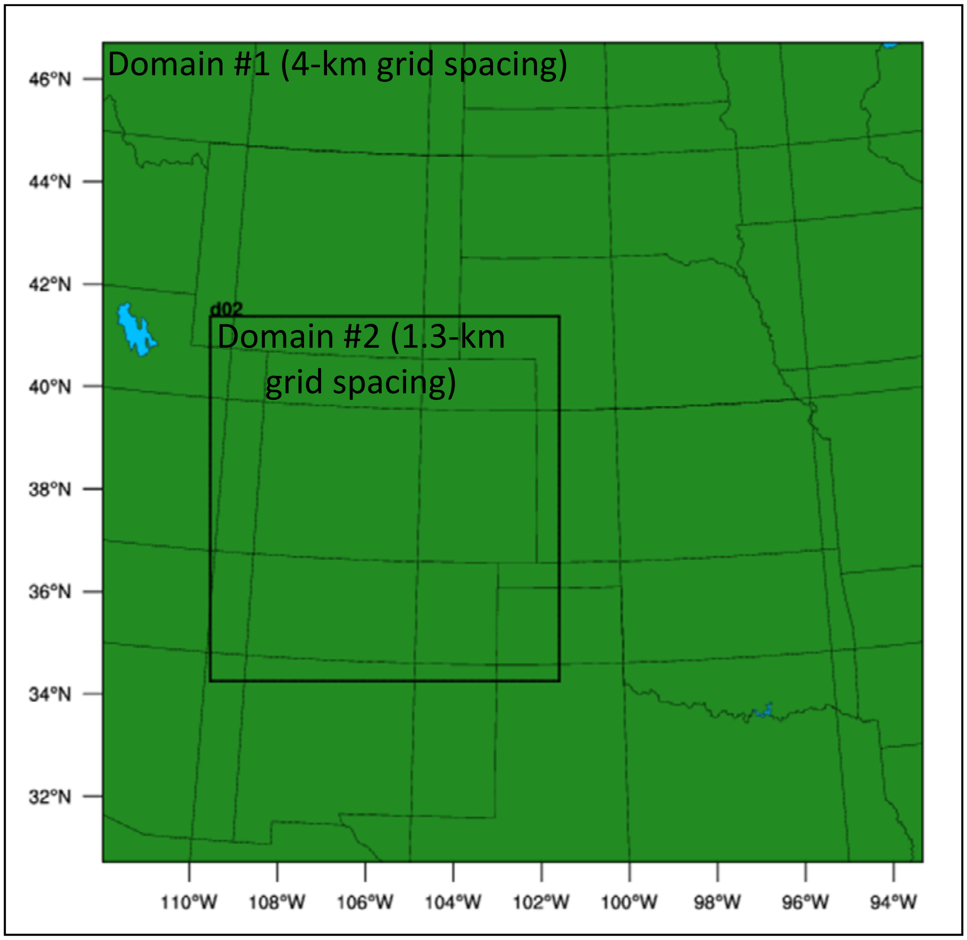


Figure 5 – Map of West-Central United States showing the outer 4-km WRF model domain ("Domain 1"), and the inner 1.3-km WRF model domain ("Domain 2"; inset box).

Table 5 – WRF model set-up and parameterization for Green Mountain Dam simulations.

Model Version	WRF (ARW) Version 3.3.1
Duration	72 hours; output frequency: 1-hour
Grid	1.3-km grid spacing (within a 4-km outer nest) 574 x 601 gridpoint domain (outer domain 450 x 450) 54 vertical levels
Physics	Explicit convection (no cumulus parameterization) Thompson microphysics YSU planetary boundary layer (PBL) scheme NOAH land-surface model, Monin-Obukhov surface layer physics Dudhia, RRTM radiation physics
Initial Conditions	NCEP/NCAR Reanalysis Project (NNRP) dataset (Kalnay et al., 1996)

5.2 Moisture maximization

Ohara et al. (2011) demonstrated a model-based method for obtaining a maximum precipitation estimate (i.e., PMP). Abbs (1999) and Cotton et al. (2003) provided some alternative model-based PMP approaches. A similar framework and set of objectives as Ohara et al. (2011) is adopted in the present work, seeking to perform model-based moisture maximization of the September 1970 control simulation. While determining the ideal moisture maximization method is an iterative process, two simulations have been produced: (1) setting the relative humidity to be 50% greater than its original value (up to 100%) at all grid points in both the initial and boundary conditions ("RH1.5x", hereafter) and (2) setting the relative humidity to be 100% at all model gridpoints in both the initial and boundary conditions ("RH100%", hereafter).

Due to the steep terrain within the model domain in this highly orographic region (Figure 6a), the first two approaches yielded excessive model numerical instability that resulted in early termination of the simulation. When both simulations were re-run using smoothed terrain data (Figure 6b), the simulations successfully ran to completion. Preliminary results are detailed below.

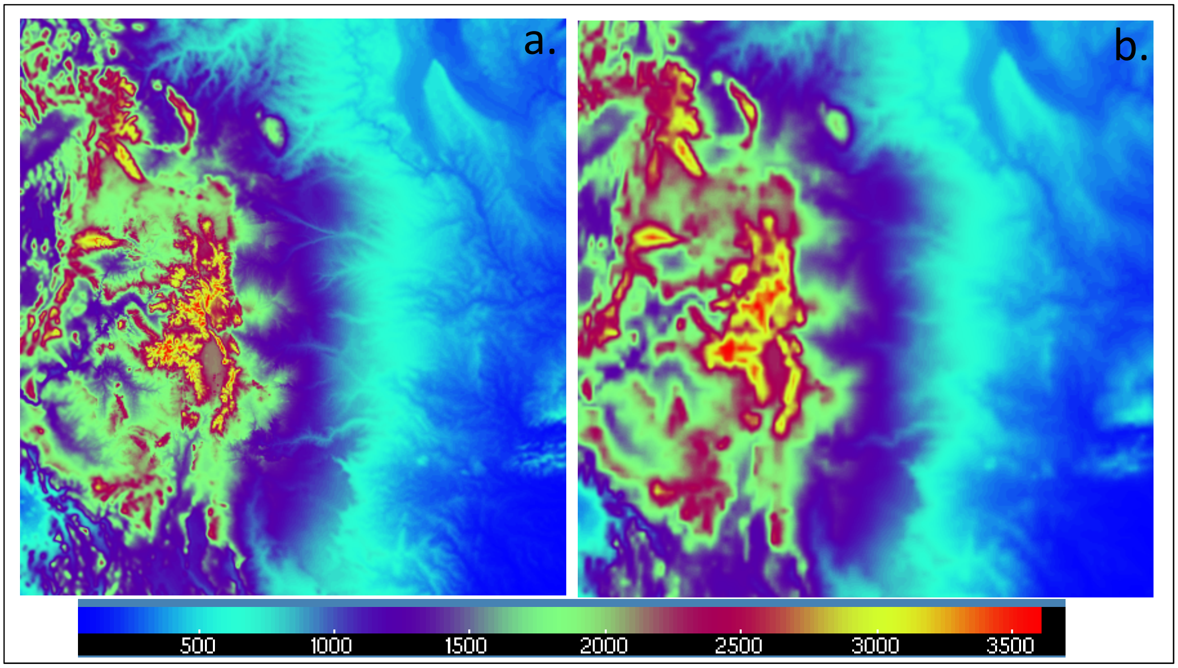


Figure 6 - Comparison of model terrain (m, as shaded at bottom) using a) high-resolution (30-sec), and b) coarser-resolution (10-min) data.

5.3 Climate change perturbation

The third methodology mimics the "climate perturbation," or "pseudo-global-warming" approach used by past studies such as Rasmussen et al. (2011), Schär et al. (1996), Hara et al. (2008), and Kawase et al. (2009). This technique is often used in order to see how observed weather dynamics might evolve under altered temperature and humidity fields as dictated by a specific climate change projection. While most past work has been focused on seasonal-scale simulations, here we modify the initial conditions of a single extreme precipitation event by adding an “average climate change signal” to the thermodynamic fields of the original event. An additional unique facet of our particular approach adopted here is that the average climate change signal is based on extreme event environments, and so the selected change signal may be better suited to represent changes specific to extreme events. The general climate-perturbation type of approach has some well-documented shortcomings, such as the assumption that synoptic-scale storm tracks and intensities remain unchanged (e.g., Rasmussen et al. 2011), but it can also offer great insight into how changes in thermodynamics may impact certain types of storm events. Particularly when used as one part of a larger downscaling assessment study such as this, it offers several strengths and areas of potential limitations, worthy of further exploration.

Average changes in temperature and moisture were calculated from future and past extreme event composites generated from regional climate model datasets obtained from the North American Regional Climate Change Assessment Program (NARCCAP; Mearns et al. 2009). These changes in temperature and relative humidity were then applied to initial conditions for the September 1970 storm (discussed more fully in Section 6.3). To date, two simulations has been successfully produced as proofs-of-concept, but improvement is planned such that the climate change signal is defined in a way that is more specific to the Green Mountain Dam watershed region as opposed to the Colorado Front Range.

6. Preliminary Results and Discussion

Both the September 1970 and October 1970 storms were simulated to first obtain an adequate control simulation. Based on a superior simulation of the September storm relative to the October storm, it was chosen as the storm of interest. All of the model runs discussed below thus focus on the 4 – 6 September 1970 event.

6.1 Control simulation: September 1970 Storm

The control simulation of the September 1970 storm (“CTRL”, hereafter), produces precipitation maxima in excess of 6 inches in the Silverton/Vallecito region (Figure 7a) where 8 inches of precipitation was reported from bucket surveys. As observations of this event are limited due to the remote, orographic region and early historical date of the event, it is difficult to comment on the skill of CTRL in accurately simulating details of the event. However, given that maximum precipitation values agree to a large degree for both the spatial distribution and overall amount of precipitation, this simulation is reasoned to be a suitable control run, and sufficient to serve as the basis for experiments such as moisture maximization and climate change perturbation methods.

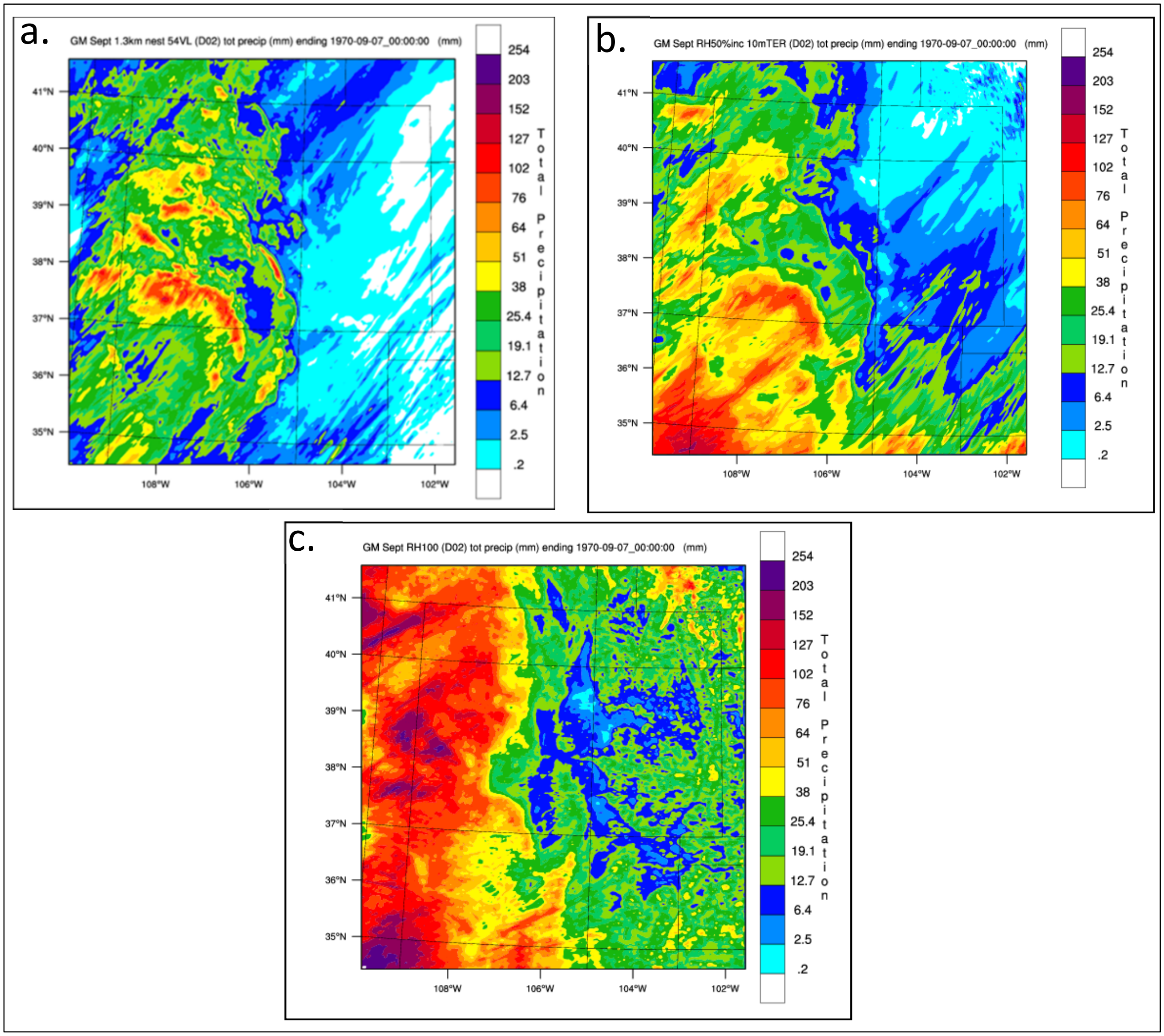


Figure 7 – Comparison of storm-total (72-hour precipitation; mm, as shaded according to scale at right) for a) Control, b) RH 1.5x, and c) RH 100%.

The temporal distribution of precipitation is compared to the temporal distributions assumed in earlier studies. The 72-hr distribution of precipitation for CTRL at a point near Vallecito is shown in Figure 8, demonstrating that the precipitation fell over a period of about 36 hours, and was characterized by 3 main intense periods between 15 – 21UTC 4 Sept, 15 – 21UTC 5 Sept, and 2 – 4UTC 6 Sept 1970. This distribution is significantly different from the “Reclamation PMP temporal distribution line” (blue) shown in Figure 8b. However, it is more similar to the “Modified PMP temporal distribution” (green) shown in the same panel (despite the fact that the modified pattern was the result of adjusting for a different storm (21-24 Sept. 1961)).

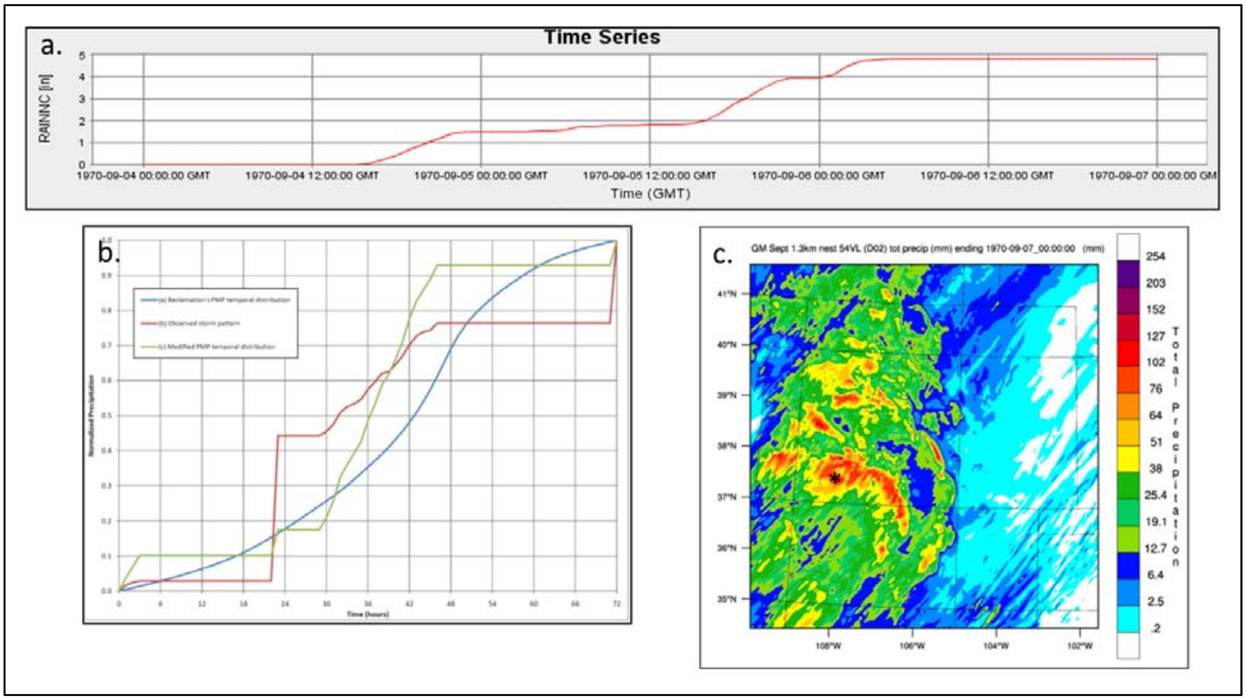


Figure 8 - a) Time series taken for accumulated rainfall (inches) at (37.5N, -108W) b) Reclamation time series, c) point shown in asterisk is time series location from panel a.

6.2 Moisture maximization

6.2.1 *RH 1.5x*

The experiment in which relative humidity is increased to be 50% larger than the original value (again “RH1.5x”) results in greater precipitation in the southwestern corner of the domain (Figure 7b). This result is consistent with higher initial moisture in that region; thus readily increasing the already-large moisture values to, or near, saturation. In the presence of southwesterly low-level wind flow, the upstream-moistened air optimally impinges on the curved topography of the San Juan Mountains, yielding even greater upslope-flow-generated precipitation maximization due to the increased moisture (relative to CTRL).

Maximum precipitation values near the Silverton/Vallecito area remain in the 5-6 inch range, but significantly higher values cover a considerably larger area; thus, area-averaged precipitation values are higher in some (but not all) locations relative to corresponding averages in the CTRL simulation (Table 6).

6.2.2 RH 100%

The RH100% simulation produces larger total precipitation maxima and far more widespread heavy precipitation in the western portion of the domain (Figure 7c) as the steadily saturated air at the boundary conditions impinges on the western slopes of the Rocky Mountains throughout the simulation. Maximum precipitation values in the Silverton/Vallecito region specifically do not show large increases, but maxima in the western portion of the domain exceed 8 inches in several locations, and within the Silverton/Vallecito region, regionally-averaged precipitation is much greater (Table 6).

Despite the increase in the total precipitation, maximum values only increase by up to ~25% and still do not come close to the 18.58 inches cited in HMR 49. Totals do compare somewhat favorably with those listed for the Dillon Dam Design Storm. An important caveat of this preliminary evaluation of precipitation totals relative to previous reports is that the comparison is based only on the simulation of *one* historical storm (of which observations are very sparse) and of which an extremely limited number of maximization and perturbation-based experiments have been conducted so far. As noted below, additional work is planned to address some of these limiatations.

Table 6 – Maximum point- and area-averaged precipitation values within a geographical box with latitude/longitude dimensions 0.22° x 0.32° (~330 mi^2; approximate size of Dillon Dam watershed) and lower left corner located at (37.25, -108.2) and upper right corner at (37.52, -107.9).

Simulation	Area-average storm-total precipitation (mm)	Max point value within selected region (mm)
CTRL	80.2	167.5
RH1.5x	81.7	107.2
RH100%	100.6	132.6
CCpert-CW	111.7	201.0

6.2.3 Discussion of moisture maximization simulations and future runs

Moisture maximization of the initial conditions increases the precipitation in both overall precipitation amount and in local maximum values. This is a relatively intuitive result based on the straightforward expectation of increasing moisture in an environment known to possess strong forcing for precipitation.

Future simulations are intended to test alternate ways to maximize moisture. These tests may include holding relative humidity constant while increasing the atmospheric mixing ratio/specific humidity in order to isolate the effect of moisture increase in the absence of temperature dependence. Adjusting moisture (and/or heating) preferentially at low levels may also result in precipitation increase, and isolating the adjustment to incorporate only the effect of adopting the maximum persisting dewpoint as done in HMR PMP methods will also provide better understanding of the moisture maximization process and model-based potential for further exploration.

Note also that the RH1.5x and RH100% experiments both use smoothed terrain data. If the native high-resolution terrain data was used, it is likely that localized precipitation maxima would increase, but that over a given area, amounts would most likely remain qualitatively similar.

6.3 Climate change perturbation

Based on earlier work from the CIRES-Reclamation Cooperative Agreement project "Improving extreme precipitation estimation and climate change projections using regional and high-resolution model simulations", extreme event composite environments were defined based on events occurring in the Colorado Front Range region in specific models in the NARCCAP regional climate model project (as described above). The extreme event composites and resulting climate change signals will ultimately be re-defined based on the Green Mountain Dam region (see Future Work section below). The two simulations shown here use a climate change perturbation signal based on temperature and moisture differences from the GFDL-Timeslices experiment (GT hereafter; http://www.narccap.ucar.edu/about/timeslices.html) and the CCSM+wrfg experiment (CW, hereafter; http://www.narccap.ucar.edu/data/model-info.html). The surface temperature and precipitable water changes from the future extreme event composite and the past extreme event composite are shown in Figure 9.

Adding the prescribed temperature and moisture anomalies to the CTRL simulation initial conditions results in altered precipitation fields as shown in Figure 10. The CW experiment's ("CCpert-CW") warmer and wetter future climate over the region of interest results in considerably more precipitation relative to CTRL. Both localized and area-averaged amounts of precipitation in the Silverton/Vallecito Dam region increase considerably (Table 6), but do not exceed significantly beyond the maximum values listed for the Dillon Dam Design Storm (7.97 inches), nor do they increase values to be even half of those listed in HMR 49. Temporal and spatial patterns are generally unchanged; the regions of largest precipitation in CTRL are also those that receive enhanced precipitation in the CW-perturbed experiment (particularly along the general moisture transport path to the south and west of Silverton/Vallecito). The temporal distribution of precipitation is largely unchanged, although the time of peak rainfall (~15UTC 5 Sept – 01UTC 6 Sept) is more accentuated in the CW-perturbed climate change simulation (Figure 11). Such results are also fairly intuitive based on the assumed strong synoptic- and orographic- forcing that drive this case. Changes in thermodynamics only will generally not affect the dynamical drivers of the event, but will rather affect the intensity of the rainfall that is generated.

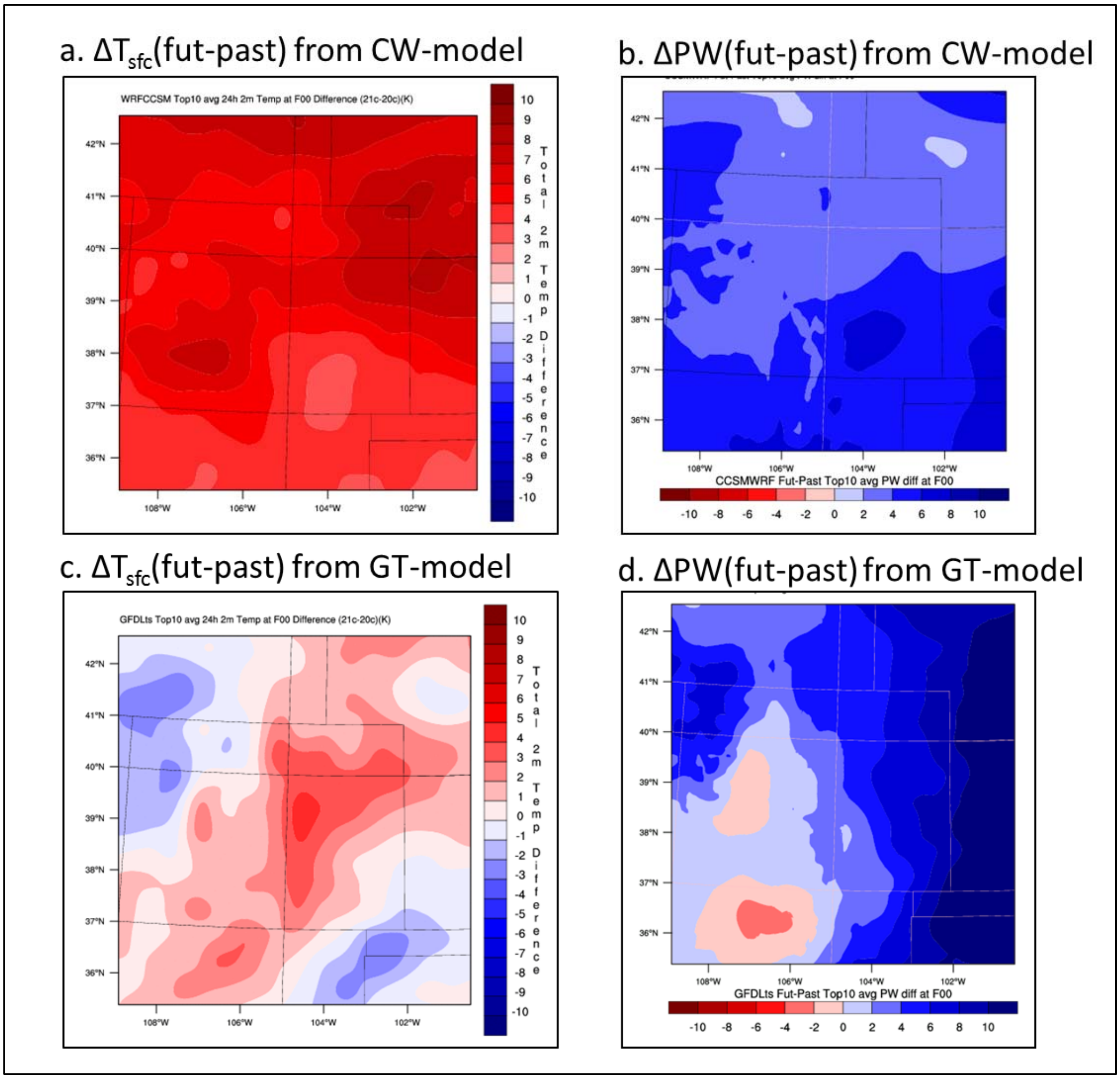
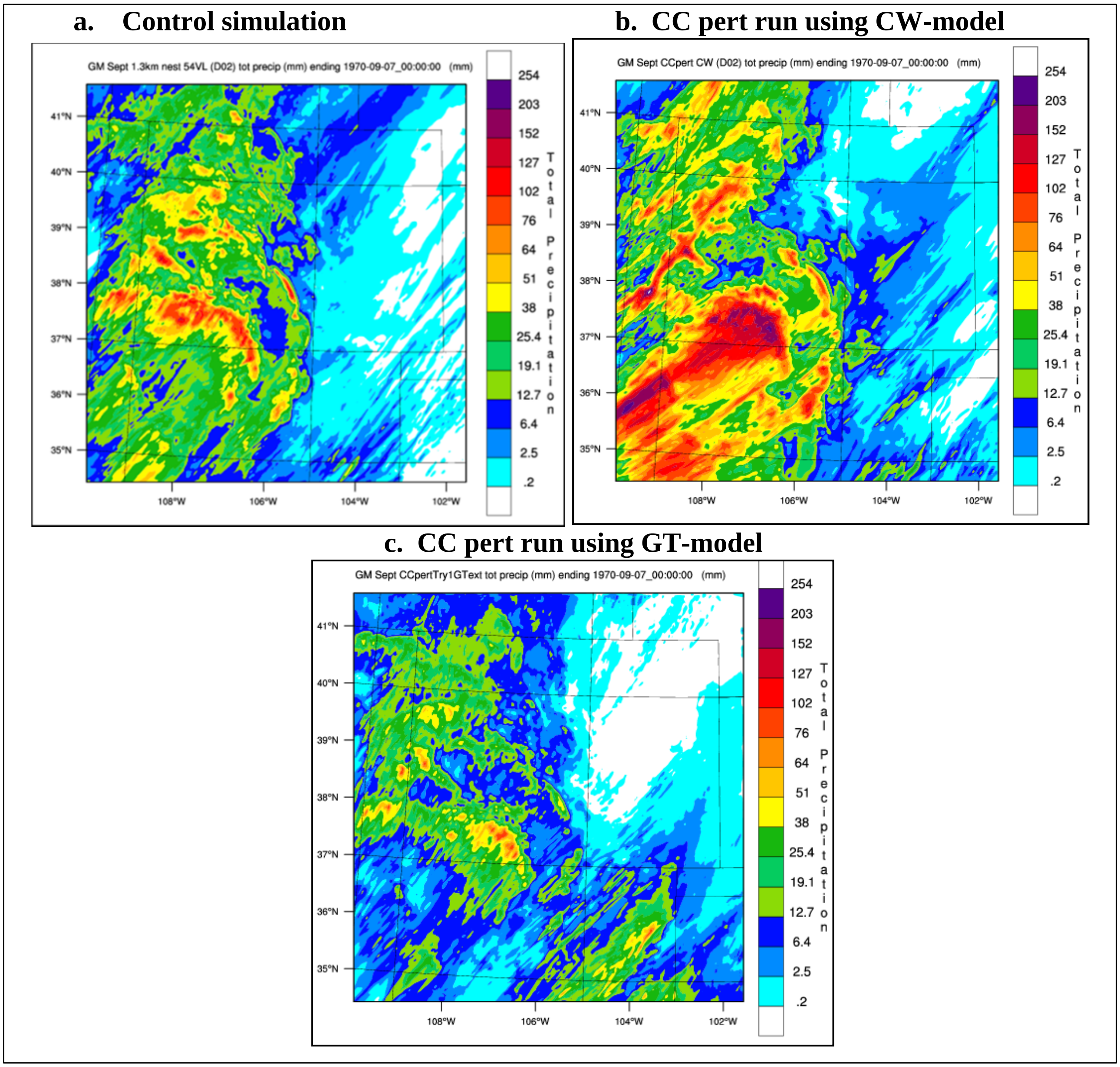


Figure 9 - Future-Past extreme event Colorado Front-Range-based composite changes in temperature and moisture from the CW regional climate model (a and b respectively) and the GT regional climate model (c and d respectively). In a) and c) red (blue) represents warming (cooling), and in b) and d) red (blue) represents drying (moistening).


a. Control simulation

b. CC pert run using CW-model

c. CC pert run using GT-model

Figure 10 – Comparison of storm-total (72-hr precipitation; mm, as shaded according to scale at right), for a) Control (same as Figure 7a), b) CC-CW, and c) CC-GT.

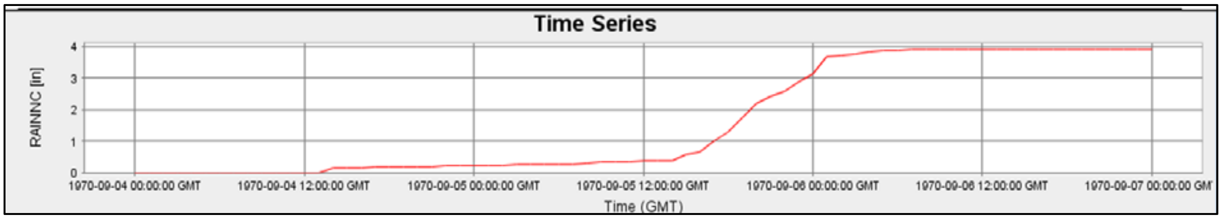


Figure 11 - Time series taken for accumulated rainfall (inches) at (37.5N, -108W) for CW-Climate Change perturbation experiment.

As the GT experiment's climate change perturbation was defined based on Front Range (eastern Colorado) events, there is actually a drying signal over much of southwestern Colorado. This decrease in moisture and weaker warming signal (relative to CW) actually results in a decrease in 72-h precipitation totals in this case. ***This latter (GT) experiment is shown purely as a proof-of-concept; the climate change perturbation chosen is not relevant to this region*.**

Future work will use both Green Mountain Dam extreme event-centered definitions of climate change as well as seasonal mean-based perturbations to provide representation of climate-driven changes that are more relevant to this specific region. These additional simulations will also expand the parameter space of potential climate projections considered.

6.4 Discussion

From the above results, the WRF model appears to be capable of simulating storms in orographic locations and offers potential utility for use in model-based storm-maximization and climate-change assessment studies. The WRF model appears to be a useful tool that can be used as part of the storm analysis process needed to complete Dam Safety Hydrologic Hazard Analyses.

There are many ways in which the initial results presented here should be improved upon before applying any of the findings to operational use. First, choosing a more recent storm (preferably after 1979 when higher resolution reanalysis data are available, and ideally as recent as possible to maximize available observations) would likely generate superior simulations and a framework for better simulation verification. Tables 7 and 8 list the top 10 precipitation events that have affected the Green Mountain Dam region from two more recent (1979 – present) datasets: the Global Daily Climatology Network (GDCN) and North American Regional Reanalysis (NARR). Selecting key storms from these more recent lists (and perhaps other recent events from Cotton et al., 2003) may facilitate the analysis of future simulations. Choosing a storm of smaller duration (i.e., a local storm instead of general storm) so that a shorter simulation period is needed (24-hr vs. 72-hr) would save computational cost (and would presumably cause resources to become available for additional experimental simulations, discussed below). This would also simplify the analysis overall.

Table 7 - Global Daily Climatology Network (GDCN) station-data top 10 precip events for GMD region (1 deg lat/lon box centered on GMD) for June, July, August, September, and October, 1979 – present.

Rank	Year	Month	Day	24-hr Precip (mm)	Lat	Lon	Elevation (m)
1	2000	8	29	63.5	39.8789	-106.333	2359
2	2008	9	12	38.9	40.1850	-105.867	2526
3	1997	7	31	38.9	40.1850	-105.867	2526
4	1995	7	3	38.6	39.8789	-106.333	2359
5	1997	9	21	34.5	39.8789	-106.333	2359
6	1984	6	7	34.3	39.6261	-106.035	2763
7	1984	6	6	33.0	39.8789	-106.333	2359
8	1985	10	7	33.0	39.8789	-106.333	2359
9	1993	9	30	32.5	40.1850	-105.867	2526
10	2004	8	19	31.8	40.1850	-105.867	2526

Table 8 - North American Regional Reanalysis (NARR) top 10 precip events for GMD region (1 deg lat/lon box centered on GMD) for June, July, August. 1979 – present.

Rank	Year	Month	Day	24-hr Precip (mm)	Lat	Lon	Elevation (m)
1	1985	6	4	43.3	40.38	-106.44	8797.7
2	1979	6	7	37.7	39.52	-106.07	10857.2
3	1984	7	19	36.6	40.38	-106.44	8797.7
4	2008	7	22	34.6	40.38	-106.06	9763.9
5	2001	8	6	33.6	39.52	-106.07	10857.2
6	1979	6	7	33.3	39.52	-106.45	8797.7
7	2001	8	6	33.2	39.52	-106.45	8797.7
8	2001	8	6	31.8	40.38	-106.06	9763.9
9	1979	6	7	31.6	39.80	-106.07	9763.9
10	2001	8	6	31.4	39.80	-106.07	9763.9

With respect to the experimental simulations, despite significant computational and logistical hurdles that arise when running a high-resolution model with perturbed initial conditions, there is considerable promise that the results can be strengthened. For the moisture maximization objectives, future tests will be aimed at experimenting with the effect of holding relative humidity constant while increasing the atmospheric mixing ratio/specific humidity, as well as adjusting moisture preferentially at low levels to replicate the maximum persisting dewpoint method as used in HMR PMP documentation. To better address the questions related to the potential impacts of climate change, future work will utilize Green Mountain Dam extreme event-centered definitions of climate change as well as seasonal mean-based perturbations to provide more complete and relevant representation of climate-change-driven environmental changes. The goal will be to use these additional, carefully-designed simulations to optimally represent the largest spectrum of potential climate projections with a computationally-feasible number of simulations.

While the above suggestions can and will certainly strengthen the findings shown so far, it is important to discuss the scope of effort that would be involved in achieving a truly robust model-based storm analysis framework. In order to rigorously address PMP questions, a large ensemble approach is likely the best way to represent a wide range of possibilities for storm changes. The goal of ensemble modeling is to simulate the spectrum of possible environmental permutations as completely as possible (e.g., Mullen and Baumhefner 1994; Stensrud et al. 2000). Ensembles of simulations are generally generated by perturbing model initial conditions and model physics, and for a purpose such as storm analysis within this study's framework, the ensemble could be comprised of different levels of increasing moisture (or other parameters) in the initial conditions, and also using various model physics settings to increase the range of possible storm changes. Such an ensemble approach would also ideally include dynamical perturbations to the initial conditions in order to address some of the weaknesses and limitations encountered when only perturbing environmental thermodynamics (e.g., Rasmussen et al. 2011). Ensembles of simulations would then be performed for a number of storms known to be relevant to the region of interest. The larger the resulting collection of simulations, the more representative the study sample size, and thus the more robust the estimate of model-based PMP, and potentially quantifying uncertainty of the estimates. Logistically, such an approach would be relatively computationally-demanding, but it would be robust, and would likely contribute valuable, intuitive, and detailed information for future Dam Safety Hydrologic Hazard Analyses.

7. Conclusion

Two historical storm events that occurred in the vicinity of the Green Mountain watershed were modeled using the WRF model. The model appears to be capable of simulating storms in this highly orographic location. The 4-6 Sept. 1970 storm event was deemed sufficient to serve as the basis for experiments for moisture maximization and climate perturbation methods. For the results to be robust, the methodology presented above would require further improvements.

From this research project, it was learned that running a high resolution model requires significant computational resources. The WRF model can provide benefits to storm analyses for Dam Safety Hydrologic Hazard Analyses, especially in regard to high-elevation, orographic regions where there are distinct differences between PMP amounts and streamflow and paleoflood observations. The methodology is also flexible so that climate change inquires could be addressed. This research project demonstrated that the WRF model is capable of modeling large precipitation events, allowing model users to maximize storm parameters, and allowing model users to examine storm characteristics in climate change regimes. Further, computational and logistical hurdles can be better anticipated and handled, and the robustness of results can be better understood and portrayed.

8. Future Work

The experiments shown here have proven to be useful proofs-of-concept toward demonstrating promising WRF model utility for storm analysis in highly orographic regions. As part of the research process of developing the prototype simulations discussed above, many ideas for ways to improve upon the initial methods were identified. As this work is also a component of the CIRES-Reclamation Cooperative Agreement project “Improving extreme precipitation estimation and climate change projections using regional and high-resolution model simulations”, these strategies for improving our results will be pursued. Implementation of these improvements is planned for October 2012 – December 2012, so that strengthened findings may be presented at the American Meteorological Society (AMS) Annual Meeting in January 2013. Our objectives for this ongoing work currently include the following items:

1. Test additional moisture maximization techniques, e.g., surface dewpoint maximization.
2. Calculate more relevant climate change signatures using both seasonal average deltas and extreme deltas that are chosen using the Green Mountain Dam region specifically as opposed to a more general Colorado region.
3. Investigate the utility of using more recent cases from NARR and GDCN (see Tables 7 and 8); take advantage of better observations to validate the model results.
4. Connect these results to specific metrics used in previous reports such as basin-average precipitation totals, temporal distribution over 24-, 48-, and 72-h intervals, and compare specific fields (e.g., surface dewpoint) with data used to calculate the original PMP.
5. Expand simulation perturbations to be dynamical too; identify methods to incorporate potential storm track shifts in future climates, explore the feasibility of an larger ensemble-based approach.

These results may be added to this report as an addendum following the AMS meeting in early 2013.

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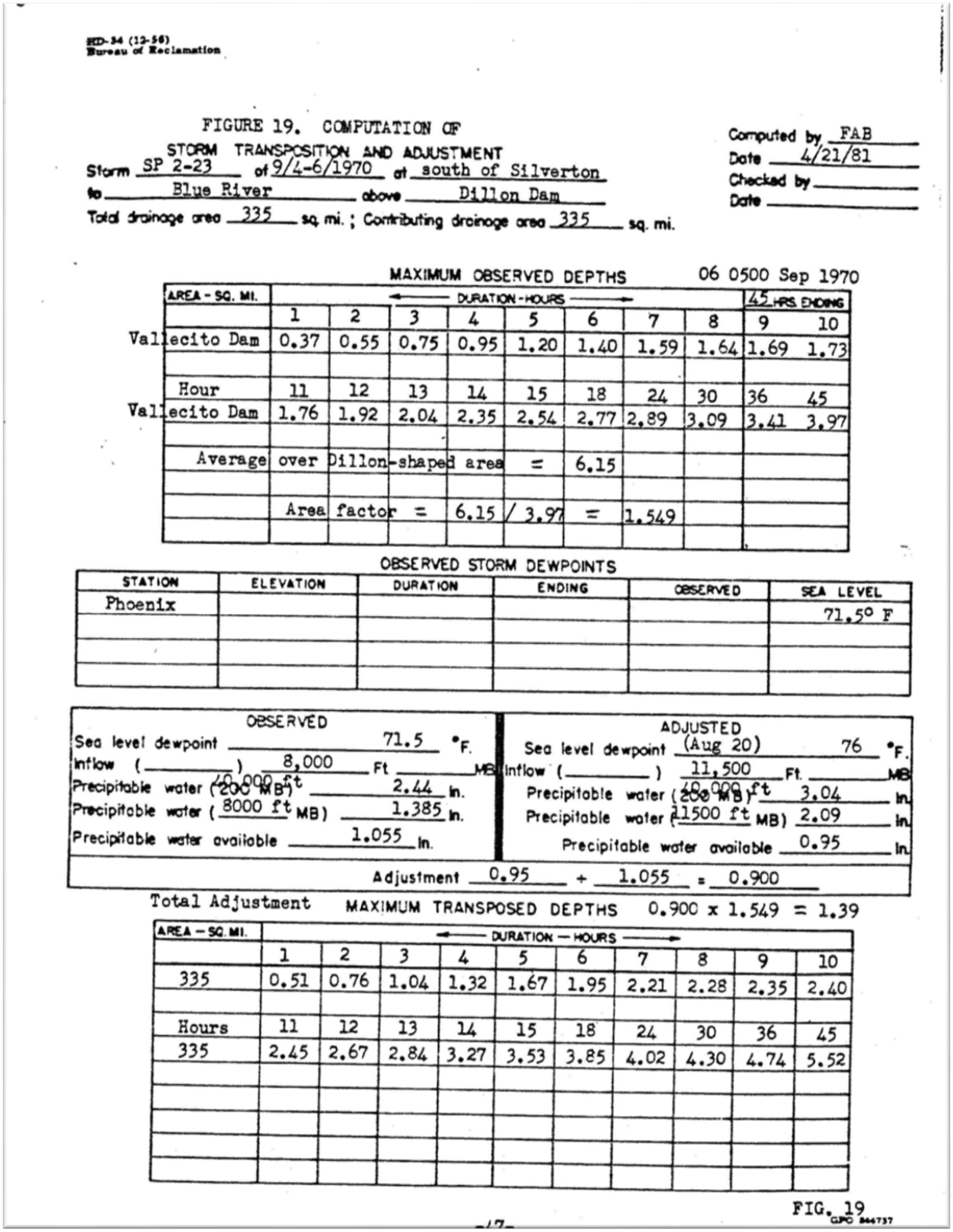
Appendix A: Computation of Storm Transposition and Adjustment, 4-6 September 1970



HD-34 (12-56)
Bureau of Reclamation

FIGURE 19. COMPUTATION OF
STORM TRANSPOSITION AND ADJUSTMENT

Computed by FAB
Date 4/21/81
Checked by
Date

Storm SP 2-23 of 9/4-6/1970 at south of Silverton
to Blue River above Dillon Dam
Total drainage area 335 sq. mi.; Contributing drainage area 335 sq. mi.

MAXIMUM OBSERVED DEPTHS 06 0500 Sep 1970

AREA - SQ. MI.	← DURATION - HOURS →							45 HRS. ENDING	
	1	2	3	4	5	6	7	8	9	10
Vallecito Dam	0.37	0.55	0.75	0.95	1.20	1.40	1.59	1.64	1.69	1.73
Hour	11	12	13	14	15	18	24	30	36	45
Vallecito Dam	1.76	1.92	2.04	2.35	2.54	2.77	2.89	3.09	3.41	3.97
Average	over	Dillon-	shaped	area	=	6.15				
	Area	factor	=	6.15	/ 3.97	=	1.549			

OBSERVED STORM DEWPOINTS

STATION	ELEVATION	DURATION	ENDING	OBSERVED	SEA LEVEL
Phoenix					71.5° F

OBSERVED
Sea level dewpoint 71.5 °F.
Inflow ( ) 8,000 Ft MB
Precipitable water (200 MB) 40,000 ft 2.44 In.
Precipitable water (8000 ft MB) 1.385 In.
Precipitable water available 1.055 In.

ADJUSTED
Sea level dewpoint (Aug 20) 76 °F.
Inflow ( ) 11,500 Ft. MB
Precipitable water (200 MB) 40,000 ft 3.04 In.
Precipitable water (11500 ft MB) 2.09 In.
Precipitable water available 0.95 In.

Adjustment 0.95 ÷ 1.055 = 0.900

Total Adjustment MAXIMUM TRANSPOSED DEPTHS 0.900 x 1.549 = 1.39

AREA – SQ. MI.	← DURATION — HOURS →								
	1	2	3	4	5	6	7	8	9	10
335	0.51	0.76	1.04	1.32	1.67	1.95	2.21	2.28	2.35	2.40
Hours	11	12	13	14	15	18	24	30	36	45
335	2.45	2.67	2.84	3.27	3.53	3.85	4.02	4.30	4.74	5.52

FIG. 19
GPO 844737

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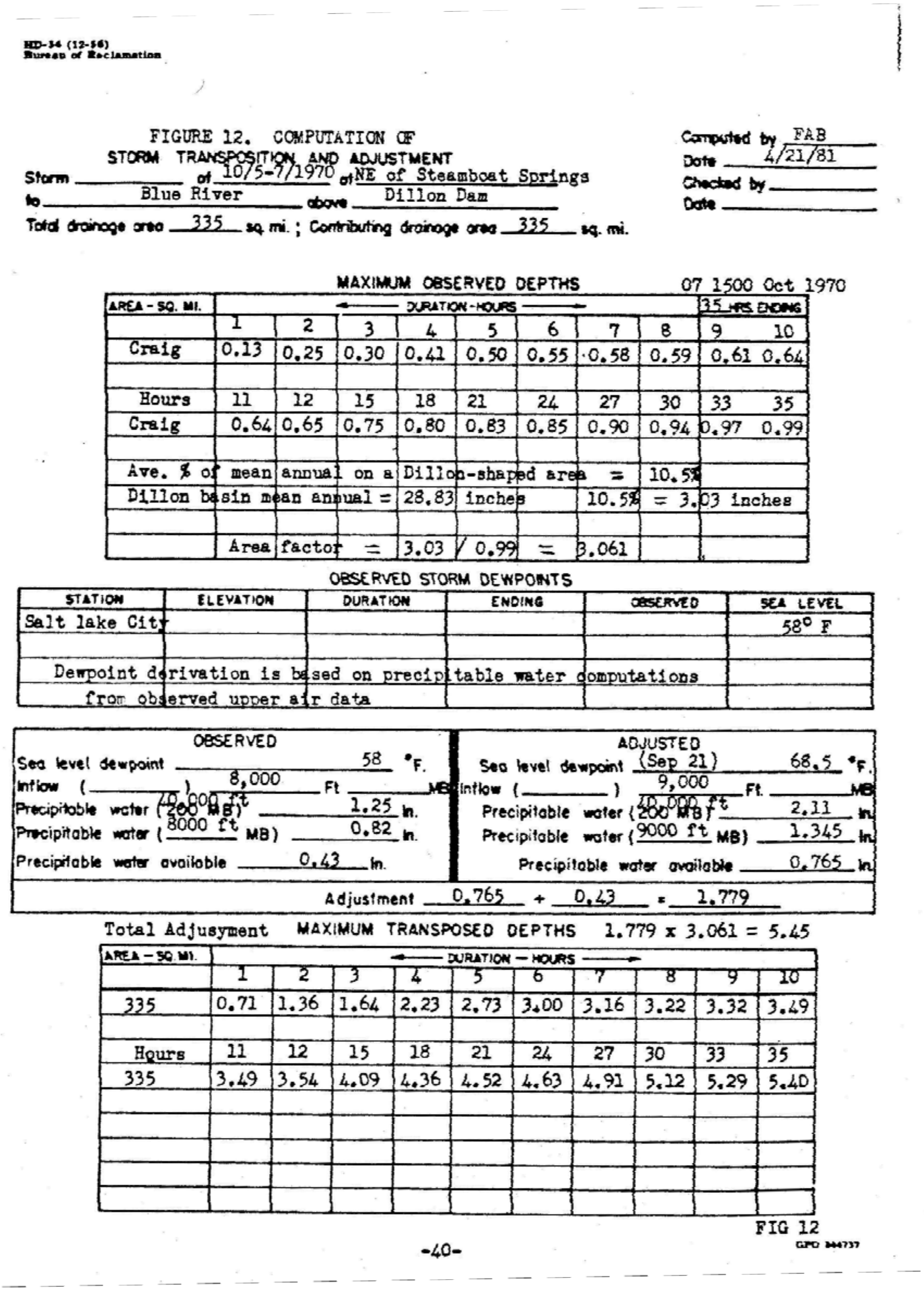
Appendix B: Computation of Storm Transposition and Adjustment, 5-7 October 1970



HD-34 (12-56)
Bureau of Reclamation

FIGURE 12. COMPUTATION OF
STORM TRANSPOSITION AND ADJUSTMENT

Computed by FAB
Date 4/21/81
Checked by
Date

Storm ____ of 10/5-7/1970 at NE of Steamboat Springs
to Blue River above Dillon Dam
Total drainage area 335 sq. mi.; Contributing drainage area 335 sq. mi.

MAXIMUM OBSERVED DEPTHS 07 1500 Oct 1970

AREA - SQ. MI.	DURATION - HOURS								35 HRS. ENDING	
	1	2	3	4	5	6	7	8	9	10
Craig	0.13	0.25	0.30	0.41	0.50	0.55	·0.58	0.59	0.61	0.64
Hours	11	12	15	18	21	24	27	30	33	35
Craig	0.64	0.65	0.75	0.80	0.83	0.85	0.90	0.94	0.97	0.99

Ave. % of mean annual on a Dillon-shaped area = 10.5%
Dillon basin mean annual = 28.83 inches 10.5% = 3.03 inches
Area factor = 3.03 / 0.99 = 3.061

OBSERVED STORM DEWPOINTS

STATION	ELEVATION	DURATION	ENDING	OBSERVED	SEA LEVEL
Salt lake City					58° F

Dewpoint derivation is based on precipitable water computations
from observed upper air data

OBSERVED

Sea level dewpoint 58 °F.
Inflow ( ) 8,000 Ft MB
Precipitable water (40,000 ft ~~200 MB~~) 1.25 in.
Precipitable water (8000 ft MB) 0.82 in.
Precipitable water available 0.43 in.

ADJUSTED

Sea level dewpoint (Sep 21) 68.5 °F.
Inflow ( ) 9,000 Ft. MB
Precipitable water (40,000 ft ~~200 MB~~) 2.11 in.
Precipitable water (9000 ft MB) 1.345 in.
Precipitable water available 0.765 in.

Adjustment 0.765 + 0.43 = 1.779

Total Adjusyment MAXIMUM TRANSPOSED DEPTHS 1.779 x 3.061 = 5.45

AREA — SQ. MI.	DURATION — HOURS									
	1	2	3	4	5	6	7	8	9	10
335	0.71	1.36	1.64	2.23	2.73	3.00	3.16	3.22	3.32	3.49
Hours	11	12	15	18	21	24	27	30	33	35
335	3.49	3.54	4.09	4.36	4.52	4.63	4.91	5.12	5.29	5.40

FIG 12

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