Colorado September Rainfall Analysis: Comparisons to the Calgary 2013 Rainfall and PMP Along the Rocky Mountain Front Range

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***Abstract*--**Extreme rainfall during June 2013 in and around Calgary, Alberta caused extensive flooding and damage in the region. Although the combination of meteorological conditions which led to this rainfall were not uncommon, the high levels of atmospheric moisture and total amounts of rain were extremely rare. Several comparable events have been recorded along the eastern slopes of the Rocky Mountains from the United States through Alberta. Notable examples include the June 1975 storm near Waterton Red Rocks, Alberta, and the June 1964 storm at Gibson Dam, Montana. Recently, a storm in September of 2013 occurred over the foothills and Front Range of the Rocky Mountains in Colorado and Southern Wyoming. This rainfall event had similar meteorological and topographical stetting when compared to the Calgary storm a few months earlier, with both events producing extreme rainfall and devastating flooding.

Applied Weather Associates (AWA) has analyzed each of these events using our Storm Precipitation Analysis System (SPAS) for use in determining Probable Maximum Precipitation (PMP), which is then used by hydrologists to compute the Probable Maximum Flood (PMF). These and other storms analyzed with SPAS provide high spatial resolution (approximately 1 square kilometer) and high temporal resolution (as frequent as 5 minutes when weather radar data are available) rainfall information for hydrologic model calibrations and hydrologic investigations. This presentation will provide comparisons of the magnitude and spatial extent of these extreme rainfall events, how the rainfall is enhanced by the similar terrain along the eastern foothills of the Rocky Mountains, how they relate to PMP values in regions where similar storms could occur, and lessons learned regarding recognition and real-time monitoring of the meteorological conditions leading up to and during these types of storms.

I. Introduction

A "perfect" mix of moisture, instability and a slow moving storm system brought record-breaking rainfall to northeastern Colorado during the period September 8-17, 2013. The Front Range foothills and adjacent plains of Colorado received over 20 inches of rain, shattering numerous rainfall records and producing catastrophic flooding. The storm claimed 8 lives and caused on the order of $1 billion dollars in damage [1].

However, this storm wasn't unprecedented along the Front Range of the Rockies. In fact, just a few months earlier, Calgary, Alberta experienced a similar storm with similar devastating results. Applied Weather Associates (AWA) has performed more than 350 storm analyses (Figure 1) as part of more than 50 Probable Maximum Precipitation (PMP) studies completed since 1996 (Figure 2). As part of these analyses, a consistent pattern of extreme rainfall development has become evident along the Front Range of the Rocky Mountains extending from Canada through Colorado. Other similar major storms in the period of record include Spionkop Creek June 1995, Waterton Red Rocks June 1975, Big Elk Meadows May 1969, Gibson Dam June 1964, Lake Maloya May 1955, Colorado Front Range September 1938, and Penrose June 1921. Each of these storm events exhibited similar meteorological characteristics, which results in these regions being preferred locations for this type of rainfall event.

Comparisons between the meteorological settings of each will be discussed. In addition, the relationship of the maximized rainfall values of each storm compared to PMP values at each storm location will be detailed.

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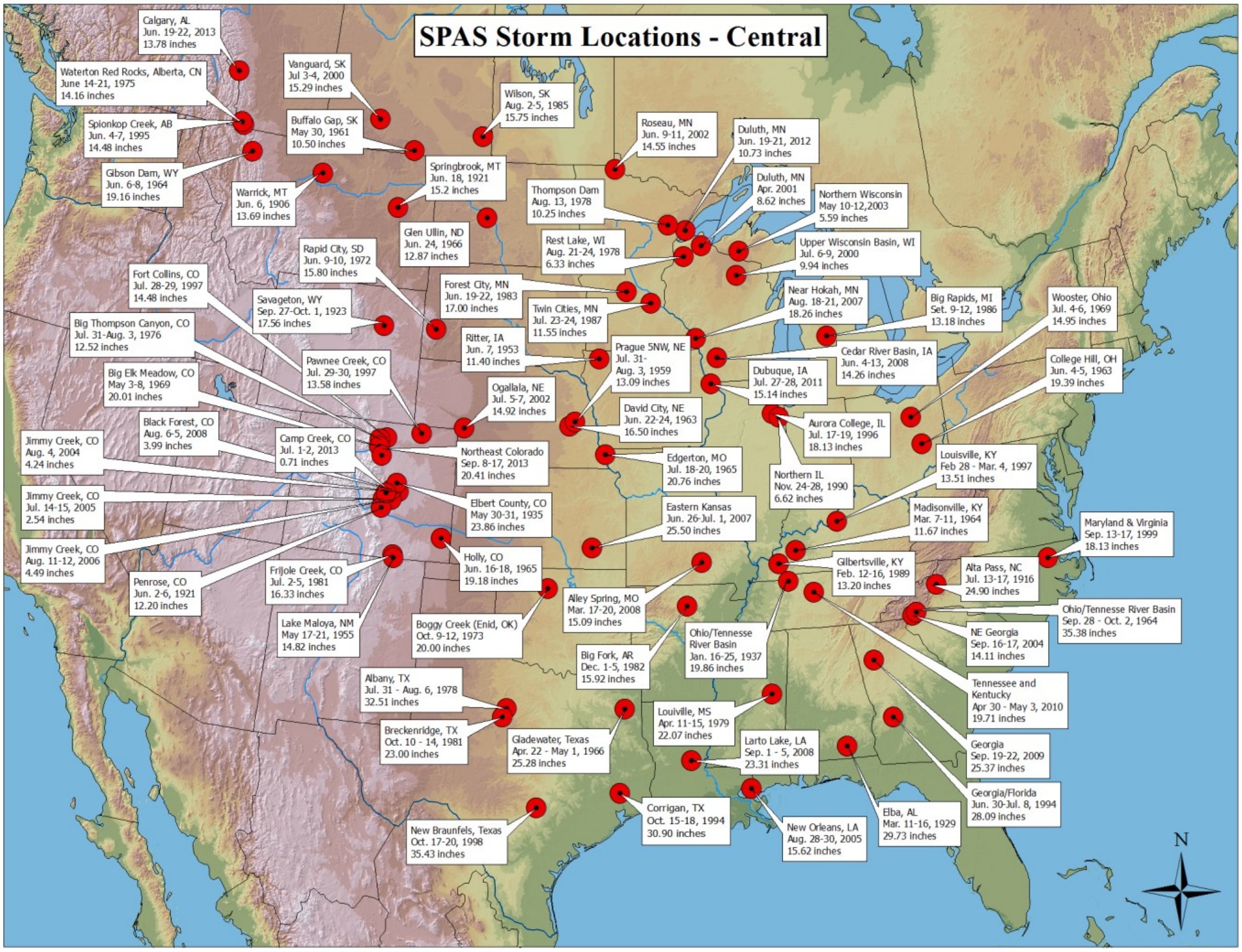

Figure 1. SPAS storm locations across the central United States.

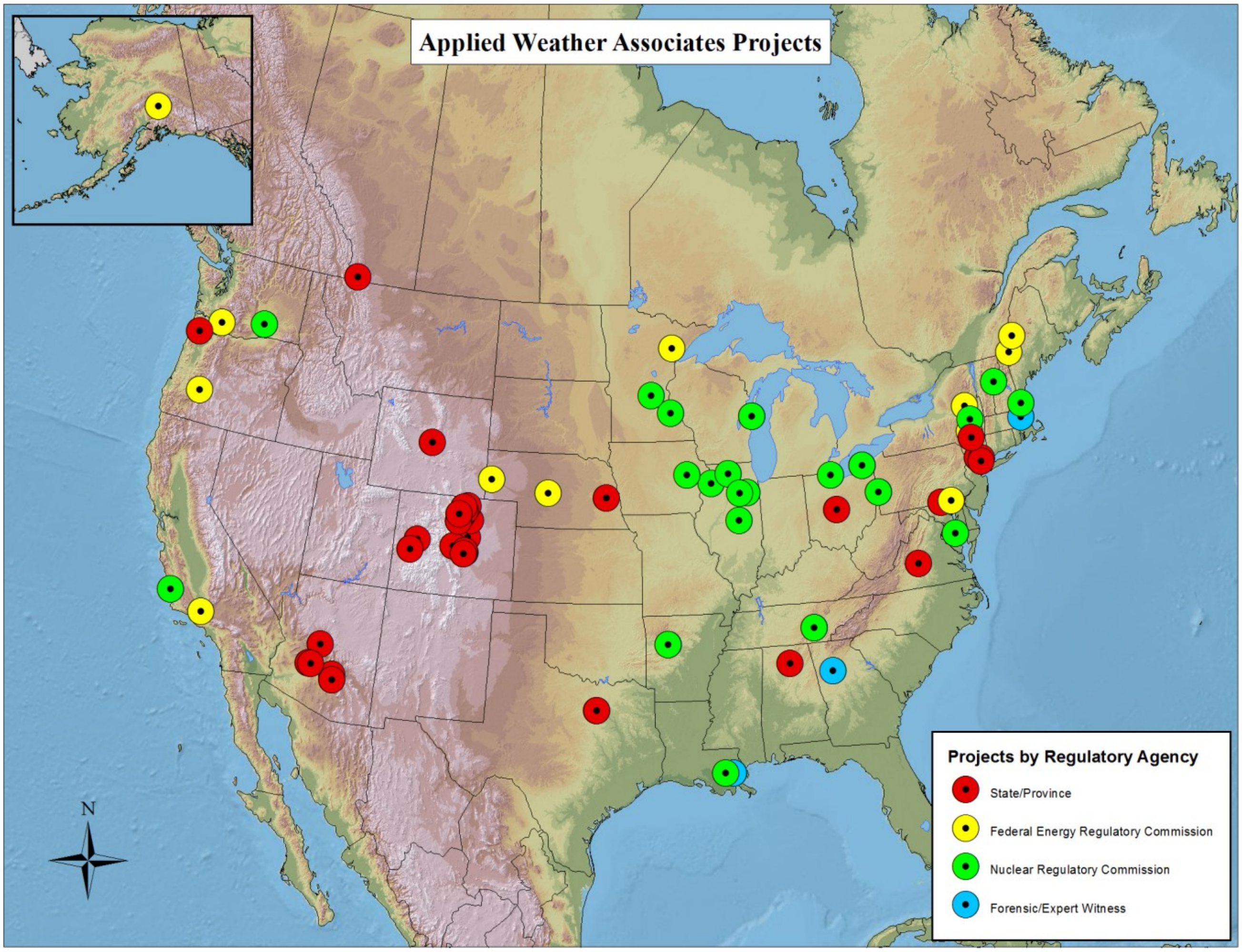

Figure 2. Applied Weather Associates project locations.

II. Meteorological Setting

The general synoptic situation during the September 2013 Colorado rainfall included an unusually persistent and moist flow of tropical moisture rotated into Colorado during the period September 8th through the 17th. A nearly stationary upper-level low pressure system over southwestern Utah circulated deep monsoonal moisture into Colorado from Gulf of Mexico and Pacific Ocean. In fact, some of the moisture may have been remnants of tropical cyclone Lorena, which dissipated off Baja California the week prior. As the upper-level low pressure area slowly moved east, the circulation entrained more moisture from the Gulf of Mexico in an easterly and southeasterly flow. Winds of this direction are upslope along the Front Range of Colorado, where the deep moisture was forced up and into the foothills, where it was translated into rainfall. In addition, a low-level high pressure area (anticyclonic circulation), pushed into the Midwest which further pushed the moisture westward towards the Front Range. A stalled front helped to generate additional lift and heavier rainfall. Most of the rain fell in a 36-hour period from the afternoon of September 11th through the early morning of September 13th.

This meteorological setting mirrors those of the past events as well. The difference being the spring storms do not have a remnant tropical system connection, but often have more instability involved because of a higher thermal contrast between air masses. It is also important to note the preferred times of the year for these storm patterns to occur, that being spring and fall. This is because during those times there is an ideal combination of moisture available and instability in the atmosphere. During summer, the storm dynamics are generally not as efficient as the spring and fall, while during the winter there is a lack of moisture. Both components need to be present and at their maximum for these types of storms to occur. In addition, it helps to have a blocked or slow moving overall pattern, so the same storm situation can affect the same region for an extended period of time.

In each situation, the Gulf of Mexico was the main supply of low level moisture, while storm dynamics and upper level moisture were fed from the Pacific Ocean. In addition, in all cases, each factor was enhanced by the interaction of topography with low-level winds and moisture. The gently rising topography of the Midwest changes to an abrupt rise as it encounters the Front Range of the Rockies. This topographical set up in relation to low-level winds and moisture is nearly identical from Alberta through Southern Colorado.

It is interesting to note that during the Colorado September 2013 event, radar grossly underestimated the actual precipitation which ranged from 15-20 inches in parts of Boulder and Larimer Counties. In Boulder and Larimer counties, the Q3 radar-only product only showed 6-7 inches, while the DualPol did slightly better, inferring localized amounts of up to about 12 inches [1]. This was because warm-cloud process very efficiently produced the extremely heavy rains with only a few imbedded thunderstorms during the event. For these reasons, radar grossly underestimated the actual precipitation which ranged from 15-20 inches in parts of Boulder and Larimer Counties. In Boulder and Larimer counties, the Q3 radar-only product only showed 6-7 inches, while the DualPol did slightly better, inferring localized amounts of up to about 12 inches.

A. During The Colorado 2013 Storm

Utilizing real-time gauge-adjusted radar-estimated precipitation from Weather Decision Technologies, the precipitation was translated into the Extreme Precipitation Index (EPI), a depiction of the precipitation as an equivalent average recurrence interval (ARI), in years. The real-time gauge-adjusted radar-estimated precipitation was created by coupling 1-hour quality-controlled precipitation data and radar-estimated precipitation each hour of the storm. Twenty-four hour moving totals of precipitation, together with known precipitation frequency estimates from NOAA Atlas 14, allowed real-time Extreme Precipitation Index (EPI) maps to be created.

The EPI maps provided the Colorado Dam Safety office with an objective and quick means of determining which dams were experiencing the rarest rainfall, and helped plan an emergency inspection response plan. In some cases, the precipitation exceeded a 1,000-year ARI for the 24-hour period and caused a few dams to overtop and even fail (e.g. five small dams in the Big Elk Meadows area of Larimer County). In addition, a new Colorado state 24-hour rainfall record was established, with 11.85" of rainfall accumulating at Fort Carson, CO from midnight to midnight, September 12th [2]. The previous record occurred in June 1965, when 11.08" was recorded in Holly.

B. After The Colorado 2013 Storm

Immediately after the storm, a “bucket survey” was undertaken by the Colorado Climate Center (CCC) and AWA to collect as much observed precipitation data as possible to support a detailed analysis. Over 2,600 reports were collected and quality controlled from a variety of networks, including: NWS, USDA SNOTEL, USFS/BLM RAWS, USGS, Flood Warning Networks, Ag networks, CWOP, Wxunderground, Weather Bug, CoCoRaHS (Community Collaborative Rain, Hail & Snow Network) and miscellaneous other reports. The CCC launched a public outreach program to encourage people to share their precipitation reports and stories via a dedicated Google mail account. Additionally, AWA provided dam safety engineers with a bucket survey form to pass out during dam inspections. The highly successful “bucket survey” provided the ensuing precipitation analysis with an extremely large “ground truthing” database.

The Storm Precipitation Analysis System (SPAS), a state-of-the-science hydrometeorological tool [4], was used for analyzing the spatial and temporal characteristics of precipitation for the storm (Figure 3). SPAS utilized the over 2,600 precipitation measurements and nearly 3,000 5-minute radar scans to derive hourly precipitation maps at a spatial resolution of $1km^2$. SPAS utilized quality-controlled radar reflectivity data together with concurrent precipitation gauge data to calibrate the reflectivity-rainfall (ZR) relationship each hour, therefore overcoming the underestimation of traditional ZRs. After imposing bias adjustments, final 5-minute and hourly precipitation maps/grids were derived (Figure 4).

The SPAS analysis produced an array of precipitation data that was subsequently evaluated to serve the purposes of Probable Maximum Precipitation (PMP) studies, hydrologic modeling, all-time record-breaking rainfall assessments, updated EPI maps and comparisons to rainfall products issued in real-time during the event.

Total Storm Precipitation (inches)
September 8 (800 UTC) - September 18 (700 UTC), 2013

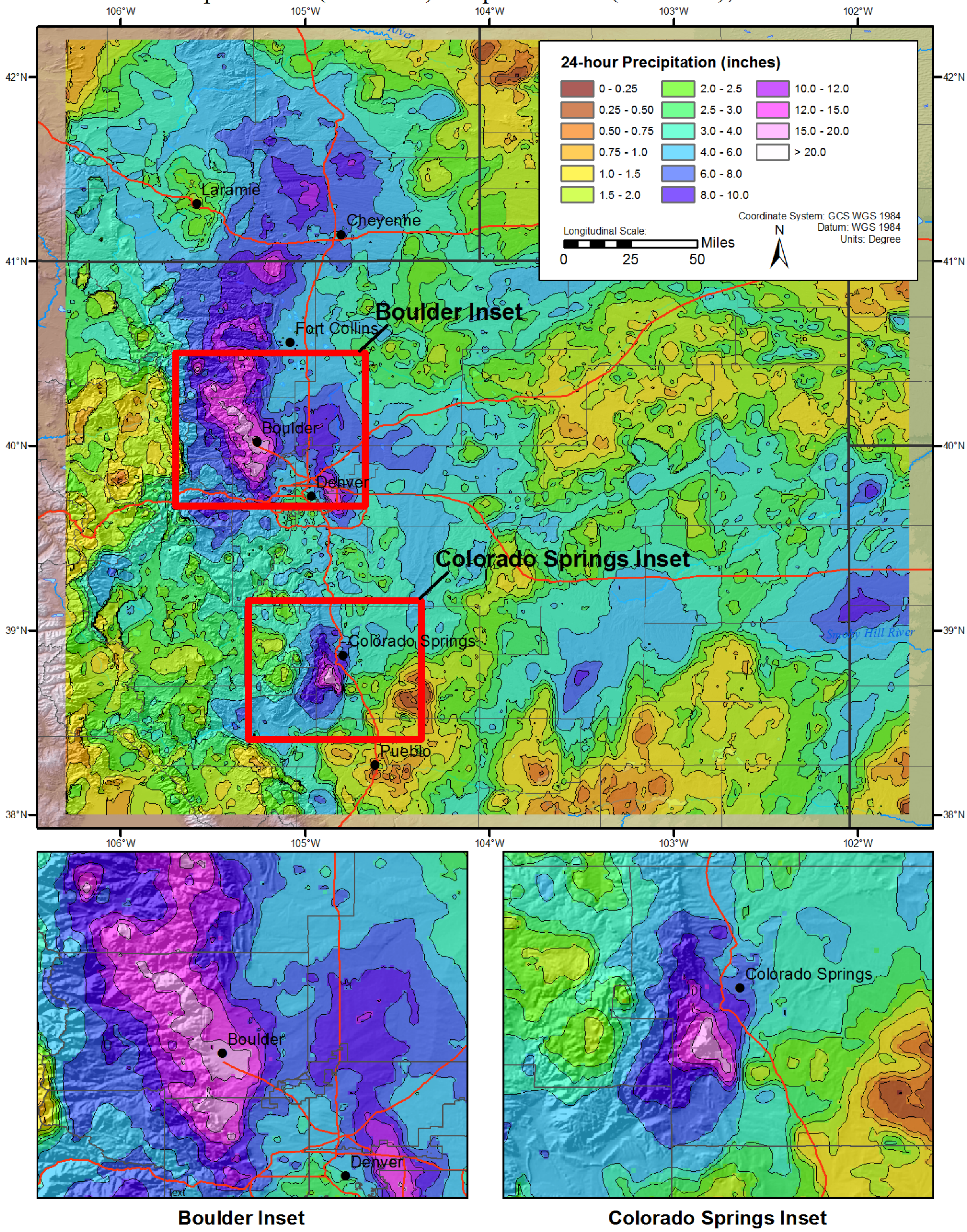

Figure 3. September 2013 total storm isohyetal.

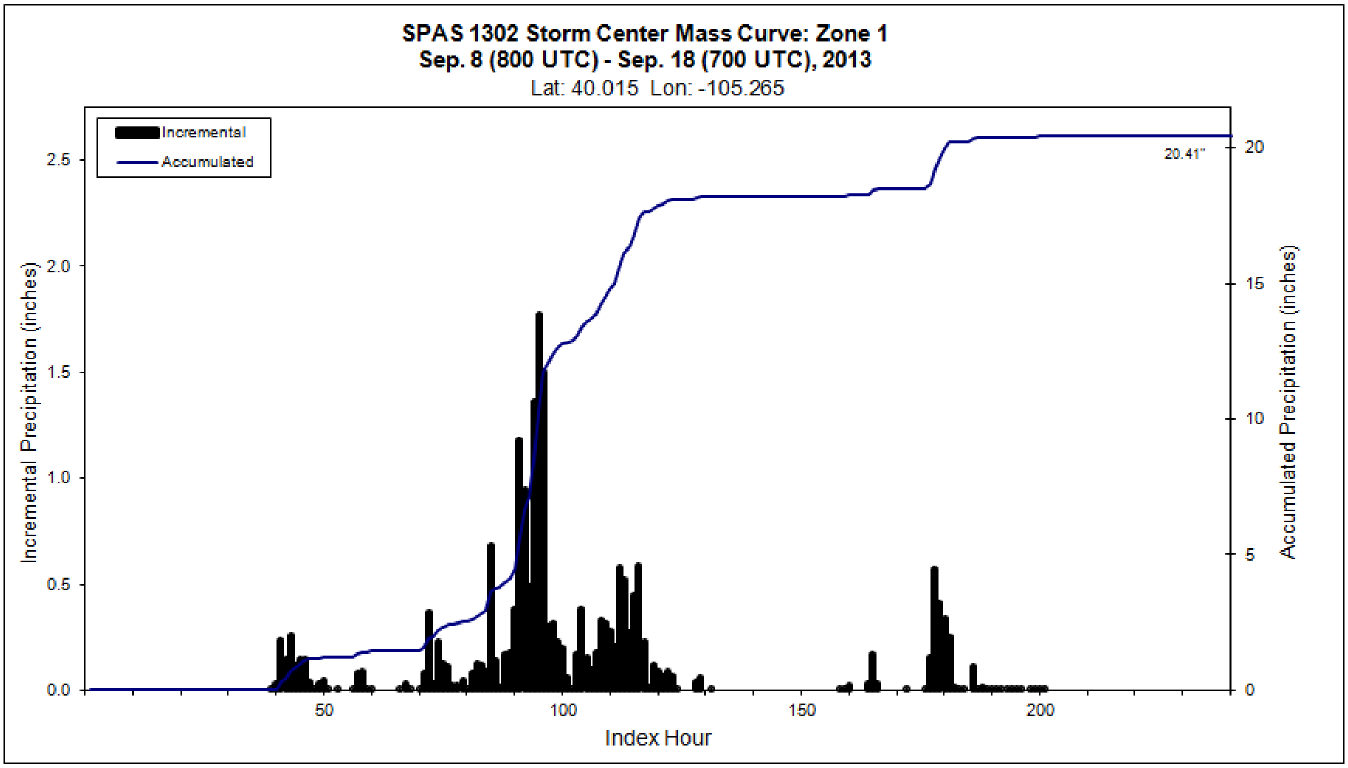

Figure 4. September 2013 storm center mass curve.

C. Comparison of The Colorado 2013 Storm to Previous Events

Although the September 2013 rainfall and flood event may have seemed unprecedented, in many ways similar rainfalls and floods have occurred, not only in the hardest hit areas of Colorado, but along much of the Front Range of the Rocky Mountains. For example, in the hardest hit areas around Boulder, CO, floods in 1894, 1938, and 1969 were of similar magnitude or even greater at some locations. The 1894 and 1969 floods both occurred in late May/early June and where snowmelt runoff augmented the rainfall runoff. Figure 5 shows the locations of similar rainfalls in the region. Another interesting comparison is provided in Figures 6-8. These display the total storm isohyetal patterns of the Calgary 2013, Spionkop Creek 1995 and Gibson Dam 1964 events. Notice, how the heaviest rainfall is anchored to the first upslopes of the Rocky Mountain Front Range. This occurs where the combination of available moisture and orographic enhancement are maximized. The difference between the storm events is a functions of distance from moisture source (Gulf of Mexico) and atmospheric instability. The further north (away from the Gulf of Mexico) the harder it is to maintain high levels of atmospheric moisture over significant amounts of time.

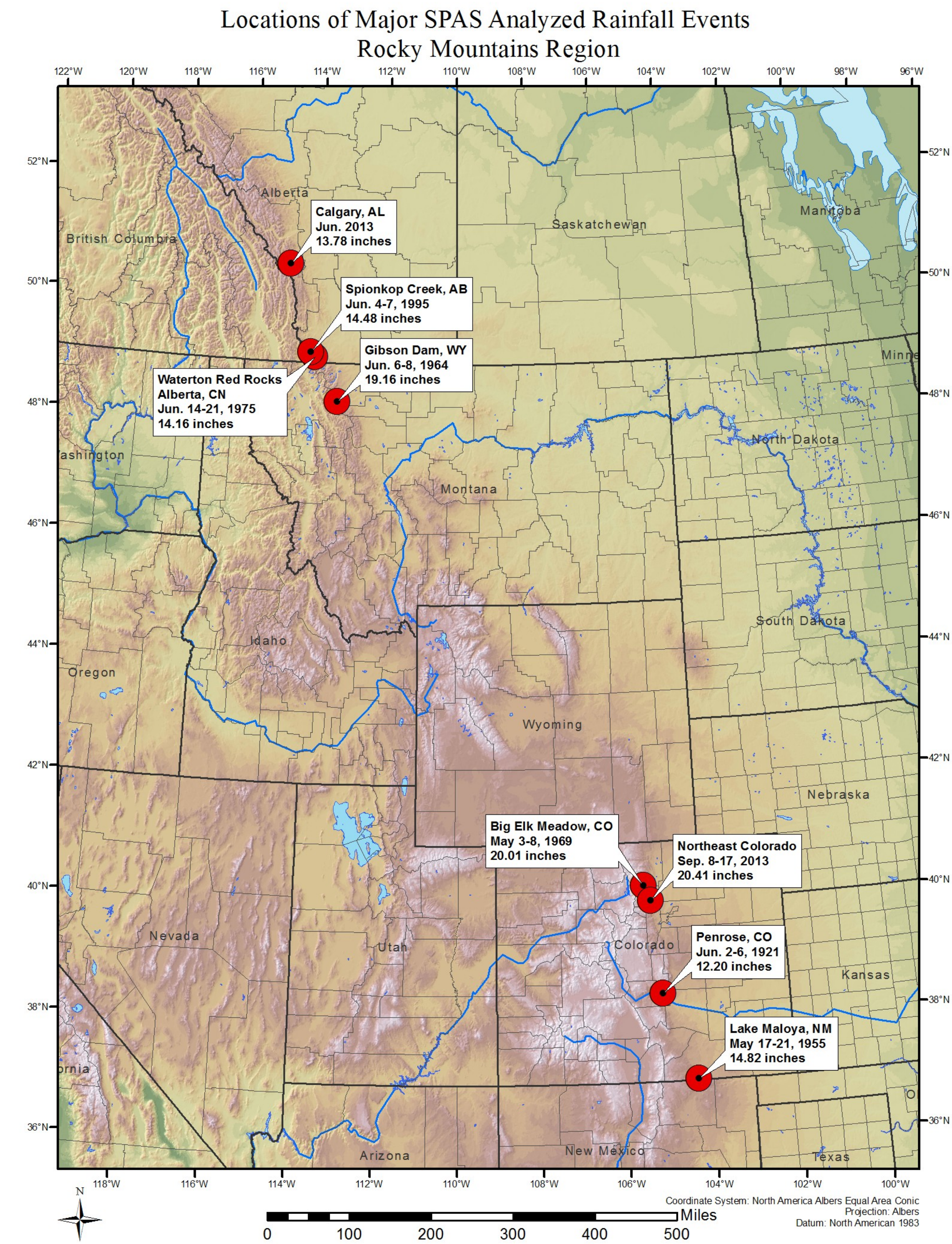

Figure 5. Storm locations discussed in this analysis.

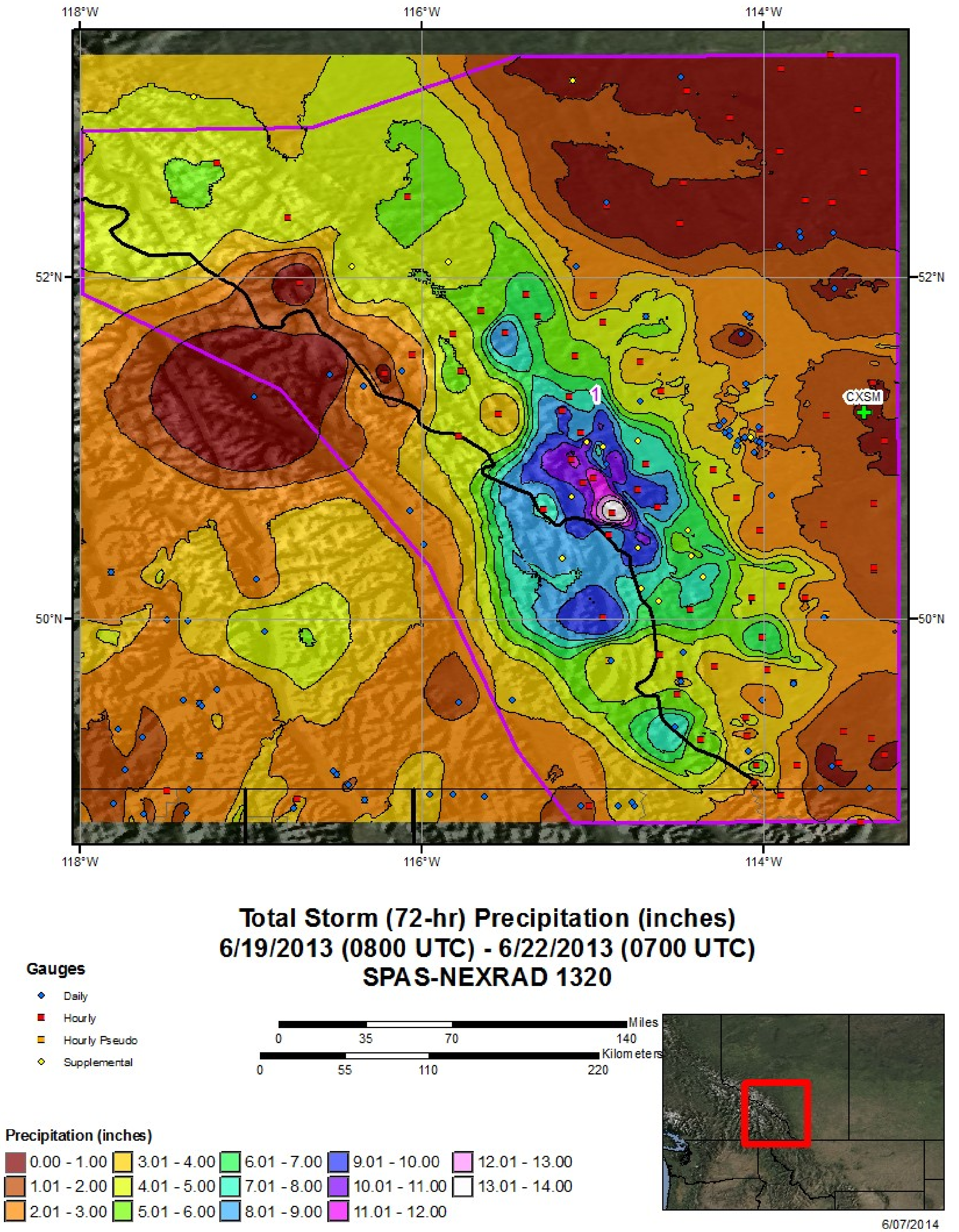

Figure 6. Calgary 2013 total storm isohyetal.

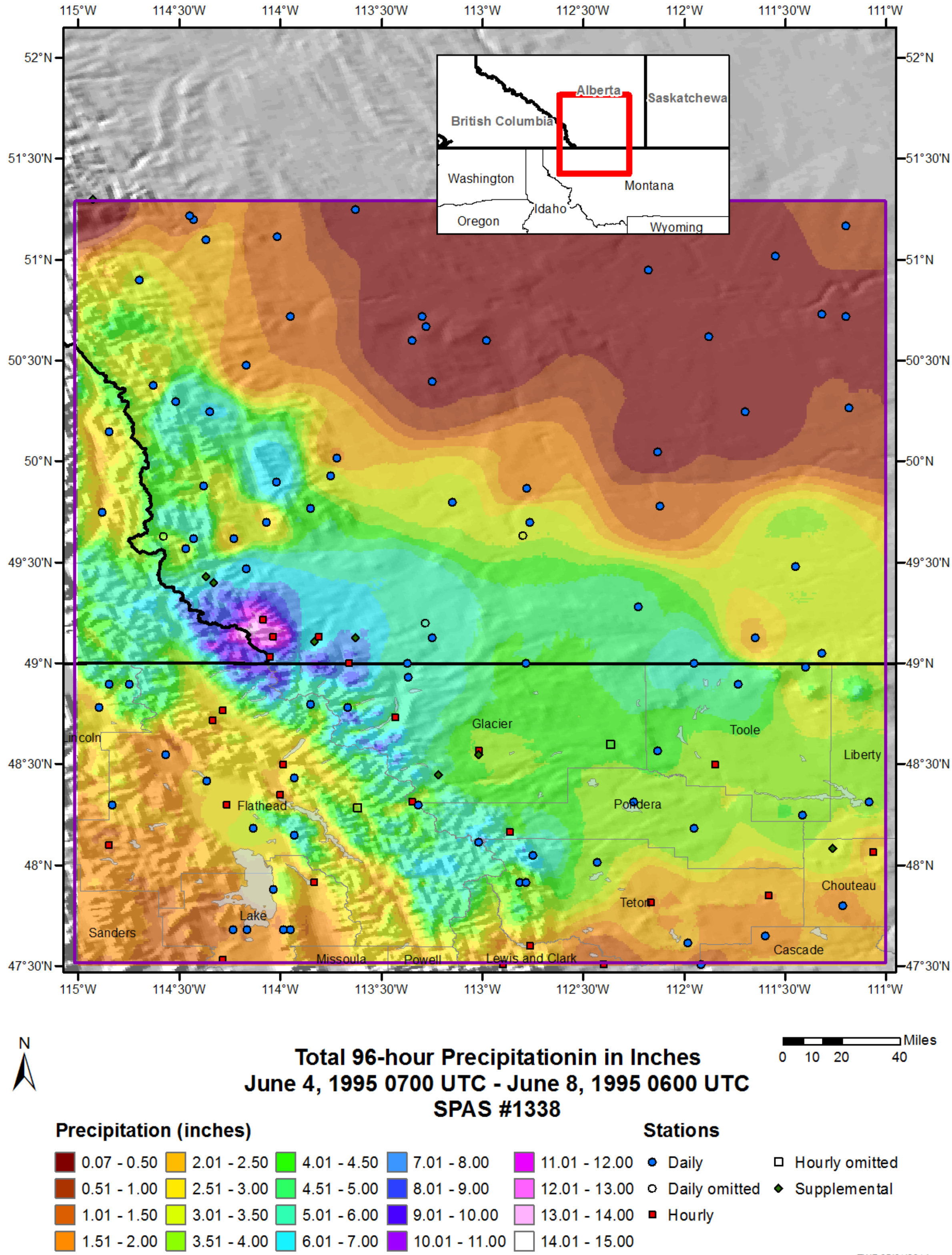

Figure 7. Spionkop Creek 1995 total storm isohyetal.

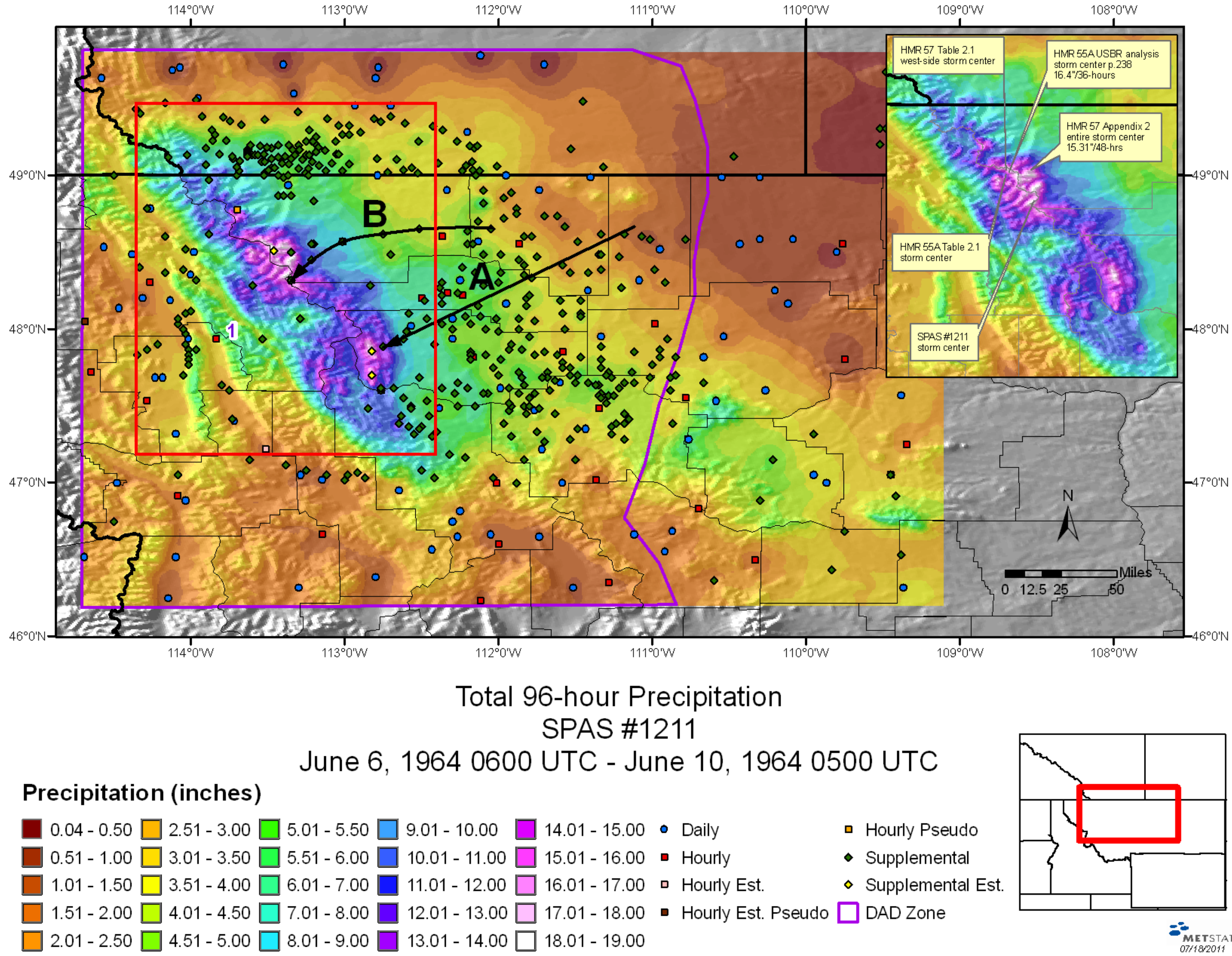

Figure 8. Gibson Dam 1964 total storm isohyetal.

D. Comparison of The Colorado 2013 Storm to PMP

Each of these storms plays an important role in defining PMP values for the region. Dam safety is intimately connected to this information, especially the adequacy of high hazard dams to pass the resulting Probable Maximum Flood. Therefore, it is informative to see how the rainfall from these events compares to PMP at the location where the storm occurred. For this comparison, the in-place maximized 24-hour 10-square mile rainfall amounts where compared to the HMR 55A 24-hour 10-square mile PMP value (Table 1) [3]. These comparisons show how much larger the HMR 55A PMP values are than even the most extreme events, even after a given storm has been maximized. Although conservatism in PMP values is required to ensure safety of life and property downstream of high hazard dams, the amount of conservatism should be justified technically based on the current understanding of meteorology and its relation to maximum rainfall production. This analysis demonstrates that the values provided in HMR 55A are far too high compared to what actual storm data and understanding of meteorology support. Therefore, updated PMP studies, which take into consideration more refined rainfall analyses and apply current state-of-the-science technology and understanding, should be completed to properly design infrastructure.

Table 1. Comparisons of in-place maximized rainfall against HMR 55A PMP values at the same location.

SPAS Storm	HMR 55A 24-hr 10-mi2 PMP	SPAS In-place Maximized 24-hr 10-mi^2 Rainfall	Percent Difference from HMR 55a
Colorado Septmeber 2013	36.5"	11.2"	69%
Spionkop Creek June 1995	24.0"	14.5"	40%
Waterton Red Rocks June 1975	24.0"	10.4"	57%
Gibson Dam June 1964	26.0"	24.9"	4%
Lake Maloya May 1955	31.5"	17.0"	46%
Penrose June 1921	31.5"	16.1"	49%

III. Conclusion

The rainfall and resulting flooding of this storm were among the most devastating in history along the Front Range of Colorado. However, this storm pattern and resulting floods are not as uncommon as one might think. This type of storms has occurred on several occasions along the Rocky Mountain Front Range from Alberta to Colorado. Understanding the processes which create these devastating events, being able to plan for them ahead of time, and being able to respond to them in real time are important lesson learned from this event. The important collaborative effort and comprehensive precipitation analysis between AWA, CCC, the NWS, and others will serve the hydrologic engineering community with a valuable dataset for years and provide valuable rainfall and meteorological data from which to complete analyses and further understand the rainfall and flooding associated with these events.

IV. References

1. Boulder National Weather Service Forecast Office, http://www.crh.noaa.gov/bou/
2. Colorado State University, http://www.news.colostate.edu/Release/7147
3. Hansen, E.M., Fenn, D.D., Schreiner, L.C., Stodt, R.W., and J.F., Miller, 1988: Probable Maximum Precipitation Estimates, United States between the Continental Divide and the 103rd Meridian, *Hydrometeorological Report Number 55A*, National weather Service, National Oceanic and Atmospheric Association, U.S. Dept of Commerce, Silver Spring, MD
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V. Author Biography

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Bill Kappel is President and Senior Meteorologist of Applied Weather Associates (AWA) in Monument, Colorado. Mr. Kappel received an AA from Skagit Valley College in 1992, a BS in Physical Science from Mesa State College (now Colorado Mesa University) in 1998 and a Broadcast Meteorology degree from Mississippi State University in 2001. He served as an on-air meteorologist for 10 years at various television stations across the country prior to joining AWA in 2003. The focus of activity at AWA has been Probable Maximum Precipitation and extreme storm analysis. Mr. Kappel has been the project manager for several PMP studies while working extensively in the development, analysis, and publication of the PMP values. Mr. Kappel has also been heavily involved in several forensic meteorology cases, meteorological input parameters development for use in hydrologic model calibration/validation, reservoir inflow management/operations, and rain-on-snow melt calculations. Mr. Kappel has been a guest instructor at the University of Colorado in Colorado Springs and is a member of the numerous related organizations, including AMS, ASDSO, NHWC, NWA, USSD.

