Protections 2016 Ft. Collins, Colorado, USA, 7-9 September 2016
2nd International Seminar on
Dam Protection Against Overtopping
ISBN: 978-1-1889143-27-9 DOI:

Areal-Reduction Factors for the Colorado Front Range and Analysis of the September 2013 Colorado Storm

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ABSTRACT

Information about extreme precipitation is of interest in hydrologic engineering applications such as dam design, river management, and rainfall-runoff-relations. These require knowledge on the spatial and temporal variability of precipitation over an area. In order to obtain areal average values for hydrologic modeling purposes, point rainfall amounts are often transformed to average rainfall amounts over a specified area. This is addressed using depth-area curves which require the use of areal reduction factors (ARFs).

The Colorado Department of Transportation (CDOT) Flood Hydrology Committee tasked Applied Weather Associates (AWA) to derive 24-hour ARFs for the Front Range of Colorado for area sizes of 1- to 1000-sqmi. In addition, basin specific ARFs for the September 2013 rainfall event were calculated for four basins (Boulder Creek, St. Vrain Creek, Big Thompson River, and Thompson River basin). This study was initiated due to areal limitations and potential issues associated with NOAA Atlas 2 ARF curves.

AWA analyzed storm events along the Front Range of the Rocky Mountains extending from northern New Mexico through southern Canada, including the September 2013 event. Each storm event utilized in the analysis represented meteorological and topographical characteristics that were similar to each other and to the September 2013 event. These storms were selected to derive storm specific ARFs which represented to the meteorological and topographical characteristics of the four basins. The individual storm ARFs were utilized to derive a site-specific set of 24-hour ARF values to be used in the hydrologic analysis of four basins along the northern Front Range of Colorado.

Keywords: *Areal Reduction Factors, Extreme Precipitation Events, Probable Maximum Precipitation, September 2013 Rainfall, Colorado Flooding.*

1. INTRODUCTION

Information about extreme precipitation is of interest for a variety of purposes, which include meteorological and hydrologic engineering applications such as dam design, river management, and rainfall-runoff-relations. These entail knowledge on the spatial and temporal variability of precipitation over an area. In order to obtain areal average values for an area, point rainfall amounts (in inches) are transformed to average rainfall amounts over a specified area (in square miles). These issues are addressed using depth-area curves which require the use of ARFs. The derivation of ARFs is an important topic that has been dealt with using several methodologies.

The National Ocean and Atmospheric Administration (NOAA) defines an ARF as the ratio between area-averaged rainfall to the maximum depth at the storm center (NOAA Atlas 2 1973). The most common sources for generalized ARFs and depth-area curves in the United States are from the NOAA Atlas 2 (NOAA Atlas 2 1973) (Figure 1), and the U.S. Weather Bureau's Technical Paper 29 (U.S. Weather Bureau 1957-1960). Examples of site specific ARFs and depth-area curves are referenced in the NOAA Technical Report 24 (Meyers and Zehr 1980) for the semi-arid southwest, the NOAA Technical Memorandum Hydro- 40 (NOAA Hydro-40 1980) for the semi-arid southwest, and the city of Las Vegas, Nevada (Gou 2011).

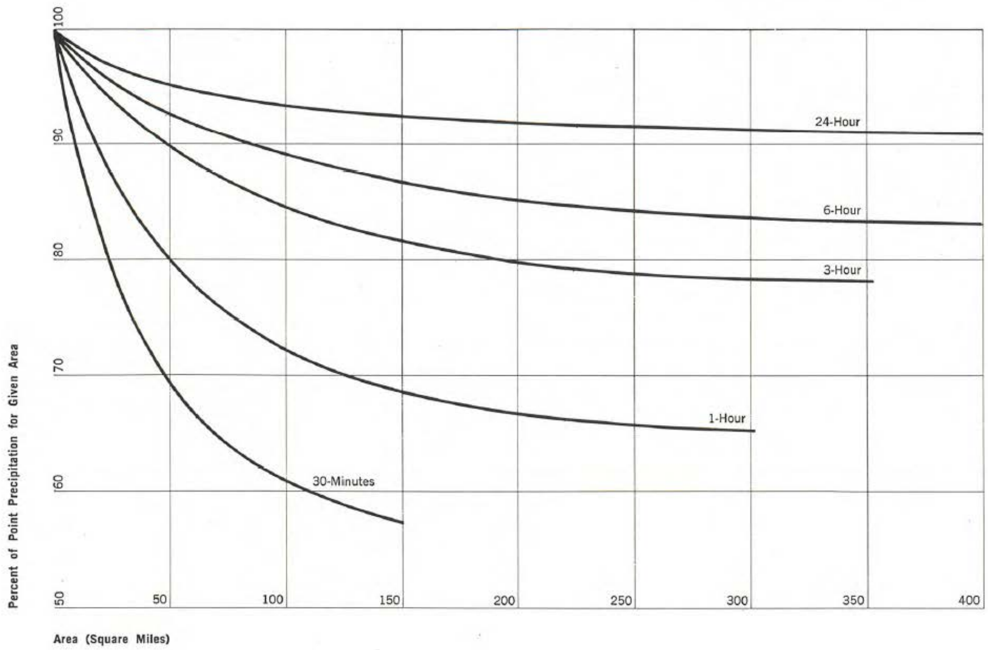

Figure 1. NOAA Atlas 2 Volume 3 ARF curves (NOAA 1973).

2. METHODS

There are two common methods for deriving ARFs: geographically fixed and storm centered. Geographically fixed ARFs originate from rainfall statistics, whereas storm centered ARF values are based on discrete rainfall events. Geographically fixed ARFs relate the precipitation depth at a point to a fixed area. The representative point is the mean of annual maximum point rainfall values at gauged points located within the network (U.S. Weather Bureau 1957-1960; NOAA Atlas 2 1973; Osborn et al 1980). This is a hypothetical point rather than a point for a particular location. The areas within the network are known beforehand and are both fixed in time and space (U.S. Weather Bureau 1957-1960; Osborn et al 1980). With geographically fixed ARFs, the storm center does not correspond with the center of the location and does not need to fall within the area at all (Omolayo 1993). Geographically fixed ARFs (ARF_{Fixed}) are based on different parts of different storms instead of the maximum point values located at the representative storm centers. ARF_{Fixed} is calculated as:

$$ARF_{Fixed} = \frac{\frac{1}{n}\sum_{j=1}^{n}\hat{R}_j}{\frac{1}{k}\sum_{i=1}^{k}\left(\frac{1}{n}\sum_{j=1}^{n}R_{ij}\right)} \qquad (1)$$

where $\hat{R}_j$ is the annual maximum areal rainfall for year *j*, R_{ij} is the annual maximum point rainfall for year *j* at station *i*, *k* is the number of stations in the area, and *n* is the number of years.

The storm centered ARF does not have a fixed area in which rain falls but changes dynamically with each storm event (NOAA Atlas 2 1973; Gou 2011). Instead of the representative point being an average, the representative point is the center of the storm, defined as the point of maximum rainfall. Storm centered ARFs are calculated as the ratio of areal storm rainfall enclosed between isohyets equal to or greater than the isohyet value to the maximum point rainfall at the storm center. A storm centered ARF (ARF_{center}) is calculated as:

$$ARF_{center} = \frac{\overline{R}_i}{R_{center}} \tag{2}$$

where $\overline{R}_i$ is the areal storm rainfall enclosed between isohyets equal to or greater than the isohyets, and R_{center} is the maximum point rainfall at the storm center.

AWA calculated ARFs using a storm centered depth-area approach based on gridded hourly rainfall data from the Storm Precipitation Analysis System (SPAS). SPAS has demonstrated reliability in producing highly accurate, high resolution rainfall analyses during hundreds of post-storm precipitation analyses (Tomlinson and Parzybok 2004; Parzybok and Tomlinson 2006). SPAS has evolved into a hydrometeorological tool that provides accurate precipitation data at a high spatial and temporal resolution for use in a variety of sensitive hydrologic applications. AWA and Metstat, Inc. initially developed SPAS in 2002 for use in producing storm centered Depth-Area-Duration (DAD) values for Probable Maximum Precipitation (PMP) analyses. SPAS utilizes precipitation gauge data, "basemaps" and radar data (when available) to produce gridded precipitation at time intervals as short as 5-minutes, at spatial scales as fine as 1-km^2 and in a variety of customizable formats. To date, (December 2015) SPAS has analyzed over five-hundred storm centers across all types of terrain, among highly varied meteorological settings and with some events occurring over 100-years ago. For more detailed discussions on SPAS and DAD calculations refer to (Tomlinson et al 2003-2013; Kappel et al 2012-2014).

3. SEPTEMBER 2013 BASIN ARFS

The September 2013 can be classified as an upslope synoptic storm event associated with an area of low pressure to the east/southeast causing the air to flow into the Front Range (upslope) from the Midwest and Southern Plains. This air was forced to lift by both interaction with the terrain and the lift associated with the storm system. The storm event exhibited low to moderate intensity rainfall that occurred over long durations and contained periods of higher intensity rainfall. A detailed description of the meteorology associated with the storm can be found at http://coflood2013.colostate.edu/meteo.html.

The Colorado September 8-17, 2013 rainfall event was analyzed using the SPAS (SPAS number 1302) for use in several PMP and hydrologic model calibration studies (Figure 2). The hourly gridded rainfall data, based on gauge adjusted radar data, were used to derive basin specific ARFs. Four basins (Table 1) located along the Colorado Front Range were used to derive the 24-hour basin specific ARFs. The SPAS DAD program was used to derive basin specific 24-hour depth-area values. The point maximum (1-mi^2) 24-hour rainfall (within each basin) was selected as the storm center. The maximum average basin 24-hour rainfall depth for standard area sizes (1-, 10-, 25-, 50-, 100-, 200-, 300-, 400-, and 500-mi^2) up to the basin total area were calculated. The point maximum and maximum areal average depths were used to calculate the basin specific ARFs.

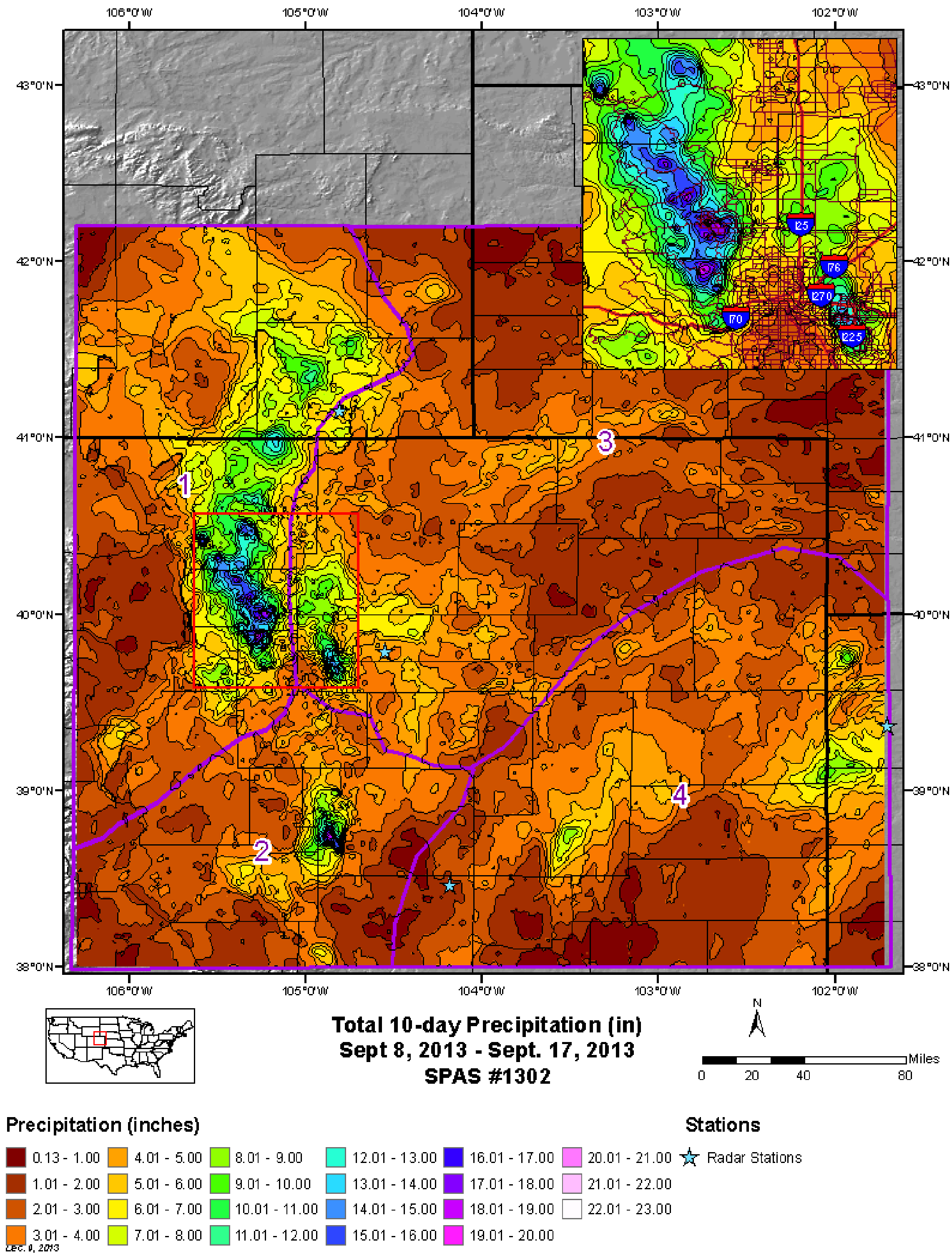

Figure 2. SPAS total rainfall for the Colorado September 8-17, 2013 storm event.

Table 1. Basin specific 24-hour ARFs for the September 2013 storm event.

Basin	**Area (mi^2)**	**ARF**
Boulder Creek	446	0.352
St. Vrain Creek	982	0.384
Big Thompson River	630	0.357
Thompson River	827	0.355

The four calculated basin specific 24-hour ARFs for the September 2013 event were compared to NOAA Atlas 2 24-hour ARF curve and to the HMR 55A Orographic C 24-hour ARF curve (Hansen et al 1988) (Figure 3). Table 1 shows the basin specific 24-hour ARF values. As expected, the four September 2013 basin ARF values have a significantly larger reduction in rainfall than published NOAA Atlas 2 and HMR 55A ARFs.

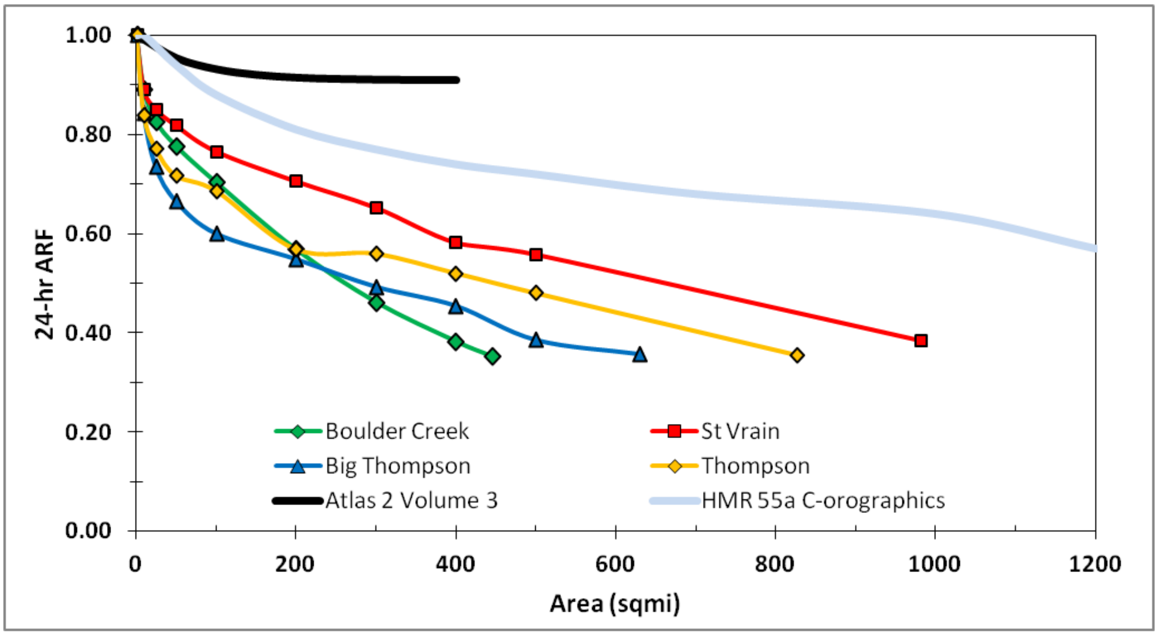

Figure 3. Basin specific 24-hour ARFs for the September 2013 event compared to NOAA Atlas 2 24-hour ARF curve and to the HMR 55A Orographic C 24-hour ARF curve.

4. COLORADO FRONT RANGE ARFS

Initially, 28 SPAS storm center DAD zones were identified to have occurred over similar meteorological and topographic regions as the September 2013 storm event that occurred along the Colorado Front Range. The initial list was refined to nine storm centers that had storm characteristics representative of an upslope synoptic event similar to the four basins analyzed in this study. Each storm event utilized in this analysis represented meteorological and topographical characteristics that were similar to each other and similar to the September 2013 event. All storms were of the synoptic type (aka HMR 55A General Storm). Each were associated with an area of low pressure to the east/southeast causing the air to flow into the Front Range (upslope) from the Midwest and Southern Plains. This air was forced to lift by both interaction with the terrain and the lift associated with the storm system. All nine events used exhibited low to moderate intensity rainfall, which occurred over long durations, interspersed with periods of higher intensity rainfall. Storm events removed from the initial list were representative of shorter duration, higher intensity storms, i.e. local storms/thunderstorms or occurred in significantly different topographical settings. This allowed the ARF data derived during this analysis to represent the same storm type and meteorological setting as occurred during the September 2013 event. The final set of nine storm centers (Table 2) were used to derive 24-hour storm center ARFs.

The point maximum (1-mi^2) 24-hour rainfall (within each SPAS DAD zone) was selected as the storm center. The maximum average 24-hour rainfall depth for standard area sizes (1-, 10-, 25-, 50-, 100-, 150-, 200-, 250-, 300-, 350-, 400-, 450-, 500-, 700-, and 1000-mi^2) were calculated, these area sizes were selected to be consistent with NOAA HydroMeteorological Reports (HMRs). The point maximum and maximum areal averages depths were used to calculate each storm events ARFs. Based on the nine events, an average ARF for each area size was calculated. Several other ARF curves were created for comparison purposes: i) maximum, minimum, ii) +1-sigma, iii) 85% confidence, iv) 90% confidence, and v) 95% confidence. Based on discussions with the CDOT flood review committee and Nolan Doesken (Colorado State Climatologist), the 85% confidence ARF ($ARF_{85\%}$) was selected as the best representation of ARFs along the Colorado Front Range. The 85% confidence limit ARF was selected based on several justifications. Similar use of the 85% percentile was employed in the HMRs in determining various Depth-Area and Depth-Duration relationships. Further, during the site-specific Probable Maximum Precipitation (PMP) study for Lewis River, WA, the 85% was used to determine which Depth-Duration relationship were appropriate for deriving PMP values at durations other than 24-hours. That study was accepted for use by Federal Energy Regulatory Commission (Tomlinson et al 2011). In addition, the 85% ARF curve is similar to independent study in HMR 55A (see Figure 6 and Table 3 below). Finally, the 85% ARF curve adds a level of conservatism compared to using the average ARF which is typical in most ARF studies. The final equation used to represent Colorado Front Range 24-hour ARFs is:

$$ARF_{85\%} = 0.646 + 0.354 * exp(-kA) \tag{3}$$

where $ARF_{85\%}$ is the 85% confidence ARF, k is a decay coefficient, and A is storm area in mi^2. The average ARF curve and final 85% confidence ARF curve are shown in Figure 6. The NOAA Atlas 2 ARF curve and HMR 55A Orographic C curve are also shown for comparison (Figure 4 and Table 3).

Table 2. Final SPAS storm centered locations with similar meteorology and topography as the September 2013 storm event used to derive 24-hr ARFs.

ID	**SPAS ID**	**Storm Location**	**Date**	**Latitude**	**Longitude**	**Max. Precipitation (in)**	**HMR 55a Subunit**
1	1211	Gibson Dam, MT	June. 6-8, 1964	48.3541	-113.3708	19.16	Orographic "A"
2	1251	Lake Maloya, NM	May 17-21, 1955	37.0090	-104.3410	14.82	Orographic "E"
3	1252	Waterton Red Rock, AB	June 14-21, 1975	49.0875	-114.0458	14.46	Orographic "A"
4	1253	Big Elk Meadows, CO	May 3-8, 1969	40.2700	-105.4200	20.01	Orographic "C"
5	1302	Northeast Colorado	Sept. 8-17, 2013	40.0150	-105.2650	20.41	Orographic "C"
6	1320	Calgary, AB	June 19-22, 2013	50.6350	-114.8550	13.78	Orographic "A"
7	1325	Savageton, WY	Sept. 27-Oct 1, 1923	43.8458	-105.8042	17.56	Min. Orographic "A"
8	1335	Warrick, MT	June 5-10, 1906	48.0791	-109.7041	13.69	Orographic "A"
9	1338	Spionkop Creek, AB	June 4-7, 1995	49.1708	-114.1625	14.48	Orographic "A"

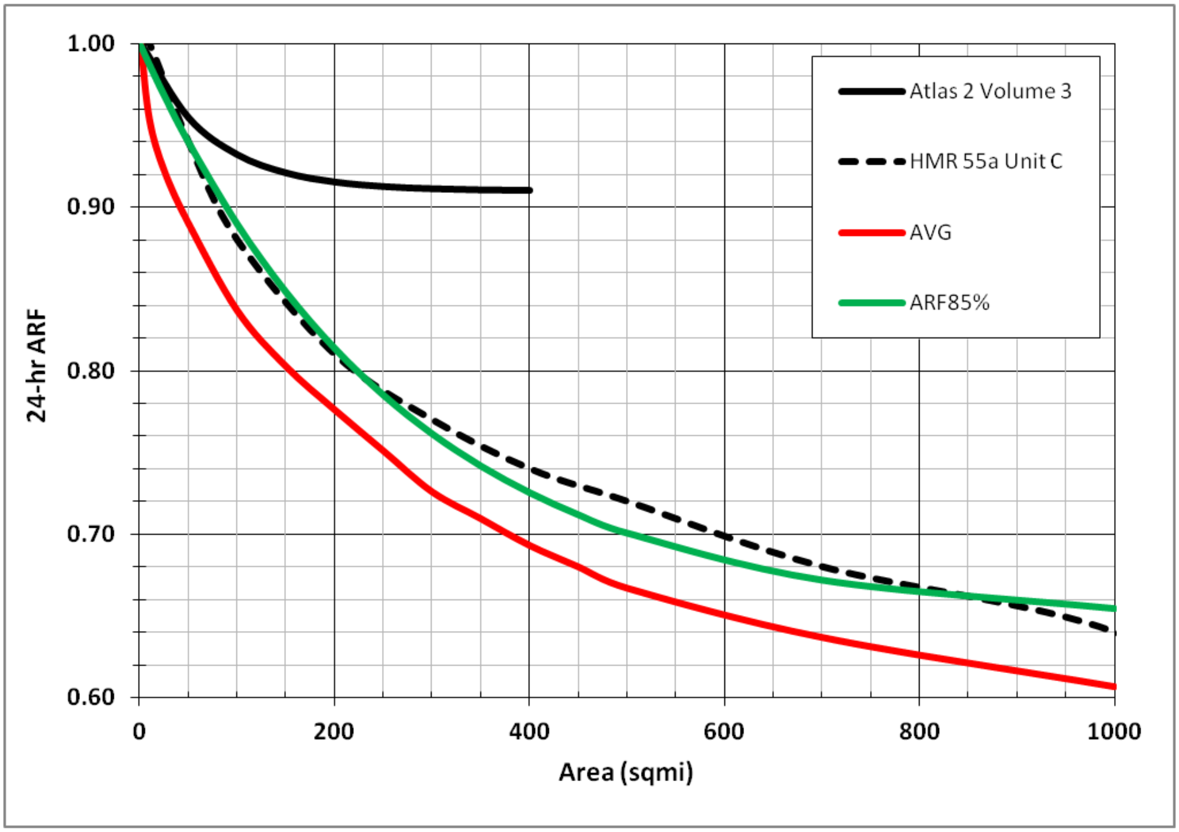

Figure 4. The average 24-hour ARF curve and final 85% confidence 24-hour ARF curve. The NOAA Atlas 2 24-hour ARF curve and HMR 55A Orographic C 24-hour ARF curve are shown for comparison.

Table 3. Comparison of 24-hour ARF values. *AVG* is the average ARF, $ARF_{85\%}$ is the 85% confidence ARF, HMR 55A is HMR 55A Orographic C ARF, and Atlas 2 is NOAA Atlas 2 ARF.

General Storm 24-hour ARF				
Area (mi^2)	*AVG*	$ARF_{85\%}$	HMR 55a	Atlas 2
1	1.00	1.00	1.00	1.00
10	0.95	0.99	1.00	-
25	0.92	0.97	0.97	-
50	0.89	0.94	0.94	0.95
100	0.84	0.89	0.88	0.93
150	0.80	0.85	0.85	0.92
200	0.78	0.81	0.81	0.92
250	0.75	0.78	0.79	0.91
300	0.73	0.76	0.77	0.91
350	0.71	0.74	0.76	0.91
400	0.69	0.73	0.74	0.91
450	0.68	0.71	0.73	-
500	0.67	0.70	0.72	-
700	0.64	0.67	0.68	-
1000	0.61	0.65	0.64	-

5. RESULTS

The final derived $ARF_{85\%}$ values created significantly larger reductions in point rainfall as compared to NOAA Atlas 2. Because results of the Phase I CDOT September 2013 Flood Study are not being changed as part of this work, a smooth transition between NOAA Atlas 2 24-hour ARF and the derived 24-hour $ARF_{85\%}$ is needed for Phase II basins. The largest basin used in Phase I was 315-mi^2 and the smallest basin used in Phase II was 446-mi^2. In order to maintain consistency between Phase I results and Phase II results, a linear transition was applied between NOAA Atlas 2 315-mi^2 ARF value and $ARF_{85\%}$ 500-mi^2 (Figure 5 and Table 4). Based on the areal limitations of NOAA Atlas 2, the larger point precipitation reductions based on $ARF_{85\%}$, and maintaining consistency with Phase I study the linear transition between NOAA Atlas 2 315-mi^2 ARF value and $ARF_{85\%}$ 500-mi^2 was chosen for application of Phase II of the CDOT September 2013 Flood Study. In addition, application of this transition in the hydrologic modelling for the four basins investigated showed good agreement and acceptable results. The final 24-hour $ARF_{85\%}$ curve is compared to the four basin specific 24-hour ARF curves for the September 2013 event (Figure 6).

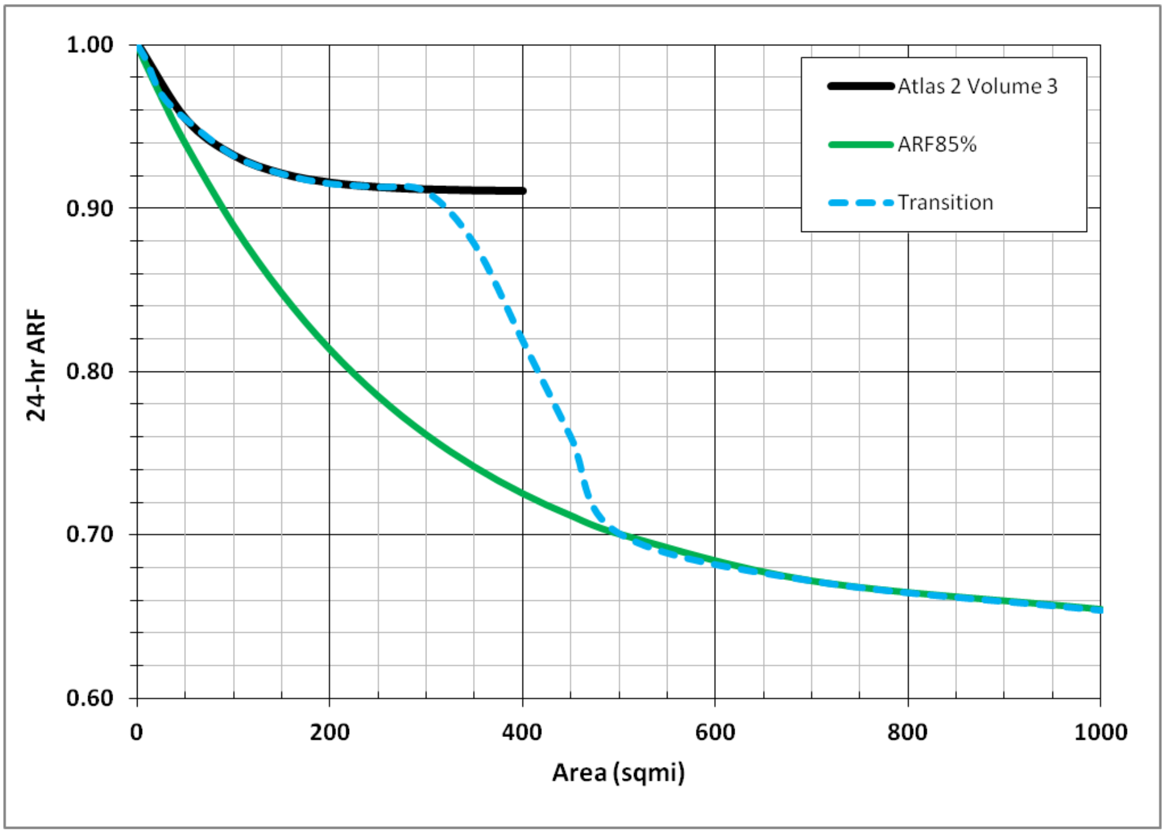

Figure 5. Final 24-hr ARF curve with transition between NOAA Atlas 2 and AWA $ARF_{85\%}$.

Table 4. Comparison of final 24-hour ARF values. $ARF_{85\%}$ is the 85% confidence ARF. Transition is the transition between NOAA Atlas 2 and $ARF_{85\%}$, and Atlas 2 is NOAA Atlas 2 ARF.

General Storm 24-hour ARF			
Area (mi^2)	$ARF_{85\%}$	Transition	Atlas 2
1	1.00	1.00	1.00
10	0.99	0.99	-
25	0.97	0.97	-
50	0.94	0.95	0.95
100	0.89	0.93	0.93
150	0.85	0.92	0.92
200	0.81	0.92	0.92
250	0.78	0.91	0.91
300	0.76	0.91	0.91
350	0.74	0.88	0.91
400	0.73	0.82	0.91
450	0.71	0.76	-
500	0.70	0.70	-
700	0.67	0.67	-
1000	0.65	0.65	-

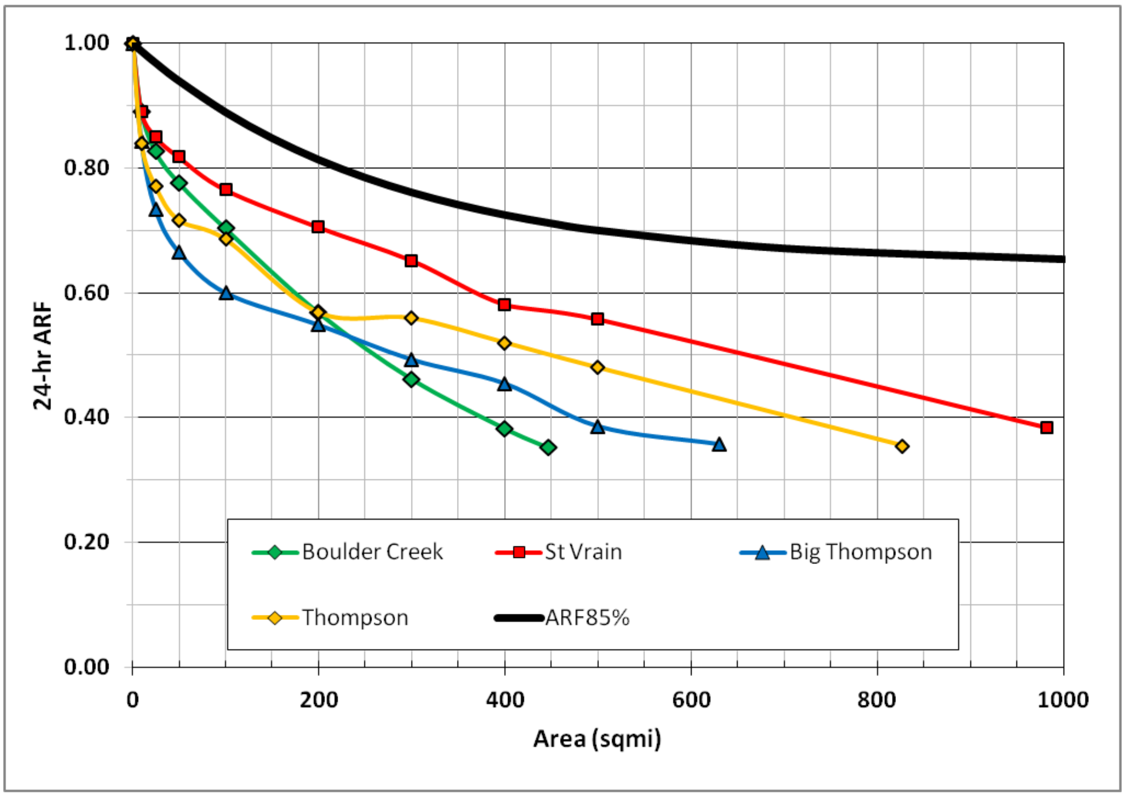

Figure 6. 24-hour ARF curve compared to basin specific ARFs for the September 2013 event

6. CONCLUSION

The final 24-hour $ARF_{85\%}$ values create significantly larger reductions of point rainfall at larger area sizes as compared to NOAA Atlas 2. These are based on actual storms that have occurred along the Front Range of the Rockies and of similar storm type as the September 2013 event. These updated ARF values produce more realistic and representative point to areal reductions for synoptic storm events along the Colorado Front Range. The 24-hour $ARF_{85\%}$ curve is only representative and applicable for large synoptic and orographic storm events similar to the September 2013 storm event in Colorado. Future hydrology and engineering flood studies should utilize a more site and duration specific ARF curve based on procedures applied in this study and storms specific to a given locations. This investigation has shown that the generalized ARF curves provided in NOAA Atlas 2 are not necessarily representative of spatial rainfall accumulations along the Colorado Front Range.

7. ACKNOWLEDGMENTS

This work was conducted in collaboration with Applied Weather Associates staff, the Colorado Flood Hydrology committee, and the Colorado Water Conservation board.

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