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

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Outline

- Study
- Review of September 2013 Rainfall Event
- Areal Reduction Factor (ARF)
  - Calculation
  - NOAA Atlas 2
  - Site Specific
- 2013 Basin Specific ARFs
- 24-hour ARFs for Colorado Front Range
- Summary

Study Purpose

- Study was initiated due to areal limitations associated with the NOAA Atlas 2 ARF curves

- NOAA Atlas 2 ARF curves extend from 1-sqmi to 400-sqmi.

- For Phase I of the CDOT September 2013 Flood Study, the NOAA Atlas 2 ARFs were used since drainage area sizes analyzed were less than 400-sqmi.

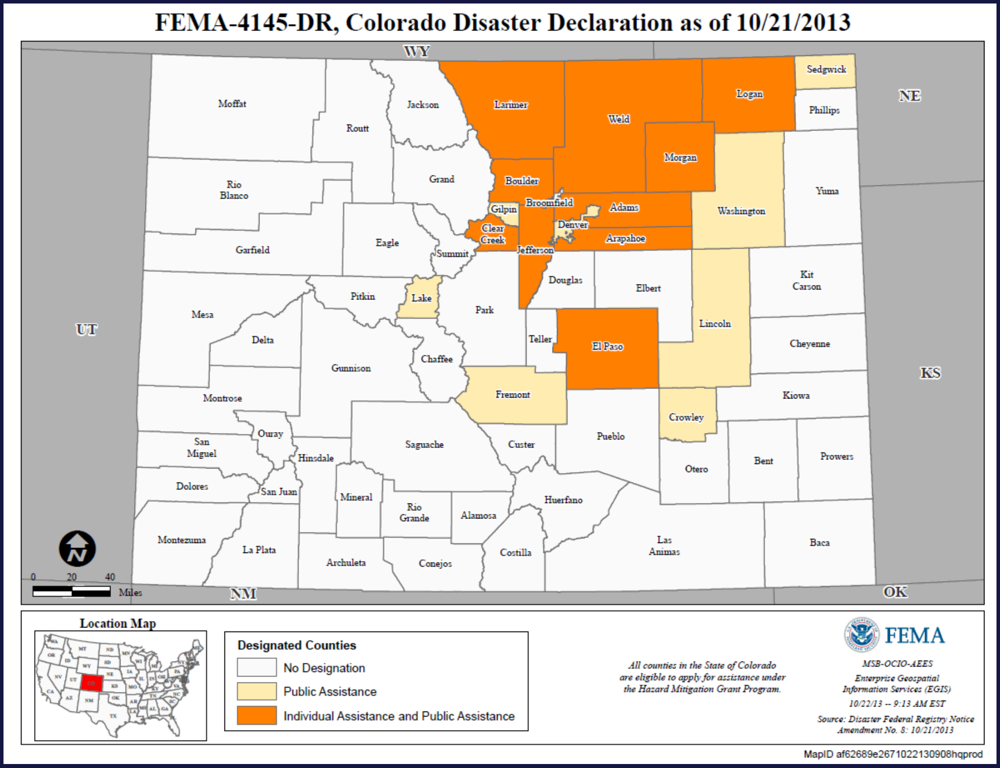
- For Phase II of the CDOT September 2013 Flood Study, the NOAA Atlas 2 ARFs required an update specific to each basin because the drainage area sizes were larger than 400-sqmi.

Study Purpose

- CDOT Flood Hydrology Committee tasked Applied Weather Associates to
  - derive 24-hour ARFs for the Front Range of Colorado for area sizes of 1- to 1000-sqmi.
  - derive basin specific ARFs for the September 2013 rainfall event for four basins (Boulder Creek, St. Vrain Creek, Big Thompson River, and Thompson River basin).
- The Phase II 24-hour ARF curve extends out to 1,000-sqmi and are only applicable to Phase II of the CDOT September 2013 Flood Study

The Storm: Storm Toll

- ❑ Fatalities: 10 (most in a Colorado flood since 1976)
- ❑ Counties impacted: 20
- ❑ Damaged homes: 16,000-plus
- ❑ Destroyed homes: 1,882
- ❑ Damaged businesses: 750
- ❑ Destroyed businesses: 200
- ❑ Miles of state highways damaged: 200
- ❑ Economic toll: $2-3 billion



The Storm: Stats

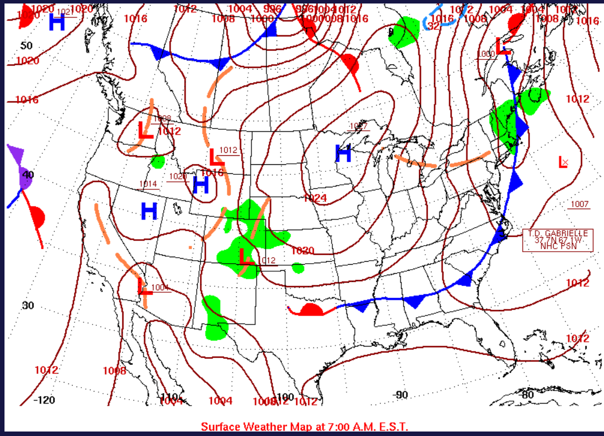
- Optimum combination of monsoon moisture, instability and slow-moving storm system produced record-breaking rainfall over Colorado during September 8-17, 2013

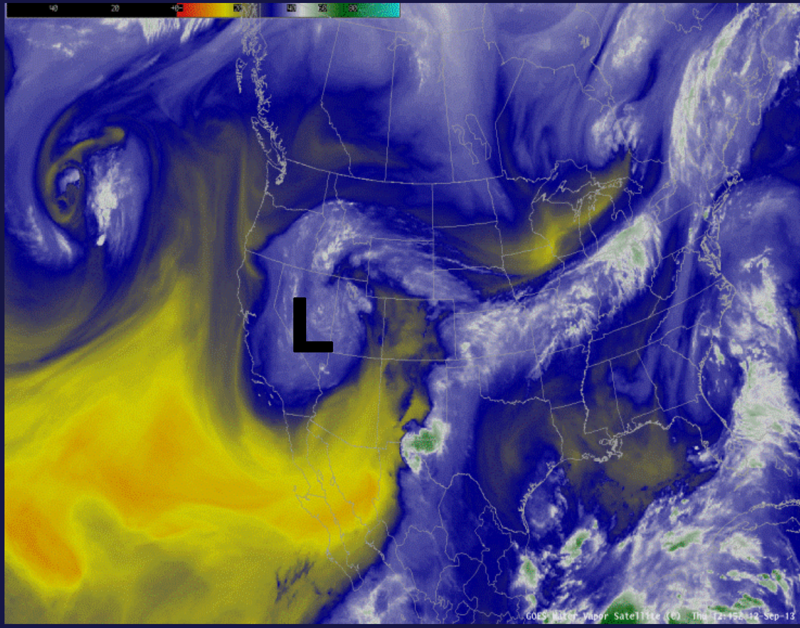
- Up to 20” of rain in 7 days – exceeded 1,000-year recurrence interval in places

- During the period Sep. 10th - 15th, the Boulder, CO NWS Office issued 64 Flash Flood Warnings

- Wet anteceded conditions, saturated soils and burn scars lead to amplified flooding

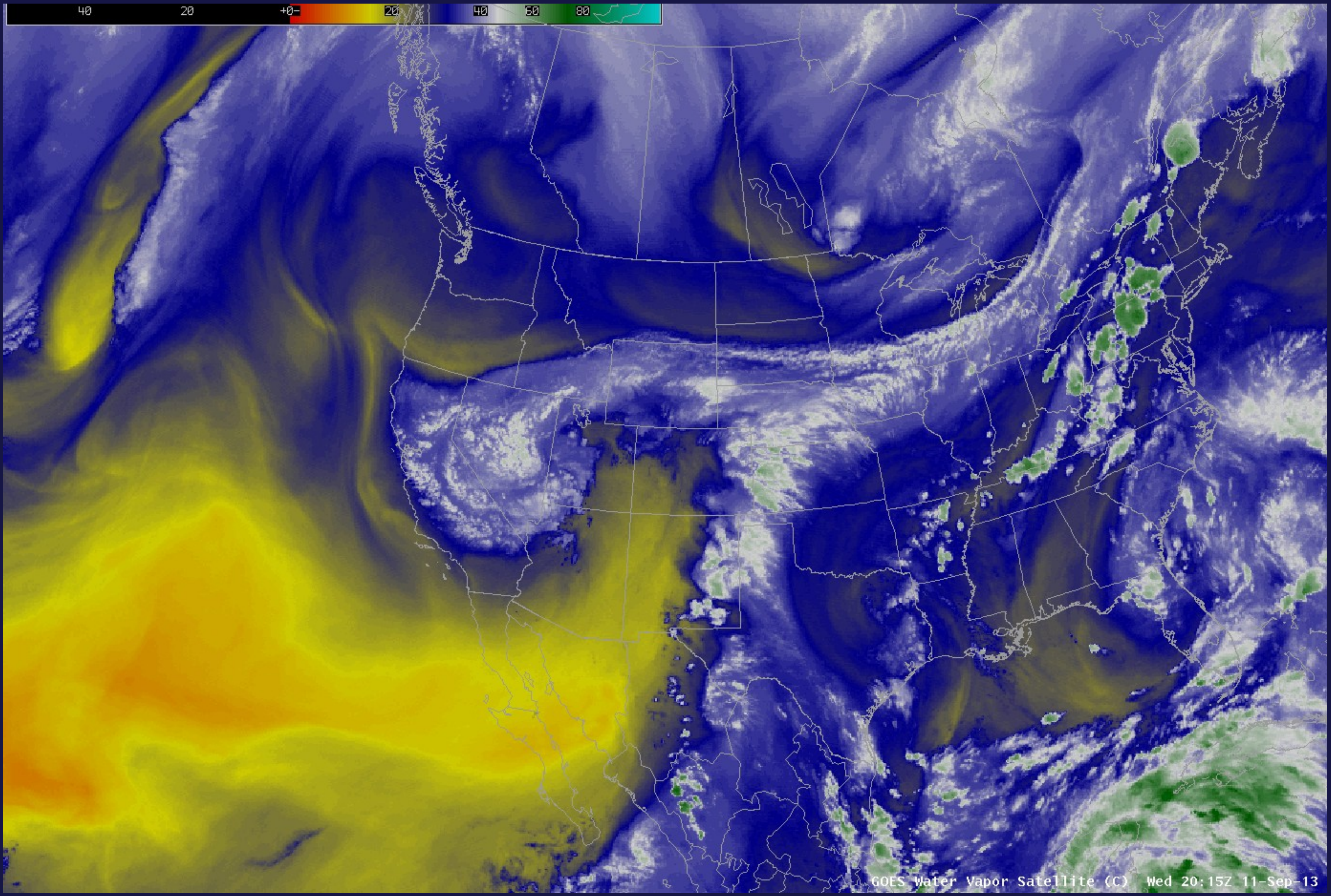
Weather Map 7am EST 9/13/2013





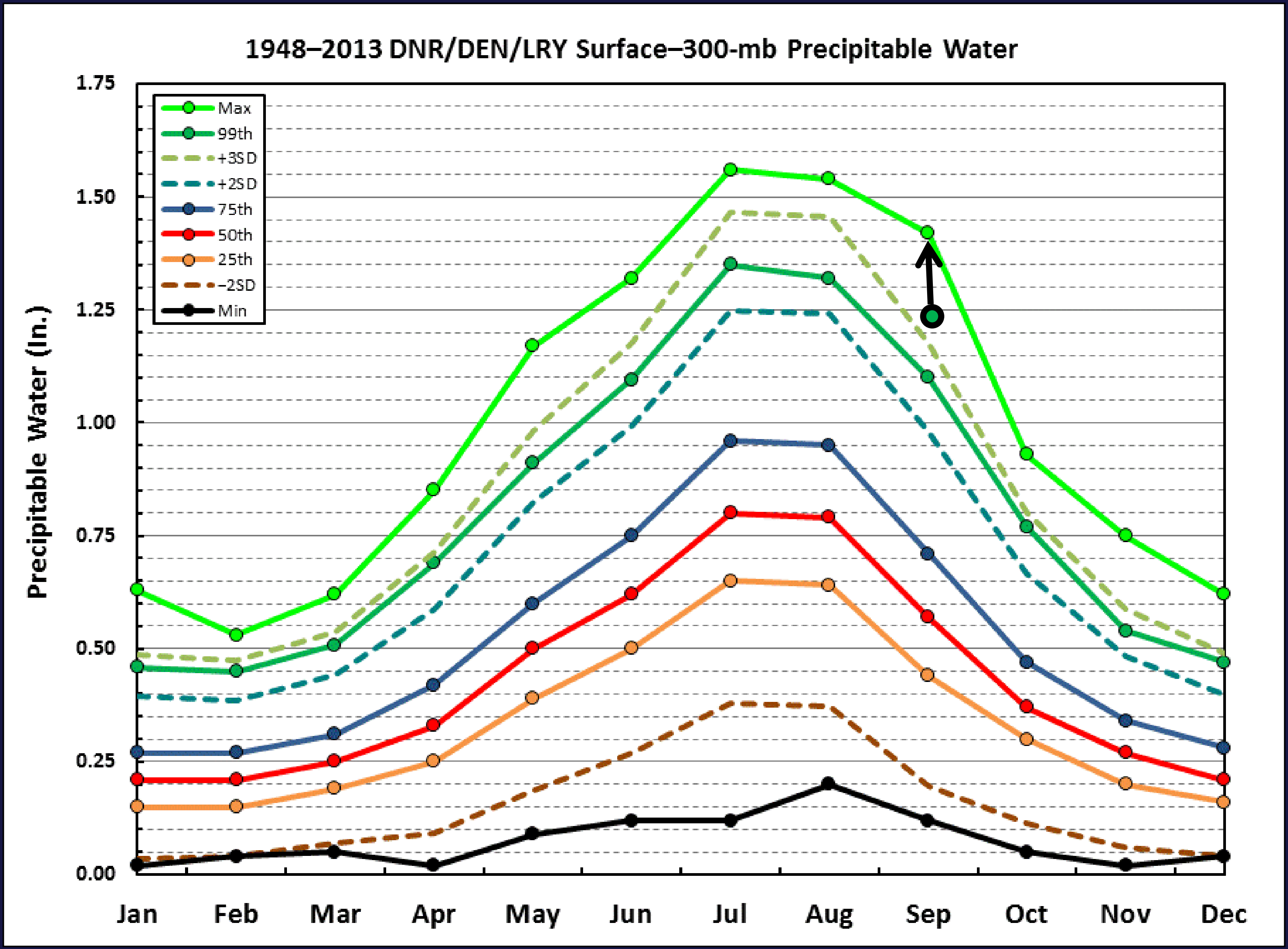
Water vapor Sept. 12, 2013

The Storm: Water Vapor

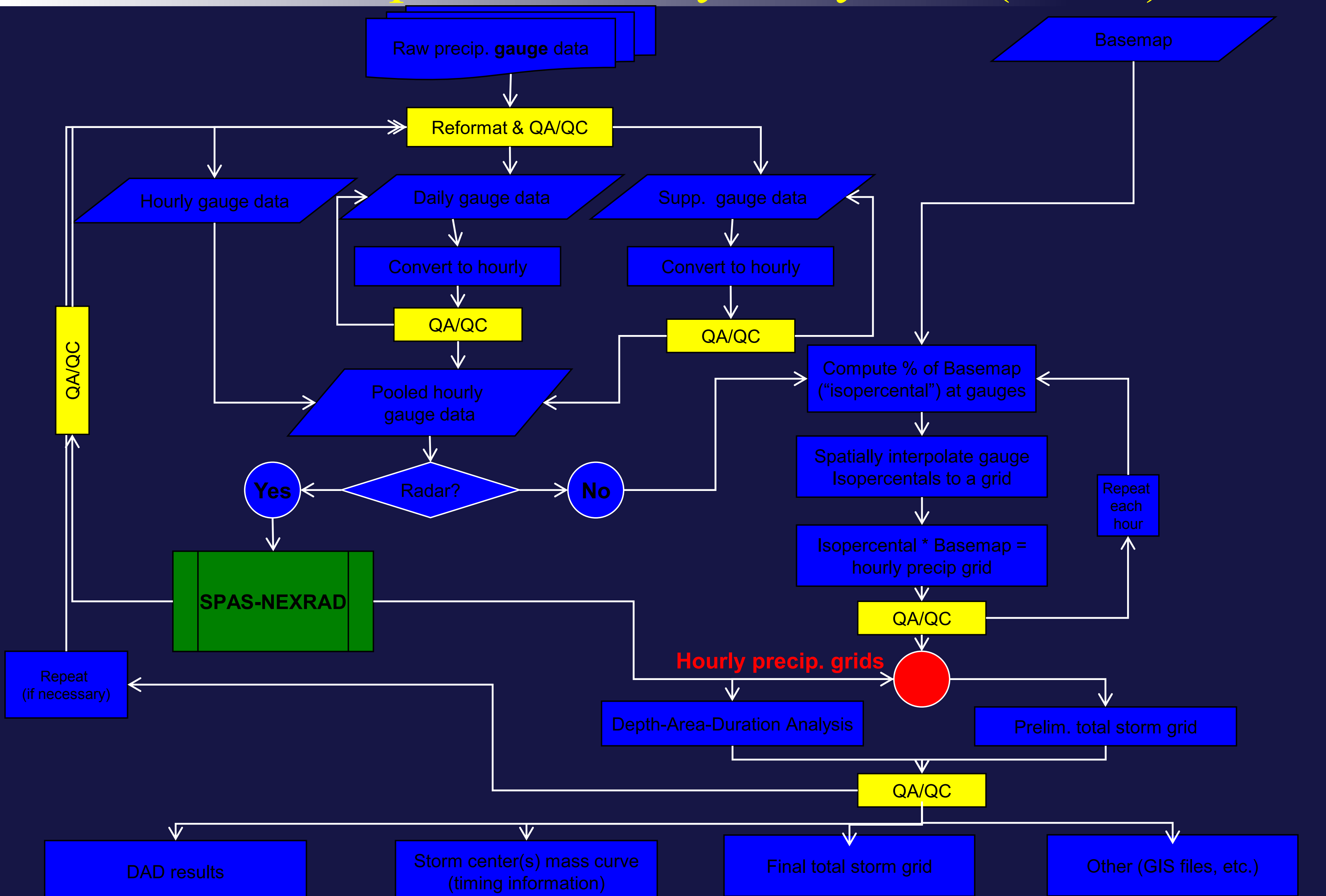


Water vapor Sept. 11-12, 2013

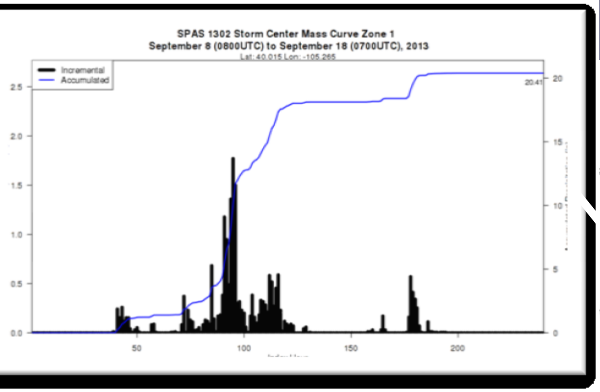
The Storm: Precipitable Water

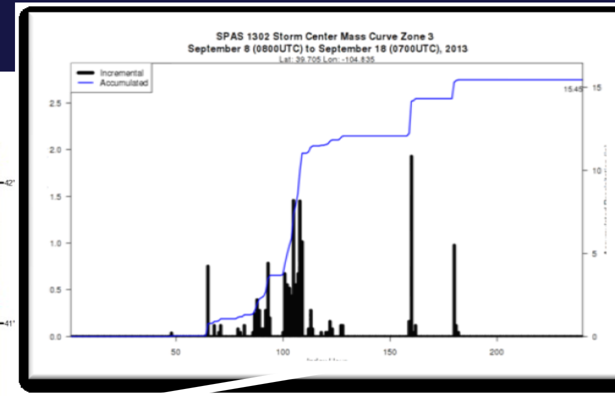


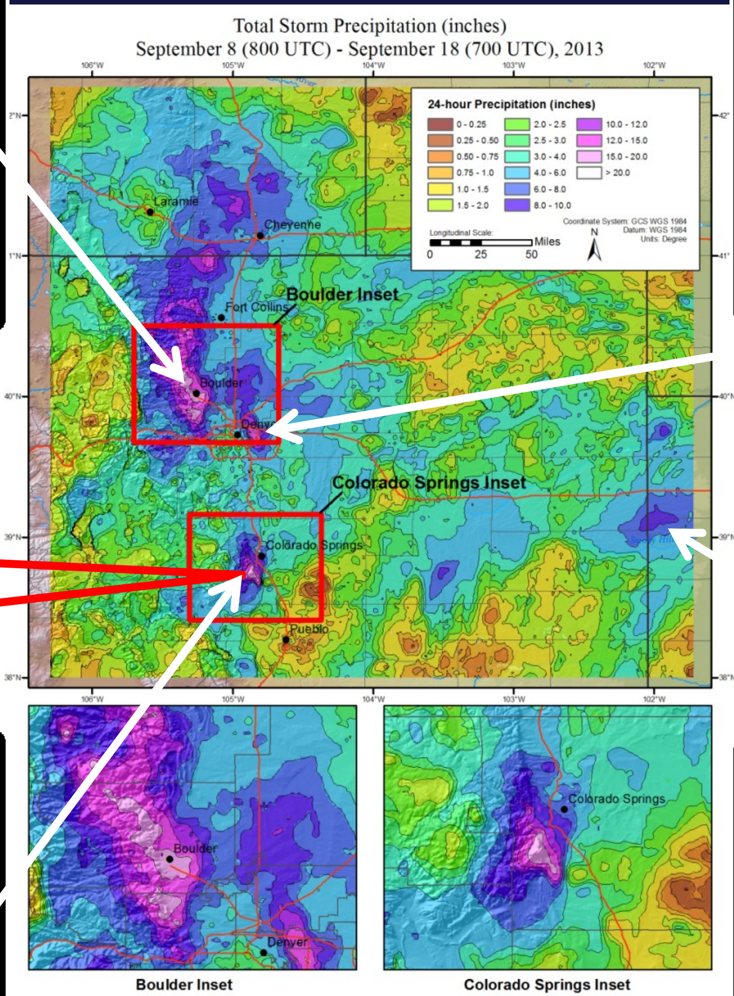
Storm Precipitation Analysis System (SPAS)



Storm Precipitation Analysis System (SPAS)





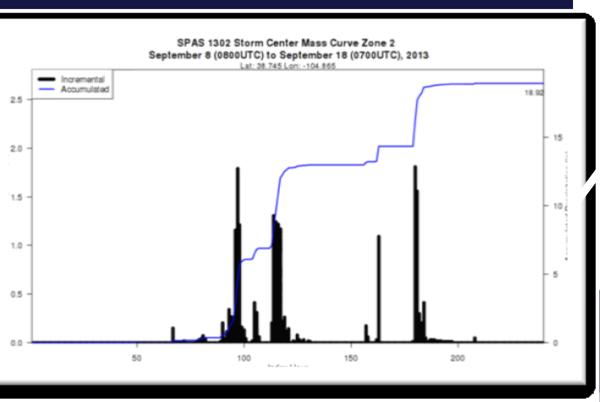


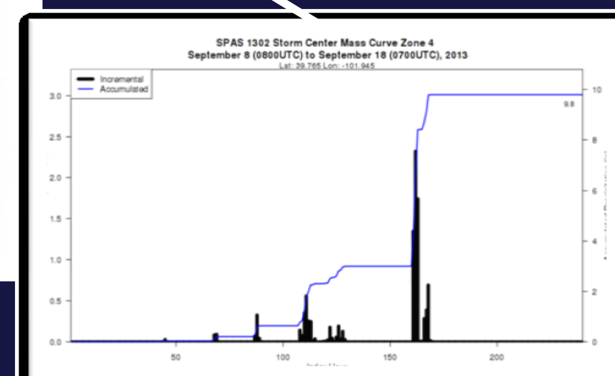
New Colorado 24-hr rainfall record: 11.85" USGS gauge near Fort Carson (prior record 11.08")

Total 10-day (Sept 8-18, 2013)

Precipitation From SPAS

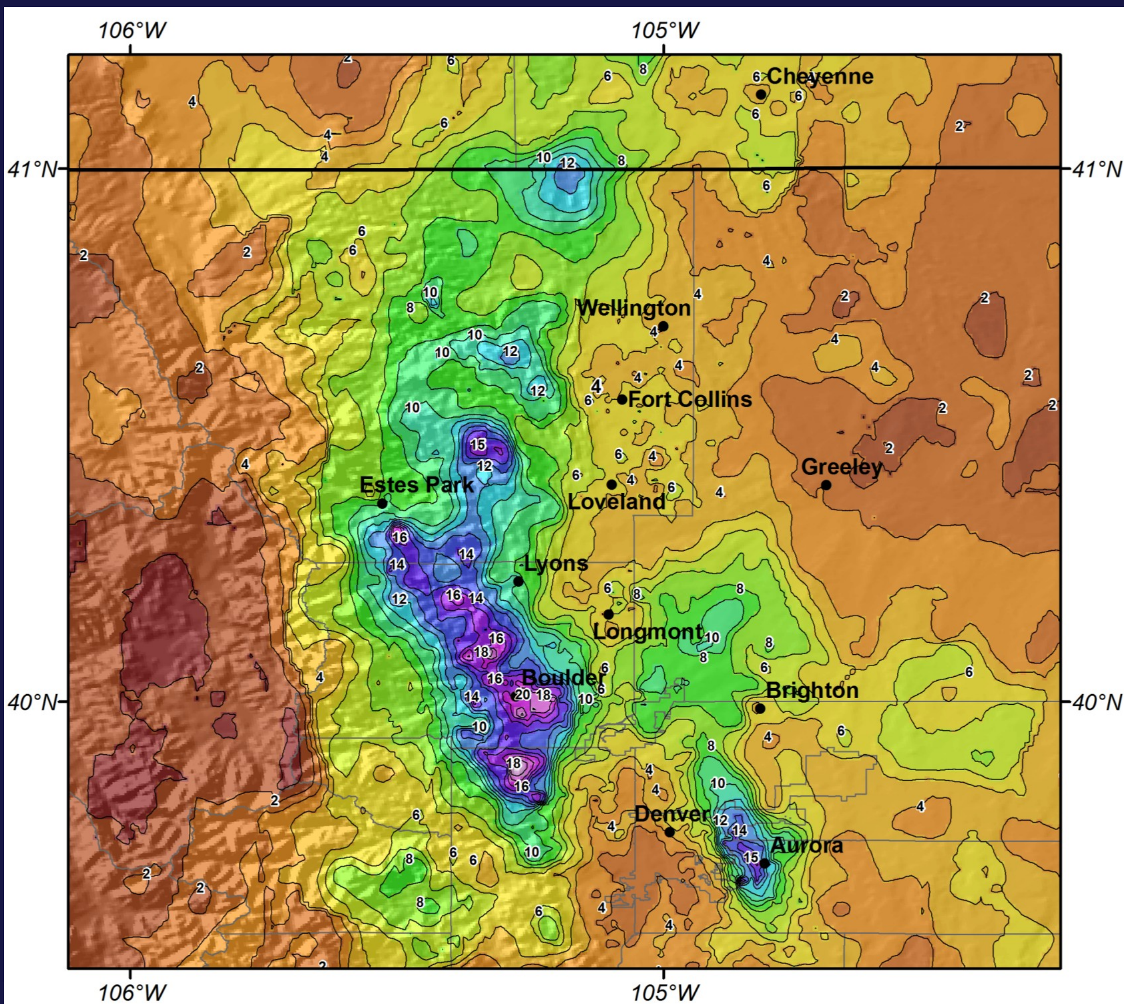
5 min x 1 km²





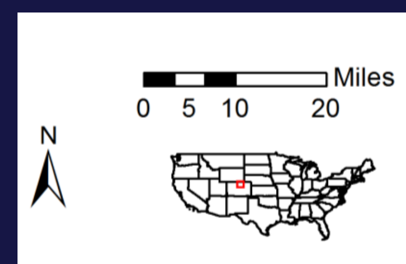
The Storm

- Classified as an upslope synoptic 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.

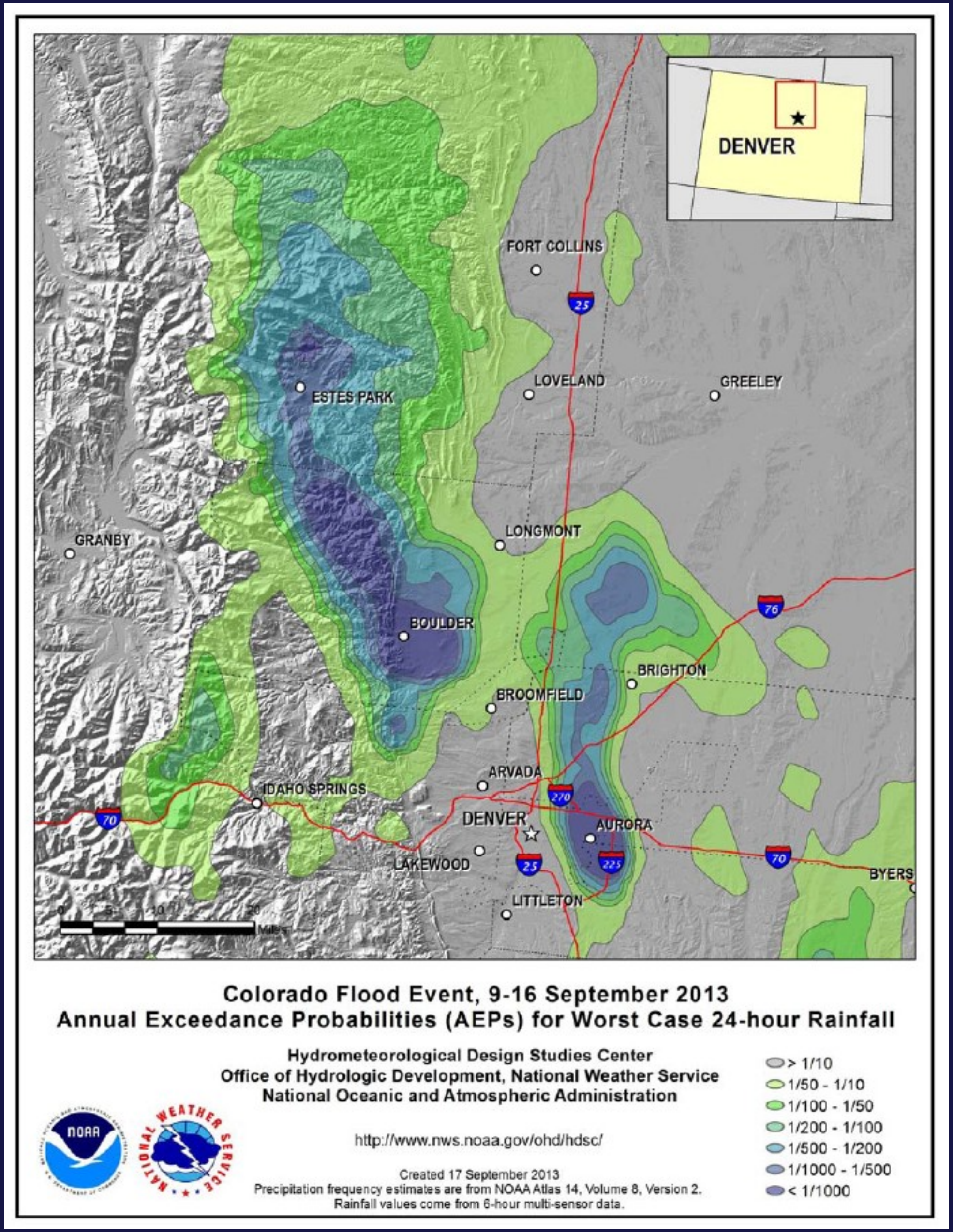


Total 7-day Precipitation (inches)

<= 1.00	5.01 - 6.00	10.01 - 11.00	15.01 - 16.00
1.01 - 2.00	6.01 - 7.00	11.01 - 12.00	16.01 - 17.00
2.01 - 3.00	7.01 - 8.00	12.01 - 13.00	17.01 - 18.00
3.01 - 4.00	8.01 - 9.00	13.01 - 14.00	18.01 - 19.00
4.01 - 5.00	9.01 - 10.00	14.01 - 15.00	> 19.00



The Storm: 24-hr Annual Exceedance Probability



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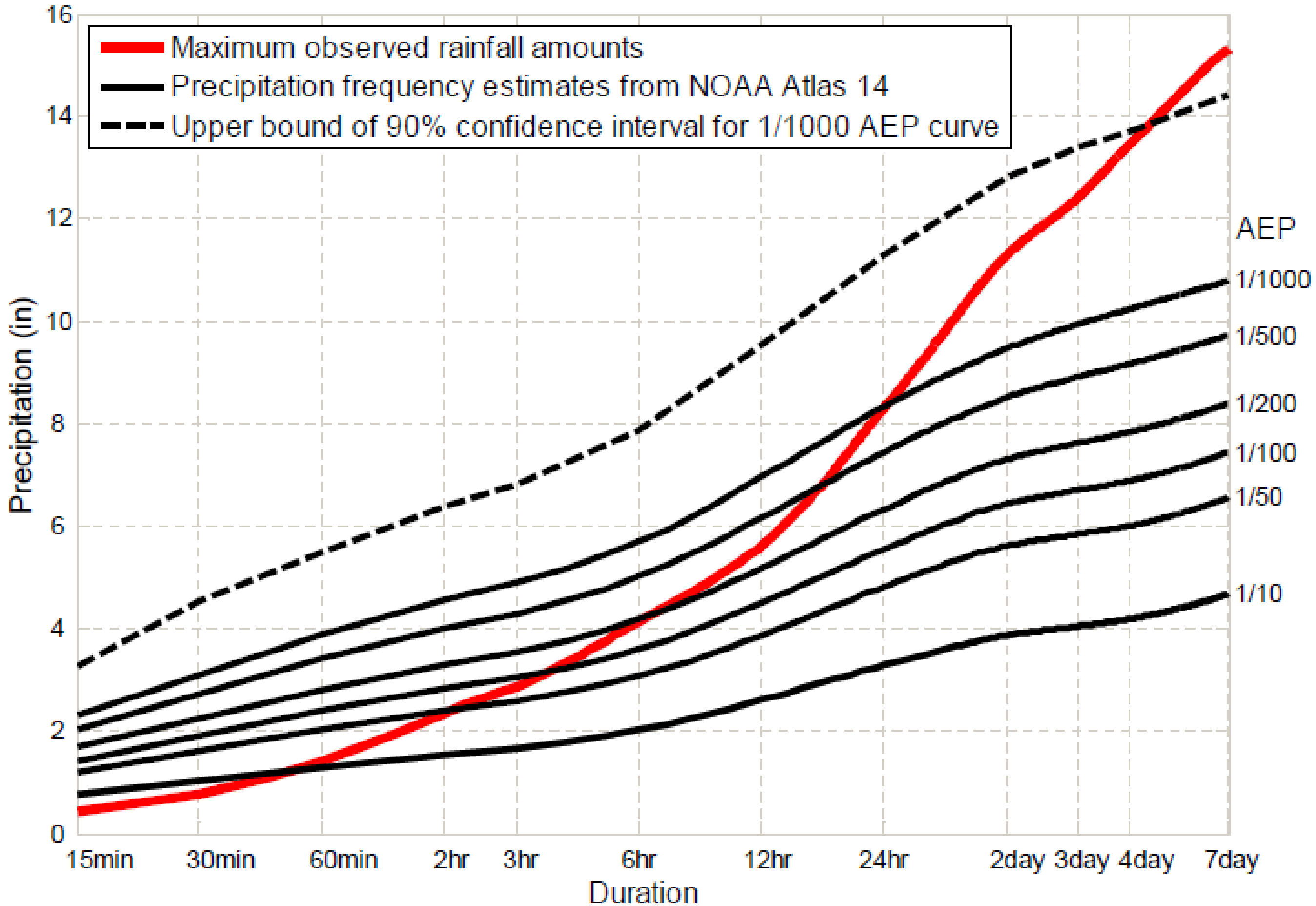


Figure 1. Maximum observed rainfall amounts in relationship to corresponding precipitation frequency estimates for the Justice Center gauge.

The Storm: Flood Damage

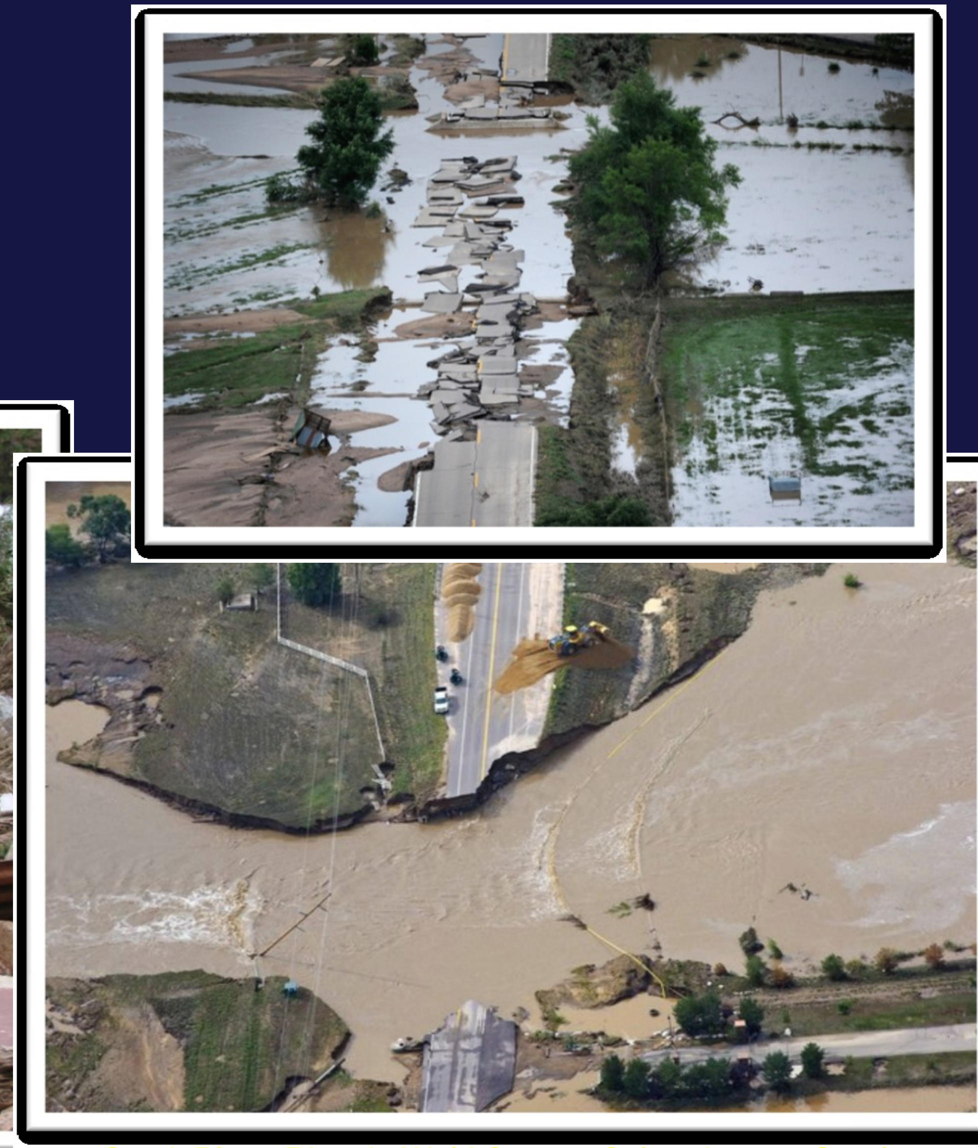
Coal Creek Canyon and damage to Highway 72. Photo courtesy of CDOT.

Lost Bogie Canyon, south of Boulder, CO

Big Thompson Canyon west of Loveland, CO

The Storm: Flood Damage

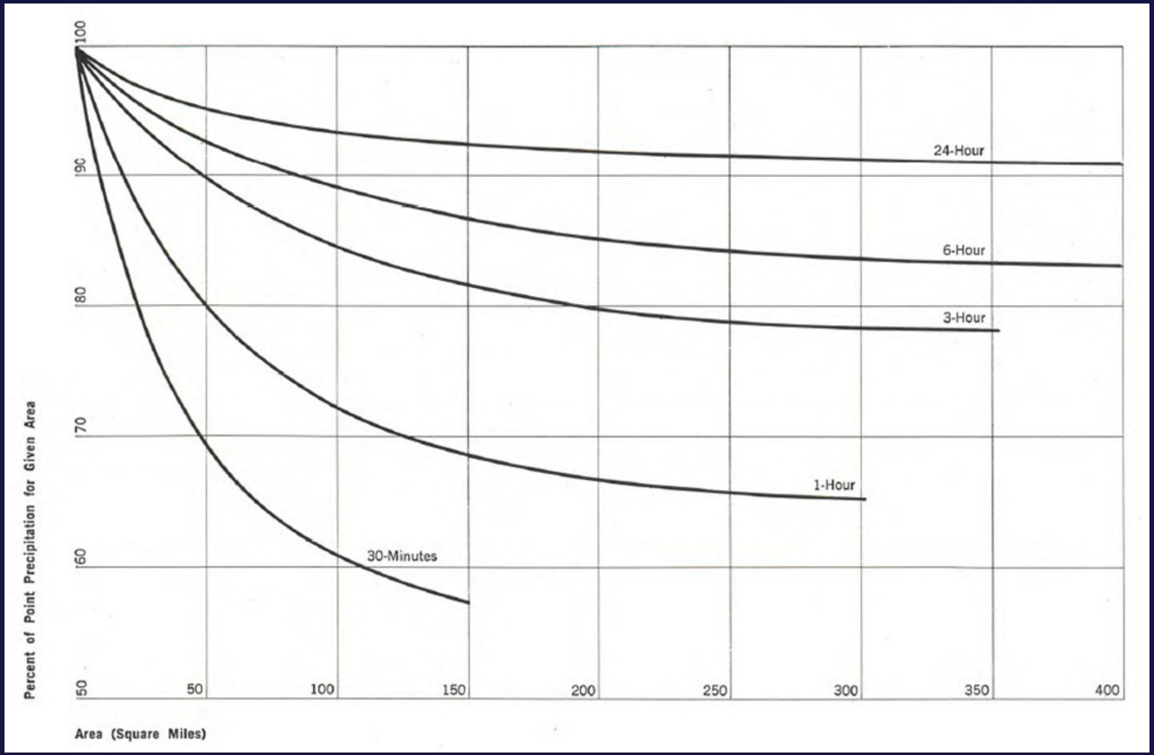
Big Thompson Canyon (taken by Noel Bryan)



South Platte River in Weld County, Colorado near Greeley

ARFs: Background

- NOAA defines an ARF as the <u>ratio between area-averaged rainfall to the maximum depth at the storm center</u>
- The most common sources for generalized ARFs and depth-area curves in the United States are from the NOAA Atlas 2 and the U.S. Weather Bureau's Technical Paper 29



ARFs: Background

- Several site specific ARFs and depth-area curves are referenced in:
  - 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
  - City of Las Vegas, Nevada (Gou, 2011)
  - Fountain Creek Watershed Colorado (Carlton Engineering, 2011)

ARFs: Methods

- Two common methods for deriving ARFs:
  - Geographically Fixed and Storm Centered

Geographically Fixed:

- originate from rainfall statistics
- relate the precipitation depth at a point to a fixed area
- storm center has an arbitrary location relative to the measurement array
- Sometimes the measurement array captures the storm center, sometimes the array captures the edge of the storm

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

Storm Centered:

- do not have a fixed area in which rain falls but changes dynamically with each storm event
- the representative point is the center of the storm, defined as the point of maximum rainfall

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

ARFs: Methods

- AWA calculated ARFs using a storm centered depth-area approach based on gridded hourly rainfall data from the Storm Precipitation Analysis System (SPAS)
  - Used SPAS hourly precipitation grids for calculation

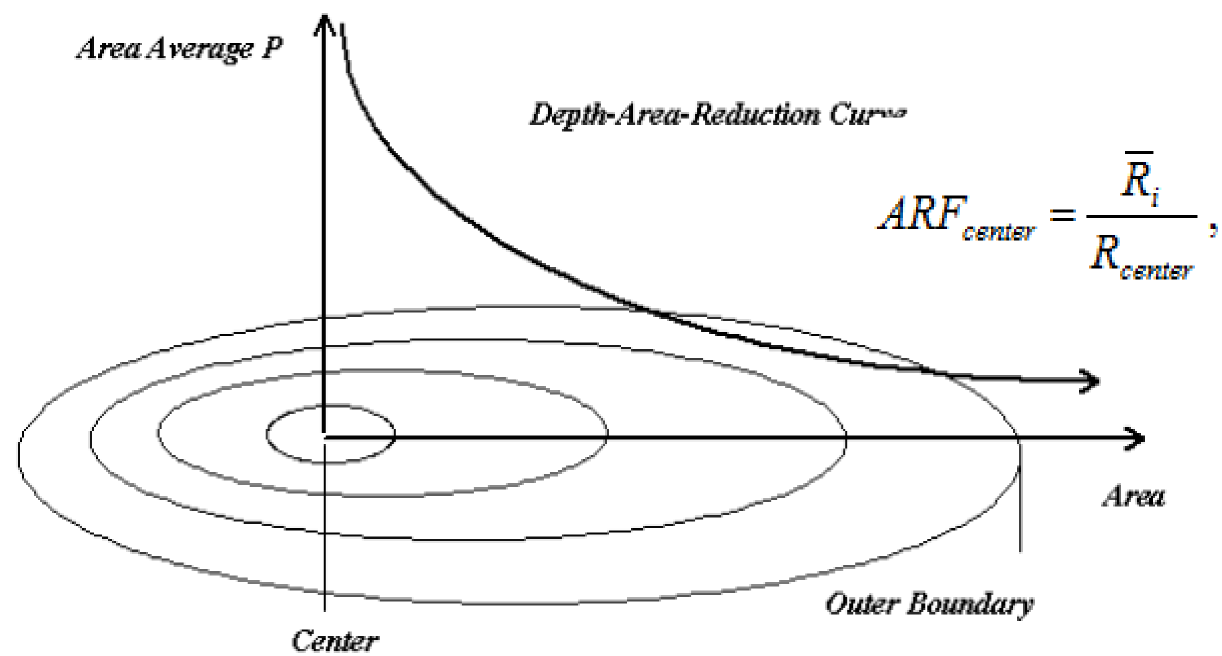


Figure 1 Illustration of Decay of Rainfall Depth from the Storm Center.

2013 Basin Specific ARFs

- The hourly gridded rainfall data, based on gauge adjusted radar data, were used to derive basin specific ARFs

- Four basins located along the Colorado Front Range were used to derive the 24-hour basin specific ARFs.

  Boulder Creek | St Vrain Creek
  Big Thompson River | Thompson River

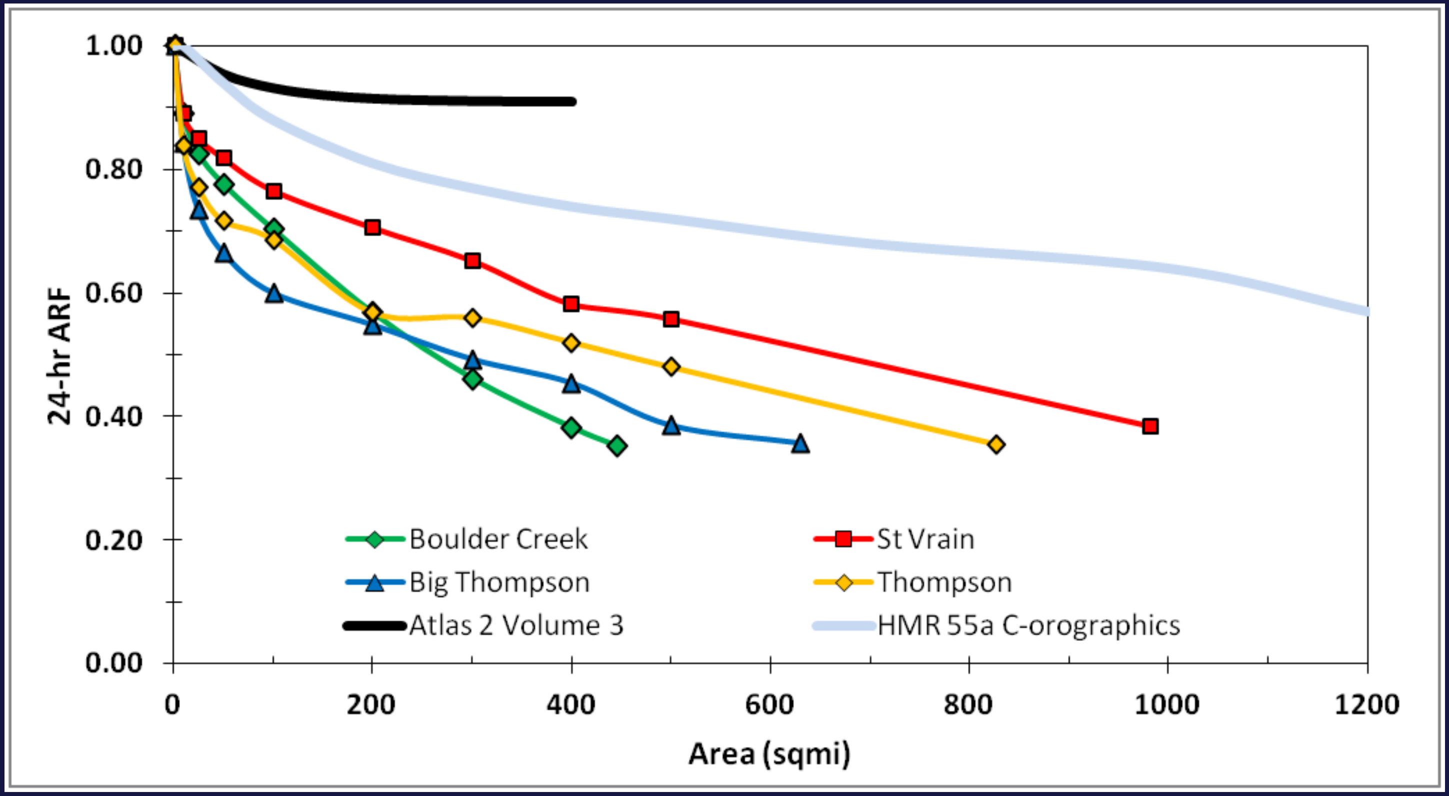
- Calculated the point maximum (1-mi^2) 24-hour rainfall within each basin (storm center)

- 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

2013 Basin Specific ARFs

- 2013 storm event basin specific ARFs rapidly decrease

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



Colorado Front Range ARFs

- Initially, 28 SPAS storm storms were identified to have occurred over similar meteorological and topographic regions

- The initial list was refined to nine storm centers

- 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

- 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

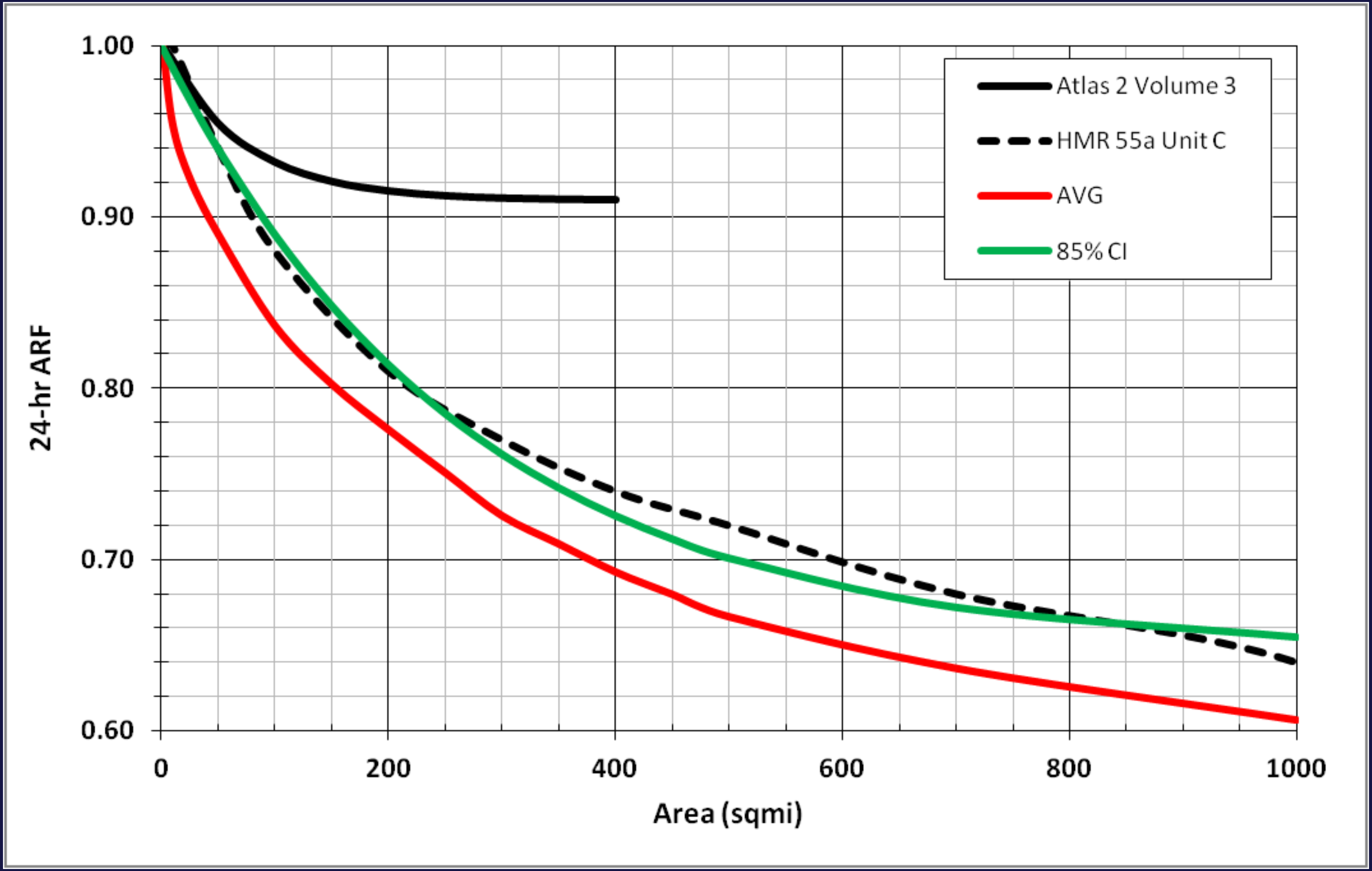
Colorado Front Range ARFs

- The point maximum (1-mi^2) 24-hour rainfall selected as storm center
- The maximum average 24-hour rainfall depth for standard area sizes were calculated

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

Area	1211 ARF	1251 ARF	1252 ARF	1253 ARF	1302 ARF	1320 ARF	1325 ARF	1335 ARF	1338 ARF	Avg	Max	85%	.+1 StDev
1	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
10	0.96	1.00	0.98	0.87	0.88	0.99	0.98	0.98	0.94	0.95	1.00	0.98	1.00
25	0.93	0.97	0.96	0.78	0.84	0.98	0.96	0.96	0.92	0.92	0.98	0.96	0.99
50	0.90	0.93	0.92	0.71	0.81	0.96	0.92	0.95	0.90	0.89	0.96	0.93	0.97
100	0.88	0.87	0.86	0.61	0.77	0.90	0.86	0.92	0.86	0.84	0.92	0.88	0.93
150	0.86	0.79	0.82	0.60	0.74	0.87	0.82	0.89	0.83	0.80	0.89	0.85	0.89
200	0.85	0.77	0.79	0.59	0.70	0.84	0.79	0.87	0.79	0.78	0.87	0.82	0.86
300	0.81	0.67	0.74	0.54	0.69	0.79	0.74	0.82	0.73	0.73	0.82	0.77	0.81
400	0.79	0.67	0.71	0.53	0.64	0.73	0.71	0.79	0.67	0.69	0.79	0.73	0.77
500	0.76	0.58	0.69	0.52	0.62	0.73	0.69	0.75	0.66	0.67	0.76	0.71	0.75
1000	0.70	0.54	0.66	0.45	0.55	0.69	0.66	0.63	0.57	0.61	0.70	0.65	0.69

Colorado Front Range ARFs

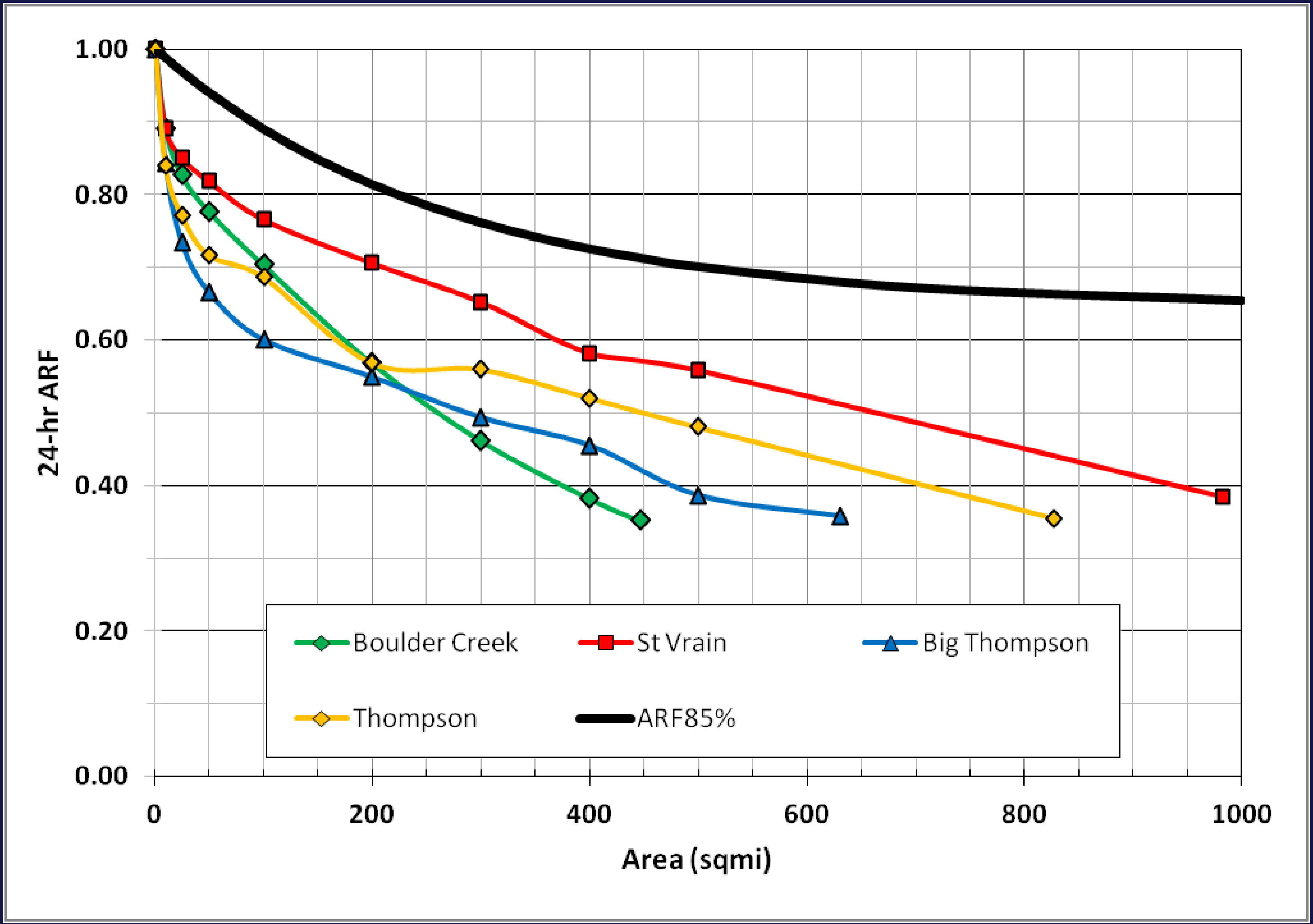


The final equation used to represent Colorado Front Range 24-hour ARFs is:

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

where $ARF_{85\%}$ is the 85% confidence ARF, k is a decay coefficient (0.00374), and A is storm area in square miles.

Summary



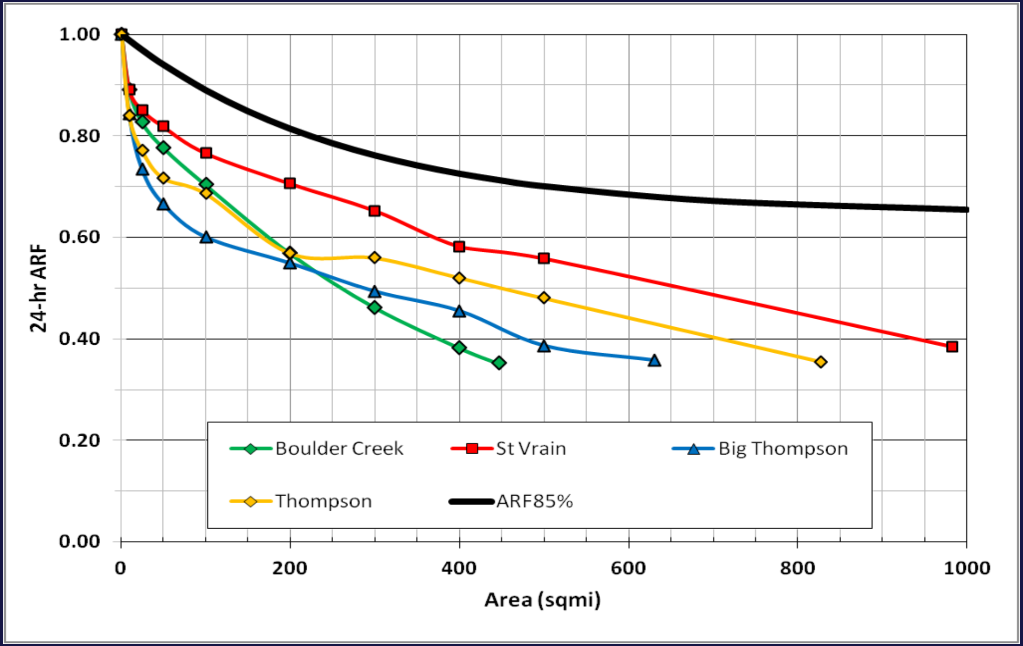
1.00
0.80
0.60
0.40
0.20
0.00
24-hr ARF
0
200
400
600
800
1000
Area (sqmi)
Boulder Creek
St Vrain
Big Thompson
Thompson
ARF85%

Take Home Messages

- ❑ The derived ARFs create significantly larger reductions in point rainfall as compared to NOAA Atlas 2.

- ❑ The final 24-hour $ARF_{85\%}$ curve compared well to the four basin specific 24-hour ARF curves for the September 2013 event

- ❑ The updated ARF values produce more realistic and representative point to areal reductions



Thank you!

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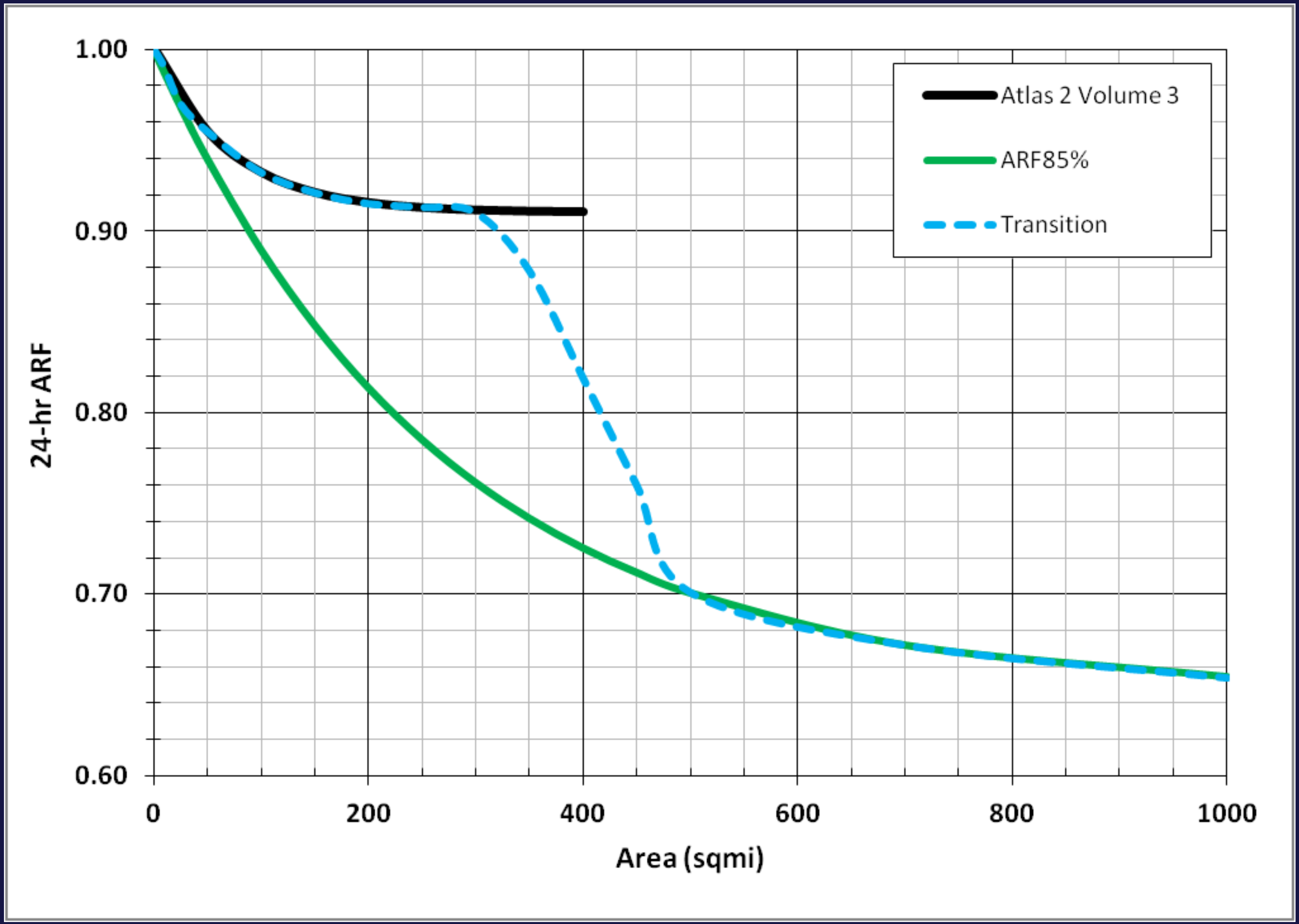
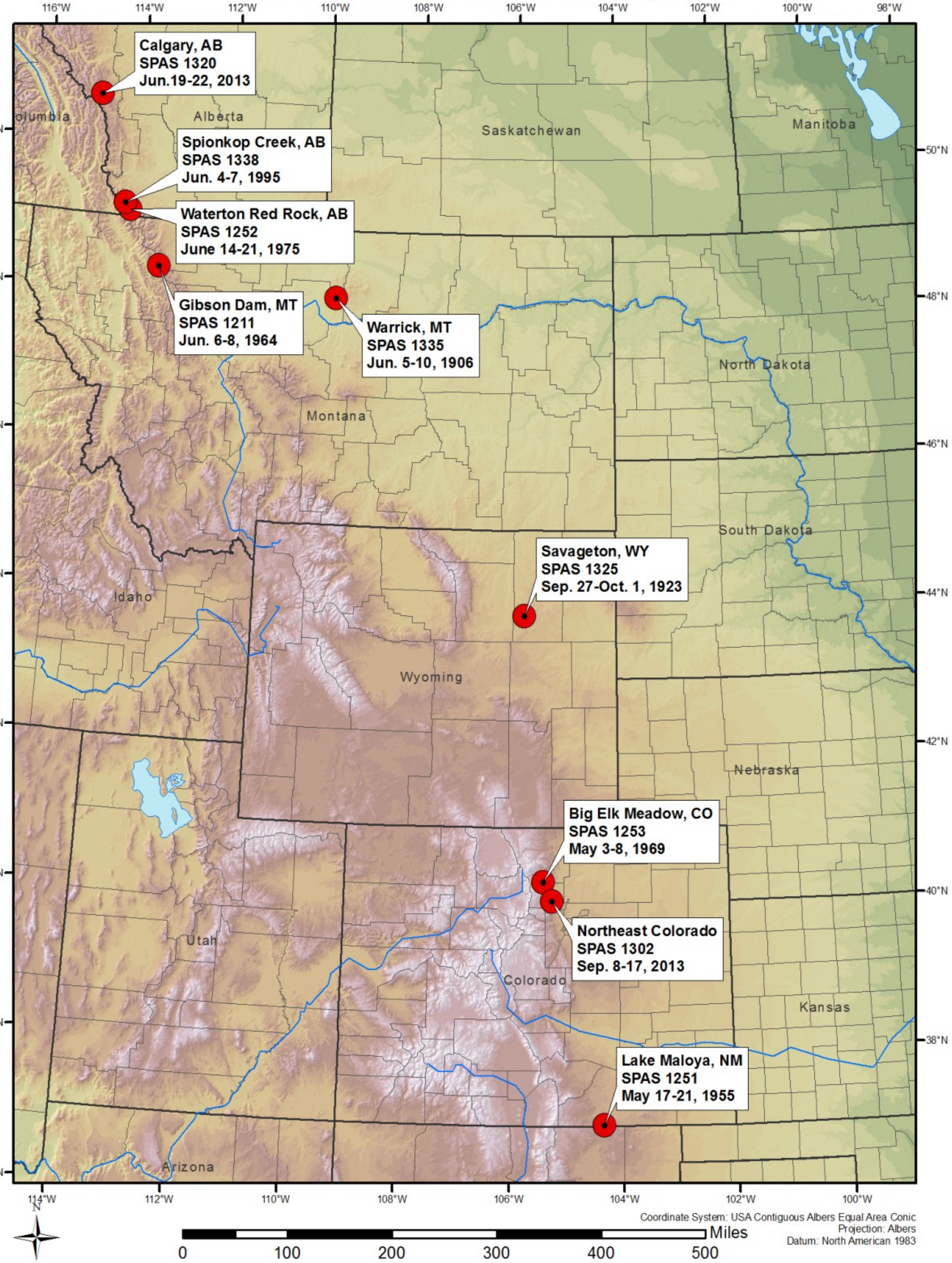

1.00
0.90
0.80
0.70
0.60
24-hr ARF
0
200
400
600
800
1000
Area (sqmi)
Atlas 2 Volume 3
ARF85%
Transition

Locations of SPAS Analyzed Rainfall Events Used for Areal Reduction Factor Analysis



Summary

- Derived ARFs created significantly larger reductions in point rainfall as compared to NOAA Atlas 2.

- Because results of the Phase I CDOT September 2013 Flood Study were not being changed as part of this work, a smooth transition between NOAA Atlas 2 24-hour ARF and the derived 24-hour $ARF_{85\%}$ was 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.

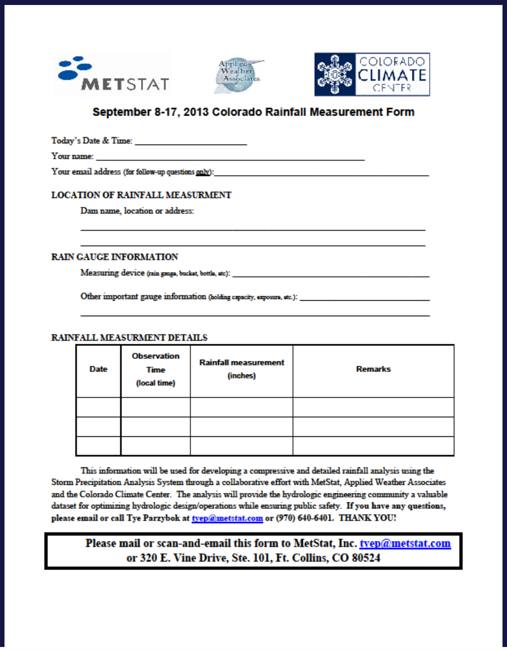
Summary

- 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 modeling 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

Data Mining, "Bucket Survey" & Field Survey

Over 2,600 rainfall reports collected during virtual "bucket survey"


METSTAT Applied Weather Associates COLORADO CLIMATE CENTER

September 8-17, 2013 Colorado Rainfall Measurement Form

Today's Date & Time: ____________

Your name: ____________

Your email address (for follow-up questions only): ____________

LOCATION OF RAINFALL MEASUREMENT

Dam name, location or address: ____________

RAIN GAUGE INFORMATION

Measuring device (rain gauge, bucket, bottle, etc): ____________

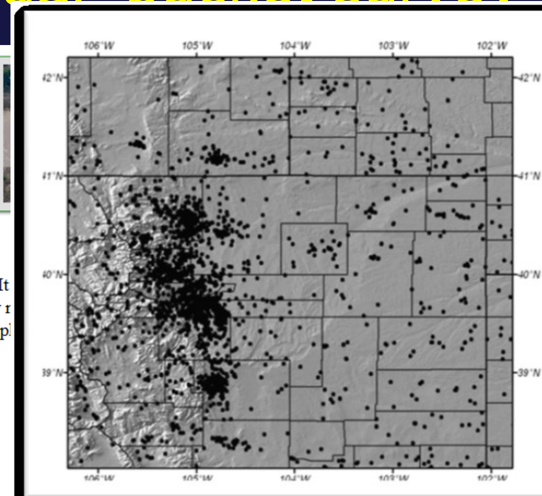
Other important gauge information (holding capacity, exposure, etc.): ____________

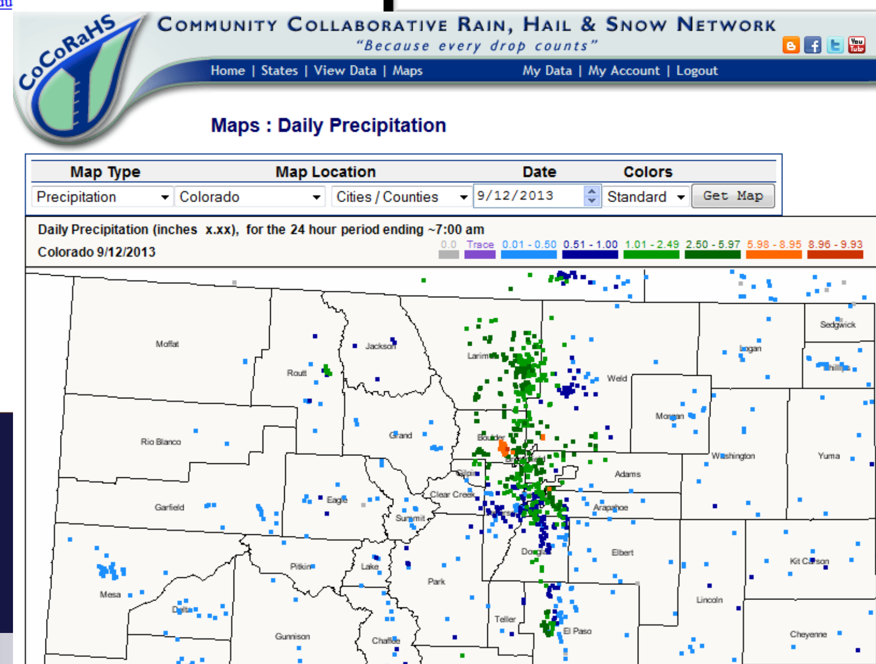
RAINFALL MEASUREMENT DETAILS

Date	Observation Time (local time)	Rainfall measurement (inches)	Remarks

This information will be used for developing a compressive and detailed rainfall analysis using the Storm Precipitation Analysis System through a collaborative effort with MetStat, Applied Weather Associates and the Colorado Climate Center. The analysis will provide the hydrologic engineering community a valuable dataset for optimizing hydrologic design/operations while ensuring public safety. If you have any questions, please email or call Tye Parzybok at tyep@metstat.com or (970) 640-6401. THANK YOU!

Please mail or scan-and-email this form to MetStat, Inc. tyep@metstat.com or 320 E. Vine Drive, Ste. 101, Ft. Collins, CO 80524



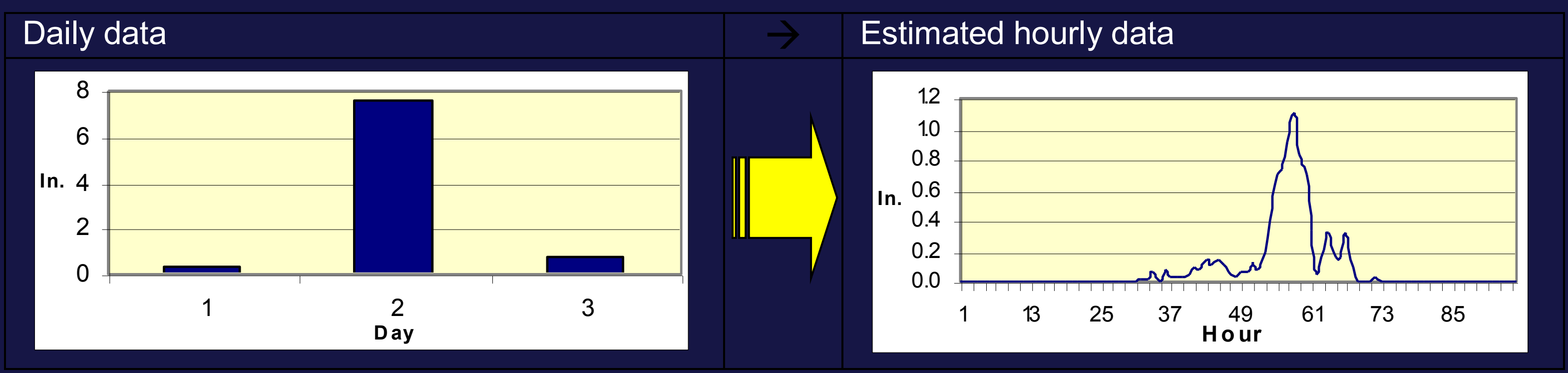


SPAS: Daily to Hourly Precipitation

- To achieve an hourly time step at ALL stations, its necessary to convert daily & supplemental stations into estimated hourly stations.

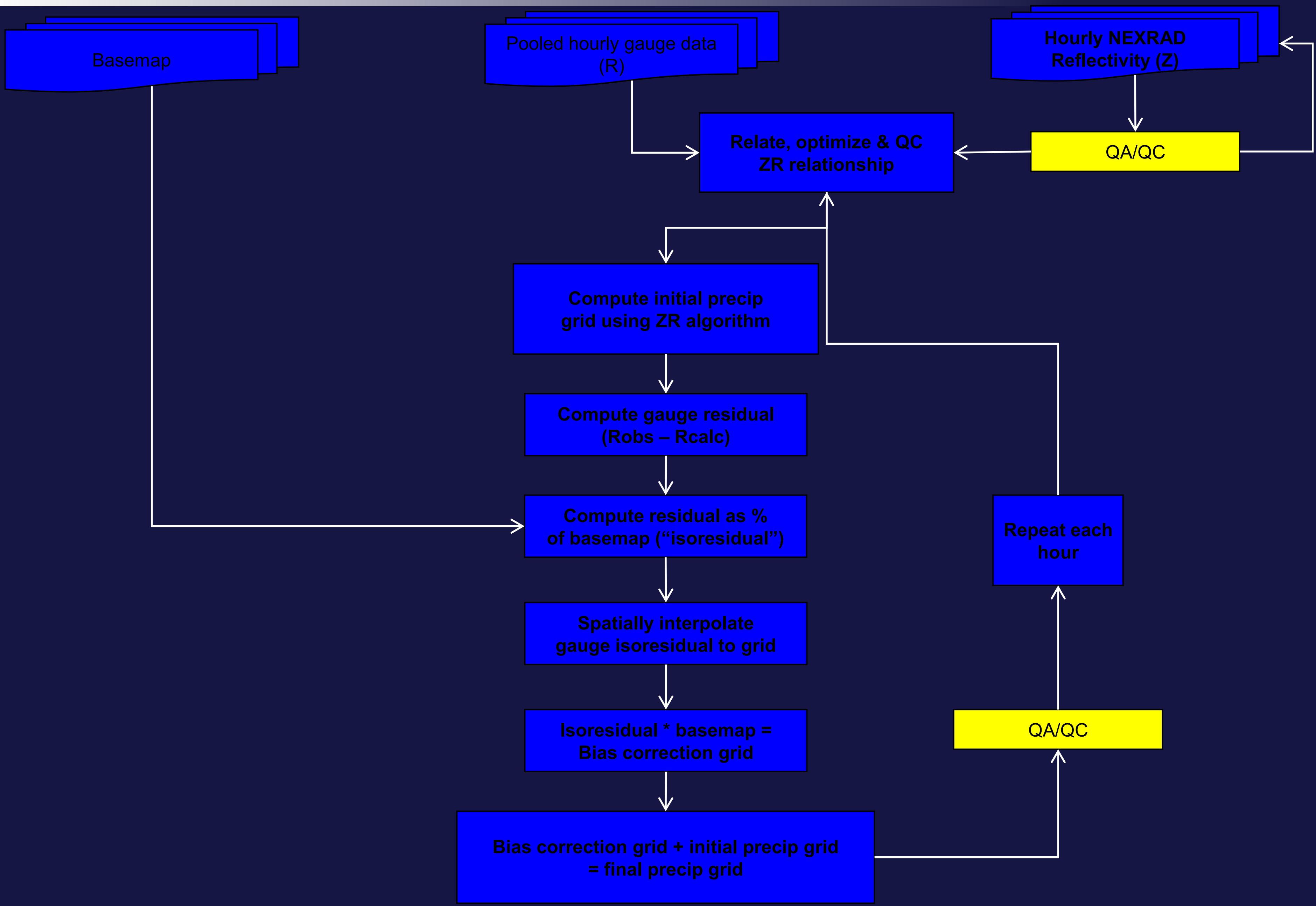
- In the past, timing of daily measured data was accomplished by associating each daily station with <u>a single</u> nearby hourly station.

- SPAS, however, uses several hourly stations to time each of the daily stations, thereby allowing the hourly precipitation distribution to be unique at each daily station.



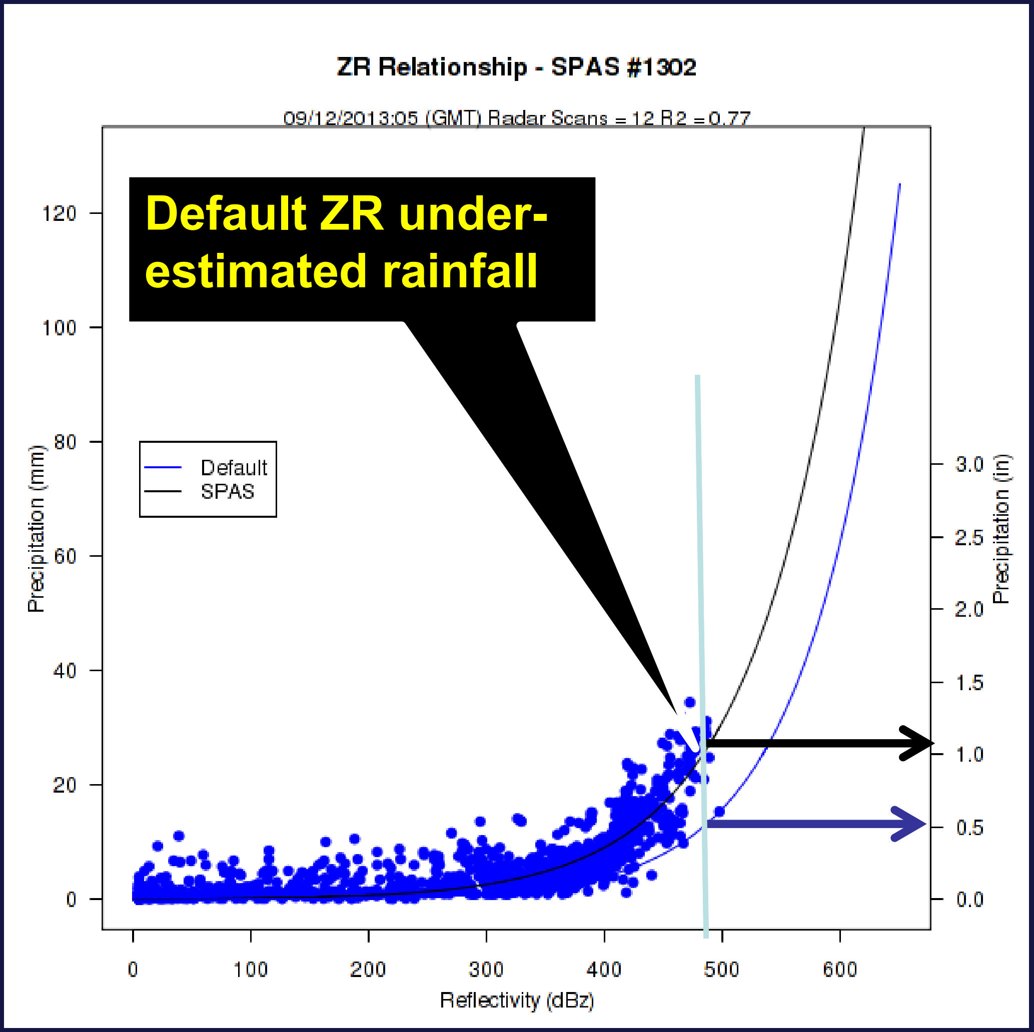
- This provides more representative spatial and temporal detail.

SPAS-NEXRAD

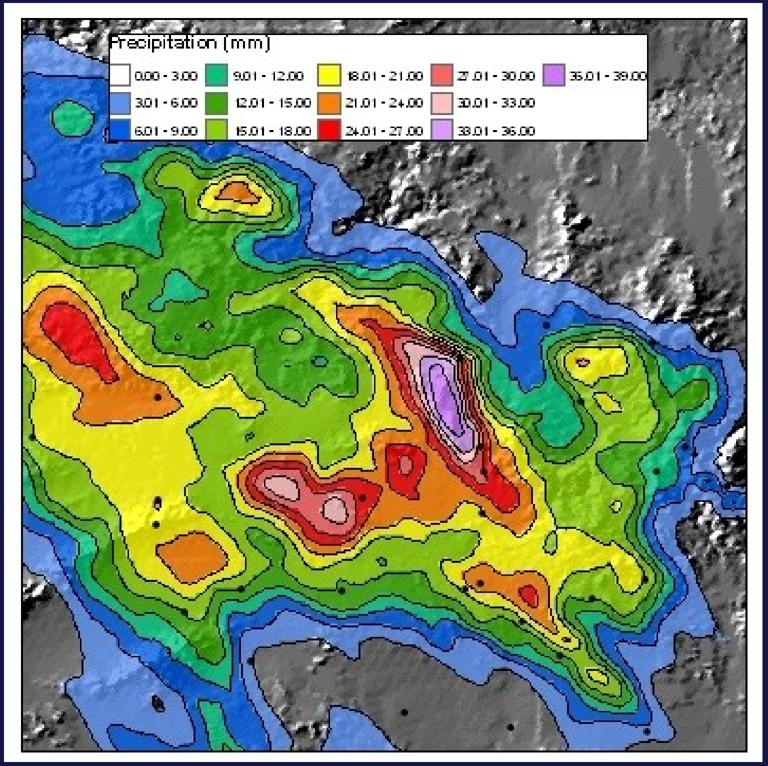

Basemap
Pooled hourly gauge data (R)
Hourly NEXRAD Reflectivity (Z)
Relate, optimize & QC ZR relationship
QA/QC
Compute initial precip grid using ZR algorithm
Compute gauge residual (Robs – Rcalc)
Compute residual as % of basemap (“isoresidual”)
Repeat each hour
Spatially interpolate gauge isoresidual to grid
Isoresidual * basemap = Bias correction grid
QA/QC
Bias correction grid + initial precip grid = final precip grid

Storm Rainfall Analysis

Determine hourly Z-R based on concurrent radar and station data

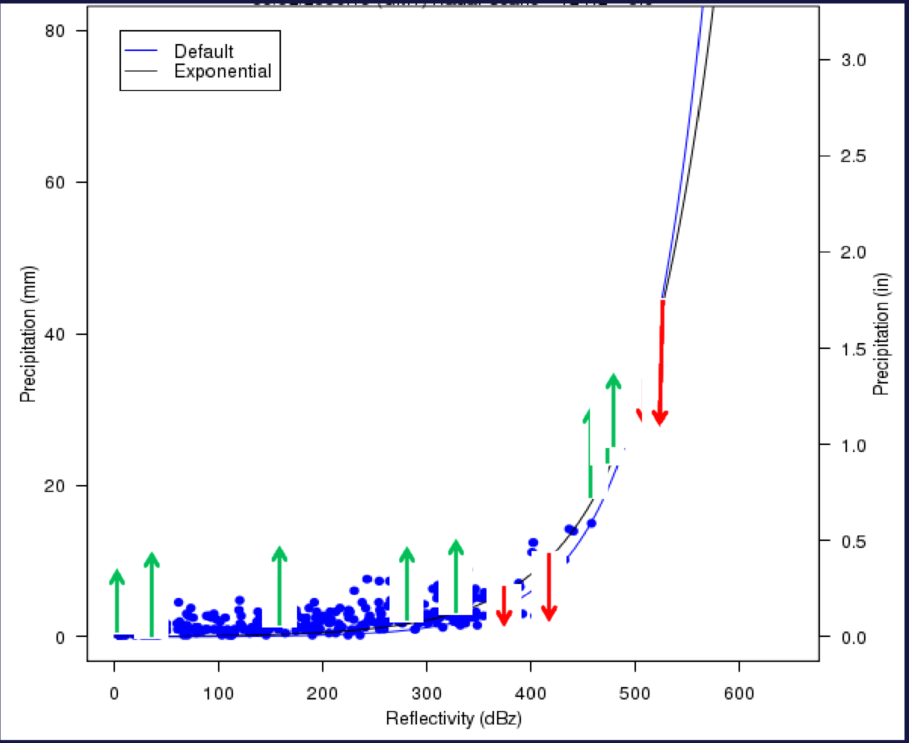


Apply ZR to radar data (initial precip. grid)

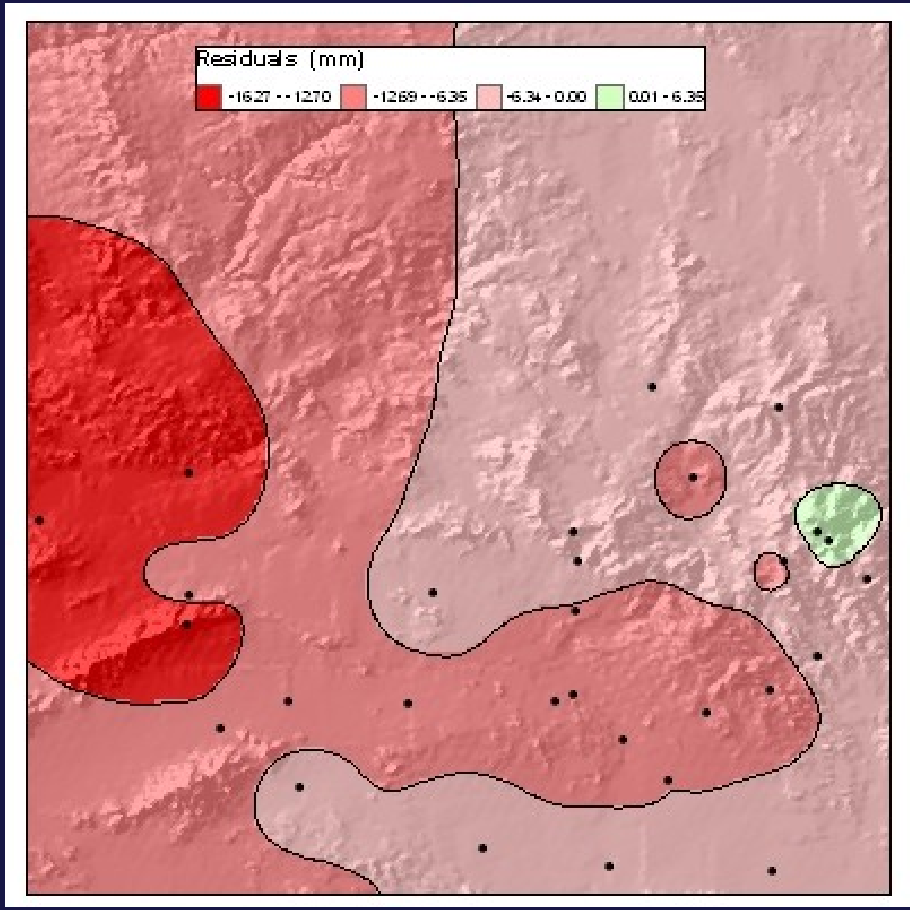


Storm Precipitation Analysis System (SPAS)

Compute bias (residual) at all stations

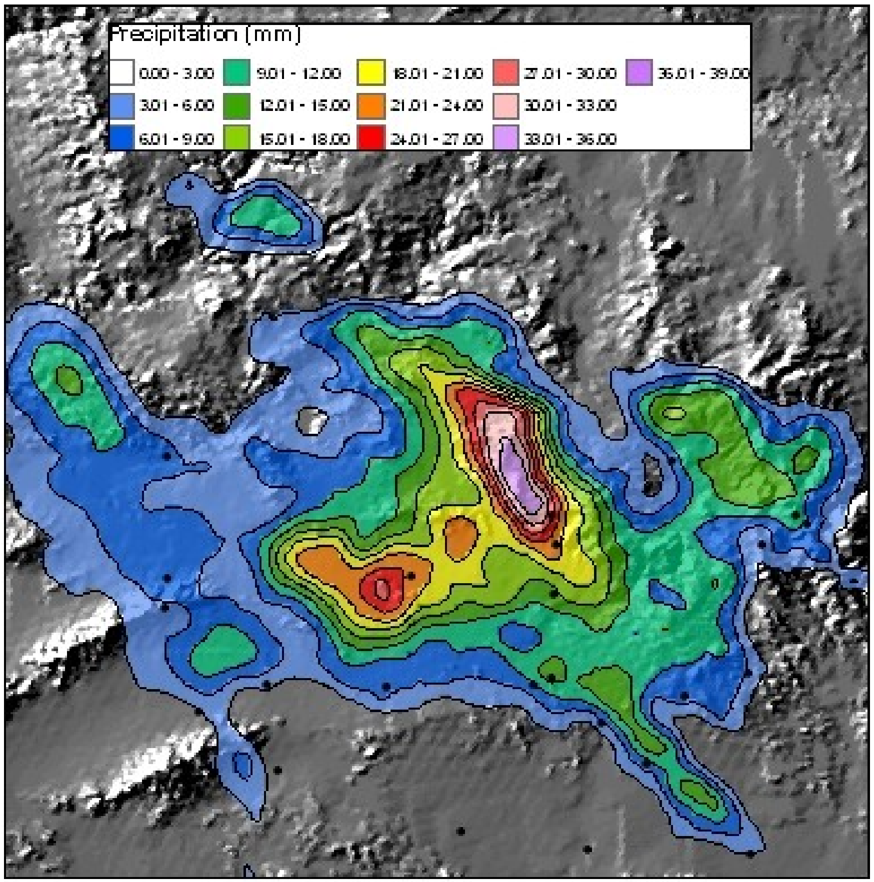


Interpolate bias adjustments

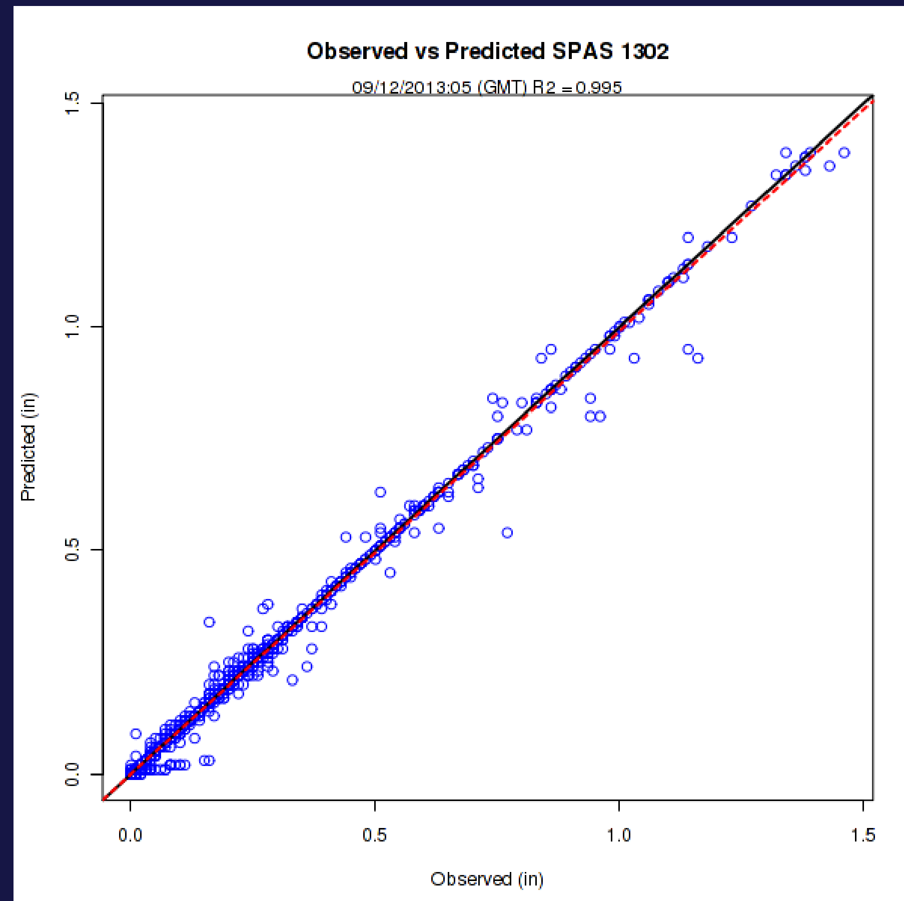


Storm Precipitation Analysis System (SPAS)

Add initial to bias to create final grid



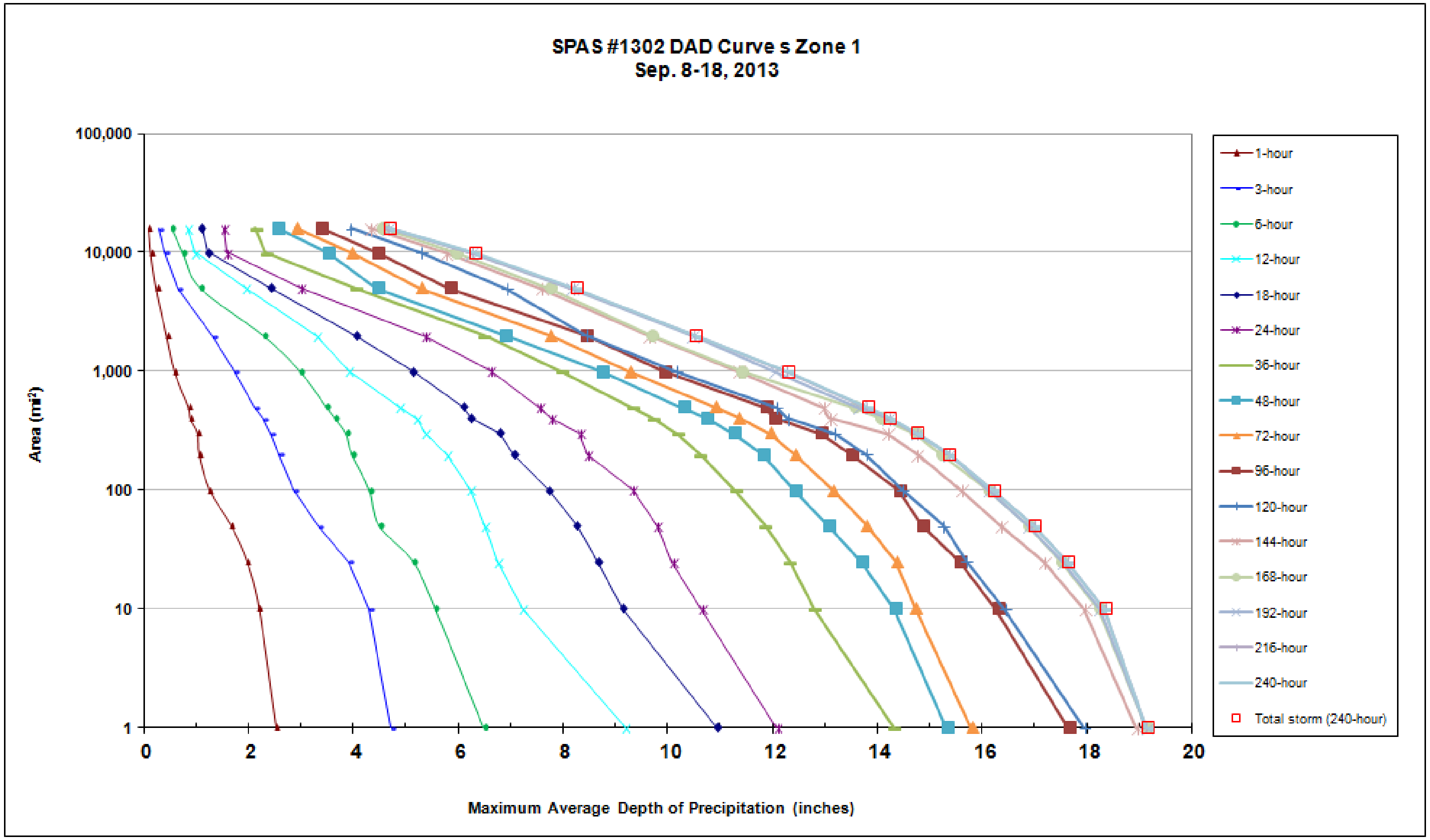
Good correlation between observed value and modeled value



SPAS 1302 DAD Zone 1- Boulder/NW Domain

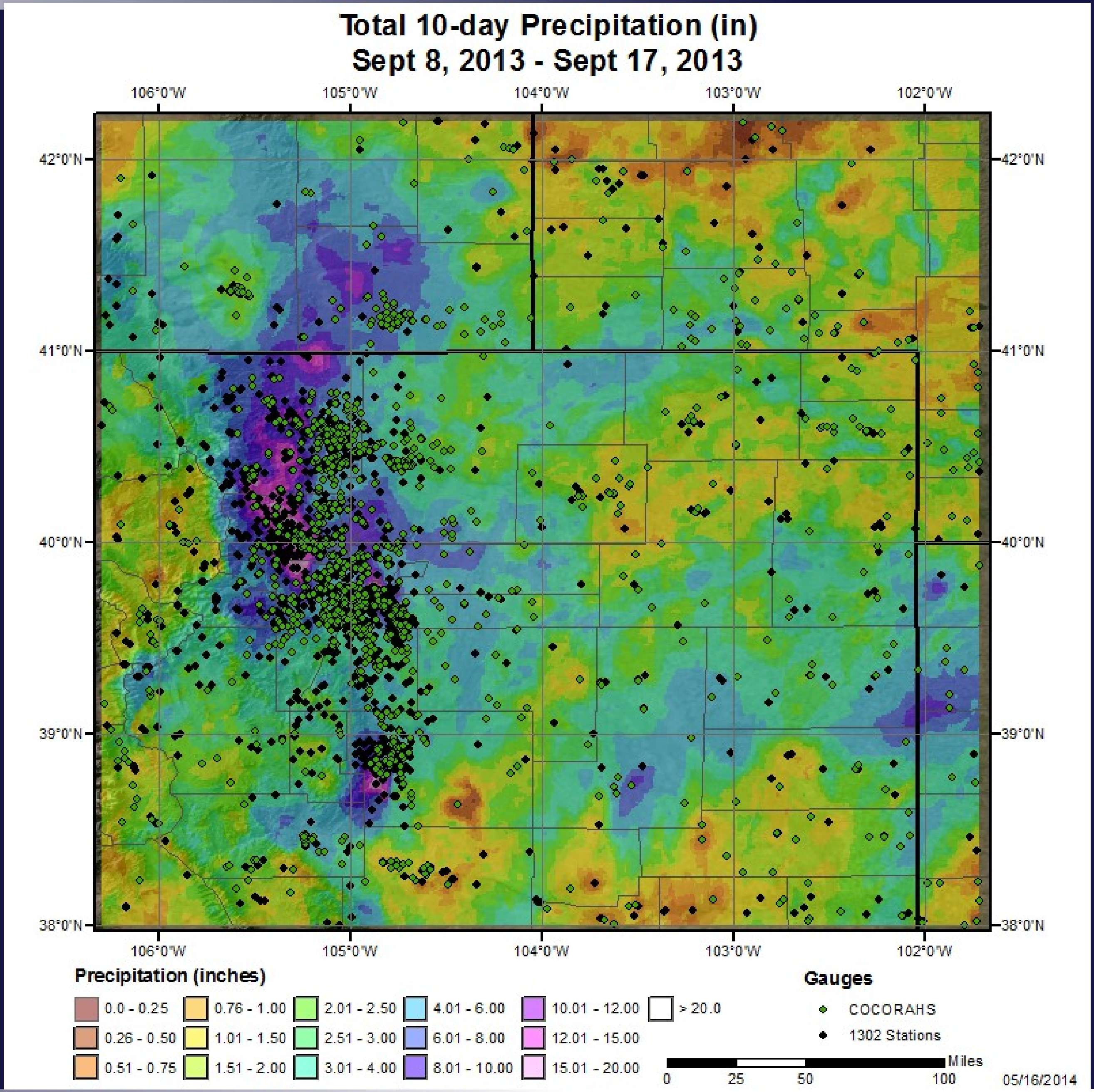
Storm 1302 - Sep. 8 (800 UTC) - Sep. 18 (700 UTC), 2013
MAXIMUM AVERAGE DEPTH OF PRECIPITATION (INCHES)

Area (mi²)	Duration (hours)															
	1	3	6	12	18	24	36	48	72	96	120	144	168	192	216	240	Total
0.4	2.59	4.83	7.25	9.46	11.21	12.44	15.04	16.24	16.89	18.2	18.93	20.23	20.41	20.41	20.41	20.41	20.41
1	2.52	4.72	6.49	9.18	10.94	12.08	14.31	15.32	15.8	17.64	17.95	18.93	19.13	19.13	19.13	19.13	19.13
10	2.2	4.31	5.57	7.23	9.15	10.64	12.79	14.33	14.73	16.27	16.42	17.94	18.23	18.24	18.33	18.33	18.33
25	1.97	3.9	5.15	6.75	8.66	10.08	12.32	13.68	14.35	15.56	15.7	17.18	17.51	17.53	17.61	17.61	17.61
50	1.67	3.33	4.5	6.5	8.27	9.8	11.85	13.04	13.79	14.84	15.25	16.35	16.86	16.87	16.98	16.98	16.98
100	1.26	2.85	4.31	6.24	7.74	$\boxed{9.32}$	11.29	$\boxed{12.41}$	13.15	14.4	14.48	15.59	16.13	16.13	16.2	16.2	16.20
200	1.06	2.59	3.98	5.79	7.07	8.46	10.61	11.8	12.42	13.49	13.77	14.75	15.21	15.36	15.36	15.36	15.36
300	1.03	2.42	3.86	5.38	6.79	8.31	10.18	11.26	11.95	12.92	13.18	14.19	14.71	14.74	14.75	14.75	14.75
400	0.89	2.27	3.66	5.22	6.25	7.78	9.71	10.72	11.35	12.03	12.28	13.09	14.04	14.2	14.22	14.23	14.23
500	0.85	2.12	3.49	4.87	6.1	7.54	9.33	10.27	10.91	11.85	12.07	12.96	13.55	13.64	13.79	13.81	13.81
1,000	0.59	1.72	2.99	3.91	5.12	6.61	7.97	8.73	9.27	9.93	10.15	11.34	11.41	12.04	12.26	12.28	12.28
2,000	0.44	1.32	2.29	3.29	4.06	5.35	6.49	6.88	7.74	8.43	8.44	9.62	9.67	10.45	10.5	10.51	10.51
5,000	0.24	0.64	1.09	1.94	2.41	2.99	4.05	4.46	5.29	5.83	6.92	7.58	7.75	8.16	8.2	8.24	8.24
10,000	0.14	0.41	0.75	0.98	1.23	1.58	2.32	3.51	3.96	4.46	5.29	5.74	5.94	6.23	6.26	6.3	6.30
16,014	0.1	0.29	0.54	0.85	1.11	1.53	2.14	2.54	2.91	3.37	3.95	4.31	4.54	4.65	4.67	4.68	4.68

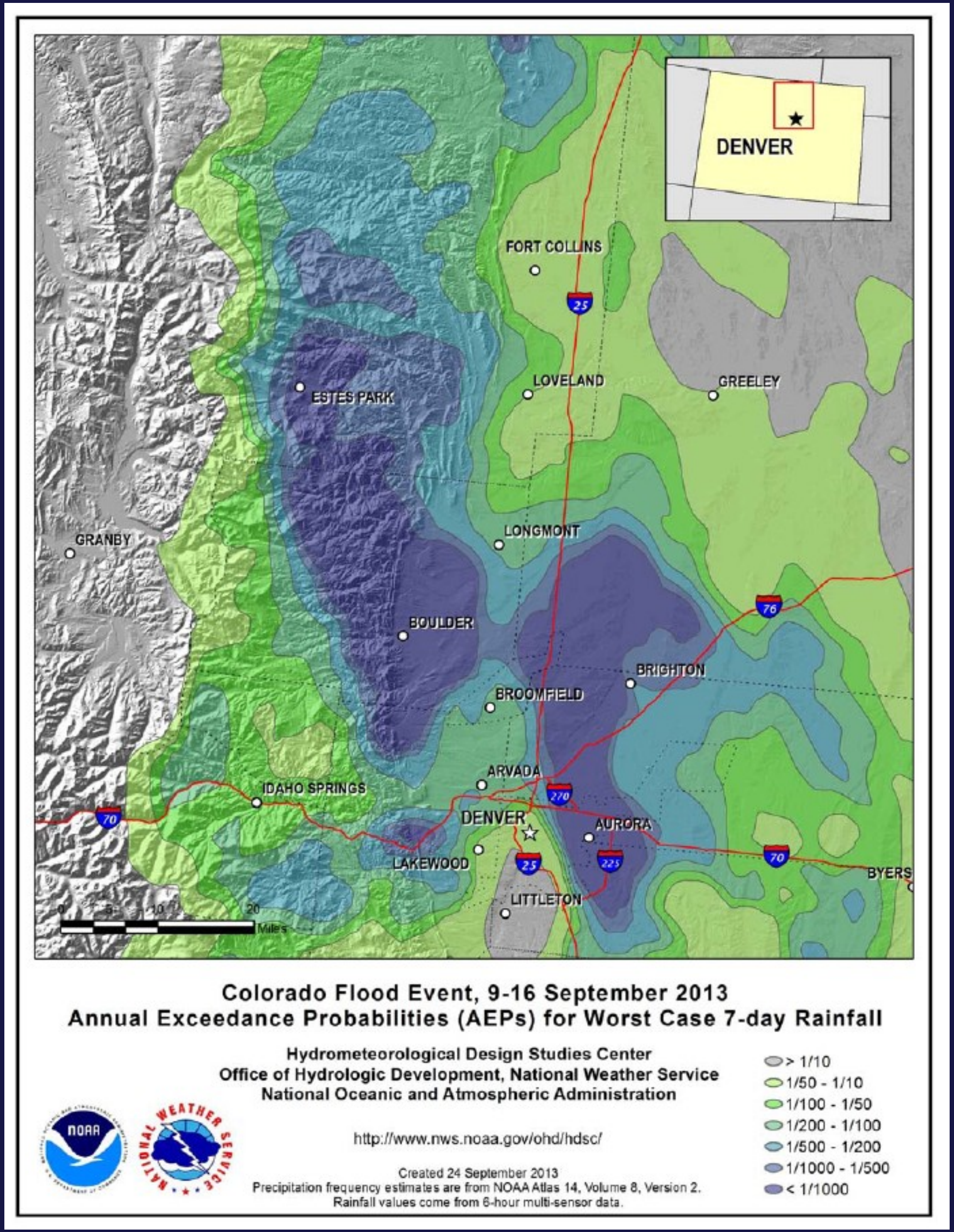


CoCoRaHS Data

- 2,635 Stations
- 1,237 CoCoRaHS

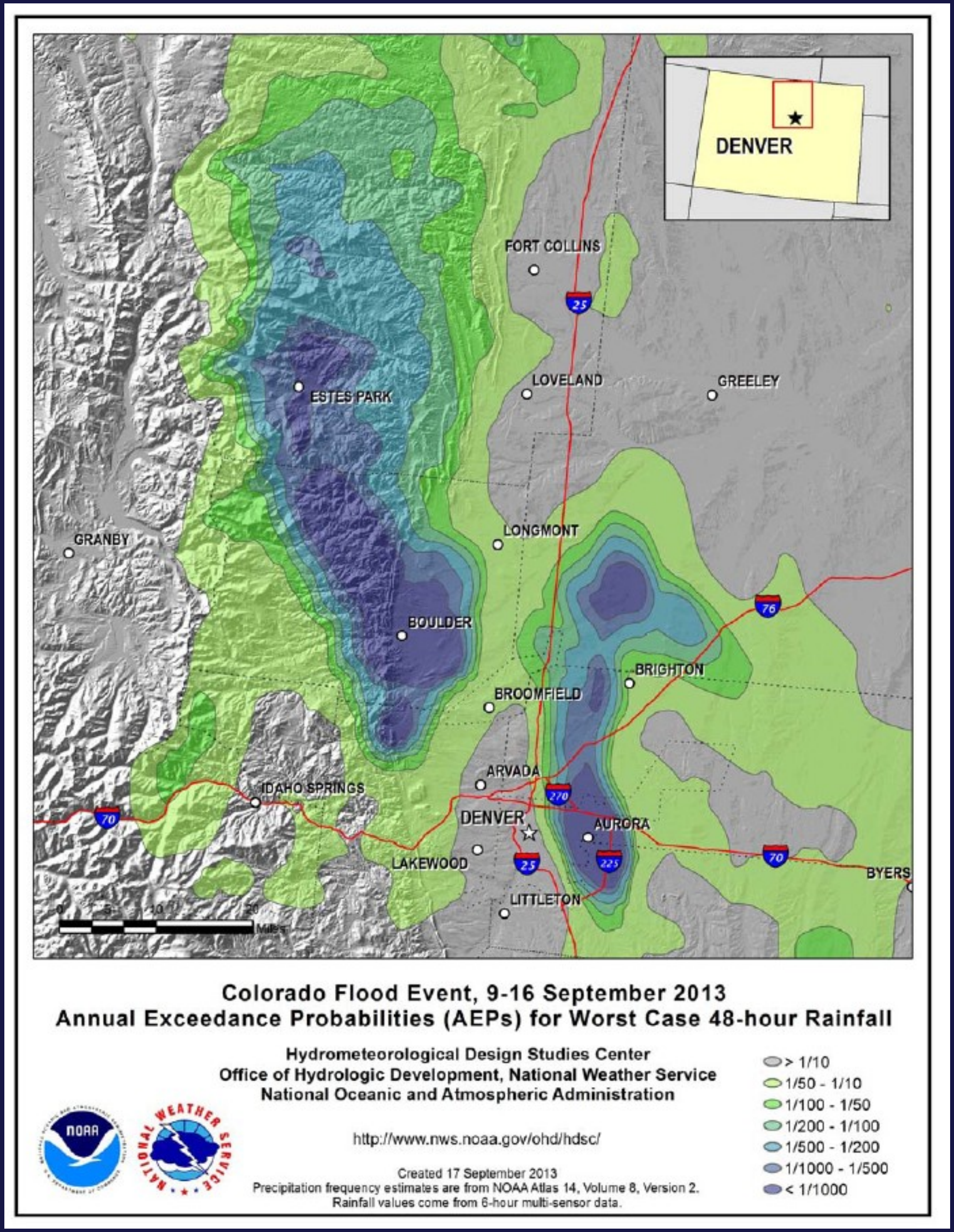


168-hr Annual Exceedance Probability



http://www.nws.noaa.gov/oh/hdsc/

48-hr Annual Exceedance Probability



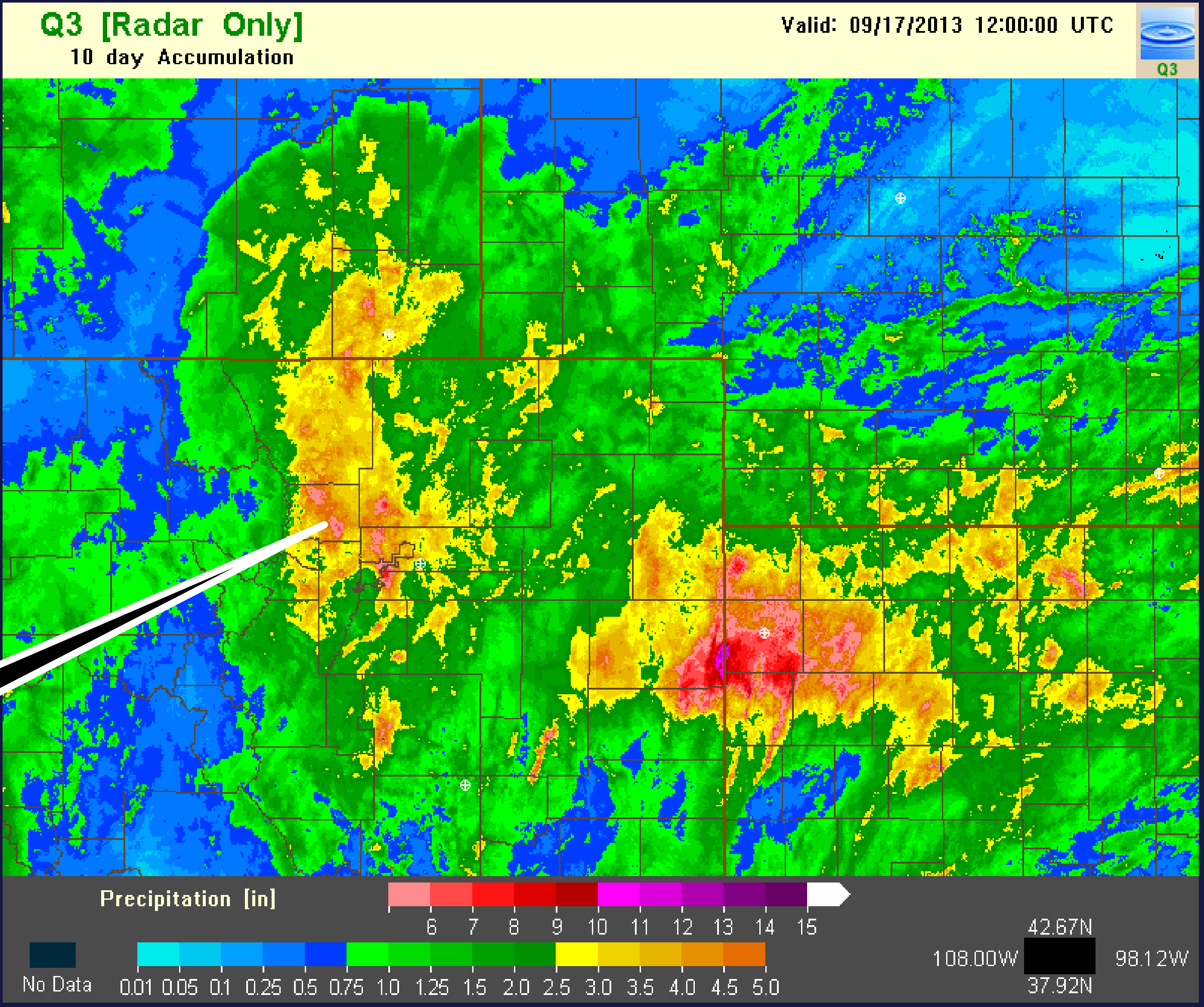
Flood Damage

Coal Creek Canyon and damage to Highway 72. Photo courtesy of CDOT.

Lost Bogie Canyon, south of Boulder, CO

Big Thompson Canyon west of Loveland, CO

- Radar-only tended to under-estimate the rainfall
- Gauge-adjusted radar-precipitation preformed much better.



**6-8” vs.
18-20” actually measured**

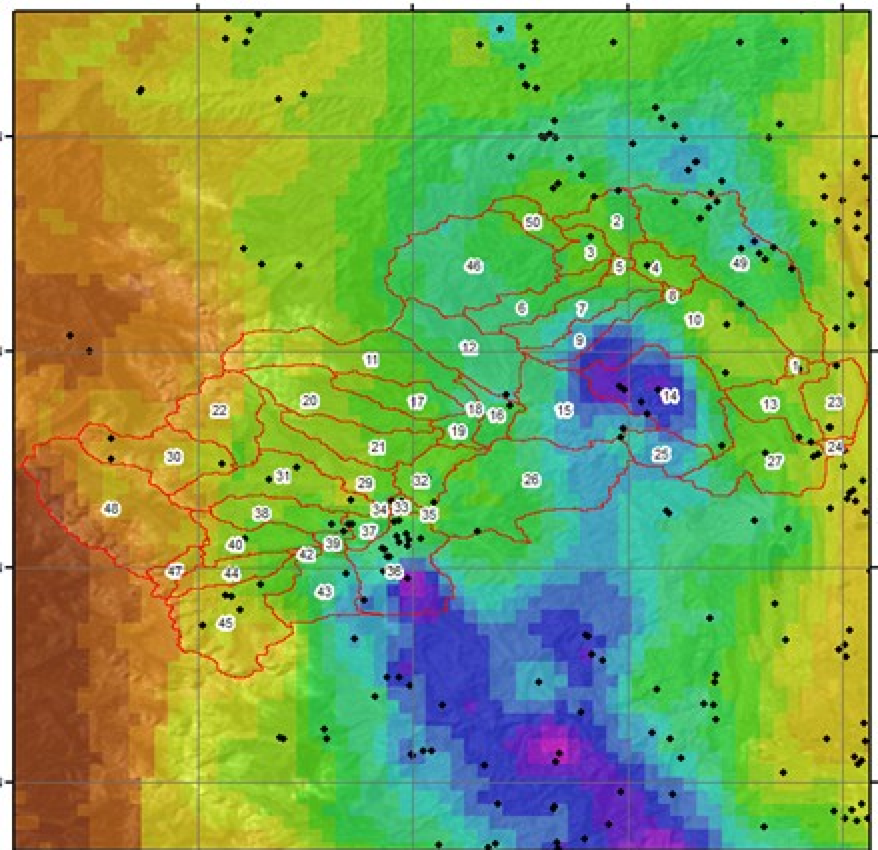
The Storm

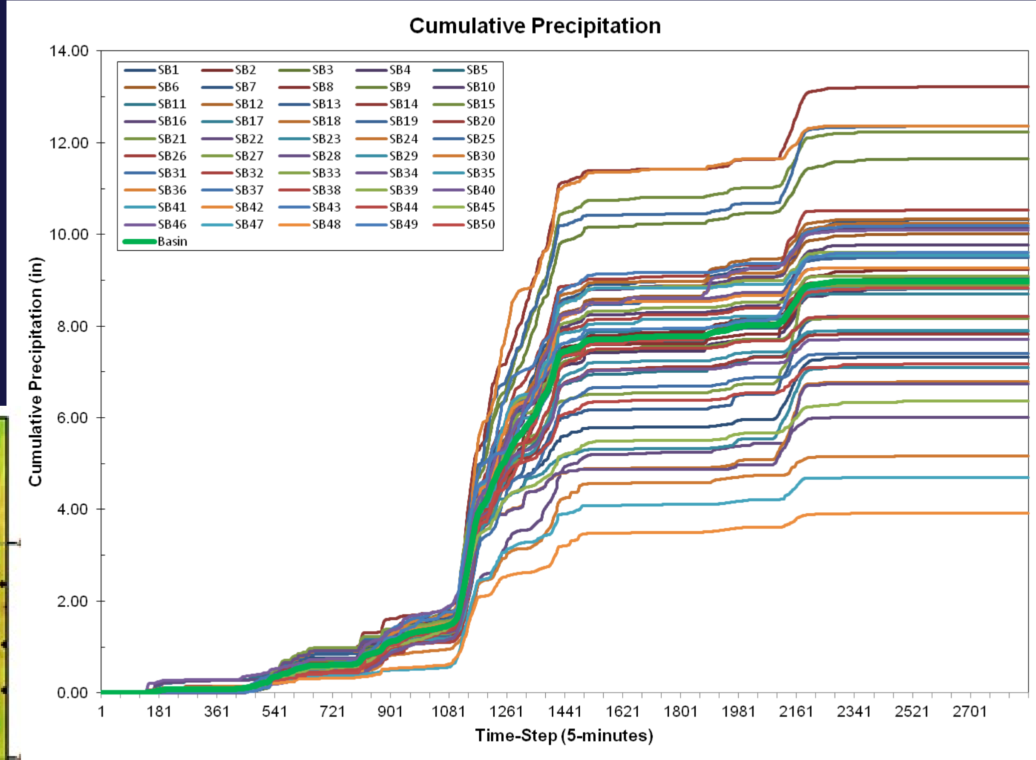
MODIS Sept. 7, 2013

The Storm

MODIS Sept. 13, 2013

SPAS 1302: Big Thompson-Buckhorn Calibration

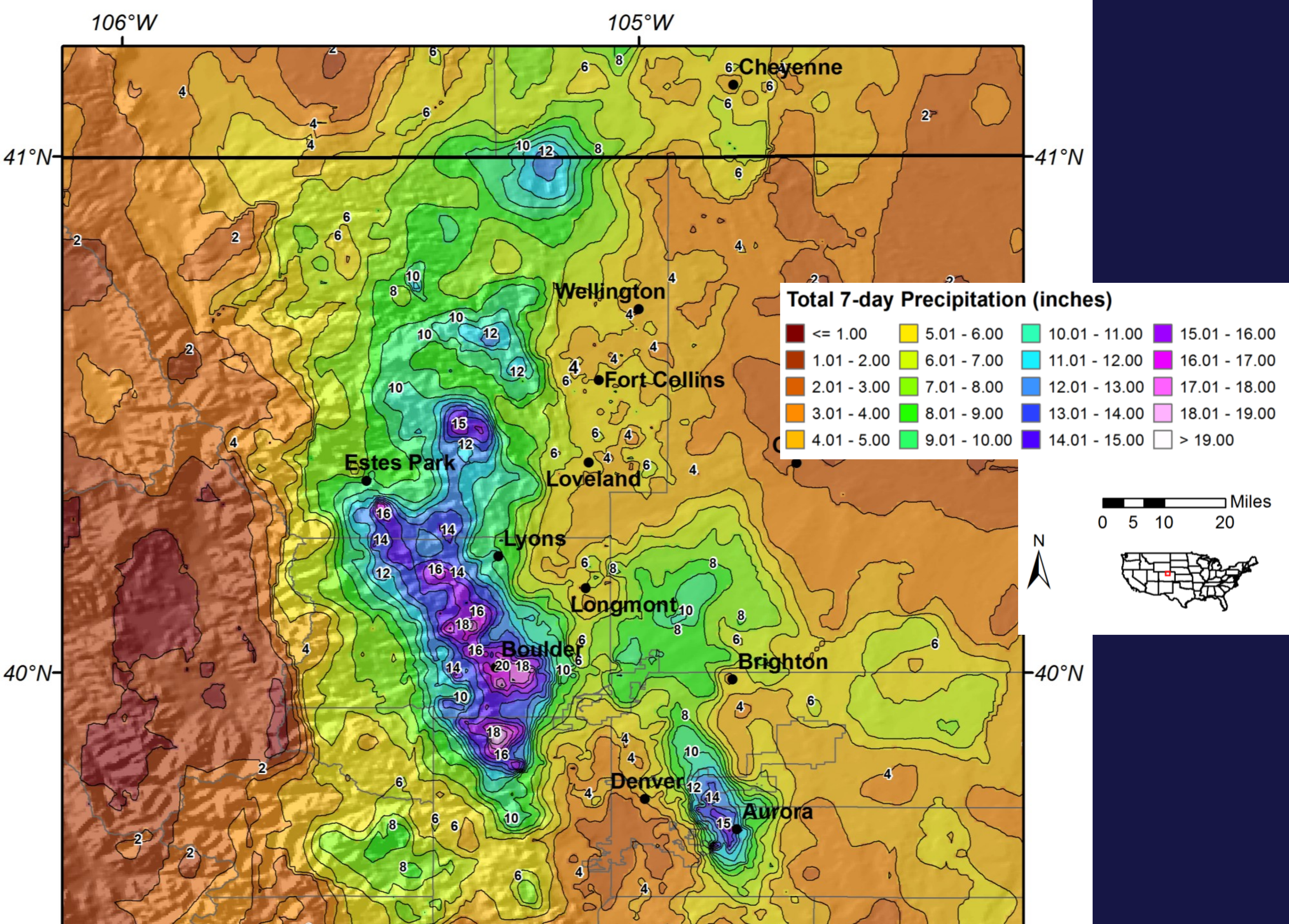




Flood Damage: Estes Park

Flood Damage: Estes Park

Flood Damage: Fall River



106°W
105°W
41°N
40°N
Cheyenne
Wellington
Fort Collins
Loveland
Estes Park
Lyons
Longmont
Boulder
Brighton
Denver
Aurora
Total 7-day Precipitation (inches)
<= 1.00
1.01 - 2.00
2.01 - 3.00
3.01 - 4.00
4.01 - 5.00
5.01 - 6.00
6.01 - 7.00
7.01 - 8.00
8.01 - 9.00
9.01 - 10.00
10.01 - 11.00
11.01 - 12.00
12.01 - 13.00
13.01 - 14.00
14.01 - 15.00
15.01 - 16.00
16.01 - 17.00
17.01 - 18.00
18.01 - 19.00
> 19.00
Miles
0 5 10 20
N