CITY OF BOULDER

WATER RESOURCES ADVISORY BOARD
AGENDA ITEM

MEETING DATE: May 19, 2014

AGENDA TITLE: Information Item – Preliminary Draft September 2013 Boulder Rainfall Analysis Results

PRESENTERS:
Jeff Arthur, Director of Public Works for Utilities
Bob Harberg, Principal Engineer – Utilities
Kurt Bauer, Engineering Project Manager

There has been much discussion regarding the magnitude of the September 2013 flood disaster. The city recently commissioned an analysis of the rainfall recurrence interval by Wright Water Engineers (WWE) and the preliminary draft results are attached.

Alert gauges and gridded radar data was used to determine rainfall characteristics for durations ranging from 5 minutes to 24 hours for the watersheds in Boulder. In addition, the rainfall characteristics are compared with the Colorado Urban Hydrograph Procedure (CUHP) to compare 5-, 10-, 15-, 30-, and 60-minute intensities which is the basis of the design storm for flood analysis and mapping. This comparison provides an understanding of how the actual event differed from the design storm in terms of short-duration rainfall depths and intensities.

Prior to finalizing this analysis WWE will submit the preliminary draft analysis to the Colorado Division of Water Resources for review.

Representatives of Wright Water Engineers will make a presentation to the WRAB on May 19, 2014 and be available for questions and answers.

Attachments:
A: Preliminary Draft September 2013 Boulder Rainfall Analysis Results

Preliminary Draft

WWE

MEMORANDUM

To: Bob Harberg, P.E.
Kurt Bauer, P.E.
City of Boulder
Via Email: HarbergB@bouldercolorado.gov; BauerK@bouldercolorado.gov

From: Wright Water Engineers, Inc.
Shannon Tillack, P.E. and T. Andrew Earles, Ph.D., P.E.

Date: May 12, 2014

Re: September 2013 Boulder Rainfall Analysis

EXECUTIVE SUMMARY

Many people in the City of Boulder and across the Front Range recall the "biblical" rainfall and "1000-year" storm characterizations during the September 9 – 16, 2013 flood. Flooding was devastating in many watersheds in the City of Boulder as steep mountain canyons emptied runoff, rocks and debris into drainageways crossing the City for days. While many stream gages were washed out in the flood, observed high water marks during the flood and hydraulic analysis conducted since to approximate the September 2013 floodplain and estimate flows indicate that for many streams in Boulder, the runoff response from the event was below adopted regulatory 100-year peak flow rates, significantly lower in many watersheds.

This memorandum presents analyses conducted by Wright Water Engineers, Inc. (WWE), working with the City of Boulder and the Denver Urban Drainage and Flood Control District (UDFCD), to determine 5-, 10-, 15-, 30-minute, 1-, 6-, 12-, and 24-hour worst case rainfall return periods for the September 2013 flood event for watersheds within and draining through the City. Based on analysis of "worst-case"[1] rainfall (e.g. the maximum depth of precipitation falling during a given "window of time" during the storm), the short-duration (5-, 10-, and 15-minute) rainfall depths resulted in return periods of typically less than the 5-year design storm event. However, for longer durations, return period increased dramatically. For the 12- and 24-hour durations, rainfall depths exceeded the 1,000-year NOAA Atlas 14 precipitation depths. Coupled with rainfall-runoff modeling by others, this information helps to explain why a "1000-year" storm, as was recorded for durations in excess of 24-hours, did not produce "1000-year flood."

[1] The National Oceanic and Atmospheric Administration (NOAA) used "worst case" to refer to the maximum amount of precipitation that fell within a "given time window" during the event (i.e., maximum amount falling within any given hour). In this analysis, this same "worst case" terminology was used for shorter durations as well.

INTRODUCTION

Wright Water Engineers, Inc. has prepared this memorandum for the City of Boulder (City) to provide the results of analyses to determine the 5-, 10-, 15-, 30-minute, 1-, 6-, 12-, and 24-hour worst case rainfall return periods for the September 2013 flood event in Boulder. In addition to the analyses to characterize rainfall frequencies, WWE also performed comparisons with the Colorado Urban Hydrograph Procedure (CUHP) to compare the 5-, 10-, 15-, 30-minute, 1-, and 2-hour intensities for the design storm with the observed intensities from the actual flood event. Primary goals of this assignment were to characterize rainfall frequency for watersheds in and around the City and to examine how observed rainfall depths and intensities[2] relate to the characteristics of the CUHP design storm. Coupled with rainfall-runoff modeling by others, this information helps to explain why a "1000-year" storm, as was widely reported for durations in excess of 24-hours, did not produce 1000-year runoff.

RAINFALL ANALYSIS

In order to determine the return periods for the September 2013 rainfall event in Boulder, WWE used ALERT rain gage rainfall measurements from the UDFCD. UDFCD provided data for maximum 5-, 10-, 15-, 30-minute, 1-, 6-, 12-, and 24-hour rainfall depths (and associated rainfall intensities) for ALERT gages. A total of 60 ALERT rain gages located near the City of Boulder were used in this analysis. Using the National Oceanic and Atmospheric Administration (NOAA) *Atlas 14 Precipitation-Frequency Atlas of the United States*, Volume 8, Version 2, point precipitation frequency estimates were obtained for the locations of each of the 60 ALERT rain gages. Using the rainfall depths and peak intensities from UDFCD, the NOAA Atlas 14 point precipitation frequency estimates were linearly interpolated and a return period was assigned to the 5-, 10-, 15-, 30-minute, 1-, 6-, 12-, and 24-hour "worst-case" rainfall depths.

Additionally, UDFCD provided 1-square kilometer (km^2) grid cell radar precipitation data that had been gage-corrected (essentially calibrated to on-the-ground measurements). These data provided the 5-minute rainfall depths from the evening of September 11, 2013 through the morning of September 13, 2013. The 1-km^2 grid cells were clipped in a Geographic Information System (GIS) based on the watershed boundaries within and near the City. Weighted hyetographs were calculated using the radar precipitation data for these watersheds. The 5-, 10-, 15-, 30-minute, 1-, 6-, 12-, and 24-hour rainfall peak intensity depths were identified from the weighted hyetograph. A "pseudo," radar-based rain gage was placed at the centroid of each of the watersheds within and near the City. Similar to the UDFCD ALERT data, the NOAA Atlas 14 point precipitation frequency estimates were obtained at the locations of the "pseudo," radar-based rain gages. A return period was assigned to the radar-based peak intensities and depths for the various durations based on linear interpolation.

---

[2] Rainfall depths and intensities for a given duration are directly related. The rainfall intensity for a given duration is calculated by dividing the depth by the duration. For purposes of this memorandum, we primarily discuss depths; however, the results of the analyses lead to the same findings for rainfall depths or intensities.

GEOGRAPHIC INFORMATION SYSTEM (GIS) ANALYSIS

Using the return periods assigned to the 60 UDFCD ALERT rain gages and the return periods from the "pseudo," radar-based rain gages assigned to each watershed in and near the City, the "Worst Case Rainfall Return Period" maps that are attached were created using the inverse distance weighted interpolation method within the Spatial Analyst tool in ArcGIS. The output provided an interpolated surface raster that was visually displayed with other GIS data such as roads, watershed boundaries, cities, etc.

The "Worst Case Rainfall Return Period" maps for the 5-, 10-, 15-, 30-minute, 1-, 6-, 12-, and 24-hour durations are provided in Appendix A. These maps provide a broad viewport extent, as well as a viewport extent zoomed in to the City.

WORST CASE RAINFALL RETURN PERIOD MAP INTREPRETATION

The "Worst Case Rainfall Return Period" maps are based on the maximum rainfall depths within any 5-, 10-, 15-, 30-minute, 1-, 6-, 12-, or 24-hour period that occurred during the September 2013 flood. The worst-case depths (and associated intensities) for a given duration were determined by evaluating a moving "window" of time, summing incremental rainfall depths over the specified duration for the overall storm. The worst-case depth at each gage is the maximum depth recorded over the specified duration during the storm event. For example, the worst-case depth/intensity for a one-hour duration represents the maximum amount of precipitation that fell in any 1-hour period during the storm at the gage being analyzed. It is important to note that the worst-case 1-hour period at one gage does not necessarily correspond the same time period that the worst-case 1-hour depth occurred at other gages. Similarly, the 24-hour worst-case rainfall return period is not defined as the maximum rainfall within a calendar day. Instead, it is the maximum depth recorded over 24 consecutive hours (which could span two calendar days) that occurred during the storm at a given gage. Also, for a given gage, the maximum 5- or 10-minute worst-case rainfall period would not necessarily correspond to the same window of time that maximum 30-minute or 1-hour depths were recorded. These maps are not "snapshots" of the same period of time for all gages during the September 2013 flood event.

As the maps show, in all of the watersheds analyzed, rainfall depths and intensities for durations from 5- to 15-minutes were on the order of a 5-year event or less when compared with NOAA Atlas 14 statistics. For longer durations, however, the return periods increased substantially, and the results of the 24-hour worst-case depths correspond to return periods of greater than 1000-years, consistent with previous regional analysis by the Hydrometeorological Design Studies Center (NOAA and National Weather Service) (HDSC 2013). Table 1 presents estimated return periods for the durations analyzed for watersheds in the City. The 2013 event was indisputably a massive rainfall event; however, when evaluating depths and intensities for shorter durations (i.e, 2-hours), which normally drive the rainfall-runoff relationships in the Colorado Urban Hydrograph Procedure (CUHP), rainfall was less intense than assumed in design storms that are used to define regulatory peak flow rates and floodplains. To provide one example, the estimated return period for the worst case 1-hour duration within the Bear Canyon Creek watershed is less than 25-years.

When evaluating peak depths/intensities and associated recurrence intervals of shorter durations it is important to keep in mind that these intensities, in many cases, occurred at a time when the ground was already saturated. Therefore, the watersheds would have had a rainfall-runoff response similar to an impervious watershed and runoff would be significantly greater than the same intensity would produce with a drier, more typical, antecedent condition.

Table 1. Estimated Return Periods (Frequencies) for Worst Case Peak Rainfall Depths/Intensities for September 2013 Flood Event for 5-minute to 24-hour Durations

Watershed	Duration							
	5-Minute	10-Minute	15-Minute	30-Minute	1-Hour	6-Hour	12-Hour	24-Hour
Bear Canyon Creek	< 1-yr	< 1-yr	< 2-yr	< 5-yr	< 25-yr	> 100-yr	> 100-yr	> 1000-yr
Boulder Creek	< 1-yr	< 1-yr	< 1-yr	< 1-yr	< 2-yr	< 100-yr	< 100-yr	> 100-yr
Boulder Creek Drainageway A	< 1-yr	< 1-yr	< 1-yr	< 2-yr	< 5-yr	< 25-yr	< 25-yr	> 100-yr
Doudy Draw	< 2-yr	< 5-yr	< 10-yr	< 25-yr	< 100-yr	> 100-yr	< 100-yr	> 1000-yr
Dry Creek	< 1-yr	< 1-yr	1-yr	< 5-yr	< 10-yr	< 100-yr	~ 50-yr	> 100-yr
Dry Creek North	< 1-yr	< 1-yr	< 1-yr	~ 1-yr	< 5-yr	25-50-yr	25-50-yr	> 100-yr
Foothills Highway Creek	< 1-yr	< 2-yr	< 5-yr	< 5-yr	< 10-yr	> 100-yr	> 100-yr	> 100-yr
Fourmile Canyon Creek	< 2-yr	< 5-yr	< 5-yr	~ 10-yr	< 25-yr	> 100-yr	> 100-yr	> 100-yr
Goose/Twomile Canyon	< 2-yr	< 5-yr	~ 5-yr	< 25-yr	25-50-yr	> 100-yr	> 100-yr	> 1000-yr
Gregory Creek	< 1-yr	< 1-yr	< 2-yr	< 5-yr	~ 10-yr	> 100-yr	> 100-yr	> 100-yr
Marshall Gulch	< 1-yr	< 1-yr	< 1-yr	< 1-yr	< 5-yr	~ 50-yr	< 100-yr	> 100-yr
Martin Gulch	< 1-yr	< 2-yr	< 2-yr	< 5-yr	< 10-yr	> 100-yr	25-50-yr	> 100-yr
Phelps Drainage	< 1-yr	< 2-yr	~ 2-yr	< 5-yr	< 10-yr	> 100-yr	> 100-yr	> 100-yr
Sixmile Canyon	< 1-yr	< 2-yr	< 5-yr	~ 5-yr	< 25-yr	> 100-yr	> 100-yr	> 1000-yr
Sixmile Reservoir Drainage	< 1-yr	< 2-yr	< 1-yr	< 2-yr	< 5-yr	25-50-yr	~ 50-yr	> 100-yr
Skunk Creek	< 1-yr	< 2-yr	< 5-yr	< 10-yr	< 25-yr	> 100-yr	> 100-yr	> 1000-yr
South Boulder Creek	< 1-yr	< 1-yr	< 2-yr	< 5-yr	~ 10-yr	> 100-yr	< 100-yr	> 100-yr
Sunshine Canyon Creek	< 1-yr	< 2-yr	< 2-yr	< 5-yr	~ 10-yr	> 100-yr	> 100-yr	> 100-yr
Valmont Reservoir Drainage	< 1-yr	< 1-yr	< 1-yr	< 2-yr	< 5-yr	25-50-yr	25yr	> 100-yr
Viele Lake Channel	< 2-yr	< 5-yr	< 10-yr	~ 10-yr	~ 25-yr	~ 1,000-yr	> 100-yr	> 1000-yr
Wonderland Creek	< 2-yr	< 5-yr	< 10-yr	< 25-yr	~ 50-yr	> 100-yr	> 100-yr	> 1000-yr

COMPARISON WITH COLORADO URBAN HYDROGRAPH PROCEDURE (CUHP)

The CUHP model has been calibrated to the Colorado Front Range using data collected by the U.S. Geological Survey beginning in 1969 and calculates the output peak flow based on an input rainfall hyetograph (UDFCD 2010). This hydrologic modeling is the basis for the hydraulic modeling that is performed for Major Drainageway Plans, Outfall System Plans, or Flood Hazard Area Delineation Studies (delineation of the 100-year floodplain).

Based on an analysis of historical precipitation data in the Denver area, an overwhelming majority of the intense rainstorms produce their greatest intensities in the first hour of the storm (UDFCD 2010). It is these short-duration, intense rainstorms that appear to cause most of the flooding problems in the great majority of the urban watersheds. Therefore, the UDFCD developed a "design storm distribution" that takes into account the short-duration, intense rainstorms that serves as the basis for Denver area hydrologic modeling. CUHP typically uses a 2-hour design storm as the input rainfall hyetograph to calculate the output peak flow (UDFCD 2011), although this will vary depending on site-specific circumstances such as the applicable time of concentration.

In addition to the analysis to characterize rainfall return periods, WWE also performed comparisons with CUHP to compare the 5-, 10-, 15-, 30-minute, 1-, and 2-hour intensities from the CUHP design storms with the observed depths and intensities from the actual September 2013 flood event. This analysis helps understand how the actual flood event differed from the design storm in terms of short-duration rainfall depths and intensities, which influenced peak flow rates observed in creeks in Boulder.

Comparisons were conducted for the following watersheds within and near the City:

- South Boulder Creek
- Bear Canyon Creek
- Skunk Creek
- Gregory Canyon Creek
- Boulder Creek
- Goose/Twomile Canyon Creek
- Wonderland Creek
- Fourmile Canyon Creek

For each of the above watersheds, the 2-, 5-, 10-, 25-, 50-, and 100-year, 2-hour rainfall distributions were calculated using the UDFCD UD-Rain, Version 1.01 spreadsheet (same rainfall distribution that would be input into CUHP). Then the 5-, 10-, 15-, 30-minute, 1-, and 2-hour maximum depths (corresponding to peak intensities) from these 2-hour rainfall distributions were identified and compared to the maximum depths/peak intensities observed during the September 2013 flood event. Appendix B provides graphs showing the comparison of peak rainfall intensities for the September 2013 flood event with the CUHP design storm intensities for the various watersheds near the City of Boulder. Table 2 provides a summary of these comparisons.

Table 2. Comparison of Peak Rainfall Depths/Intensities for September 2013 Flood Event with CUHP Design Storm Intensities[1]

Watershed	5-Minute	10-Minute	15-Minute	30-Minute	1-Hour	2-Hour
South Boulder Creek	< CUHP 2-yr	< CUHP 2-yr	~ CUHP 2-yr	> CUHP 2-yr	> CUHP 10-yr	> CUHP 10-yr
Bear Canyon Creek	< CUHP 2-yr	~ CUHP 2-yr	~ CUHP 2-yr	~ CUHP 5-yr	> CUHP 10-yr	> CUHP 25-yr
Skunk Creek	< CUHP 2-yr	< CUHP 2-yr	~ CUHP 2-yr	> CUHP 2-yr	> CUHP 5-yr	> CUHP 25-yr
Gregory Canyon Creek	< CUHP 2-yr	< CUHP 2-yr	< CUHP 2-yr	> CUHP 2-yr	> CUHP 5-yr	~ CUHP 25-yr
Boulder Creek	< CUHP 2-yr	< CUHP 2-yr	< CUHP 2-yr	< CUHP 2-yr	< CUHP 2-yr	< CUHP 5-yr
Goose/Twomile Canyon Creek	> CUHP 2-yr	~ CUHP 5-yr	~ CUHP 5-yr	> CUHP 10-yr	> CUHP 10-yr	> CUHP 25-yr
Wonderland Creek	~ CUHP 2-yr	> CUHP 2-yr	> CUHP 2-yr	> CUHP 10-yr	> CUHP 25-yr	~ CUHP 50-yr
Fourmile Canyon Creek	> CUHP 2-yr	> CUHP 2-yr	> CUHP 2-yr	> CUHP 10-yr	> CUHP 10-yr	> CUHP 25-yr

[1] > 2-yr = between 2 and 5-yr; > 5-yr = between 5 and 10-yr; > 10-yr = between 10 and 25-yr; > 25-yr = between 25 and 50-yr

Additionally, WWE compared the 100-year, 2-hour CUHP design storm hyetograph (which is commonly used to define rainfall-runoff relationships that form the hydrologic basis of 100-year floodplain limits) with the maximum (worst-case) 2-hour weighted rainfall hyetograph from the September 2013 flood event for the same watersheds listed above. The graphs showing this comparison are provided in Appendix C.

CONCLUSIONS

Based on the "Worst-Case Rainfall Return Period" maps, the short-duration (5-, 10-, and 15-minute) rainfall depths resulted in return periods of typically less than the 5-year design storm event. However, for longer durations, return period increased dramatically. For the 12- and 24-hour durations, rainfall depths exceeded the 1,000-year NOAA Atlas 14 precipitation depths. However, there is not a direct correlation between rainfall return periods and peak flow return periods. For example, if the 24-hour worst-case rainfall return period for the Boulder Creek watershed was greater than 1,000-years, that does not necessarily mean that the flow in Boulder Creek exceeded the 1,000-year peak flow. As shown in the graphs in Appendix C, the actual 2-hour weighted hyetographs from the September 2013 flood event are well below the CUHP 100-year, 2-hour design storm that are used to estimate the 100-year peak flows and define floodplains. Therefore, it is expected that the peak flows experienced during the September 2013 flood event for Boulder Creek, South Boulder Creek, Skunk Creek, etc. should be smaller than the 100-year peak flows projected from CUHP analysis.

REFERENCES

Hydrometeorological Design Studies Center (HDSC), *Exceedance Probability Analysis for the Colorado Flood Event, 9 – 16 Septembre, 2013*. 17 September 2013.

National Oceanic and Atmospheric Administration (NOAA) Atlas 14 Point Precipitation Frequency Estimates: CO, 2013.

Urban Drainage and Flood Control District (UDFCD). CUHP 2005 User Manual, Version 1.3.3. January 21, 2010.

Urban Drainage and Flood Control District (UDFCD). *Urban Storm Drainage Criteria Manual, Volume 1, Rainfall*. UDFCD, Denver, Colorado. June 2011.

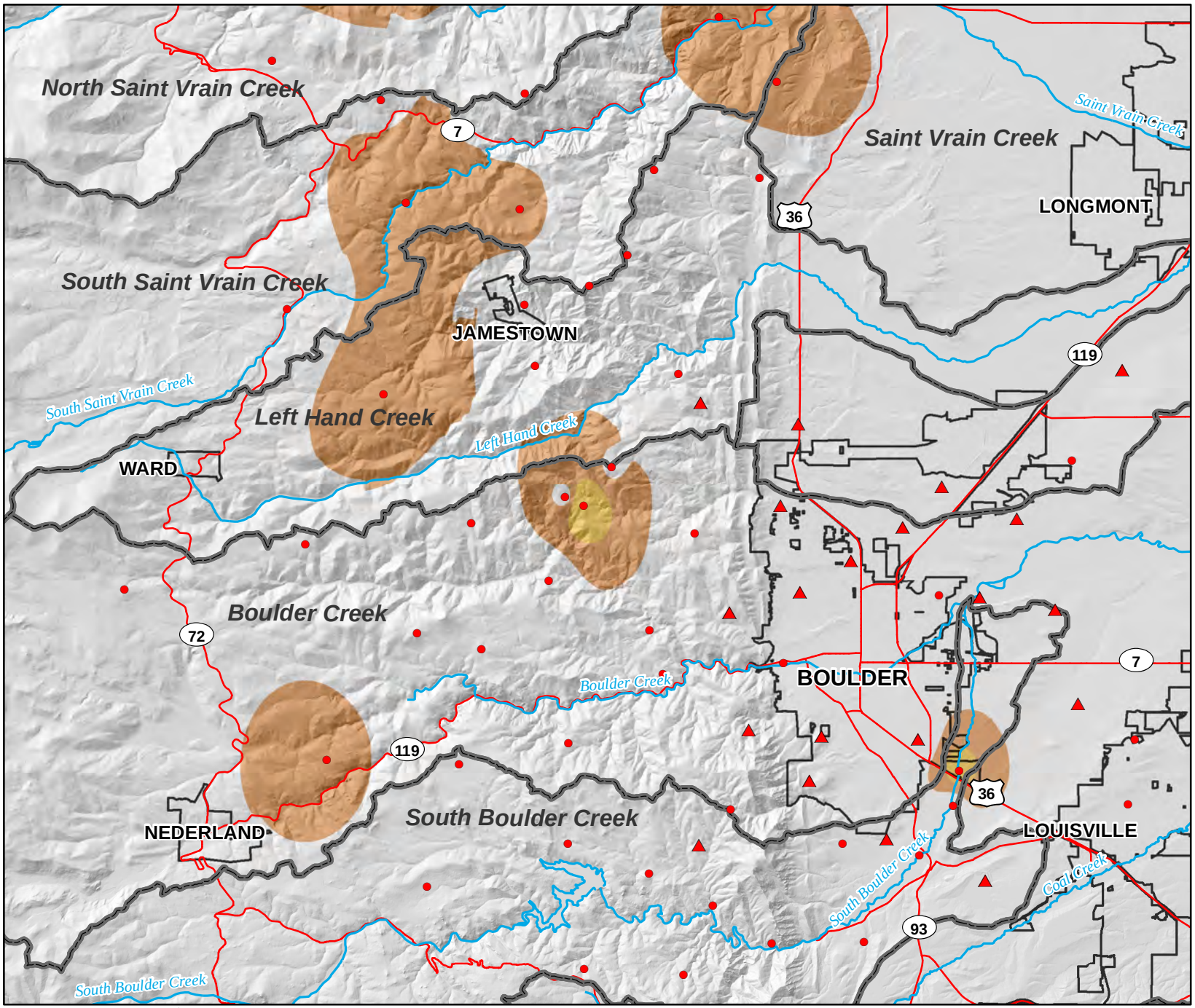
Attachments:

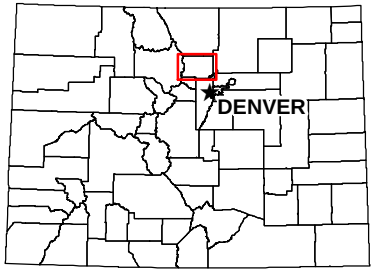
Appendix A: Worst Case Return period Maps (Figures 1 -16)

Appendix B: Comparison of Peak Rainfall Intensities for September 2013 Flood Event with CUHP Design Storm Intensities Graphs

Appendix C: Comparison of 2-Hour Rainfall Hyetograph for September 2013 Flood Event with CUHP Design Storm Graphs

Appendix A





Legend

- ALERT Gage
- Radar-based Gage
- Watershed Boundary

Return Period (year)

- < 5
- > 5-10
- > 10-25
- > 25-50
- > 50-100
- > 100-200
- > 200-500
- > 500-1000
- > 1000

N W E S

0 1 2 4 Miles

FIGURE 1

5-minute Worst Case Rainfall Return Period

for City of Boulder & Vicinity

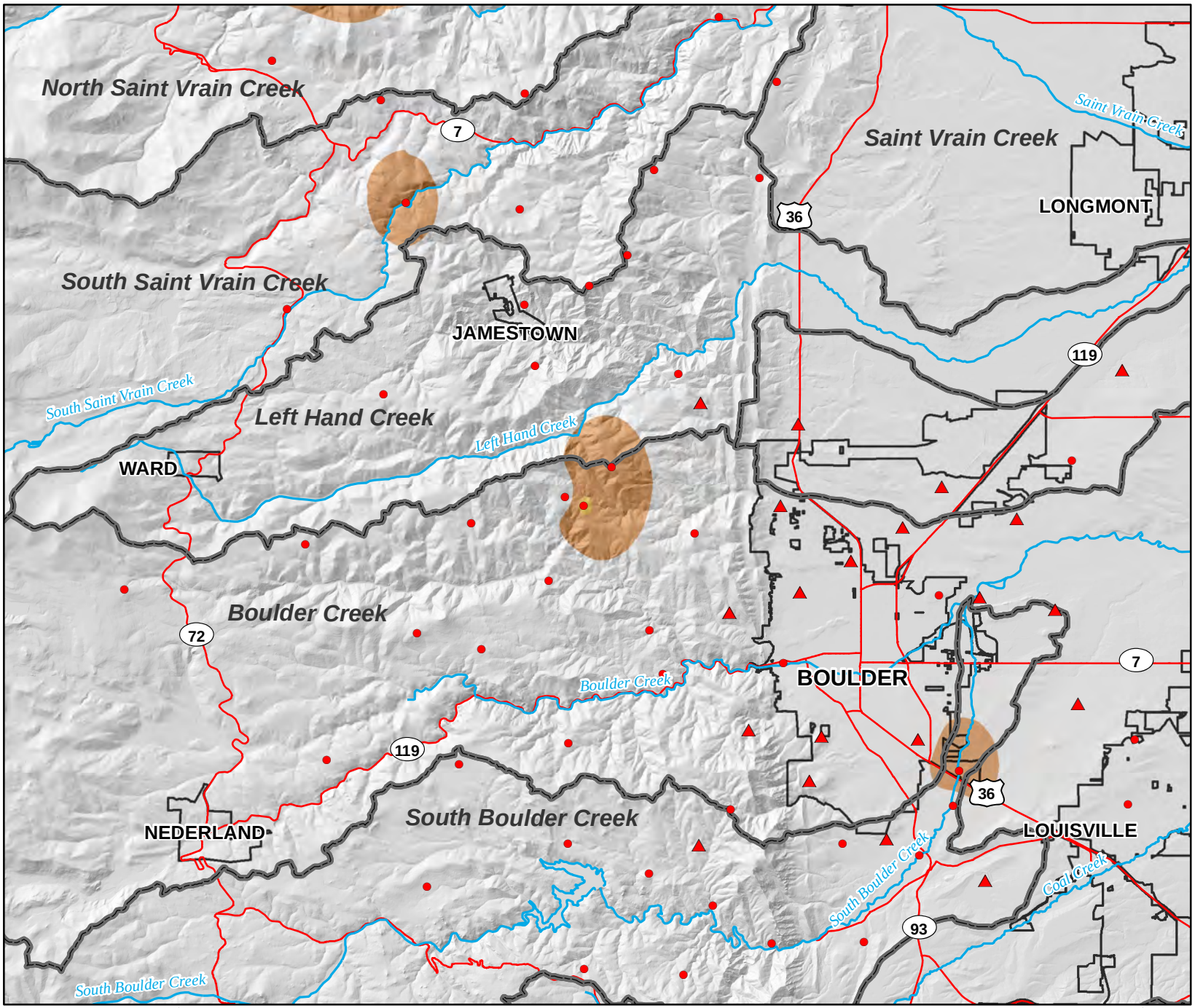
September 9-16, 2013 Flood Event

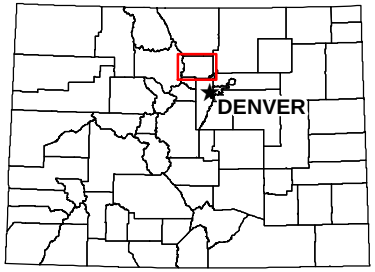
WRIGHT WATER ENGINEERS, INC.
2490 W 26TH AVE 100A
DENVER, CO. 80211
(303) 480-1700

Draft

Draft

Document Path: Z:\Project Files\14\141-024\141-024.000\CAD-GIS\GIS\Figure 1\FIGURE1_5MINUTE_new5714.mxd





Legend

- ALERT Gage
- Radar-based Gage
- Watershed Boundary

Return Period (year)

- < 5
- > 5-10
- > 10-25
- > 25-50
- > 50-100
- > 100-200
- > 200-500
- > 500-1000
- > 1000

N W E S

0 1 2 4 Miles

FIGURE 2

Draft

10-minute Worst Case Rainfall Return Period

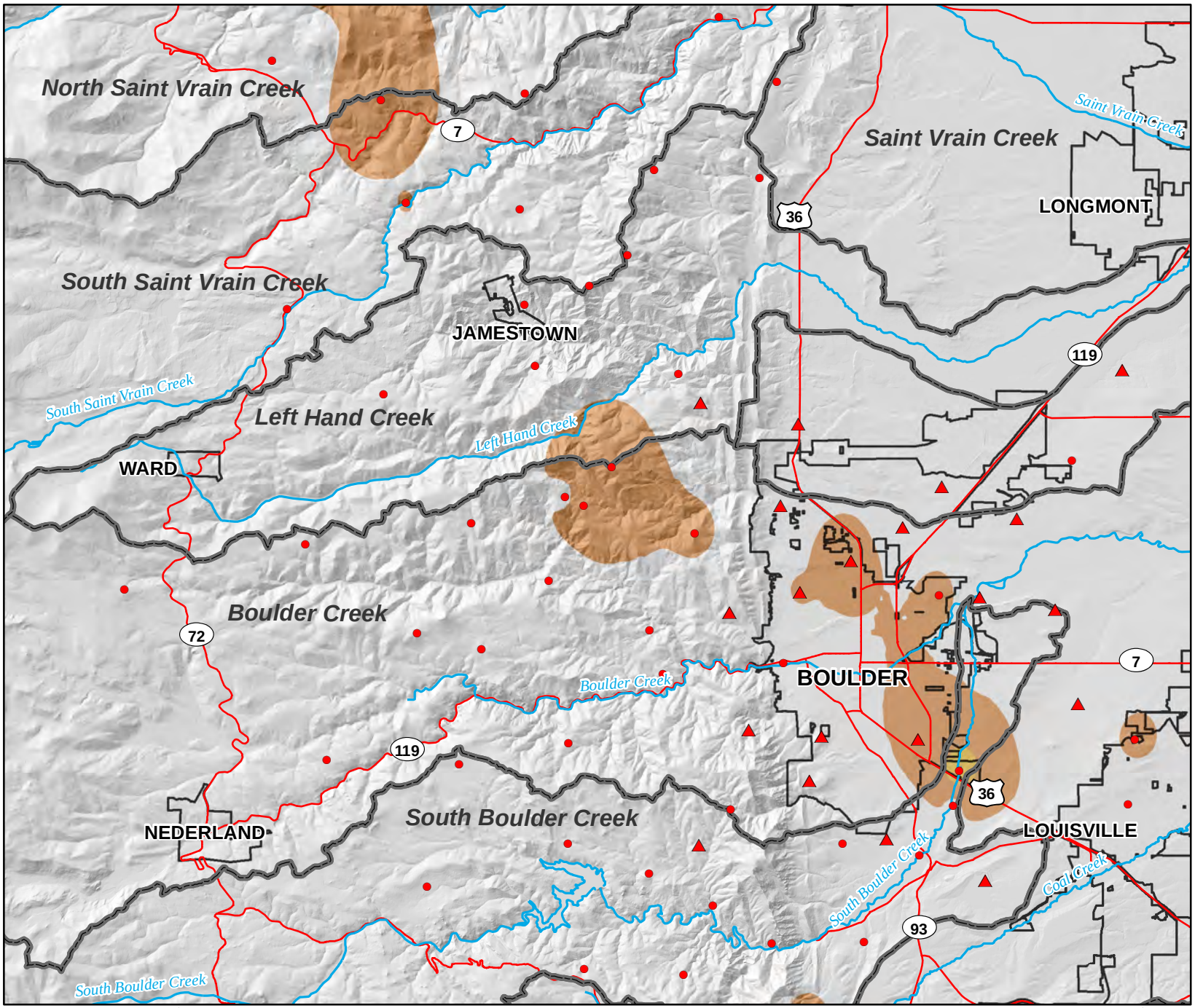
for City of Boulder & Vicinity

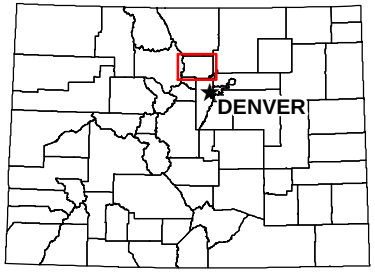
September 9-16, 2013 Flood Event

WRIGHT WATER ENGINEERS, INC.
2490 W 26TH AVE 100A
DENVER, CO. 80211
(303) 480-1700

Draft

Document Path: Z:\Project Files\14\141-024\141-024.000\CAD-GIS\GIS\Figure 1\FIGURE2_10MINUTE_new5714.mxd





Legend

- ALERT Gage
- Radar-based Gage
- Watershed Boundary

Return Period (year)

- < 5
- > 5-10
- > 10-25
- > 25-50
- > 50-100
- > 100-200
- > 200-500
- > 500-1000
- > 1000

N W E S

0 1 2 4 Miles

FIGURE 3

Draft

15-minute Worst Case Rainfall Return Period

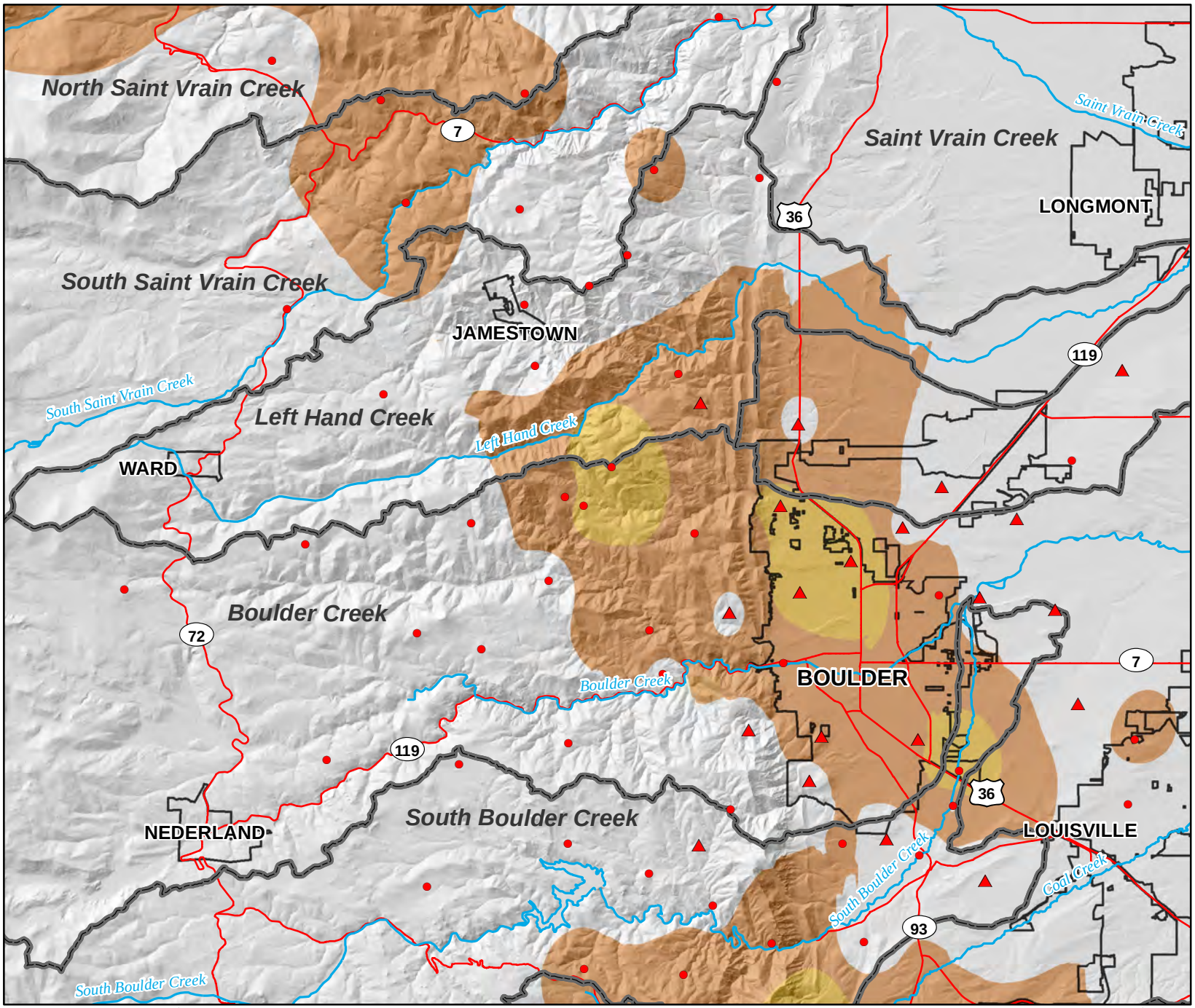
for City of Boulder & Vicinity

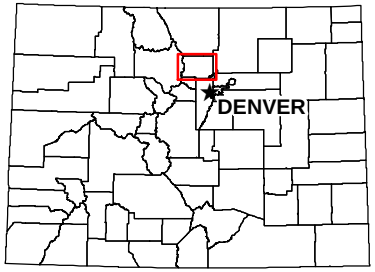
September 9-16, 2013 Flood Event

WRIGHT WATER ENGINEERS, INC.
2490 W 26TH AVE 100A
DENVER, CO. 80211
(303) 480-1700

Draft

Document Path: Z:\Project Files\14\141-024\141-024.000\CAD-GIS\GIS\Figure 1\FIGURE3_15MINUTE_new5714.mxd





Legend

- ALERT Gage
- Radar-based Gage
- Watershed Boundary

Return Period (year)

- < 5
- > 5-10
- > 10-25
- > 25-50
- > 50-100
- > 100-200
- > 200-500
- > 500-1000
- > 1000

N W E S

0 1 2 4 Miles

FIGURE 4

Draft

30-minute Worst Case Rainfall Return Period

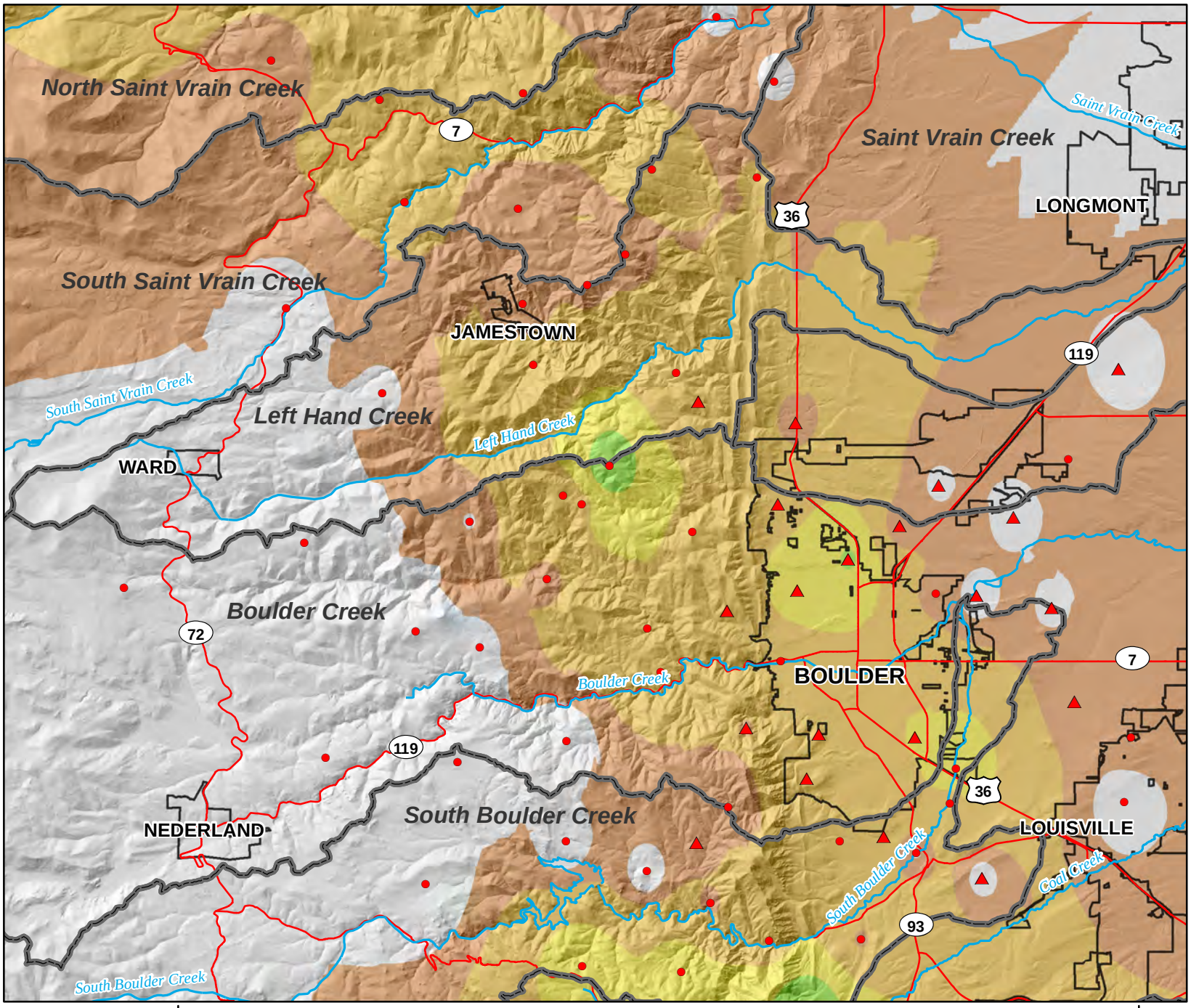
for City of Boulder & Vicinity

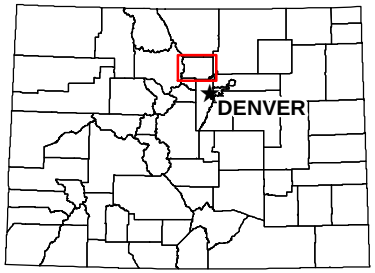
September 9-16, 2013 Flood Event

WRIGHT WATER ENGINEERS, INC.
2490 W 26TH AVE 100A
DENVER, CO. 80211
(303) 480-1700

Draft

Document Path: Z:\Project Files\14\141-024\141-024.000\CAD-GIS\GIS\Figure 1\FIGURE4_30MINUTE_new5714.mxd





Legend

- ALERT Gage
- Radar-based Gage
- Watershed Boundary

Return Period (year)

- < 5
- > 5-10
- > 10-25
- > 25-50
- > 50-100
- > 100-200
- > 200-500
- > 500-1000
- > 1000

N W E S

0 1 2 4 Miles

FIGURE 5

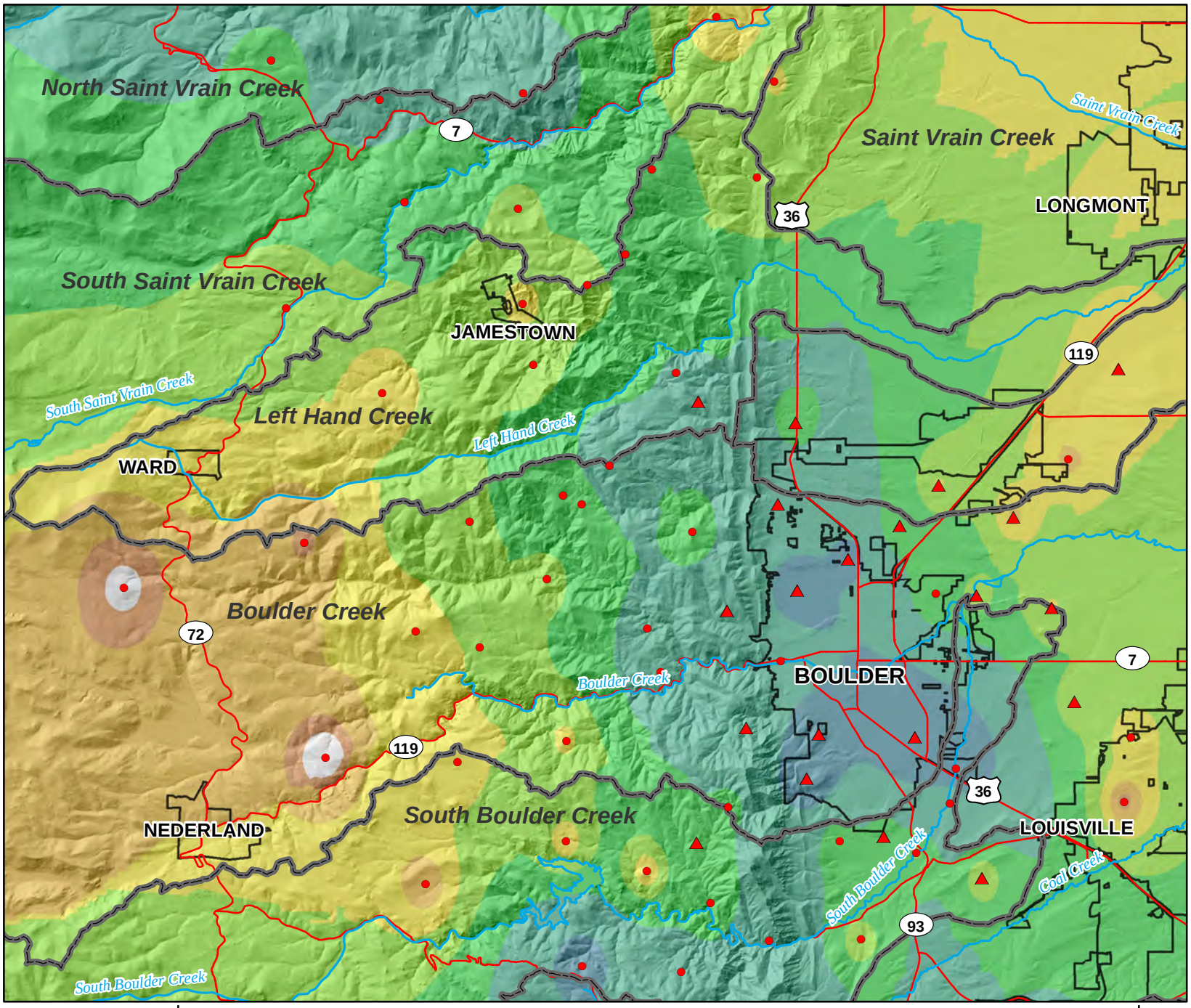
1-hour Worst Case Rainfall Return Period
for City of Boulder & Vicinity
September 9-16, 2013 Flood Event

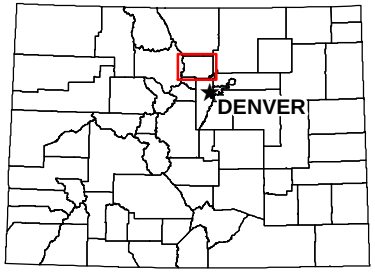
WRIGHT WATER ENGINEERS, INC.
2490 W 26TH AVE 100A
DENVER, CO. 80211
(303) 480-1700

Draft

Draft

Document Path: Z:\Project Files\14\141-024\141-024.000\CAD-GIS\GIS\Figure 1\FIGURE5_1HOUR_new5714.mxd





Legend

- ALERT Gage
- Radar-based Gage
- Watershed Boundary

Return Period (year)

- < 5
- > 5-10
- > 10-25
- > 25-50
- > 50-100
- > 100-200
- > 200-500
- > 500-1000
- > 1000

N W E S

0 1 2 4 Miles

FIGURE 6

6-hour Worst Case Rainfall Return Period

for City of Boulder & Vicinity

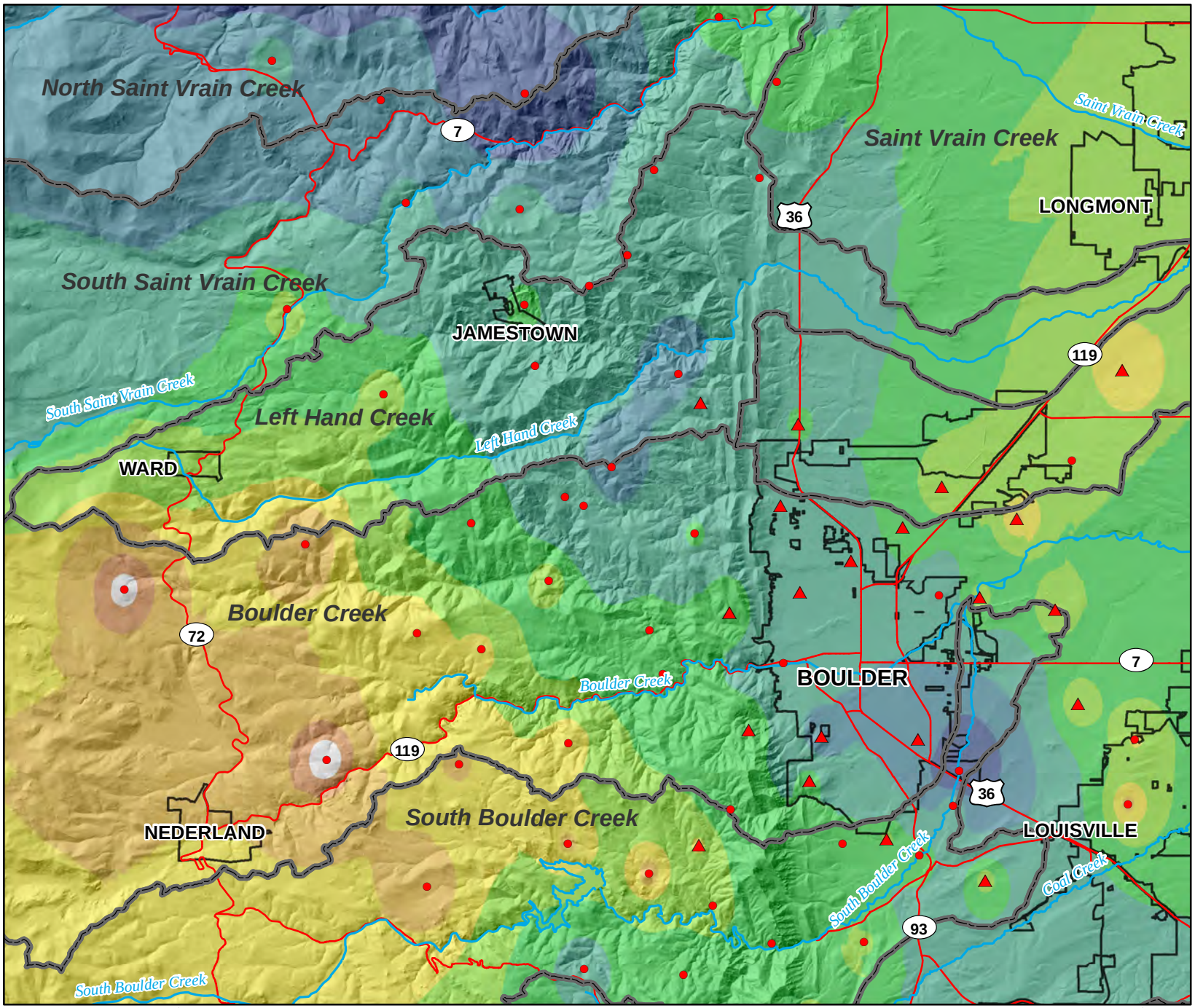
September 9-16, 2013 Flood Event

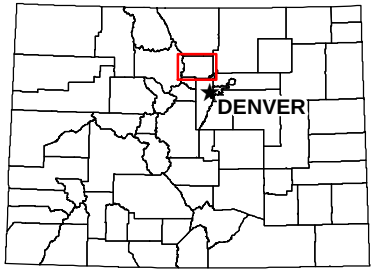
Draft

WRIGHT WATER ENGINEERS, INC.
2490 W 26TH AVE 100A
DENVER, CO. 80211
(303) 480-1700

Draft

Document Path: Z:\Project Files\14\141-024\141-024.000\CAD-GIS\GIS\Figure 1\FIGURE6_6HOUR_new5714.mxd





Legend

- ALERT Gage
- Radar-based Gage
- Watershed Boundary

Return Period (year)

- < 5
- > 5-10
- > 10-25
- > 25-50
- > 50-100
- > 100-200
- > 200-500
- > 500-1000
- > 1000

N W E S

0 1 2 4 Miles

FIGURE 7

12-hour Worst Case Rainfall Return Period

for City of Boulder & Vicinity

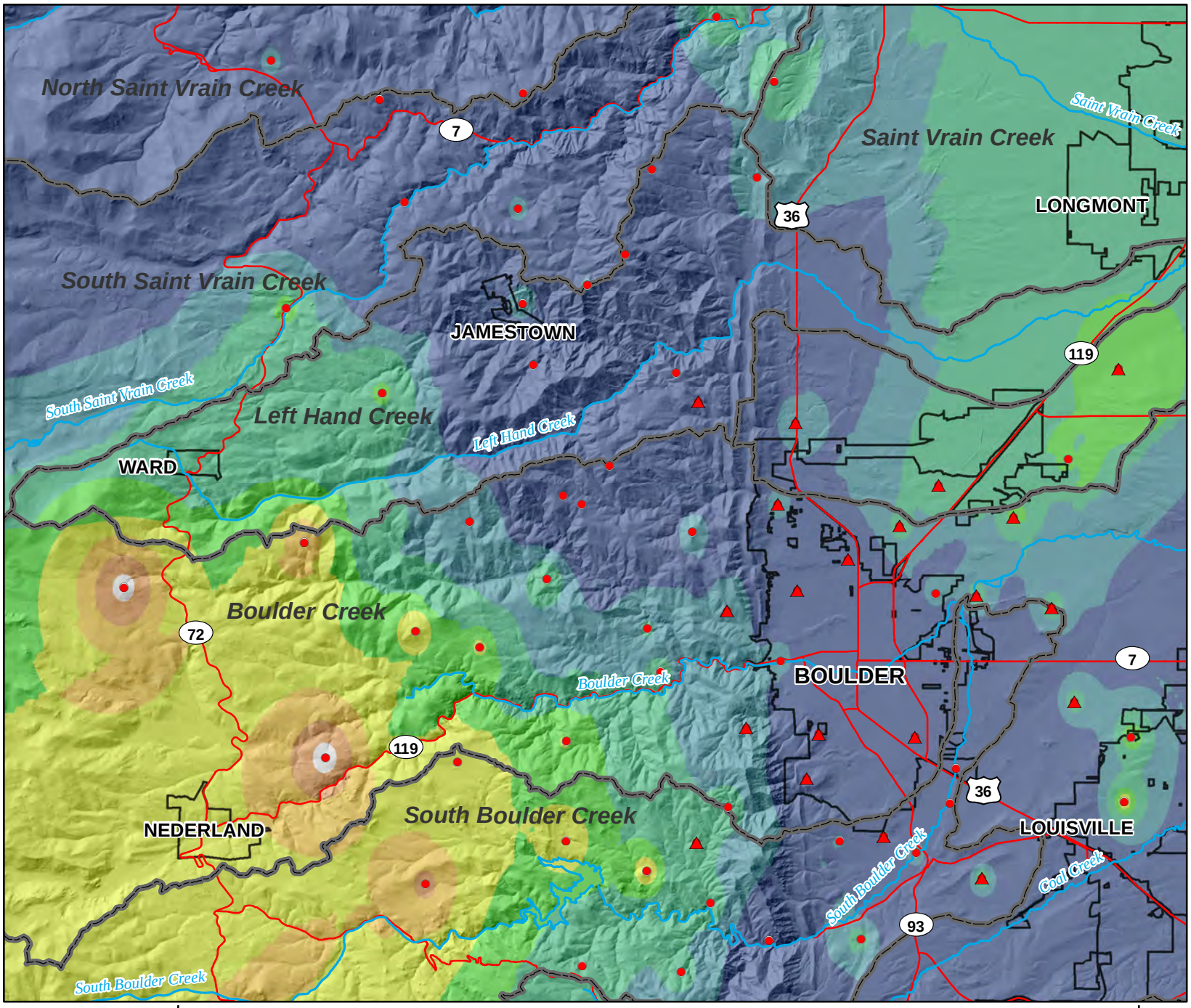
September 9-16, 2013 Flood Event

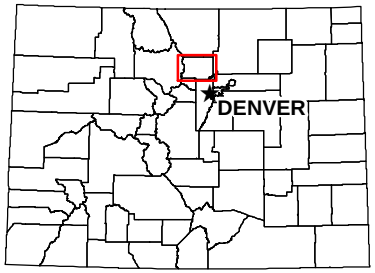
Draft

WRIGHT WATER ENGINEERS, INC.
2490 W 26TH AVE 100A
DENVER, CO. 80211
(303) 480-1700

Draft

Document Path: Z:\Project Files\14\141-024\141-024.000\CAD-GIS\GIS\Figure 1\FIGURE7_12HOUR_new5714.mxd





Legend

- ALERT Gage
- Radar-based Gage
- Watershed Boundary

Return Period (year)

- < 5
- > 5-10
- > 10-25
- > 25-50
- > 50-100
- > 100-200
- > 200-500
- > 500-1000
- > 1000

N W E S

0 1 2 4 Miles

FIGURE 8

Draft

24-hour Worst Case Rainfall Return Period

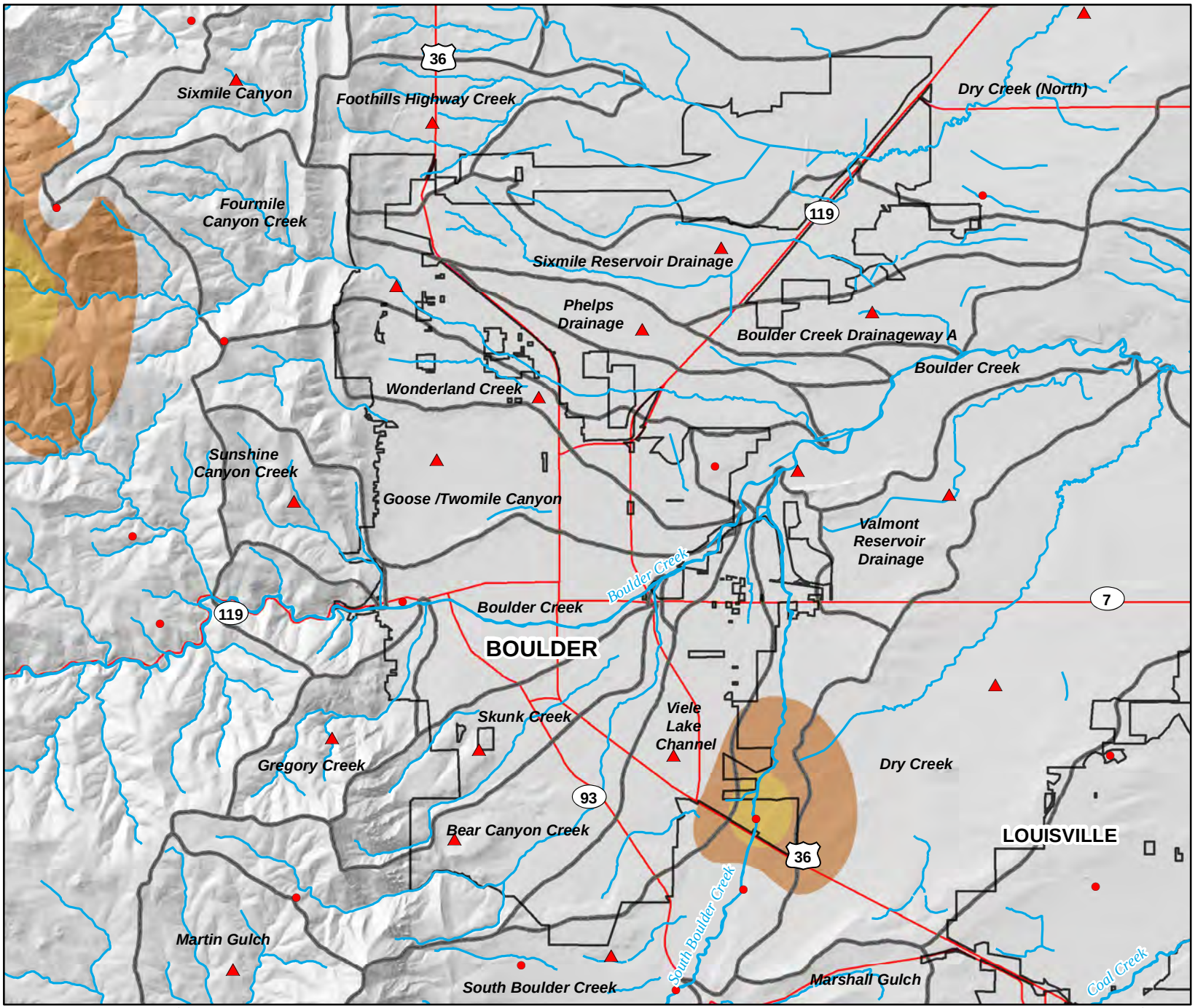
for City of Boulder & Vicinity

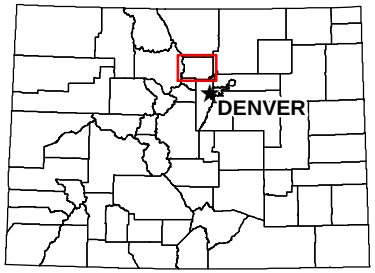
September 9-16, 2013 Flood Event

WRIGHT WATER ENGINEERS, INC.
2490 W 26TH AVE 100A
DENVER, CO. 80211
(303) 480-1700

Draft

Document Path: Z:\Project Files\14\141-024\141-024.000\CAD-GIS\GIS\Figure 1\FIGURE8_24HOUR_new5714.mxd





Legend

- ALERT Gage
- Radar-based Gage
- Watershed Boundary

Return Period (year)

- < 5
- > 5-10
- > 10-25
- > 25-50
- > 50-100
- > 100-200
- > 200-500
- > 500-1000
- > 1000

N W E S

0 0.5 1 2 Miles

FIGURE 9

Draft

5-minute Worst Case Rainfall Return Period

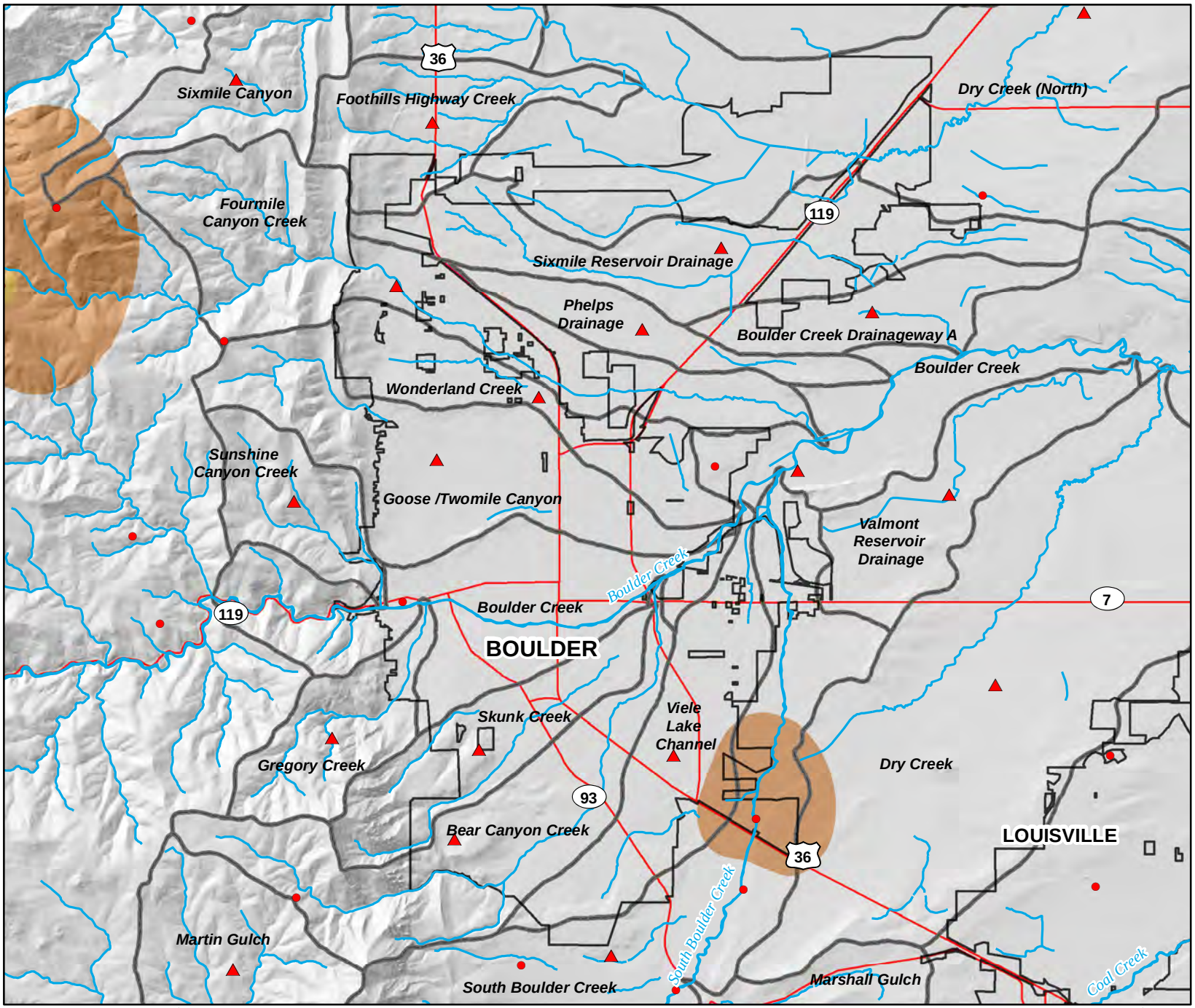
for City of Boulder & Vicinity

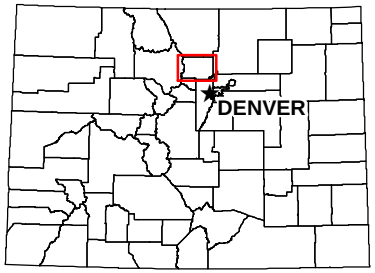
September 9-16, 2013 Flood Event

WRIGHT WATER ENGINEERS, INC.
2490 W 26TH AVE 100A
DENVER, CO. 80211
(303) 480-1700

Draft

Document Path: Z:\Project Files\14\141-024\141-024.000\CAD-GIS\GIS\Figure 2\FIGURE9_5MINUTE_new5714.mxd





Legend

- ALERT Gage
- Radar-based Gage
- Watershed Boundary

Return Period (year)

- < 5
- > 5-10
- > 10-25
- > 25-50
- > 50-100
- > 100-200
- > 200-500
- > 500-1000
- > 1000

N W E S

0 0.5 1 2 Miles

FIGURE 10

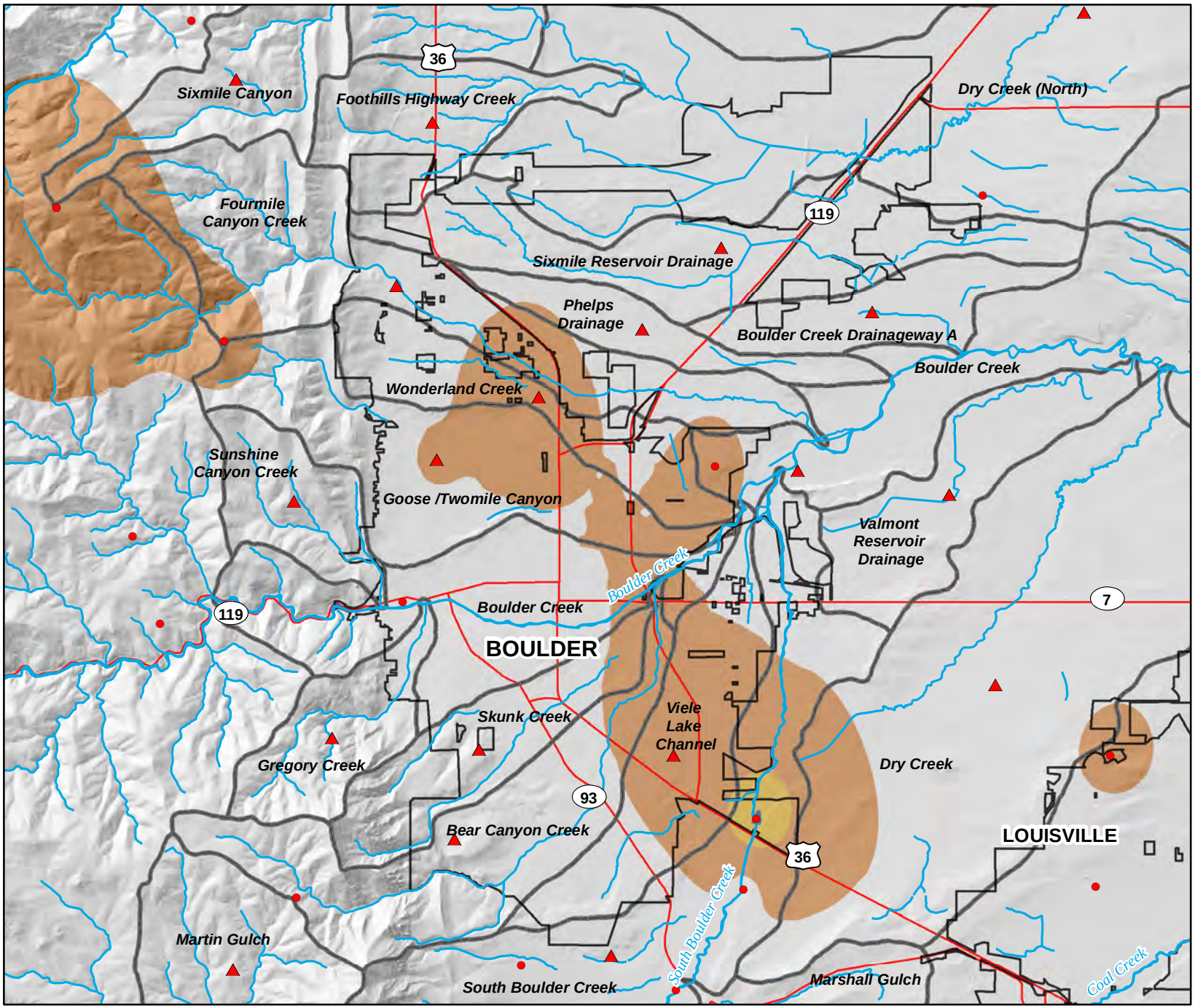
10-minute Worst Case Rainfall Return Period
for City of Boulder & Vicinity
September 9-16, 2013 Flood Event

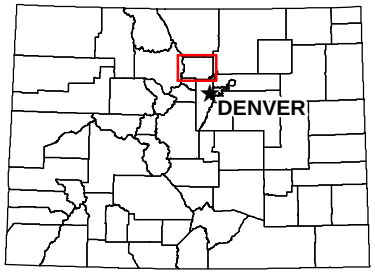
WRIGHT WATER ENGINEERS, INC.
2490 W 26TH AVE 100A
DENVER, CO. 80211
(303) 480-1700

Draft

Draft

Document Path: Z:\Project Files\14\141-024\141-024.000\CAD-GIS\GIS\Figure 2\FIGURE10_10MINUTE_new5714.mxd





Legend

- ALERT Gage
- Radar-based Gage
- Watershed Boundary

Return Period (year)

- < 5
- > 5-10
- > 10-25
- > 25-50
- > 50-100
- > 100-200
- > 200-500
- > 500-1000
- > 1000

N W E S

0 0.5 1 2 Miles

FIGURE 11

Draft

15-minute Worst Case Rainfall Return Period

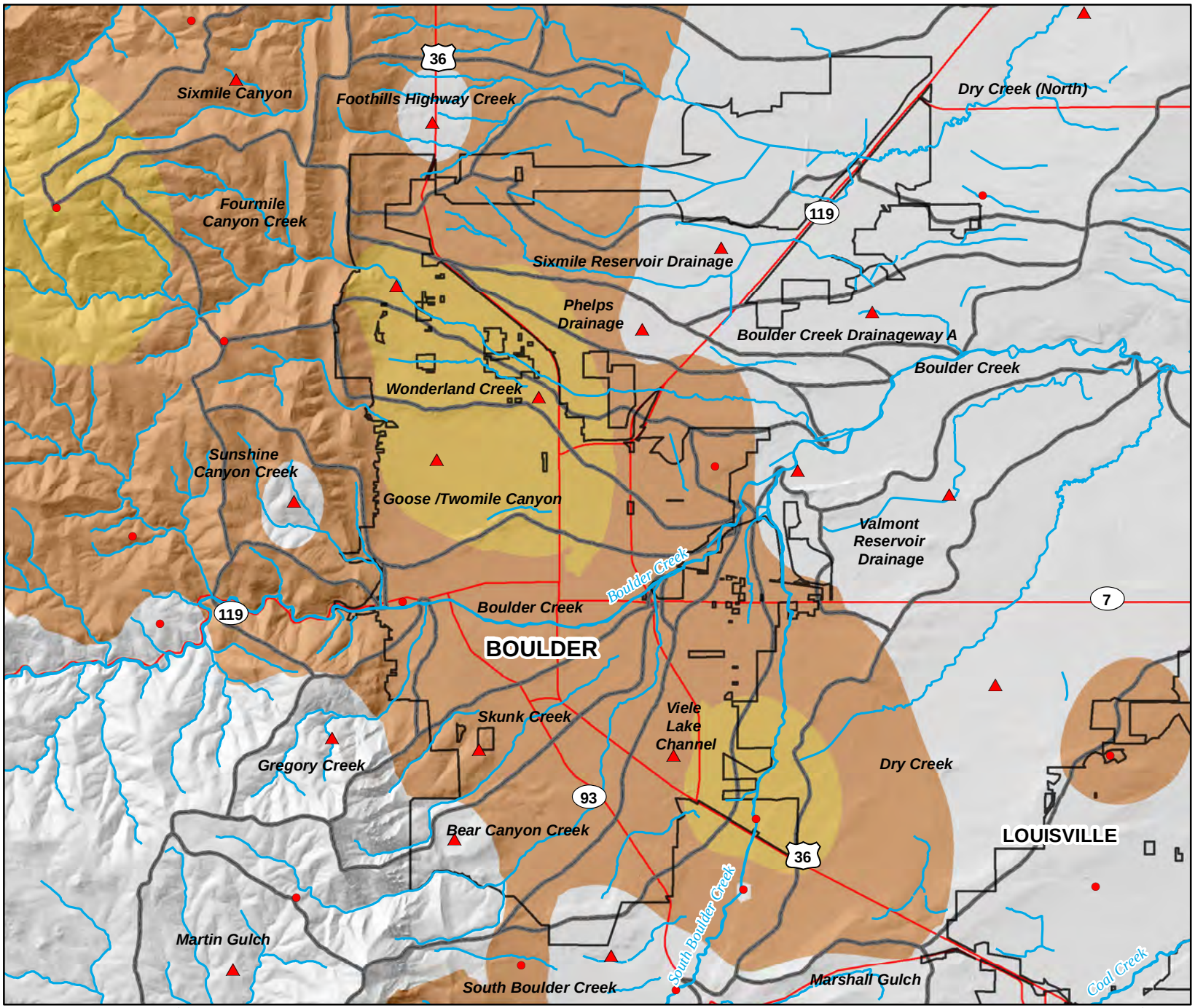
for City of Boulder & Vicinity

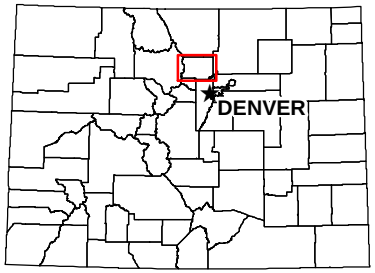
September 9-16, 2013 Flood Event

WRIGHT WATER ENGINEERS, INC.
2490 W 26TH AVE 100A
DENVER, CO. 80211
(303) 480-1700

Draft

Document Path: Z:\Project Files\14\141-024\141-024.000\CAD-GIS\GIS\Figure 2\FIGURE11_15MINUTE_new5714.mxd





Legend

- ALERT Gage
- Radar-based Gage
- Watershed Boundary

Return Period (year)

- < 5
- > 5-10
- > 10-25
- > 25-50
- > 50-100
- > 100-200
- > 200-500
- > 500-1000
- > 1000

N W E S

0 0.5 1 2 Miles

FIGURE 12

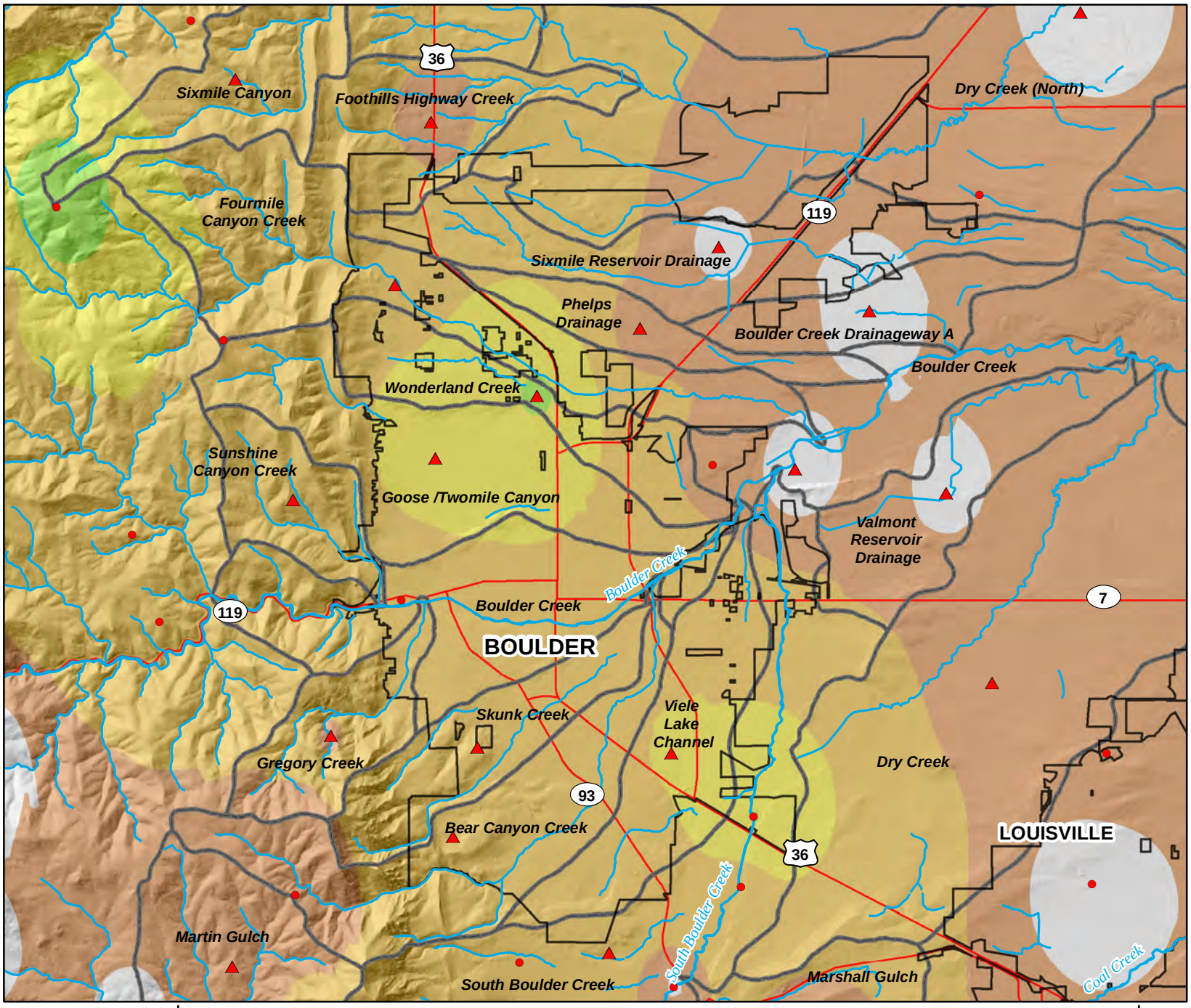
30-minute Worst Case Rainfall Return Period
for City of Boulder & Vicinity
September 9-16, 2013 Flood Event

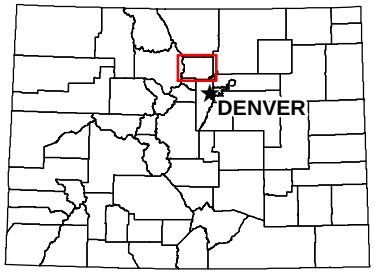
WRIGHT WATER ENGINEERS, INC.
2490 W 26TH AVE 100A
DENVER, CO. 80211
(303) 480-1700

Draft

Draft

Document Path: Z:\Project Files\14\141-024\141-024.000\CAD-GIS\GIS\Figure 2\FIGURE12_30MINUTE_new5714.mxd





Legend

- ALERT Gage
- Radar-based Gage
- Watershed Boundary

Return Period (year)

- < 5
- > 5-10
- > 10-25
- > 25-50
- > 50-100
- > 100-200
- > 200-500
- > 500-1000
- > 1000

N W E S

0 0.5 1 2 Miles

FIGURE 13

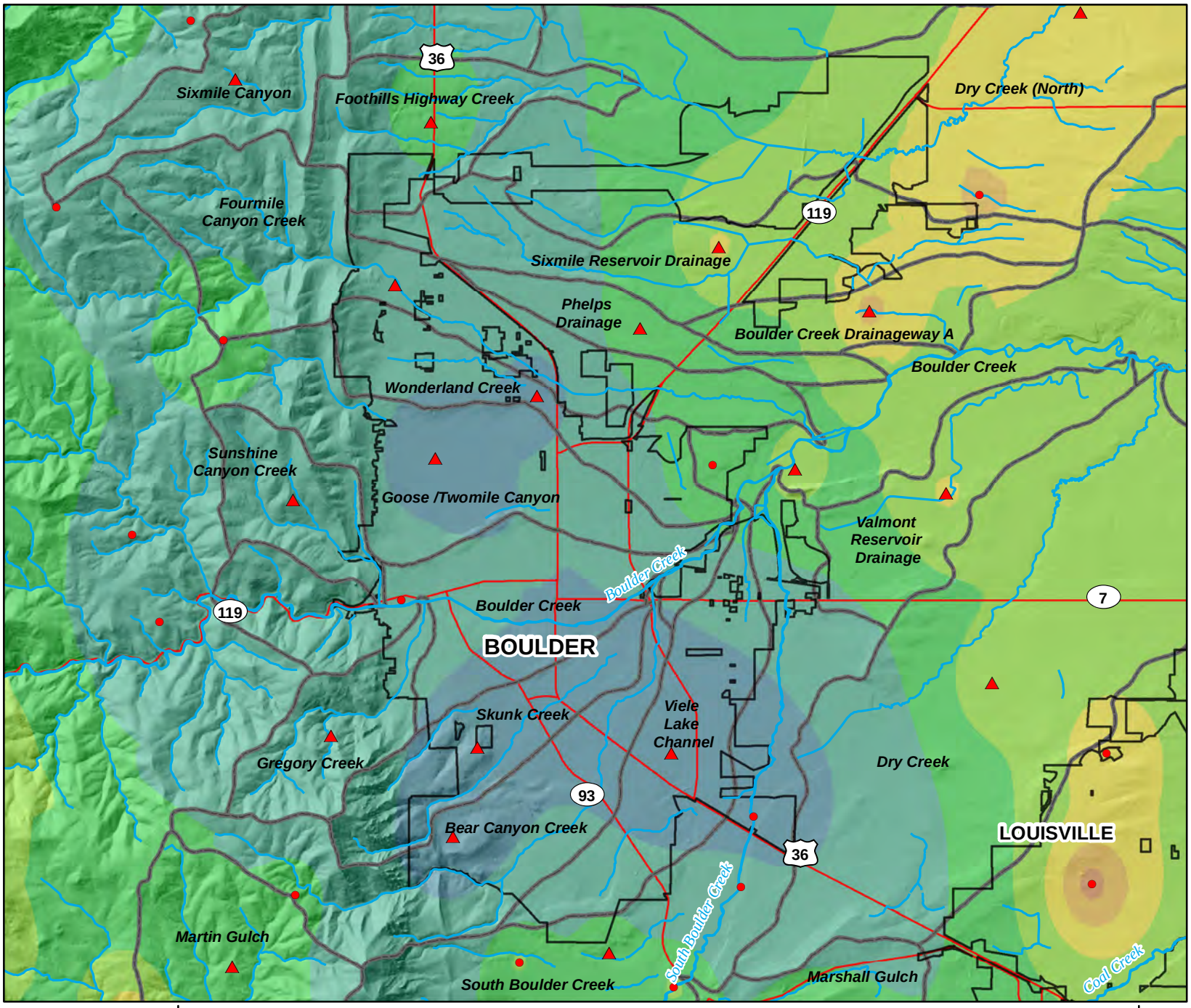
1-hour Worst Case Rainfall Return Period
for City of Boulder & Vicinity
September 9-16, 2013 Flood Event

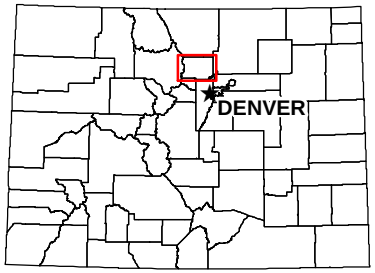
WRIGHT WATER ENGINEERS, INC.
2490 W 26TH AVE 100A
DENVER, CO. 80211
(303) 480-1700

Draft

Draft

Document Path: Z:\Project Files\14\141-024\141-024.000\CAD-GIS\GIS\Figure 2\FIGURE13_1HOUR_new5714.mxd





Legend

- ALERT Gage
- Radar-based Gage
- Watershed Boundary

Return Period (year)

- < 5
- > 5-10
- > 10-25
- > 25-50
- > 50-100
- > 100-200
- > 200-500
- > 500-1000
- > 1000

N W E S

0 0.5 1 2 Miles

FIGURE 14

Draft

6-hour Worst Case Rainfall Return Period

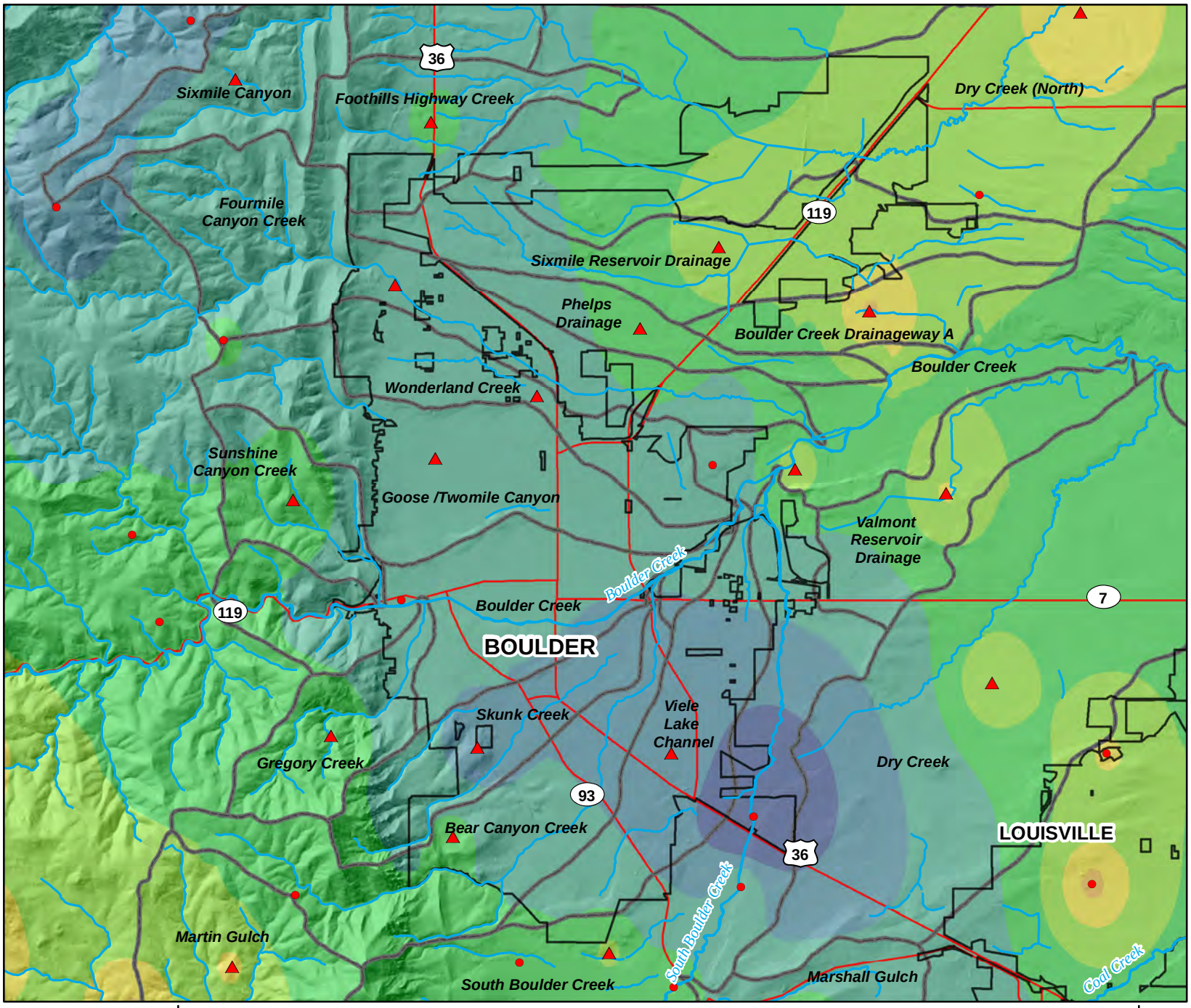
for City of Boulder & Vicinity

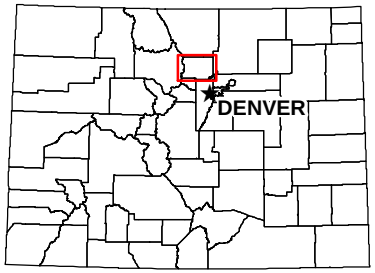
September 9-16, 2013 Flood Event

WRIGHT WATER ENGINEERS, INC.
2490 W 26TH AVE 100A
DENVER, CO. 80211
(303) 480-1700

Draft

Document Path: Z:\Project Files\14\141-024\141-024.000\CAD-GIS\GIS\Figure 2\FIGURE14_6HOUR_new5714.mxd





Legend

- ALERT Gage
- Radar-based Gage
- Watershed Boundary

Return Period (year)

- < 5
- > 5-10
- > 10-25
- > 25-50
- > 50-100
- > 100-200
- > 200-500
- > 500-1000
- > 1000

N W E S

0 0.5 1 2 Miles

FIGURE 15

Draft

12-hour Worst Case Rainfall Return Period

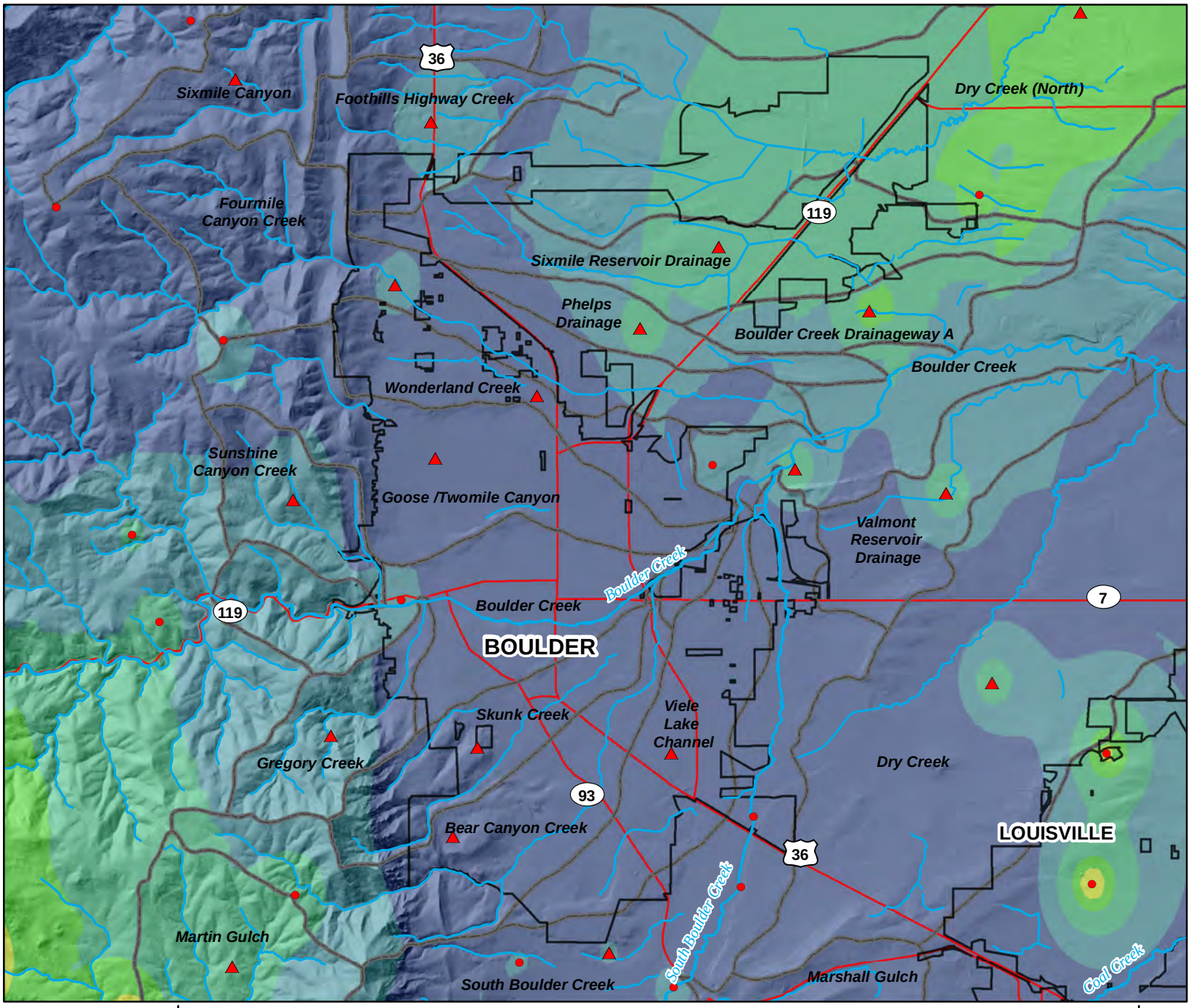
for City of Boulder & Vicinity

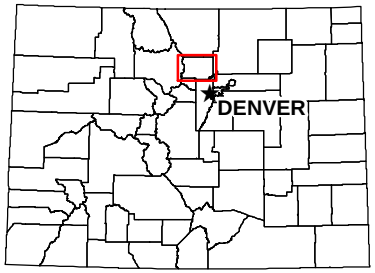
September 9-16, 2013 Flood Event

WRIGHT WATER ENGINEERS, INC.
2490 W 26TH AVE 100A
DENVER, CO. 80211
(303) 480-1700

Draft

Document Path: Z:\Project Files\14\141-024\141-024.000\CAD-GIS\GIS\Figure 2\FIGURE15_12HOUR_new5714.mxd





Legend

- ALERT Gage
- Radar-based Gage
- Watershed Boundary

Return Period (year)

- < 5
- > 5-10
- > 10-25
- > 25-50
- > 50-100
- > 100-200
- > 200-500
- > 500-1000
- > 1000

N W E S

0 0.5 1 2 Miles

FIGURE 16

Draft

24-hour Worst Case Rainfall Return Period

for City of Boulder & Vicinity

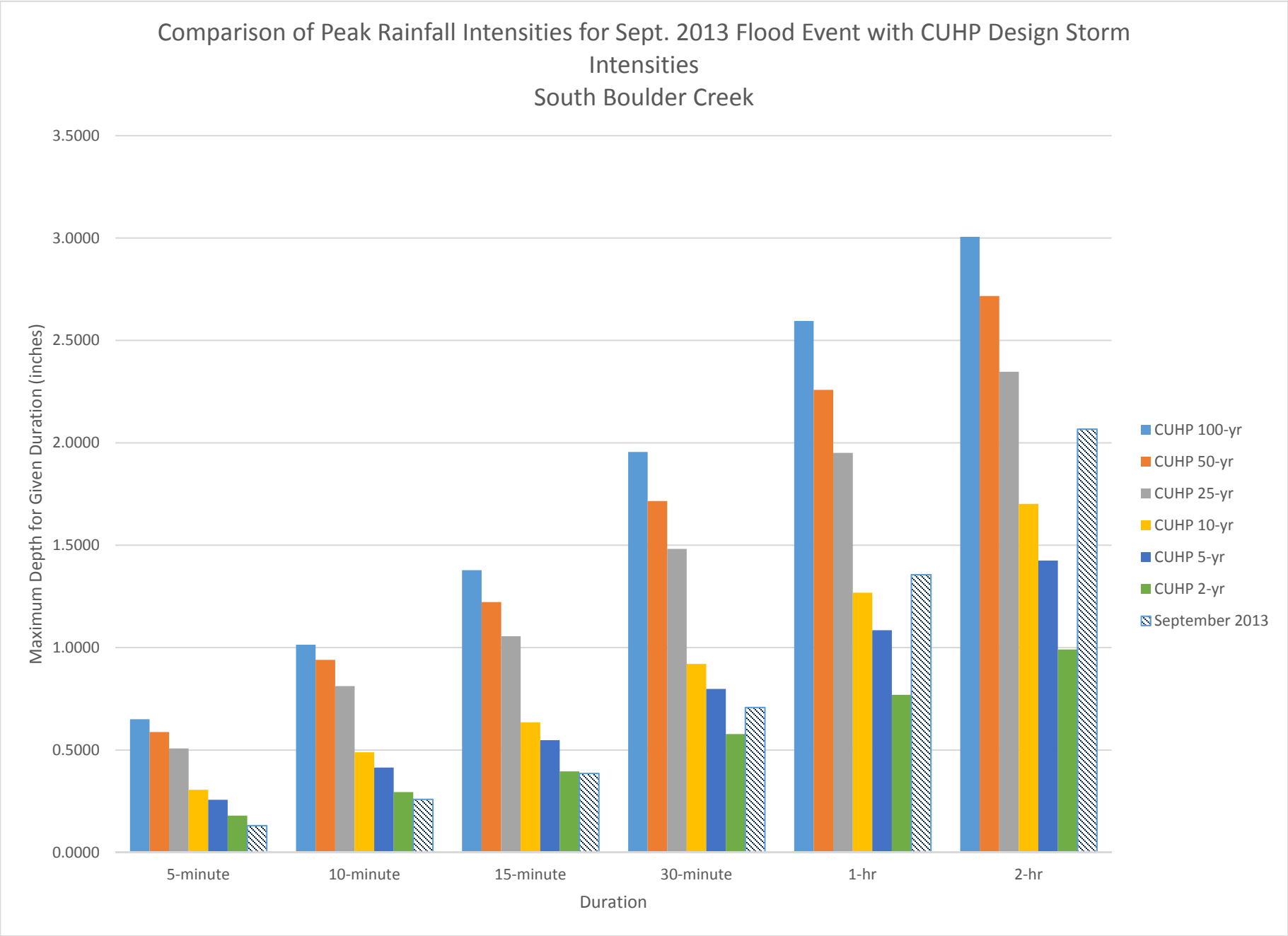
September 9-16, 2013 Flood Event

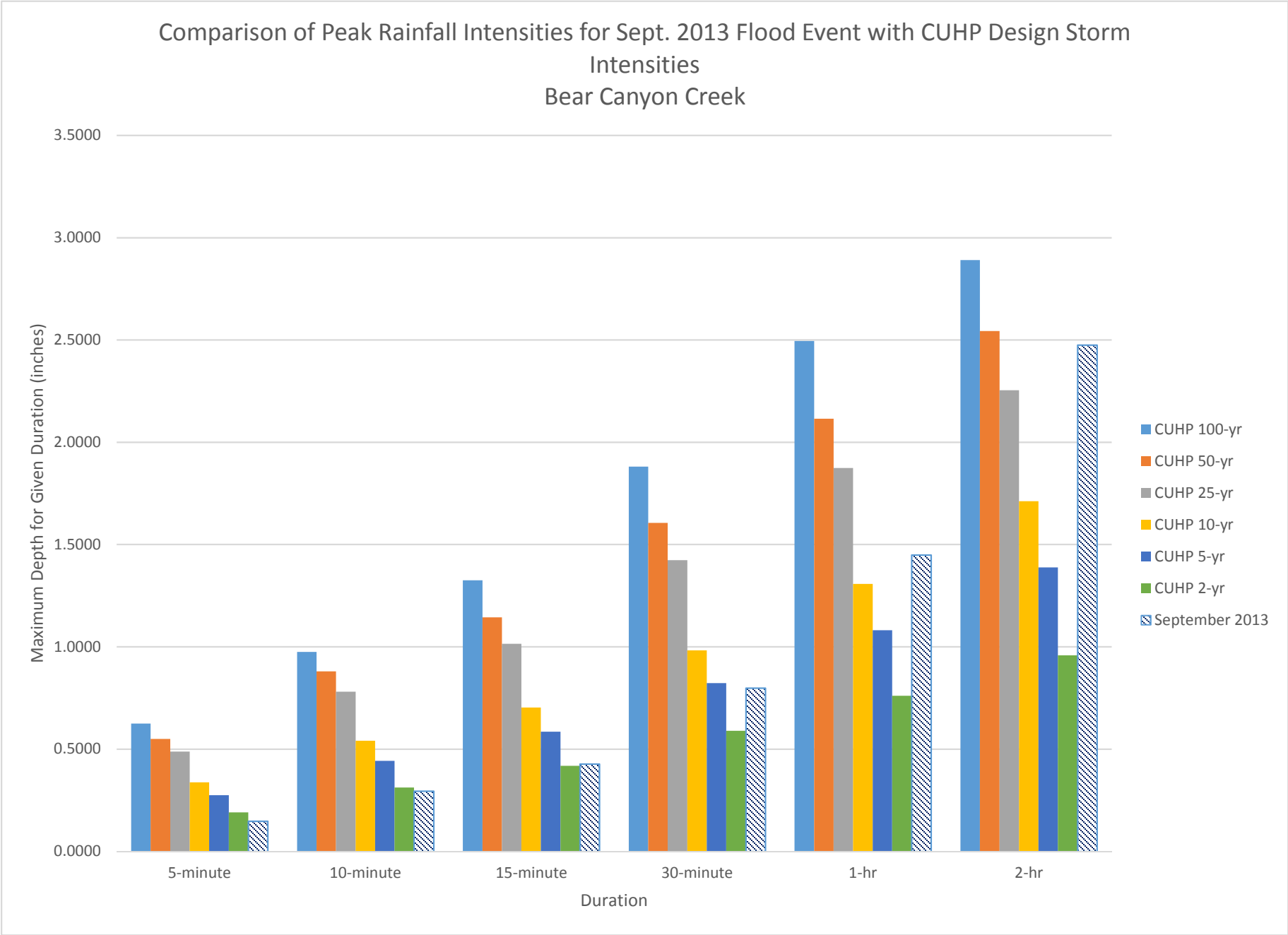
WRIGHT WATER ENGINEERS, INC.
2490 W 26TH AVE 100A
DENVER, CO. 80211
(303) 480-1700

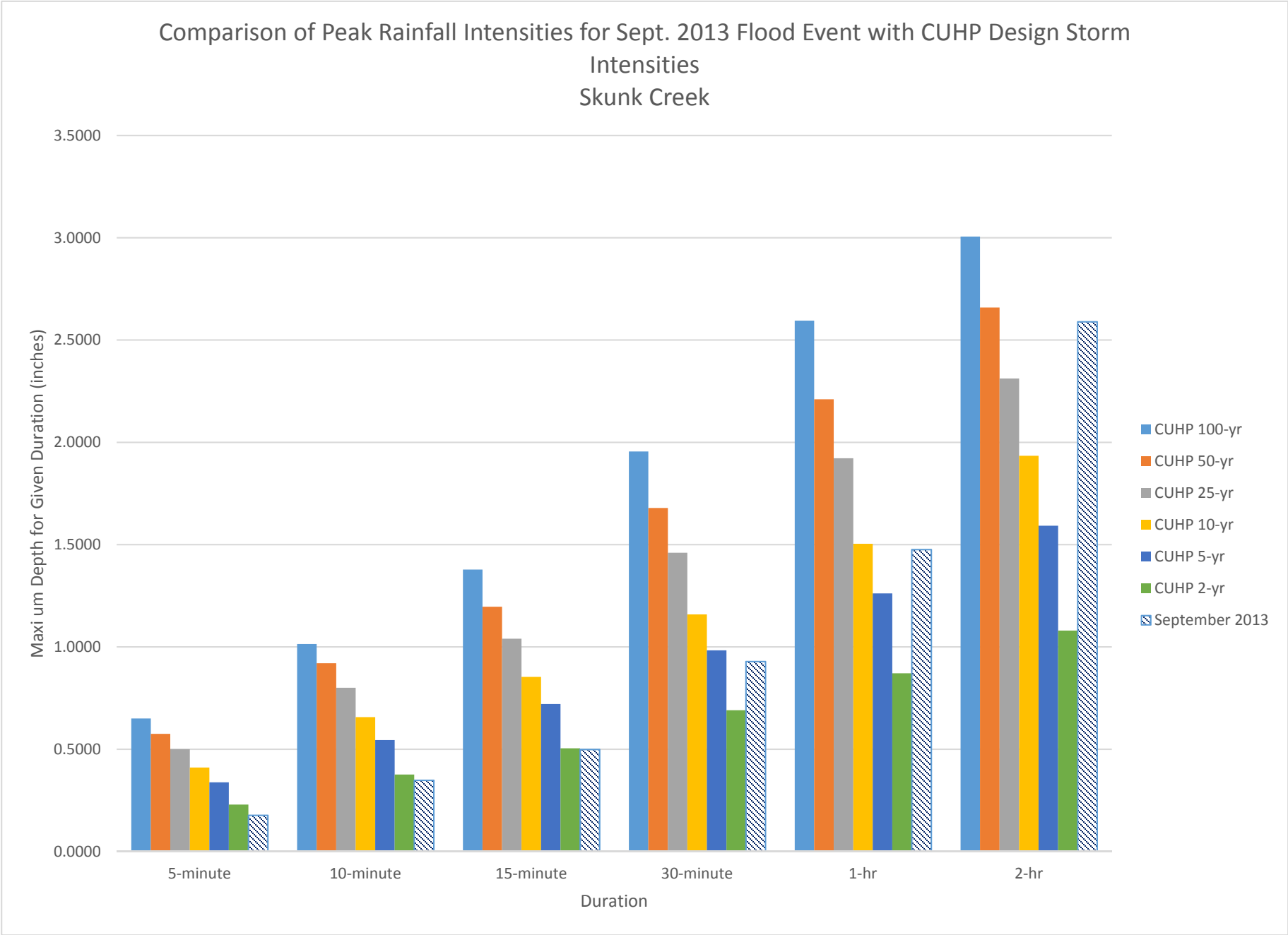
Draft

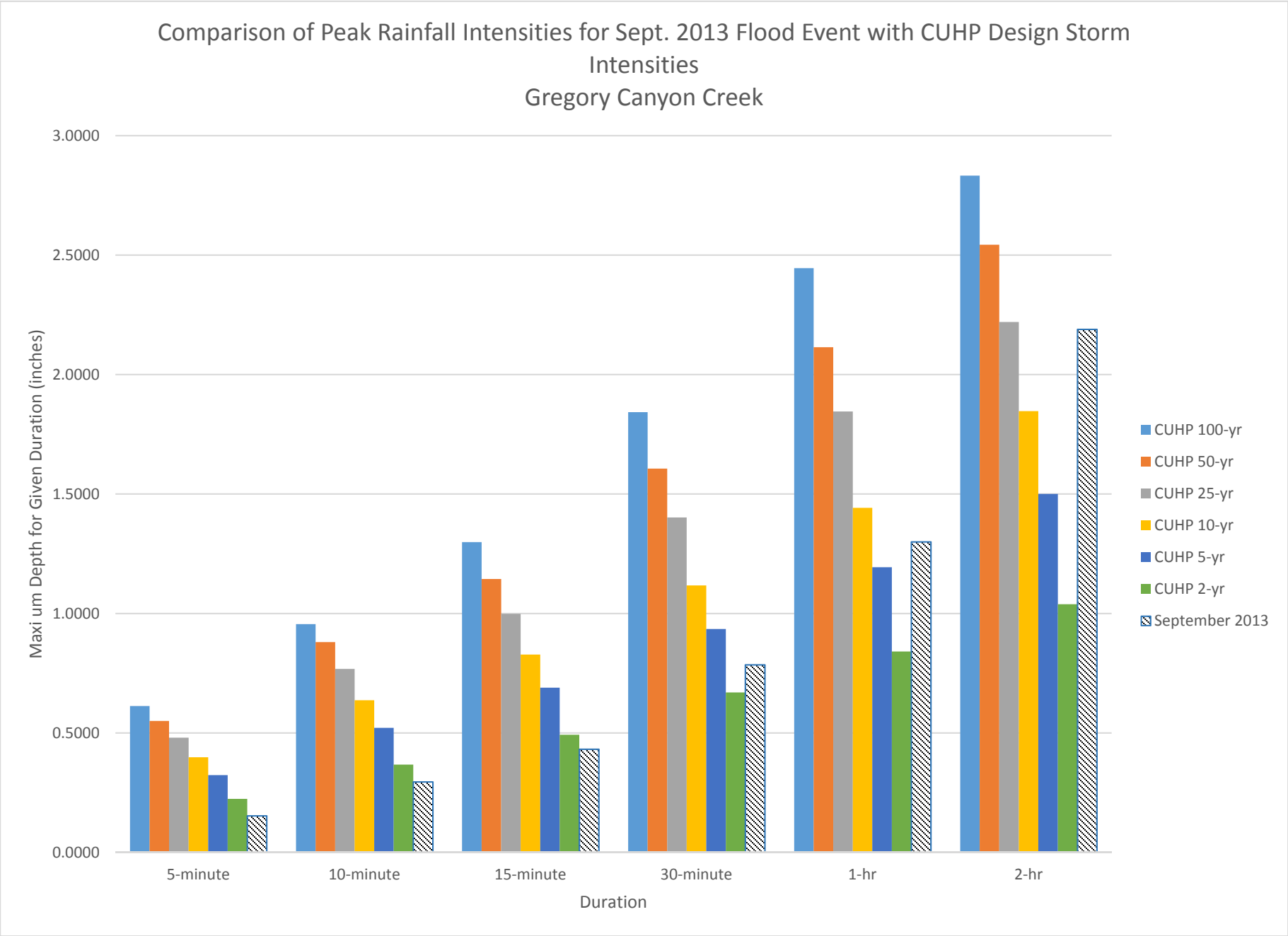
Document Path: Z:\Project Files\14\141-024\141-024.000\CAD-GIS\GIS\Series 2\FIGURE16_24HOUR_new5714.mxd

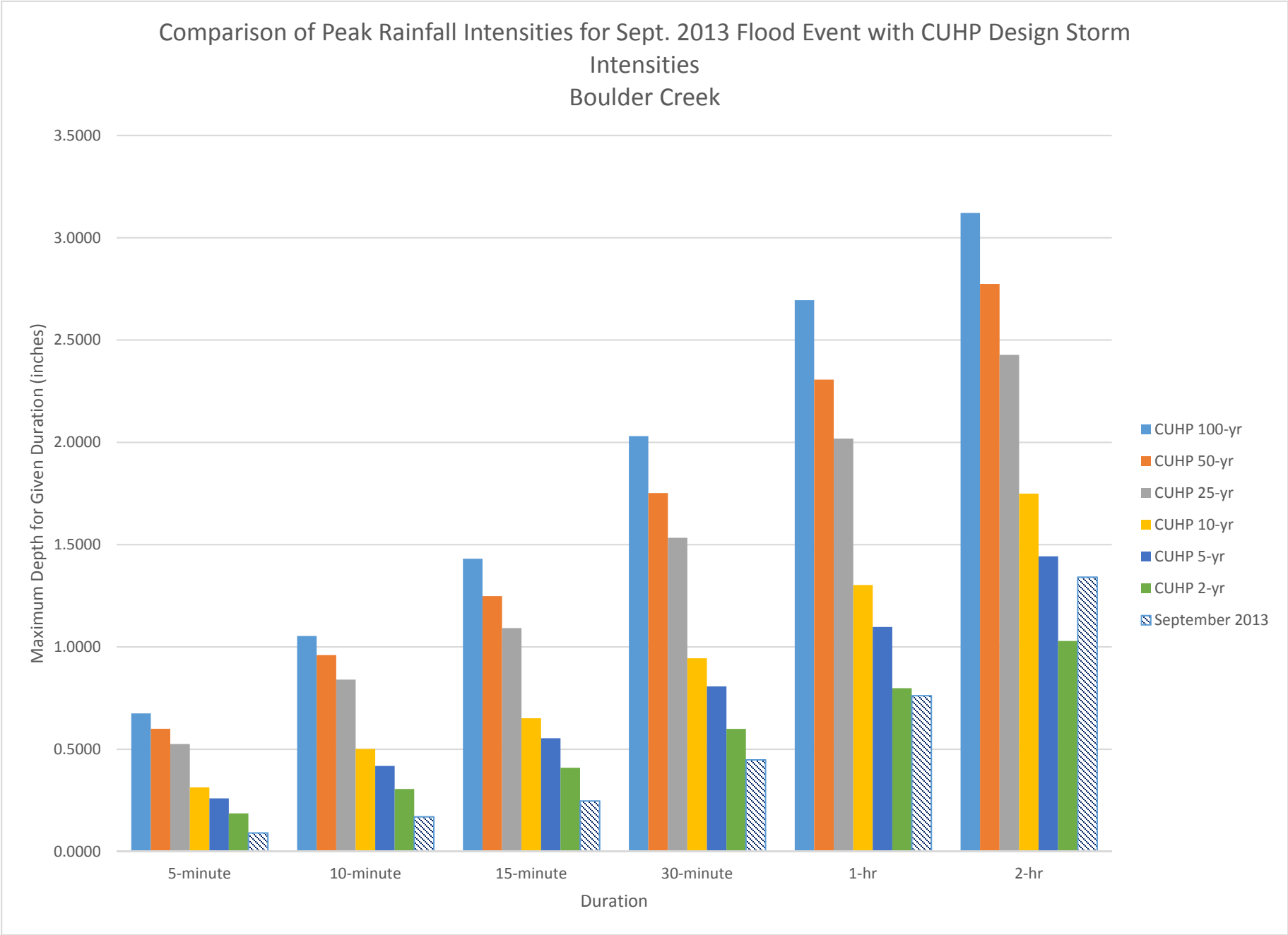
Appendix B

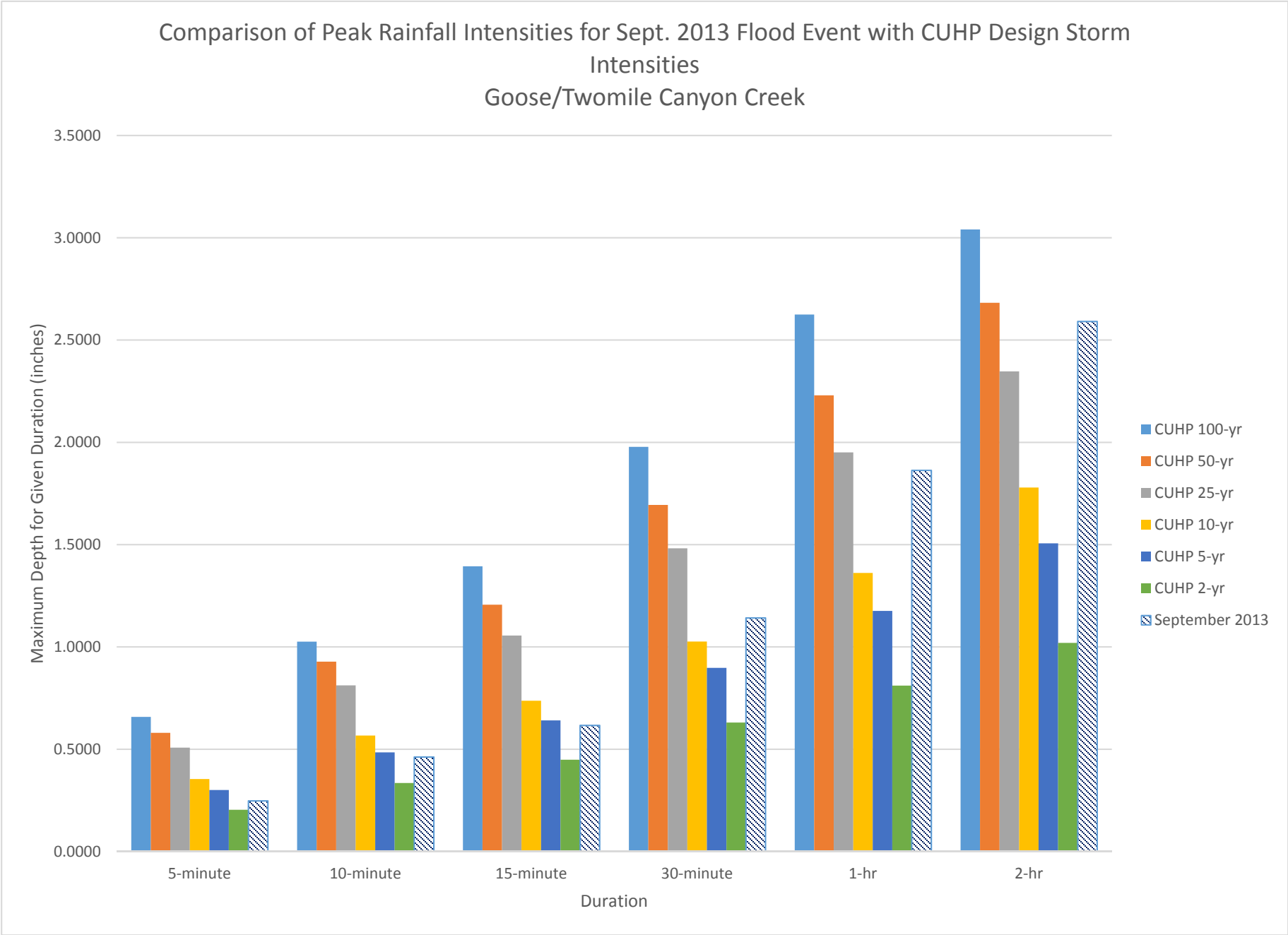

Comparison of Peak Rainfall Intensities for Sept. 2013 Flood Event with CUHP Design Storm Intensities
South Boulder Creek
Maximum Depth for Given Duration (inches)
3.5000
3.0000
2.5000
2.0000
1.5000
1.0000
0.5000
0.0000
5-minute
10-minute
15-minute
30-minute
1-hr
2-hr
Duration
CUHP 100-yr
CUHP 50-yr
CUHP 25-yr
CUHP 10-yr
CUHP 5-yr
CUHP 2-yr
September 2013

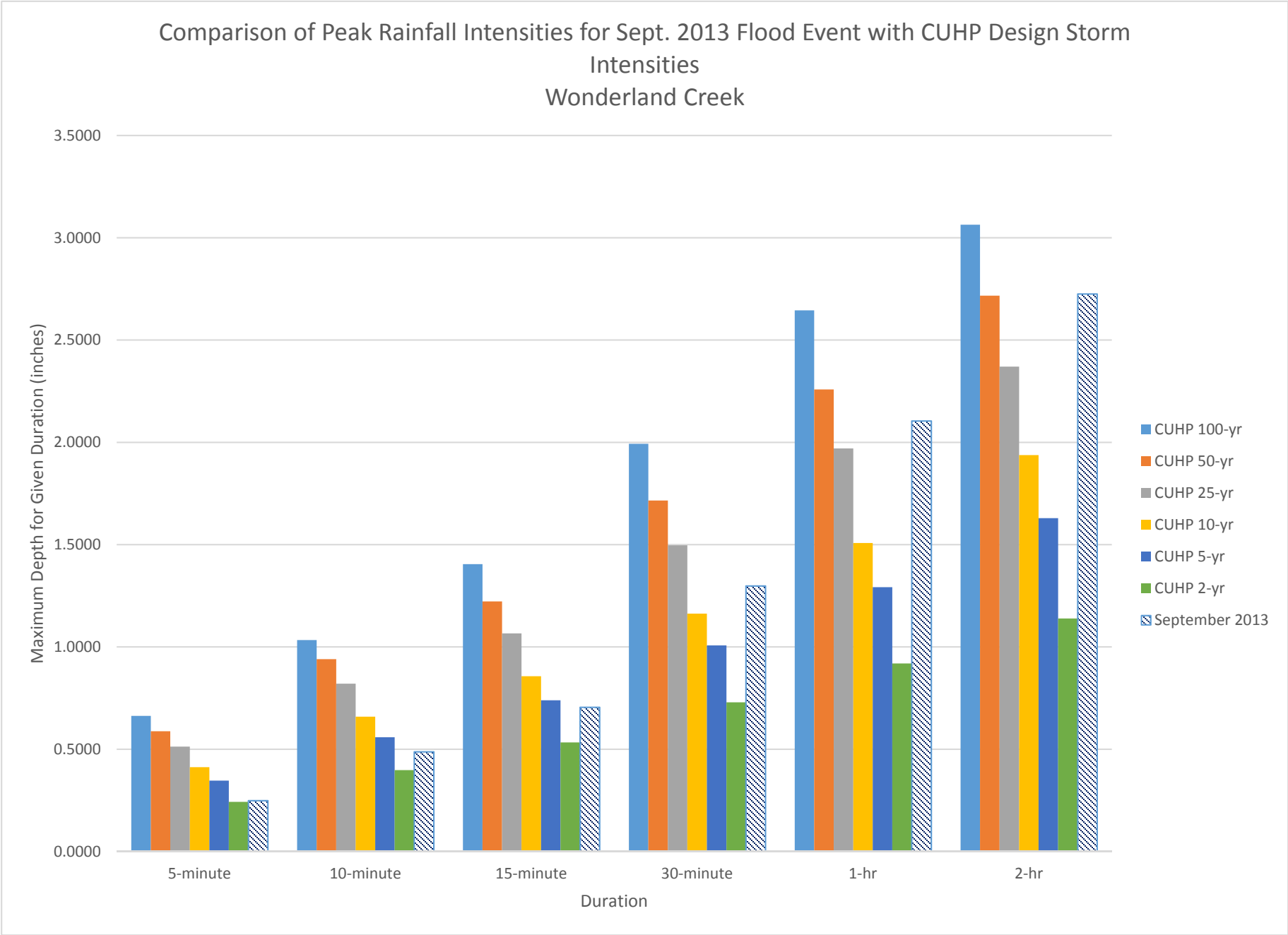

Comparison of Peak Rainfall Intensities for Sept. 2013 Flood Event with CUHP Design Storm Intensities
Bear Canyon Creek
Maximum Depth for Given Duration (inches)
3.5000
3.0000
2.5000
2.0000
1.5000
1.0000
0.5000
0.0000
5-minute
10-minute
15-minute
30-minute
1-hr
2-hr
Duration
CUHP 100-yr
CUHP 50-yr
CUHP 25-yr
CUHP 10-yr
CUHP 5-yr
CUHP 2-yr
September 2013

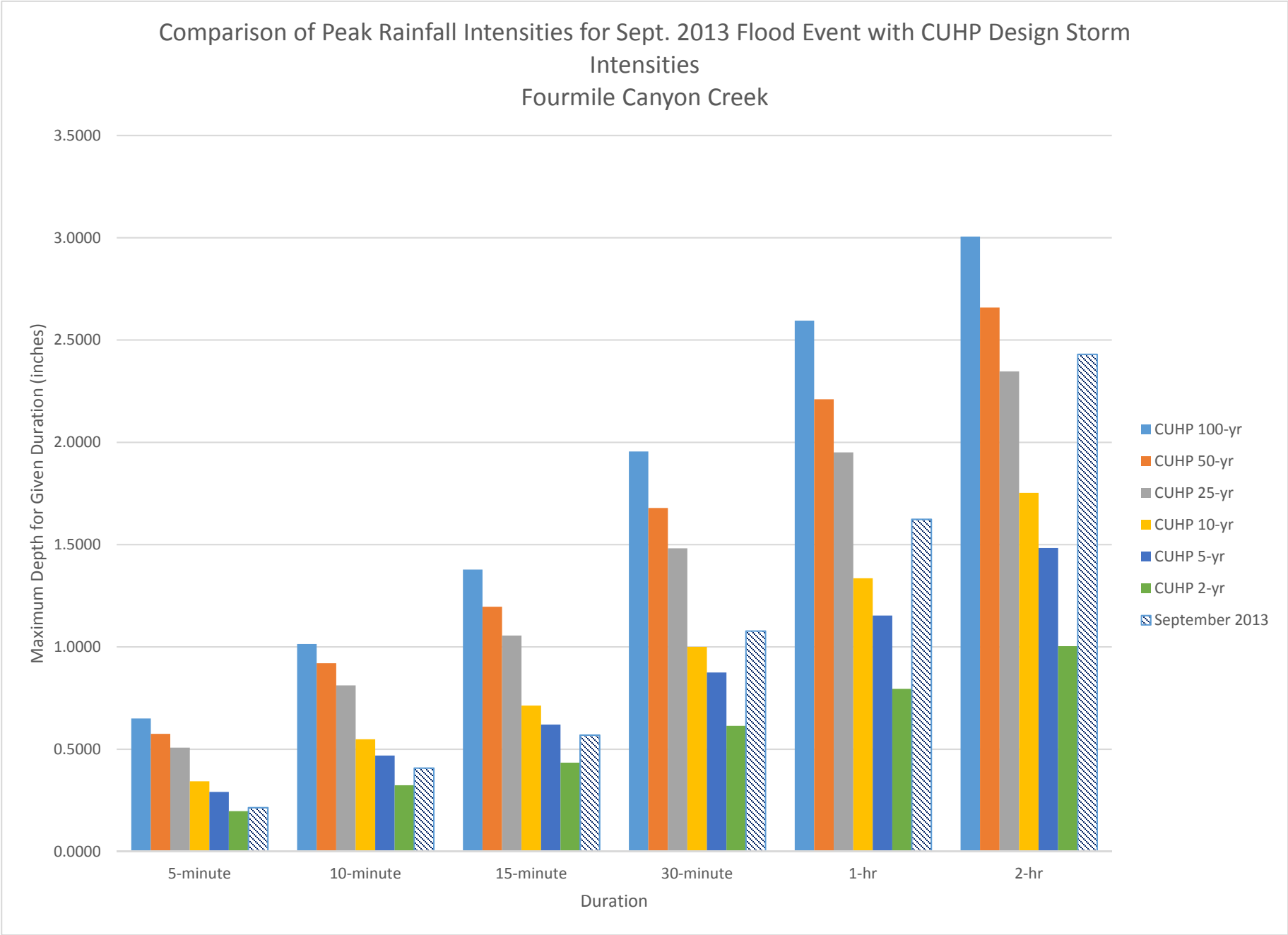

Comparison of Peak Rainfall Intensities for Sept. 2013 Flood Event with CUHP Design Storm Intensities
Skunk Creek
Maxi um Depth for Given Duration (inches)
3.5000
3.0000
2.5000
2.0000
1.5000
1.0000
0.5000
0.0000
5-minute
10-minute
15-minute
30-minute
1-hr
2-hr
Duration
CUHP 100-yr
CUHP 50-yr
CUHP 25-yr
CUHP 10-yr
CUHP 5-yr
CUHP 2-yr
September 2013


Comparison of Peak Rainfall Intensities for Sept. 2013 Flood Event with CUHP Design Storm Intensities
Gregory Canyon Creek
Maxi um Depth for Given Duration (inches)
3.0000
2.5000
2.0000
1.5000
1.0000
0.5000
0.0000
5-minute
10-minute
15-minute
30-minute
1-hr
2-hr
Duration
CUHP 100-yr
CUHP 50-yr
CUHP 25-yr
CUHP 10-yr
CUHP 5-yr
CUHP 2-yr
September 2013

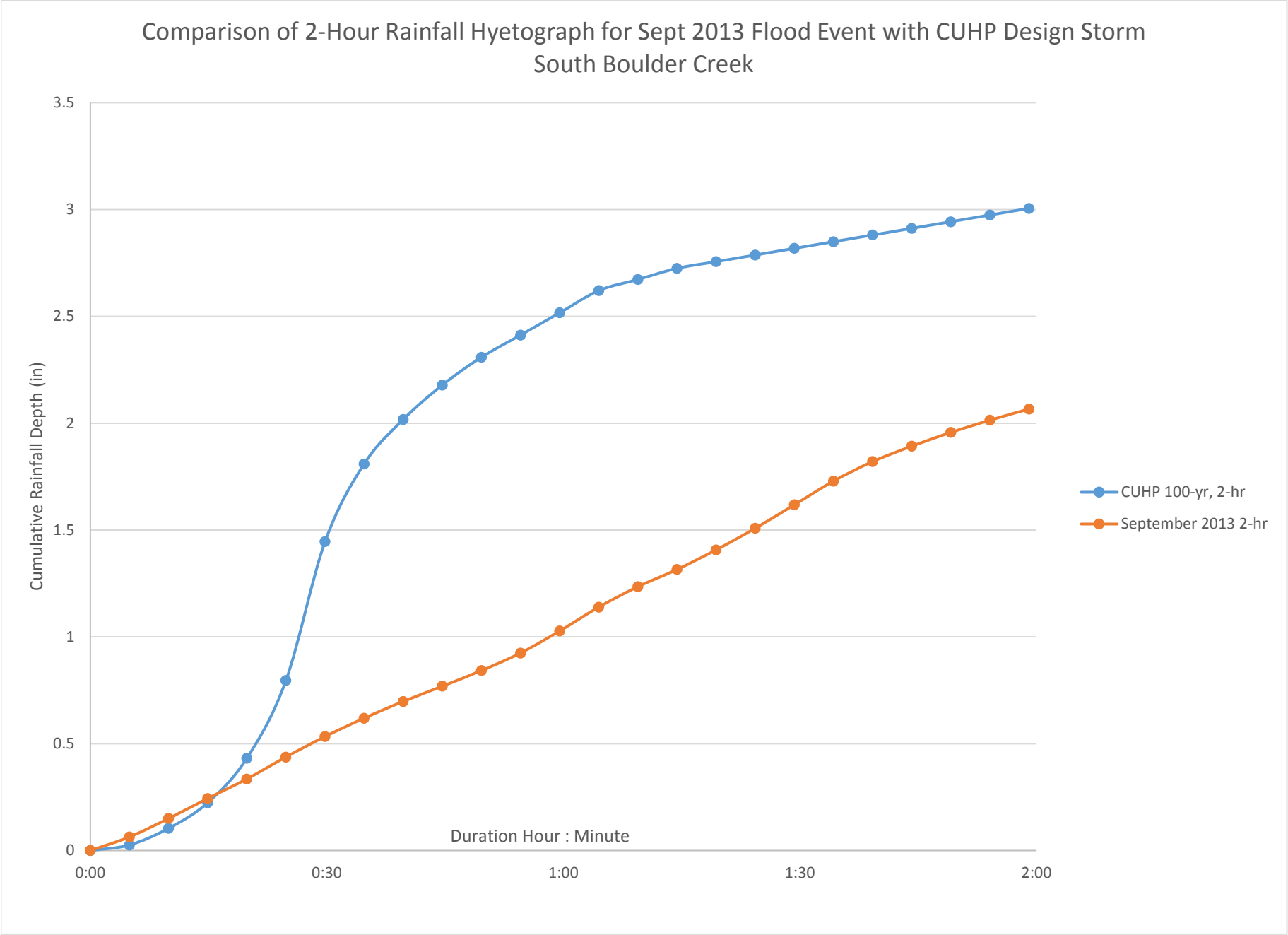

Comparison of Peak Rainfall Intensities for Sept. 2013 Flood Event with CUHP Design Storm Intensities
Boulder Creek
Maximum Depth for Given Duration (inches)
3.5000
3.0000
2.5000
2.0000
1.5000
1.0000
0.5000
0.0000
5-minute
10-minute
15-minute
30-minute
1-hr
2-hr
Duration
CUHP 100-yr
CUHP 50-yr
CUHP 25-yr
CUHP 10-yr
CUHP 5-yr
CUHP 2-yr
September 2013

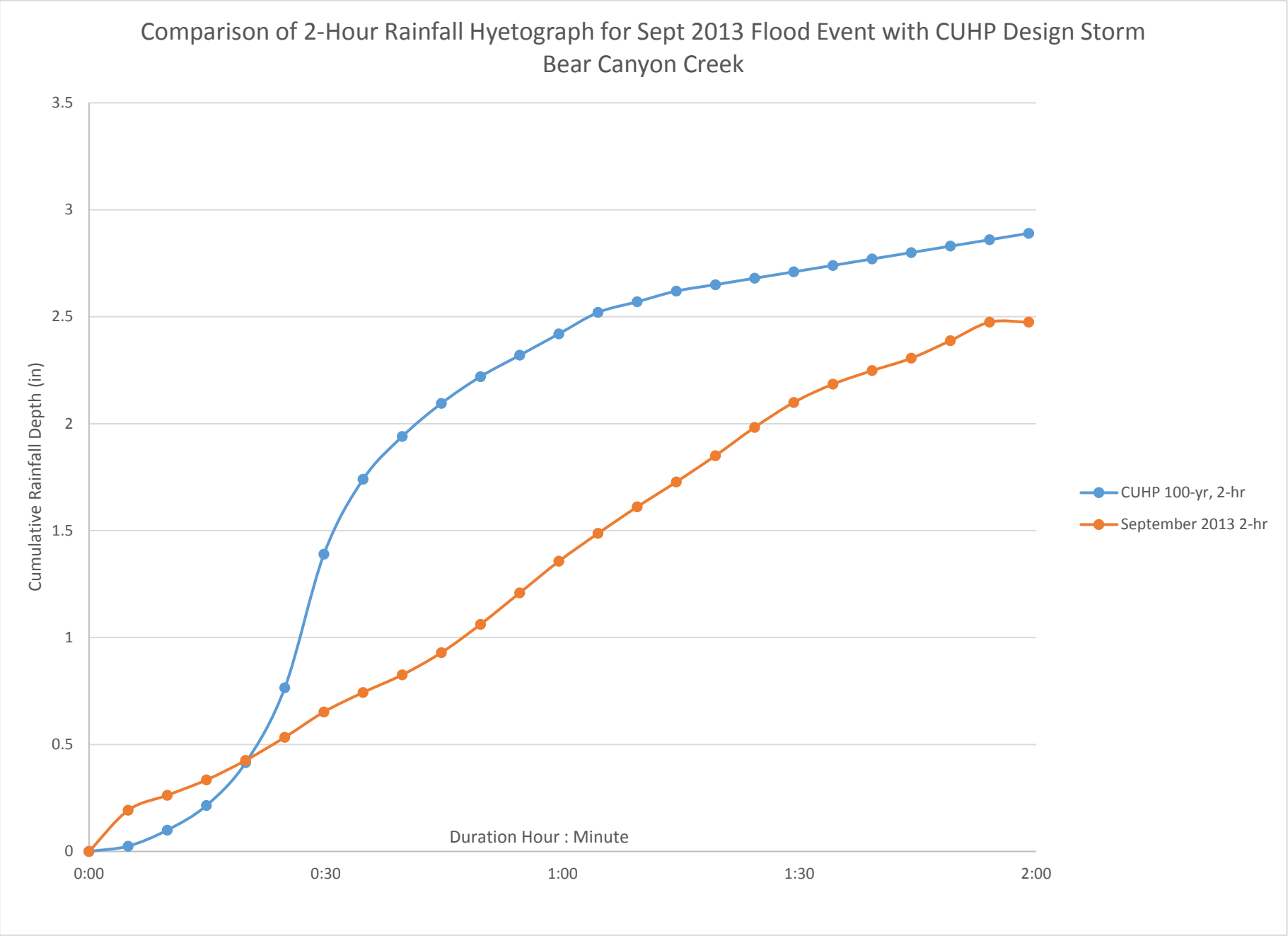

Comparison of Peak Rainfall Intensities for Sept. 2013 Flood Event with CUHP Design Storm Intensities
Goose/Twomile Canyon Creek
Maximum Depth for Given Duration (inches)
3.5000
3.0000
2.5000
2.0000
1.5000
1.0000
0.5000
0.0000
5-minute
10-minute
15-minute
30-minute
1-hr
2-hr
Duration
CUHP 100-yr
CUHP 50-yr
CUHP 25-yr
CUHP 10-yr
CUHP 5-yr
CUHP 2-yr
September 2013

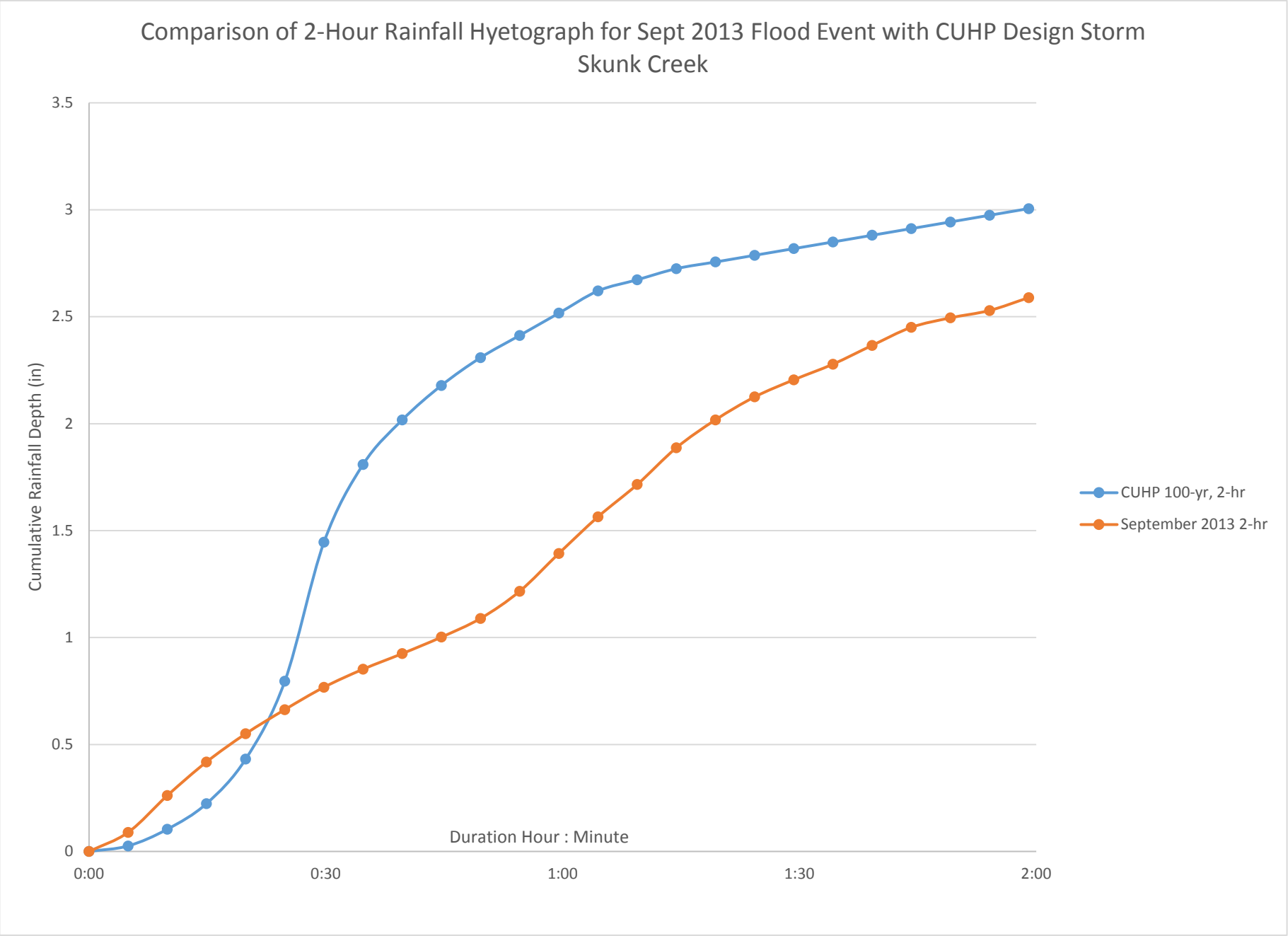

Comparison of Peak Rainfall Intensities for Sept. 2013 Flood Event with CUHP Design Storm Intensities
Wonderland Creek
Maximum Depth for Given Duration (inches)
3.5000
3.0000
2.5000
2.0000
1.5000
1.0000
0.5000
0.0000
5-minute
10-minute
15-minute
30-minute
1-hr
2-hr
Duration
CUHP 100-yr
CUHP 50-yr
CUHP 25-yr
CUHP 10-yr
CUHP 5-yr
CUHP 2-yr
September 2013

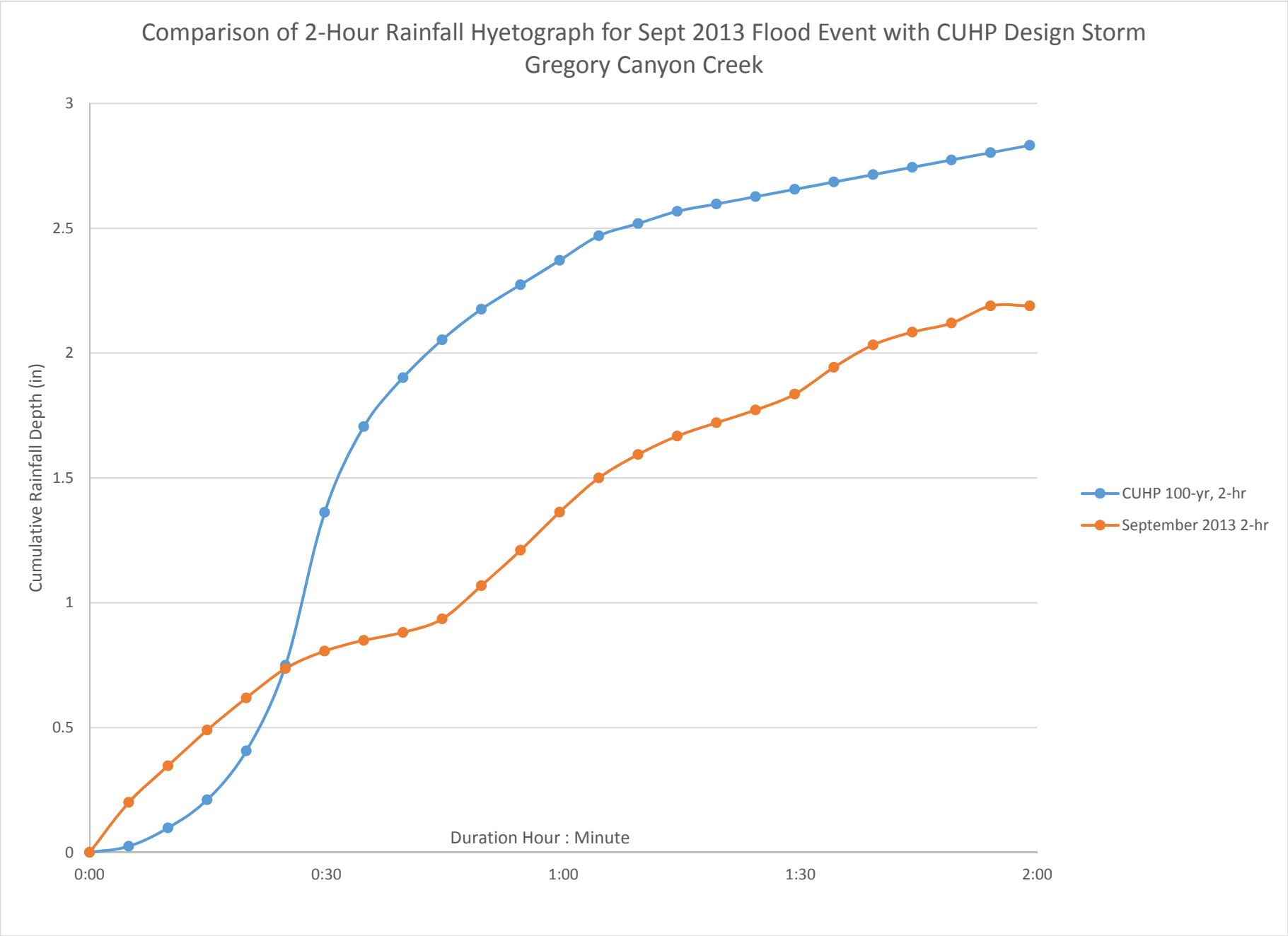

Comparison of Peak Rainfall Intensities for Sept. 2013 Flood Event with CUHP Design Storm Intensities
Fourmile Canyon Creek
Maximum Depth for Given Duration (inches)
3.5000
3.0000
2.5000
2.0000
1.5000
1.0000
0.5000
0.0000
5-minute
10-minute
15-minute
30-minute
1-hr
2-hr
Duration
CUHP 100-yr
CUHP 50-yr
CUHP 25-yr
CUHP 10-yr
CUHP 5-yr
CUHP 2-yr
September 2013

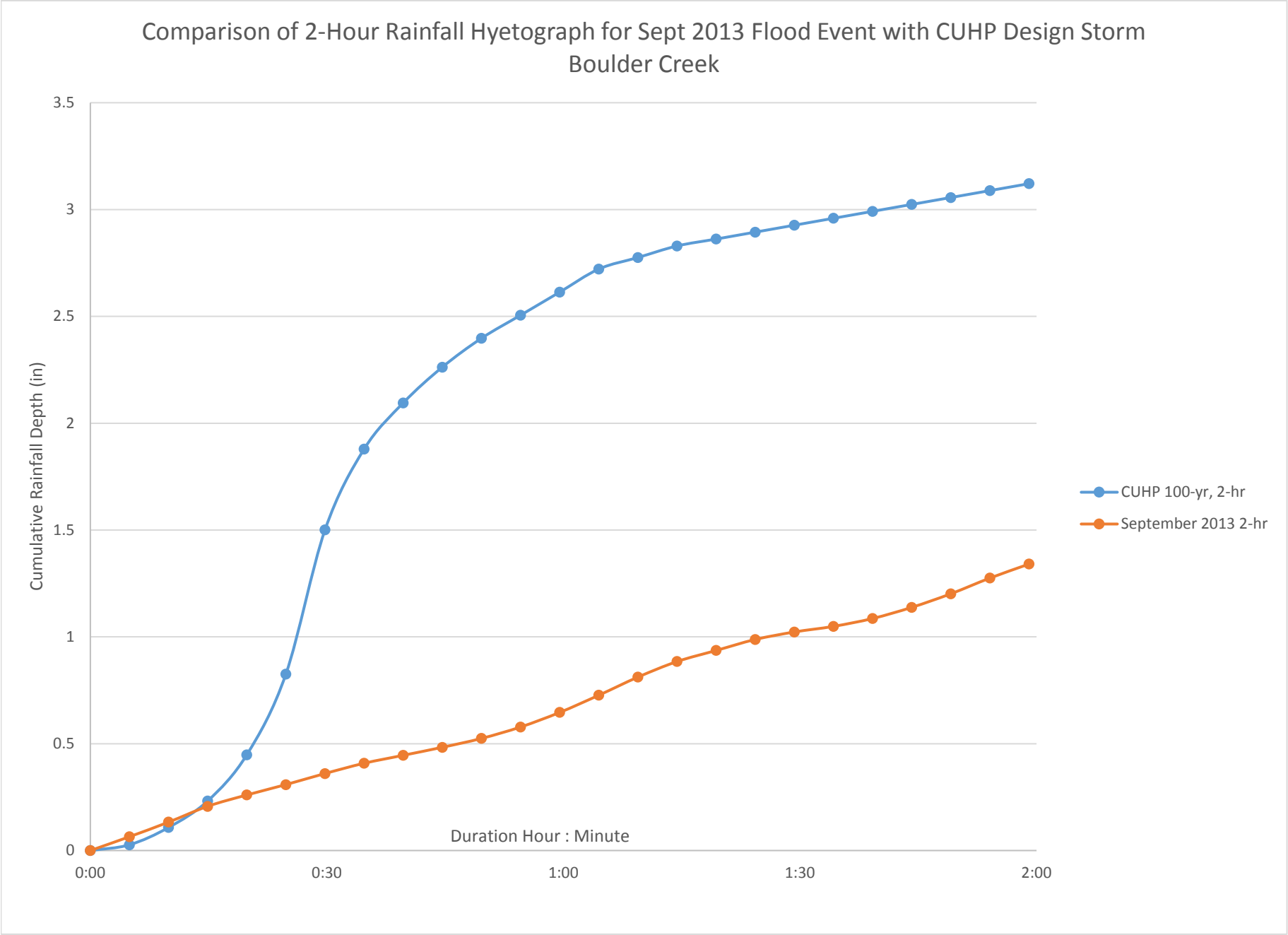
Appendix C

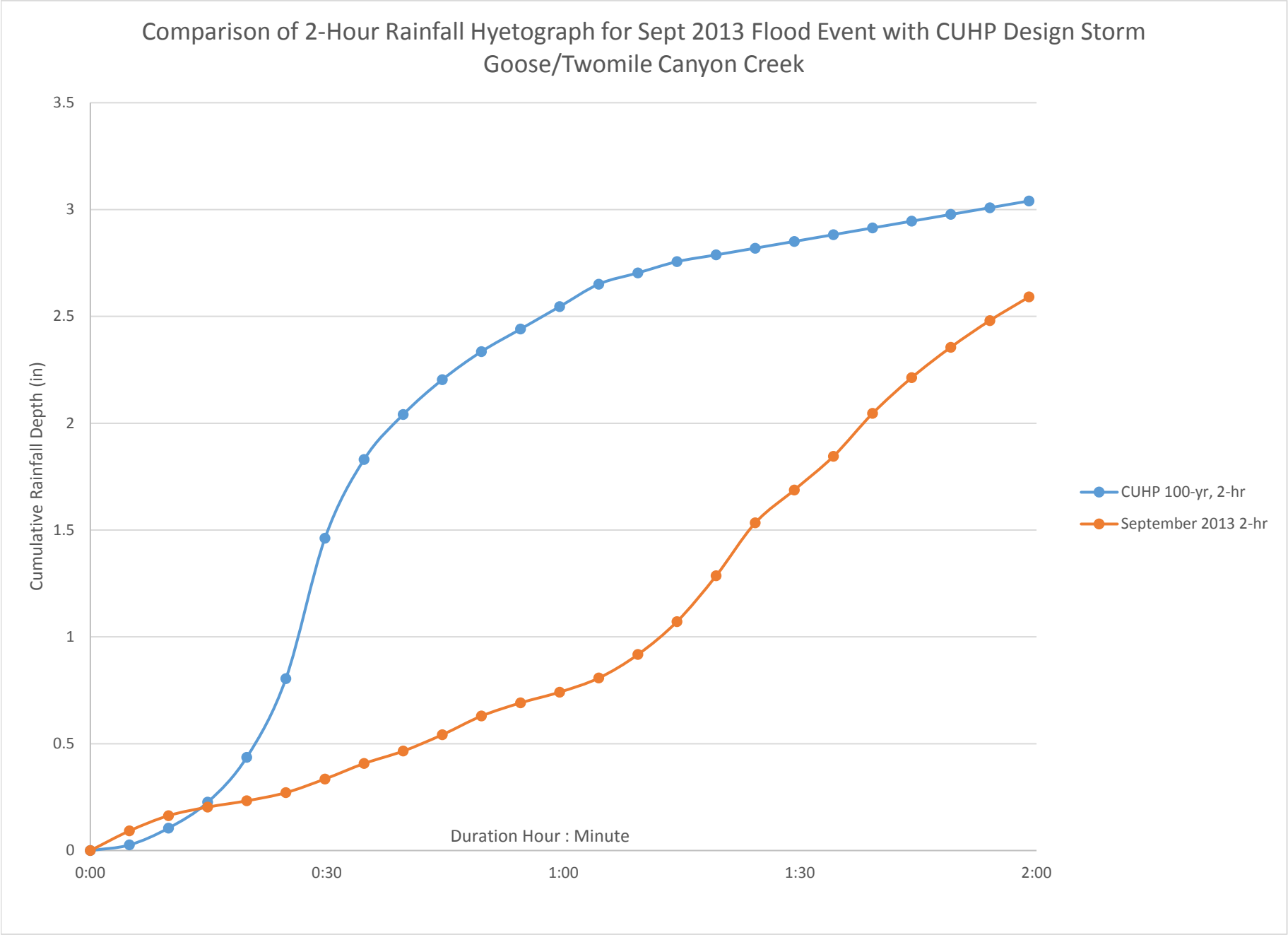

Comparison of 2-Hour Rainfall Hyetograph for Sept 2013 Flood Event with CUHP Design Storm
South Boulder Creek
Cumulative Rainfall Depth (in)
3.5
3
2.5
2
1.5
1
0.5
0
Duration Hour : Minute
0:00
0:30
1:00
1:30
2:00
CUHP 100-yr, 2-hr
September 2013 2-hr

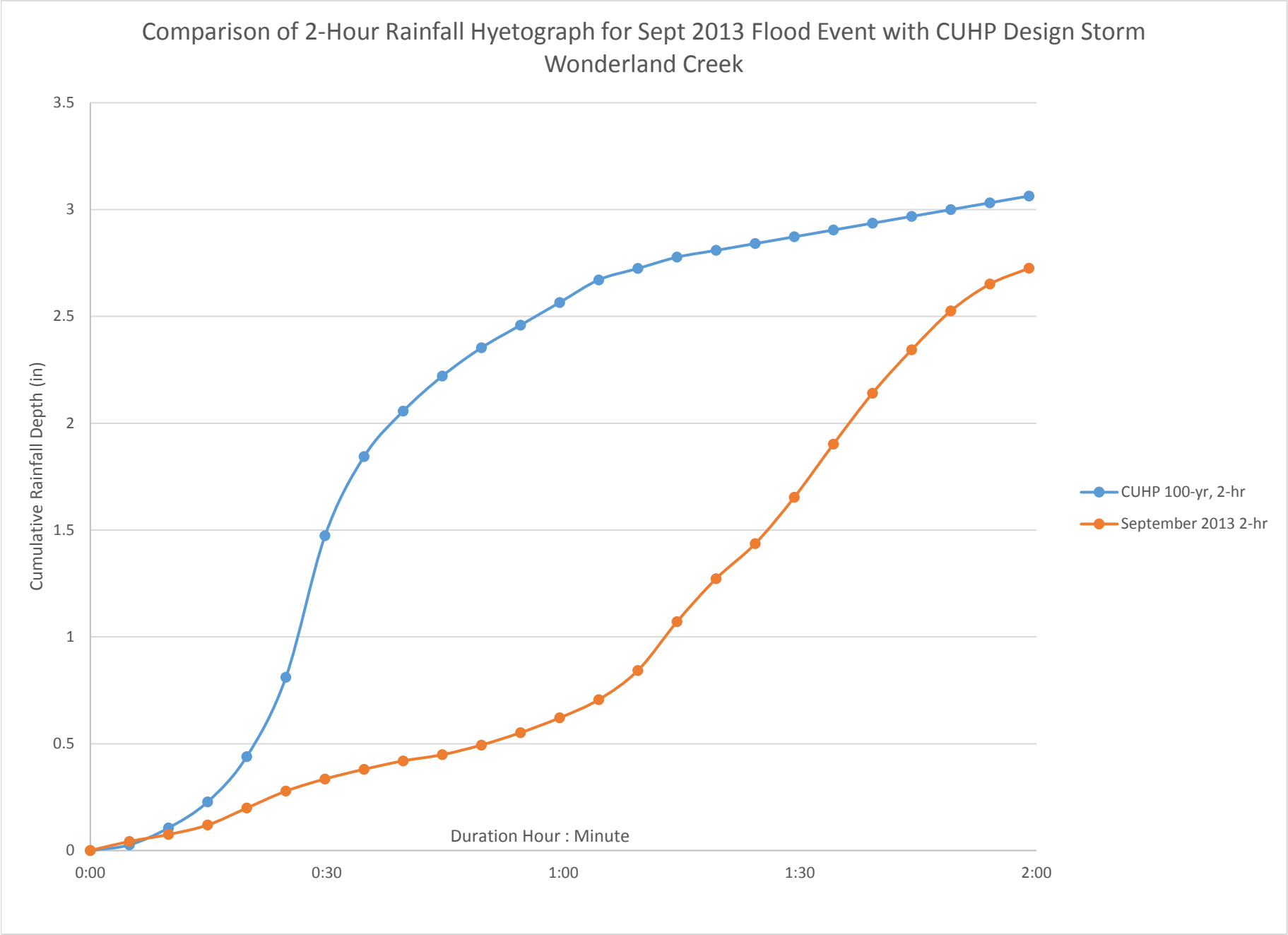

Comparison of 2-Hour Rainfall Hyetograph for Sept 2013 Flood Event with CUHP Design Storm
Bear Canyon Creek
Cumulative Rainfall Depth (in)
3.5
3
2.5
2
1.5
1
0.5
0
Duration Hour : Minute
0:00
0:30
1:00
1:30
2:00
CUHP 100-yr, 2-hr
September 2013 2-hr

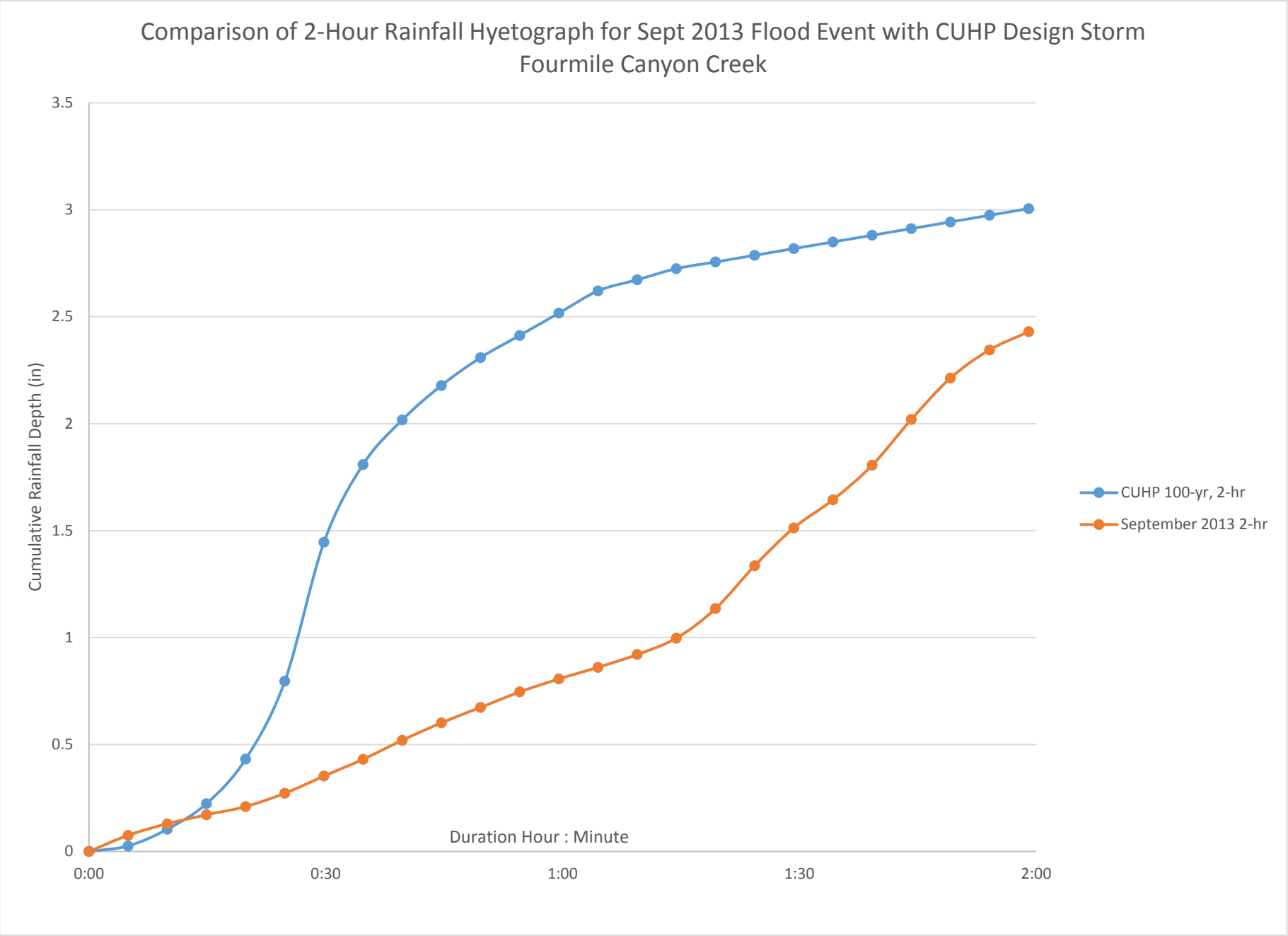

Comparison of 2-Hour Rainfall Hyetograph for Sept 2013 Flood Event with CUHP Design Storm
Skunk Creek
Cumulative Rainfall Depth (in)
3.5
3
2.5
2
1.5
1
0.5
0
Duration Hour : Minute
0:00
0:30
1:00
1:30
2:00
CUHP 100-yr, 2-hr
September 2013 2-hr


Comparison of 2-Hour Rainfall Hyetograph for Sept 2013 Flood Event with CUHP Design Storm
Gregory Canyon Creek
Cumulative Rainfall Depth (in)
3
2.5
2
1.5
1
0.5
0
Duration Hour : Minute
0:00
0:30
1:00
1:30
2:00
CUHP 100-yr, 2-hr
September 2013 2-hr


Comparison of 2-Hour Rainfall Hyetograph for Sept 2013 Flood Event with CUHP Design Storm
Boulder Creek
Cumulative Rainfall Depth (in)
3.5
3
2.5
2
1.5
1
0.5
0
Duration Hour : Minute
0:00
0:30
1:00
1:30
2:00
CUHP 100-yr, 2-hr
September 2013 2-hr


Comparison of 2-Hour Rainfall Hyetograph for Sept 2013 Flood Event with CUHP Design Storm
Goose/Twomile Canyon Creek
Cumulative Rainfall Depth (in)
3.5
3
2.5
2
1.5
1
0.5
0
Duration Hour : Minute
0:00
0:30
1:00
1:30
2:00
CUHP 100-yr, 2-hr
September 2013 2-hr


Comparison of 2-Hour Rainfall Hyetograph for Sept 2013 Flood Event with CUHP Design Storm
Wonderland Creek
Cumulative Rainfall Depth (in)
3.5
3
2.5
2
1.5
1
0.5
0
Duration Hour : Minute
0:00
0:30
1:00
1:30
2:00
CUHP 100-yr, 2-hr
September 2013 2-hr


Comparison of 2-Hour Rainfall Hyetograph for Sept 2013 Flood Event with CUHP Design Storm
Fourmile Canyon Creek
Cumulative Rainfall Depth (in)
3.5
3
2.5
2
1.5
1
0.5
0
Duration Hour : Minute
0:00
0:30
1:00
1:30
2:00
CUHP 100-yr, 2-hr
September 2013 2-hr