Rainfall-Runoff Analysis for September 2013 Flood in the City of Boulder, Colorado

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WWE

Wright Water Engineers, Inc.

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1.0 Executive Summary

On September 8, 2013, an unusual weather pattern began to set in along the Colorado Front Range, leading to a massive multi-day rainfall event. Rainfall totals were staggering and in many locations, the rainfall amounts for this one-week event were about the same as the average total annual precipitation amounts. For durations in excess of 24-hours, many areas in and around the City of Boulder (City) experienced 1,000-year rainfall. The City was one of the hardest hit areas within Colorado with total precipitation amounts from September 8 – 16, 2013 of over 16 inches. Figure ES-1 shows the precipitation along the Front Range from September 8 – 16, 2013.

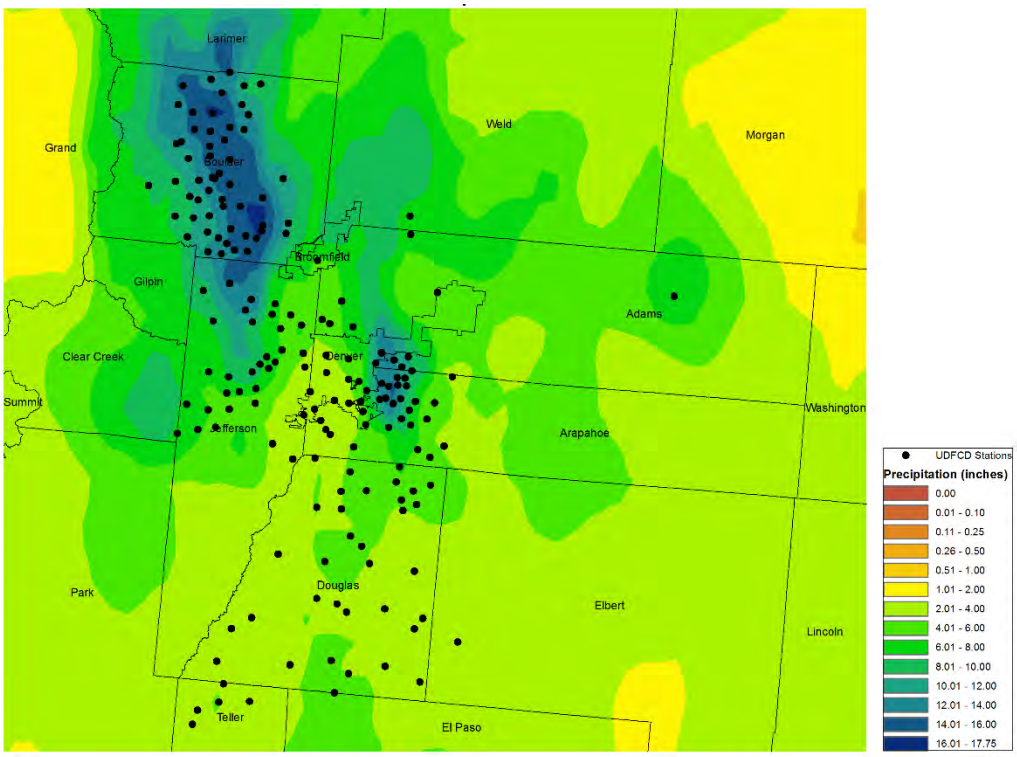

Figure ES-1 – Precipitation along Front Range September 8 – 16, 2013 (Colorado Climate Center)

Wright Water Engineers, Inc. (WWE) worked with the City and the Urban Drainage and Flood Control District to characterize this rain event with worst case rainfall return periods. The "worst case" analysis evaluated maximum rainfall totals over a range of durations to determine return periods associated with the most intense periods of the rainfall event. WWE also compared the design storms, which are utilized by Colorado Urban Hydrograph Procedure and other hydrologic models in Colorado) to rainfall intensities observed during the September 2013 event.

This rainfall event brought extensive flooding within the City as steep mountain canyons emptied runoff, rocks and debris into major drainageways across the City for days. These major drainageways are shown on Figure ES-2.

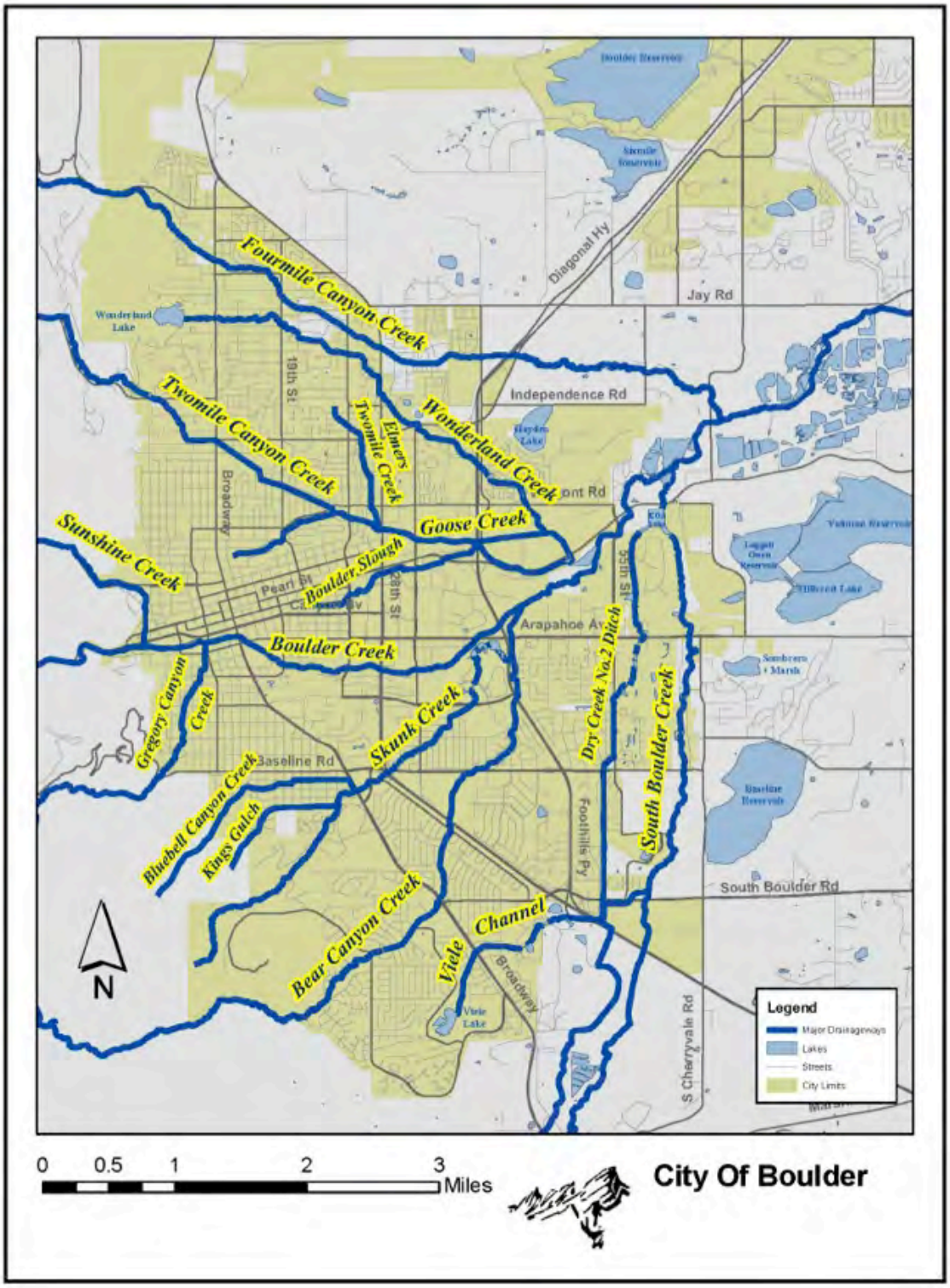

Figure ES-2 – Major Drainageways in the City of Boulder

Rainfall—Runoff Analysis for September 2013 Flood in the City of Boulder, Colorado

WWE analyzed peak flow estimates based on post-event measurements of high water marks and the plan-view of the September 2013 flood inundation mapping prepared by the City to determine approximate runoff return periods associated with the rainfall. In several cases, most notably Gregory Canyon, Bluebell Canyon and Bear Canyon Creeks, debris blockage of culverts led to inundation of areas that were consistent with 100-year or even 500-year recurrence interval floodplain mapping although actual flow rates were likely less than those associated with such events.

This analysis indicates that for many creeks in Boulder, the predicted and/or observed runoff response from the event was below adopted regulatory 100-year peak flow rates. Exceptions to this general trend, where flows approached 100-year levels or greater, include the lower portion of South Boulder Creek, the West Valley Overflow, Upper Twomile Canyon Creek and the lower portion of Fourmile Canyon Creek. Most of the creeks in the City experienced peak flows with return periods of 25-years or greater, and given the duration of the event and large volume of runoff, significant sediment transport, instream erosion and deposition occurred.

A remarkable characteristic of the September 2013 flood was the massive volume of runoff caused by rainfall far in excess of 100-year levels when evaluated over 24-hour and longer periods. While peak flows in many locations were lower than expected for a 100-year flood, the volume and duration of runoff was far greater than anticipated in any of the design storms applied to watersheds in Boulder. The runoff volume saturated soils leading to landslides and debris flows in many watersheds, and the amount of sediment transport that occurred during the flood, tied to the large runoff volume, significantly impacted many creeks in and around Boulder.

This analysis helps to explain why a "1,000-year" storm, as was recorded for durations in excess of 24-hours, did not produce a "1,000-year flood." Table ES-1 summarizes rainfall and runoff analysis for each of the watersheds evaluated.

Table ES-1. Summary of Rainfall and Runoff Return Period Estimates for Boulder Watersheds

Watershed	Subbasin	Estimated Rainfall Frequency (Years) for Given Duration--NOAA Atlas 14 Comparison						Estimated Runoff Frequency--Comparison with Master Plan Flood-Frequency				Comments
		5-min[1]	30-min[1]	1-hr[1]	2-hr	3-hr	6-hr	Location	Peak Flow (cfs)	Q100 (cfs)	Estimated Runoff Frequency (Year)	
South Boulder Creek (SBC)	Upper Watershed/ Indian Peaks	1	5	15	>100	>100	>100	SBC @ Rollinsville	400	----	< 5	Upper watershed peak rainfall occurred late in overall storm and did not significantly affect peak flow rates in lower subbasins that were driven by heavy rainfall below Gross and a railroad embankment failure in Bull Gulch/Doudy Draw.
	Upper-Mid near Peak to Peak Hwy	<1	1	10	25	30	50	SBC near Pinecliff	< 800	----	< 5	Peak flow was less than 2013 peak snowmelt.
	Middle-Gross Reservoir	<1	1	5	20	30	50	Gross Reservoir	Reservoir spillway released flow during event and for days after			Gross Reservoir stored a significant amount of runoff from the upper& middle watershed during the flood, and water was diverted south to Ralston Reservoir by Denver Water. Diversion and storage, along with desynchronized rainfall peaks and lesser totals to the west, muted the effects runoff from the watershed above on the creek below the reservoir.
	Eldorado Springs	1	2	5	20	40	~100	SBC @ Eldorado Springs	2,000	2,230 (GS) 4,250 (TS)	50 - 100 (GS) 10 -25 (TS)	GS = General Storm (longer, less intense). TS = Thunderstorm (more intense, shorter duration).
	Doudy Draw	1	20	90	400	>300	>300	Doudy Draw	2,000	----	>100 (GS & TS)	Very intense rainfall for 1-hour+ durations coupled with railroad embankment failure in Bull Gulch (tributary to Doudy Draw) that sent wave of water, sediment, rocks and debris down Doudy Draw nearly doubled the peak flow in South Boulder Creek downstream.
	South Boulder	1	2	5	20	40	100	Hwy 93/San Souci	5,600	3,490 (GS) 7,120 (TS)	>500 yr (GS) 50 -100 (TS)	Heavily influenced by 2000 cfs surge from Doudy Draw. GS = General Storm (longer, less intense). TS = Thunderstorm (more intense, shorter duration).
		1	2	5	20	40	100	SBC Main Channel @ South Boulder Road	3,600	4,120 (GS) 8,770 (TS)	50 - 100 (GS) 25 -50 (TS)	GS = General Storm (longer, less intense). TS = Thunderstorm (more intense, shorter duration).
		1	2	5	20	40	100	West Valley Overflow	1,250	1,230 (GS & TS)	>100 (GS & TS)	No direct flow measurement available. Estimate based on street flow observations on Thunderbird Drive and difference between main channel flows at Hwy 93 and Baseline Road.

Bear Canyon Creek (BCC)	Upper Watershed, West of NCAR	1	< 5	15	50	50-100	>200	No flow estimates available. Floodplain mapping does not extend to upper reaches of watershed.				Upper watershed generated significant rock, sediment and debris that was deposited along Table Mesa Drive in channel and in eastbound lane.
	NCAR to Highway 93	1	10	25	70	100	>300	BCC @ Table Mesa & Broadway	1,400	1,930	~50	Flow across intersection. Split flow to north along Broadway. Inundation mapping similar to 100-year boundaries along Table Mesa and in many other areas (freeboard remaining in many streets) with some additional street flooding outside of mapped floodplains. Flow reported based on estimates from Dr. Jarrett and Belt Collins West, Ltd.
	East of Highway 93	5	25	75	80	>1000	>1000	BCC @ Baseline	1,330	2,930	~25	Differences in rainfall versus runoff frequency due to more even distribution of rainfall over critical durations of the actual storm in September versus "front loaded" design storm assumptions with much higher short-duration rainfall intensities than experienced in September 2013.
Skunk Creek	Bluebell Creek	<1	5	15	33	~100	>400	No flow measurements/estimates available for this watershed.			~ 25	Significant debris flow from upper watershed areas contributed rocks, sediment and debris. Debris dam/breach effects caused localized flooding more severe than suggested by return periods.
	Kings Gulch	<1	3	5	15	~25	60				~ 10	Significant debris flow from upper watershed areas contributed rocks, sediment and debris. Debris dam/breach effects caused localized flooding more severe than suggested by return periods.
	Upper Skunk Creek	<1	7	20	70	~100	>100				~ 25	Significant debris flow from upper watershed areas contributed rocks, sediment and debris. Debris dam/breach effects caused localized flooding more severe than suggested by return periods.
	Lower Skunk Creek	3	10	25	75	>100	>1000				~25	Flood damages generally minor in lower watershed due to improved channel and floodplain preservation.
Gregory Canyon Creek	West Subwatershed	1	5	10	40	~100	>300	No flow measurements/estimates available for this watershed.			~ 25 - 50	Landslides and debris flows affected the upper and middle watersheds with significant transport of rocks, sediment and debris that plugged culverts and forced flows onto streets. Streets that generally run south-north toward Boulder Creek have steep slopes and once flow left the channel (typically at road crossings) it followed the path of least resistance (paved streets with steep longitudinal slopes from near Chautauqua to Boulder Creek
	Middle Subwatershed	1	5	15	50	>100	>400					
	Lower Subwatershed	1	5	10	40	>100	>400					

Boulder Creek (BC)	West Boulder Creek	1	2	7	24	25	26	No flow measurements/estimates available for this watershed.				
	West-Central Boulder Creek	0	1	6	30	~35	48	Middle Boulder Creek at Nederland	409	825	<10	Flow estimate source: CDWR
								North Boulder Creek downstream CO Hwy 72 near Nederland	340	--	--	Flow estimate source: Jarrett
								North Boulder Creek u/s Boulder Creek and CO Hwy 119 near Orodell	740	--	--	Flow estimate source: Jarrett - canyon rock fall risk; poor estimate
	East-Central Boulder Creek	0	1	3	8	~25	72	Boulder Creek u/s Keystone Gulch near Orodell	1,560	--	--	Flow estimate source: Jarrett
								Boulder Creek at Orodell (above Fourmile)	2,020	7,080	10 - 15	Flow estimate source: CDWR - peak on September 12 at 23:30
								Fourmile Creek u/s burned area	490	--	--	Flow estimate source: Jarrett
								Fourmile Creek d/s Poorman Rd u/s #1267 Fourmile Cr Rd near Orodell	2,300	5,570	~20	Flow estimate source: Jarrett - USGS gage near mouth (not much d/s inflow)
	East Boulder Creek	1	3	9	19	>100	364	Boulder Creek at Broadway	~5,000	12,000	25	Flow estimate source: UCAR estimate based on CDWR
								Boulder Creek at 28th Street	5,300	~11,500	25	Flow estimate source: CWCB
								Boulder Creek at 75th Street in Boulder	8,400	~13,000	25 - 50	Flow estimate source: USGS - provisional data

Goose & Twomile Creeks (GC & TMC)	TMC above Broadway	2	5	15	50	~100	>200	TMC at North Cedar Brook Road (upstream of Spring Valley Road)	1,200	710	>100	Flow measurement reflects bulking effects due to entrained mud and debris. These bulking effects would have been most significant in the upper portions of the watershed where landslides occurred on slopes that fed into the steep channel.
	TMC above GC confluence	4	30	60	>100	>100	1000	No flow measurements/estimates available. Return period estimates based on observations, high water mark data and City inundation mapping.			~ 100	Twomile Canyon Creek is a classic alluvial fan situation in an urban area. In large floods, there will be significant debris that will clog culverts, damage or destroy bridges, reroute flows, etc., and thus fanning out from the apex of the fan at the base of the foothills.
	Elmer's Twomile	4	35	>100	>100	>100	>1000				~25	Merrick estimated return period of 10-25 years for Elmer's Twomile.
	GC above confluence with TMC	1	5	15	50	~100	>500				~ 25 - 50	Goose Creek is an urban drainage success story and performed very well during the 2013 flood. For the improved section of Goose Creek channel, which starts just upstream of Folsom Street and runs all the way to the confluence with Twomile Canyon Creek, damages were minimal having been remedied by maintenance and sediment removal. Merrick estimated flow return period of approximately 25 years for lower Goose Creek. 25-50 range is presented based on these observations, rainfall data and City inundation mapping.
	GC at confluence with Boulder Creek	5	50	>200	>200	~500	>1000					
Wonderland Creek (WC)	WC W of 15th	2	20	50	50 - 100	~200	~500	WC DS of Broadway @ 15th	170	530	5 - 10	Wonderland Lake provided storage. Minimal impacts along channel west of Broadway.
	WC E of US 15th	<5	25	100	>100	>200	~1000	No flow estimates available.			25-100	Flooding on WC in eastern watershed was more severe due to intense rainfall and runoff. Flood inundation mapping shows extents slightly less than 100-year floodplain. Overflow from FCC contributed flows to WC between Broadway and 19th, and flow return periods were greater downstream of the spillover.
Fourmile Canyon Creek (FCC)	Upper FCC	1	10	40	50-100	>100	>200	FCC near Anne U. White Trailhead	1,080	1,722	25 - 50	Canyon experienced severe erosion and massive debris flows that destroyed homes in the canyon as well as infrastructure.
	FCC above W City Limits	2	10	25	75	~200	300	No flow estimates available.				Severe erosion and significant debris and sediment transport.
	FCC US of Hwy 36	2	20	50	50-100	>100	>300	FCC US of Broadway	1,460	1,967 to 3,590	25 - 50	Channel avulsion upstream of Broadway, significant sediment deposition DS of Broadway & US 36. Flood frequency estimate based on average of modeled spill scenarios, with and without spill from FCC to WC upstream of Broadway (limited spill observed in 2013).
	FCC E of Hwy 36	<1	5 - 10	10	10	40	~200	FCC at Diagonal Hwy	2,300	1,757 to 2,594	50 - 100	Flood frequency estimate based on average of modeled spill scenarios, with and without spill from FCC to WC upstream of Broadway (limited spill observed in 2013). Flood inundation mapping shows extents similar to 100-year floodplain.

IMPORTANT NOTES: 1. Low return periods for short rainfall durations of the September 2013 event can be misleading if not considered in the context of antecedent rainfall, ground saturation, shallow bedrock and other factors that would potentially magnify the runoff response substantially.

2.0 Introduction and Background

Many people in the City of Boulder (City) and across the Front Range recall the "biblical" rainfall and "1,000-year" storm characterizations during the September 8 – 16, 2013 flood. Flooding was devastating in many watersheds as steep mountain canyons emptied runoff, rocks and debris into drainageways crossing the City for days. While many stream gages were washed out during the flood, observed high water marks and hydraulic analysis conducted following the flood were used to estimate peak flows and to approximate the September 2013 floodplain extents. This analysis indicates that for many creeks in Boulder, the runoff response from the event was below adopted regulatory 100-year peak flow rates. Exceptions to this general trend, where flows approached 100-year levels or greater, include the lower portion of South Boulder Creek, the West Valley Overflow, Upper Twomile Canyon Creek and the lower portion of Fourmile Canyon Creek. Most of the creeks in the City experienced peak flows with return periods of 25-years or greater, and given the duration of the event and large volume of runoff, significant sediment transport, instream erosion and deposition occurred.

A remarkable characteristic of the September 2013 flood was the massive volume of runoff caused by rainfall far in excess of 100-year levels when evaluated over 24-hour and longer periods. While peak flows in many locations were lower than expected for a 100-year flood, the volume and duration of runoff was far greater than anticipated in any of the design storms applied to watersheds in Boulder. The runoff volume saturated soils leading to landslides and debris flows in many watersheds, and the amount of sediment transport that occurred during the flood, tied to the large runoff volume, significantly impacted many creeks in and around Boulder.

This report 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-, 2-, 6-, 12-, and 24-hour worst case rainfall return periods for the September 2013 flood for watersheds within, and draining through, the City[1]. Based on analysis of "worst case[2]" 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 10-year design storm event. However, for longer durations, return periods increased dramatically. For 12-

[1] WWE has developed this report through preparation of a series of technical memoranda on rainfall-runoff relationships for each of the watersheds analyzed. Peer reviewers for the technical memoranda and this report have included: Ben Urbonas, P.E., former Chief of Master Planning for UDFCD; Dr. Bob Jarrett, formerly of USGS and working for UDFCD and CDOT on post-flood flow estimates; Kevin Stewart, UDFCD Manager of Information Services and Flood Warning; Bob Harberg, P.E., CFM, Kurt Bauer, P.E., CFM and City of Boulder staff; and other consultants working for the City of Boulder on post-flood assessments including ICON Engineering, Merrick and Company, Belt Collins West, Ltd. and CH2M-Hill.

[2] 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 24-hour period). In this analysis, this same "worst case" terminology was used for shorter durations as well.

and 24-hour durations, rainfall depths often exceeded the 1,000-year NOAA Atlas 14 precipitation depths. Coupled with rainfall-runoff modeling by others, this information helps to explain why a "1,000-year" storm, as was recorded for durations in excess of 24-hours, did not produce a "1,000-year flood."

In addition to the work to characterize rainfall return periods, WWE also performed comparisons with design storms (Colorado Urban Hydrograph Procedure [CUHP] for many watersheds) to compare rainfall intensities for the design storms with the observed intensities from the actual flood event. This information, along with flow estimates/measurements collected by Dr. Bob Jarrett, flow estimates from City consultants[3] and plan-view 2013 flood inundation mapping prepared by the City, allowed WWE to evaluate the relationship between return periods for rainfall (defined by comparison with NOAA Atlas 14) and return periods for runoff (defined by comparison with peak flow return period data from existing master plans).

Watersheds analyzed include South Boulder Creek, Bear Canyon Creek, Skunk Creek (including Kings Gulch and Bluebell Canyon Creek), Gregory Canyon Creek, Boulder Creek, Goose and Twomile Canyon Creeks, and Wonderland and Fourmile Canyon Creeks. This report presents methodologies used for all watersheds and then presents results for each of the watersheds studied.

[3] David Love, P.E. of Belt Collins West, Ltd. (BCW) provided flow estimates for locations in the Bear Canyon Creek and Fourmile Canyon Creek watersheds, and Mike Galuzzi, P.E. of Merrick and Company (Merrick) provided observations and estimates for Goose and Elmer's Twomile Creeks. ICON Engineering provided flow estimates for Fourmile Canyon Creek in the vicinity of Broadway.

3.0 Methodology

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-, and 30-minute and 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. Figure 1 in Appendix A shows ALERT gage locations in the vicinity of Boulder. Using the National Oceanic and Atmospheric Administration (NOAA) Atlas 14 Precipitation-Frequency Atlas of the United States, Volume 8, Version 2, point precipitation return period estimates were obtained for the locations of each of the 60 ALERT rain gages[4].

Using the rainfall depths and peak intensities from UDFCD, the NOAA Atlas 14 point precipitation return period 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. Rainfall occurred from September 8 – 16; however, the most intense rainfall occurred during the September 11 – 13 period covered by the 5-minute gridded rainfall data. The 1-km^2 grid cells were clipped in a Geographic Information System (GIS) based on watershed boundaries. Weighted hyetographs were calculated using the radar precipitation data for these watersheds. The 5-, 10-, 15-, and 30-minute and 1-, 2-, 6-, 12-, and 24-hour rainfall peak intensities and depths were identified from the weighted hyetographs[5]. "Pseudo" radar-based rain gages were placed at the centroids of each of the sub-watersheds within and near the City. Typically, watersheds were broken into west, middle and eastern portions to capture east-west precipitation trends, which generally showed greater rainfall totals and higher peak intensities in eastern portions of watersheds. Similar to the UDFCD ALERT data, the NOAA Atlas 14 point precipitation return period 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.

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, the attached "Worst Case Rainfall Return Periods" maps were created using the inverse distance weighted interpolation method within the Spatial Analyst tool in ArcGIS. The output provided an

[4] While UDFCD continues to rely on rainfall data based on the 1973 NOAA Atlas 2 for hydrologic studies, NOAA Atlas 14 provides coverage within and outside of UDFCD boundaries for the range of return periods and durations of interest. It should be noted that one-hour point precipitation values from NOAA Atlas 14 are somewhat lower than those in NOAA Atlas 2 and those used by UDFCD.

[5] 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.

interpolated surface raster that was visually displayed with other GIS data such as roads, watershed boundaries, cities, etc. The "Worst Case Rainfall Return Periods" maps for the 5-, 10-, 15-, and 30-minute and 1-, 2-, 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. Rainfall return periods for each watershed are discussed in more detail below.

The "Worst Case Rainfall Return Periods" maps are based on the maximum rainfall depths within any 5-, 10-, 15-, and 30-minute and 1-, 2-, 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 duration of one hour 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 to the same time period during which 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, the watershed analyzed rainfall depths and intensities for durations from 5- to 15-minutes were on the order of a 10-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 1,000-years, consistent with previous regional analysis by the Hydrometeorological Design Studies Center (NOAA and National Weather Service-HDSC 2013).

The 2013 event was indisputably a massive rainfall event; however, when evaluating depths and intensities for shorter durations (i.e. 2-hours and less), which normally drive the rainfall-runoff relationships in CUHP, rainfall was less intense than assumed in design storms that are used to define regulatory peak flow rates and floodplains. The CUHP 100-year design storm is "front loaded" with approximately 50% of the rainfall in the first 30 minutes, and with roughly 80% of the precipitation occurring in the first hour of the design storm, a characteristic that was not observed in the actual storm event in September.

When evaluating rainfall for short-duration return periods and the resulting runoff, it is important to keep in mind that in many watersheds, there were several "waves" of intense rainfall over the duration of the storm, the rainfall that occurred later in the storm was on saturated ground, and the runoff response would be magnified beyond what the rainfall return period would indicate. It is also important keep in mind the significance of the storm

totals that occurred over the entire event. Although short duration intensities were below 100-year design storm intensities in most cases, the volume of runoff produced by record rainfall over a period of days had significant effects in terms of landslides, debris flows and sediment transport, which impacted many creeks in and around Boulder.

3.1 Runoff

To assess runoff, WWE used peak flow estimates from Dr. Jarrett, formerly of USGS. Dr. Jarrett collected runoff data in the Boulder area on behalf of UDFCD and CDOT using high water marks and other post-flood observations. Flow estimates from Dr. Jarrett were available for many but not all watersheds. In addition, City consultants including Belt Collins West, Ltd. (BCW), ICON Engineering (ICON) and Merrick and Company (Merrick) provided flow estimates for locations in several watersheds. When flow estimates were available, WWE compared to flow-frequency data from existing master plans to assign return periods to runoff. It is important to note that, in general, flow estimates are expected to have accuracy on the order of +/- 20% or more. There are many uncertainties associated with flow estimates including the quality of the high water marks, channel and floodplain morphology, entrainment of mud, rocks and debris, and other factors. Typically, bulking effects due to mud, rocks, and debris would have been most significant in the upper portions of the watersheds, where landslides occurred on slopes that fed into the steep channels.

In areas where peak flow estimates were unavailable, WWE relied on plan-view inundation mapping from the September 2013 flood from the City (included as Appendix B) as well as crowd-sourcing data from posts to the internet during and following the flood. Assessing flood return periods in this manner provides only a rough approximation. Mapping that shows flow on streets would typically indicate a runoff return period of greater than 10-years (exceeding storm sewer capacity); however, when flow is contained in streets, which often act as major drainage paths during a flood, it is more difficult to assign return periods as the range of depths between an event that floods the streets (>10-year, typically) and the 100-year event are often contained within the street curbs.

In assessing relationships between rainfall and runoff, WWE considered information related to real storm versus design storm characteristics, effects of saturation at the time intense rainfall occurred, temporal and spatial rainfall characteristics, and field estimates of flow rates and inundated areas.

4.0 South Boulder Creek

South Boulder Creek, which drains an area of 132 square miles, is a right-bank tributary of Boulder Creek. From its headwaters at the Continental Divide, South Boulder Creek flows in an easterly direction through relatively steep and narrow mountain canyons for nearly 22 miles to where it emerges onto the high plains at Eldorado Springs. From there, the creek flows northeasterly through a moderately wide valley over a distance of about 9.7 miles to its confluence with Boulder Creek. Rainfall "pseudo" gage locations and locations of flow estimates are shown in Appendix A.

Gross Reservoir is a storage facility located on South Boulder Creek, approximately 3.5 miles upstream of Eldorado Springs, owned by Denver Water. The reservoir was constructed in 1955 and has a storage capacity of 43,000 acre-feet. During the flood, Denver Water was able to divert water from Gross Reservoir to Ralston Reservoir through the South Boulder Diversion Canal, and Gross Reservoir provided considerable storage of runoff. Peak inflows upstream of the reservoir reached nearly 800 cfs but were largely attenuated by the reservoir and diversion to Ralston Reservoir. The extreme volume of runoff filled Gross Reservoir to the spillway elevation, and even several days after the rain had stopped the spillway continued to release water.

Once emerging from Eldorado Canyon, South Boulder Creek floodwaters split between two major paths and a number of irrigation and small drainage ditches. The South Boulder Creek channel is one of the main flood paths and is generally located on the east side of the valley bottom; however, at a number of locations, the creek spilled to the west side of the valley. This second main flow path is referred to as the "West Valley Overflow." Some of the floodwaters in the West Valley Overflow eventually returned to South Boulder Creek, although not before flowing through residential and commercial areas, causing extensive damage. In both the 1969 and 2013 floods, water followed many of the West Valley Overflow routes. HDR Engineering (HDR) completed the current regulatory hydraulic model and floodplain mapping for South Boulder Creek in 2007, and this was adopted by FEMA in 2008.

September storm totals from volunteer rainfall observers' gages ranged from approximately 8.5 inches to isolated reports of more than 21 inches near Marshall (CoCoRAHS[6]), with greatest total precipitation in the lower portions of the watershed. Runoff from the September flood eclipsed floods of recent memory on South Boulder Creek, and occupied much of the available floodplain storage space. Peak flows were on the order of 4,000 cfs downstream of Eldorado Springs with significant contributions (on the order of 2,000 cfs) from Doudy Draw. The peak flow along South Boulder Creek upstream of Highway 93 at San Souci was estimated to be greater than 5,600 cfs.

Further downstream, the estimated peak discharge for South Boulder Creek at South Boulder Road was 3,600 cfs. This does not include the water diverted at the West Valley Overflow and

[6] Community Cooperative Rain, Hail and Snow Network: http://www.cocorahs.org. Pending publication "Rainfall Patterns and timing contributing to the great Colorado Flood of September 2013" by N. Doesken et al. provides additional information and analysis of CoCoRAHS data from flood.

indicates a peak discharge between a 50- to 100-year return period. This is substantiated by the comparison between the mapped inundation areas and the published 100-year floodplain.

4.1 Rainfall

Table 1 shows return periods calculated for various rainfall durations in the South Boulder Creek watershed. HDR developed the 100-year design storms for the South Boulder Creek watershed as a part of the "Climatology and Hydrology Report for South Boulder Creek." The HDR study defined a 6-hour Thunderstorm distribution and a 72-hour General Storm distribution for the watershed. Given the multiday duration of the September flood, the most applicable comparisons are with the 72-hour General Storm. However, the 6-hour Thunderstorm is the storm event used for mapping the 100-year floodplain.

The upper portions of the South Boulder Creek watershed experienced total rainfall depths somewhat lower than those used in the 100-year General Storm; however, short-duration intensities were higher than those used in the General Storm. The heavy rainfall in the upper watershed did not begin until the evening of September 12, at which point considerable downstream flooding had occurred from runoff from the portion of the watershed below Gross Reservoir. The middle and lower portions of the watershed experienced several strong surges of rainfall, the heaviest of which was on September 11, when flooding in many urban areas in Boulder was at its worst. The additional surge, on the 12th and into the 13th added another 3 to 5 inches of precipitation on saturated soils, producing further flooding. Total rainfall depths for the lower watersheds were considerably larger than for the 100-year General Storm and rainfall intensity was also greater, which helps to explain the severe flooding experienced on South Boulder Creek and the West Valley Overflow despite relatively minor runoff contributions from the upper watershed above Gross Reservoir.

4.2 Runoff

Runoff measurements by Dr. Jarrett and from UDFCD ALERT Stream Gages are summarized in Table 2. Inundation mapping from the September 2013 flood is provided in Appendix B. Runoff estimates indicate that the watershed above Gross Reservoir was not a major contributor to the flooding experienced in the City. This is due to a variety of factors, including the fact that the heaviest rain in the upper watershed occurred late on the 12th and into the 13th of September, while the lower watershed had the most intense rain (and flooding) on September 11. In addition, storage was available in Gross Reservoir that aided in attenuating runoff, and Denver Water diverted some of the runoff from the upper watershed to Ralston Reservoir. It is somewhat surprising that the rainfall in the upper watershed late on the 12th and early on the 13th did not produce greater peak flows, with 3- to 6-hour rainfall depths with return periods of greater than 100-years falling on the upper basin. However, the largely forested upper watershed would have substantial hydrologic losses from depression storage (alpine lakes), interception, infiltration and storage in forest litter, as well as transient storage (i.e., temporary storage in floodplain overbank areas as the flood moves down the canyon), which would delay and lessen peak flow rates and helps to explain the runoff response observed.

To evaluate the return periods of runoff, WWE evaluated flow estimates from the 2013 flood in comparison to hydraulic model results for the General Storm (72 hours) and the Thunderstorm (6 hours, higher intensity). The estimated flow rate at Eldorado Springs between 2,000 and 2,100 cfs corresponds to between a 50- and 100-year return period for the General Storm and to between a 10- and 25-year return period for the Thunderstorm, which tends to produce higher peak flows than the General Storm for larger return period events.

Table 1 – Summary of "Worst Case" Precipitation Duration, Depth and Return Periods for South Boulder Creek Watershed in September 2013 Flood

Duration	Upper South Boulder Creek Watershed (SBC 1)		Upper-Middle Watershed Surrounding Peak to Peak Highway (SBC 2)		Middle Watershed--Gross Reservoir (SBC 3)		Eldorado Springs and South Boulder (SBC 4)		Valmont Reservoir		Doudy Draw		Marshall Gulch		Martin Gulch	
	Depth (in)*	Est. Ret. Per. (yr)**	Depth (in)	Est. Ret. Per. (yr)	Depth (in)	Est. Ret. Per. (yr)	Depth (in)	Est. Ret. Per. (yr)	Depth (in)	Est. Ret. Per. (yr)	Depth (in)	Est. Ret. Per. (yr)	Depth (in)	Est. Ret. Per. (yr)	Depth (in)	Est. Ret. Per. (yr)
5-min	0.11	1	0.09	0	0.09	0	0.12	1	0.12	1	0.24	1	0.12	1	0.18	1
10-min	0.21	1	0.18	1	0.18	1	0.25	1	0.24	1	0.47	5	0.22	1	0.34	1
15-min	0.31	1	0.26	1	0.26	1	0.36	1	0.35	1	0.68	5	0.30	1	0.45	2
30-min	0.59	5	0.50	1	0.51	1	0.64	2	0.60	2	1.34	20	0.45	1	0.72	5
60-min	1.09	15	0.95	10	1.00	5	1.12	5	0.99	5	2.36	90	0.86	5	1.18	5
2-hr	2.00	>100	1.54	25	1.80	20	1.94	20	1.82	15	3.74	400	1.45	10	2.24	40
3-hr	2.19	>100	1.71	30	2.09	30	2.35	40	2.14	25	3.92	>300	1.87	20	2.61	60
6-hr	2.74	>100	2.22	45	2.97	55	3.60	~100	3.09	50	4.44	>300	3.13	50	3.73	>100
12-hr	2.95	65	2.52	25	3.13	25	4.21	75	3.65	50	4.47	~100	4.03	70	3.87	~50
24-hr	3.04	25	2.81	15	5.51	>100	7.57	>500	6.42	>300	8.80	>1,000	5.92	>100	7.14	>300

*Note: Radar rainfall data provided from 9/11/13 6:00 pm on September 11 to 6:00 am on September 13, 2013. Rainfall for each sub-watershed is based on area-weighted compositing of 5-minute gage-corrected, radar-based hyetograph data. In general, for South Boulder Creek middle and lower watersheds, the peak rainfall intensities occurred in the first wave of the storm on September 11.

** Estimated return periods are rounded. Estimates beyond a 100-year return period are rough approximations only since there is little actual rainfall data of this magnitude in the period of recorded data, leading to greater uncertainty in assigning very large return periods to data.

Table 2 – September 2013 Peak Flow Estimates for South Boulder Creek Watershed

Location	Peak Discharge (cfs) *values rounded	Source & Comments
South Boulder Creek at Rollinsville	400	Jarrett
South Boulder Creek d/s Beaver Creek near Pinecliffe	< 2013 snowmelt peak of approximately 800 cfs	DWR/Jarrett
South Boulder Creek at Eldorado Springs	2,100	Jarrett
UDFCD Gage SBC at Eldorado Springs	2,000	UDFCD
Doudy Draw upstream from South Boulder Creek near Eldorado Springs	2,000	Railroad Embankment Failure in Bull Gulch/Doudy Draw
South Boulder Creek at San Souci/US Highway 93	5,600	UDFCD
South Boulder Creek at South Boulder Road, Boulder	3,600	9/13 HWMs marked on u/s side of SBC Road bridge

The flow estimate of roughly 5,600 cfs along South Boulder Creek near San Souci and Highway 93, exceeds the 500-year return period modeling results for the General Storm and falls between a 50- and a 100-year event for the Thunderstorm modeling results. The flow at this location was heavily influenced by a large (2,000 cfs) contribution from Doudy Draw, which experienced very intense rainfall, well in excess of design storm parameters, as well as a large surge of water and debris from a railroad embankment failure in Bull Gulch, a tributary to Doudy Draw. The area above the embankment failure was approximately 0.80 square miles (only a small portion of the overall watershed); however, the sudden release associated with the embankment failure, coupled with very intense rainfall, drove the high runoff rates observed for the Doudy Draw watershed.

The estimated flow at South Boulder Road of approximately 3,600 cfs falls between a 50- and 100-year return period for the General Storm and between a 25- and 50-year return period for the Thunderstorm. The difference between the flow observed at San Souci/Highway 93 of 5,600 cfs and the flow estimate at South Boulder Road of 3,600 cfs gives a rough estimate of the magnitude of the West Valley Overflow, which experienced peak flows and sustained runoff that likely were at or above a 100-year event in terms of flow return period (~1,250 cfs). In general, the runoff response is reasonable given that the rainfall occurred with total storm depths in the lower watershed exceeding those of the General Storm, with some periods of rainfall intensity more in line with the Thunderstorm distribution than the General Storm distribution.

The fact that the lower watershed alone, with heavy rainfall and a large contribution from Doudy Draw due to a railroad embankment failure, produced 50- to 100-year peak flows is generally consistent with past modeling efforts, which show that the magnitude and timing

of peak flow rates in the lower watershed are largely unaffected by flows above Gross Reservoir.

4.3 Summary

Intense rainfall in the lower watershed and the embankment failure in Bull Gulch, which sent a 2,000 cfs surge down Doudy Draw, produced flows in South Boulder with return periods in the range of 50 to 100 years and caused flows to reach 100-year levels for the West Valley Overflow. The rainfall data, runoff measurements, and modeling support observations in the field that the portions of the watershed above Gross Reservoir did not heavily contribute to flooding experienced from Eldorado Springs downstream. The peak flow rate on South Boulder Creek was significantly increased by inflows from Doudy Draw and other small watersheds downstream of Eldorado Springs that experienced heavy precipitation and mud and debris flows.

5.0 Bear Canyon Creek

The Bear Canyon Creek watershed is about 5 miles in length and begins near Kossler Lake southeast of the City. The drainage basin is rugged, steep, and narrow, draining portions of Boulder Open Space & Mountain Parks land. Below the open space, Bear Canyon Creek runs in an engineered channel in the median of Table Mesa Drive to Broadway, where the channel crosses Broadway in a culvert and emerges in Martin Park. The creek then flows through the Martin Park residential area, crosses U.S. 36 in a culvert, and daylights on the University of Colorado's Williams Village property. From Williams Village, the creek flows to the northeast joining Boulder Creek near Foothills Highway and Arapahoe Avenue.

Love & Associates completed the current regulatory hydraulic model and floodplain mapping for Bear Canyon Creek upstream of Foothills Parkway in 2002, and this was adopted by FEMA in 2003. In August 2014, the City submitted a Letter of Map Revision (LOMR) request to update mapping based on improvements at the Foothills/Arapahoe intersection and Harrison Avenue levee improvements downstream of Foothills Parkway.

For purposes of analysis, WWE analyzed the Bear Canyon Creek watershed using three sub-watersheds: West Bear Canyon Creek (sub-watershed west of NCAR), Middle Bear Canyon Creek (sub-watershed between NCAR and Highway 93), and East Bear Canyon Creek (sub-watershed east of Highway 93 including Martin Park and surrounding neighborhoods). These sub-basins were selected to refine earlier analysis due to west-east trends in precipitation and to correspond to flow estimate locations. Rainfall "pseudo" gage locations and locations of flow estimates are shown in Appendix A.

5.1 Rainfall

Table 3 shows return periods calculated for various rainfall durations in the Bear Canyon Creek watershed. The 100-year design storm for Bear Canyon Creek was developed as a part of the Flood Hazard Area Delineation (FHAD) and uses a 2-hour rainfall distribution, based on UDFCD guidance. More recent analysis of the Boulder Creek watershed (including contributions from Bear Canyon Creek) used a 6-hour storm distribution; however, the current Bear Canyon Creek floodplain mapping and regulatory 100-year peak flow rates were based on the 2-hour storm distribution in the 1987 FHAD.

During the 2013 flood, precipitation depths and intensities generally increased from west to east, with total rainfall from September 11-13 of approximately 9.5 inches in the west sub-watershed (maximum 5-minute rainfall depth less than 0.20 inches) increasing to approximately 12 inches in the east sub-watershed (maximum 5-minute rainfall depth of approximately 0.35 inches). As Table 3 shows, rainfall return periods for the worst case 2-hour duration ranged from a 50-to 80-year event. It is notable that the most intense rainfall in the Bear Canyon Creek watershed occurred in roughly the first 6 to 8 hours of the storm. Shorter duration rainfall intensities (e.g. maximum 5-minute depths) were considerably less than 100-year design storm values, which are two to three times greater than maximum 5-minute depths observed during the flood.

Table 3 – Summary of "Worst Case" Precipitation Duration, Depth and Return Periods for Bear Canyon Creek Watershed in September 2013 Flood

Duration	Bear Canyon Creek West Sub-watershed		Bear Canyon Creek Middle Sub-watershed		Bear Canyon Creek East Sub-watershed	
	Depth (in)*	Est. Ret. Per. (yr)**	Depth (in)	Est. Ret. Per. (yr)	Depth (in)	Est. Ret. Per. (yr)
5-min	0.17	1	0.18	1	0.35	5
10-min	0.32	1	0.36	2	0.61	10
15-min	0.45	2	0.52	3	0.81	13
30-min	0.75	3	0.95	10	1.39	25
60-min	1.42	15	1.66	25	2.24	75
2-hr	2.40	50	2.59	70	2.71	80
6-hr	4.21	>200	4.70	>300	6.70	>1,000
12-hr	4.45	90	4.98	>150	7.21	>1,000
24-hr	7.81	>500	8.38	>1,000	10.56	>1,000

*Note: Radar rainfall data provided from 9/11/13 6:00 pm to 6:00 am on 9/13/13. Rainfall for each sub-watershed is based on area-weighted compositing of 5-minute gage-corrected, radar-based hyetograph data.

** Estimated return periods are rounded.

5.2 Runoff

Dr. Jarrett collected runoff measurements/estimates for Bear Canyon Creek at two locations: (1) Bear Canyon Creek at Baseline Road and (2) Bear Canyon Creek at Highway 93/Broadway. In addition, David Love, P.E. of BCW estimated flows for Bear Canyon Creek at Broadway (including overflow paths). These measurements, along with flow return period relationships from the Flood Insurance Study (FIS), are presented in Table 4. Inundation mapping prepared by the City from the September 2013 flood is provided in Appendix B.

Based on inundation mapping, the floodplain for September 2013 was generally contained within the regulatory 100-year floodplain boundary. A notable exception was Broadway north of Table Mesa, where flows split to the north, flooding some areas in the Martin Park neighborhood that were not mapped in the 100-year floodplain. Peak flows at Broadway approached 50-year levels, while further downstream near Baseline Road, peak flow rates were around 25-year levels.

The seeming disparity between rainfall return period (between a 50- and 100-year event) and runoff return period (25- to 50-year event) can best be explained by differences in the rainfall distributions of the worst case 2-hour rainfall during the flood compared to the 2-hour design storm used to establish regulatory flood frequency relationships. As the figures in Appendix A and Table 3 show, maximum 5-minute depths in the September flood were only about ⅓ to ½ of the 100-year design storm peak 5-minute depths. Depths for durations of 30 minutes to 1-hour generally correlate to frequencies of 25-years or less (with the exception of the east sub-watershed).

Table 4 – Peak Discharges for Bear Canyon Creek during September 2013 Flood

Location	Peak Flow Rates (cfs)							
	2-yr	5-yr	10-yr	25-yr	50-yr	100-yr	Est. Sept. 2013	Comment
Above Confluence with Boulder Creek	720	1,415	2,050	2,896	3,762	4,880		September 2013 flood extents near 100-year boundary.
Above Confluence with Skunk Creek	355	780	1,170	1,745	2,360	3,070		
Baseline Road	330	740	1,110	1,702	2,352	2,930	1,330	September 2013 flood extents near 100-year boundary.
US 36	240	540	820	1,275	1,780	2,210		
Broadway/ Hwy 93	140	440	680	1,072	1,512	1,930	1,400	Flow estimate based on average of Jarrett and BCW box culvert flows and BCW overflow estimates.
Yale Road	110	290	480	805	1,190	1,600		
500 feet Upstream of Lehigh	68	180	307	526	791	1,063		Large debris flow scoured rock and mud in reach upstream of Lehigh and deposited mud and rock down the eastbound lane of Table Mesa Drive.

5.3 Summary

While rainfall in the Bear Canyon Creek watershed for durations of 6 hours and greater produced rainfall that exceeded 100-year levels (in the case of the east watershed 1,000-year levels), rainfall intensities for shorter durations that are comparable to the 100-year design storm were not as intense. For a 2-hour worst case scenario, rainfall return periods were typically on the order of a 50- to 80-year event; however, 5-minute peak rainfall depths from the storm were only about ⅓ to ½ of the peak 5-minute values in the 100-year design storm. The rainfall produced peak flows approaching 50-year levels at Broadway, overflowing the channel, and further downstream near Baseline Road, peak flows were on the order of a 25-year event. Heavier rainfall was observed further east, and flooding in the lower watershed (where flow estimates are not available) was likely greater than in western and central portions of the watershed. Floodplain inundation mapping was generally contained within the designated 100-year flood boundaries, with the exception of split flow that headed north on Broadway from the Table Mesa/Broadway intersection.

6.0 Kings Gulch, Bluebell Canyon Creek and Skunk Creek

The Skunk Creek watershed begins in Boulder Open Space and Mountain Park property southwest of the City of Boulder, and flows northeast for approximately 2 miles before discharging to Bear Canyon Creek. The overall drainage area of the Skunk Creek watershed is approximately 8.24 square miles. The upper portion of the watershed is an undeveloped mountainous area with steep, narrow and rocky channels. The lower portion of the watershed flows through commercial and residential areas.

Kings Gulch and Bluebell Canyon Creek are tributaries to Skunk Creek. Bluebell Canyon Creek runs along the southeast border of Chautauqua Park, and Kings Gulch lies approximately 2,000 feet to the south. Both tributaries flow through a residential neighborhood south of Baseline Road and east of Chautauqua Park before joining the main stem of Skunk Creek southwest of the intersection of Broadway and Baseline Road. The main Skunk Creek channel then passes under Broadway via a culvert with a bike path. In large floods, a portion of Bluebell Canyon Creek passes over the intersection of Broadway and Baseline and flows down Baseline. The Bluebell Canyon Creek overflow down Baseline merges with the Skunk Creek main channel near the intersection of Baseline and U.S. Highway 36.

Through most of the areas from the western City boundary to Colorado Avenue, Skunk Creek and its tributaries are small, unimproved drainageways running through backyards and along streets. Culverts have been installed at major road crossings; however, through the residential areas, the creek follows a narrow corridor with little maintenance access except for at road crossings. Downstream of Colorado Avenue, Skunk Creek enters the University of Colorado (CU) Research Park, where significant channel improvements and stormwater detention have been implemented.

For purposes of this analysis, WWE analyzed the Skunk Creek watershed using four sub-watersheds: Upper Skunk Creek (sub-watershed containing the headwaters of Skunk Creek), Bluebell Canyon Creek (northern most sub-watershed), Kings Gulch (located between Bluebell Canyon Creek and Upper Skunk Creek), and Lower Skunk Creek (eastern portion of the watershed). These sub-watersheds were selected to refine earlier analysis due to trends in precipitation.

6.1 Rainfall

Table 5 shows return periods calculated for various rainfall durations from the 2013 flood event in the Skunk Creek watershed. Rainfall "pseudo" gage locations and locations of flow estimates are shown in Appendix A. The 100-year design storm for the Skunk Creek watershed was taken from ICON's floodplain mapping update for the Skunk Creek watershed. The ICON study titled *Skunk Creek, Bluebell Canyon Creek, and Kings Gulch Request for a Physical Map Revision* (PMR) used data from the 1987 FHAD, which uses a 2-hour rainfall distribution, based on UDFCD guidance. More recent analysis of the Boulder Creek watershed (including contributions from Skunk Creek and its tributaries) used a 6-hour storm distribution; however, the current Skunk Creek floodplain mapping and

regulatory 100-year peak flow rates were based on the 2-hour storm distribution in the 1987 FHAD.

During the 2013 flood, precipitation depths and intensities generally increased from west to east, and for Skunk Creek, from south to north. Total rainfall from September 11-13 was approximately 10.14 inches in the Upper Skunk Creek sub-watershed with a maximum 5-minute rainfall depth less than 0.20 inches. The Bluebell Canyon Creek sub-watershed had similar rainfall and intensities with a total rainfall depth of 10.30 inches from September 11-13 and a maximum 5-minute rainfall depth of approximately 0.17 inches. Rainfall along Skunk Creek increased in the lower portion of the watershed with Lower Skunk Creek receiving approximately 11.04 inches and a maximum 5-minute rainfall depth of approximately 0.27 inches. Kings Gulch, which received total rainfall of slightly more than 5 inches in a 24-hour period (between a 50- and 100-year return period) had modest 5-minute and 1-hour worst case depths corresponding to a return period of 5 years or less.

As Table 5 indicates, rainfall return periods for the worst case 2-hour duration (same duration as design storm) ranged from a less than 20-year event for Kings Gulch to a 75-year event for Lower Skunk Creek. It is notable that the most intense rainfall in the Skunk Creek watershed occurred in roughly the first four hours of the storm. Shorter duration rainfall intensities (e.g. maximum 5-minute depths) were considerably less than 100-year design storm values, which are approximately two to three times greater than maximum 5-minute depths observed during the flood. Even though the short-duration intensities reported in Table 5 are considerably lower than those used in the 100-year design storm, the rocky soils and shallow bedrock in the upper sub-watersheds limit infiltration, and intense periods of rainfall later in the event, when soils were saturated, produced significant runoff and debris flows.

Each of the Skunk Creek sub-watersheds experienced several significant periods of rainfall throughout the storm, in addition to intermittent rainfall between major rainfall pulses. The first wave of the storm produced between approximately 3.2 and 6.2 inches of rain in four hours on September 11th. This was the most intense wave of the storm, with 5-minute depths of around 0.15 to almost 0.3 inches. The second wave of the storm occurred during the morning on the September 12, with an additional 0.6 to 1.4 inches of rain. The third wave of the storm started in the early afternoon of the September 12 and added, on average, around 3 inches of rain in approximately 6 hours to already saturated soils.

Based on Table 5 and the mapping in Appendix A, maximum 5-minute depths in the September flood were only about ½ to ⅓ of the 100-year design storm peak 5-minute depths. Depths for durations of 30 minutes to 1 hour generally correlate to frequencies of 25 years or less.

Table 5 – Summary of "Worst Case" Precipitation Duration, Depth and Return Periods for Skunk Creek Watershed in September 2013 Flood

Duration	Upper Skunk Creek		Kings Gulch		Bluebell Canyon Creek		Lower Skunk Creek	
	Depth (in)*	Est. Ret. Per. (yr)**	Depth (in)	Est. Ret. Per. (yr)	Depth (in)	Est. Ret. Per. (yr)	Depth (in)	Est. Ret. Per. (yr)
5-min	0.18	0	0.14	0	0.17	0	0.28	3
10-min	0.35	2	0.27	0	0.34	2	0.49	5
15-min	0.52	3	0.36	0	0.49	3	0.63	5
30-min	0.96	7	0.68	3	0.90	6	1.00	10
60-min	1.55	20	1.03	5	1.44	15	1.69	25
2-hr	2.58	70	1.69	15	2.52	33	2.65	75
6-hr	4.78	>100	3.20	60	4.90	>400	6.03	>1,000
12-hr	5.04	>100	3.33	25	5.15	~200	6.46	>500
24-hr	8.21	>500	5.25	80	8.37	>1,000	9.58	>1,000

*Note: Radar rainfall data provided from 9/11/13 6:00 pm on September 11 to 6:00 am on September 13, 2013. Rainfall for each sub-watershed is based on area-weighted compositing of 5-minute gage-corrected, radar-based hyetograph data.

**Estimated return periods are rounded.

6.2 Runoff

Peak-discharge estimates were not taken within the Skunk Creek watershed for the September 2013 flood. However, the City has developed approximate 2013 flood extent maps using field surveys completed by City of Boulder staff and consultants, Digital Globe Wordview-2 satellite imagery (9/13/2013), and public input from Boulder Crowd Sourcing online maps, as well as discussions with affected property owners. This flood extent mapping for Skunk Creek is included in Appendix B.

Examination of the 2013 flood extent maps for Skunk Creek and its tributaries shows that much of the flood was contained within the regulatory 100-year floodplain, especially in the lower reaches. Areas that flooded outside of the 100-year floodplain, and other information of interest, are listed below:

- In the upper portion of Skunk Creek, a large portion of the Chautauqua Park open space north of the creek and Rayleigh Road and a portion of open space on the southeast side of the creek were inundated.
- A substantial area on the south side of the creek adjacent to the National Institute of Standards and Technology (NIST) complex flooded, including a portion of Compton

Road. The September 2013 floodplain appeared to be reduced from the 100-year flood as it neared South Broadway and on the east side of South Broadway.

- As Skunk Creek flowed northeast from Baseline Road, the floodplain again spread beyond the 100-year floodplain with street flow on East Aurora Avenue and 30th Street. Skunk Creek also flooded a portion of the southern end of University of Colorado Boulder campus between Discovery Drive and Innovation Drive. Multiple ponds and channel improvements constructed on the CU campus before Skunk Creek converges with Bear Canyon Creek east of Foothills Parkway helped handle the September 2013 flood flows.
- Flooding in Kings Gulch appeared to be within 100-year floodplain limits in many locations, which correlates well with the lower rainfalls totals and intensities recorded for the sub-watershed. Some flooding was recorded on streets off of the two main streets modeled to convey the majority of the flood flows, Bluebell and King Avenues. Storm sewer systems in these areas were not adequate to handle the large flows with debris and sediment from the open space above.
- Bluebell Canyon Creek flooding appeared to locally exceed the 100-year floodplain as the creek flowed down from Chautauqua Park and into the adjacent residential neighborhood. Runoff and debris flows overflowed the banks of the creek and flowed parallel to the creek beginning at Bellevue Drive and continuing down Mariposa Avenue. As with Kings Gulch, flooding was recorded on a number of streets that were not identified as being inundated in the FHAD model. This was primarily due to conveyance limitations, worsened by sediment and debris. For many of the mountainous watersheds studied, including Bluebell Canyon Creek and Upper Skunk Creek, there was evidence of debris damming and subsequent breaching. This phenomenon explains the surges of runoff observed in many of these watersheds and would produce peak flow rates that would be greater than would be expected based on the rainfall return periods.
- Historically during large floods a portion of Bluebell Canyon Creek has passed over the intersection of Broadway and Baseline Road and flowed down Baseline Road. The Bluebell Canyon Creek overflow down Baseline Road merges with the Skunk Creek main channel near the intersection of Baseline and U.S. Highway 36. This flooding was observed during the September 2013 flood, and flooding along Baseline Road east of South Broadway was observed to be more severe than the 100-year storm FHAD modeling depicted for that location.

Considering rainfall data, runoff analysis in other watersheds and the flooding extents shown in Appendix B, it is likely that Kings Gulch experienced a peak discharge on the order of a 10-year event; Upper and Lower Skunk Creek and Bluebell Canyon Creek experienced a peak discharge on the order of a 25-year event. However, as discussed above, Bluebell Canyon Creek flooding appeared to locally exceed the 100-year floodplain near Chautauqua Park and the nearby neighborhoods along Mariposa Avenue due to debris dams and the subsequent surge of water after the debris dam broke. This phenomenon was also likely a factor for Kings Gulch and Upper Skunk Creek. The difference between a 25- to 50-year event and a 100-year event would not be that great in terms of plan-view floodplain mapping, since runoff is often contained within streets that serve as major drainage flow paths during flood events. In addition, sediment and debris exacerbated flows in upper watersheds, plugging inlets and

culverts in some locations while reducing capacity in others.

6.3 Summary

In the Skunk Creek watershed, rainfall return periods for the worst case 2-hour duration ranged from a less than 20 years for Kings Gulch to 75 years for Lower Skunk Creek. The Upper and Lower Skunk Creek sub-watersheds received 2-hour worst case rainfall depths between 50- and 100-year return periods. It is notable that the most intense rainfall in the Skunk Creek watershed occurred in roughly the first four hours of the storm. Shorter duration rainfall intensities (e.g., maximum 5-minute depths) were considerably less than 100-year design storm values, which are approximately two to three times greater than maximum 5-minute depths observed during the flood. Even though the short-duration intensities from the September 2013 flood were considerably lower than those assumed in the 100-year design storm, the rocky soils and shallow bedrock in the upper sub-watersheds limited infiltration, and intense periods of rainfall later in the event, when soils were completely saturated, produced significant runoff and debris flows.

Peak-discharge estimates from the September 2013 flood were not available for Skunk Creek, so runoff return period analysis relied on plan-view inundation mapping and observations from during the flood. Considering rainfall data, runoff analysis in other watersheds and the flooding extents mapped by the City following the flood, it is likely that Kings Gulch experienced a peak discharge on the order of a 10-year event or greater (due to debris effects). Upper and Lower Skunk Creek and Bluebell Canyon Creek experienced peak discharges on the order of a 25-year event.

7.0 Gregory Canyon Creek

The Gregory Canyon Creek watershed is approximately 1,400 acres, which is relatively small compared to the surrounding watersheds, including the Boulder Creek watershed to the north and east, and Skunk Creek and Bear Canyon Creek watersheds to the south and east. The Gregory Canyon Creek drainage basin is steep, narrow, and approximately 1.9 miles long. The watershed originates on Boulder Open Space and Mountain Parks property between Flagstaff and Green Mountains. The creek enters fully developed residential areas near Chautauqua Park where Baseline Road turns into Flagstaff Road, then flows northeast through Boulder to the west of 9th Street between Baseline Road and Arapahoe Road for a distance of approximately 1 mile. The downstream section of the channel that flows through developed areas is an open channel with culvert crossings at roads and is relatively steep. The channel within this section is narrow, with steep banks at several locations. Gregory Canyon Creek crosses the Anderson Ditch near Flatirons Elementary School near 7th Street and Pleasant Street and finally joins Boulder Creek downstream of Arapahoe Avenue. BCW completed the current regulatory hydraulic model and floodplain mapping for Gregory Canyon Creek in 2010, and this was adopted by FEMA in 2010.

The figures in Appendix A show the Gregory Canyon Creek watershed with locations of estimated peak flows and rainfall gage locations used for analysis. For purposes of this analysis, WWE analyzed the Gregory Canyon Creek watershed using three sub-watersheds: West Gregory Canyon Creek (sub-watershed containing the headwaters of Gregory Canyon Creek), Middle Gregory Canyon Creek (sub-watershed south and west of Baseline Road) and East Gregory Canyon Creek (sub-watershed containing urban area of Boulder). These sub-watersheds were selected to refine earlier analysis due to west-east trends in precipitation.

7.1 Rainfall

Table 6 shows return periods calculated for various rainfall durations in the Gregory Canyon Creek watershed. The 100-year design storm for the Gregory Canyon Creek watershed was developed as a part of the 1987 FHAD and uses a 2-hour rainfall distribution, based on UDFCD guidance. More recent analysis of the Boulder Creek watershed [7] (including contributions from Gregory Canyon Creek) used a 6-hour storm distribution; however, the current Gregory Canyon Creek floodplain mapping and regulatory 100-year peak flow rates were based on the 2-hour storm distribution in the 1987 FHAD.

During the 2013 flood, precipitation depths and intensities generally increased from west to east with total rainfall from September 11-13 of approximately 9.8 inches in the west sub-watershed increasing to approximately 10.3 inches in the middle sub-watershed and slightly more than 10 inches in the east sub-watershed. As Table 6 and Appendix A show, rainfall return periods for the worst case 2-hour duration ranged from a 40-to 50-year event. It is notable that the most intense rainfall in the Gregory Canyon Creek watershed occurred in roughly the first 6 to 8 hours of the storm. Shorter duration rainfall intensities (e.g. maximum

[7] Anderson Consulting Engineers, Inc., "Hydrology Verification Report for Boulder Creek," prepared for the City of Boulder, October 2009.

5-minute depths) were considerably less than 100-year design storm values, with design storm values being approximately three times greater than maximum 5-minute depths observed during the flood. Even though the short-duration intensities reported in Table 6 are considerably lower than those assumed in the 100-year design storm, the rocky soils and shallow bedrock in the upper sub-watersheds limit infiltration, and intense periods of rainfall later in the event, when soils were saturated, produced significant runoff and debris flows.

Table 6 – Summary of "Worst Case" Precipitation Duration, Depth and Return Periods for Gregory Canyon Creek Watershed in September 2013 Flood

Duration	Gregory Canyon Creek West Sub-watershed		Gregory Canyon Creek Middle Sub-watershed		Gregory Canyon Creek East Sub-watershed	
	Depth (in)*	Est. Ret. Per. (yr)**	Depth (in)	Est. Ret. Per. (yr)	Depth (in)	Est. Ret. Per. (yr)
5-min	0.17	1	0.16	1	0.17	1
10-min	0.32	1	0.32	1	0.34	2
15-min	0.46	2	0.47	2	0.49	3
30-min	0.76	5	0.82	5	0.85	5
60-min	1.31	10	1.40	15	1.36	10
2-hr	2.17	40	2.35	50	2.26	40
6-hr	4.41	>300	4.78	>400	4.81	>400
12-hr	4.58	>100	4.98	>100	5.02	>100
24-hr	7.83	>500	8.23	~1,000	8.19	~1,000

*Note: Radar rainfall data provided from 9/11/13 6:00 pm to 6:00 am on 9/13/13. Rainfall for each sub-watershed is based on area-weighted compositing of 5-minute gage-corrected, radar-based hyetograph data.
** Estimated return periods are rounded.

7.2 Runoff

The City documented areas flooded in September 2013, and inundation mapping is provided in Appendix B. Runoff measurements/estimates were not collected for Gregory Canyon Creek during the September 2013 flood. As the inundation mapping shows, the floodplain for September 2013 was generally contained within the 100-year floodplain boundary. A notable exception is west of the intersection of Aurora and 6th Street, where flows overtopped the creek's west bank and flowed along Aurora and south along Park Lane and onto Circle Drive. Additionally, the flood flows went north along Gilbert Street and flooded Smith Park, which was outside of the mapped 100-yr floodplain. Further north, at the intersection of College Avenue and 6th Street, some of the flow was also outside of the 100-year floodplain and flowed north along 6th Street until it turned east and flowed along Pleasant Street. Downstream of Pleasant Street, floodwaters exceeded the 100-year floodplain boundary, running along 7th Street to the intersection with Boulder Creek. Neighborhoods to the east of 7th Street were inundated during the September 2013 flood, which are located outside of the 100-year floodplain. The Anderson Ditch was reported to

be overflowing and may have been a contributing factor in the widespread flooding along Gregory Canyon Creek downstream of Pleasant Street.

In many areas, out-of-channel flows occurred at crossings (i.e. culverts) that were partially or mostly plugged with rocks, sediment, and debris, forcing flows to leave the defined channels and flow onto a street system with steep downhill slopes. A landslide occurred below Flagstaff Road, affecting properties below and sending rocks and sediment into the Gregory Canyon Creek drainage system. Erosion and transport of sediment, rocks and debris from the steep channels and trails in the upper watershed open space placed a heavy load on the urban storm sewer system and the largely-unimproved channel.

Considering rainfall data, runoff analysis in other watersheds and the flooding extents shown in Appendix B, it is likely that the peak runoff response from the September flood in Gregory Creek Canyon had a return period between 25 and 50 years. Even though 1-hour return periods for rainfall are on the order of 10 to 15 years, there was enough precipitation early in the storm that saturated ground conditions would have existed before intense rainfall during the first wave of the storm (on the order of 0.15 inches in 5 minutes). In addition, the third wave of the storm on the evening of September 12 had peak rainfall intensities and 1- and 2-hour depths similar to the first wave of the storm and occurred at a time when soils in the watershed were saturated. This intense rainfall on saturated ground produced a runoff response that was magnified beyond what would have been expected from the rainfall return periods. In addition, debris damming and subsequent breaches would have sent surges of runoff and debris down the canyon as the debris dams failed. This also would magnify the runoff response beyond what rainfall return periods would indicate.

Rocks, sediment and debris were a major aggravating factor in the flooding along the urban reaches of Gregory Canyon Creek, with many partially and fully plugged culverts forcing flows out of the defined channel onto and down the streets. The extent of flooding in September 2013 was beyond what would be normally mapped for a 25- to 50-year "clear water" flood due to the effects of this blocking at culverts, reducing their flow carrying capacity. Runoff return period estimates for Gregory Canyon Creek presented in this report are only rough approximations given the fact that direct flow measurements and reliable estimates from the event are not available.

7.3 Summary

The rainfall-runoff relationship for the Gregory Canyon Creek watershed is difficult to quantify due to the effects of debris and the lack of flow estimates in the watershed. While durations of 6 hours and greater produced rainfall depths that exceeded the published 100-year levels, rainfall intensities for shorter durations, comparable to the 2-hour design storm, were significantly lower. For the 2-hour duration worst case scenario, rainfall return periods were typically on the order of a 40- to 50-year event; however, 5-minute peak rainfall depths were only about ⅓ of the published peak 5-minute values for the 100-year design storm.

The rainfall during this storm produced runoff peak flows that were likely on the order of a 25- to 50-year event; however flow estimates/measurements were not available for this

Creek to directly confirm these estimates. Rocks, sediment and debris were an aggravating factor in flooding urban reaches of Gregory Canyon Creek, with many plugged culverts forcing flows out of the channel and along streets. Debris dams and subsequent breaches also increased peak flow rates in the watershed. The extent of flooding in September 2013 was beyond what would be mapped for "clear water" flood conditions due to the effects of these debris blockages from rocks and sediment at culverts. Floodplain inundation was generally within the designated 100-year flood boundaries, with the exception of where split flows west of the intersection of Aurora and 6th Streets, flow that headed north on 6th Street from the intersection of College Avenue and 6th Street, and flow along 7th Street north of Pleasant Street occurred.

8.0 Goose and Twomile Canyon Creeks

The Goose Creek and Twomile Canyon Creek watersheds drain major portions of the City of Boulder between Wonderland Creek and Boulder Creek. Twomile Canyon Creek is a tributary to Goose Creek, with the low flow confluence generally located upstream of Folsom Street. However, in large flood events, a significant portion of the Twomile Canyon Creek flow is conveyed as overland flow down streets draining into Goose Creek via Broadway and 19th Street.

The Twomile Canyon Creek watershed originates in the foothills just west of Boulder and has a drainage area of approximately 5 square miles. Twomile Canyon Creek emerges from the foothills near Spring Valley Drive and Linden Avenue. The creek has a small channel that carries base flows and smaller flood flows along a narrow riparian corridor winding through neighborhoods and via several piped sections from Linden Avenue and Spring Valley Road to the confluence with Goose Creek upstream of Folsom Street.

Goose Creek originates near North Boulder Park. The creek follows Balsam Avenue to Broadway, where the floodplain overtops Broadway, resulting in shallow flooding of the area bound by Balsam Avenue on the north, North Street to the south, Broadway to the west and 13th Street to the east. Downstream of 13th Street there is split flow, with a portion of flow running down Alpine Avenue and the remainder flowing in a small channel through a residential area between Alpine Avenue and North Street.

Downstream of the confluence of Goose Creek and Twomile Canyon Creek, Goose Creek continues via open channel and culverts to the east. The Goose Creek bike path, which provides recreation as well as maintenance access, begins just upstream of Folsom Street, and the Goose Creek channel downstream of Balsam is an improved channel with drop structures and culverts crossings of major roadways. Elmer's Twomile Creek watershed joins Goose Creek just upstream of 28th Street. From 28th Street, Goose Creek crosses beneath 30th Street and Foothills Parkway and then flows along Pearl Parkway to the confluence with Boulder Creek.

Twomile Canyon Creek is a classic alluvial fan situation in an urban area. In large floods, there will be significant debris that will clog culverts, damage or destroy bridges, reroute flows, etc., and thus spread out from the apex of the fan at the base of the foothills (the apex is located just upstream of Spring Valley Road). The upstream area is too large to cost-effectively control sources of debris, and there is limited room for any sort of debris basin that would provide meaningful storage in large floods. The streets west of Broadway along Twomile Canyon Creek were established decades ago, and this is a long-established residential area in Boulder. At the time of the 2013 flood, the City was working to update mapping and better identify flood risk to improve residents' awareness of potential flooding. This is a good first step in improving drainage and managing risk in the area; however, there is little available room for a major drainage channel in this area, and property values are high.

During the September 2013 flood, Twomile Canyon experienced landslides on steep slopes in the canyon. The resultant debris flow and avulsion at the mouth of the canyon caused street and overland flooding in urban areas west of Broadway.

8.1 Rainfall

Table 7 shows return periods calculated for various rainfall durations in the Goose Creek and Twomile Canyon Creek watersheds. Rainfall "pseudo" gage locations and locations of flow estimates are shown in Appendix A. The 2-, 5-, 10-, 50-, and 100-year design storms for the Goose and Twomile Canyon Creek watersheds were developed in the Hydrology Verification Report (which were taken directly from the 1987 FHAD). Per the 1987 FHAD, the 1-hour duration rainfall obtained from NOAA Atlas 2 was distributed into a 2-hour design storm for use with the CUHP program.

Table 7 – Summary of "Worst Case" Precipitation Duration, Depth and Return Periods for Goose Creek and Twomile Canyon Creek Watersheds in September 2013 Flood

Duration	Twomile Canyon Creek at Broadway		Twomile Canyon Creek at Confluence with Goose Creek		Elmer's Twomile		Goose Creek at Confluence with Twomile Canyon Creek		Goose Creek at Confluence with Boulder Creek	
	Depth (in)*	Est. Ret. Per. (yr)**	Depth (in)	Est. Ret. Per. (yr)	Depth (in)	Est. Ret. Per. (yr)	Depth (in)	Est. Ret. Per. (yr)	Depth (in)	Est. Ret. Per. (yr)
5-min	0.23	2	0.31	4	0.31	4	0.22	1	0.33	5
10-min	0.40	3	0.53	6	0.60	7	0.40	3	0.62	10
15-min	0.54	4	0.74	8	0.82	15	0.53	3	0.90	20
30-min	0.85	5	1.47	30	1.54	35	0.90	5	1.70	50
60-min	1.43	15	2.29	60	2.75	>100	1.39	15	3.00	>200
2-hr	2.39	50	2.94	>100	3.34	>100	2.39	50	3.60	>200
6-hr	4.59	>200	5.88	1,000	6.22	>1,000	5.17	>500	6.50	>1,000
12-hr	5.03	>100	6.24	>200	6.71	>500	5.42	>200	7.16	>1,000
24-hr	8.38	>1,000	8.69	>1,000	8.97	>1,000	8.26	>500	9.64	>1,000

*Note: Radar rainfall data provided from 9/11/13 6:00 pm on September 11 to 6:00 am on September 13, 2013. Rainfall for each sub-watershed is based on area-weighted composting of 5-minute gage-corrected, radar-based hyetograph data.

**Estimated return periods are rounded.

8.2 Runoff

The only peak discharge estimate available for the Twomile Canyon Creek watershed is a peak discharge estimate measurement by Dr. Jarrett. He estimated that the peak flow rate at North Cedar Brook Road (upstream of Spring Valley Road in the foothills) was approximately 1,200 cfs. ICON conducted modeling analysis of the upper Twomile Canyon Creek watershed, which produced an estimate of peak discharge in the range of 800 to 1,000 cfs. The regulatory 100-year discharge for Twomile Canyon Creek in the vicinity of Spring Valley Road is 710 cfs.

There are no direct runoff measurements or estimates within the Goose Creek watershed. However, the City of Boulder has developed approximate 2013 flood extent maps using field surveys completed by City of Boulder staff and consultants, Digital Globe Wordview-2 satellite imagery (9/13/2013), and public input from Boulder Crowd Sourcing online maps as well as discussions with affected property owners. This flood extent mapping is provided in Appendix B. It is important to note that the "Proposed 100-year Floodplain" is shown on the inundation map as proposed pre-2013 flood. This study is in the process of revision at this time based on information related to the flood event.

Information based on the flood extent mapping from the City for Twomile Canyon Creek is summarized below:

- Upstream of Broadway, Twomile Canyon Creek was not confined within the FEMA effective 100-year floodplain. There were extensive overflows to the north and south of the Twomile Canyon Creek drainage. For example, to the south of the Twomile Canyon Creek drainage, the September 2013 flood inundated the subdivision along Kalmia Avenue, Juniper Avenue, Iris Avenue, and Grape Avenue. Just upstream of Broadway, flood flows were contained within 9th Street, Grape Avenue, and Forrest Avenue, none of which are mapped within the 100-year floodplain. To the north of the Twomile Canyon Creek drainage, flood flows inundated properties outside of the FEMA effective 100-year floodplain along Jasmine Circle and Juniper Avenue.
- The confluence of Twomile Canyon Creek and Goose Creek is just upstream of Folsom Street. However, during the September 2013 flood, Broadway was inundated with flows from both Twomile Canyon Creek and Goose Creek.
- Downstream of Broadway, overflows from the south of Twomile Canyon Creek continued in a southwesterly direction until its confluence with Goose Creek. Flows were conveyed through various streets such as Elder Avenue, 13th Street, Cedar Avenue, and 17th Street, none of which are within the FEMA effective 100-year floodplain. Overflows from the north of Twomile Canyon Creek extended along Iris Avenue until its confluence with Elmer's Twomile Creek, approximately one mile east of the FEMA effective 100-year floodplain.
- From Broadway to the confluence with Goose Creek, there was relatively little flow within the FEMA effective 100-year floodplain for Twomile Canyon Creek. The debris flow and avulsion at the mouth of the canyon resulted in widespread street and overland flooding in urban areas east of Broadway between Twomile Canyon Creek and Goose Creek, areas that generally were not mapped in the 100-year floodplain.

As discussed previously, the Twomile Canyon Creek watershed is a classic alluvial fan situation in an urban setting. Due to the alluvial fan situation, as shown by the flood inundation mapping, the Twomile Canyon Creek watershed has a highly variable floodplain with a high degree of uncertainty. Due to this uncertainty, it cannot be confirmed that homes wouldn't potentially flood during another large storm event just because homes did not flood in September 2013.

Information based on the flood extent mapping from the City of Boulder for Goose Creek and Elmer's Twomile Creek is summarized below:

- The 2013 flood extent closely follows the FEMA effective 100-year floodplain within North Boulder Park.
- Further downstream, the 2013 flood followed the flow path defined by the FEMA effective 100-year floodplain, with the exception of Alpine Avenue between 13th and 15th Streets where the 2013 flood extents are shown outside of the regulatory floodplain.
- The 2013 flood extents do not expand to the FEMA effective 100-year floodplain from 9th Street to just west of 19th Street, suggesting flows along Goose Creek in this area were less than the regulatory 100-year flow.
- At 19th Street, the 2013 flood extents closely match the regulatory floodplain. According to the Hydrology Verification Report, the 100-year peak discharge of Goose Creek at 19th Street is 1,741 cfs. High water marks were documented along the improved channels of Elmer's Twomile Creek and Lower Goose Creek by Merrick immediately following the September 2013 flood. Based on Merrick's observations, trails at underpasses were typically inundated by several feet of water, indicating that peak flows for these reaches were considerably less than the regulatory 100-year flood event.

Considering rainfall data and the flooding extents shown in Appendix B, it is likely that the Twomile Canyon Creek watershed experienced a peak runoff of roughly a 100-year event and Upper Goose Creek experienced runoff peaks on the order of a 50- to 100-year event. Based on high water marks along Elmer's Twomile Creek and Lower Goose Creek, a 25-year runoff return period was estimated for Elmer's Twomile Creek and Lower Goose Creek.

The seeming disparity between the 2-hour rainfall return period (between a 50- and greater than 200-year event) and runoff return period (50- to 100-year event for Upper Goose Creek and roughly a 100-year event for Twomile Canyon Creek) can best be explained by differences in the rainfall distributions of the worst case 2-hour rainfall during the flood compared to the 2-hour design storm used to establish regulatory flood frequency relationships. Maximum 5-minute depths in the September flood were only about ⅓ to ½ of the 100-year design storm peak 5-minute depths. Depths for durations of 30 minutes generally correlate to frequencies of 50-years or less.

For Elmer's Twomile Creek and Lower Goose Creek, flow measurements were unavailable; however, based on observations by Merrick, the runoff was contained in the improved sections of these channels. The effects of debris flows and sediment transport were diminished for these reaches relative to areas to the west due to channel improvements that limited instream erosion and significant deposition that occurred further to the west where steep channels transition to milder slopes as they enter the City. Given the worst case rainfall return periods of 15-20 years for the 15-minute duration and 35-50 years for the 30-minute duration, a runoff return period of approximately 25 years is a reasonable estimate for these reaches since the shorter duration periods drive the peak runoff response of the watersheds.

8.3 Summary

Rainfall return periods for the worst case 2-hour duration ranged from approximately 50 years to greater than 100 years within the Twomile Canyon Creek and Goose Creek watersheds. Shorter duration rainfall intensities (e.g. maximum 5-minute depths) were considerably less than 100-year design storm values, which are approximately three to four times greater than maximum 5-minute depths observed during the flood. Even though the short-duration intensities from the September 2013 flood were considerably lower than those assumed in the design storm, the rocky soils and shallow bedrock in the upper sub-watersheds limited infiltration, and intense periods of rainfall later in the event when soils were saturated produced significant runoff and debris flows.

The only peak discharge estimate from the September 2013 flood for the Twomile Canyon Creek watershed was by Dr. Jarrett upstream of Spring Valley Road. The estimated peak flow at this location was approximately 1,200 cfs, which was substantiated by modeling analysis by ICON. This peak flow estimate exceeds the regulatory 100-year discharge for Twomile Canyon Creek in the vicinity of Spring Valley Road of 710 cfs. Runoff estimates from the September 2013 flood were not available for Elmer's Twomile and Goose Creek so flow-return period analysis relied on plan-view inundation mapping and observations during and after the flood. Considering rainfall data, runoff analysis in other watersheds and the flooding extents mapped by the City following the flood, it is likely that Twomile Canyon Creek experienced a peak runoff rate on the order of a 100-year event and Upper Goose Creek experienced peak runoff with a return period between 50 and 100 years. Runoff return periods for Elmer's Twomile Creek and Lower Goose Creek were estimated to be approximately 25 years; however, these estimates are based on observations and plan-view mapping and do not have a high degree of accuracy. For Elmer's Twomile Creek and Lower Goose Creek, flood flows were contained in improved sections of the channels, which reduced in-channel and overbank flood damages.

9.0 Wonderland and Fourmile Canyon Creeks

The Fourmile Canyon Creek watershed is approximately 11 miles long and has a tributary watershed area of approximately 10 square miles. The watershed has a west to east orientation, with approximately 70 percent of the watershed area located in the foothills west of Boulder. After leaving the foothills at the mouth of the canyon, the creek flows through the northern part of the City before eventually discharging on the left bank of Boulder Creek approximately 3,000 feet north of Valmont Butte. The watershed shape is relatively wide in the foothills west of the City and becomes narrower to the east as it flows through the City. The channel is rocky, steep and narrow in the foothills and then flattens out with a wider floodplain as it flows through a mostly residential area. There is no significant detention storage provided within the Fourmile Canyon Creek watershed.

The Wonderland Creek watershed is approximately 4 miles long and has a tributary watershed area of approximately 2 square miles. The watershed begins just west of Wonderland Lake in northwest Boulder and flows east crossing Broadway to 26th Street in a relatively small, unimproved channel. Downstream of 26th Street, Wonderland Creek flows southeast in an improved channel with major crossings at 28th Street, Highway 119, Foothills Parkway, and Valmont Road before discharging on the left bank of Goose Creek near the confluence with Boulder Creek. Love & Associates completed the current regulatory hydraulic model and floodplain mapping for Fourmile Canyon and Wonderland Creeks in 2005, and this was adopted by FEMA in 2007.

The Fourmile Canyon Creek and Wonderland Creek watersheds are shown in Appendix A with locations of estimated peak discharges and rainfall gage locations used for this analysis. Flood inundation mapping from the City for the September 2013 flood is included as Appendix B.

Fourmile Canyon Creek has experienced historic flooding, with notable events occurring in 1916, 1941, and 1951. Limited information is available on the details of these floods except that they reportedly washed out the railroad tracks located near the Diagonal Highway. The Fourmile Canyon wildfire, which occurred in 2010, burned upper portions of the Fourmile Canyon Creek watershed. Flooding and debris plagued the Anne U. White Trailhead and downstream road crossings in 2011 and 2012. By mid-summer of 2013, significant recovery of vegetation had taken place in the burned watersheds. However, the volume of rainfall and runoff from the September 2013 flooding dwarfed previous post-fire runoff events and wreaked havoc in the canyon. The estimated 2013 peak discharge on Fourmile Canyon Creek near the Anne U. White Trailhead was 1,080 cfs and indicates a peak discharge between a 25- and 50-year return period based on the peak discharges in the *Fourmile Canyon Creek and Wonderland Creek Major Drainageway Planning (MDP) Report* (2011).

While the effects of the wildfire on rainfall-runoff relationships in recently burned watersheds can be pronounced due to loss of vegetation, loss of the duff layer, increased water repellency and other factors; the amount of rain that occurred with the September 2013 floods would have overwhelmed any watershed whether burned or unburned. The burned area in Fourmile Canyon Creek likely saw an earlier onset of runoff due to the effects of the fire and had a greater availability of sediment, rock and debris; however, after the first few hours of heavy rainfall, the

soils in the remainder of the unburned watershed would have reached saturation and the runoff rates would have been similar to the burned areas.

As Fourmile Canyon Creek leaves the canyon it runs parallel to Rosewood Avenue, crosses under Broadway and continues east along the north side of Violet Avenue. The channel then crosses to the south of Violet Avenue and flows southeast towards 19th Street. Between the canyon mouth and 19th Street, the channel is perched in alluvial fan deposits, which results in the potential for floodwaters that exceed the channel capacity to spill south into Wonderland Creek. Based on City inundation mapping, runoff spilled from Fourmile Canyon Creek to Wonderland Creek between Broadway and 19th Street, but spillover did not occur west of Broadway. This exacerbated flooding problems downstream on Wonderland Creek and caused flooding along Upland, Tamarack, Sumac and Riverside Avenues in the area between Fourmile Canyon Creek to the north and Wonderland Creek to the south.

The 2011 MDP indicates that flood flows that spill from the channel do not return to Fourmile Canyon Creek except where a portion of the spilled flow is conveyed north around Crestview Elementary School. While it is clear that spillover occurred from Fourmile Canyon Creek to Wonderland Creek between Broadway and 19th Street, there is insufficient data to determine how much of the flow returned to Fourmile Canyon Creek and how much continued down Wonderland Creek. Given the extent of the inundation mapping between Violet and Riverside Avenues and the Wonderland Creek inundation mapping downstream of 19th Street, it is clear that overflows from Fourmile Canyon Creek contributed to flooding on Wonderland Creek east of Broadway.

The 2011 MDP assumed that the majority of the spill to Wonderland Creek (70% of peak flows for the 100-year flood) would occur on the west side of Broadway by spilling south near present day 9th Street before reaching Broadway. This was not observed in the 2013 flood. This is believed to be the result of several potential factors. The first is the significant channel avulsion (rapid formation of a new channel) that occurred in Fourmile Canyon Creek upstream of Broadway. A new channel formed on the north side of Fourmile Canyon Creek, which conveyed a significant portion of the flood flows east through a storage unit complex and across Broadway toward Violet Park. A second potential factor is the new residential development along 9th Street south of Fourmile Canyon Creek, which was under construction during the 2013 flood. It is not known whether this development involved the placement of fill, which may have blocked a portion of the spill path identified in the 2011 MDP or if the new channel to the north alleviated the need for this flow path to the south. Regardless, the differences between the 100-year floodplain delineation and the 2013 flood extents, as shown in Appendix B, help illustrate how the 2013 flood differed from the anticipated spill flow path in the 2011 MDP.

Dr. Jarrett's estimated 2013 peak discharge just upstream of Broadway was 1,460 cfs, which indicates a peak discharge between a 25-year and 50-year return period based on interpolations from the 2011 MDP. A separate analysis conducted by BCW estimated the total peak discharge at Broadway to be 3,900 cfs, which would indicate a discharge between a 100-year and 200-year return period based on the 2011 MDP. This discharge estimate is deemed to be conservatively high because it is based on the direct summation of three separate discharge estimates including: culvert discharge under Broadway, conveyance in new avulsed channel

through the storage unit complex and across Broadway, and weir flow spills to the south. A third independent analysis by ICON estimated peak discharges of 1,800 cfs at the mouth of the canyon (upstream of Broadway) and 1,000 cfs at Riverside Lane (downstream of Broadway), both of which indicate a peak discharge between a 25-year and 50-year return period based on interpolations from the 2011 MDP, consistent with the range for Dr. Jarrett's estimate. In the 25-year to 50-year return period range, the 2011 MDP indicates a spill to Wonderland Creek upstream of 19th Street somewhere between 138 cfs and 1,484 cfs, which appears reasonable given the flooding extents shown in Appendix B.

Another factor that potentially affected the spill to Wonderland Creek was that Crestview Elementary School was apparently enlarged into the floodplain after the MDP was developed. According to BCW the enlarged school footprint blocked previous flood conveyance flow paths and worsened the flood situation at the school. This may have diverted some of the flow back to Fourmile Canyon Creek as opposed to Wonderland Creek.

Downstream of 19th Street, Fourmile Canyon Creek continues southeast crossing 28th Street and then turns east crossing 47th Street and Highway 119. Dr. Jarrett's estimated 2013 peak discharge just upstream of Highway 119 was 2,300 cfs, which indicates a peak discharge between a 100-year and 500-year return period. However, this range is based on the assumption in the 2011 MDP that a significant spill occurs to Wonderland Creek during large flood events. As noted previously, significant spills from Fourmile Canyon Creek into Wonderland Creek were not observed west of Broadway, where a large portion of the overflow was expected to occur. The 2011 MDP also included modeled peak discharges in Fourmile Canyon Creek assuming no spills to Wonderland Creek. Based on these results, the estimated peak discharge of 2,300 cfs is in the range of a 50-year to 100-year flood. The actual 2013 flood event appears to have fallen somewhere in between these two scenarios (no spills west of Broadway but overflow to the east between Broadway and 19th Street), indicating roughly a 100-year peak discharge, which is substantiated by the close comparison between the mapped inundation areas and the published 100-year floodplain. Downstream of Highway 119, the channel meanders through mostly undeveloped land before reaching the confluence with Boulder Creek.

In the Wonderland Creek watershed, the creek flows east from Wonderland Lake crossing Broadway and continues east to 26th Street through a large-lot residential area in a relatively small, unimproved channel. The estimated 2013 peak discharge just downstream of Broadway at 15th Street was 170 cfs and indicates a peak discharge between a 5-year and 10-year return period based on the 2011 MDP. The peak discharge at this location was most likely influenced by attenuation of flood flows through Wonderland Lake since the peak rainfall occurred early in the storm and storage volume may have been available in the lake.

Downstream of 26th Street, Wonderland Creek flows southeast in an improved channel with major crossings at 28th Street, Highway 119, Foothills Parkway, and Valmont Road before discharging on the left bank of Goose Creek near the confluence with Boulder Creek. It should be noted that the improvements made to the lower reach of Wonderland Creek were designed based on a 100-year conveyance capacity that did not consider potential spills from Fourmile Canyon Creek upstream of 19th Street. No peak discharge estimates were obtained in the lower

reaches of Wonderland Creek; however, with spillover from Fourmile Canyon Creek between Broadway and 19th Street, runoff from Fourmile Canyon Creek worsened flooding along lower reaches of Wonderland Creek

9.1 Rainfall

Table 8 shows return periods calculated for various rainfall durations from the 2013 flood event in the Fourmile Canyon Creek and Wonderland Creek watersheds. Rainfall "pseudo" gage locations and locations of flow estimates are shown in Appendix A. Within the upper and middle Fourmile Canyon Creek sub-watersheds west of the City (FCC 1 and FCC 2), maximum 5-minute rainfall depths for these sub-watersheds were approximately one-third of the maximum 5-minute depths used in the 2011 MDP 100-year design storm (2-hour storm with sharp peak at 30-minutes). Maximum 1-hour rainfall depths correspond to between NOAA 10- and 50-year design rainfall depths, which are consistent with the peak discharge estimates developed by Dr. Jarrett at these locations. For durations of 3 to 12 hours, the maximum rainfall depths from the 2013 flood were in the range of a 100- to 200-year NOAA design rainfall depths. The maximum 24-hour rainfall depths were approximately 8.5 inches, which are greater than the NOAA 1,000-year, 24-hour design rainfall depths.

Table 8 – Summary of "Worst Case" Precipitation Duration, Depth and Return Periods for Fourmile Canyon Creek and Wonderland Creek Watersheds in September 2013 Flood

Duration	Upper Fourmile Canyon Creek Watershed (FCC 1)		Middle Fourmile Canyon Creek Watershed (FCC 2)		Lower Fourmile Canyon Creek Watershed above Highway 36 (FCC 3)		Lower Fourmile Canyon Creek Watershed below Highway 36 (FCC 4)		Upper Wonderland Creek Watershed (WC 1)		Lower Wonderland Creek Watershed (WC 2)	
	Depth (in)*	Est. Return Period (yr)**	Depth (in)	Est. Return Period (yr)	Depth (in)	Est. Return Period (yr)	Depth (in)	Est. Return Period (yr)	Depth (in)	Est. Return Period (yr)	Depth (in)	Est. Return Period (yr)
5-min	0.21	1	0.23	2	0.26	2	0.19	< 1	0.25	2	0.27	3
10-min	0.42	3	0.43	3	0.49	5	0.36	2	0.48	5	0.53	6
15-min	0.59	5	0.59	5	0.68	7	0.52	3	0.68	7	0.78	10
30-min	1.00	10	1.09	10	1.30	20	0.92	7	1.31	20	1.47	30
60-min	1.81	40	1.66	25	2.00	45	1.32	10	1.99	45	2.50	100
2-hr	2.39	60	2.62	75	2.74	80	1.64	10	2.77	85	3.06	>100
3-hr	3.13	>100	3.46	~200	3.39	>100	2.50	40	3.57	~200	3.87	>200
6-hr	4.10	>200	4.48	300	4.73	>300	4.28	~200	5.12	~500	5.87	~1,000
12-hr	4.87	~200	5.13	>200	5.36	>200	4.91	~200	5.60	>300	6.55	>500
24-hr	8.49	> 1,000	8.84	> 1,000	8.11	880	7.32	580	8.41	> 1,000	8.91	> 1,000

*Note: Radar rainfall data provided from 9/11/13 6:00 pm on September 11 to 6:00 am on September 13, 2013. Rainfall for each sub-watershed is based on area-weighted compositing of 5-minute gage-corrected, radar-based hyetograph data.

**Estimated return periods are rounded.

The lower Fourmile Canyon Creek sub-watersheds east of the foothills (FFC 3 and FFC 4) experienced more intense rainfall in the early part of the storm (evening of September 11th) than the upper sub-watersheds, but had less total rainfall over the 36-hour period. The lower sub-watersheds did not experience the later surges in rainfall intensity on September 12th that the upper sub-watersheds did. Similar to the upper sub-watersheds, the maximum 5-minute rainfall depths were approximately one-third of the maximum 5-minute depths used in the 2011 MDP 100-year design storm. Maximum 1-hour rainfall depths for these sub-watersheds corresponded to between NOAA 10-year and 50-year design rainfall depths.

The Wonderland Creek sub-watersheds (WC 1 and WC 2) experienced a similar multi-modal rainfall distribution with an initial intense period of rainfall on the evening of September 11th. These sub-watersheds also experienced an additional surge of rainfall on the evening of September 12th when soils would have been saturated; however, intensities were lower than the initial surge on the 11th. The maximum 24-hour rainfall depth for the Wonderland Creek watershed was 8.5 inches which is greater than the NOAA 1,000-year, 24-hour design rainfall depth.

9.2 Runoff

Runoff measurements by Dr. Jarrett are summarized in Table 9 and compared against the peak discharges for various return periods provided in the 2011 MDP. The peak discharges from the 2011 MDP are based on 1-hour rainfall depths (slightly different than current NOAA rainfall depths) applied to a 2-hour UDFCD storm distribution. The estimated peak discharges by Dr. Jarrett for the upper reaches of Fourmile Canyon Creek indicate a 25-year to 50-year flood, consistent with the 1-hour rainfall depth return periods for sub-watersheds FCC 1 and FCC 2, which correspond to approximately the same locations.

Table 9 – September 2013 Peak Flow Estimates for Fourmile Canyon Creek and Wonderland Creek Watersheds

Location	Jarrett Estimated 2013 Peak Discharge (cfs)	Estimated Return Period (yr) from 2011 MDP
Fourmile Canyon Creek at 55 Pinto Drive near Anne U. White Trailhead	1,080	25-yr to 50-yr[+] (723 cfs to 1,231 cfs)
Fourmile Canyon Creek upstream of Broadway	1,460	25-yr to 50-yr[*+] (1,282 cfs to 1,842 cfs)
		10-yr to 25-yr[**+] (794 cfs to 1,589 cfs)
Fourmile Canyon Creek upstream of Highway 119 (Diagonal Highway)	2,300	100-yr to 500-yr [*] (1,757 cfs to 2,500 cfs)
		50-yr to 100-yr [**] (1,905 cfs to 2,594 cfs)
Wonderland Creek at 15th Street downstream of Broadway	170	5-yr to 10-yr (150 cfs to 205 cfs)

[*] Peak discharges and return periods assume flow spills to Wonderland Creek upstream of this location.
[**] Peak discharges and return periods assume no spills to Wonderland Creek upstream of this location.
[+] Estimated return period interpolated using the 2011 MDP.

Further downstream on Fourmile Canyon Creek at Highway 119, the estimated peak discharge of 2,300 cfs is in the range of a 100-year to 500-year flood. However, this range is based on the assumption in the 2011 MDP that a significant spill occurs to Wonderland Creek during large flood events. As noted previously, significant spills from Fourmile Canyon Creek into Wonderland Creek were not observed west of Broadway, and the extent of the spill east of Broadway cannot be easily quantified. The 2011 MDP also included modeled peak discharges in Fourmile Canyon Creek assuming no spills to Wonderland Creek. Based on these results, the estimated peak discharge of 2,300 cfs is in the range of a 50-year to 100-year flood. The actual 2013 flood event appears to have fallen somewhere in between these two scenarios indicating a 100-year peak discharge, which is substantiated by the close comparison between the mapped inundation areas in Appendix B and the published 100-year floodplain. Considering the larger watershed area and longer travel time through the watershed to this location, it seems reasonable to consider a longer storm duration. The maximum 2-hour rainfall depths from the 2013 flood correspond to between a NOAA 50-year and 100-year design rainfall depth, consistent with the peak discharge estimate.

On Wonderland Creek, the estimated peak discharge downstream of Broadway at 15th Street was 170 cfs and is in the range of a 5-year to 10-year flood based on the 2011 MDP. This location is not impacted by potential spills from Fourmile Canyon Creek. The tributary drainage area to this location is less than one square mile and was most likely influenced by attenuation of flood

flows through Wonderland Lake since the peak rainfall occurred early in the storm and storage volume may have been available in the lake. The lower reach of Wonderland Creek had the highest rainfall intensities and largest total rainfall depths for all storm durations. The rainfall analysis indicates that a 100-year flood likely occurred in this location. The 2013 flood extents shown in Appendix B also generally match well with the 100-year floodplain. Unfortunately a peak discharge estimate in the lower reaches of Wonderland Creek was not obtained to confirm the 100-year estimate; however, spills from Fourmile Canyon Creek to Wonderland Creek between Broadway and 19th Street help to explain the contrast between the relatively modest flooding in the upper reaches of Wonderland Creek and the substantial flooding that occurred in the lower reaches.

9.3 Summary

Given the hydrologic uncertainty in peak discharge estimates (+/- 20%), assumptions made in the *Fourmile Canyon Creek and Wonderland Creek Major Drainageway Planning Report* (2011) relative to spills between the two watersheds, and other factors, the rainfall and runoff relationships for Fourmile Canyon Creek and Wonderland Creek watersheds generally make sense. The rainfall data analysis and peak discharge estimates support observations in the field that there was not a significant spill from the Fourmile Canyon Creek watershed to the Wonderland Creek watershed west of Broadway; however, it is clear from inundation mapping that spillover did occur between Broadway and 19th Street.

The peak discharge estimates for Fourmile Canyon Creek at the Anne U. White Trailhead (1,080 cfs) and upstream of Broadway (1,460 cfs) indicate a discharge with a 25-year to 50-year return period. This return period range is also consistent with the NOAA 1-hour design rainfall depths, which are close to the values used in the 2011 MDP design storms.

Further downstream on Fourmile Canyon Creek at Highway 119, the estimated peak discharge of 2,300 cfs is in the range of a 50-year to 100-year flood (assuming no spills to Wonderland Creek). Considering the larger watershed area and longer travel time through the watershed to this location, the maximum 2-hour rainfall depths from the 2013 flood correspond to between a NOAA 50-year and 100-year design rainfall depth, consistent with the peak discharge estimate.

On Wonderland Creek, the estimated peak discharge at 15th Street is in the range of a 5-year to 10-year flood. The tributary drainage area to this location is less than one square mile and was most likely influenced by attenuation of flood flows through Wonderland Lake since the peak rainfall occurred early in the storm and storage volume may have been available in the lake. The lower reach of Wonderland Creek had the highest rainfall intensities and largest total rainfall depths for all storm durations. The rainfall analysis and 2013 flood extents in Appendix B indicate that a 100-year flood likely occurred in this location; unfortunately a peak discharge estimate in the lower reaches was not obtained to confirm this.

10.0 Boulder Creek

The Boulder Creek Watershed contains 440 square miles of drainage area, including 130 square miles above the City of Boulder. The watershed is oriented west to east from the Continental Divide to its confluence with the Saint Vrain Creek. The watershed ranges in elevation from approximately 5,358 feet above mean sea level to 13,409 feet at Navajo Peak. The basin is primarily mountains and foothills and is characterized by steep streams with rock and gravel beds. As Boulder Creek emerges from the mountains, its valley widens to form a broad flat floodplain. East of the City of Boulder, Boulder Creek flows through a wide and generally undeveloped floodplain, with several major road crossings. Anderson Consulting Engineers completed the current regulatory hydraulic model and floodplain mapping for Boulder Creek in 2012 and this was adopted by FEMA in 2013.

The figures in Appendix A show the Boulder Creek watershed with locations of estimated peak flows and rainfall gage locations used for analysis. For purposes of this analysis, WWE analyzed the Boulder Creek watershed using four sub-watersheds: West Boulder Creek (sub-watershed containing the headwaters of Boulder Creek), West-Central Boulder Creek (sub-watershed containing Nederland), East-Central Boulder Creek (sub-watershed just west of the City of Boulder), and East Boulder Creek (sub-watershed containing the City of Boulder). These sub-watersheds were selected to refine earlier analysis due to west-east trends in precipitation.

10.1 Rainfall

Table 10 shows return periods calculated for various rainfall durations in the Boulder Creek watershed. The 100-year design storm for the Boulder Creek watershed was developed as a part of the 1977 U.S. Army Corps of Engineers (USACE) study. A more recent analysis of the Boulder Creek watershed developed in 2009[8] confirmed and revised the 1977 study. This Hydrology Verification Report for Boulder Creek uses a 6-hour storm distribution which WWE used to compare against the rainfall depths and intensities that occurred during the September 2013 storm.

During the 2013 flood, precipitation depths and intensities generally increased from west to east with total rainfall from September 11-13 of approximately 2.6 inches in the West Sub-watershed increasing to approximately 4.4 inches in the West-Central Sub-watershed, approximately 7.3 inches in the East-Central Sub-watershed, and approximately 9.7 inches in the East Sub-watershed. As Table 10 shows, rainfall return periods for 6-hour durations ranged from a 25- to greater than a 300-year event for the worst case 6-hours of the event. It is notable that the West Sub-watershed only experienced one pulse of intense rainfall; however, the eastern sub-watersheds exhibited up to three pulses of precipitation. Shorter duration rainfall intensities (e.g. maximum 5-minute depths) were considerably less than 100-year design storm values with design storm values being approximately three to six

[8] Anderson Consulting Engineers, Inc., "Hydrology Verification Report for Boulder Creek," prepared for the City of Boulder, October 2009.

times greater than maximum 5-minute depths of approximately 0.15 inches observed during the flood.

Interestingly, several tributary watersheds of Boulder Creek including Dry Creek watershed, Phelps Drainage watershed, and Sunshine Canyon Creek watershed did not exhibit a pattern of increasing precipitation depths and intensities from west to east. Table 10 shows that the rainfall return period for a 6-hour duration storm in the Sunshine Canyon Creek watershed was approximately a 300-year event, while Phelps Drainage and Dry Creek watersheds further east experienced only between a 75- to 100-year event. However, similar to the Boulder Creek watershed, these tributaries had 5-minute depths considerably less than 100-year design storm values with maximum 5-minute depths of approximately 0.15 inches. Even though the short duration intensities reported in Table 10 are considerably lower than those used in the 100-year design storm, the rocky soils and shallow bedrock in the upper sub-watersheds limit the total volume of infiltration, and intense periods of rainfall later in the event, when soils were saturated, produced significant runoff and debris flows.

Table 10 – Summary of "Worst Case" Precipitation Duration, Depth and Return Periods for Boulder Creek Watershed in September 2013 Flood

Duration	West Boulder Creek		West-Central Boulder Creek		East-Central Boulder Creek		East Boulder Creek		Sunshine Canyon		Phelps Drainage		Dry Creek	
	Depth (in)*	Est. Ret. Per. (yr)**	Depth (in)	Est. Ret. Per. (yr)	Depth (in)	Est. Ret. Per. (yr)	Depth (in)	Est. Ret. Per. (yr)	Depth (in)	Est. Ret. Per. (yr)	Depth (in)	Est. Ret. Per. (yr)	Depth (in)	Est. Ret. Per. (yr)
5-min	0.13	1	0.08	0	0.07	0	0.14	1	0.16	1	0.17	1	0.14	1
10-min	0.24	1	0.17	1	0.14	0	0.27	1	0.32	1	0.33	1	0.26	1
15-min	0.34	1	0.25	1	0.21	1	0.39	1	0.43	2	0.47	2	0.38	1
30-min	0.59	2	0.48	1	0.41	1	0.72	3	0.75	4	0.78	4	0.71	3
1-hr	0.97	7	0.90	6	0.80	3	1.22	10	1.29	10	1.11	6	1.18	7
2-hr	1.56	25	1.55	30	1.30	8	1.82	20	2.26	40	1.53	10	1.80	15
6-hr	2.06	25	2.28	50	2.88	70	4.69	>300	4.46	~300	3.82	>100	3.40	75
12-hr	2.21	15	2.58	30	3.09	35	5.17	~200	4.73	>100	4.51	>100	3.79	50
24-hr	2.37	7	3.18	25	5.66	~200	8.23	>500	8.01	>500	6.83	~400	6.40	>300

*Note: Radar rainfall data provided from 9/11/13 6:00 pm to 6:00 am on 9/13/13. Rainfall for each sub-watershed is based on area-weighted compositing of 5-minute gage-corrected, radar-based hyetograph data.

** Estimate return periods are rounded.

10.2 Runoff

Runoff estimates that were based on post-event measurements of high water marks and other evidence by Dr. Jarrett, the Colorado Division of Water Resources, the Colorado Water Conservation Board, and the U.S. Geological Survey, are summarized in Table 11. Inundation mapping from the September 2013 flood is provided in Appendix B. To understand the flooding that occurred along Boulder Creek during the September flood, it is important to recognize that the creek characteristics change dramatically over a short distance as it passes through the City. The creek goes from a steep mountain stream, to an urban waterway/greenway within the City, to a plains stream downstream of the City with a broad floodplain and meandering channel. Runoff estimates indicate that peak flows in the upper Boulder Creek watersheds ranged from less than a 10-year to an approximate 15-year event. Through the City, the peak flow estimates increase to an approximate 25-year event. East of the City, near the City of Boulder Wastewater Treatment Plant, the runoff estimates were approximately equivalent to a 25-year event, where Boulder Creek spread out across a broad floodplain, flowing into many gravel pit lakes along the corridor. In many areas, gravel pit embankments overtopped or breached, connecting a broad floodplain. This study did not evaluate runoff further to the east than the wastewater treatment plant; however, there were significant contributions of runoff from the tributaries that join Boulder Creek in the eastern part of the City as well as Coal Creek and Rock Creek further downstream.

Table 11 – September 2013 Peak Flow Estimates for Boulder Creek and Major Tributaries West of City

Location	Peak Flow Estimate (cfs)	Comments and Source of Data	Estimated Runoff Return Period (year)	Q_{100} (cfs)
Middle Boulder Creek at Nederland	409	CDWR	< 10	825
North Boulder Creek d/s CO Hwy 72 nr Nederland	340	Jarrett	-----	-----
North Boulder Creek u/s Boulder Creek and CO Hwy 119 nr Orodell	740	Jarrett--Canyon rockfall risk; poor estimate	-----	-----
Boulder Creek u/s Keystone Gulch nr Orodell	1,560	Jarrett	-----	-----
Boulder Creek @ Orodell (above Fourmile)	2,020	CDWR--Peak on Sept. 12 23:30	10 - 15	7,080
Fourmile Creek u/s burned area	490	Jarrett	-----	-----
Fourmile Creek d/s Poorman Rd u/s #1267 Fourmile Cr Rd nr Orodell	2,300	Jarrett--USGS gage nr mouth (not much d/s inflow)	~20	5,570
Boulder Creek @ Broadway	~5,000	UCAR estimate based on CDWR	25	12,000
Boulder Creek @ 28th Street	5,300	CWCB	25	~11,500
Boulder Creek at 75th St in Boulder	8,400	USGS--Provisional Data	25-50	~13,000

10.3 Summary

While rainfall durations of 6 hours and greater produced rainfall depths that had return periods of 25 to greater than 100 years, rainfall depths over shorter durations had lower return periods. Peak flows in the Boulder Creek watershed increased from less than a 10-year event in the upper watershed to an approximate 25-year event through the City, to a 25- to 50-year event further east.

11.0 Conclusions

Based on the detailed analysis presented above, the following are general conclusions that can be drawn from the analysis:

- For longer durations, watersheds in the City experienced very infrequent return periods (e.g. 100-year, 500-year, 1,000-year). Shorter durations have lesser return periods and for sub-hour durations in many cases rainfall return periods corresponded to less than a 10-year event. Peak intensities never rose to the levels used in the 100-year design storms, and the runoff response in many cases was less than a 100-year return period. When evaluating rainfall for short-duration return periods and the resulting runoff, it is important to keep in mind that in many watersheds, there were several "waves" of intense rainfall over the duration of the storm, and the rainfall that occurred later in the storm was on saturated ground, and the runoff response would be magnified beyond what the rainfall return period would indicate.
- The comparisons with design storms demonstrate that the assumptions relative to the temporal distribution of rainfall are conservative (e.g. high intensities over short durations). In most cases, peak rainfall intensities from the actual September event were no more than ⅓ to ½ of design storm values and did not produce the peak flow rates that the design storm produces for the same amount of rainfall due to the temporal and spatial distribution of rainfall.
- The runoff response typically was between a 25- and 50-year event for many watersheds; however, some watersheds including lower portions of South Boulder Creek, Upper Twomile Canyon Creek and the lower portion of Fourmile Canyon Creek experienced flows on the order of a 100-year event or greater. In many areas, peak flow estimates were unavailable, so WWE relied on City inundation mapping from the September 2013 flood.
- Inundation mapping from the September 2013 flood generally showed the floodplain within the regulatory 100-year floodplain boundaries. In cases where flooding occurred outside of the regulatory 100-year floodplain, it was typically due to overflows at intersections and effects of culvert/bridge blockage. The assumption for most floodplain mapping in Boulder and throughout the country is for "clear water" flows (e.g. not including sediment, rocks, and debris), and effects of debris in many watersheds were significant, especially in the western parts of the City.
- Landslides, mud and debris flows were common in the upper mountainous portions of the watershed. Contributions of sediment, rock and debris from upper portions of the watershed influenced flow paths and affected storm sewer and other conveyance capacity in the areas where the canyons enter the City.

Additional details of the analyses performed for the watersheds addressed in this report, including 5-minute hyetographs for each sub-watershed analyzed, can be found in the technical memoranda that WWE prepared for the City of Boulder. These technical memoranda are available on request from the City.

12.0 References

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13.0 Appendices

Appendix A: Worst Case Rainfall Return Periods Maps (Figures 1 -19)

Appendix B: City of Boulder September 2013 Flood Inundation Mapping

Appendix A
Worst Case Rainfall Return Periods Maps (Figures 1 -19)

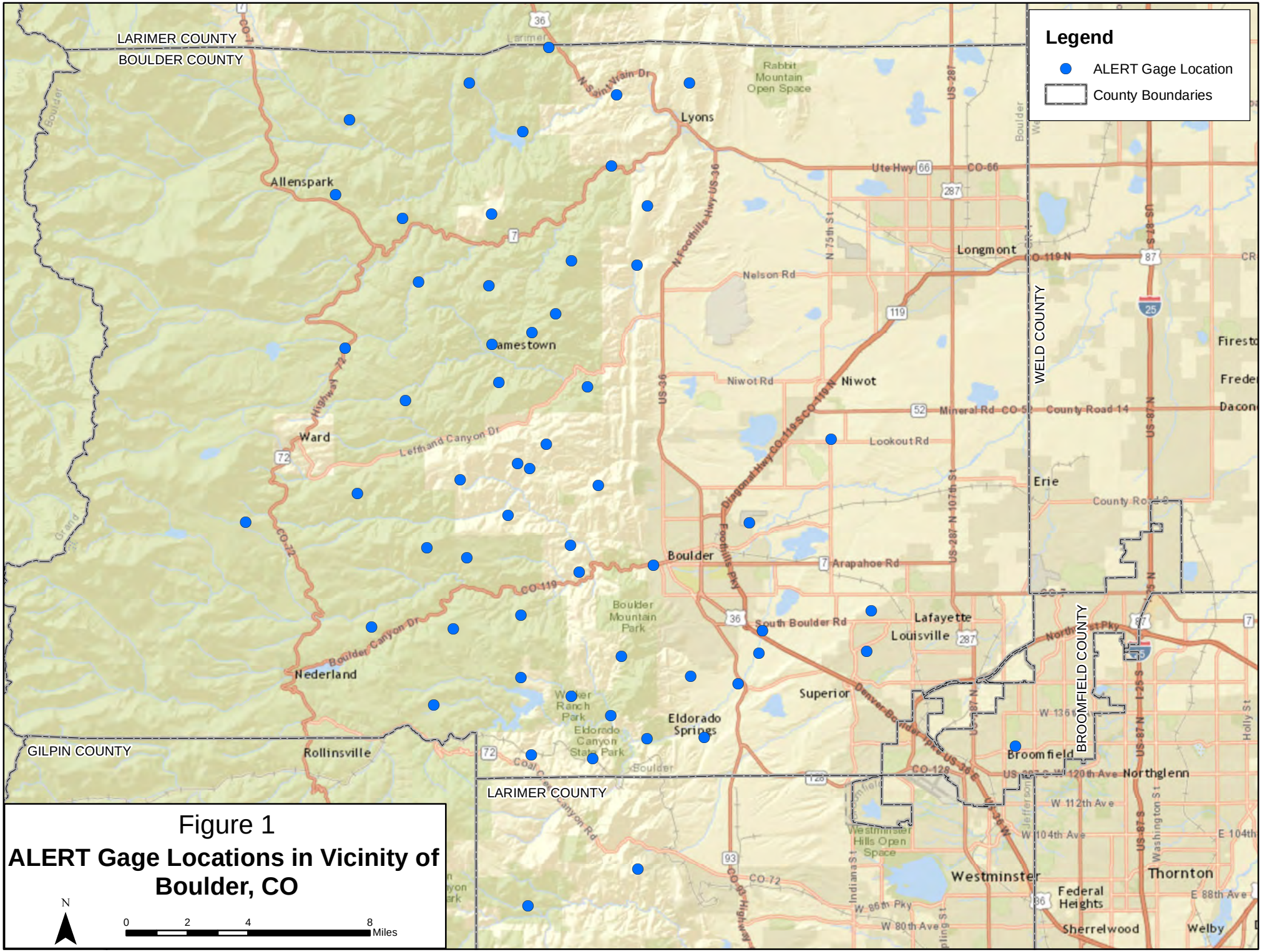

Figure 1

ALERT Gage Locations in Vicinity of Boulder, CO

N

0 2 4 8 Miles

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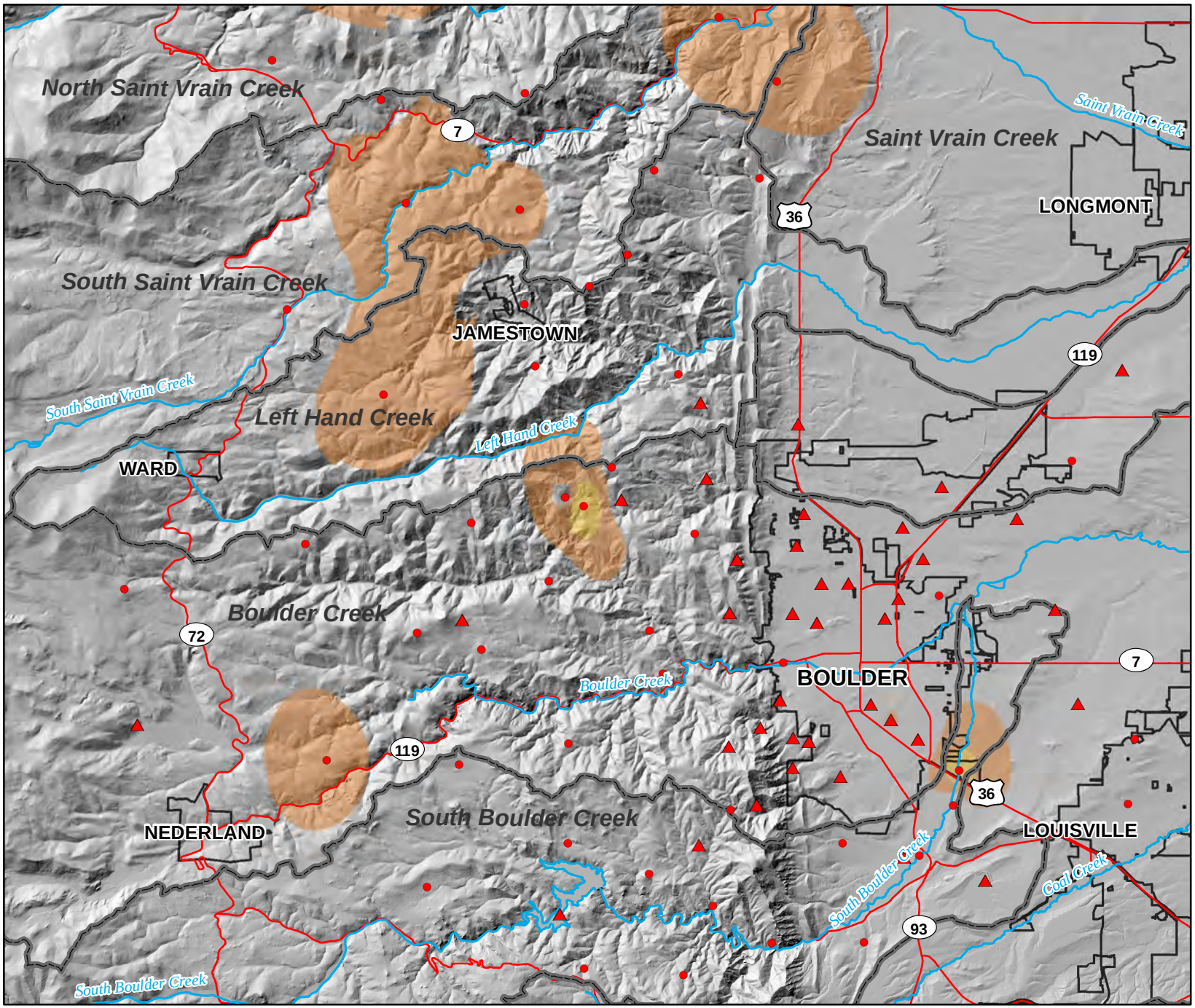

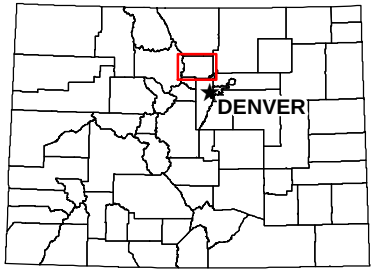

Legend

- 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

Watershed-Scale Extent

5-minute Worst Case Rainfall Return Periods 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

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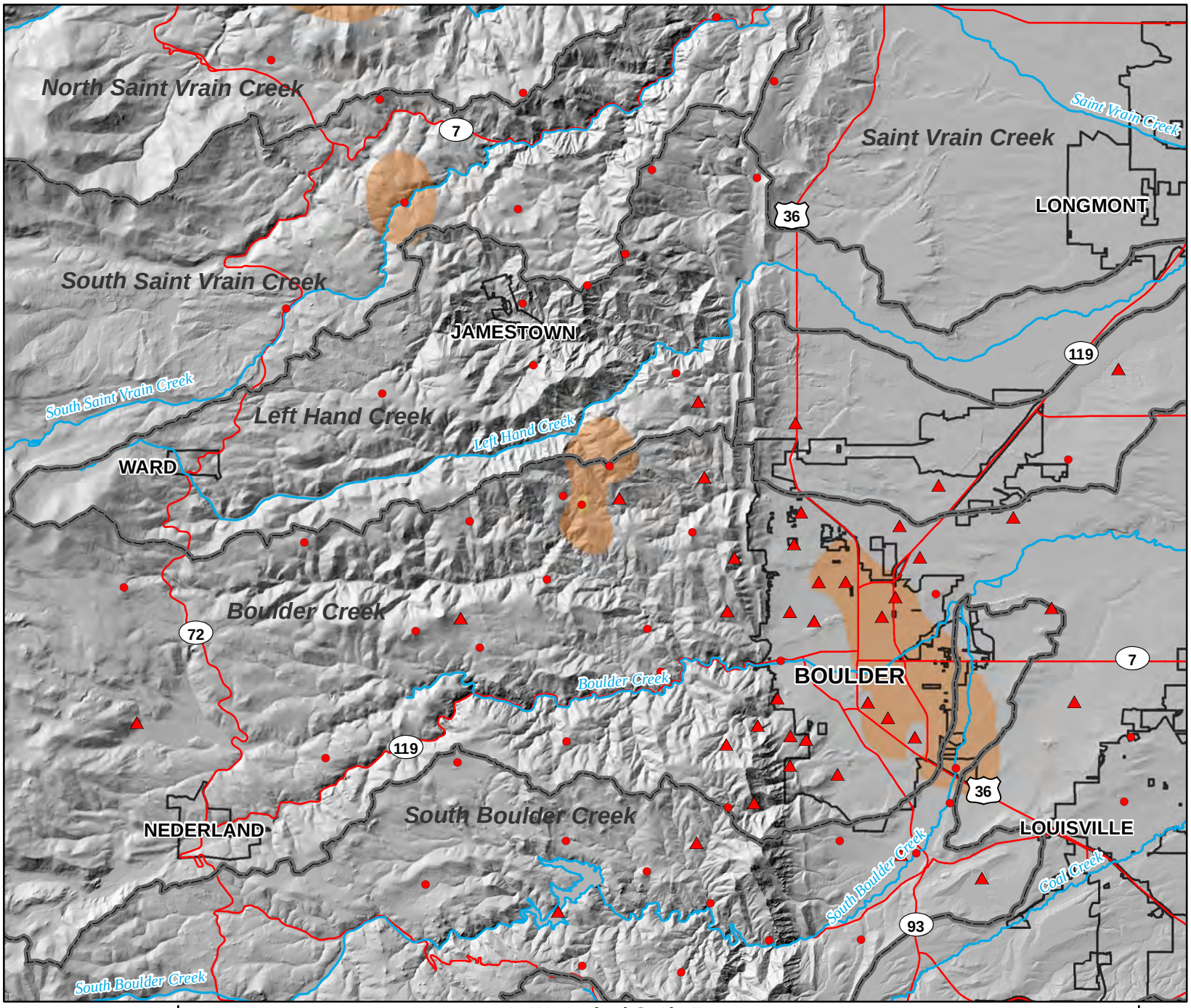

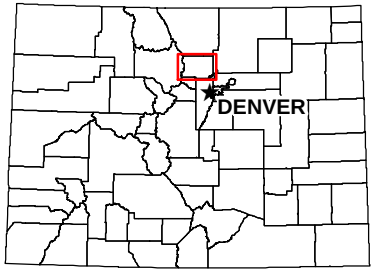

Legend

- 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

Watershed-Scale Extent

10-minute Worst Case Rainfall Return Periods for City of Boulder & Vicinity

September 9-16, 2013 Flood Event

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2490 W 26TH AVE 100A
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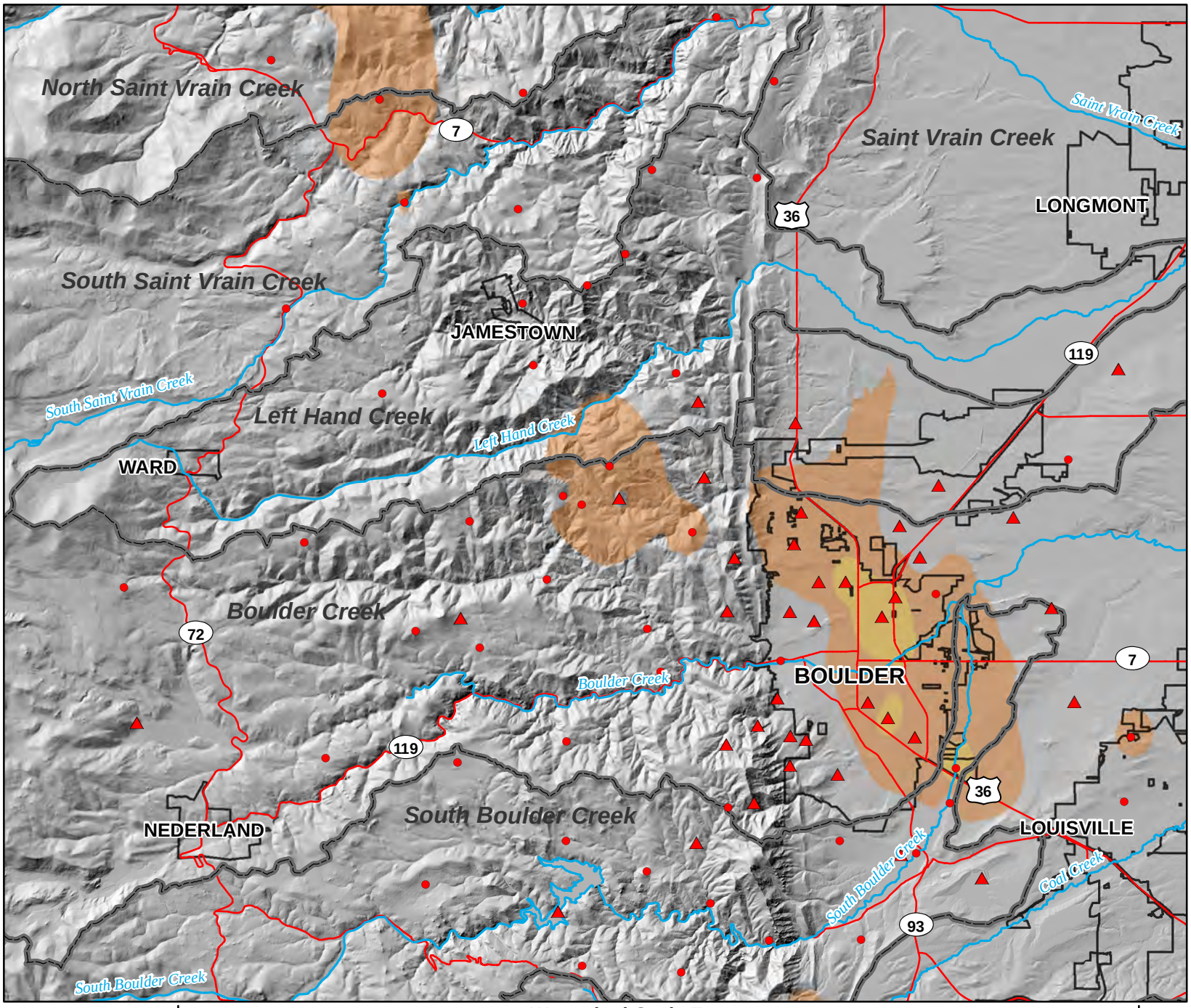

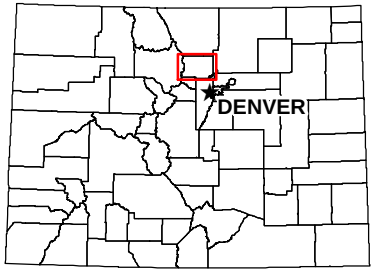

Legend

- 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

Watershed-Scale Extent

15-minute Worst Case Rainfall Return Periods for City of Boulder & Vicinity

September 9-16, 2013 Flood Event

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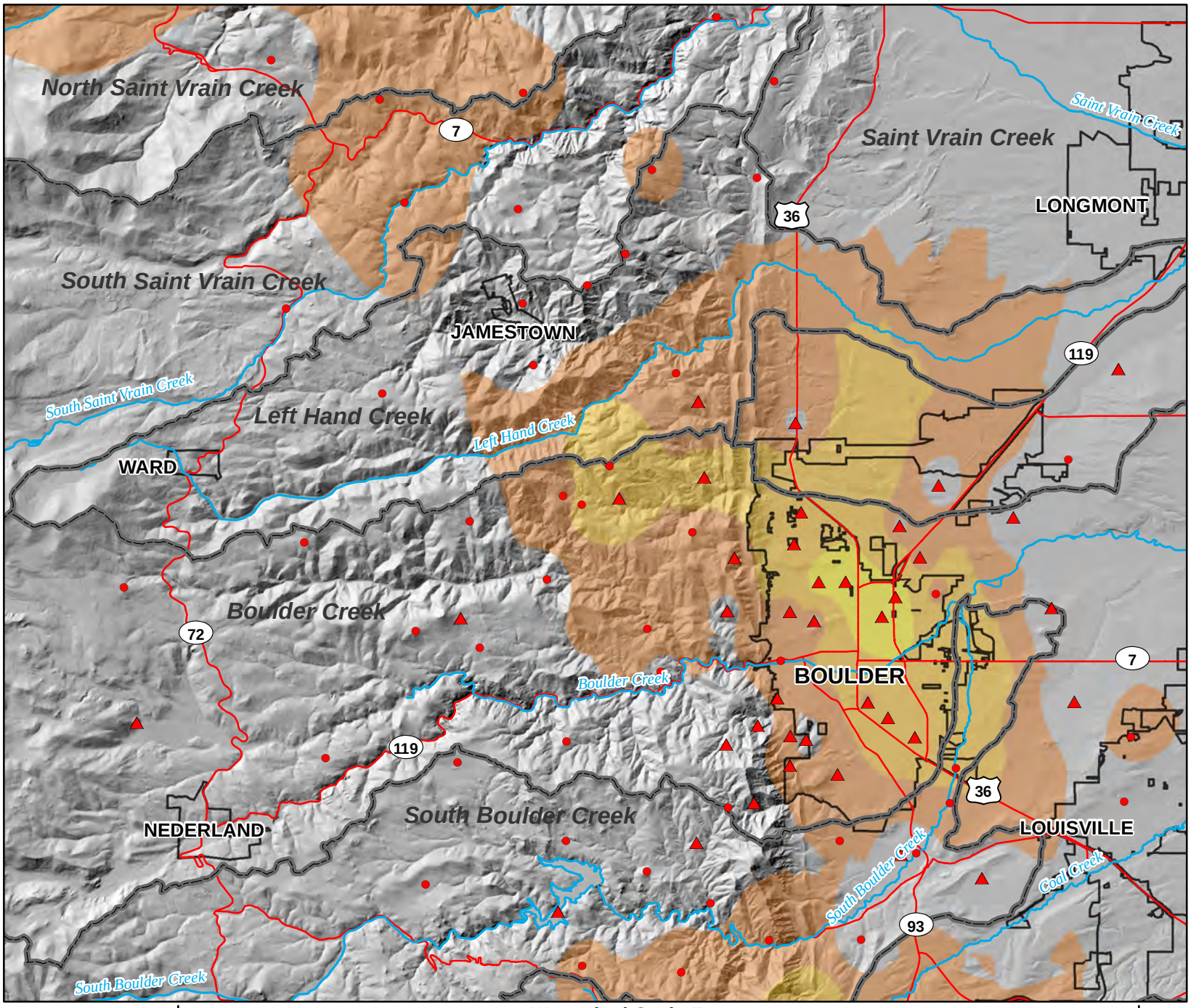

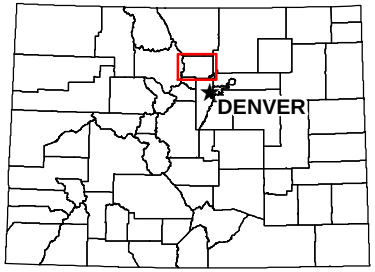

Legend

- 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

Watershed-Scale Extent

30-minute Worst Case Rainfall Return Periods for City of Boulder & Vicinity

September 9-16, 2013 Flood Event

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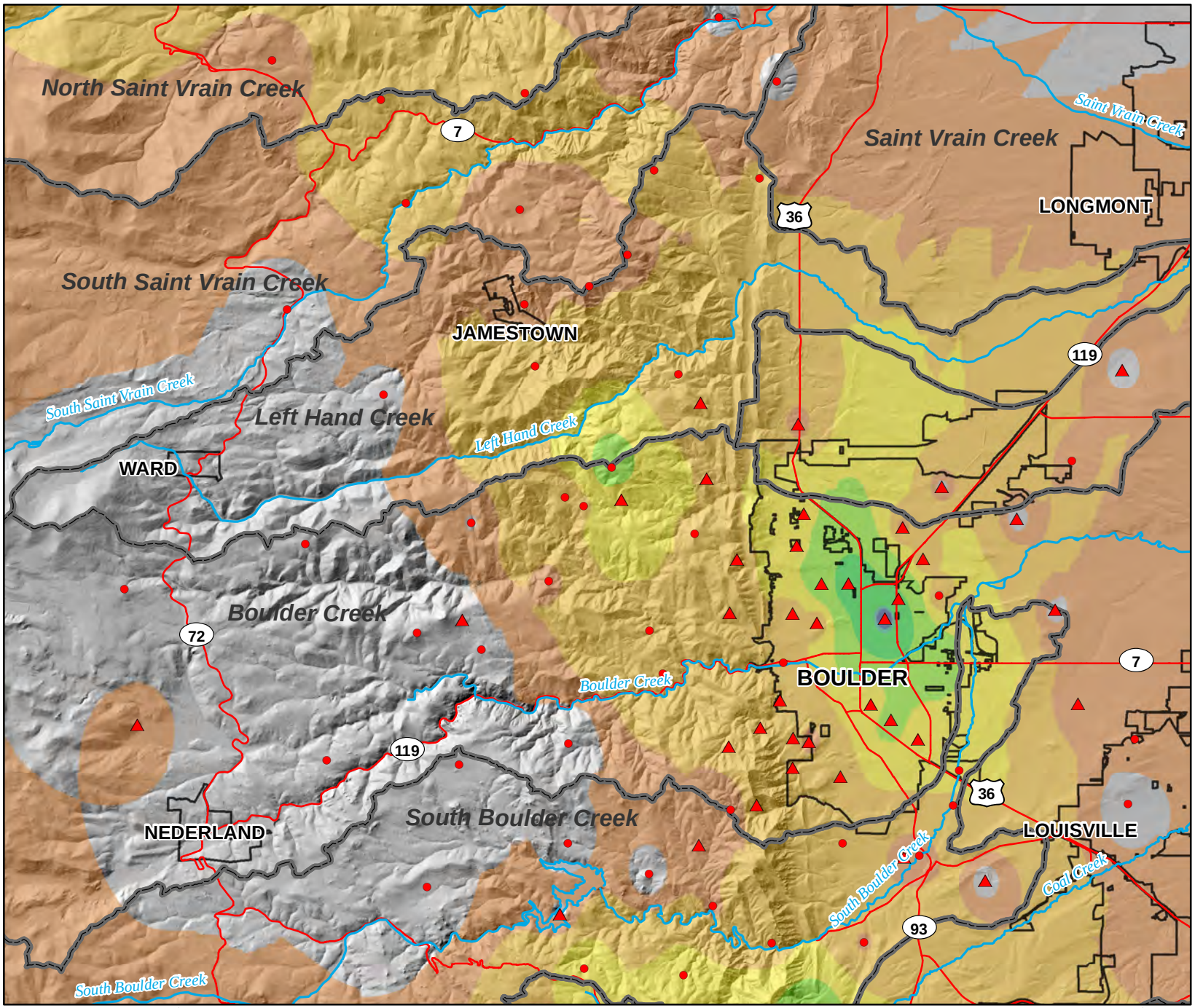

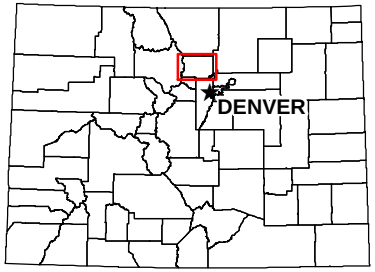

Legend

- 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

Watershed-Scale Extent

1-hour Worst Case Rainfall Return Periods for City of Boulder & Vicinity

September 9-16, 2013 Flood Event

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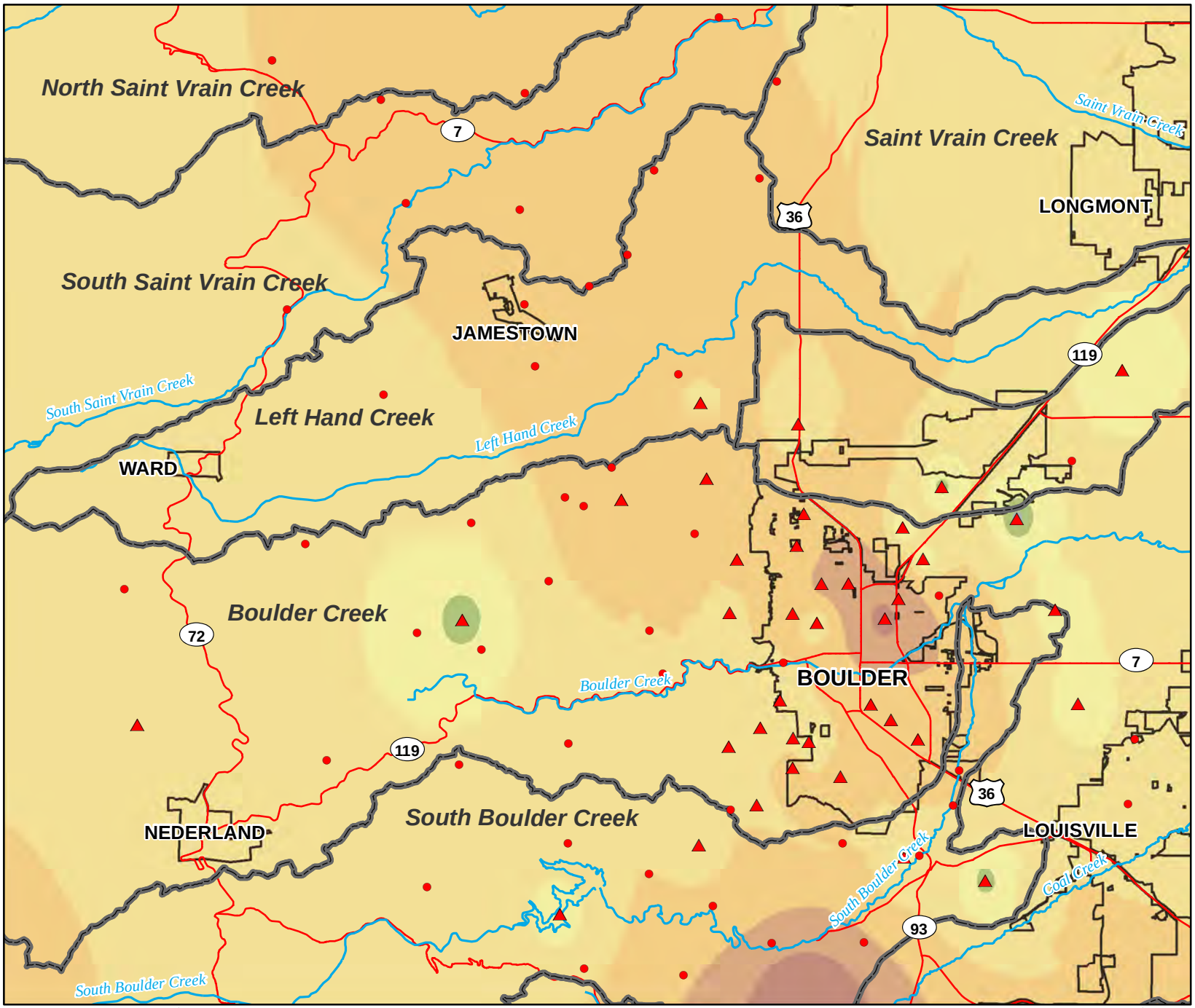

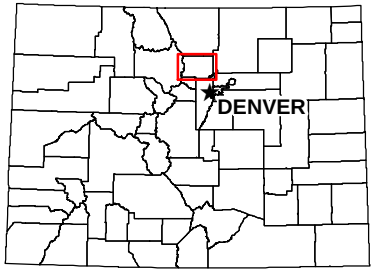

Legend

- 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

Watershed-Scale Extent

2-hour Worst Case Rainfall Return Periods for City of Boulder & Vicinity

September 9-16, 2013 Flood Event

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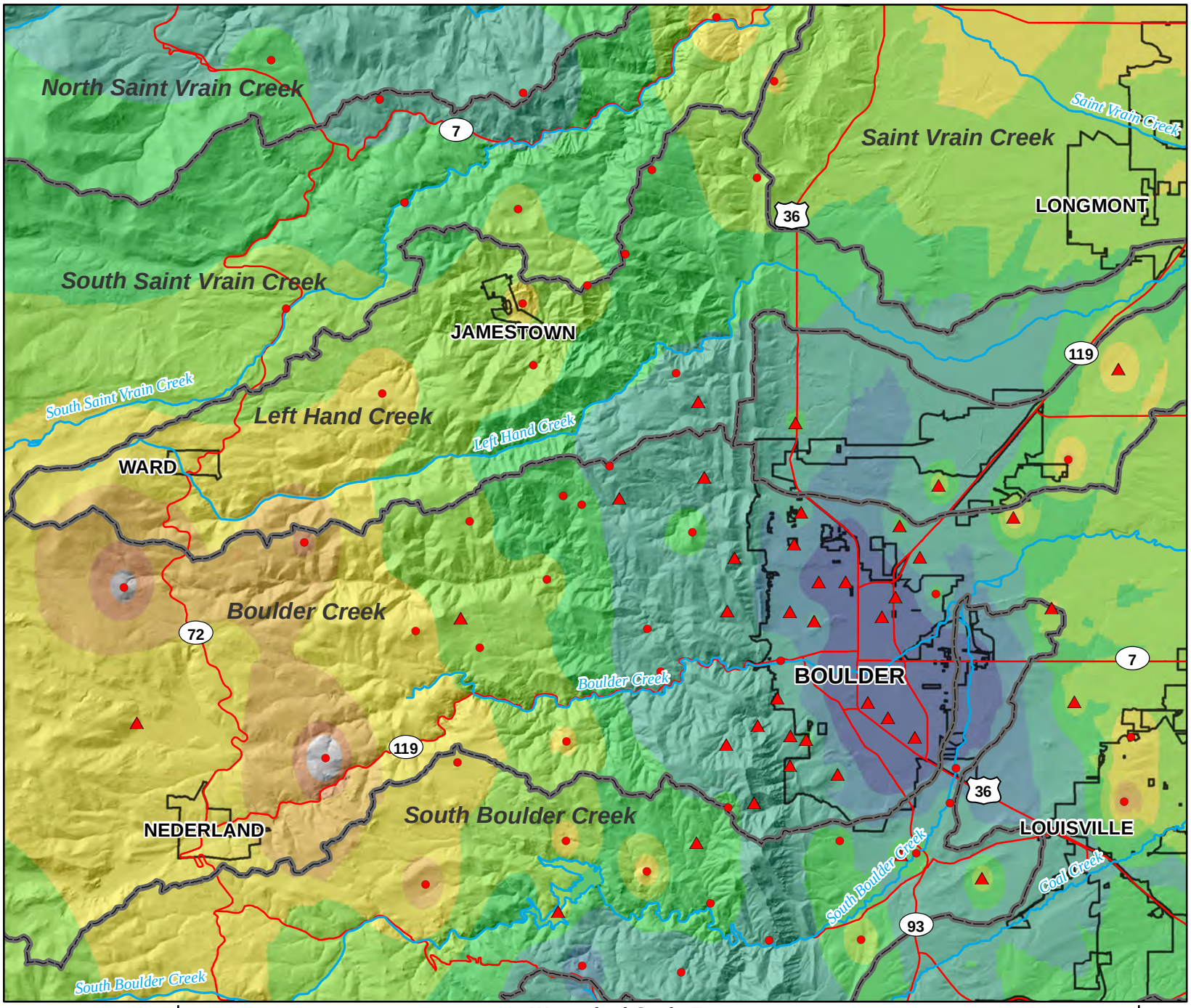

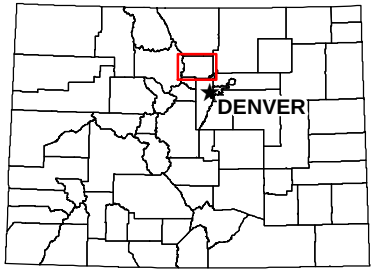

Legend

- 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

Watershed-Scale Extent

6-hour Worst Case Rainfall Return Periods for City of Boulder & Vicinity

September 9-16, 2013 Flood Event

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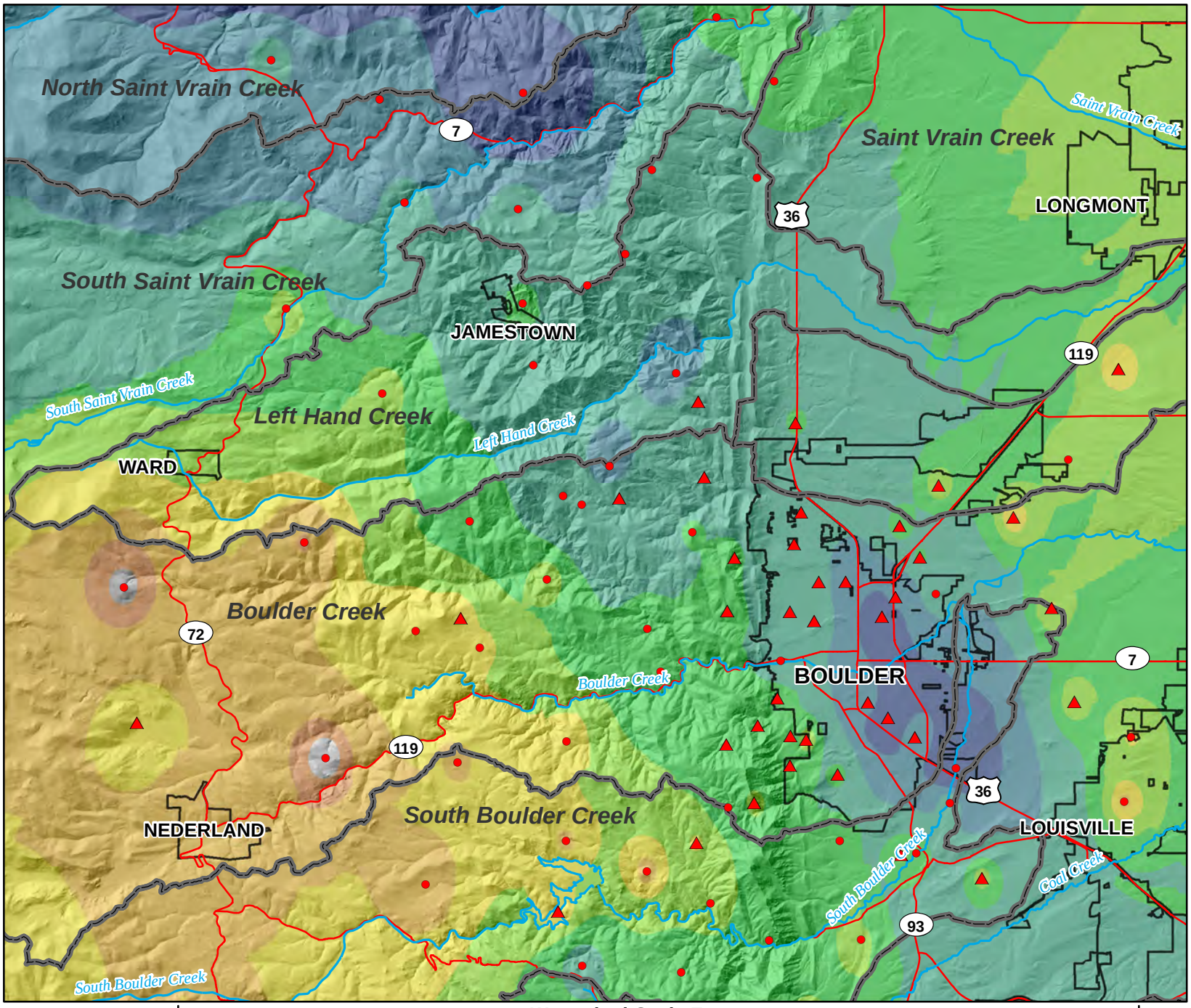

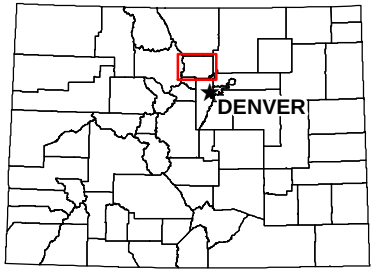

Legend

- 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 9

Watershed-Scale Extent

12-hour Worst Case Rainfall Return Periods for City of Boulder & Vicinity

September 9-16, 2013 Flood Event

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2490 W 26TH AVE 100A
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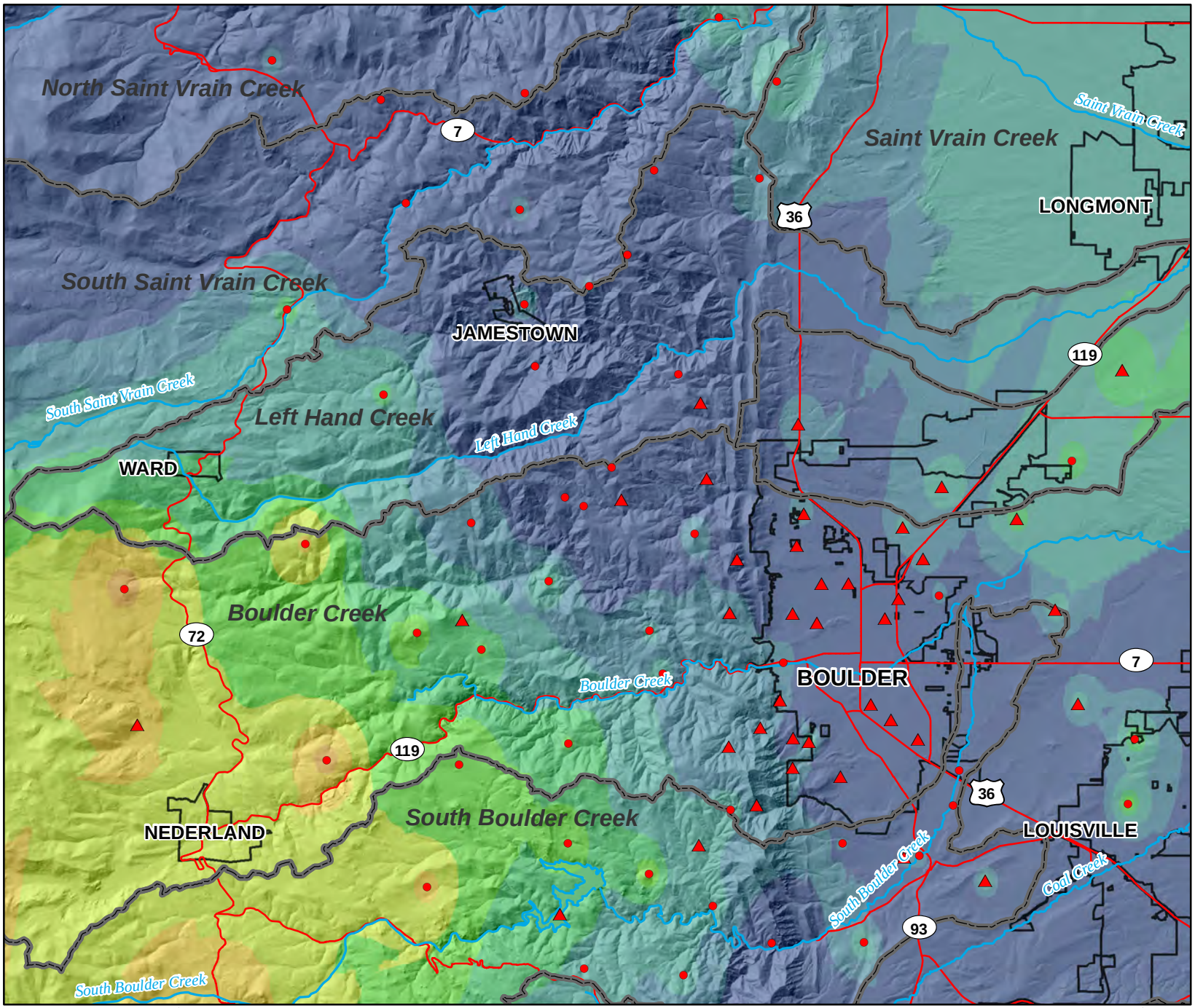

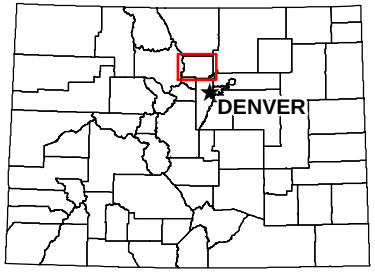

Legend

- 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 10

Watershed-Scale Extent

24-hour Worst Case Rainfall Return Periods for City of Boulder & Vicinity

September 9-16, 2013 Flood Event

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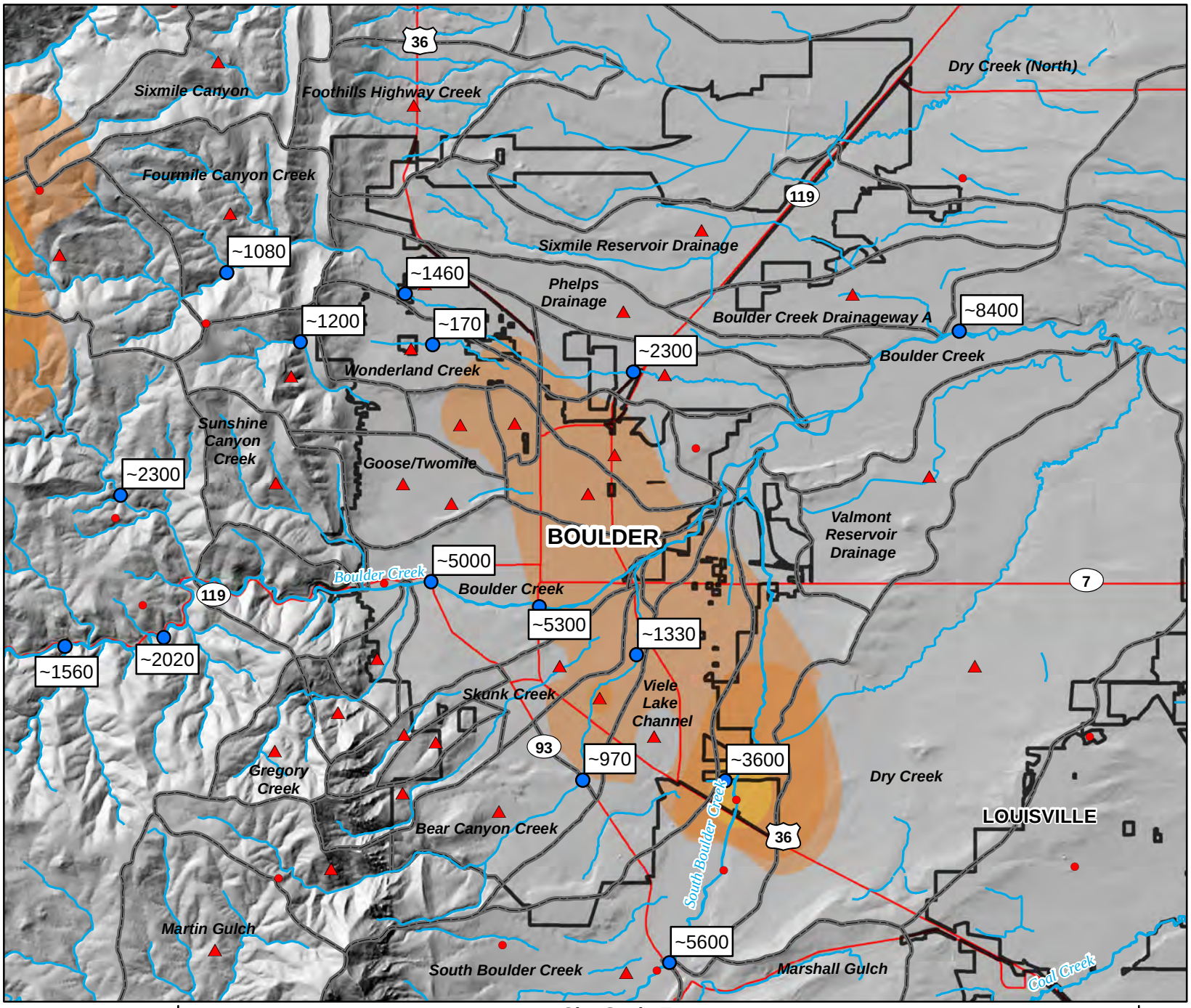

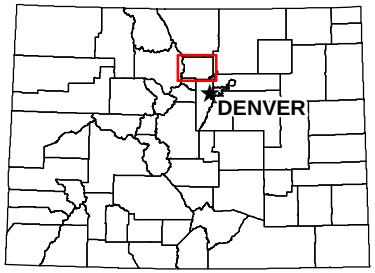

Legend

- Sept 2013 Flow Estimate (cfs)
- 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

City-Scale Extent

5-minute Worst Case Rainfall Return Periods for City of Boulder & Vicinity

September 9-16, 2013 Flood Event

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2490 W 26TH AVE 100A
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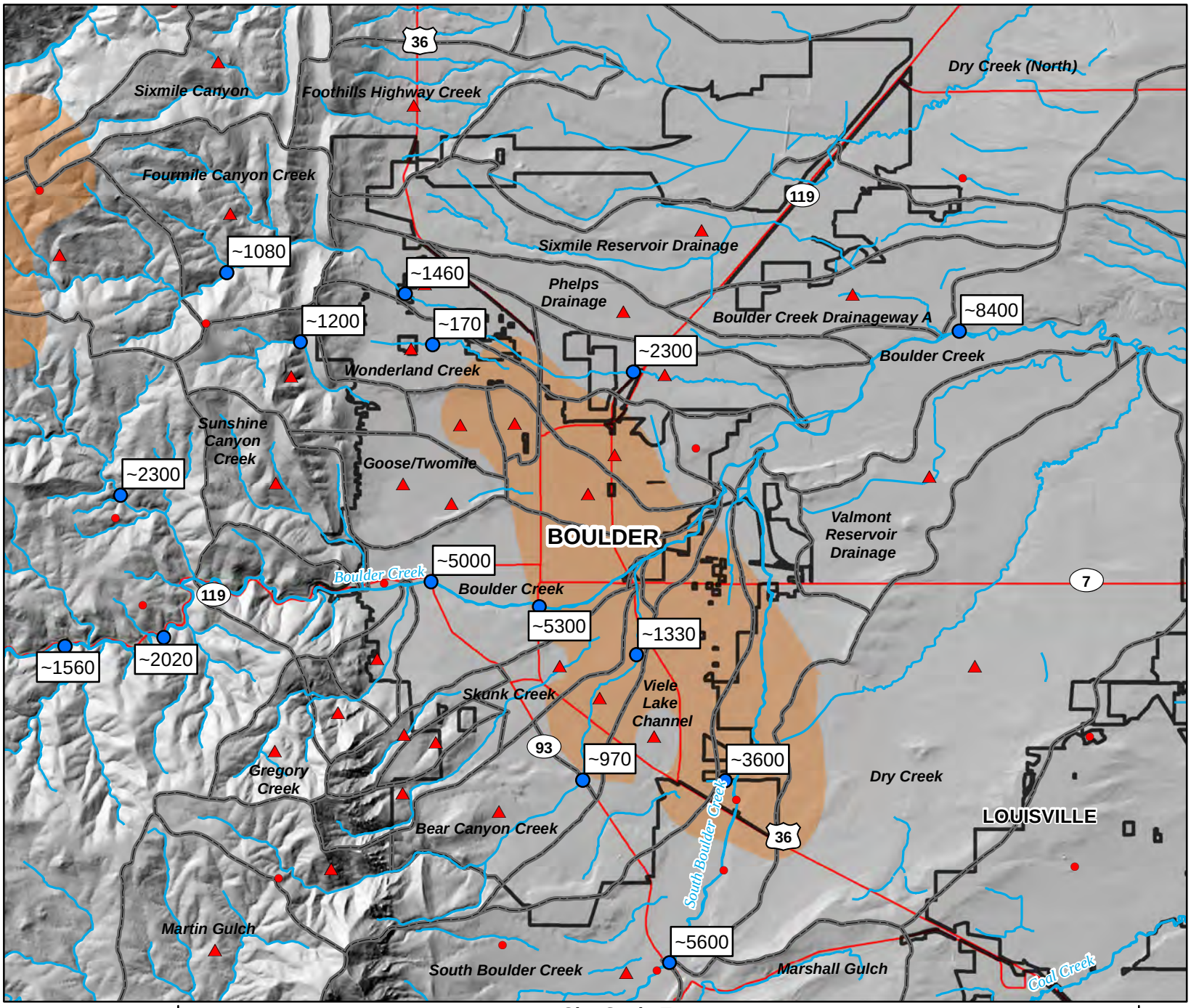

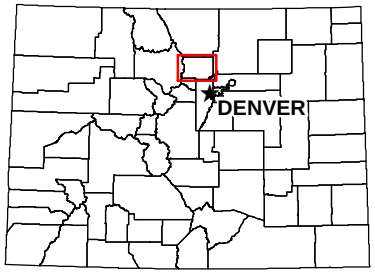

Legend

- Sept 2013 Flow Estimate (cfs)
- 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

City-Scale Extent

10-minute Worst Case Rainfall Return Periods for City of Boulder & Vicinity

September 9-16, 2013 Flood Event

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2490 W 26TH AVE 100A
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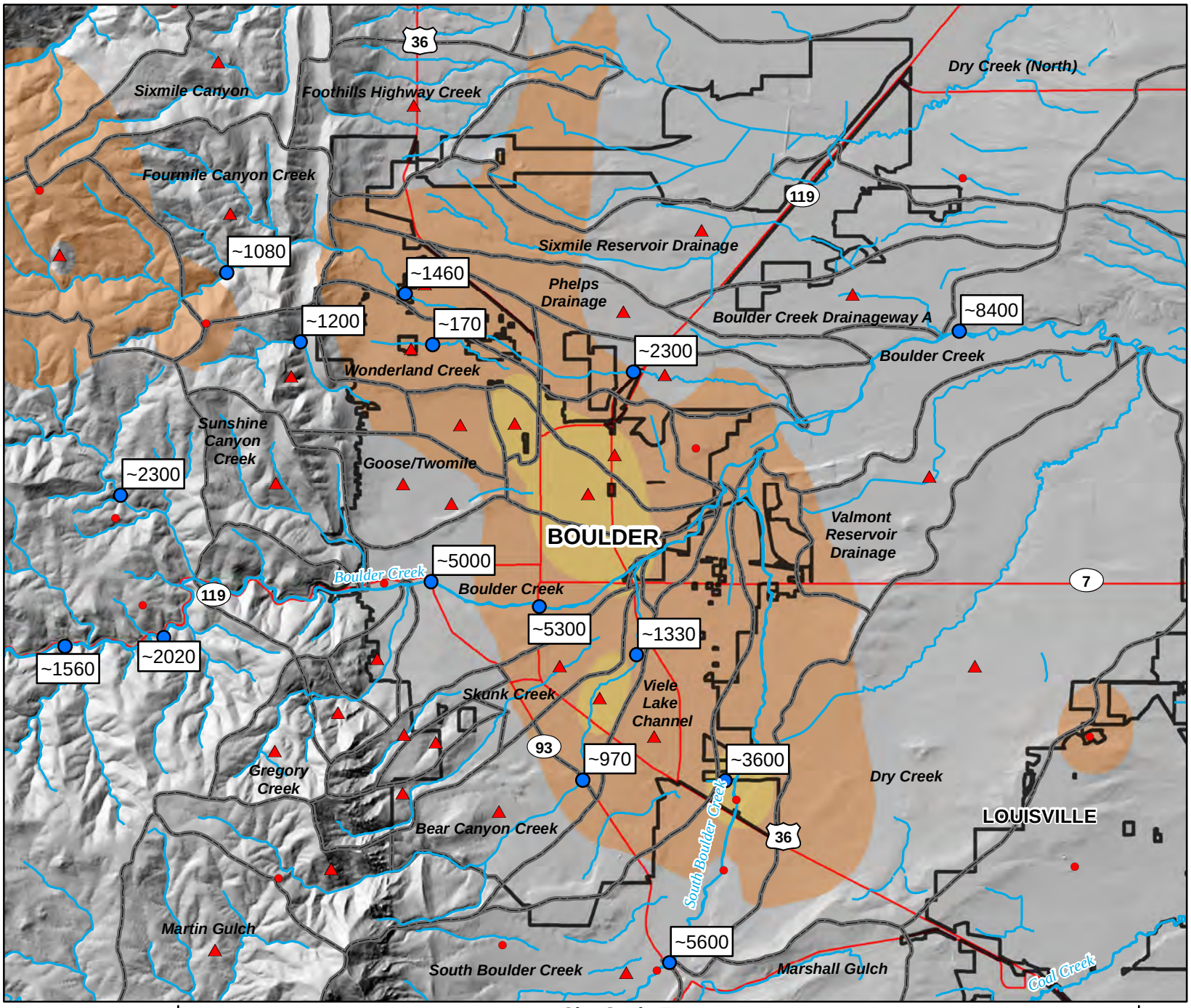

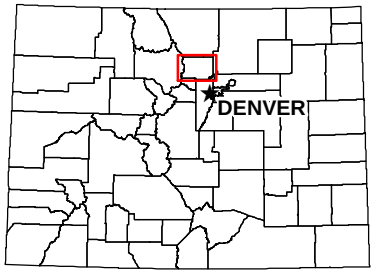

Legend

- Sept 2013 Flow Estimate (cfs)
- 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

City-Scale Extent

15-minute Worst Case Rainfall Return Periods for City of Boulder & Vicinity

September 9-16, 2013 Flood Event

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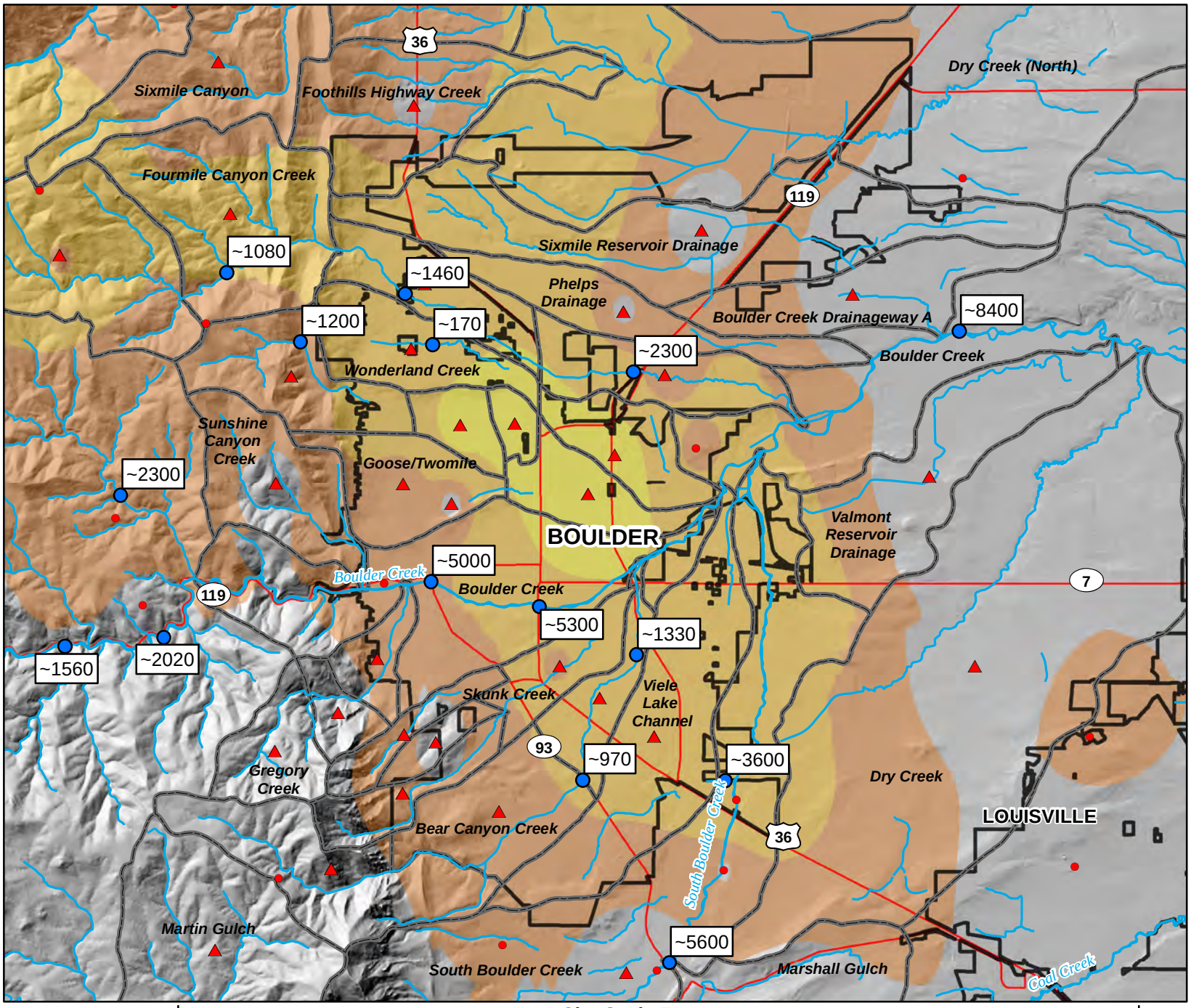

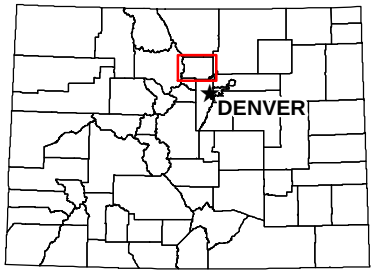

Legend

- Sept 2013 Flow Estimate (cfs)
- 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

City-Scale Extent

30-minute Worst Case Rainfall Return Periods for City of Boulder & Vicinity

September 9-16, 2013 Flood Event

WRIGHT WATER ENGINEERS, INC.
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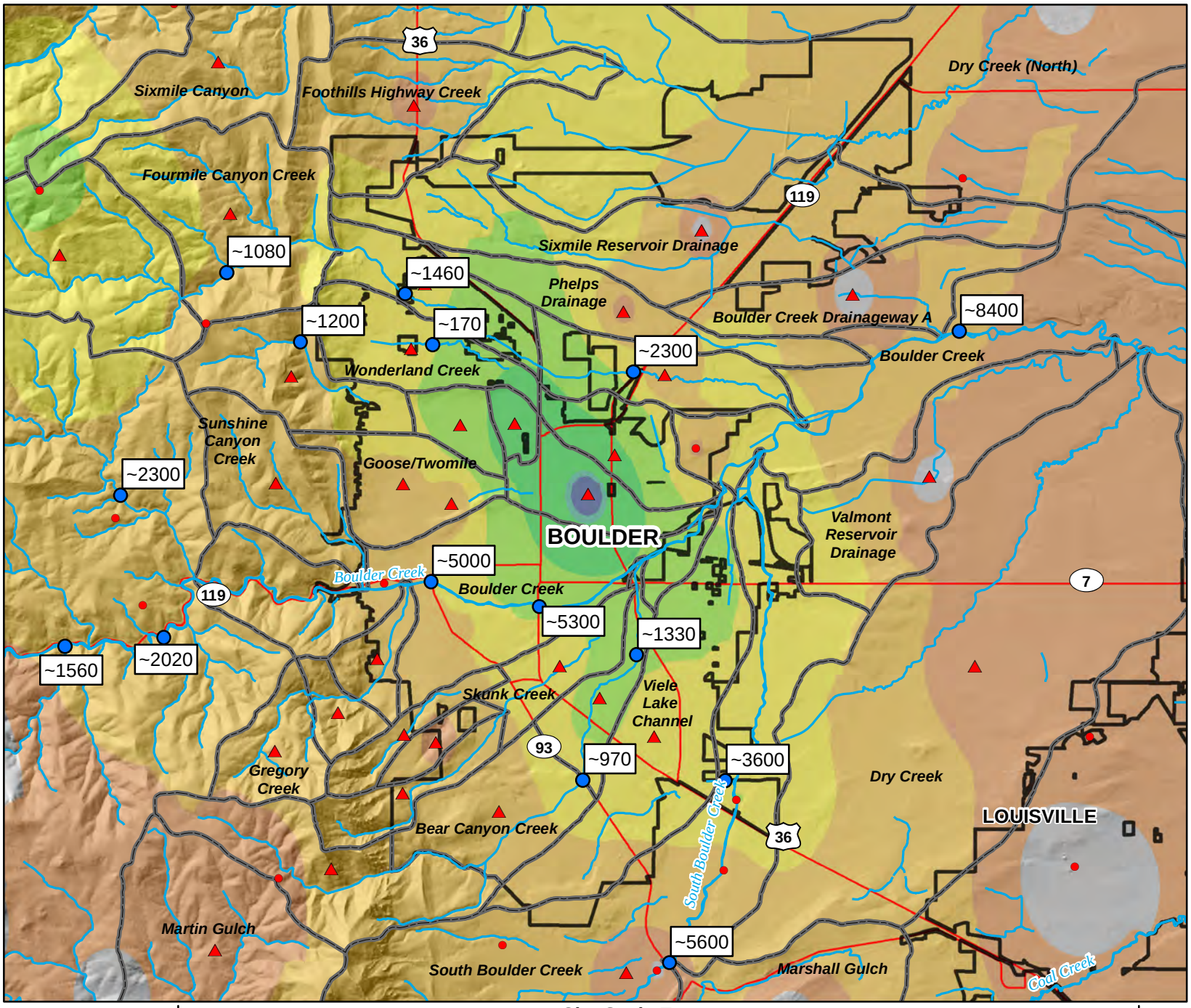

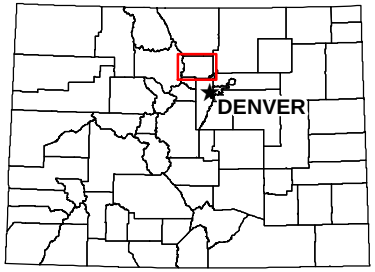

Legend

- Sept 2013 Flow Estimate (cfs)
- 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

City-Scale Extent

1-hour Worst Case Rainfall Return Periods for City of Boulder & Vicinity

September 9-16, 2013 Flood Event

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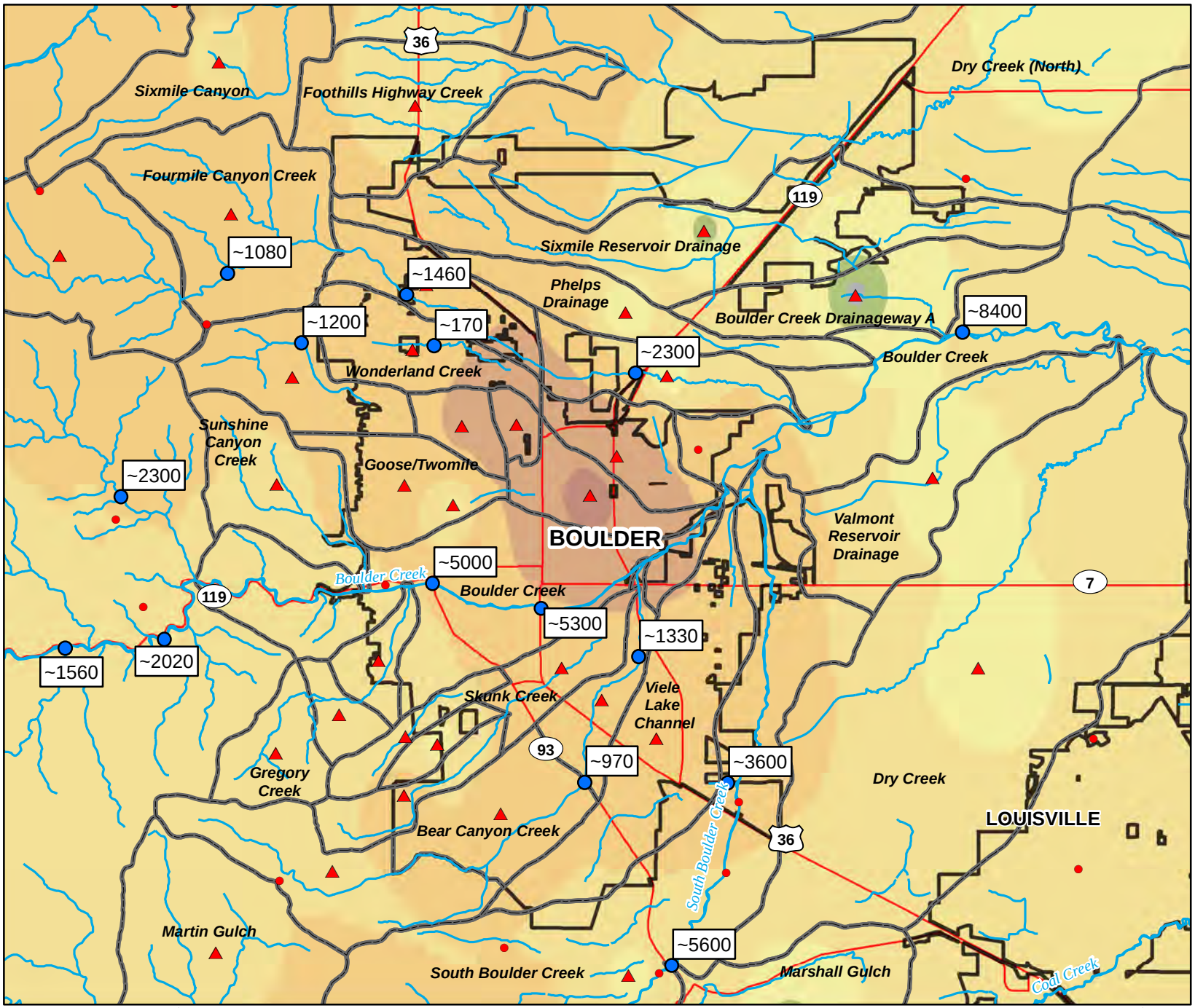

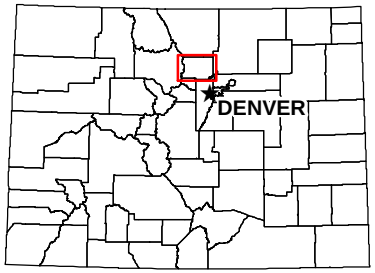

Legend

- Sept 2013 Flow Estimate (cfs)
- 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

City-Scale Extent

2-hour Worst Case Rainfall Return Periods 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

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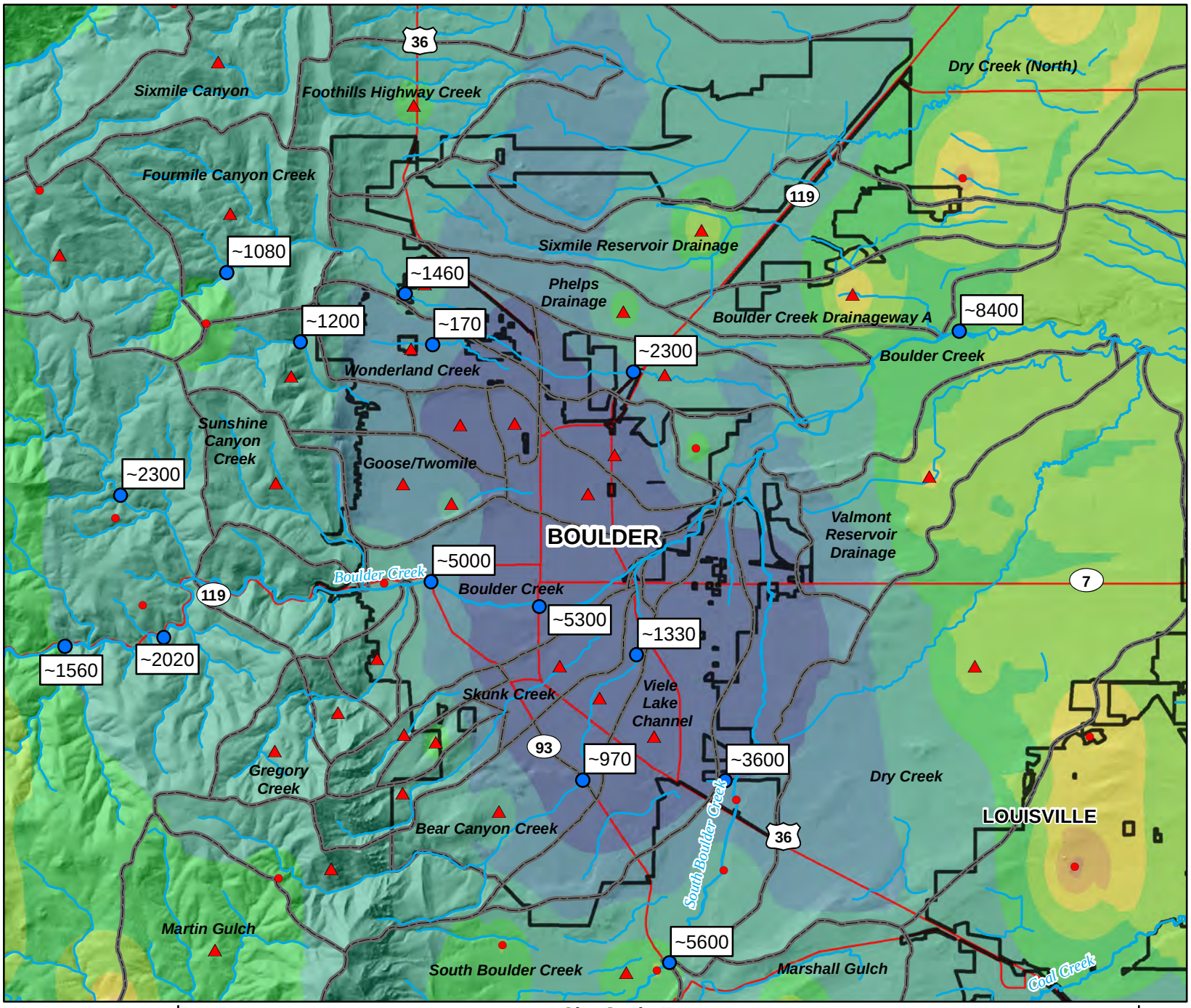

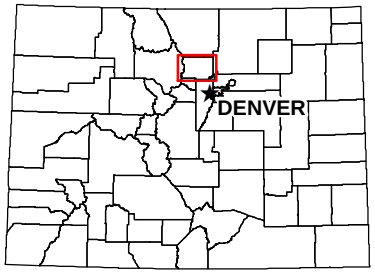

Legend

- Sept 2013 Flow Estimate (cfs)
- 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 17

City-Scale Extent

6-hour Worst Case Rainfall Return Periods for City of Boulder & Vicinity

September 9-16, 2013 Flood Event

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2490 W 26TH AVE 100A
DENVER, CO. 80211
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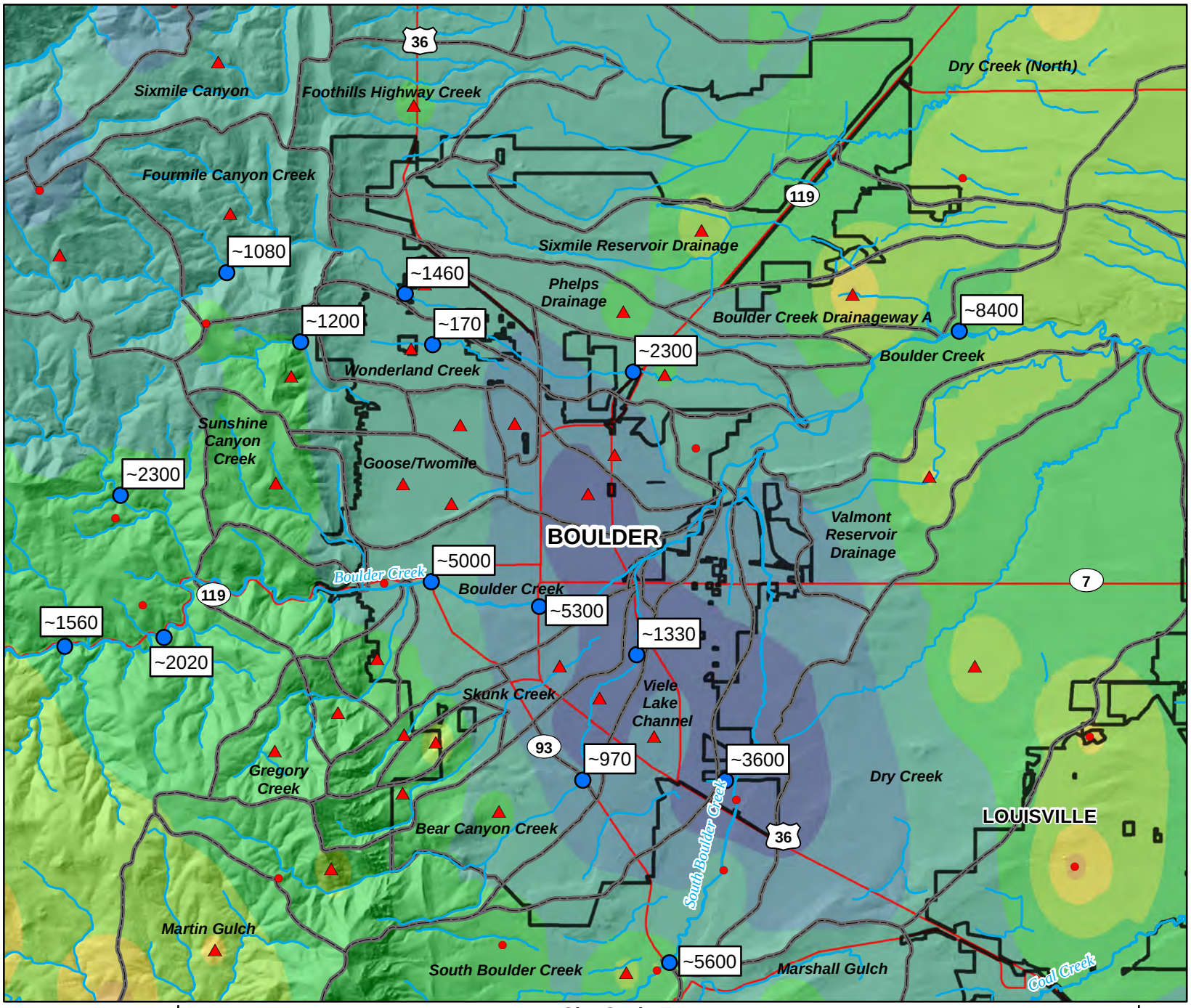

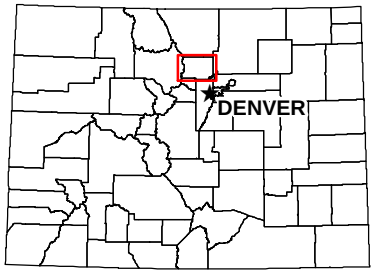

Legend

- Sept 2013 Flow Estimate (cfs)
- 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 18

City-Scale Extent

12-hour Worst Case Rainfall Return Periods for City of Boulder & Vicinity

September 9-16, 2013 Flood Event

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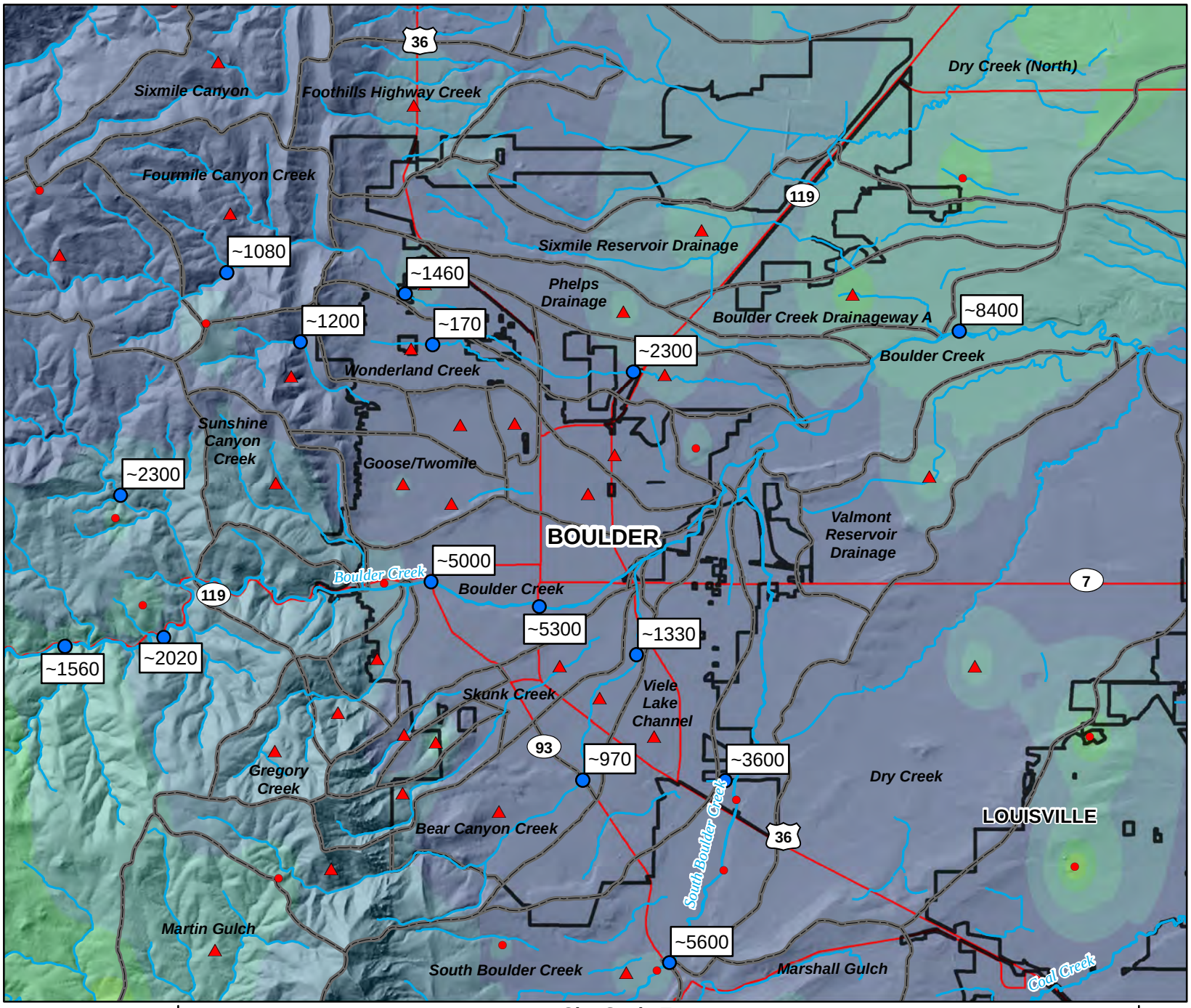
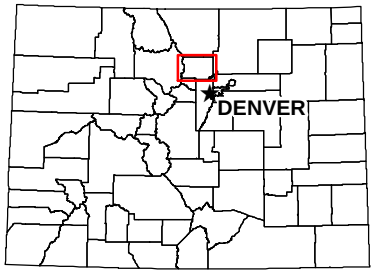
(303) 480-1700

Document Path: Z:\Project Files\14\141-024\141-024.000\CAD-GIS\GIS\FINAL Rainfall Sereis\FIGURE 18_12HOUR.mxd





Legend

- Sept 2013 Flow Estimate (cfs)
- 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 19

City-Scale Extent

24-hour Worst Case Rainfall Return Periods 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

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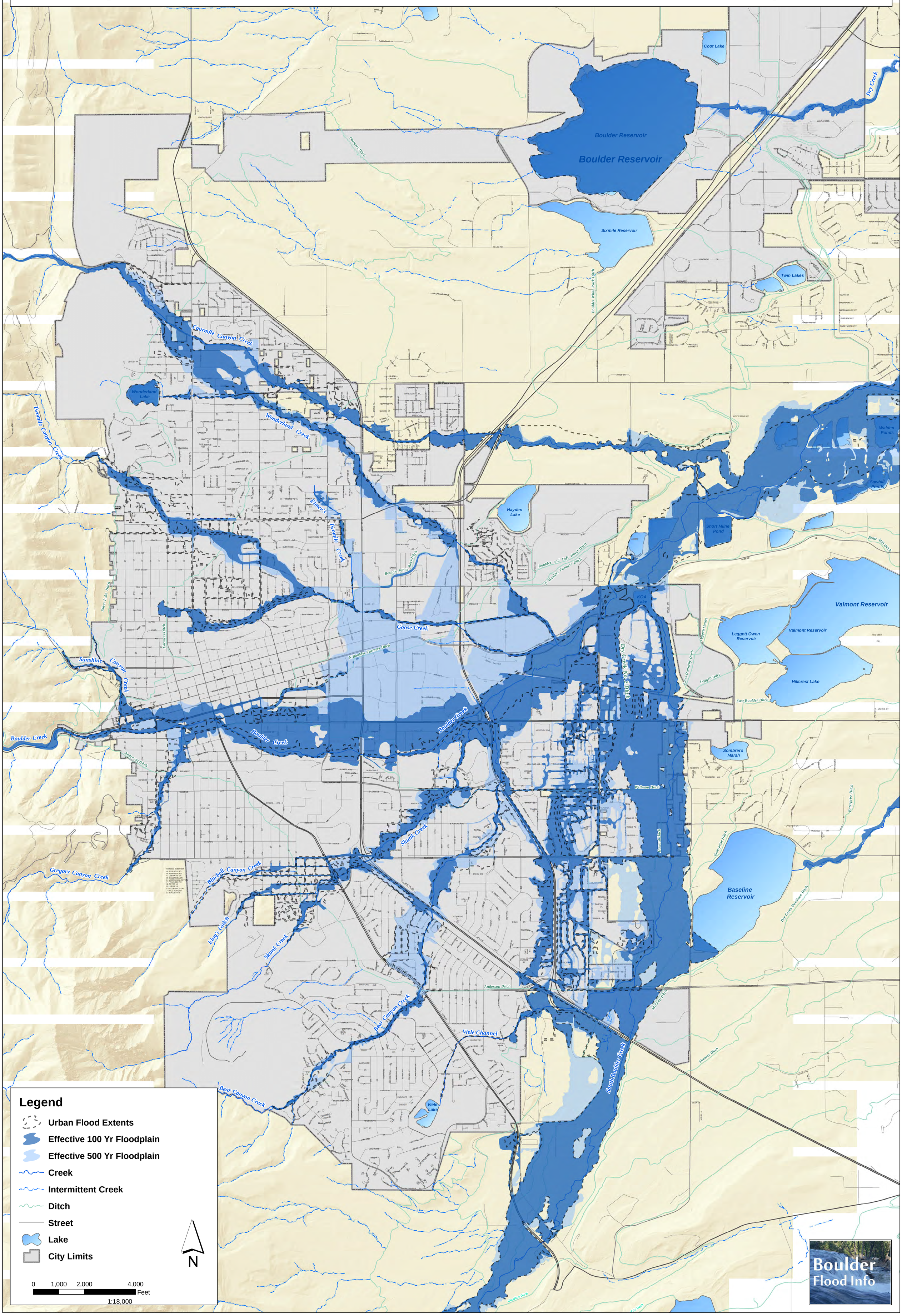
Appendix B
City of Boulder September 2013 Flood Inundation Mapping

September 2013 Urban Flood Extents and Effective Floodplains



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