Final Report

Boulder Creek Hydrologic Analysis

Prepared for

Colorado Department of Transportation

August 2014

CH2MHILL®

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Acronyms and Abbreviations

AMC	Antecedent Moisture Condition
AWA	Applied Weather Associates
CDOT	Colorado Department of Transportation
CDWR	Colorado Division of Water Resources
cfs	cubic feet per second
CN	curve number
CWCB	Colorado Water Conservation Board
DARF	Depth-area Reduction Factor
DRCOG	Denver Regional Council of Governments
ESRI	Environmental Systems Research Institute
FEMA	Federal Emergency Management Agency
FIRM	Flood Insurance Rate Map
FIS	Federal Insurance Study
GIS	geographic information system
HEC-HMS	Hydrologic Engineering Center's Hydrologic Modeling System
LiDAR	Light Detection and Ranging
NED	National Elevation Dataset
NLCD	National Land Cover Dataset
NOAA	National Oceanic and Atmospheric Administration
NRCS	Natural Resources Conservation Service
QC	Quality Control
SCS	Soil Conservation Service
SH	State Highway
SPAS	Storm Precipitation Analysis System
SWMM	Storm Water Management Model
USACE	U.S. Army Corps of Engineers
USDA	U.S. Department of Agriculture
USEPA	U.S. Environmental Protection Agency
USGS	U.S. Geological Survey

I hereby affirm that this report and hydrologic analysis for the Boulder Creek was prepared by me, or under my direct supervision, for the owners thereof, in accordance with the current provisions of the Colorado Floodplain and Stormwater Criteria Manual, and approved variances and exceptions thereto.

Signature:

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Executive Summary

In September 2013, the Colorado Front Range experienced an extensive rainstorm event spanning approximately 10 days from September 9 to September 18. The event generated widespread flooding as the long duration storm saturated soils and increased runoff potential. Flooding resulted in substantial erosion, bank widening, and realigning of stream channels; transport of mud, rock, and debris; failures of dams; landslides; damage to roads, bridges, utilities, and other public infrastructures; and flood impacts to many residential and commercial structures. Ten fatalities were attributed to the floods.

During and immediately following the rainstorm event, the Colorado Department of Transportation (CDOT) engaged in a massive flood response effort to protect the traveling public, rebuild damaged roadways and bridges to reopen critical travel corridors, and engage in assessments and analyses to guide longer-term rebuilding efforts. As part of this effort, CDOT collaborated with the Colorado Water Conservation Board (CWCB) to initiate hydrologic analyses in several key river systems impacted by the floods. The work was contracted to three consultant teams led by the following firms:

Boulder Creek, Little Thompson River	CH2M HILL
Big Thompson River, St. Vrain Creek, Lefthand Creek	Jacobs
Coal Creek, South Platte River	URS

The purpose of the analyses is to ascertain the approximate magnitude of the September flood event in key locations throughout the watershed and to prepare estimates of peak discharge that can serve to guide the design of permanent roadway and other infrastructure improvements along the impacted streams. These estimates of peak discharges for various return periods will be shared with local floodplain administrators for their consideration in revising or updating any current regulatory discharges. The primary tasks of the hydrologic analyses include the following:

1. Estimate peak discharges that were believed to have occurred during the flood event at key locations along the study streams. Summarize these discharges along with estimates provided by others in comparison to existing regulatory discharges. Document the approximate return period associated with the September flood event based on current regulatory discharges.
2. Prepare rainfall-runoff models of the study watersheds, input available rainfall data representing the September rainstorm, and calibrate results to provide correlation to estimated peak discharges.
3. Prepare updated flood frequency analyses using available gage data and incorporate the estimated peak discharges from the September event.
4. Use rainfall-runoff models to estimate predictive peak discharges for a number of return periods based on rainfall information published by the National Oceanic and Atmospheric Administration (NOAA) (*NOAA Atlas 14*, Volume 8, Updated 2013 [NOAA, 2013]). Compare results to updated flood frequency analyses and unit discharge information and calibrate as appropriate.

This report documents the hydrologic evaluation for Boulder Creek above its confluence with Fourmile Creek, near Orodell, Colorado. An overview map of the study area is provided as **Figure ES-1**.

As part of the evaluation, CH2M HILL developed a rainfall-runoff model to transform the recorded rainfall to stream discharge using the U.S. Army Corps of Engineers' (USACE's) HEC-HMS hydrologic model (USACE, 2010). The hydrologic model was calibrated to observed September 2013 peak discharges through adjustment of model input values that represent land cover and soil conditions (see **Table ES-1**). The calibration of these parameters is common because they take into account vegetative cover, soil structure, topography, land use history, and other considerations that are not easily accessible using aerial imagery. In addition to closely evaluating land use cover, research was completed to determine how Barker Reservoir, a water supply reservoir operated by the City of Boulder, was operated during the September 2013 storm event. It was determined that the reservoir was approximately 11 feet below maximum storage capacity at the beginning of the storm event but, ultimately, water levels in the reservoir exceeded the storage capacity and engaged the emergency spillway multiple times during the storm. This effect was included in the calibrated model to avoid under-calibration.

TABLE ES-1
Comparison of Modeled Discharges to Observed Discharges

Location	Calibration Source	Observed Discharge (cfs)	Modeled Discharge (cfs)	Percent Difference
Boulder Creek near Orodell	Jarrett, in press	2,020	1,950	-3.5%
Middle Boulder Creek at Nederland	USGS Gage	409	410	+ 0.2%
North Boulder Creek at Confluence with Middle Boulder Creek	Jarrett, in press	740	829	+ 12.0%
Fourmile Creek Upstream Burned Area	Jarrett, in press	490	551 [a]	+ 12.4%
Fourmile Creek Downstream of Emerson Gulch	Jarrett, in press	1,070	1,101 [a]	+ 2.9%
Fourmile Creek near Orodell	Jarrett, in press	2,300	2,568	+ 11.6%

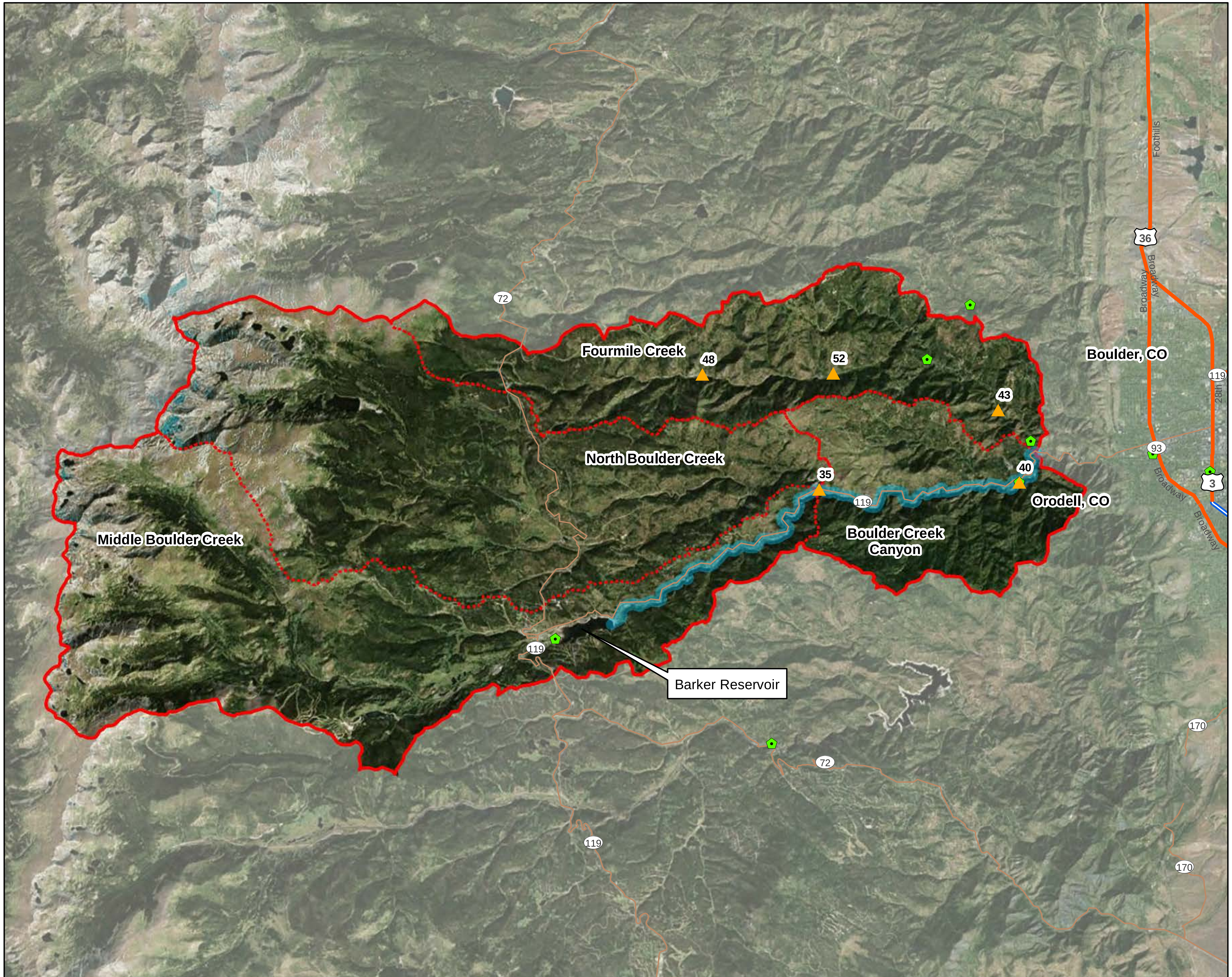
[a] Interpolated between HEC-HMS junctions based on contributing drainage areas.

The calibrated model was then modified to conservatively disregard flood storage at Barker Reservoir and used to estimate the 10, 4, 2, 1, and 0.2 percent annual chance peak discharges (10-, 25-, 50-, 100-, and 500-year storm event) based on a 24-hour Soil Conservation Service (SCS) (now the Natural Resources Conservation Service [NRCS]) Type II Storm and recently released *NOAA Atlas 14* (NOAA, 2013) rainfall values (see **Table ES-2**). The modeled discharges were then compared to previous and concurrent alternative estimates of annual chance peak discharges. The assumptions and limitations of the various methodologies were closely reviewed, compared, and contrasted. Considering potentially outdated and unvalidated methodologies used in previous studies, the impacts of flow regulation on gage records, and continuous review of current modeling methodology by a team of local engineers and project sponsors, the predictive model developed as part of the current study is proposed as the appropriate model to estimate high-flow hydrology and the recurrence interval of the September 2013 event along Boulder Creek upstream of Orodell. With this recommendation, the peak discharges observed along Boulder Creek during the September 2013 storm event had an estimated recurrence interval of approximately 2 percent annual chance peak discharge, or a 50-year storm event.

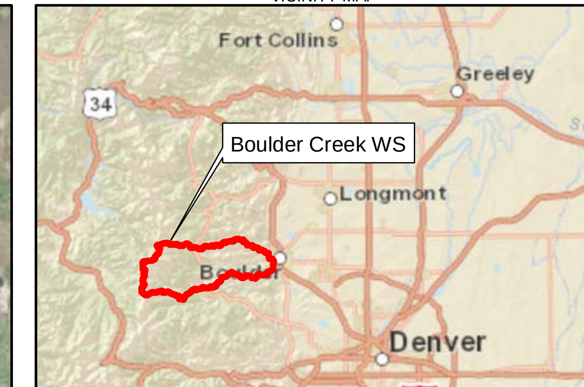
TABLE ES-2
Estimate of September 2013 High-Flow Recurrence Interval

Location	Observed Discharge, per Jarrett, in press (cfs)	Annual Chance Peak Discharge (cfs)					Estimated Recurrence Interval (yr)
		10 Percent	4 Percent	2 Percent	1 Percent	0.2 Percent	
Fourmile Creek Upstream Burned Area	490	213 [a]	426 [a]	656 [a]	949 [a]	1,886 [a]	~ 25
Fourmile Creek Downstream of Emerson Gulch	1,070	400 [a]	789 [a]	1,209 [a]	1,734 [a]	3,388 [a]	25 to 50
Fourmile Creek near Orodell	2,300	922	1,680	2,442	3,425	6,376	~ 50
Middle Boulder Creek at Nederland	409 [b]	629	1,239	1,949	2,888	6,163	< 10
North Boulder Creek at Confluence with Middle Boulder Creek	740	334	757	1,298	2,045	4,760	~ 25
Boulder Creek near Orodell	2,020	1,134	2,287	3,640	5,392	11,399	~ 25
Boulder Creek below Orodell (watershed outlet)	4,818 [c]	1,567	3,033	4,726	6,850	13,993	~ 50

[a] Interpolated between HEC-HMS junctions based on contributing drainage areas.
[b] Per Colorado Division of Water Resources (CDWR) Middle Boulder Creek at Nederland gage.
[c] Per Calibrated Hydrologic Model.
cfs = cubic feet per second



VICINITY MAP



LEGEND

- Study Reach
- Stream Gage
- Subwatershed Boundary
- Boulder Creek Watershed
- Critical Depth Estimate Used in Calibration
- Limited Access
- Highway
- Local Road

0 0.5 1 2 Miles

1 in = 2 miles

FIGURE ES-1
Boulder Creek Overview Map

CDOT Flood Recovery Hydrologic Evaluation

1.0 Purpose and Objective

1.1 Background

In September 2013, the Colorado Front Range experienced an intense, widespread rainfall event that resulted in damaged infrastructure and property loss in multiple watersheds. CH2M HILL was retained by the Colorado Department of Transportation (CDOT) and Colorado Water Conservation Board (CWCB) to evaluate the hydrology of two watersheds that experienced flooding and damage as a part of this storm event: the Little Thompson River and Boulder Creek. The purpose of the analyses is to determine the approximate magnitude of the September flood event in key locations throughout the Boulder Creek watershed and to prepare estimates of peak discharge that can serve to guide the design of permanent roadway and other infrastructure improvements along the impacted streams.

1.2 Project Area Description

The study area of Boulder Creek watershed (HUC 1019000504) is situated largely in southern Boulder County, with less than 1 square mile located in Gilpin County. The watershed is generally bounded by the Town of Ward to the north, the City of Boulder to the east, and the Town of Rollinsville to the south. The study reach extends from Barker Reservoir near Nederland, Colorado, to the confluence with Fourmile Creek, approximately 2 miles west of Boulder along State Highway (SH) 119 (see **Figure B-1** in **Appendix B** for a vicinity map of the watershed). The watershed for this reach is approximately 129 square miles. Boulder Creek is a Federal Emergency Management Agency (FEMA)-designated Zone AE floodplain and is documented on Flood Insurance Rate Map (FIRM) panel 08013C0390J for Boulder County. FEMA FIRM documentation for Boulder Creek is presented in **Appendix A**.

The Boulder Creek watershed has been divided into four contributing *sub*-watersheds for the purpose of discussion. The four sub-watersheds 1) coincide with U.S. Geological Survey (USGS) HUC12 watersheds; 2) roughly distinguish differences in sub-watershed basin shape, vegetative cover, and flood history; and 3) coincide with key calibration measurements near the outfall of each of these sub-watersheds (i.e., upstream of a major confluence). The four contributing tributary sub-watersheds identified on **Figure B-1** in **Appendix B** include Middle Boulder Creek (HUC 101900050402), North Boulder Creek (HUC 101900050401), Fourmile Creek (HUC 101900050403), and Boulder Canyon Creek (HUC 101900050404).

1.2.1 Middle Boulder Creek and North Boulder Creek

Middle Boulder Creek and North Boulder Creek sub-watersheds are located at the upper limits of the watershed and drain areas of approximately 44 and 45 square miles, respectively. These two contributing sub-watersheds exhibit some of the same physical attributes, including large amounts of rock outcropping in the upper limits, multiple alpine lakes, and steep terrain. With the exception of the Town of Nederland, this area is widely undeveloped, forested land with various intermittent mountain streams. The confluence of Middle Boulder Creek and North Boulder Creek marks the upstream end of Boulder Creek and occurs just downstream of Boulder Falls.

Barker Reservoir, at the upper limits of the study area, is located in the Middle Boulder Creek sub-watershed immediately downstream of the Town of Nederland. Barker Reservoir was constructed in 1910 as a water supply reservoir and has been owned and operated by the City of Boulder since 2002. Barker Reservoir is not explicitly operated as a flood control dam but has approximately 11,300 acre-feet of storage capacity below the spillway elevation for water supply (City of Boulder, 2013a).

1.2.2 Fourmile Creek

The Fourmile Creek sub-watershed is located along the northern limits of the Boulder Creek watershed, and consists mainly of forested areas with large-lot, single-family residences. Fourmile Creek is located in Fourmile Canyon and, as a result, the majority of runoff is conveyed via the steep terrain directly into

Fourmile Creek. Fourmile Creek outlets to Boulder Creek, at the downstream boundary of the study area near Orodell, Colorado.

In 2010, the Fourmile Canyon Fire burned approximately 10 square miles of land near Salina, Colorado, before being successfully contained. Of the 10-square-mile burn area, the majority occurred within the 24-square-mile Fourmile Creek sub-watershed, as illustrated in **Figure B-1** in **Appendix B**. During this event, more than 160 homes were destroyed, resulting in $217 million in insurance claims. Since 2010, new vegetation has emerged in the sub-watershed, although this area is not fully restored to pre-fire conditions.

1.2.3 Boulder Creek

Boulder Creek begins at the confluence of Middle Boulder Creek and North Boulder Creek, and extends east to the City of Boulder along SH 119. Several small businesses and residences are located adjacent to Boulder Creek. A recreational trail is used to link Boulder Canyon to the City of Boulder via Boulder Creek corridor. The majority of the contributing 15-square-mile area is forested land with steep terrain along the south side of SH 119. The sub-watershed as it is defined in this report extends to the confluence with Fourmile Creek at Orodell, Colorado.

1.3 Mapping

Elevation data for the study area were derived from the USGS National Elevation Dataset (NED), which provides 1/3 arc-second (approximately 30 feet) coverage across the Boulder Creek watershed (USGS, 2013). NED raster tile ID “n40w106” and “n41w106” covered the entirety of the watershed. In addition to the NED dataset, 2013 Light Detection and Ranging (LiDAR) data, in LAS format, was provided by the project sponsors for use on this project. The LiDAR survey was sponsored by FEMA and collected after the September 2013 event; thus, it includes any horizontal channel or floodplain changes that may have occurred during the September 2013 event (FEMA, 2013a). Both the NED and LiDAR data were converted to the NAVD 88 US Survey Foot vertical datum and the NAD 83 Colorado State Plane Central (FIPS 0502) US Survey Foot horizontal datum used in the study. Aerial photography (2012) from the Environmental Systems Research Institute (ESRI) ArcGIS online data catalog was used for the background imagery (ESRI, 2013).

1.4 Data Collection

For this analysis, CH2M HILL collected a range of data covering the Boulder Creek watershed, including recent hydrologic studies, gage data, and hydrologic parameters. Detailed explanations of how the data were used during this analysis is described in the subsequent sections. The primary references used for this study are documented in **Table 1**.

TABLE 1
Data Collected for Boulder Creek

Document Type	Source	Description
Aerial Imagery	ESRI, 2012	Aerial Raster
LiDAR LAS	Federal Emergency Management Agency (sponsor), 2013a	Raw LiDAR survey data
GIS Raster	U.S. Geological Survey, 2013	Elevation data for approximately 30’ x 30’ grid
GIS Shapefile	U.S. Department of Agriculture, 2013	Soil Classification
GIS Shapefile	U.S. Geological Survey, 2013	Land Use Cover
Flood History	U.S. Geological Survey, 1948	*Water-Supply Paper 997: Floods in Colorado*
Gage Data	Colorado Division of Water Resources; U.S. Geological Survey	Historical stream flow data at Orodell and Nederland

TABLE 1
Data Collected for Boulder Creek

Document Type	Source	Description
Hydrologic Study	U.S. Army Corps of Engineers, 1969	*Floodplain Information: Boulder Creek and South Boulder Creek, Volume II, Boulder Metropolitan Region, Colorado*
Hydrologic Study	U.S. Army Corps of Engineers, 1977	*Water and Related Land Resources Management Study, Metropolitan Denver and South Platte River and Tributaries, Colorado, Wyoming, and Nebraska, Volume V – Supporting Technical Reports Appendices, Appendix H – Hydrology* (source of most effective FEMA peak discharges)
Hydrologic Study	U.S. Army Corps of Engineers, undated	*Review Report, Boulder Creek* (details on hydrologic parameters for effective discharges)
Hydrologic Study	Anderson Consulting Engineers, 2009	*Hydrology Verification Report for Boulder Creek*
Peak Discharge Estimates	Jarrett, in press	Estimates of September 2013 peak discharges using indirect methods
Rainfall Data (Frequency tables)	National Oceanic and Atmospheric Administration, 2014	*NOAA Precipitation Frequency Data Server*
Rainfall Data (September 2013)	Applied Weather Associates, 2014	5-minute rainfall data at subbasin centroids from September 8, 2013, to September 18, 2013

1.5 Flood History

1.5.1 Historical Flood Events

The USGS maintains a stream gage along Boulder Creek at Orodell that has been in operation since 1907. Before the September 2013 flood event, the two largest peak flows on record occurred on June 6, 1921, and May 7, 1969, at 2,500 and 1,220 cubic feet per second (cfs), respectively. Prior to the period of record for the stream gage at Orodell, two large flood events occurred in May 1876 and May 1894. Little is known about the magnitude of the 1876 flood other than what was reported in local newspapers of the time, which chiefly recounted the loss of farmland and rail service in the City of Boulder. However, more is known about the damage caused by the flood in 1894. This event was studied in 1912 by Metcalf & Eddy, a Boston-based consulting engineering firm that estimated a peak flow between 9,000 and 10,000 cfs. A review of historical flood events, summarized in **Table 2**, supports the assessment in the Boulder County Flood Insurance Study (FIS) that identifies the principal cause of flooding in the Boulder Creek watershed as rain or rain-on-snow events (FEMA, 2012).

TABLE 2
Summary of Flooding Events Documented for Boulder Creek

Date	Summary of Flood Event
May 21-23, 1876	General storm; "At least 4 inches of rain fell during the 24 hours, and three-fourths of an inch in 2 hours on Monday evening"; inundated farm land and disrupted rail service.
June 2, 1894	General storm; 5.75 inches of rainfall at Gold Hill (on Fourmile Creek), with 5.25 inches recorded in 2 days; "melting snow was less important a factor in causing high water in this flood than in 1921"; highway and railroad destroyed up to Fourmile Canyon; estimated flow between 9,000 and 10,000 cfs.
June 2, 1914	1 inch of rain on North Boulder Creek watershed on significant snowpack; estimated flow of 5,000 cfs in Boulder; maximum peak discharge of 811 cfs recorded at Nederland gage.
June 21, 1921	General storm; maximum peak discharge of 2,500 cfs recorded at Orodell.
May 4-8, 1969	General storm; 9.34 inches of rain recorded near Barker Reservoir; Bear Canyon, Skunk, and Twomile Canyon Creeks overflowed their banks; streets and bridges damaged; recorded flow of 1,220 cfs at Orodell gage.

Source: USGS, 1948; FEMA, 2012.

1.5.2 September 2013

The high-flow event in September 2013 was one of only a few high-flow events on record that did not occur in the typical peak snowmelt months of May, June, and July. The days preceding the event saw record-breaking heat and high humidity throughout the Front Range of Colorado. The heat and influx of tropical moisture from the Gulf of Mexico combined over Colorado's Front Range to saturate the atmosphere and develop conditions ideal for heavy sustained rainfall.

The Boulder Creek watershed experienced rainfall from September 9, 2013, to September 16, 2013, with the maximum rainfall exceeding 1 inch per hour in some areas. The heaviest rainfall in the Fourmile Creek and Boulder Creek sub-watersheds was measured as 1.67 inches per hour on September 11 at approximately 11 p.m. Rainfall in the upper basin did not peak until the following day, September 12, at approximately 7:30 p.m. During the September 13 rainfall burst, the heaviest rainfall intensity estimated in the Fourmile Creek watershed was 0.73 inch per hour. Middle and North Boulder Creek saw estimated maximum rainfall intensities closer to 0.32 inch per hour.

The steady rain, which varied in intensity across the event, produced multiple runoff peaks over the 8-day period. While several peaks were measured at the Nederland and Orodell gages, a single peak at approximately midnight on September 12 (early morning of September 13) was nearly double the magnitude of other measured peak discharges and almost coincided with the peak stage recorded a few hours earlier by the Urban Drainage and Flood Control District (UDFCD) ALERT gage on Fourmile Creek near Orodell. The measured peak discharges at the Boulder Creek at Orodell gage were affected by flow attenuation provided by Barker Reservoir: prior to the storm, Barker Reservoir was approximately 11 feet below capacity due to the drought conditions Colorado experienced during 2012 and 2013. Although Barker Reservoir was and is not operated as a flood control dam, City of Boulder records indicated that Barker Reservoir stored almost the entirety of runoff that occurred prior to the evening of September 15, discharging an average of 4 cfs before the storage capacity was exceeded and the emergency spillway engaged.

Property loss and damage to infrastructure occurred across the Front Range and, specifically, varied in magnitude across the Boulder Creek watershed. The upper portions of the Boulder Creek watershed experienced little to no flood damage. Towards the confluence with Fourmile Creek, stream bank erosion threatened private drives and some roadway infrastructure. The more severe damage occurred downstream of Fourmile Canyon, in the City of Boulder, outside of the study reach.

2.0 Hydrologic Analyses

When determining an appropriate method to develop watershed hydrology, it is common to compare several statistical-, physical-, and model-based estimates. Statistical-based estimates include the regression analysis of historical peak flow measurements to estimate the magnitude of infrequent high-flow events using statistical distributions. Physical-based estimates estimate peak discharges based on watershed characteristics, high-water marks, hydraulic parameters, or other physically relevant parameters. Model-based estimates are based on conceptual or theoretical hydrologic models that estimate discharges based on watershed characteristics and meteorological conditions.

For this analysis, it was concluded that a rainfall-runoff model would be used to determine peak discharges for the 10, 4, 2, 1, and 0.2 percent annual chance events due to the availability of calibration data, general acceptance of calibrated rainfall-runoff models to predict infrequent discharges, inability of physical-based estimates to predict future flood hydrology, and limitations in statistical-based estimates, discussed in subsequent sections. Physical- and statistical-based methods discussed in the following sections of this report were used for calibration or comparison purposes to validate the rainfall-runoff model.

2.1 Previous Studies

To date, at least seven reports have been published documenting the hydrology of Boulder Creek within the study reach. Of those, four are hydrologic studies that document the engineering analysis of flood hydrology along Boulder Creek. The four hydrologic studies, described in detail in the following subsections, consist of the following: 1) *Floodplain Information: Boulder Creek and South Boulder Creek, Volume II, Boulder Metropolitan Region, Colorado* (U.S. Army Corps of Engineers [USACE], 1969); 2) *Water and Related Land Resources Management Study, Metropolitan Denver and South Platte River and Tributaries, Colorado, Wyoming, and Nebraska, Volume V – Supporting Technical Reports Appendices, Appendix H – Hydrology* (USACE, 1977); 3) *Review Report, Boulder Creek* (USACE, undated), which provides additional hydrologic modeling details not documented in USACE, 1977; and 4) *Hydrology Verification Report for Boulder Creek* (Anderson Consulting Engineers, 2009). The remaining publications include the current FIS, previous FISs, and hydraulic modeling reports, none of which is discussed in detail because each references one of the hydrologic studies cited above. No map revisions have been approved by FEMA since the latest revision of the FIS (FEMA, 2012) on December 18, 2012. Therefore, as documented in the current FIS, the effective hydrology along the study reach is based on the USACE, 1977 study (FEMA, 2012).

2.1.1 *Floodplain Information: Boulder Creek and South Boulder Creek, Volume II, Boulder Metropolitan Region, Colorado* (USACE, 1969)

In response to an application from the Denver Regional Council of Governments (DRCOG) via the CWCB, USACE conducted a study to “define the flood characteristics on portions of Boulder and South Boulder Creeks near Boulder, Colorado” (USACE, 1969). As part of the study, USACE estimated the magnitude of two high-flow events: an “Intermediate Regional Flood,” representative of the 1 percent annual chance flow, and “Standard Project Flood,” representative of the “reasonable upper limit of expected flooding” (USACE, 1969). The 1 percent annual chance discharges were estimated by analyzing gage records using Log-Pearson Type III regression analysis methodology in accordance with *Bulletin No. 15: A Uniform Technique for Determining Flood Flow Frequencies* (Water Resources Council, 1967). Additional description of the 1969 USACE analysis found in *Review Report, Boulder Creek* (USACE, undated) notes that statistical parameters from the Boulder Creek at Orodell gage (USGS Gage #06727000) were used in conjunction with a regional standard deviate distribution to estimate the 1 percent annual chance discharge in Boulder Creek above South Boulder Creek. Although documentation of the exact methodology is lacking, **a 1 percent annual chance flow of 7,400 cfs for Boulder Creek above South Boulder Creek** was reported (USACE, 1969).

2.1.2 Water and Related Land Resources Management Study, Metropolitan Denver and South Platte River and Tributaries, Colorado, Wyoming, and Nebraska, Volume V – Supporting Technical Reports Appendices, Appendix H – Hydrology (USACE, 1977) and Review Report, Boulder Creek (USACE, undated)

Following its 1969 study, USACE re-analyzed the high-flow hydrology of Boulder Creek as part of the larger Metropolitan Denver, South Platte River, and Tributaries Study and Flood Hazard Evaluation project. As part of the hydrologic analysis, USACE estimated the 10, 4, 2, 1, and 0.2 percent annual chance peak discharges along Boulder Creek above Valmont Road using the U.S. Environmental Protection Agency's (USEPA's) Storm Water Management Model (SWMM) and the Missouri River Division diffusion routing technique; the former was used to estimate rainfall-runoff across the entire basin while the latter technique was used to route the high-flows in the "lower basin" downstream of the Flatirons (USACE, 1977).

No discussion of Boulder Creek model calibration, verification, or comparison to previous studies was provided in the USACE, 1977 study; however, *Review Report, Boulder Creek* noted that the gage record for Boulder Creek at Boulder was selected as the primary comparison for model calibration. It should be noted that three historical floods not included in the systematic gage record were included in the development of flow estimates using gage data, in accordance with *Technical Manual No. 1* (Jarrett and McCain, 1976) methodology (USACE, undated). Including such historical floods may result in an overestimation of high-flow magnitudes because extreme historical floods were "added" to the systematic gage record with no weighting to consider intervening flow years of presumably low-to-moderate discharges, as is standard for current Bulletin 17B (USGS, 1982) methodology. Final parameter selection was based on comparison of modeled discharges to the discharge-probability curve for the Boulder Creek at Boulder gage (USGS Gage #06728000) and regional regressions presented in *Technical Manual No. 1* (Jarrett and McCain, 1976). The following parameters were discussed in the two documents:

- **Detention Storage:** It was noted that the model was quite sensitive to detention storage parameters; 0.5 was used in lieu of the default 1.84 but no description of the physical relevance of these parameters was provided (USACE, undated).
- **Flood Routing:** Due to evident overbank storage downstream of the Flatirons, the Missouri River Division's diffusion routing technique, an unsteady finite-difference hydraulic model, was used to route flows in the lower basin.
- **Infiltration Losses:** It was noted that rainfall-runoff relationships were not readily available and, on the basis of a few infiltrometer studies, a constant infiltration rate of 1.0, 0.5, and 0.0 inch per hour (i.e., no infiltration) were used for the mountain, plains, and urban areas, respectively (USACE, 1977). It was noted that the infiltration rates for plains and mountains were approximately 50 percent of the field-measured average infiltration rates (USACE, 1977).
- **Overland, Channel, and Overbank Roughness:** Sensitivity testing indicated that the hydrologic model was sensitive to selection of roughness values (USACE, undated). Calibration studies on lower Cherry Creek, near and within Denver, Colorado, and observations of channel and overbank material were used to select roughness values of 0.12 for overland areas and 0.06 to 0.09 for channel and overbank areas (USACE, undated).
- **Rainfall:** A 6-hour duration storm divided into 30-minute intervals was developed from a study of hourly precipitation data recorded for major storms in the South Platte River basins and subsequently used as the design rain event in the SWMM model (USACE, 1977). Five rainfall depths were used across the watershed to reflect the varying depth of rainfall that would occur across the basin. (USACE, undated). Rainfall-frequency relationships were obtained from 1973 National Oceanic and Atmospheric Administration (NOAA) publications (NOAA, 1973), adjusted for expected probability based "on [an] equivalent rainfall record length of 48 years," and an area-depth correction applied based on the 155-

square-mile study area (USACE, undated). The 6-hour rainfall distribution was provided as shown in **Table 3**. Discussion of the hyetograph in comparing USACE, 1977 results to the rainfall-runoff model estimates is provided in Section 3.

TABLE 3
Rainfall Distribution for Effective Rainfall-Runoff Model (per USACE, 1977)

End of Period (minutes)	Percent of Total 6-Hour Precipitation (percent)
30	2
60	4
90	4
120	5
150	9
180	10
210	40
240	10
270	6
300	4
330	4
360	2

- **Rainfall-Runoff Transformation:** Kinematic wave routing was used in the SWMM model employed by USACE to transform rainfall-runoff into an outflow hydrograph (Anderson Consulting Engineers, 2009). Parameters for the kinematic wave routing were determined from the development of a calibrated model for the May 1973 flood event downstream of Cherry Creek Dam, an urbanized portion of the high plains in the Denver suburbs (USACE, 1977).

Using the methodology and parameters described above, the USACE, 1977 study **estimated the 1 percent annual chance flow at Orodell and Boulder as 6,270 and 11,650 cfs, respectively.** Discussion of the flow estimates was limited to stating they were greater than estimates provided in the 1969 USACE study and that the revised estimates were more realistic based on the then-recent 1976 Big Thompson Flood and 1894 Boulder Creek flood, estimated as 11,000 cfs at the Boulder Creek at Boulder gage, and also assumed as the 1 percent annual chance flow by the USGS in 1969.

2.1.3 *Hydrology Verification Report for Boulder Creek* (Anderson Consulting Engineers, 2009)

Prior to revising the regulatory flood hazard delineation along Boulder Creek through the City of Boulder, the City contracted with Anderson Consulting Engineers to evaluate and verify the appropriateness of the Boulder Creek hydrology developed in the USACE, 1977 report. The majority of the report described the creation of the duplicate effective model using modern versions of SWMM to replicate hydrology estimates from the USACE, 1977 study. Discussion of high-flow estimates were limited to comparing the modeled discharges to discharges estimated using regression equations developed by USGS for the Plains Region (USGS, 2009) and by CWCB for the Central Foothills Sub-Region (CWCB, 2009). The modeled 1 percent annual chance flow compared well with regression estimates except for at the Orodell gage, where the modeled flow was 37 and 34 percent lower, respectively, than that estimated from the USGS and CWCB regression and outside the CWCB regression's 23 percent standard error of estimate. No comparison of modeled discharges to the statistical analysis of gage records was made on the grounds that Barker Reservoir negated the appropriateness of such an analysis. Although no detailed evaluation of the parameters used in the original (and duplicate) hydrologic model was performed, it was **concluded that the**

1 percent annual chance flow at Orodell and Boulder of 6,270 and 11,650 cfs, respectively, remained appropriate.

2.2 Stream Gage Analysis

Six stream gages, four owned and operated by the Colorado Division of Water Resources (CDWR) and two owned and operated by the USGS, are located in or shortly downstream of the study area, as shown in **Figure B-2** in **Appendix B**. Four of the six gages are located in the studied watershed. These include two USGS gages: 1) Fourmile Creek at Logan Mill Road near Crisman, Colorado (USGS 06727410), and 2) Fourmile Creek at Orodell, Colorado (USGS 06727500); and two CDWR gages: 1) Boulder Creek near Orodell (CDWR Gage BOCOROCO), located at a point upstream of the Fourmile Creek confluence, the downstream study limit, and 2) Boulder Creek at Nederland (CDWR Gage BOCOMIDCO), located on Middle Boulder Creek, immediately upstream of the inlet to Barker Reservoir. Both USGS gages were damaged during the September 2013 event, but both CDWR gages were unaffected and recorded and provided reliable discharge measurements during that storm event.

Both USGS gages on Fourmile Creek have a relatively short period of record (3 years at Crisman and 22 years at Orodell) and were not considered further. The gage at Orodell has a continuous record of annual peak flow rates beginning in 1907 and ending with the September 2013 flood. The gage at Orodell recorded a peak discharge of 1,720 cfs for the 2013 flood. In comparison, the highest discharge recorded at the Orodell gage was 2,500 cfs in June 1921. The gage at Nederland has a continuous record of annual peak discharges dating back to 1908, with a maximum discharge of 811 cfs recorded in June 1914. In contrast to the gage at Orodell, the peak discharge of 409 cfs recorded during the September 2013 event at the Nederland gage was less than the 469-cfs snowmelt peak discharge measured in June 2013. Although peak discharge estimates exist for the historic flood of 1894 in the City of Boulder itself, no such estimates exist for gages analyzed as part of the current study.

Ayres Associates and CH2M HILL performed flood frequency analyses to supplement the hydrologic evaluation of Boulder Creek and Middle Boulder Creek, respectively. The analyses followed the methods described in the document *Guidelines for Determining Flood Flow Frequency* published by USGS on behalf of the Interagency Advisory Committee on Water Data, dated September 1981 (USGS, 1982). This document is commonly known as *Bulletin 17B*. Following the *Bulletin 17B* methods using the computer program HEC-SSP, Ayres Associates and CH2M HILL conducted the flood frequency analyses using the annual peak flow records at CDWR Gage BOCOROCO / USGS Gage 06727000, Boulder Creek near Orodell, and CDWR Gage BOCOMIDCO / USGS Gage 06725500, Middle Boulder Creek at Nederland.

Stream gage analysis by *Bulletin 17B* methods requires as input the highest peak discharge for every available year of record. The engineer must also decide how to treat the skew coefficient. The possible options include the following:

1. Using a weighted skew coefficient in which the station skew is weighted with a regional skew determined from the map included in *Bulletin 17B*. A drawback to this method is that the stream flow data used to develop that map were from the 1960s).
2. Weighting the skew coefficient with a regional coefficient developed from a current regional regression analysis. The initial attempts to use this approach had the drawback that very few gages were available for the regression analysis that had measured or approximated peak values for the September 2013 flood. Furthermore, many of the available gages were missing peak flows from other known large flood events. The results from this approach appeared unreliable at several gages, in that the resulting 100-year flow values were lower than two or three of the observed peaks in periods of record no more than 120 years.
3. Use the station skew coefficient, without any regional skew weighting. This approach yielded the most reasonable results and was adopted for this study.

The detailed input to and output from HEC-SSP is included as part of **Appendix C**. The results of the flood frequency analyses are summarized in **Table 4** below. Comparison of flood frequency results to September 2013 discharges is provided in Section 3.2.

TABLE 4
Discharge-Frequency Based on Flood Frequency Analysis of Gage Records

Exceedance Recurrence Interval (years)	Boulder Creek near Orodell (cfs)	Middle Boulder Creek at Nederland (cfs)
2	586	410
5	874	540
10	1,078	618
50	1,563	770
100	1,784	829

2.3 Peak Flow Estimates

One technique for estimating the peak flow after a significant storm event is to apply indirect methods that utilize observed high-water marks, channel geometry, and hydraulic properties to estimate recent peak discharges. USGS has been actively developing and applying indirect methodologies to estimate peak discharges in various watersheds along the Front Range. In fact, USGS has validated one such methodology, the critical-depth method, to be accurate to within 15 percent of direct discharge measurements for streams with gradients exceeding 0.005 ft/ft, such as the streams in the affected Front Range area (Jarrett, 2013). This methodology was applied by Applied Weather Associates (AWA) and its subconsultant, Bob Jarrett, to estimate peak discharges along Front Range streams that witnessed high flows during the September 2013 event. The evaluated locations are identified in **Figure B-2** in **Appendix B** and the peak discharge estimates for each location used in the calibration of the rainfall-runoff model are provided in **Table 5** (Jarrett, In press). Due to frequent damage of gaging stations and the relative density of indirect measurements, it was concluded that peak discharges determined from the critical-depth methodology were the most reliable estimates of peak discharges for the September 2013 storm event and as such were used for the calibration of the rainfall-runoff model. Peak discharge measured at the Boulder Creek near Orodell gaging station, which was not damaged, compared well with the critical-depth estimate, at 1,720 versus 2,020 cfs, respectively.

TABLE 5
Critical-Depth Method Peak Discharge Estimates and Locations

Location	Description	Drainage Area (square miles)	Peak (cfs)
Site #40	Boulder Creek Near Orodell	102	2,020
Site #35	North Boulder Creek Upstream of Boulder Creek and SH 119 near Orodell	36	740
Site #48	Fourmile Creek Upstream of Burned Area	9.0	490
Site #52	Fourmile Creek Downstream of Emerson Gulch (Sheila Murphy's WQ Site)	14.7	1,070
Site #43	Fourmile Creek Downstream of Poorman Road and Upstream of #1267 Fourmile Creek Road near Orodell	21.4	2,300

Source: Jarrett, In press.

2.4 Rainfall-Runoff Modeling

2.4.1 Overall Modeling Approach

In general, hydrologic modeling of Boulder Creek entailed the development and calibration of a hydrologic model to the September 2013 high-flow event, which was then used to estimate the magnitude of the 10, 4, 2, 1, and 0.2 percent annual chance peak discharge. Given that the September 2013 high-flow event and historical high-flow events noted during the literature review were driven by substantial rainfall, a rainfall-runoff model was used to evaluate hydrologic conditions within Boulder Creek. The USACE Hydrologic Engineering Center's Hydrologic Modeling System (HEC-HMS) version 3.5 (USACE, 2010) was selected to model the hydrologic conditions within Boulder Creek due to FEMA approval of HEC-HMS version 1.1 and newer to model single-event flood hydrographs (FEMA, 2013b) and the ability to incorporate complex calibration data and modeling parameters into the program. The hydrologic modeling process entailed the development of two separate hydrologic models to evaluate hydrologic conditions in Boulder Creek:

- A *calibrated hydrologic model* was developed to model the September 2013 event. Hydrologic conditions unique to the September 2013 event (e.g., measured rainfall, storage capacity of Barker Reservoir) were used to calibrate remaining model parameters to match modeled peak discharges to peak discharges observed during the September 2013 event at stream gages and estimated following the September 2013 event by indirect measurements.
- Following development of the calibrated hydrologic model, a *predictive hydrologic model* was developed to estimate discharge-frequency relationships based on calibrated model parameters, rainfall-frequency relationships, and adjusted hydrologic conditions that reflected anticipated flood conditions, rather than the unique conditions preceding the September 2013 event.

Detailed discussion of difference between the two hydrologic models is provided in following sections.

Beyond the selection of the hydrologic model itself, selection of modeling methodologies would control the subsequent calibration and implementation of the hydrologic model: selection of an infiltration loss method, which controls the conversion of rainfall to runoff; selection of a transformation method, which controls the transformation of runoff volume to an outflow hydrograph; and selection of a routing method, which controls the routing of hydrographs from various watersheds to the downstream outlet. The Soil Conservation Service (SCS, now the Natural Resources Conservation Service [NRCS]) curve number (CN) method was selected to model infiltration losses due to its relative simplicity, acceptance in the *Colorado Floodplain and Stormwater Criteria Manual* (CWCB, 2008), and its ability to reflect varying land use conditions and infiltration properties of underlying soils. The Snyder's unit hydrograph was used also due to its acceptance in the *Colorado Floodplain and Stormwater Criteria Manual* (CWCB, 2008) and its ability to calibrate the transformation method to observed data. The Muskingum-Cunge routing methodology was selected to route runoff hydrographs due to the method's ability to attenuate runoff based on a specified hydraulic roughness and channel-floodplain cross section.

At a detailed level, the hydrologic model was calibrated to the 24-hour period in which peak discharge measurements were recorded to replicate the assumptions used to develop the NRCS infiltration loss model; the 24-hour period of rainfall associated with the peak discharge observed on Boulder Creek was determined to occur from 6 a.m. on September 12 to 6 a.m. on September 13. Prior to model calibration, a decision was made to include the effects of Barker Reservoir in both the calibrated and predictive model. In the calibrated model, Barker Reservoir was modeled as a reservoir to account for its storage during the September 2013 event to avoid under-calibration of downstream reaches. In the predictive model, only the time-attenuation effects of Barker Reservoir at full stage were considered (i.e., no volume attenuation). Further discussion of the time-attenuation effects of Barker Reservoir are provided in subsequent sections.

2.4.2 Summary of Modeling Approaches Considered

Throughout the development of the rainfall-runoff model, modeling methodology was reviewed and discussed between a joint team of local engineers and project sponsors; meeting minutes from these discussions and responses to review comments are provided as part of **Appendix D**. Several modeling methodologies were considered, applied, evaluated, and subsequently discarded over the course of hydrologic model development to assess the performance of alternative modeling methodologies or to synchronize model development efforts with other consultants. These alternative modeling methodologies are described briefly in the following subsections.

Calibration of Model to Entirety of September 2013 Event

Initially, hydrologic model development and calibration were performed for the entirety of the September 2013 rainfall event, which spanned approximately 7 days from September 9 to September 16. The calibration process resulted in calibrated parameters that were outside of published values, including CNs that were generally consistent with Antecedent Moisture Condition (AMC) I (usually associated with severe drought or unusually dry conditions), Snyder's peaking coefficients (C_p) of less than 0.4, and basin roughness factors (K_n) greater than those recommended in the *Colorado Floodplain and Stormwater Criteria Manual* (CWCB, 2008). Due to the parameters outside of the published ranges and acknowledgement that the NRCS method was developed for single-event storms rather than several closely distributed events, such as occurred in September 2013, this methodology was noted for the modeling lessons learned that formed the foundation for the development of the calibrated model.

Calibration of Model using Green-Ampt Loss Method

Recognizing that the NRCS method was developed for single-event storms and may not accurately model the closely distributed events that comprised the September 2013 rainfall event, the Green-Ampt infiltration loss model, which accounts for the recovery of infiltration capacity between discrete events, was evaluated. Two methods were used in an attempt to calibrate the Green-Ampt parameters to measured runoff volumes measured at CWCB's Middle Boulder Creek at Nederland and Boulder Creek at Orodell gages. The first method, which relied on assigning Green-Ampt parameters in accordance with the infiltration capacity of underlying soils provided in the U.S. Department of Agriculture's (USDA) Soil Survey (USDA, 2013), resulted in Green-Ampt parameters that infiltrated the entire September 2013 event such that no runoff occurred. The second method assigned Green-Ampt parameters based on the surface texture of underlying soils provided in the Soil Survey. Using conservative literature-cited values of Green-Ampt Parameters based on soil texture, the resultant Green-Ampt parameters infiltrated the majority of the September 2013 event – modeled runoff volume was approximately 10 percent of observed runoff volumes. Calibration of the Green-Ampt parameters resulted in parameters that were significantly beyond the values reported in literature and, as such, the Green-Ampt infiltration loss model was discarded in favor of the NRCS model.

Calibration of Fourmile Creek Sub-Model and Prediction of 6-Hour Peak Discharges

Following the development of the 24-hour calibrated and predictive hydrologic models discussed in detail in subsequent sections, a separate sub-model of the Fourmile Creek watershed was calibrated and developed to assess the sensitivity of the estimated peak discharges to the duration of the storm event and provide a comparison to USACE, 1977 results that were based on a 6-hour storm. The Fourmile Creek sub-model was extracted from the calibrated 24-hour hydrologic model (discussed in subsequent sections) and re-calibrated using the 6-hours of rainfall preceding the peak discharges measured on Fourmile Creek. Similar to the 24-hour calibration, the Fourmile Creek HEC-HMS model was calibrated by adjusting the CN to match peak discharge estimates. Runoff due to rainfall that occurred prior to the calibration period was not considered in the re-calibration such that calibrated CNs would be conservative. This was considered a conservative approach due to discounting the portion of the peak discharge that was attributable to rainfall that occurred prior to the calibration period. In contrast to the 24-hour calibrated hydrologic model, the initial abstraction in the calibrated 6-hour sub-model was set to zero, as upwards of 12 inches of rain had fallen on some Fourmile Creek subbasins at the start of the analysis window. As direct evidence that the initial abstraction capacity had been expended in Fourmile Creek, UFDCD ALERT system gage records of stage measurements indicated a rising hydrograph at the start of the 6-hour calibration period, suggesting that runoff was already occurring at the beginning of the calibration period.

Similar to the creation of the 24-hour predictive hydrologic model, the calibrated CNs were adjusted from a saturated soil condition to a “normal” condition to develop the predictive Fourmile Creek sub-model; the initial abstraction ratio was also reset to the standard value of 0.20 times the soil storage capacity for the predictive sub-model. Utilizing 6-hour point precipitation frequency estimates for each subbasin from NOAA’s precipitation frequency data server (NOAA, 2014) and a 6-hour NRCS Type II hyetograph, the estimated 1 percent chance annual exceedance discharge at the mouth of Fourmile Creek was estimated as 3,630 cfs – a 6 percent increase beyond that estimated by the 24-hour predictive hydrologic model (which did not adjust rainfall depths specifically for Fourmile Creek), but short of the 6,230 cfs estimated as part of the USACE, 1977 study.

To further assess the impacts of varying rainfall patterns and compare the sub-model directly to the USACE, 1977 model, the 6-hour rainfall distribution used in the USACE, 1977 study was also evaluated: the estimated 1 percent chance annual exceedance discharge was slightly less than the 3,630 cfs estimated using the NRCS Type II hyetograph. In an attempt to replicate the discharge estimated for Fourmile Creek in the USACE, 1977 study, CNs were re-calibrated to match the peak discharge of 6,230 cfs that was estimated at the mouth of Fourmile Creek. The calibration to the USACE, 1977 model yielded an average CN of 93, with some subbasins approaching a CN of 96, to replicate the USACE, 1977 discharge estimates.

In summary, the Fourmile Creek sub-model study yielded the following observations:

1. Estimated 10, 4, 2, 1, and 0.2 percent chance annual exceedance discharge are relatively insensitive to the duration of rainfall – despite the conservative calibration procedure (neglecting to separate the portion of the estimated peak discharge that was attributable to rainfall runoff preceding the sub-model analysis period), the estimated 6-hour, 1 percent chance annual exceedance discharge was only 6 percent greater than that estimated for a 24-hour storm.
2. The NRCS Type II distribution is representative of storm events in the study area, as the USACE, 1977 study developed a unique rainfall hyetograph based on rainfall records in the South Platte basin and the 1 percent chance annual exceedance discharges estimated using the USACE, 1977 distribution were nearly identical to the 1 percent chance annual exceedance discharges estimated using the NRCS Type II distribution.
3. USACE, 1977 estimates of peak discharges along Fourmile Creek appear unrealistically high – a CN comparable to urbanized and largely impervious commercial and business districts would be needed to replicate the USACE, 1977 estimates along Fourmile Creek.

2.4.3 Basin Delineation

Subbasins (i.e., smaller divisions of aforementioned sub-watersheds for hydrologic modeling) were delineated manually using USGS Topographic Maps. The Boulder Creek watershed consists of various mountain stream and lakes and subbasins were delineated to have design points at key locations, including confluences, lakes or reservoirs, census-designated places, gaging stations, or calibration points. Subbasins were generally delineated to be less than 5 square miles, per the *Colorado Floodplain and Stormwater Criteria Manual* (CWCB, 2008), unless such delineation would have unnecessarily divided a homogenous subbasin. Delineated subbasins are primarily mountains with steep terrain. In areas where steep valley conditions occur along the channel corridor, the basins were delineated extending from the high point along the overbank to the channel centerline, resulting in subbasins on both the left and right overbanks of the stream. This was done to better represent the runoff from the steep valley slopes. This approach resulted in 44 subbasins that varied in size from 0.5 square mile to approximately 5 square miles, with an average size of approximately 3 square miles. Delineated subbasins are provided in **Figure B-3** in **Appendix B**; delineated subbasin areas are provided in **Table B-1** in **Appendix B**.

2.4.4 Basin Characterization

The entirety of the study area is located upstream of the Boulder Creek canyon mouth, parallel to the Boulder Flatirons, and is considered mountainous terrain with relatively rapid flood responses (in the hydraulic sense). In terms of vegetation cover, pine forest dominates the watershed, with a gradual transition to semi-arid brush on south-facing slopes in the lower portion of the basin. As elevations increase in the upper basin, alpine meadows and riparian forests develop in response to long-duration snowmelt emanating from even higher elevations characterized by steep, barren slopes located above timberline. The relatively lush alpine meadows and riparian forests likely contribute to increased infiltration and interception of rainfall in comparison to slopes above timberline or semi-arid brush that likely run off a greater proportion of an identical rainfall depth. Differentiating between sub-watersheds, vegetative cover along Fourmile Creek is generally less dense than other portions of the basin and may result in the potential for greater runoff and sediment delivery. Similarly, the 2010 wildfire discussed in Section 1.2.2 that burned approximately half of the Fourmile Creek sub-watershed would be expected to further increase runoff and erosion potential of the Fourmile Creek sub-watershed in comparison to other sub-watersheds. As discussed later, the differences in vegetative cover were incorporated into the model based on visual characterization of land use and cover provided in the National Land Cover Dataset (NLCD) (USGS, 2006) in conjunction with engineering judgment of the impacts of recent wildfire.

In terms of watershed shape, the upper portions of Middle Boulder Creek and North Boulder Creek are more dendritic in nature, whereas the lower portion of the watershed, including the majority of Fourmile Creek, is characterized by narrow watersheds with hillslopes from the sub-watershed divide draining directly into Boulder Creek or Fourmile Creek. The shape of the Fourmile Creek and lower Boulder Creek watersheds results in flashier hydrographs: rainfall will run off relatively quickly via gulches with little attenuation before being conveyed down Fourmile Creek to the confluence with Boulder Creek. In Middle Boulder Creek and North Boulder Creek, the comparable drainage boundaries drain to several mountain streams with varied topography, floodplains, alpine lakes, and vegetation that attenuate flows to a greater degree than the lower basin watershed shape. To reflect this difference in watershed shape, hydrologic flowpaths for hillslopes draining directly to the main channel were developed from the furthest drainage divide to the main channel, in contrast to the dendritic watersheds where hydrologic flowpaths were developed from the furthest drainage divide to the lowermost point in the watershed.

Annual average precipitation depth increases gradually with increasing elevation in the watershed, with a greater proportion of the average annual precipitation falling as snow at higher elevations. Conversely, storm intensities are generally greater in the lower basin where local convective storms are more frequent and likely to cause high runoff. Design event rainfall depths published by NOAA are generally consistent across the basin with a slight decrease in rainfall depths at mid-elevations. It should be noted that this relationship is different from previously published design rainfall maps where design rainfall depths generally decreased with increasing elevation. Therefore, the most recent NOAA rainfall maps could result in greater design discharges at higher elevations than would result from the use of previous NOAA rainfall maps.

Considering rainfall characteristics in conjunction with vegetative cover and watershed shape, inferred runoff responses correspond well to historical observations: the Boulder County FIS and previous hydrologic studies note that flooding on Boulder Creek in Boulder is frequently a result of flooding along Fourmile Creek (FEMA, 2012), despite Fourmile Creek comprising less than one-fifth of the Boulder Creek watershed above Boulder. This supports the conclusion that runoff potential is relatively greater in Fourmile Creek. Supporting the concept of decreased runoff potential at higher elevations, the peak flow in Middle Boulder Creek at Nederland during the September 2013 event was less than the snowmelt peak measured in that same year. As discussed in subsequent sections, hydrologic modeling results agree well with the general runoff concepts described above.

2.4.5 Model Development

The developed HEC-HMS hydrologic models used "hydrologic elements" in the form of subbasins, junctions, reaches, and reservoirs to convert input rainfall to output hydrographs. Subbasin elements contain parameters to estimate infiltration losses and convert the resultant runoff to an outflow hydrograph. Reach elements route inflow hydrographs based on the hydraulic characteristics of the conveying element, e.g., Boulder Creek, while reservoir elements route inflows based on reservoir storage capacity and outlet works. Junction elements have no hydrologic function other than congregating multiple inflows to a single outflow. A description of input parameters, presented by hydrologic elements and then hydrologic order, is provided below:

Rainfall Analysis

The Storm Precipitation Analysis System (SPAS) was used to analyze the rainfall for the September 2013 event. SPAS uses a combination of climatological base maps and NEXRAD weather radar data that is calibrated and bias corrected to rain gage observations (considered ground truth) to spatially distribute the rainfall accumulation each hour over the entire domain of the storm. Therefore, through the use of climatological base maps and weather radar data, SPAS accounts for topography and locations of rain gages. For quality control (QC), SPAS storm analyses withheld some rain gages observations and ran the rainfall analysis to see how well the magnitude and timing fit at the withheld rain gage locations. In nearly all cases, the analyzed rainfall was within 5 percent of the rain gage observations and usually within 2 percent. In data-sparse regions where there are a limited number of rain gages, there can be increased uncertainty in traditional rainfall analyses, especially in topographically significant regions. For the September 2013 storm, this was not the case. Excellent weather radar coverage existed as well as many rainfall observations with excellent overall spatial distributions at both low- and high-elevation locations (AWA, 2014).

Rainfall Inputs

AWA provided rainfall data for the September 2013 storm event through the methodology described in the preceding section (AWA, 2014). **Figure B-4** in **Appendix B** illustrates the total precipitation depth measured during this period (AWA, 2014). Individualized rainfall hyetographs were generated by AWA for each modeled subbasin using weighting techniques to adjust precipitation gage measurements collected during the event to the centroid of each subbasin. Individualized rainfall hyetographs were provided as 5-minute incremental rainfall depths from 1 a.m. on September 8, 2013, to 1 a.m. on September 18, 2013. **Figure B-5** in **Appendix B** provides the incremental rainfall depth measured for each of the subbasins. Two periods of peak rainfall were observed in several subbasins during the 10-day period: a rainfall burst occurring in the late evening of September 11 caused high flows along Fourmile Creek, and a second rainfall burst the evening of September 12 caused the measured peak discharge in Boulder Creek at Orodell and Middle Boulder Creek at Nederland and the peak stage recorded by the UDFCD ALERT gage on Fourmile Creek near Orodell (UDFCD, 2013).

The 24-hour rainfall depths for the 10, 4, 2, 1, and 0.2 percent annual chance precipitation were developed for each subbasin from *NOAA Atlas 14* (NOAA, 2013) point precipitation frequency estimates by inputting the centroid of each basin into NOAA's online, geographic information system (GIS)-based precipitation frequency database server (NOAA, 2014). The reported NOAA rainfall estimates used in the hydrologic model are the 50th percentile rainfall depths estimated from a population frequency curve of expected rainfall depths at each of the subbasin centroids. Therefore, in addition to providing the 50th percentile rainfall depths, the NOAA tables also provide the bounding 90 percent confidence intervals for expected rainfall depth at each of the subbasin centroids, thereby providing an estimate of uncertainty in the rainfall-frequency estimates. In general, the 90 percent confidence intervals vary ± 25 percent from the 50th percentile rainfall depth. Rainfall-frequency curves for each subbasin centroid are provided in **Table B-2** in **Appendix B**. In addition, total measured rainfall depths for the modeled 24-hour period of the September 2013 event are provided in **Table B-2** in **Appendix B** to provide a comparison of September 2013 rainfall to NOAA rainfall-frequency estimates (NOAA, 2014). In general, measured rainfall depths during the modeled

24-hour period of the September 2013 event ranged from less than the estimated 10-year rainfall depths in the upper portions of the watershed (North and Middle Boulder Creek, the very upper portion of Fourmile Creek). In the eastern portions of the basin (lower Fourmile Creek and Boulder Creek) observed rainfall depths were approximately equal to the 25-year rainfall depths, with some observed rainfall depths in Fourmile Creek approaching the 50-year rainfall depth.

Prior to input to the hydrologic model, a depth-area reduction factor (DARF) of 0.93 was applied to NOAA 50th percentile point precipitation estimates in accordance with Figure CH9-F415 of the *Colorado Floodplain and Stormwater Criteria Manual* (CWCB, 2008). The depth-area reduction factor accounts for the gradual decrease in rainfall intensity with increasing distance from the storm centroid, and corrects the NOAA point precipitation estimate to the average rainfall that would occur over the spatial extent of the storm. Per the *Colorado Floodplain and Stormwater Criteria Manual* (CWCB, 2008), the standard NRCS 24-hour Type II rainfall distribution was used as the design hyetograph to distribute the 24-hour rainfall depths to generate hydrographs for the 10, 4, 2, 1, and 0.2 percent annual chance discharge. The NRCS 24-hour Type II rainfall distribution was incorporated into the hydrologic model as a dimensionless cumulative rainfall distribution ("unit hyetograph"), sub-divided into 5-minute increments. A table of the NRCS Type II rainfall distribution input to the model is provided as **Table B-3** in **Appendix B**; a graph of the dimensionless rainfall distribution is provided as **Figure B-6** in **Appendix B**.

Subbasin Parameters (Infiltration Losses and Hydrograph Transformation)

As discussed in previous sections, the NRCS (formerly SCS) method was selected to convert input rainfall to infiltration losses and runoff. The key parameter in the NRCS method is the CN, which defines the runoff potential of a particular land cover, land condition, and underlying soil substrate; a completely impervious surface would be represented by a CN of 100, whereas a forest in good condition with permeable substrate would have a lower CN, e.g., 30. The CN also considers soil saturation as saturated soils have less interstitial space available for the storage of rainfall and thus runoff a greater proportion of rainfall. The NRCS method accounts for soil saturation by assigning an AMC based on the rainfall during the preceding 5 days. AMCII is considered a "normal" condition and is generally assumed. AMCIII conditions represent saturated conditions, such as occurs immediately after a moderate to high rainfall, with higher resultant CNs as compared to AMCII. AMCI is a dry condition, such as occurs when no rainfall has occurred for several days, weeks, or months, with a lower resultant CN as compared to AMCII.

Two GIS-based data sources, *Technical Release 55: Urban Hydrology for Small Watersheds* ("TR-55," NRCS, 1986), and engineering judgment were used to develop CNs for each subbasin. TR-55 provides CNs for a given land cover description and hydrologic soil group (a measure of the infiltration capacity of the underlying soil alone). Land cover was delineated using the NLCD to identify land use across the subbasins on a 100-foot by 100-foot scale (USGS, 2006). Delineation of hydrologic soil groups was accomplished using USDA's Soil Survey (USDA, 2013); delineated hydrologic soil groups are presented in **Figure B-7** in **Appendix B**. The overlapping Soil Survey and NLCD datasets were then joined by intersecting the two datasets such that each land cover unit was further subdivided by hydrologic soil group. These results were then exported to Microsoft® Excel® where a CN was applied for each unique land cover condition and hydrologic soil group using engineering judgment to correlate observed land cover conditions with a representative land cover description provided in TR-55. Microsoft® Excel® was then used to adjust AMCII CNs to AMCIII CNs as appropriate (discussed later) and area-weight these results in accordance with TR-55 methodology to estimate a single, representative CN for each subbasin.

The transformation of runoff volume to an outflow hydrograph was accomplished using the Snyder's unit hydrograph. The shape of the Snyder's unit hydrograph is controlled by two factors: a peaking factor, C_p, and a lag time representative of the time elapsed between the centroid of a hyetograph and the peak of the resultant hydrograph. Snyder's C_p was estimated as 0.4 to conform to literature recommendations and values used in the parallel hydrologic studies of surrounding Front Range watersheds. Lag time was estimated using the following equation (Equation CH9-511) provided in the *Colorado Floodplain and*

Stormwater Criteria Manual (CWCB, 2008) and recommended for use in subbasins larger than 1 square mile and with basin slopes greater than 10 percent (CWCB, 2008), as occurs in the hydrologic model:

$$TLAG = 22.1\ K_n * \left(\frac{L * L_c}{\sqrt{S}}\right)^{0.33}$$

where K_n is the roughness factor for the basin channels, taken as 0.15 for pine forest, L is the length of longest watercourse, in miles, L_c is the length along longest watercourse measured upstream to a point opposite the centroid of the basin, in miles, and S is the representative slope of the longest watercourse, in feet per mile. Physical parameters were estimated using ArcHydro tools in ArcGIS to analyze the NED digital elevation model (USGS, 2013). Flowpaths for watersheds characterized by hillslopes and gulches draining directly to the main channel were determined using the watershed of a representative gulch. **Figure B-8** in **Appendix B** provides a visual depiction of the hydrologic model layout, including delineated flowpaths from the centroid of each subbasin and layout of reach elements. Verification of the appropriate selection of C_p and lag time was confirmed during the calibration process when modeled times-of-peak discharge approximated observed times-of-peak discharge, as discussed in subsequent sections. Lag times for each individual subbasin are provided in **Table B-4** in **Appendix B**.

Reach Parameters (Hydrograph Routing)

The Muskingum-Cunge routing methodology was selected to route inflow hydrographs along basin streams owing to its solution of the continuity and momentum equations to estimate lag time and flow attenuation; thus, the Muskingum-Cunge method is based on channel hydraulics, including channel roughness, cross section, and slope. Eight-point cross sections were used to model the channel cross section shape to allow for the incorporation of channel floodplains that convey a significant portion of high flows. Eight-point cross sections were derived using ArcGIS tools and manually transposed to the hydrologic model. The USGS, 2013 NED was used to develop most cross sections, whereas FEMA, 2013 LiDAR was used to develop cross sections along the mainstem of Boulder Creek where LiDAR coverage was available. A single cross section was selected for each reach based on visual identification of a representative cross section, erring slightly towards flatter, wider reaches that are likely to provide the majority of floodplain storage and flow attenuation. Graphs of the eight-point cross sections for each of the modeled reaches are provided as **Figure B-9** in **Appendix B.**

A Manning's roughness values of 0.07 was selected for the main channel to represent a cobble/boulder substrate with provision for greater losses (e.g., sediment transport, debris) during flood flows. A Manning's roughness value of 0.08 was selected for overbank areas to represent light brush (willows) during the growing season (Chow, 1959). Model sensitivity analysis indicated that hydrograph attenuation along the reach was relatively insensitive to Manning's roughness value.

Reservoir Parameters (Hydrograph Routing)

Barker Reservoir, a water supply reservoir immediately downstream of Nederland, was the only reservoir considered in the development and calibration of the hydrologic model due to its storage of a significant portion of the inflow during the September 2013 storm event. Based on CWCB and City of Boulder gage measurements, the inflow hydrograph to Barker Reservoir peaked at approximately 400 cfs on September 13, whereas flow releases from Barker Reservoir were approximately 4 cfs until the emergency spillway activated on September 15. Although water supply reservoirs are typically not modeled in hydrologic models, the decision was made to account for Barker Reservoir in the calibrated model because the 11 feet of storage available in the reservoir immediately prior to the storm event (according to City of Boulder measurements) was used to store the majority of the September 13 peak flow (see **Table B-5** in **Appendix B**). Neglecting this available storage and routing the entirety of the inflow hydrograph to the downstream reaches would result in the underestimation of calibration parameters because modeled discharges would have included discharge from Middle Boulder Creek that did not actually occur and, thus, decrease the runoff contribution from other sub-watersheds.

In the calibrated model, Barker Reservoir was effectively modeled as a “sink”: outflow was dictated by measured flow releases provided by the City of Boulder (City of Boulder, 2013b) such that inflow did not have an effect on outflow. Although Barker Reservoir stage had no effect on the hydrologic calibration, the stage of Barker Reservoir was determined within the model based on modeled inflow, starting elevation, and elevation-storage curve, the latter two of which were provided by the City of Boulder (City of Boulder, 2013a) and are presented in **Table B-5** in **Appendix B**.

In the predictive model, Barker Reservoir was removed as a reservoir element and replaced as a routing element to conservatively estimate the downstream hydrograph. Such an approach allowed for the time attenuation of flow, i.e., modeled the time elapsed between inflow and outflow peaks, but did not allow for volumetric attenuation of the flow because Barker Reservoir is not explicitly operated as a flood control dam. The time lag associated with Barker Reservoir was determined by measuring the time elapsed between the peak modeled inflow and peak modeled outflow at Barker Reservoir on September 15 using a model calibrated to the entirety of the storm event and assuming that Barker Reservoir outflow is entirely controlled by a 63-foot weir (measured from Google Earth™) at the maximum reservoir stage. This flow peak occurred following a moderate rainfall when Barker Reservoir was near-or completely-full and, therefore, it represents a realistic estimate of the time attenuation provided by Barker Reservoir when no storage is available. Using this methodology, a time lag of 4.5 hours was measured. As illustrated in **Figure B-10** in **Appendix B**, the modeled outflow compares favorably with observed flow downstream of Barker Reservoir.

2.4.6 Model Calibration

Model calibration is the iterative process of adjusting model parameters so that simulated results match real-world observations (measurements). Model calibration provides a degree of certainty beyond that achieved through the use of parameters reported in literature because calibrated parameters ideally account for unique attributes of a particular watershed. The following sections describe the calibration of the Boulder Creek HEC-HMS hydrologic model.

Calibration Event

Reviewing the flood history of Boulder Creek, summarized in **Table 2**, it can be surmised that the largest discharges observed along Boulder Creek were the result of large, long-duration “general storms” rather than localized and intense convective storms (“cloudbursts”). The majority of historical high-flow events follow a pattern characterized by a slow, steady rainfall occurring over several days punctuated by a short period of comparatively intense rainfall that drives downstream flooding. As previously discussed, such a pattern was followed during the September 2013 event and suggests that the September 2013 event is generally representative of infrequent high-flow events. As such, and given the hydrologic data available for the September 2013 event, the calibration of the predictive hydrologic model using the September 2013 event was deemed appropriate to accurately assess the 10, 4, 2, 1, and 0.2 percent annual chance peak discharges.

As discussed previously, the hydrologic model was calibrated to a 24-hour period of the September 2013 event to better align the hydrologic modeling effort with the assumptions associated with the development of the NRCS infiltration loss equations. The 24-hour period of rainfall associated with the peak discharge recorded at the Boulder Creek at Orodell Gage, which occurred between 6 a.m. on September 12 and 6 a.m. on September 13, was selected for model calibration. Although the September 2013 event occurred after a relatively dry period, the 24-hour calibration period occurred several days into the storm after 1.9 to 11.1 inches of rain observed prior to the calibration period had partially or fully saturated the watershed soils and expended much of the initial infiltration capacity of the soils. For the majority of subbasins comprising the watershed, the peak rainfall intensity and volume occurred during the selected 24-hour period. A small number of subbasins, concentrated in the portion of Fourmile Creek and lower Boulder Creek southeast of Crisman, CO, experienced peak rainfalls late September 11 that resulted in high discharges along Fourmile Creek early in the morning of September 12. However, the most destructive flooding along Fourmile Creek still occurred late evening of September 12, within the 24-hour calibration period.

Calibration Process

Model calibration requires careful consideration of which modeling parameters are best considered “fixed” and which are most appropriate to adjust to avoid the manipulation of parameters beyond physical reality to achieve desired results. For example, modeled discharges may be “calibrated” to measured discharges by increasing basin roughness parameters to an unreasonably high value that results in an excessive time lag. While the model may be “calibrated” computationally, it would not be calibrated realistically because careful review of the calibrated parameters would suggest that the resultant time lags are not consistent with physical processes. In a similar sense, topographically-derived parameters including the slope of routing elements and subbasin area, were considered fixed – while these parameters affect the model results, there is little justification to change their value short of re-defining the watershed subbasins and flowpaths.

Calibration of the model should also consider the sensitivity of model results to parameters – special attention should be paid to “sensitive” parameters that have large effect on model results. As various parameters were adjusted during the calibration process to match observations, the sensitivity of the model results to various parameters was noted. As a result of this process, the following assessment of the sensitivity of the model results to the following parameters were made:

- *Manning’s Roughness Coefficient*: No effect on modeled runoff volume; negligible effect on modeled peak discharge and time-of-peak discharge. Drastic changes to Manning’s roughness value (halving and doubling the roughness values discussed previously) caused less than a 5 percent change in estimated peak discharges and varied time-to-peak by less than 10 minutes.
- *Snyder’s Peaking Factor* and *Subbasin Lag Time:* No effect on modeled runoff volume; moderate effect on modeled peak discharge and greater effect on time-of-peak. Decreased subbasin lag times and/or increased Snyder’s peaking factor compressed the duration of the hydrograph, increased peak discharge, and resulted in earlier time-of-peak discharge.
- *CN:* Only parameter that affected modeled runoff volume; significant effect on modeled peak discharge and negligible impact on time-of-peak discharge.

Initial estimates of the Manning’s roughness coefficient for routing elements, Snyder’s peaking factor, and subbasin lag times (discussed previously) resulted in times-of-peak discharge that generally agreed with observed times-of-peak discharge such that further manipulation of these parameters, which were the only non-fixed parameters affecting the time-of-peak discharge, was not justified; therefore, the initial estimate of the parameters were considered calibrated such that the CN was the only non-fixed, justifiable parameter remaining to calibrate the model. While recommendations for CN based on land use and hydrologic soil group exist in the literature, calibration of CNs is fairly common for single-event storms due to the unique vegetative cover, soil structure, depth to bedrock, topography, land use history, and other factors that impact infiltration capacity but are not readily quantifiable.

CNs for each of the subbasins were adjusted iteratively until modeled discharges matched peak discharge estimates for the September 2013 event developed by Bob Jarrett (Jarrett, In press). Measured flows at the Middle Boulder Creek at Nederland gage, Boulder Creek at Orodell gage, and Fourmile Creek at Orodell gage (manual measurement by USGS) were also considered for model calibration and generally agreed with peak discharges estimated by Jarrett (In press).

Initial estimates of CNs based on interpretation of aerial imagery and land cover classifications yielded modeled discharges that were significantly less than observed flows and indicated a need to drastically increase CNs to calibrate the model. Given that significant rainfall was measured in the days preceding the selected 24-hour period, with some basins receiving upwards of 11 inches of rain over the previous 72 hours, there was a reasonable probability that basin soils were saturated and had a significantly reduced infiltration capacity not represented by standard CNs, which assume a 5-day antecedent rainfall of less than 2.1 inches (Novotny, 2002). AMCs were considered by estimating the total rainfall in the 5 days prior to the selected 24-hour period. Subbasins that received more than approximately 2.1 inches of rainfall were classified AMCIII; those that received less were classified as AMCII (Novotny, 2002). Three subbasins, MBC-1A, MBC-1B, and MBC-2, all near the Continental Divide, had 5-day antecedent rainfalls that identified these three basins as AMCII, whereas the remaining subbasins were AMCIII. This identification agrees with observations that Middle Boulder Creek runoff was less than was observed in other basins. CNs for AMCIII were estimated from AMCII CNs in literature using the following equation (Novotny, 2002):

$$CN_{AMCIII} = \frac{23CN_{AMCII}}{10 + 0.13CN_{AMCII}}$$

To limit the possibility of unrealistic estimates of CNs, calibration of CNs relied on the re-assignment of TR-55 land cover descriptions to NLCD land covers (USGS, 2006). The re-assignment of land cover description was mostly limited to assigning a “fair condition” instead of a “good condition” originally assigned. In general, CNs were re-assigned at the watershed scale but also at a sub-watershed scale (e.g., subbasins composing Fourmile Creek) if the unique re-assignment could be justified. For example, “forest” land cover in Fourmile Creek was re-assigned as “poor condition,” in contrast to “fair condition” in the other sub-watersheds, due to sparser vegetative cover and the 2010 Fourmile Canyon Fire.

Calibration Results

Consideration of AMC and re-classification of CNs achieved satisfactory calibration results, with modeled discharges generally calibrating to within 15 percent of observed values. Trends in modeled peak discharges were generally consistent with observations of flood intensity by sub-watershed with extensive flooding observed in Fourmile Creek and moderate flood flows observed in Middle Boulder Creek and North Boulder Creek. Calibrated CNs by subbasin are provided in **Table B-6** in **Appendix B** and the corresponding classification of land use condition is provided as **Table B-7** in **Appendix B.** Comparison of modeled discharges to observed discharges is provided below in **Table 6**.

TABLE 6
Comparison of Modeled Discharges to Observed Discharges

Location	Calibration Data Source	Observed Discharge (cfs)	Modeled Discharge (cfs)	Percent Difference
Boulder Creek near Orodell	Jarrett, in press	2,020	1,950	-3.5%
	CDWR Gage	1,720	1,950	+ 13.4%
Middle Boulder Creek at Nederland	CDWR Gage	409	410	+ 0.2%
North Boulder Creek at Confluence with Middle Boulder Creek	Jarrett, in press	740	829	+ 12.0%
Fourmile Creek Upstream Burned Area	Jarrett, in press	490	551 [a]	+ 12.4%
Fourmile Creek Downstream of Emerson Gulch	Jarrett, in press	1,070	1,101 [a]	+ 2.9%
Fourmile Creek near Orodell	Jarrett, in press	2,300	2,568	+ 11.6%
	USGS manual measurement	2,510	2,568	+ 2.3%

[a] Interpolated between HEC-HMS junctions based on contributing drainage area.

While calibration of the peak discharge was the primary focus of the calibration process, CDWR and USGS gage measurements also provided calibration data relevant to the timing and volume of runoff. With the exception of Middle Boulder Creek at Nederland, modeled times of peak discharge were within 30 minutes of observations, as reported in **Table 7**. Modeled times-of-peak discharge at Boulder Creek near Orodell and Fourmile Creek near Orodell were considered conservative as the difference from observed times-of-peak discharge would result in modeled hydrographs at the two locations peaking closer in time than what was observed. Although the modeled time-of-peak discharge of Middle Boulder Creek at Nederland was approximately 1.5 hours later than observed, its impact on the downstream calibration was minimal as Barker Reservoir released a constant 4 cfs during the analysis period. Despite the late timing, the routing parameters and lag time for Middle Boulder Creek were considered representative of high-flow events given that the peak discharge recorded at the Nederland gage was less than the 2013 snowmelt peak and that the timing of the peak was less hindered by debris and high sediment loads as had likely occurred in the other sub-watersheds (i.e., because peak discharges along Middle Boulder Creek were relatively moderate, exactly calibrated lag times may not be representative of high-flow hydrologic conditions).

TABLE 7
Comparison of Modeled Time-to-Peak to Observed Time-to-Peak

Location	Calibration Data Source	Observed Time of Peak Discharge	Modeled Time of Peak Discharge	Difference
Boulder Creek near Orodell	CDWR Gage	9/12 11:30 p.m.	9/12 11:00 p.m.	-30 min (early)
Middle Boulder Creek at Nederland	CDWR Gage	9/13 2:15 a.m.[a]	9/12 3:40 a.m.	+ 1h 25 min (late)
Fourmile Creek near Orodell	USGS Manual Measurement	9/12 10:45 p.m.	9/12 11:15 p.m.	+ 30 min (late)

[a] Observed peak of 409 cfs was measured from 2 a.m. to 2:30 a.m.; HEC-HMS results report the earliest time (2 a.m.).

Comparisons of modeled runoff volume to total volume recorded at the CDWR Boulder Creek at Orodell and Middle Boulder Creek at Nederland gages are provided in **Table 8**. It should be noted that a direct comparison of runoff volumes are difficult because of the calibration process – as the 24-hour analysis window occurred in the middle of the September 2013 event, runoff from the preceding days of rainfall was not incorporated into the model whereas it was a component of the total volume recorded by the gage measurements; **Figure B-11** in **Appendix B** provides a breakdown of the runoff volume measured at the Middle Boulder Creek at Nederland and Boulder Creek at Orodell gages to illustrate the percentage of measured runoff that may be attributable to rainfall that occurred prior to and during the 24-hour analysis window. As a result of the model not incorporating the runoff from days preceding the calibration period, the lesser volume of the modeled runoff reported in **Table 8** was expected. For comparison, when the volume of the runoff from days preceding the calibration window were estimated at Middle Boulder Creek (which had a readily identifiable rise in the hydrograph to identify the arrival of runoff emanating from the increased rainfall intensity, as illustrated in **Figure B-11** in **Appendix B**), 35 to 65 percent of the observed hydrograph was due to runoff from rainfall that occurred prior to the analysis period.

TABLE 8
Comparison of Modeled Runoff Volume to Observed Runoff Volume (24-Hour Calibration Period)

Gage	Calibration Data Source	Observed Volume (watershed-inches)	Modeled Volume (watershed-inches)
Boulder Creek at Orodell	CDWR Gage	0.34	0.26
Middle Boulder Creek at Nederland	CDWR Gage	0.22	0.10

2.4.7 Predictive Model Implementation

Development of the predictive hydrologic model required slight modification of the calibrated model to account for differences between the September 2013 event and a theoretical design event. Two modifications were made to the calibrated model to develop the predictive model as follows:

- The calibrated AMCIII CNs were converted back to AMCII to maintain consistency with procedures detailed in the *Colorado Floodplain and Stormwater Criteria Manual* (CWCB, 2008) for the estimation of peak discharges using the NRCS method.
- The volume attenuation effects of Barker Reservoir were removed from the hydrologic model. Because Barker Reservoir is operated as a water supply reservoir and not a flood control reservoir, the reservoir was assumed full and not capable of controlling outflow releases or providing flood storage. However, the lag time that would occur as a flood wave passes through an initially full Barker Reservoir was considered in the model, as described in previous sections.

With the revisions described above, the predictive model was used to estimate peak discharges throughout the watershed for the 10, 4, 2, 1, and 0.2 percent annual chance events assuming a standard 24-hour NRCS Type II rainfall distribution, as described previously.

3.0 Hydrologic Model Results

3.1 Estimate of Design Flow Magnitudes

The 10, 4, 2, 1, and 0.2 percent annual chance peak discharges provided in **Table 9** were estimated using the predictive hydrologic model with the model parameters described in Section 2.4 and respective percent annual chance rainfall depths. A DARF of 0.93 was used such that the discharges presented in **Table 9** are those discharges modeled to assess the peak discharge at the confluence of Boulder Creek and Fourmile Creek, rather than the peak discharge associated with a specifically tailored DARF for each point provided in **Table 9**. Hydrographs at key design points in the model are provided in **Figure 11 in Appendix B**. The peak flow profile for Boulder Creek is provided in **Figure 12 in Appendix B** and detailed model results, including peak discharge and runoff volume by subbasin, are provided in **Table B-8 in Appendix B**. Assessment of the recurrence interval of the September 2013 event at the various study locations is provided in Section 4.2. Comparison of peak discharge at the mouth of Fourmile Creek to Boulder Creek at Orodell is generally consistent with anecdotal evidence of Fourmile Creek as a primary source of flooding downstream of the canyon mouth (FEMA, 2012).

TABLE 9
Modeled 10, 4, 2, 1, and 0.2 Percent Chance Peak Discharge

Location	Observed Discharge (per Jarrett, In press) (cfs)	Annual Chance Peak Discharge (cfs)				
		10 Percent	4 Percent	2 Percent	1 Percent	0.2 Percent
Fourmile Creek Upstream Burned Area	490	213 [a]	426 [a]	656 [a]	949 [a]	1,886 [a]
Fourmile Creek Downstream of Emerson Gulch	1,070	400 [a]	789 [a]	1,209 [a]	1,734 [a]	3,388 [a]
Fourmile Creek near Orodell	2,300	922	1,680	2,442	3,425	6,376
Boulder Creek near Orodell	2,020	1,134	2,287	3,640	5,392	11,399
Middle Boulder Creek at Nederland	409 [b]	629	1,239	1,949	2,888	6,163
North Boulder Creek at Confluence with Middle Boulder Creek	740	334	757	1,298	2,045	4,760
Boulder Creek below Orodell (watershed outlet)	4,818 [c]	1,567	3,033	4,726	6,850	13,993

[a] Interpolated between HEC-HMS junctions based on contributing drainage area.
[b] Per CDWR Middle Boulder Creek at Nederland gage.
[c] Per Calibrated Hydrologic Model.

Modeled peak unit discharges, defined as peak discharge per square mile of contributing area, are provided in **Table 10**. Peak unit discharge by subbasin are provided as **Table B-8** in **Appendix B** and plotted against subbasin area in **Figure B-13** in **Appendix B.** In general, peak unit discharges in the Fourmile Creek sub-watershed are two to three times greater than peak unit discharges measured in other sub-watersheds. This is generally consistent with expectations and anecdotal evidence in the FIS that Fourmile Creek is the primary source of flooding along Boulder Creek downstream of Orodell (FEMA, 2012).

TABLE 10
Modeled 10, 4, 2, 1, and 0.2 Percent Chance Unit Peak Discharge

Location	Unit Discharge (per Jarrett, in press) (cfs/mi^2)	Annual Chance Peak Unit Discharge (cfs/mi^2)				
		10 Percent	4 Percent	2 Percent	1 Percent	0.2 Percent
Fourmile Creek Upstream Burned Area	55	24	47	73	105	209
Fourmile Creek Downstream of Emerson Gulch	73	27	54	82	118	230
Fourmile Creek near Orodell	107	38	69	100	141	262
Boulder Creek near Orodell	20	11	22	36	53	112
Middle Boulder Creek at Nederland	11 [a]	17	34	53	79	168
North Boulder Creek at Confluence with Middle Boulder Creek	17	7	17	29	46	106
Boulder Creek below Orodell (watershed outlet)	N/A	12	24	37	53	109

[a] Per CDWR Middle Boulder Creek at Nederland gage.

3.2 Comparison to Previous Studies, FEMA Effective Hydrology, and Stream Gage Analyses

Comparisons of the modeled 1 percent annual chance peak discharge estimates to estimates cited in previous studies, FEMA effective hydrology, and stream gage analyses are provided in **Table 11**; comparison of the measured September 2013 rainfall depths to NOAA rainfall-frequency curves was discussed as part of Section 2.4.5. It should be noted that with the exception of Middle Boulder Creek at Nederland and Fourmile Creek near Orodell, the FIS does not provide estimates of the 1 percent annual chance peak discharge at the study locations. As both the FIS and *Floodplain Information: Upper Boulder Creek and Fourmile Creek* (Gingery and Associates, 1981) reference USACE, 1977 for hydrology, the detailed peak discharge profiles presented in **Table 11** are as reported in the detailed peak discharge and water surface elevation data tables provided in the Gingery and Associates report.

TABLE 11
Comparison of Modeled 1 Percent Annual Chance Flow to Other Estimates

Location	Basin Area (mi^2)	Estimated 1 Percent Annual Chance Peak Discharge (cfs)					
		Predictive Model	USACE, 1969	USACE, 1977	FEMA Effective Hydrology [a]	Anderson Consulting Engineers, 2009	Gage Analysis
Fourmile Creek Upstream Burned Area	9	949 [b]	N/E	2,310	2,310	N/E	N/E
Fourmile Creek Downstream of Emerson Gulch	15	1,734 [b]	N/E	4,470	4,470	N/E	N/E
Fourmile Creek near Orodell	24	3,425	N/E	6,230	6,230 [c]	N/E	N/E
Boulder Creek near Orodell	102	5,392	N/E	6,270	6,270	6,270	1,823
Middle Boulder Creek at Nederland	37	2,888	N/E	N/E	960 [c]	N/E	829
North Boulder Creek at Confluence with Middle Boulder Creek	45	2,045	N/E	N/E	N/E	N/E	N/E
Boulder Creek below Orodell (watershed outlet)	129	6,850	7,400	11,650	11,650	11,650	N/E

N/E: No estimate.

[a] As reported in Table 4: Peak Discharge and Water Surface Elevation Data of Floodplain Information: Upper Boulder Creek and Fourmile Creek (Gingery and Associates, 1981), which in turn references USACE, 1977 for hydrology.

[b] Interpolated between HEC-HMS junctions based on contributing drainage area.

[c] Per Boulder County FIS (FEMA, 2012).

Review of **Table 11** indicates that estimates of 1 percent annual chance peak discharges in the Boulder Creek watershed upstream of Orodell vary considerably between studies and methodologies. In general, modeled discharges are less than those estimated by other methods with the exception of peak discharge estimates generated from gage analysis, which predict the lowest peak discharges of any estimate and generally suggest that modeled discharges are conservative. Despite a gage record in excess of 100 years, use of the Boulder Creek at Orodell gage record to estimate high-flow frequencies has historically been disregarded (USACE, 1977; Anderson Consulting Engineers, 2009) due to the construction of Barker Reservoir in 1910. Although Barker Reservoir has not been operated as a flood control reservoir, its operation as a water supply reservoir likely stores and/or attenuates high-flow discharges and, as such, may skew gage regression analysis results downward (i.e., underestimate high flow magnitude due to storage of a portion of the hydrograph.)

In general, both the Boulder Creek at Orodell and Middle Boulder Creek at Nederland gage analyses were considered unrepresentative of expected future flood conditions and were not considered in the selection of proposed effective hydrology. The Boulder Creek at Orodell gage was discarded as the reservoir operation was assumed to have stored and/or attenuated a considerable portion of annual peak discharges and would thus underestimate the flood-frequency relationship at Orodell. The Middle Boulder Creek at Nederland gage, while relatively unaffected by upstream regulation, was not considered further as annual peak discharges are predominantly driven by snowmelt events and thus may not be representative of intense rainfall events that, as discussed in **Table 2**, are surmised to drive the largest flow events along Boulder Creek. Therefore, it was determined that a rainfall-runoff model may be more accurate in the assessment of expected high-flow hydrology at Nederland due to the physical assumption in the rainfall-runoff model that peak discharges are driven by rain events as opposed to snowmelt events.

Finally, part of the apparent low estimates derived by gage analyses may be due to the mixed-flood gage analysis performed: the gage analysis considered annual peak discharge regardless of what meteorological event caused the discharge. Gage analysis of annual peak flows caused only by rain and/or rain-on-snow events, which historically have caused flooding on Boulder Creek (FEMA, 2012), could possibly estimate an increased magnitude of the 1 percent annual change discharge.

Comparing modeled 1 percent annual chance peak discharges to those estimated in the USACE, 1977 study, the basis of the effective FEMA hydrology, modeled peak discharges in Boulder Creek above Fourmile Creek compare relatively well, whereas modeled peak discharges in Fourmile Creek are approximately half of those estimated by USACE. Differences in modeling and calibration methodologies likely account for a substantial portion of the observed differences between the predictive model and the USACE, 1977 model. Differences in modeling methodologies and their expected impact are discussed briefly below:

- **Difference in Infiltration Parameters and Rainfall Hyetograph:** Infiltration parameters for the USACE, 1977 study were uniformly set to a constant 1 inch per hour in mountainous areas, regardless of soil type or vegetative cover. Reviewing the average depth of rainfall of 3.2 inches over Fourmile Creek as provided in the *Upper Boulder Creek and Fourmile Creek Floodplain Information Report* (Gingery and Associates, 1981) and the rainfall hyetograph provided as **Table 3**, a maximum runoff intensity of 1.60 inches per hour would be calculated. For comparison, runoff rates ranging from 0.61 to 1.37 inches per hour (median of 1.00 inch per hour) were estimated using the predictive hydrologic model. If infiltration rates used in the USACE, 1977 study were input to the predictive model, modeled peak discharges on Fourmile Creek would increase approximately 45 percent from those provided in **Table 11**. As concluded in the discussion of other modeling approaches, an average CN of 93 would be required in the HEC-HMS model to replicate the peak discharge estimated in the USACE, 1977 study.
- **Difference in Routing Parameters:** In accordance with the USACE, 1977 study, both in-stream and basin roughness parameters were estimated from a separate calibration study performed downstream of Cherry Creek Dam near Denver. Because the area downstream of Cherry Creek dam was, even at that time, urban and entirely located on the plains, roughness parameters were likely underestimated for Fourmile Creek such that runoff and routing times were probably underestimated as well. Decreased runoff and routing times would result in increased runoff hydrographs and increase the overlap of peak portions of runoff hydrographs that may not have occurred had roughness parameters been calibrated to the Boulder Creek watershed specifically.

In reviewing the USACE, 1977 study, it appears that although the best methodology at that time was likely used, the methodology may not be as valid as contemporary approaches that consider hydrologic variability across the watershed. In addition, given the state of the practice at the time, modeling parameters were likely chosen conservatively to avoid underestimating peak discharges. Although gage analyses were not used in the current study to develop estimates of high-flow hydrology, the gage analyses were considered useful to ground-truth previous and current estimates (on the observation that the majority of the contributing watershed above the Orodell gage is unaffected by Barker Reservoir). In this context, measured flows at the Boulder Creek at Orodell gage equaled or exceeded the 10 percent annual chance discharge estimated in the USACE, 1977 study only twice (including September 2013) in its more than 100-year history of operation (ideally, it would have been exceeded 10 or more times). Thus, it would appear that the USACE, 1977 values are conservatively high. Similarly, the September 2013 event aside, measured flows at the Fourmile Creek at Orodell gage (20-year record) and Boulder Creek at the 75th Street gage (26-year record) have not exceeded 55 percent of the USACE, 1977 10-year flow estimates for those locations, providing further evidence that the USACE, 1977 model may overestimate peak discharges. Considering the September 2013 event in comparison to the effective hydrology, the September 2013 event at most locations in the study area would have been considered a 10- 20-year recurrence interval event.

Comparing modeled peak discharges to the gage record of Boulder Creek at Orodell, the modeled 10 percent annual chance peak discharge and the modeled 4 percent annual chance peak discharge have been measured eight times and twice, respectively (compared to an ideal ten and four times). Therefore, the estimated peak discharges appear to approximately agree with the gage record at Orodell, erring slightly towards the conservative side. As discussed previously, discrepancy between the modeled discharges at

Nederland and the respective gage record are likely due to a history of snowmelt-driven flows at the gage as opposed to the modeled rainfall-driven flows. However, the estimates compare favorably with effective hydrology immediately downstream of Barker Reservoir. In regards to Fourmile Creek, the peak discharge at Fourmile Creek comprised approximately half of the peak discharge estimated at the study area outfall, agreeing with historical anecdotes that identify Fourmile Creek as a primary source of flooding on Boulder Creek. Additionally, the peak unit discharge of Fourmile Creek is significantly higher than other sub-watersheds, which is consistent with conceptual models discussed previously that would suggest increased runoff potential due to basin shape, reduced vegetation density, and recent history of fire.

While it was previously discussed that gage analysis is not wholly appropriate, the following conceptual exercise supports the conclusion that modeled discharges are likely conservative. As discussed previously, the Boulder Creek at Orodell gage was not considered due to storage/attenuation impacts of Barker Reservoir. As a conceptual exercise, consider the Middle Boulder Creek at Nederland gage immediately upstream of Barker Reservoir, which has been operated by USGS and CDWR since 1908, which takes into account a flood of record during that period measuring 811 cfs and a 1 percent annual chance peak discharge estimated by gage analysis of 829 cfs: directly adding the peak discharge estimates at the Nederland gage to the respective peak discharge estimates at Orodell to account for the “removal of Barker Reservoir,” peak discharge at Orodell would still be less than half of the peak discharges estimated by the predictive hydrologic model (although the “added” gage discharges are likely overestimated and conservative in of itself). Therefore, while peak discharges estimated by the predictive hydrologic model are less than the effective hydrology, the modeled peak discharges are interpreted to be conservative in relation to long-term history of stream flows.

4.0 Conclusions and Recommendations

The assumptions and limitations of the hydrologic model, concurrent studies, and previous studies were closely reviewed, compared, and contrasted. Peak discharge estimates based on gage analysis were considered non-applicable due to the influence of Barker Reservoir and regression analysis of mixed-flood hydrology that may not be representative of the rainfall-induced flows that have historically caused floods in the Boulder Creek watershed. Previous peak discharge estimates were concluded to be overly conservative and outdated due to the selection of modeling parameters calibrated during studies of separate and dissimilar watersheds, availability of new and better information and tools, and the lack of model validation when compared to gage records. Therefore, given the quality of calibration data, model validation via gage records and comparison to historical observations, and continuous review of modeling methodology by a team of local engineers and project sponsors, the predictive model developed as part of the current study is proposed as the appropriate model to accurately estimate high-flow hydrology along Boulder Creek upstream of Orodell.

4.1 Design Flow Magnitudes

Table 12 presents modeled discharge-frequency relationships at geographically relevant locations, i.e., populated areas, located in close proximity to hydrologic model junctions; comparison of estimated 1 percent chance peak discharges between methods and studies was provided previously as part of **Table 11**. High-flow discharges presented in **Table 12** were rounded up slightly to the nearest 10 cfs to maintain a consistent level of precision as the effective FIS. Based on the discussion in previous sections, the high-flow discharges presented in **Table 12** are considered the best estimate of high-flow hydrology for the Boulder Creek study reach upstream of Orodell, Colorado:

TABLE 12
Proposed 10, 4, 2, 1, and 0.2 Percent Chance Peak Discharge

	Annual Chance Peak Discharge (cfs)				
Location	**10 Percent**	**4 Percent**	**2 Percent**	**1 Percent**	**0.2 Percent**
Fourmile Creek near Sunset, Upstream of Todd Gulch	150	300	460	670	1,340
Fourmile Creek near Salina, Downstream of Sweet Home Gulch	570	1,090	1,660	2,370	4,550
Fourmile Creek Upstream of Orodell	920	1,680	2,440	3,430	6,380
Middle Boulder Creek at Nederland	630	1,240	1,950	2,890	6,160
Middle Boulder Creek at Confluence with North Boulder Creek	710	1,380	2,180	3,310	6,820
North Boulder Creek at Confluence with Middle Boulder Creek	330	760	1,300	2,050	4,760
Boulder Creek Upstream of Orodell	1,130	2,290	3,640	5,390	11,400
Boulder Creek Downstream of Orodell (watershed outlet)	1,570	3,030	4,730	6,850	14,000

4.2 Assessment of September 2013 Event

In accordance with the purpose of the study, the peak discharges observed during the September 2013 event were compared to the 10, 4, 2, 1, and 0.2 percent annual chance peak discharges estimated using the predictive hydrologic model to assess the recurrence interval of the September 2013 event. As provided in **Table 13**, the recurrence interval of the September 2013 event ranges from less than a 10 percent annual chance event at Nederland to a 2 percent annual chance event in the lower portions of Fourmile Creek and at the study area outfall. This general trend is consistent with measured precipitation depths recorded over the duration of the September 2013 event (refer to the AWA rainfall map provided as **Figure B-5** in **Appendix B** and the modeled 24-hour rainfall depths in comparison to *NOAA Atlas 14* (NOAA, 2013) point rainfall-frequency estimates provided as **Table B-2** in **Appendix B**), 24-hour rainfall depths measured upstream of Nederland were less than the corresponding 10-year rainfall depths, whereas 24-hour rainfall depths in Fourmile Creek were generally on the order of a 25- to 50-year rainfall depth.

TABLE 13
Estimate of the Recurrence Interval of the September 2013 Event

Location	Observed Discharge, per Jarrett, in press (cfs)	Modeled Annual Chance Peak Discharge (cfs)					Estimated Recurrence Interval (yr)
		10 Percent	4 Percent	2 Percent	1 Percent	0.2 Percent	
Fourmile Creek Upstream Burned Area	490	213 [a]	426 [a]	656 [a]	949 [a]	1,886 [a]	~ 25
Fourmile Creek Downstream of Emerson Gulch	1,070	400 [a]	789 [a]	1,209 [a]	1,734 [a]	3,388 [a]	25 to 50
Fourmile Creek near Orodell	2,300	922	1,680	2,442	3,425	6,376	~ 50
Middle Boulder Creek at Nederland	409 [b]	629	1,239	1,949	2,888	6,163	< 10
North Boulder Creek at Confluence with Middle Boulder Creek	740	334	757	1,298	2,045	4,760	~ 25
Boulder Creek near Orodell	2,020	1,134	2,287	3,640	5,392	11,399	~ 25
Boulder Creek below Orodell (watershed outlet)	4,818 [c]	1,567	3,033	4,726	6,850	13,993	~ 50

[a] Interpolated between HEC-HMS junctions based on contributing drainage area.

[b] Per CDWR Middle Boulder Creek at Nederland gage.

[c] Per Calibrated Hydrologic Model.

4.3 Discussion of September 2013 Event

Reviewing **Table 13**, the peak discharge at the study area outfall was approximately equal to a 2 percent annual chance event while a 4 percent annual chance event was estimated for most other portions of the watershed. Although the September 2013 event was unique in volume and duration, consideration of the fact that observed rainfall depths in the Middle and North Boulder Creek sub-watersheds were noticeably less than in adjacent sub-watersheds implies that peak discharges observed below Orodell could have been greater had the storm event been centered more over Boulder Creek. For context, the peak discharge from Fourmile Creek, where greater rainfall depths were observed, was 15 to 30 percent greater than the peak discharge estimated in Boulder Creek at Orodell, despite the Fourmile Creek sub-watershed being one-fourth the size of the Boulder Creek watershed above Orodell. Even accounting for the increased runoff potential of Fourmile Creek, the difference in estimated peak discharges between the two watersheds suggests the magnitude of event that could have occurred in Boulder Creek had the September 2013 storm event been centered differently.

Additionally, it should be noted that Barker Reservoir was significantly low due to a preceding drought and seasonal operation that leaves the reservoir relatively low in the fall months (operation of Barker Reservoir as a water supply reservoir would prioritize filling of the reservoir to provide drinking water to downstream citizens, and thus, it is likely to be full in the spring/summer following typical snowmelt). Thus, available storage capacity not normally available in Barker Reservoir was available in September 2013 to store nearly the entirety of the peak flow pulse measured above the reservoir on September 13, 2013, and thereby drastically reduce downstream outflow and peak discharges. Had the September 2013 event occurred earlier in the season, such as in the spring, which **Table 2** indicates is when significant floods frequently occur, Barker Reservoir would likely have had less storage capacity. Decreased storage capacity would have resulted in a greater outflow and increased peak discharges downstream. Therefore, it is important to note that while the September 2013 event was destructive, the timing of the event and distribution of rainfall prevented it from being worse.

As **Table 13** demonstrates, the September 2013 event did not approach the 1 percent annual chance peak discharge in any of the sub-watersheds above Orodell. Despite that most infrastructure is designed to the 1 percent annual chance peak discharge, the September 2013 event caused significant damage in the Boulder Creek watershed and resulted in the loss of life in other watersheds (although the event did exceed the 1 percent annual chance peak discharge in some other watersheds). Considering the relative magnitude of the September 2013 event in relation to the 1 percent annual chance peak discharge and the resulting damage, it is important for flood response officials, engineers, politicians, and the public to be aware of the potential impact that would occur during a 1 percent annual chance high-flow, and how key decisions related to flood recovery and flood management could worsen or lessen that potential impact.

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Appendix A
FEMA Information

Boulder County FIS Volume I Cover
Summary of Discharges for Boulder Creek and Fourmile Creek
Community Map History
FIRM Map Number 08013C0530J
FIRM Map Number 08013C0535J
FIRM Map Number 08013C0370J
FIRM Map Number 08013C0390J

FLOOD INSURANCE STUDY

VOLUME 1 OF 4

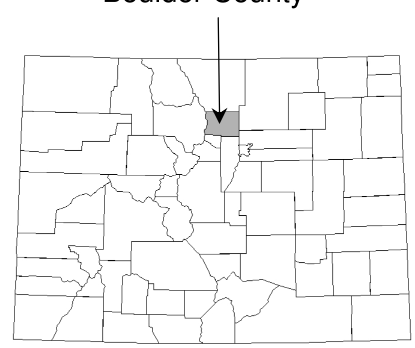
BOULDER COUNTY, COLORADO

AND INCORPORATED AREAS

Community Name	*Community Number*
BOULDER, CITY OF	080024
BOULDER COUNTY (UNINCORPORATED AREAS)	080023
ERIE, TOWN OF	080181
JAMESTOWN, TOWN OF	080216
LAFAYETTE, CITY OF	080026
LONGMONT, CITY OF	080027
LOUSIVILLE, CITY OF	085076
LYONS, TOWN OF	080029
NEDERLAND, TOWN OF	080255
SUPERIOR, TOWN OF	080203
*WARD, TOWN OF	080292

* No Special Flood Hazard Areas Identified

Boulder County



Revised: December 18, 2012

Federal Emergency Management Agency

FLOOD INSURANCE STUDY NUMBER
08013CV001B

Table 4 - Summary of Discharges

Flooding Source and Location	Drainage Area (Square Miles)	Peak Discharges (cfs) 10-Percent Annual Chance	2-Percent Annual Chance	1-Percent Annual Chance	0.2-Percent Annual Chance
Arapahoe Avenue Overflow					
At Foothills Parkway (47th Street)	--[1]	--[1]	--[1]	1,500	--[1]
At 30th Street	--[1]	--[1]	--[1]	4,200	--[1]
At 28th Street	--[1]	--[1]	--[1]	3,500	--[1]
Arapahoe Avenue Spill Flow					
Approximately 800 feet downstream of the divergence from Gregory Canyon Creek	--[1]	323	975	1,209	2,149
Balarat Creek					
At Upstream Limit of Detailed Study	0.5	30	150	270	760
Bear Canyon Creek					
At Confluence with Boulder Creek	8.24	2,050	3,762	4,880	7,500
At Confluence of Skunk Creek	5.35	1,170	2,360	3,070	5,100
At Baseline Road	4.96	1,110	2,352	2,930	5,000
At U.S. Highway 36	4.34	820	1,780	2,210	3,850
At Broadway	4.08	680	1,512	1,930	3,400
At Upstream Limit of Detailed Study	3.71	480	1,190	1,600	3,000
Boulder Creek					
At Confluence with Fourmile Canyon Creek	--[1]	3,650	10,100	14,400	29,600
At Valmont Drive	--[1]	3,450	9,200	13,000	23,000
At 28th Street	--[1]	2,200	7,800	8,000	20,600
At County Road 54	--[1]	350	1,560	2,340	4,770
Boulder Creek (Right Bank Overflow)					
Approximately 800 feet Upstream of Foothills Parkway	--[1]	--[1]	1,609	2,523	11,469
Bullhead Gulch					
Just Upstream of Confluence with Boulder Creek	8.85	1,421	1,300	4,532	6,109

[1] Data Not Available

Table 4 – Summary of Discharges (Continued)

Flooding Source and Location	Drainage Area (Square Miles)	Peak Discharges (cfs) 10-Percent Annual Chance	2-Percent Annual Chance	1-Percent Annual Chance	0.2-Percent Annual Chance
Dry Creek No. 1 (Old Channel)					
Just Downstream of State Highway 119	--[1]	260	330	350	415
Just Upstream of the confluence with St. Vrain Creek	--[1]	320	627	802	1,199
Dry Creek No. 2					
At North 107th Street	--[1]	900	1,900	2,600	4,295
Dry Creek No. 2 Ditch Split Flow					
Just Upstream of the Confluence with Dry Creek	--[1]	0	2,680	4,030	8,850
At Upstream Limit of Study	--[1]	0	100	300	800
Dry Creek No. 3					
Just Downstream of Arapahoe Road	13.6	--[1]	--[1]	1,300	--[1]
Elmers Twomile Creek					
At Confluence with Goose Creek	0.54	373	681	883	1,500
At Iris Avenue	0.32	249	508	630	1,010
At Upstream Limit of Detailed Study	0.13	160	315	384	520
Fourmile Canyon Creek					
At Confluence with Boulder Creek	10.03	119	366	500	1,020
At Longmont Diagonal	9.09	913	2,396	3,336	6,800
At 28th Street	8.60	865	2,566	3,468	6,800
At Broadway	7.92	735	2,662	3,581	6,900
At Upstream Limit of Detailed Study	3.93	350	1,170	1,750	4,000
Fourmile Creek Left Bank Overflow					
At Downstream Limit of Detailed Study	--[1]	715	2,071	2,862	5,780
Fourmile Creek Right Bank Overflow					
At Violet Avenue	--[1]	2	1,319	2,054	4,998

[1] Data Not Available

Table 4 – Summary of Discharges (Continued)

Flooding Source and Location	Drainage Area (Square Miles)	Peak Discharges (cfs) 10-Percent Annual Chance	2-Percent Annual Chance	1-Percent Annual Chance	0.2-Percent Annual Chance
Fourmile Creek					
At Confluence with Boulder Creek	25.0	1,420	4,440	6,230	11,640
Goose Creek					
At Confluence with Boulder Creek	5.46	2,865	5,065	6,315	9,325
At Confluence of Elmers Twomile Creek	3.63	1,050	2,100	2,680	4,300
At Confluence of Twomile Canyon Creek	1.32	670	1,270	1,590	2,400
At 19th Street	1.28	700	1,320	1,600	2,450
At Upstream Limit of Detailed Study	0.48	260	520	620	1,000
Gregory Canyon Creek					
At Marine Street	2.29	673	1,672	2,092	3,700
Downstream of College Avenue	--[1]	600	1,504	1,900	3,300
At Upstream Limit of Detailed Study	1.56	400	1,060	1,450	2,600
Highway 93 Split Flow					
At Downstream Limit	--[1]	0	600	1,660	5,000
At Upstream Limit	--[1]	0	2,580	3,850	7,750
James Creek					
At Cross Section A	14.5	355	2,180	3,930	10,880
At Main Street Bridge	12.2	300	1,785	3,205	8,850
At Confluence of Little James Creek	12.1	300	1,760	3,160	8,725
At Upstream Limit of Detailed Study	8.9	200	1,190	2,140	6,010
Lefthand Creek					
At Confluence with St. Vrain Creek	72.0	520	2,480	4,610	10,320
Lefthand Creek (North Overflow Channel)					
At Divergence from Lefthand Creek	--[1]	--[1]	--[1]	333	--[1]
At Confluence with Lefthand Creek	--[1]	--[1]	--[1]	333	--[1]

[1] Data Not Available

COMMUNITY NAME	INITIAL IDENTIFICATION	FLOOD HAZARD BOUNDAY MAP REVISION DATE	INITIAL FIRM EFFECTIVE DATE	FIRM REVISION DATE
Boulder, City of	June 14, 1974	March 5, 1976	July 17, 1978	February 24, 1981 August 4, 1988 May 3, 1990
Boulder County (Unincorporated Areas)	February 1, 1979	N/A	February 1, 1979	July 15, 1988 July 3, 1990
Erie, Town of	June 28, 1974	November 28, 1975	October 17, 1978	September 14, 1982 September 28, 1990 December 2, 2004
Jamestown, Town of	July 11, 1975	N/A	July 18, 1983	None
Lafayette, City of	May 24, 1974	January 16, 1976	March 18, 1980	None
Longmont, City of	October 26, 1973	N/A	July 5, 1977	August 1, 1983 September 18, 1987
Louisville, City of	May 4, 1973	N/A	May 4, 1973	July 1, 1974 July 25, 1975 June 23, 1978 December 1, 1978 January 5, 1982

TABLE 7

FEDERAL EMERGENCY MANAGEMENT AGENCY

BOULDER COUNTY, CO.
AND INCORPORATED AREAS

COMMUNITY MAP HISTORY

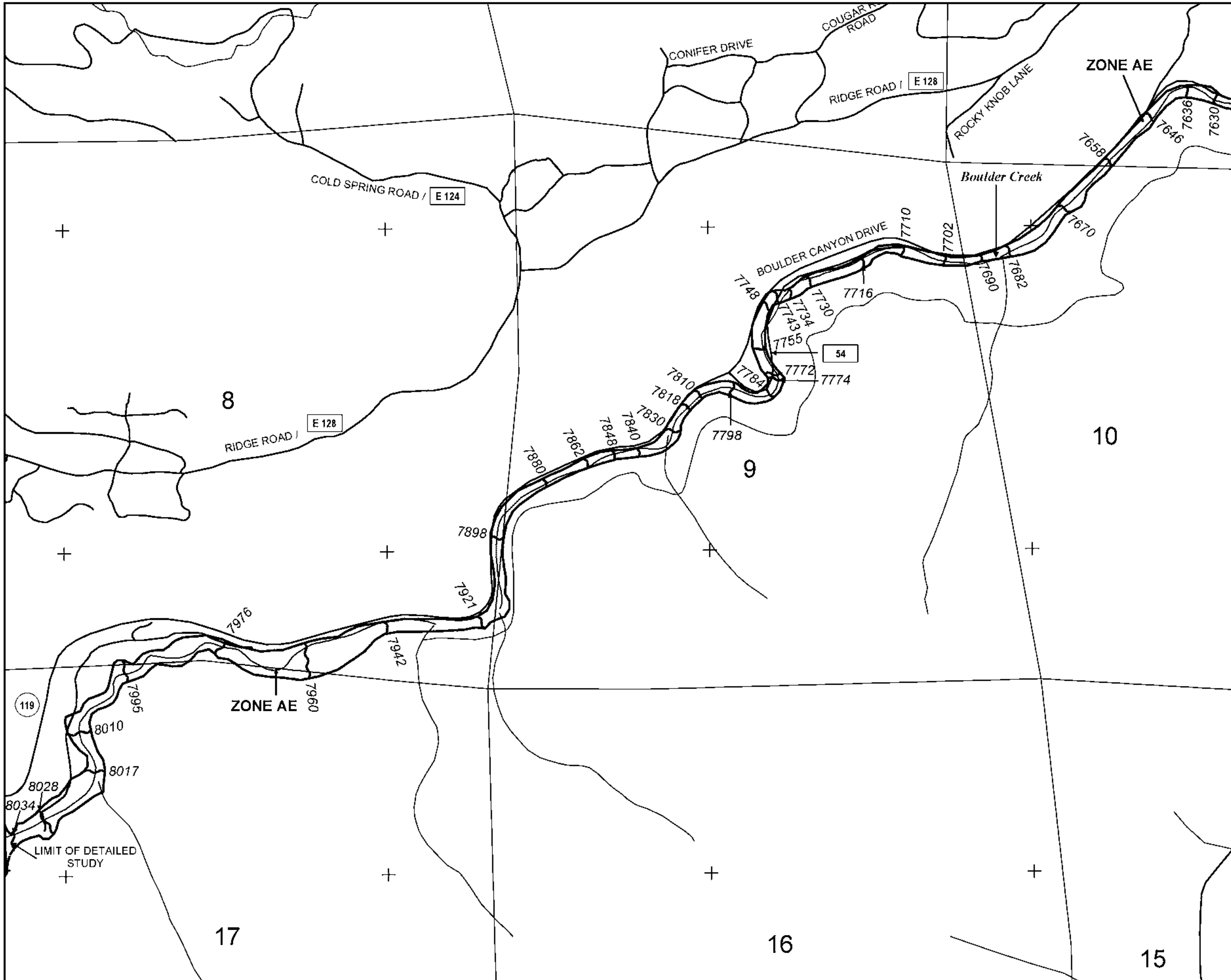
COMMUNITY NAME	INITIAL IDENTIFICATION	FLOOD HAZARD BOUNDAY MAP REVISION DATE	INITIAL FIRM EFFECTIVE DATE	FIRM REVISION DATE
Lyons, Town of	December 21, 1973	April 2, 1976	August 1, 1980	None
Nederland, Town of	August 22, 1975	N/A	August 1, 1979	None
Superior, Town of	June 4, 1976	N/A	September 28, 1979	None
Ward, Town of *	N/A	N/A	N/A	N/A

TABLE 7

FEDERAL EMERGENCY MANAGEMENT AGENCY

BOULDER COUNTY, CO.
AND INCORPORATED AREAS

COMMUNITY MAP HISTORY



MAP SCALE 1" = 1000'

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METER

NATIONAL FLOOD INSURANCE PROGRAM

NFIP

PANEL 0530J

FIRM

FLOOD INSURANCE RATE MAP

BOULDER COUNTY, COLORADO

AND INCORPORATED AREAS

PANEL 530 OF 615

(SEE MAP INDEX FOR FIRM PANEL LAYOUT)

CONTAINS:

COMMUNITY	NUMBER	PANEL	SUFFIX
BOULDER COUNTY	080023	0530	J
NEDERLAND, TOWN OF	080255	0530	J

Notice to User: The **Map Number** shown below should be used when placing map orders; the **Community Number** shown above should be used on insurance applications for the subject community.

MAP NUMBER
08013C0530J

MAP REVISED
DECEMBER 18, 2012

Federal Emergency Management Agency

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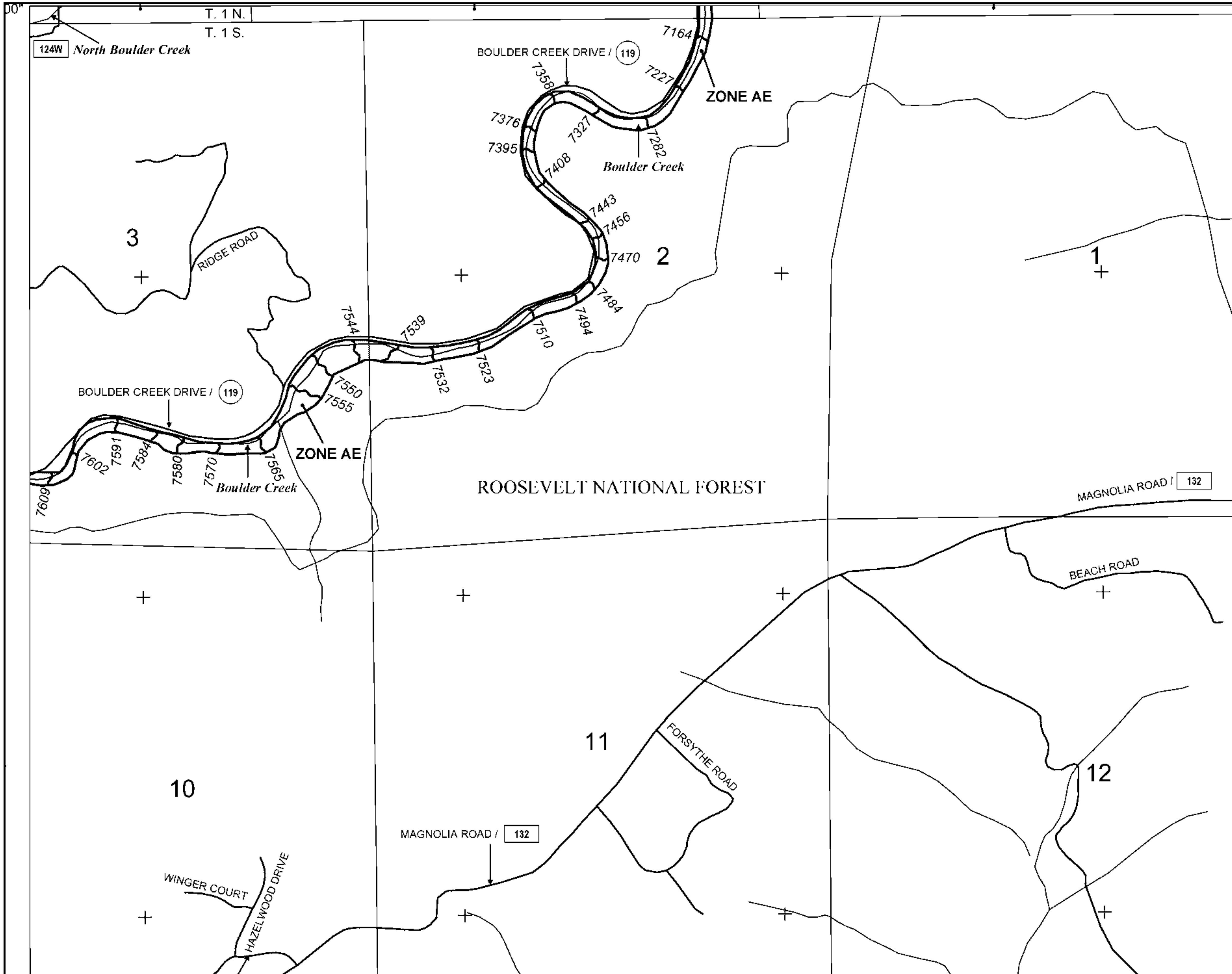

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NFIP

NATIONAL FLOOD INSURANCE PROGRAM

PANEL 0535J

FIRM
FLOOD INSURANCE RATE MAP
BOULDER COUNTY, COLORADO
AND INCORPORATED AREAS

PANEL 535 OF 615

(SEE MAP INDEX FOR FIRM PANEL LAYOUT)

CONTAINS:

COMMUNITY	NUMBER	PANEL	SUFFIX
BOULDER COUNTY	080023	0535	J

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MAP NUMBER
08013C0535J

MAP REVISED
DECEMBER 18, 2012

Federal Emergency Management Agency

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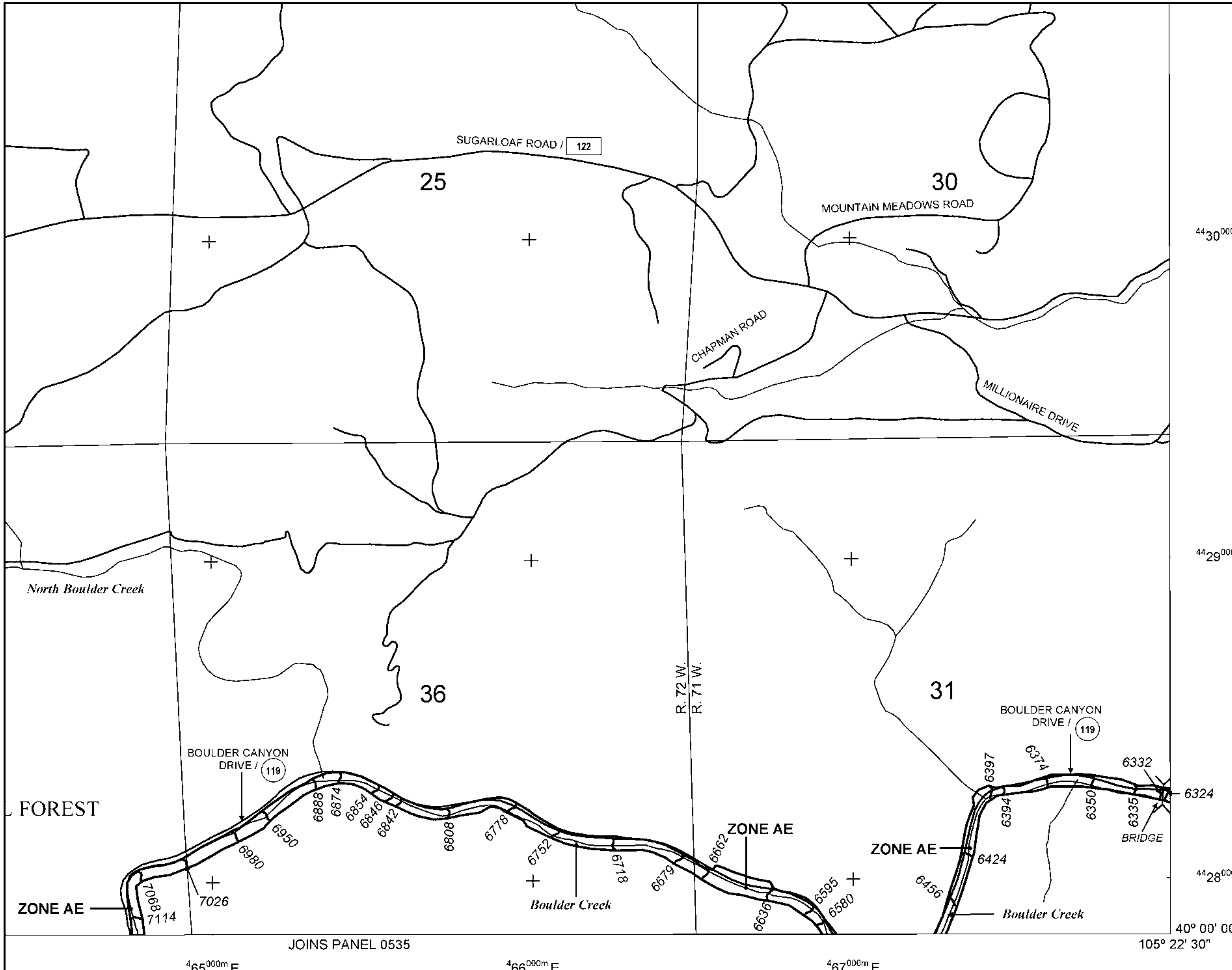

MAP SCALE 1" = 1000'

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METER

NFIP

NATIONAL FLOOD INSURANCE PROGRAM

PANEL 0370J

FIRM
FLOOD INSURANCE RATE MAP
BOULDER COUNTY, COLORADO
AND INCORPORATED AREAS

PANEL 370 OF 615

(SEE MAP INDEX FOR FIRM PANEL LAYOUT)

CONTAINS:

COMMUNITY	NUMBER	PANEL	SUFFIX
BOULDER COUNTY	080023	0370	J

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MAP NUMBER
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MAP REVISED
DECEMBER 18, 2012

Federal Emergency Management Agency

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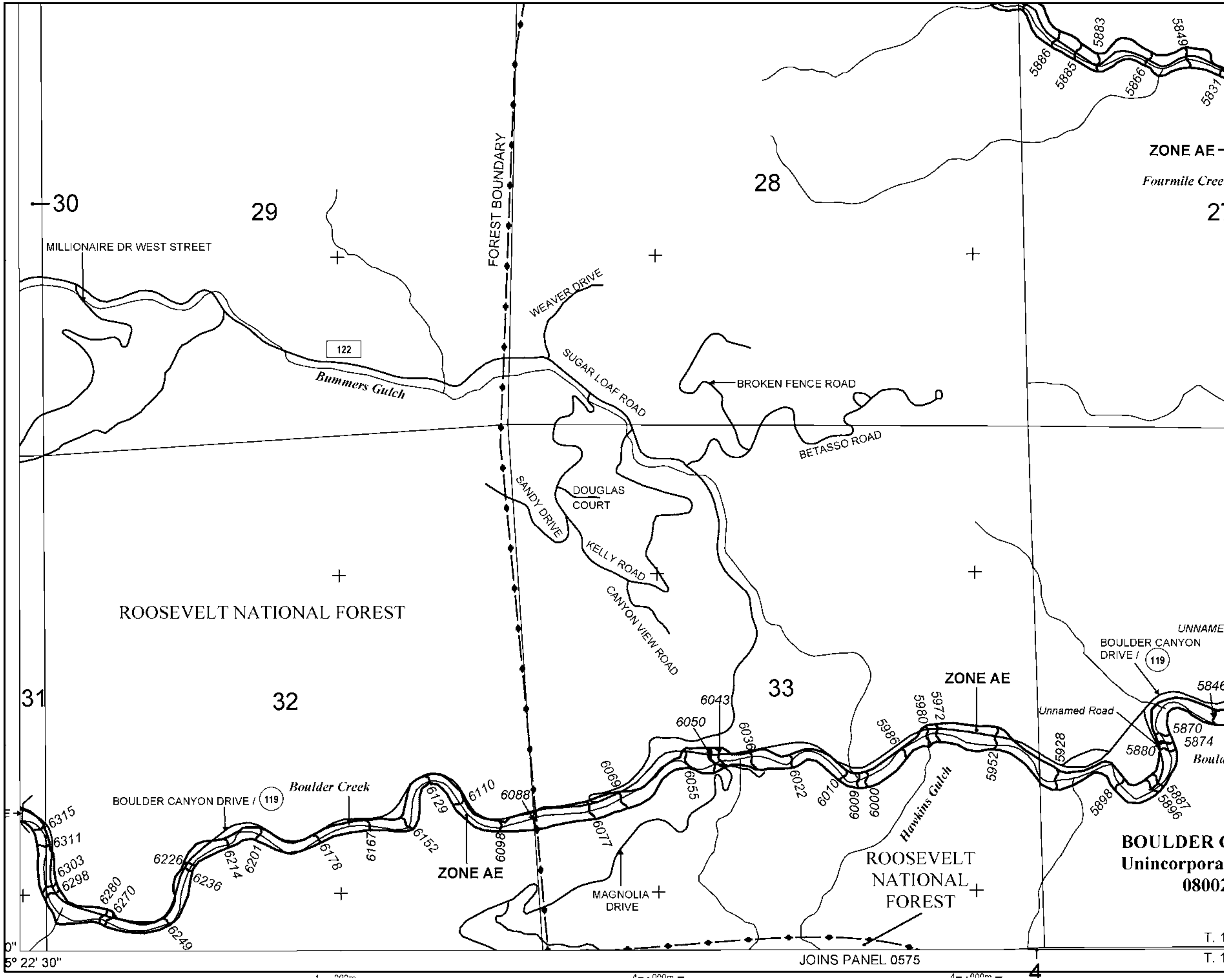


MAP SCALE 1" = 1000'

500 0 1000 2000 FEET

METER

NFIP

NATIONAL FLOOD INSURANCE PROGRAM

PANEL 0390J

FIRM

FLOOD INSURANCE RATE MAP

BOULDER COUNTY, COLORADO

AND INCORPORATED AREAS

PANEL 390 OF 615

(SEE MAP INDEX FOR FIRM PANEL LAYOUT)

CONTAINS:

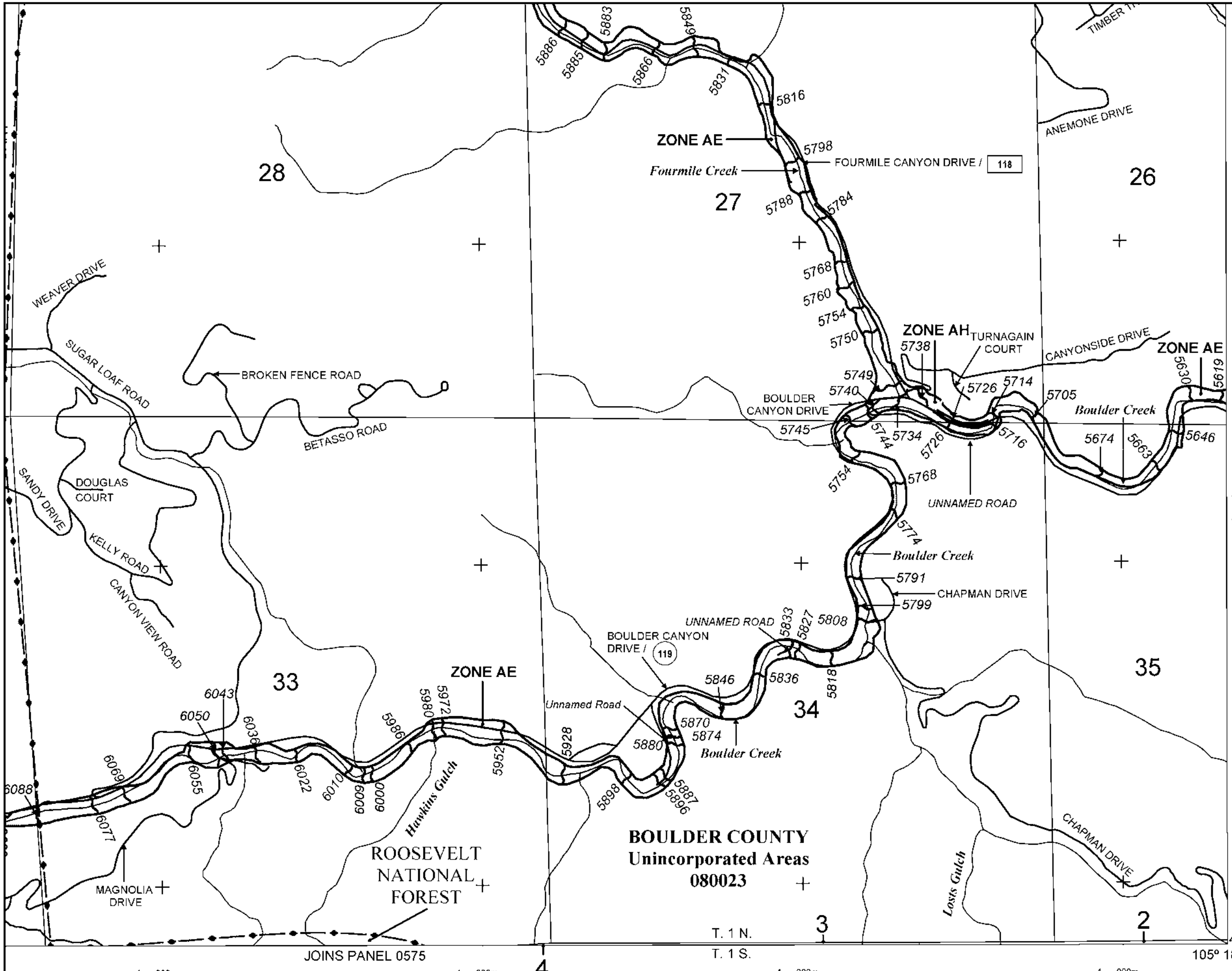
COMMUNITY	NUMBER	PANEL	SUFFIX
BOULDER COUNTY	080023	0390	J

Notice to User: The **Map Number** shown below should be used when placing map orders; the **Community Number** shown above should be used on insurance applications for the subject community.

MAP NUMBER
08013C0390J

MAP REVISED
DECEMBER 18, 2012

Federal Emergency Management Agency



MAP SCALE 1" = 1000'

500 0 1000 2000 FEET

METER

NATIONAL FLOOD INSURANCE PROGRAM

NFIP

PANEL 0390J

FIRM

FLOOD INSURANCE RATE MAP

BOULDER COUNTY, COLORADO

AND INCORPORATED AREAS

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Appendix B
Hydrologic Analysis and Parameters

Appendix B
Hydrologic Analysis and Parameters

Figures

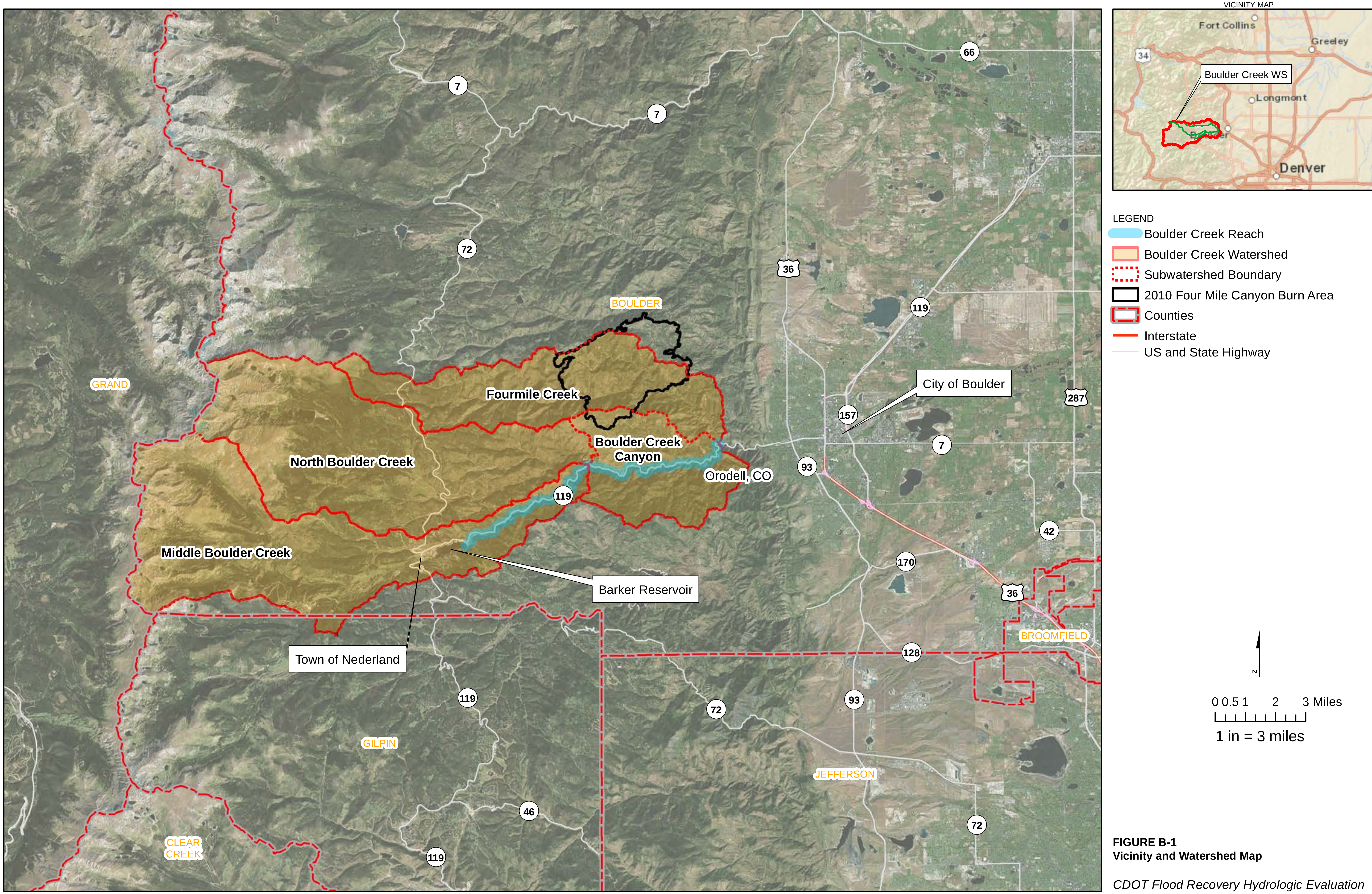
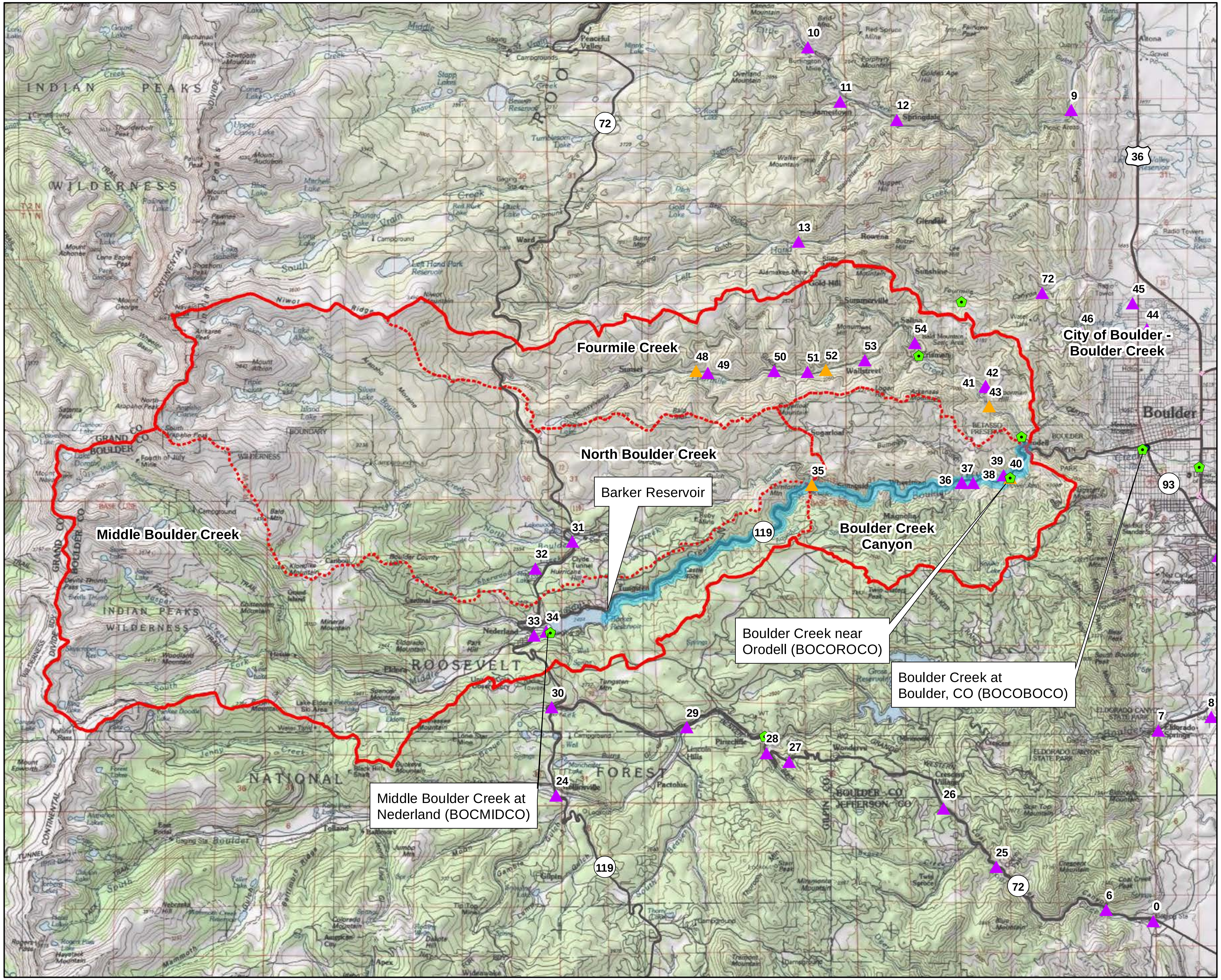
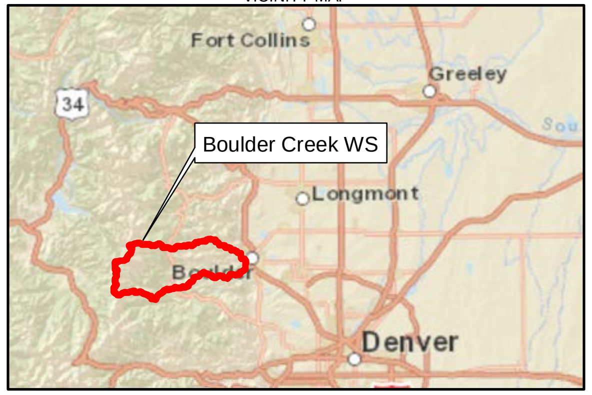


FIGURE B-1
Vicinity and Watershed Map

CDOT Flood Recovery Hydrologic Evaluation



VICINITY MAP



LEGEND

Peak Discharge Estimation Locations

- Critical-Depth Method Estimate
- Critical-Depth Estimate Used in Calibration
- CDWR / USGS Stream Gage
- Boulder Creek Reach
- Subwatershed Boundary
- Boulder Creek Watershed

N

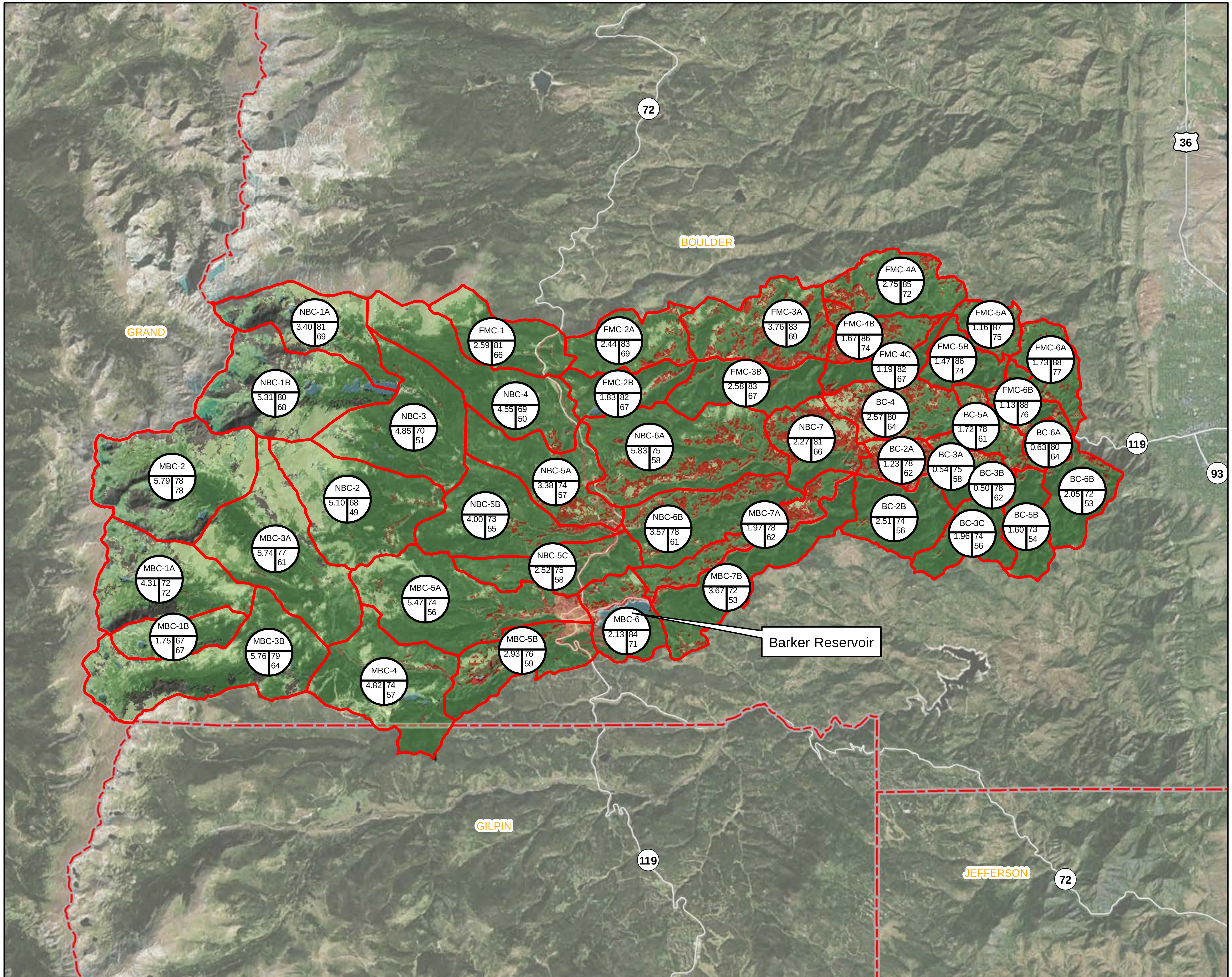
0 0.5 1 2 Miles

1 in = 2 miles

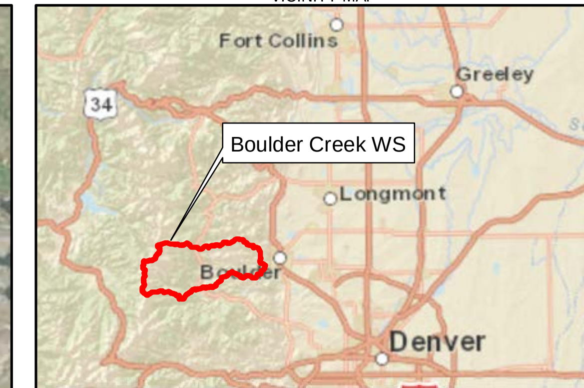
FIGURE B-2
Peak Discharge Estimate and Gage Locations

CDOT Flood Recovery Hydrologic Evaluation

CH2MHILL.



VICINITY MAP



LEGEND

Boulder Creek Subbasins

Land Use

- Open Water
- Deciduous Forest - Oak / Aspen
- Developed Open Space
- Developed, Low Intensity
- Developed, Medium Intensity
- Barren Land
- Shrub/Brush
- Grassland/Pasture
- Woody Wetlands, Herbaceous

Counties

Basin # / Area (mi²) / C-CN / D-CN — Landuse Label (C-CN - Calibrated Curve Number) (D-CN - Design Curve Number)

N

0 1 2 4 Miles

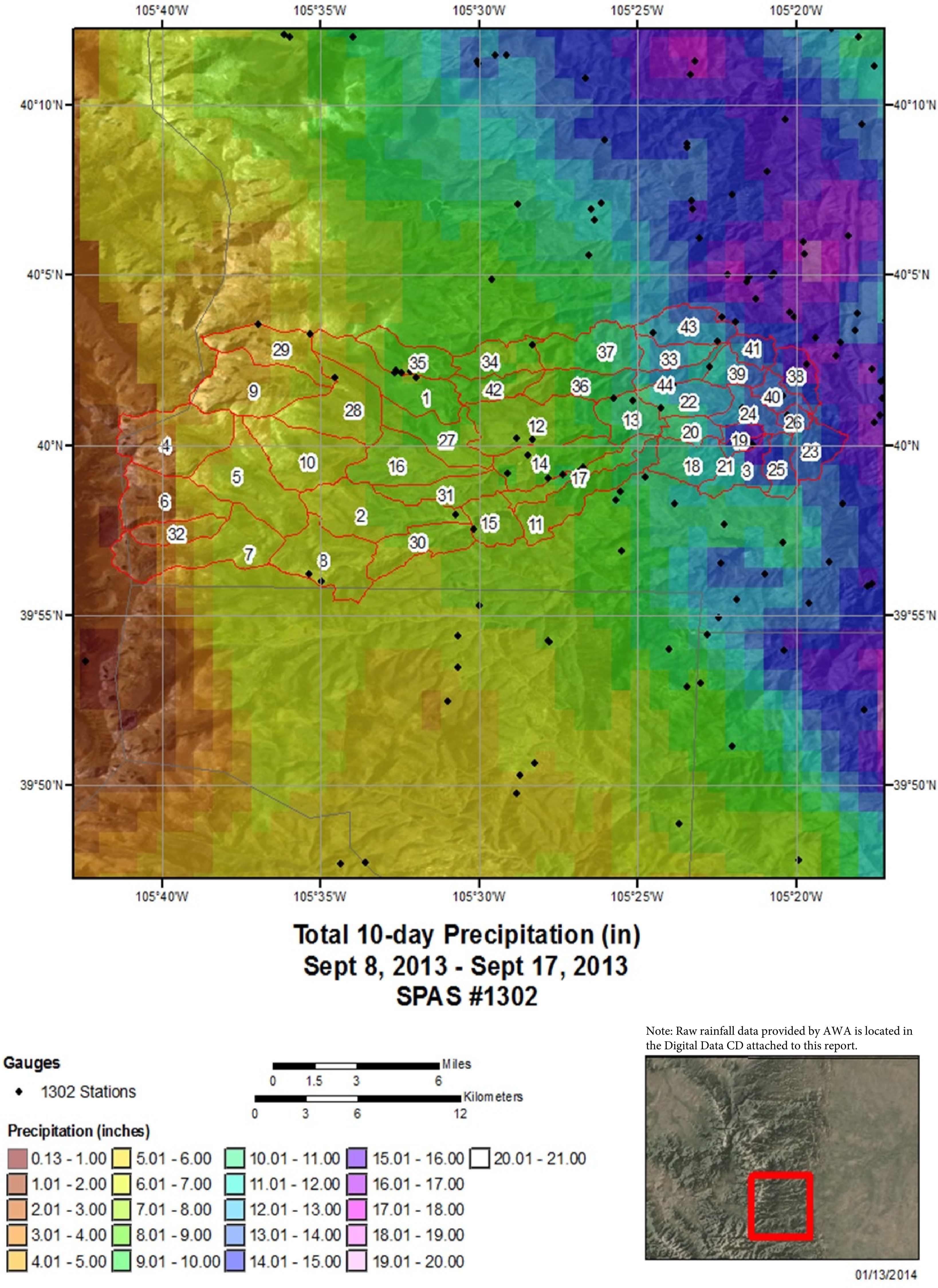
1 inch = 2 miles

FIGURE B-3
Land Use Map

CDOT Flood Recovery Hydrologic Evaluation

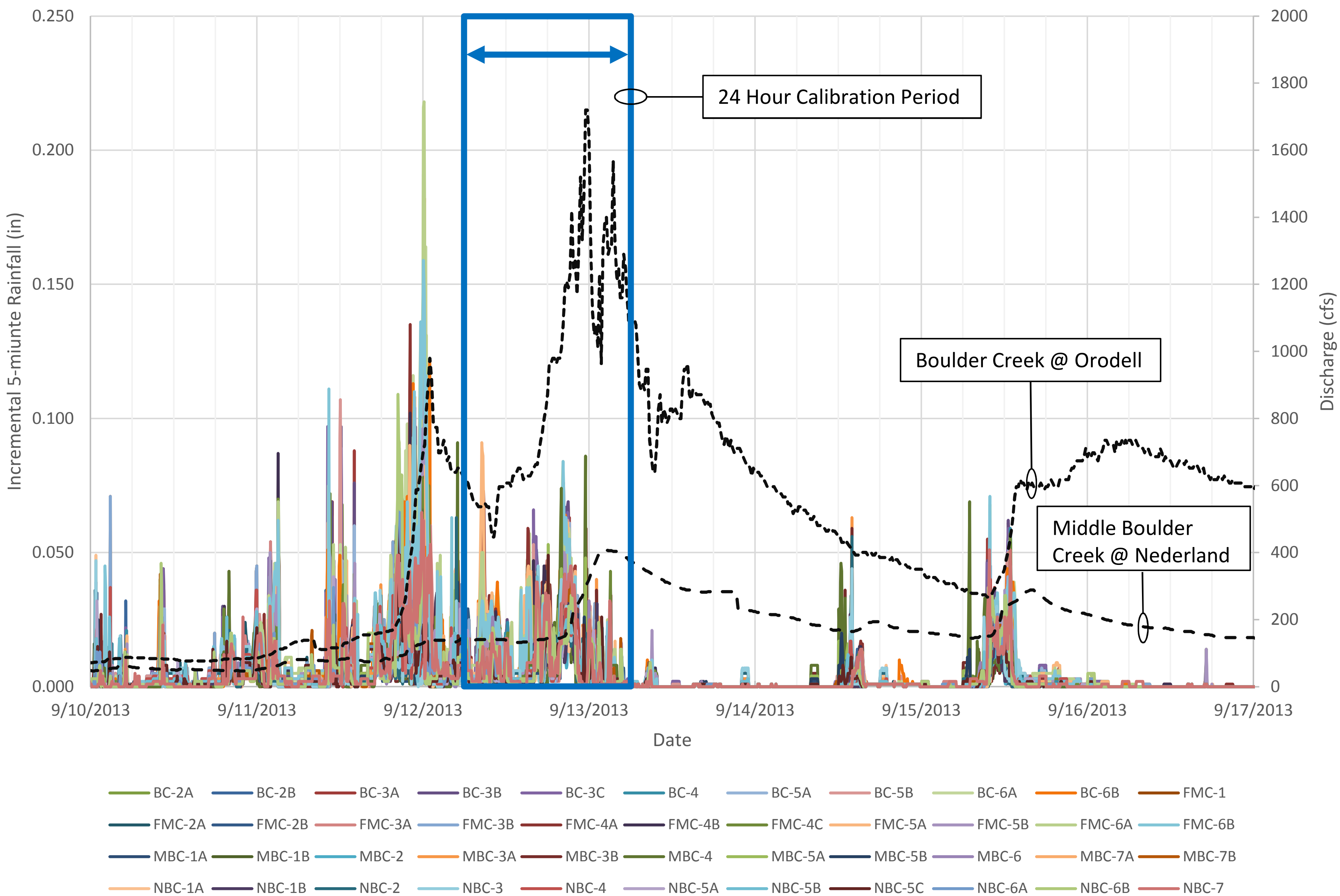
CH2MHILL.

Figure B-4 - AWA 10-Day Precipitation



Note: Raw rainfall data provided by AWA is located in the Digital Data CD attached to this report.

Figure B-5 - Boulder Creek 5-minute Increment SPAS Rainfall and CDWR Gage Measurements during September 2013 event



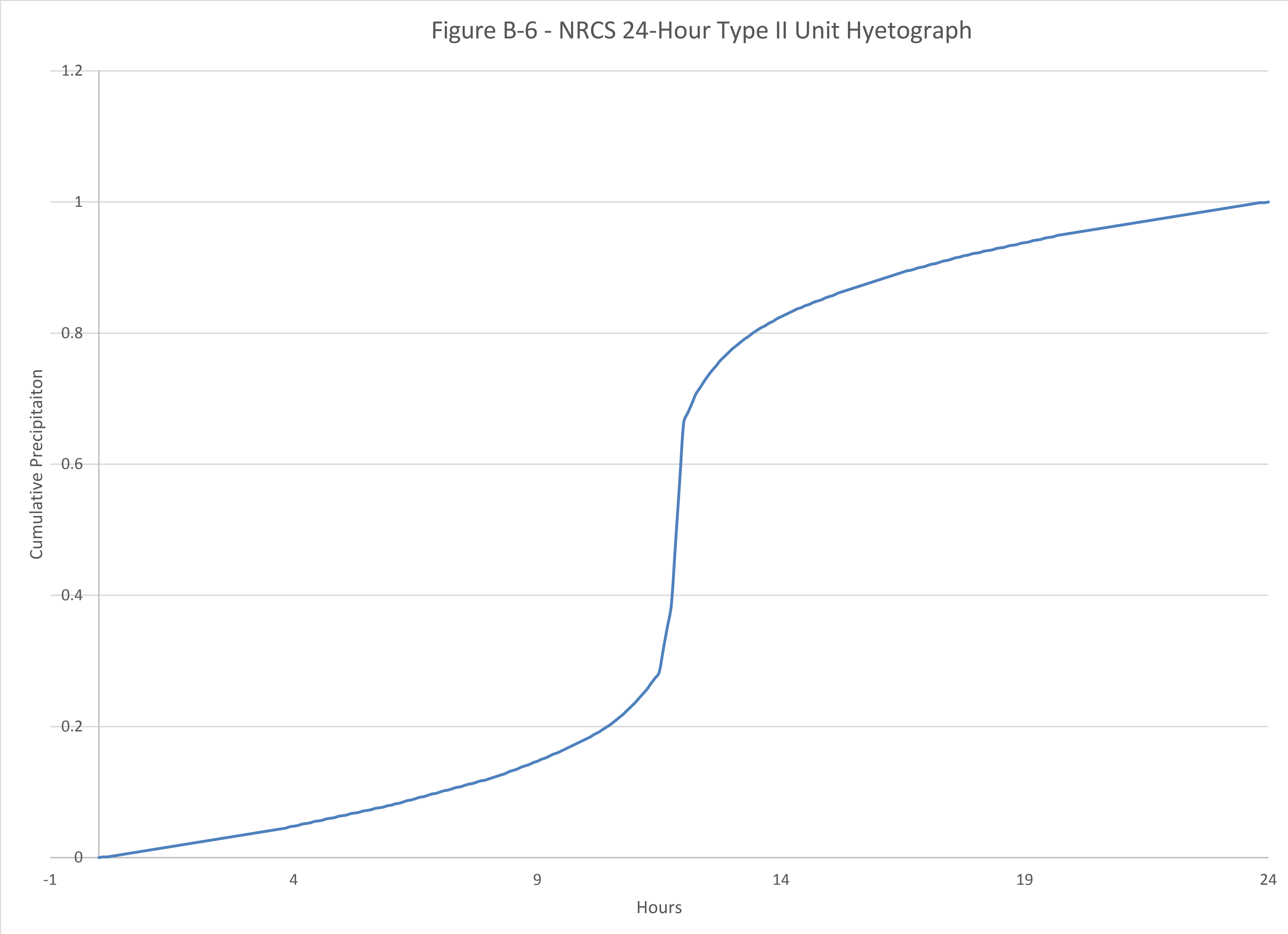
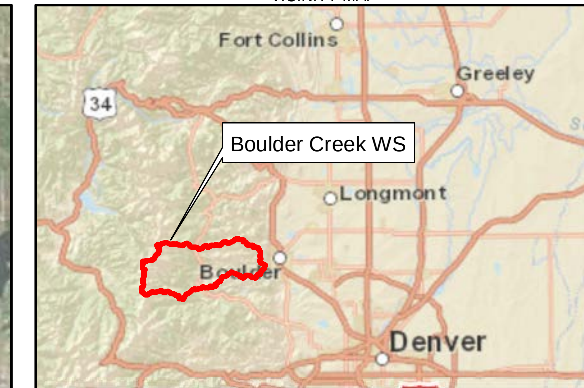
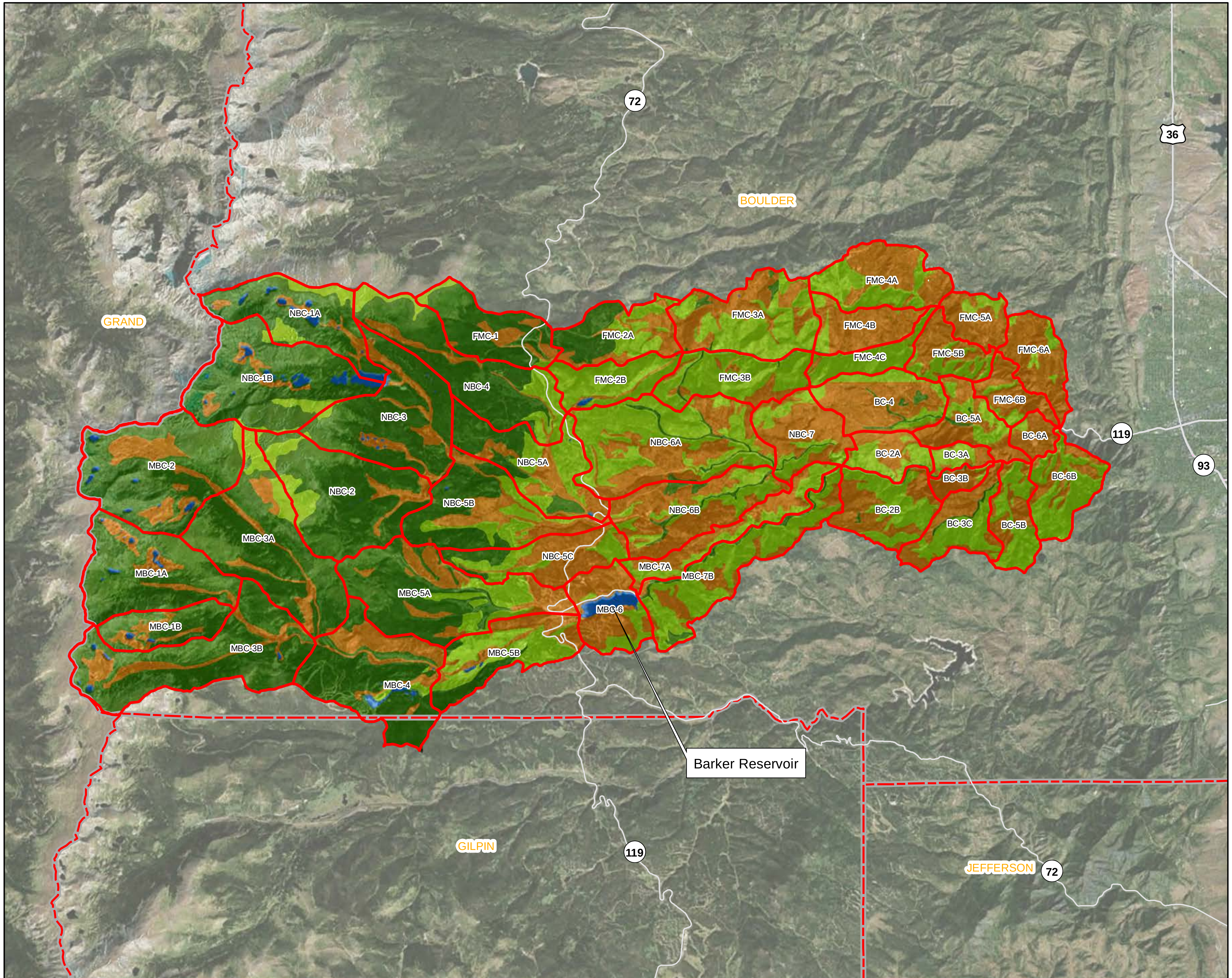


Figure B-6 - NRCS 24-Hour Type II Unit Hyetograph
Cumulative Precipitaiton
Hours
1.2
1
0.8
0.6
0.4
0.2
0
-1
4
9
14
19
24

VICINITY MAP





LEGEND

Boulder Creek Subbasins

Hydrologic Soil Group

- A
- B
- C
- D
- Water

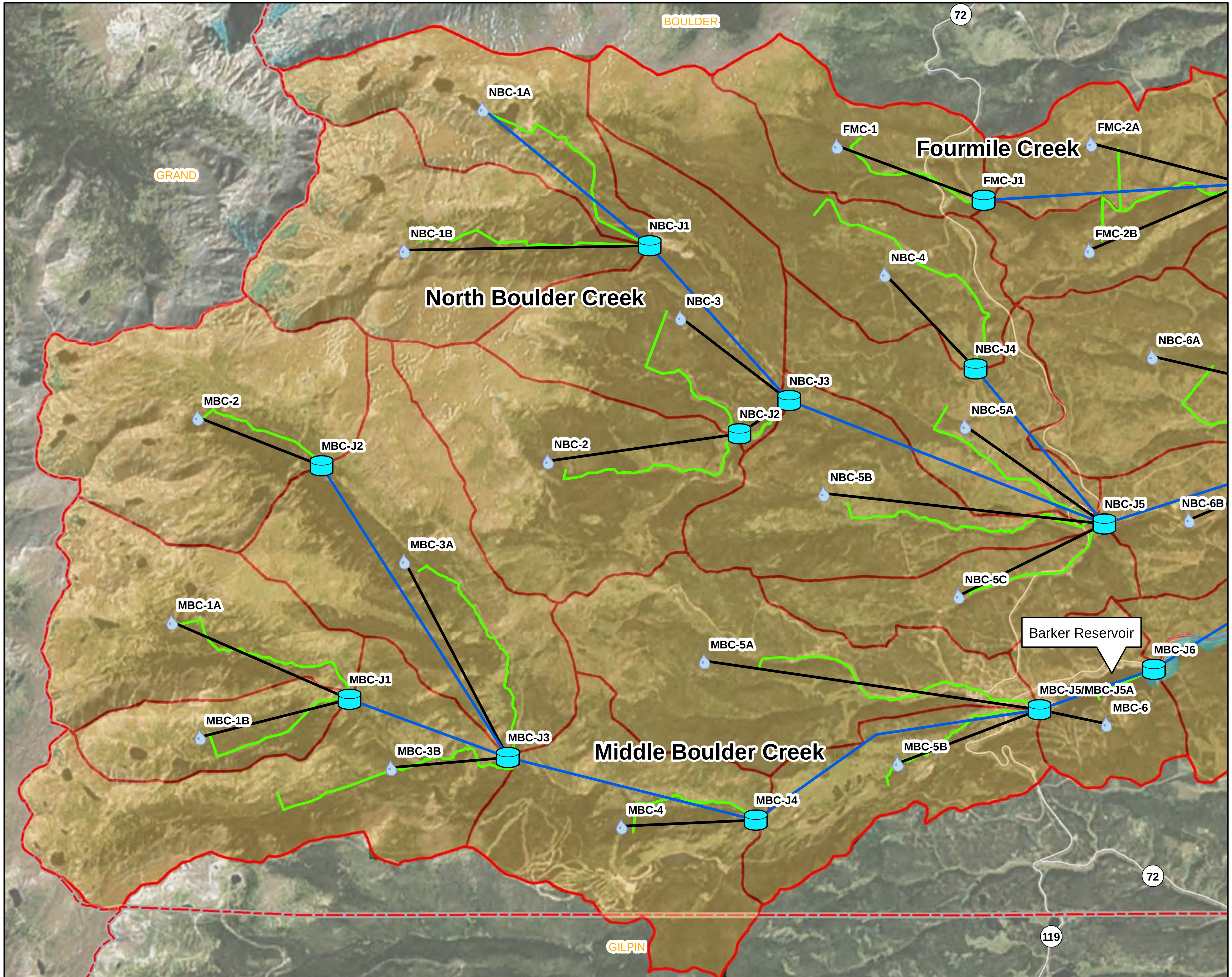
Counties

0 0.5 1 2 Miles

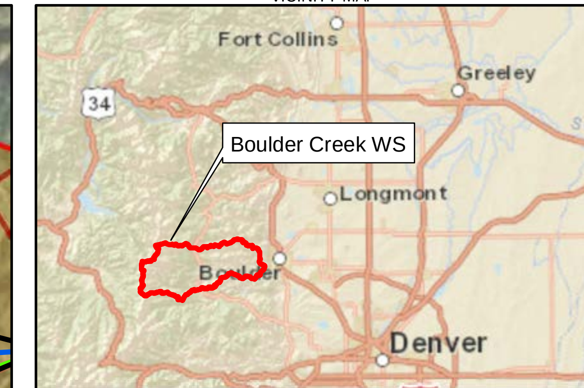
1 in = 2 miles

FIGURE B-7
Soil Data Map

CDOT Flood Recovery Hydrologic Evaluation



VICINITY MAP



LEGEND

- Model Precipitation Gage
- Subbasin Routing
  - Basin Connection;
  - Reach Segment
- Model Junctions
- Boulder Creek Reach
- Boulder Creek Subbasins
- Flow Paths to Subbasin Centroid
- Boulder Creek Watershed
- Counties

N

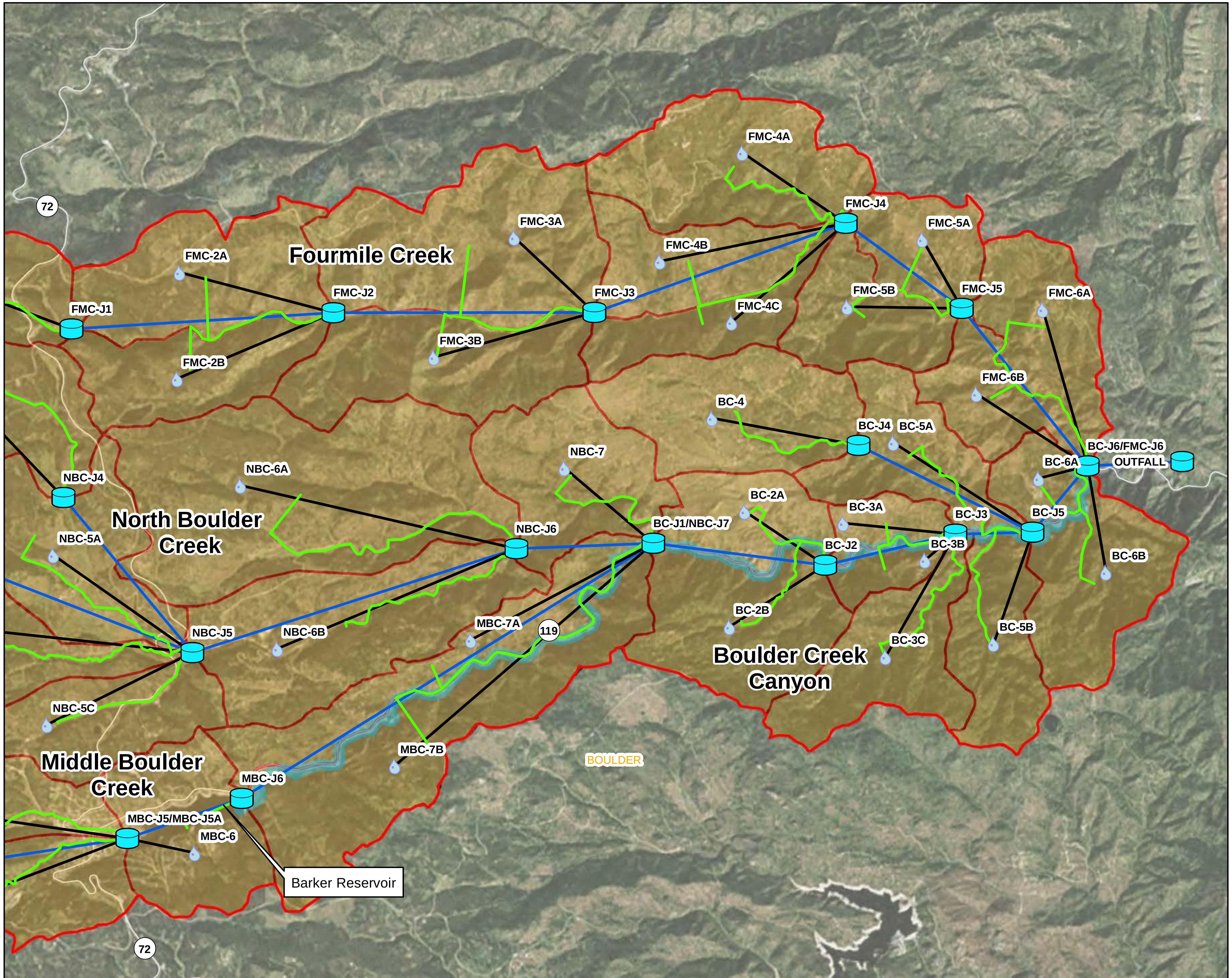
0 0.25 0.5 1 Miles

1 in = 1 miles

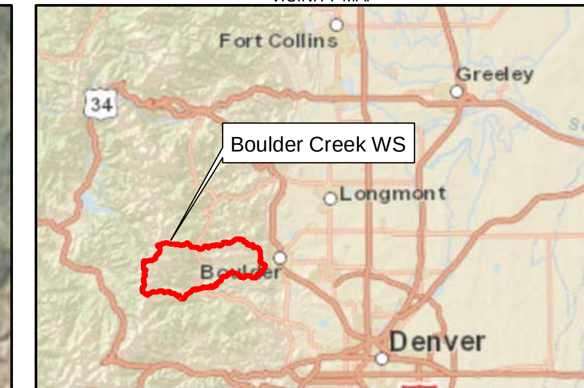
FIGURE B-8a
Connectivity Map

CDOT Flood Recovery Hydrologic Evaluation

CH2MHILL.



VICINITY MAP



LEGEND

- Model Precipitation Gage
- Subbasin Routing
  - Basin Connection
  - Reach Segment
- Model Junctions
- Boulder Creek Reach
- Boulder Creek Subbasins
- Flow Paths to Subbasin Centroid
- Boulder Creek Watershed
- Counties

N

0 0.25 0.5 1 Miles

1 in = 1 miles

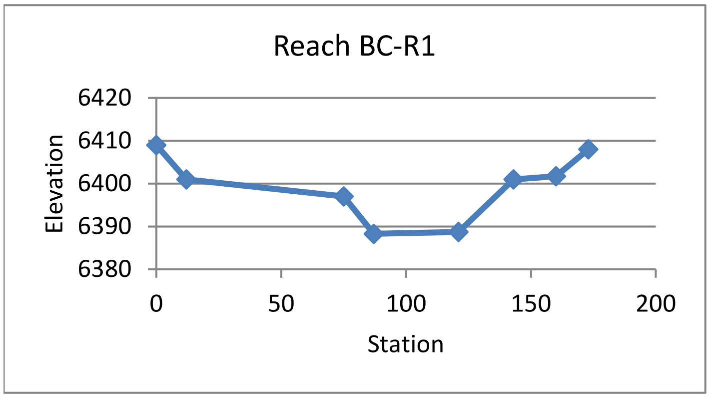
FIGURE B-8b
Connectivity Map

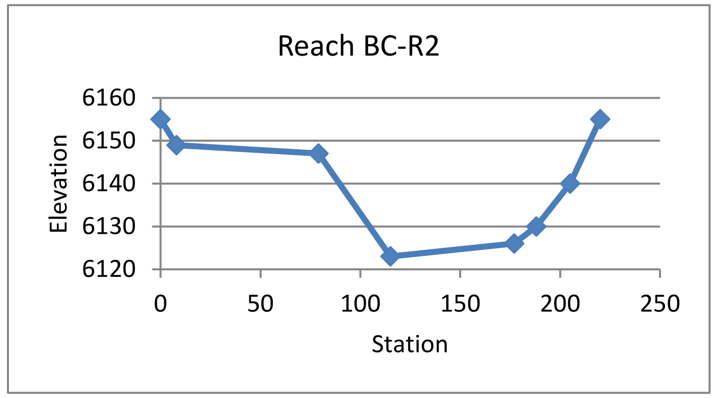
CDOT Flood Recovery Hydrologic Evaluation

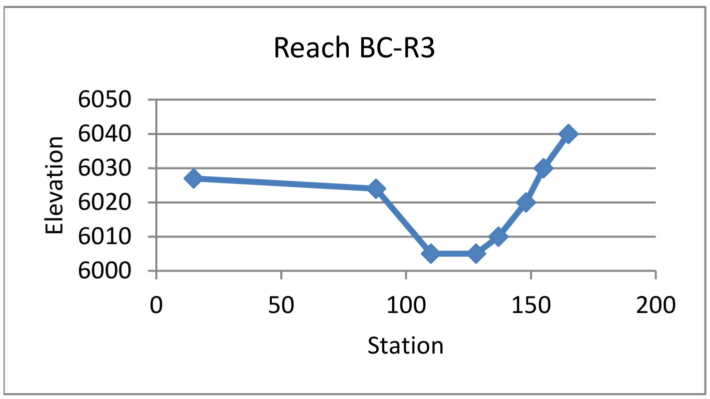
UNK \\GECKO\GROUPS\TBG\481085-482330 CDOT EMERGENCY RESPONSE SERVICES\390_DESIGN_ELEMENTS\DRAINAGE\GIS\MAPFILES\REPORT\FIGURE5B_BOULDERCONNECTIVITYMAP.MXD BBETTAG 8/8/2014 12:22:10 PM

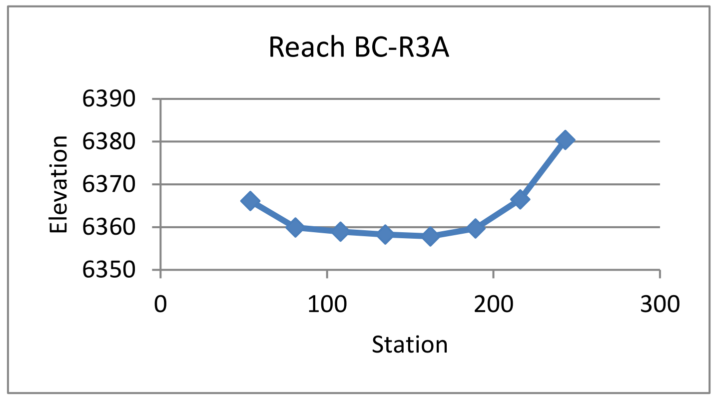
CH2MHILL.

Figure B-9 - Muskingum-Cunge Eight-Point Routing Cross Sections









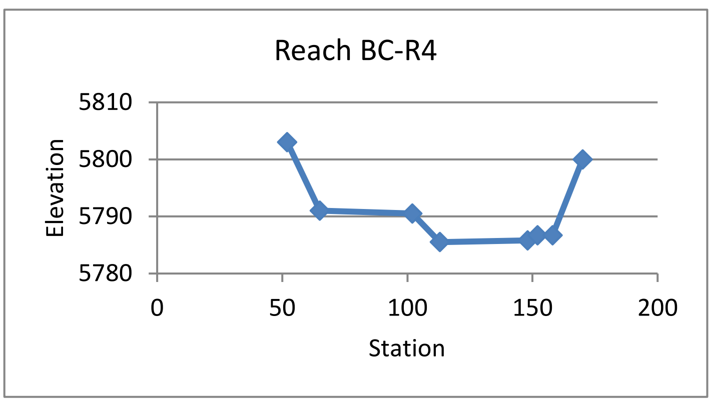
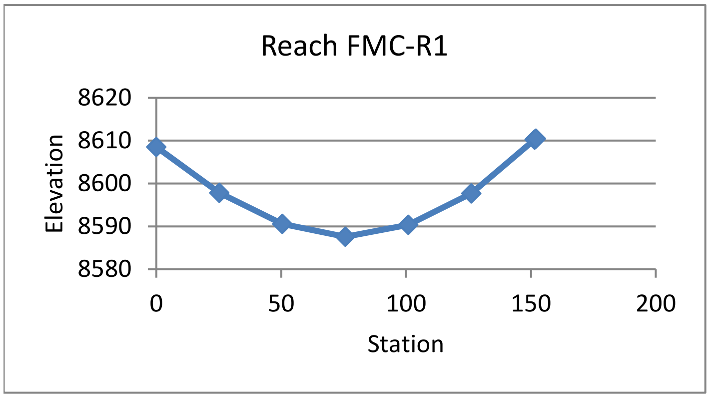
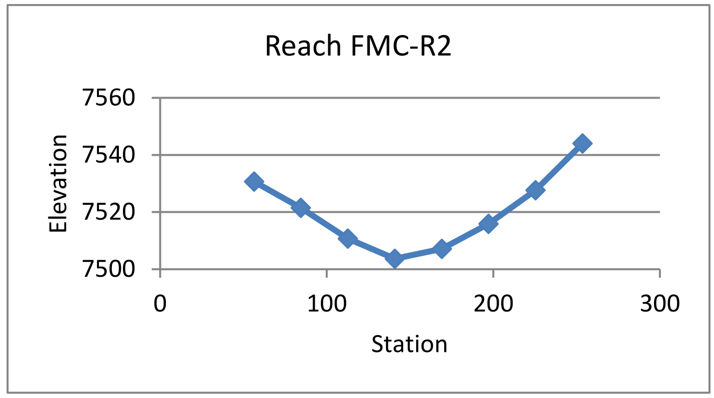
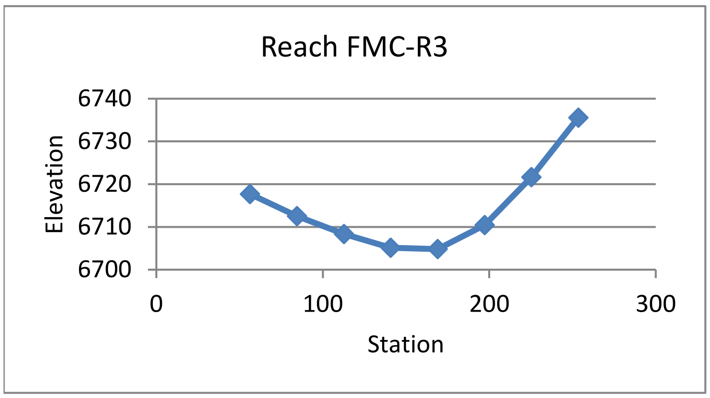
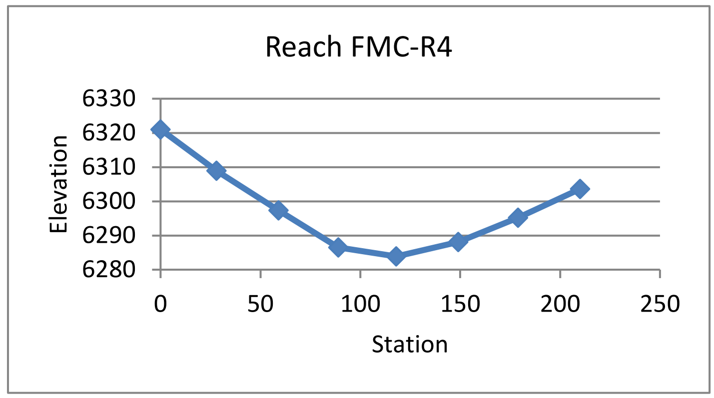


Figure B-9 - Muskingum-Cunge Eight-Point Routing Cross Sections (Continued)









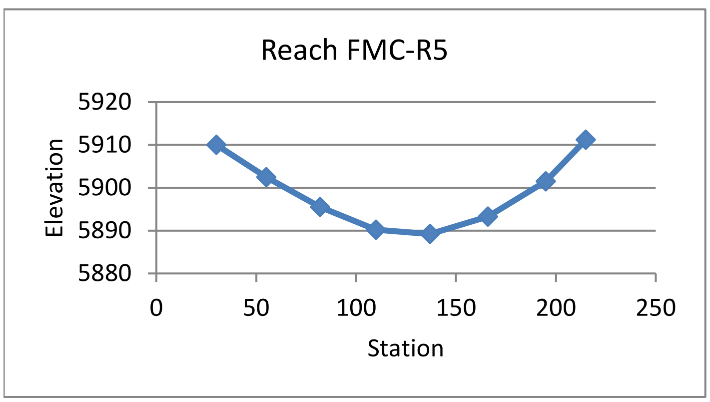
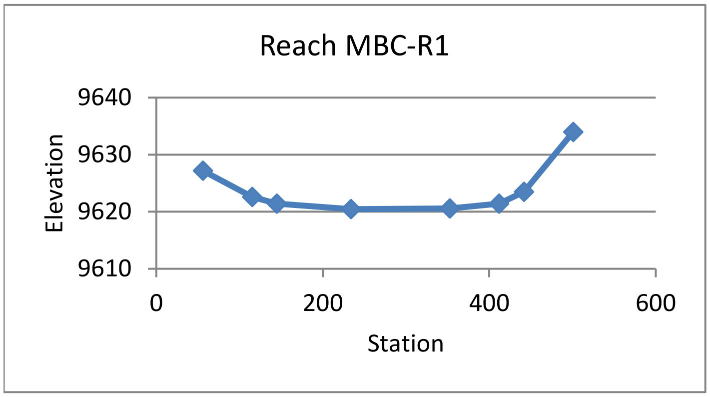
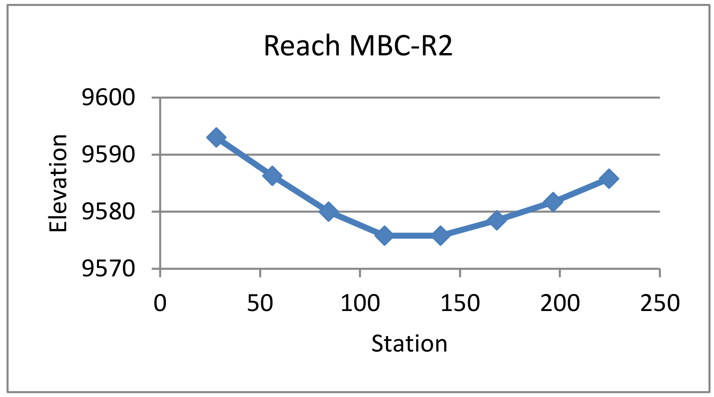
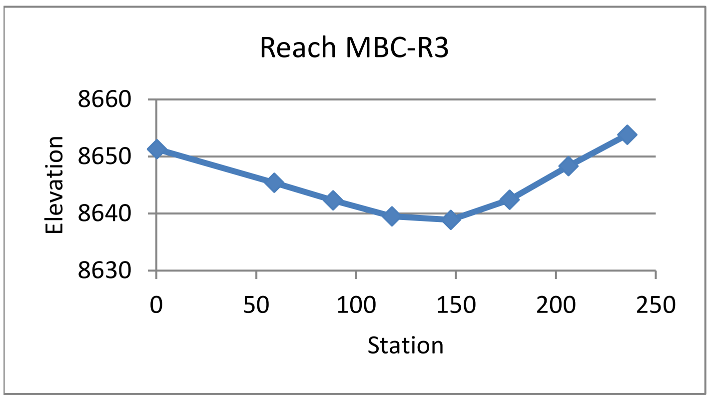
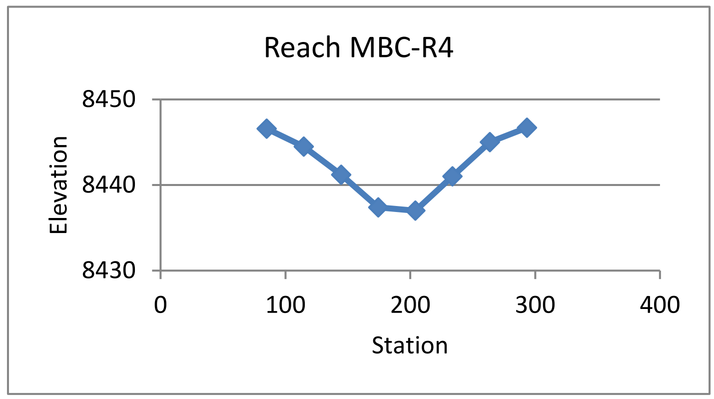


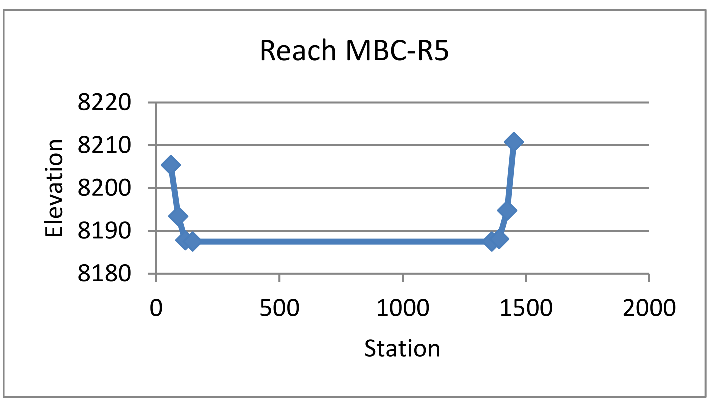
Figure B-9 - Muskingum-Cunge Eight-Point Routing Cross Sections (Continued)











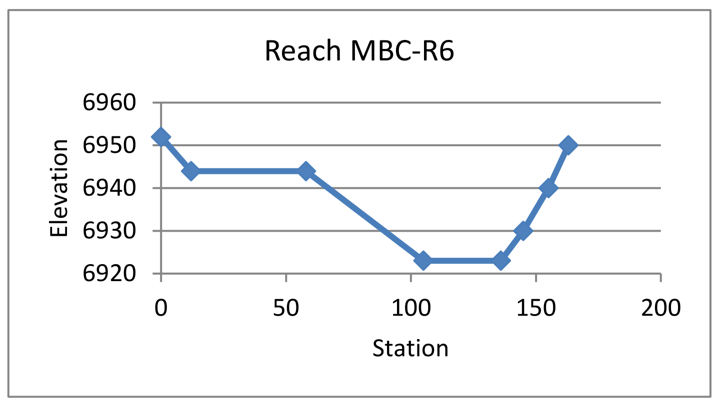
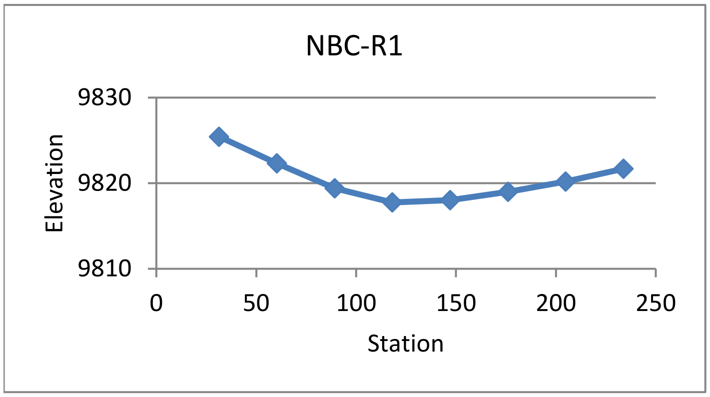
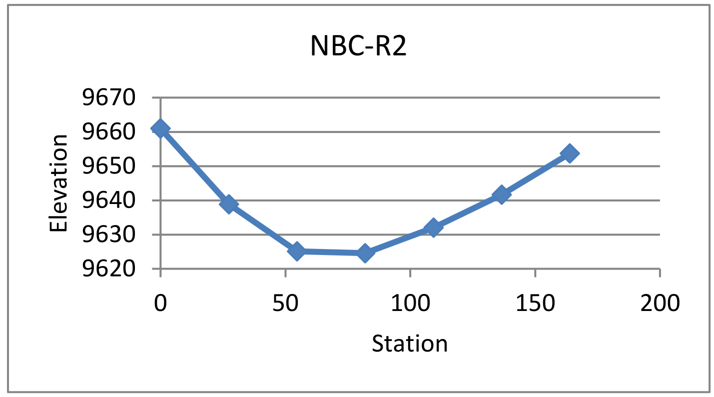
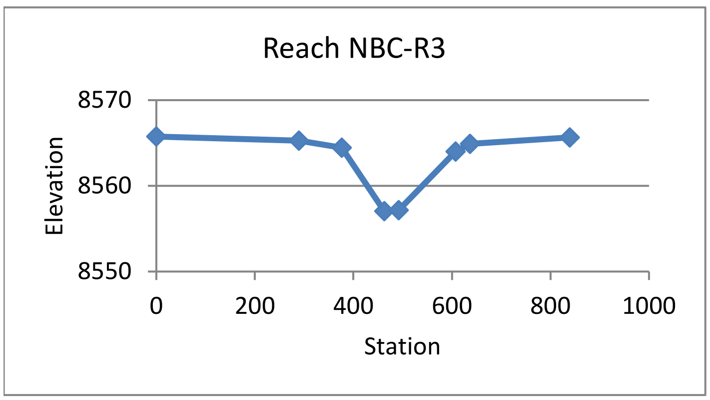
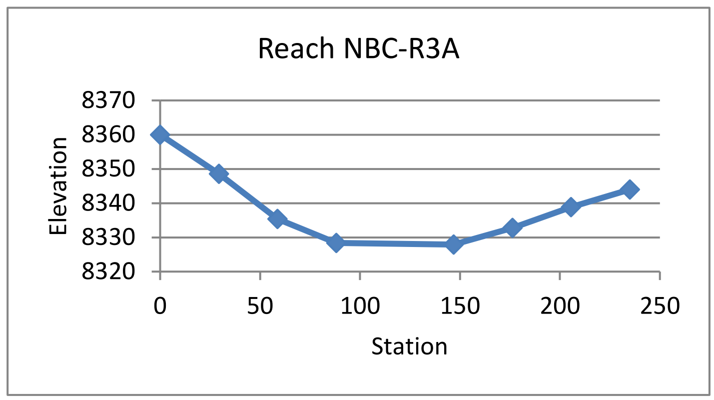


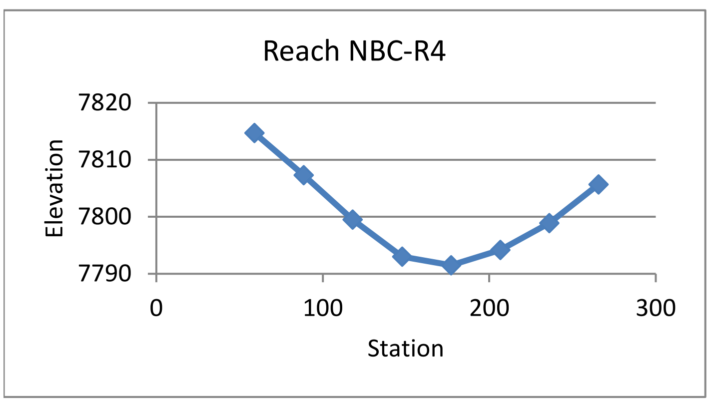
Figure B-9 - Muskingum-Cunge Eight-Point Routing Cross Sections (Continued)











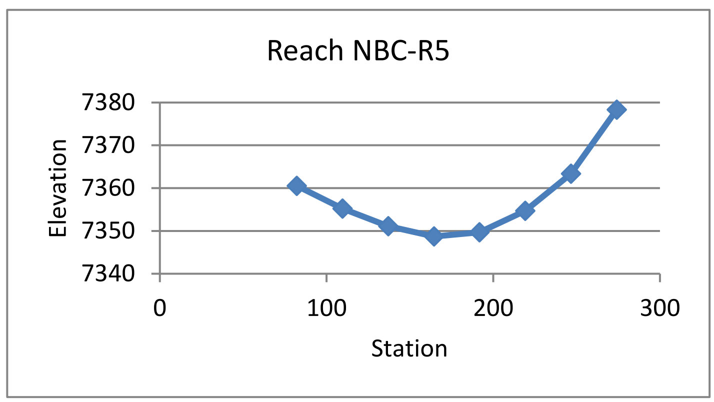
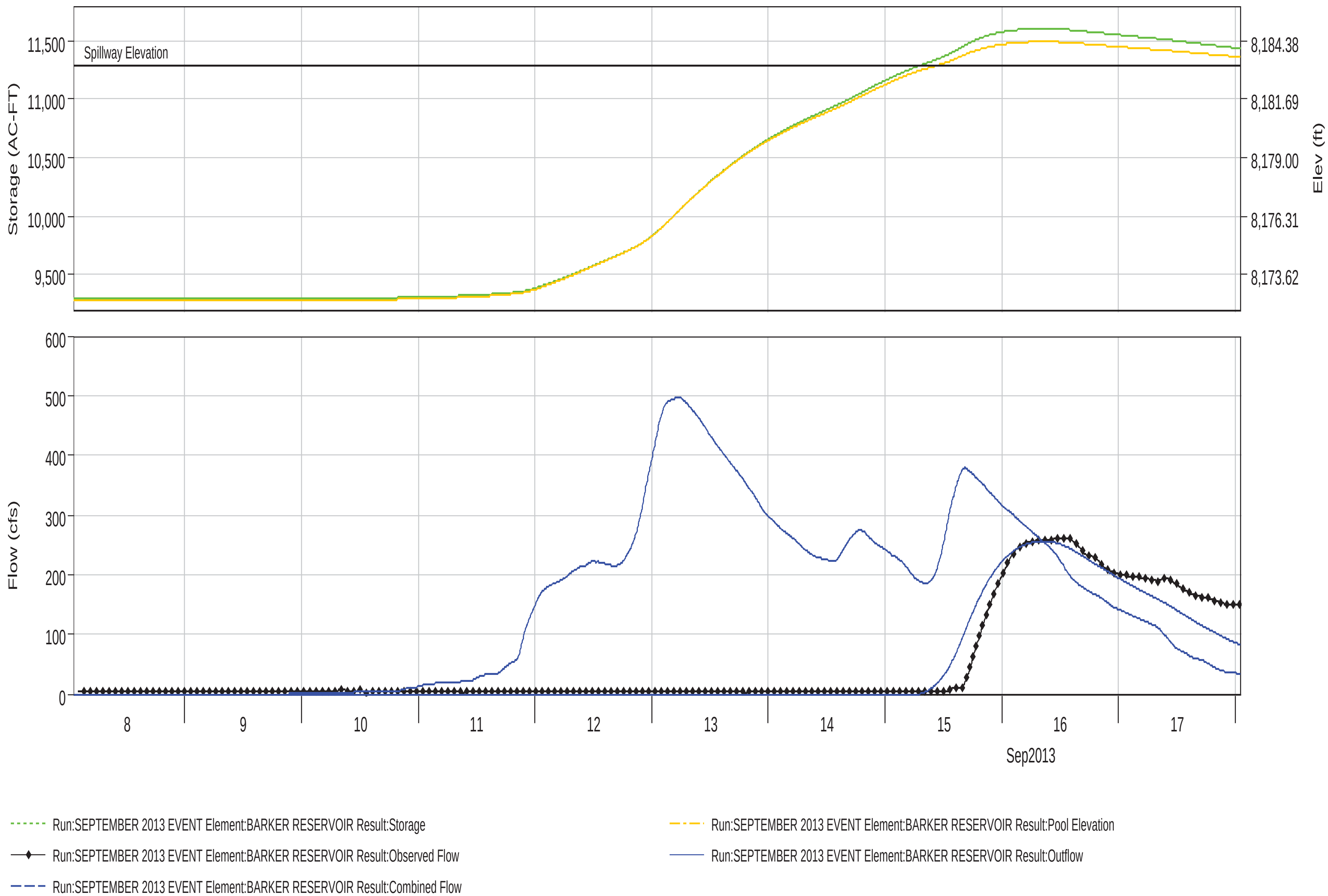


Figure B-10 - September 2013 10-day Calibration Results - Time-lag Provided by Barker Reservoir



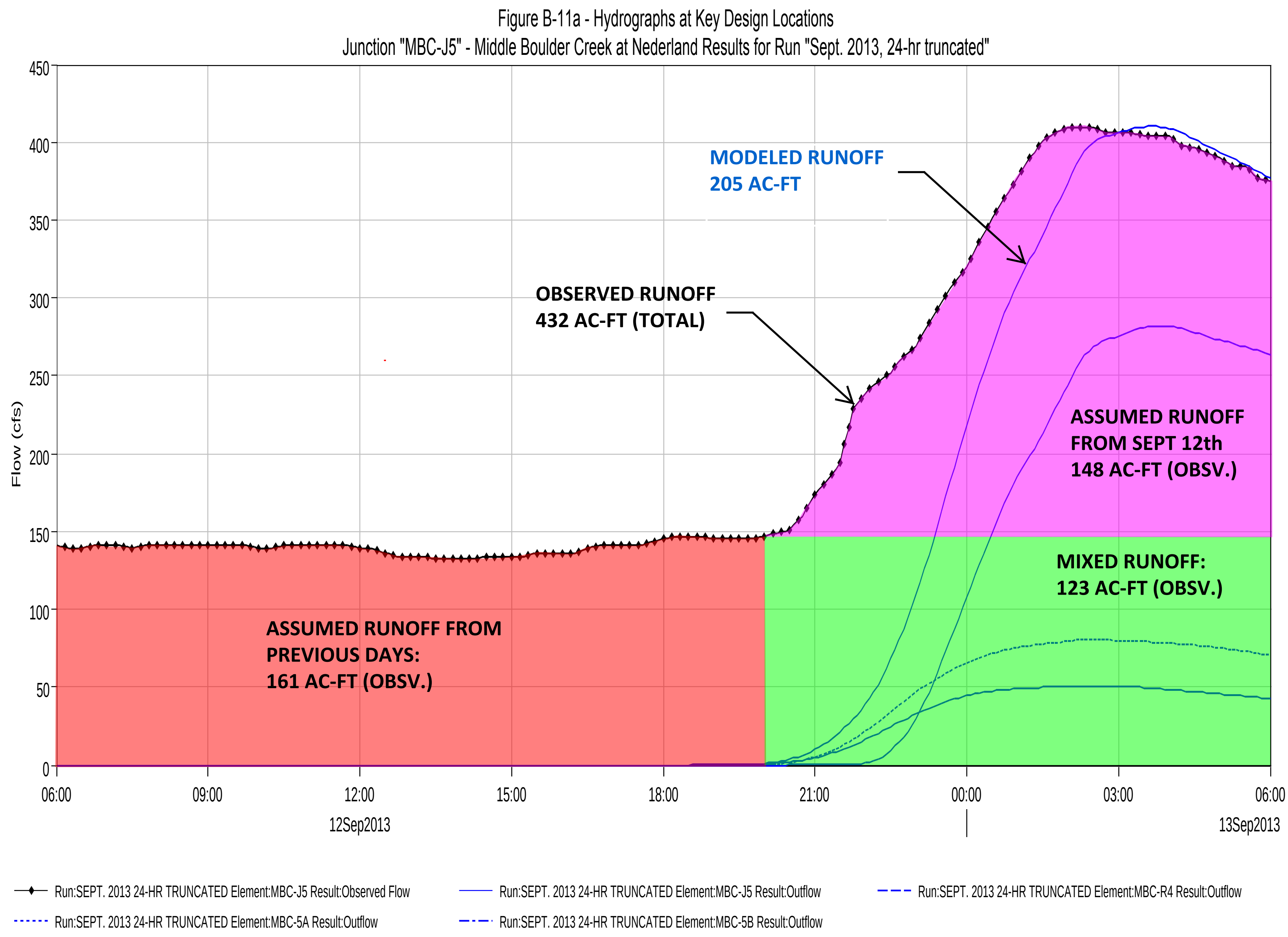


Figure B-11a - Hydrographs at Key Design Locations
Junction "MBC-J5" - Middle Boulder Creek at Nederland Results for Run "Sept. 2013, 24-hr truncated"
Flow (cfs)
450
400
350
300
250
200
150
100
50
0
06:00
09:00
12:00
15:00
18:00
21:00
00:00
03:00
06:00
12Sep2013
13Sep2013
MODELED RUNOFF
205 AC-FT
OBSERVED RUNOFF
432 AC-FT (TOTAL)
ASSUMED RUNOFF
FROM SEPT 12th
148 AC-FT (OBSV.)
MIXED RUNOFF:
123 AC-FT (OBSV.)
ASSUMED RUNOFF FROM
PREVIOUS DAYS:
161 AC-FT (OBSV.)
Run:SEPT. 2013 24-HR TRUNCATED Element:MBC-J5 Result:Observed Flow
Run:SEPT. 2013 24-HR TRUNCATED Element:MBC-J5 Result:Outflow
Run:SEPT. 2013 24-HR TRUNCATED Element:MBC-R4 Result:Outflow
Run:SEPT. 2013 24-HR TRUNCATED Element:MBC-5A Result:Outflow
Run:SEPT. 2013 24-HR TRUNCATED Element:MBC-5B Result:Outflow

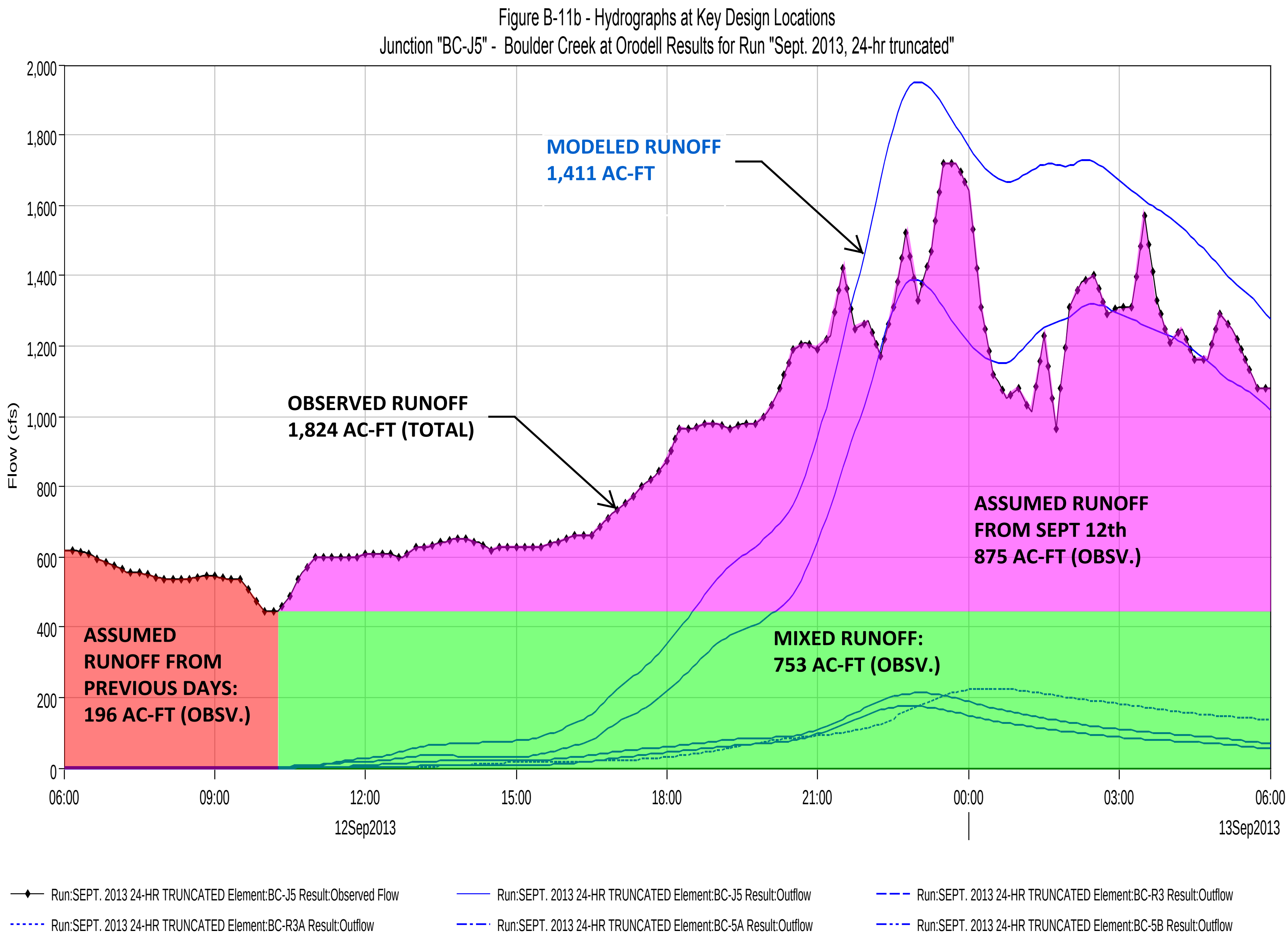


Figure B-11b - Hydrographs at Key Design Locations
Junction "BC-J5" - Boulder Creek at Orodell Results for Run "Sept. 2013, 24-hr truncated"
Flow (cfs)
2,000
1,800
1,600
1,400
1,200
1,000
800
600
400
200
0
06:00
09:00
12:00
15:00
18:00
21:00
00:00
03:00
06:00
12Sep2013
13Sep2013
MODELED RUNOFF
1,411 AC-FT
OBSERVED RUNOFF
1,824 AC-FT (TOTAL)
ASSUMED RUNOFF
FROM SEPT 12th
875 AC-FT (OBSV.)
ASSUMED
RUNOFF FROM
PREVIOUS DAYS:
196 AC-FT (OBSV.)
MIXED RUNOFF:
753 AC-FT (OBSV.)
Run:SEPT. 2013 24-HR TRUNCATED Element:BC-J5 Result:Observed Flow
Run:SEPT. 2013 24-HR TRUNCATED Element:BC-J5 Result:Outflow
Run:SEPT. 2013 24-HR TRUNCATED Element:BC-R3 Result:Outflow
Run:SEPT. 2013 24-HR TRUNCATED Element:BC-R3A Result:Outflow
Run:SEPT. 2013 24-HR TRUNCATED Element:BC-5A Result:Outflow
Run:SEPT. 2013 24-HR TRUNCATED Element:BC-5B Result:Outflow

Figure B-11c - Hydrographs at Key Design Locations - Junction "FMC-J4" - Fourmile Creek near Salina, Downstream of Sweet Home Gulch Results for Run "SCS 24-HR, 100YR"

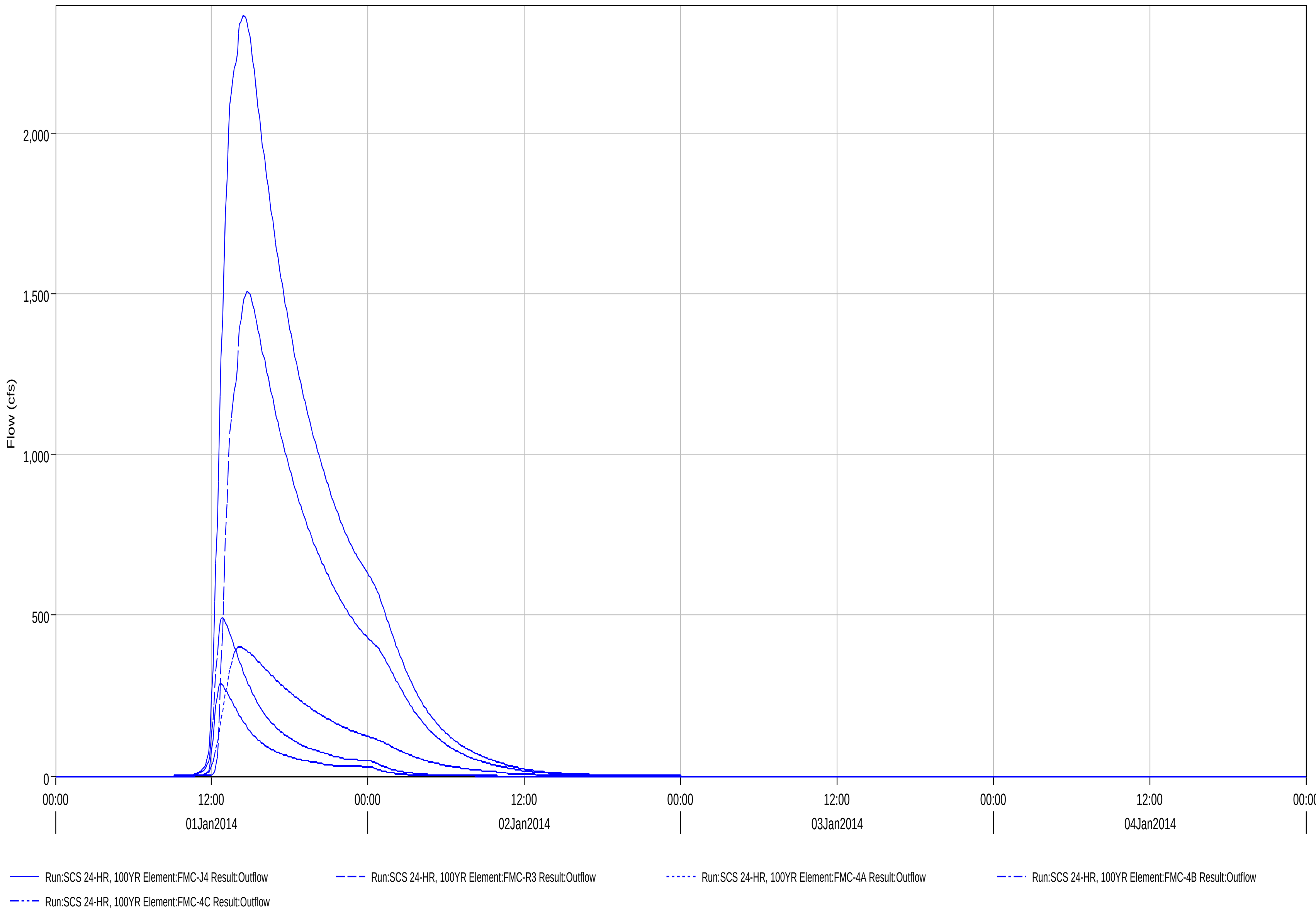


Figure B-11d - Hydrographs at Key Design Locations - Junction "FMC-J6" - Fourmile Creek d/s Poorman Rd u/s #1267 Fourmile Cr Rd nr Orodell Results for Run "SCS 24-HR, 100YR"

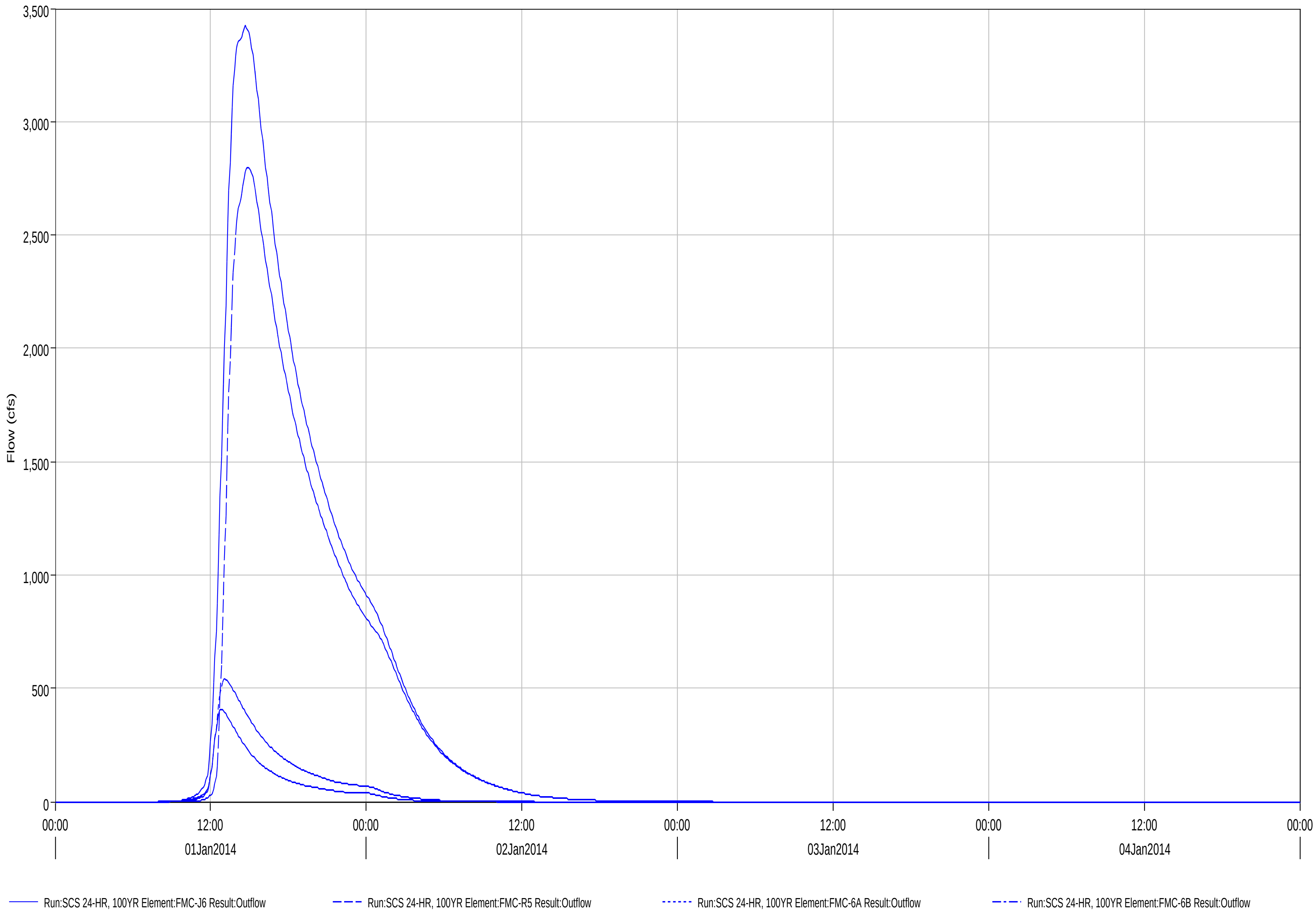


Figure B-11e - Hydrographs at Key Design Locations - Junction "MBC-J5" - Middle Boulder Creek at Nederland Results for Run "SCS 24-HR, 100YR"

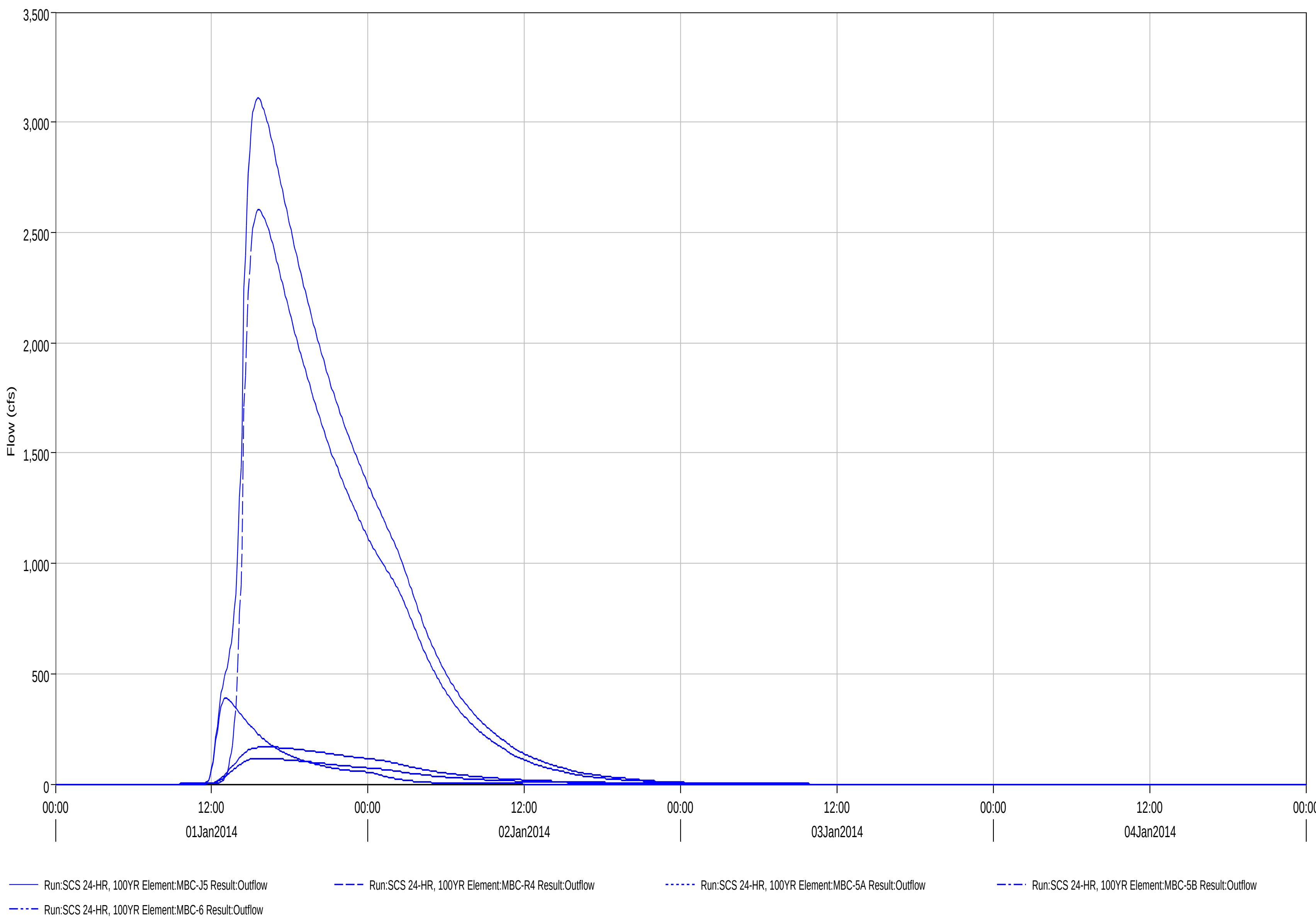


Figure B-11f - Hydrographs at Key Design Locations - Junction "BC-J1" - Confluence of Middle Boulder Creek and North Boulder Creek Results for Run "SCS 24-HR, 100YR"

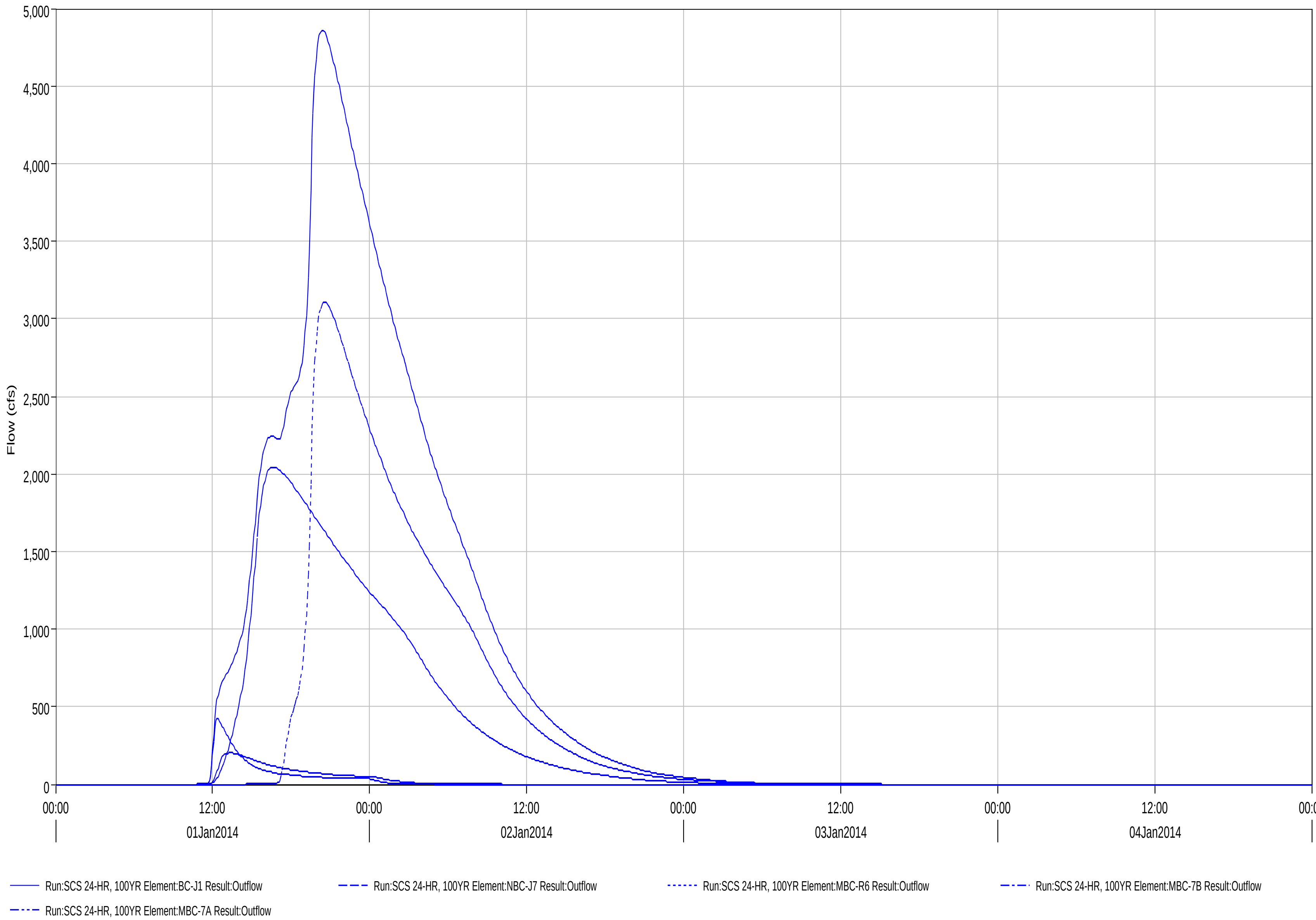
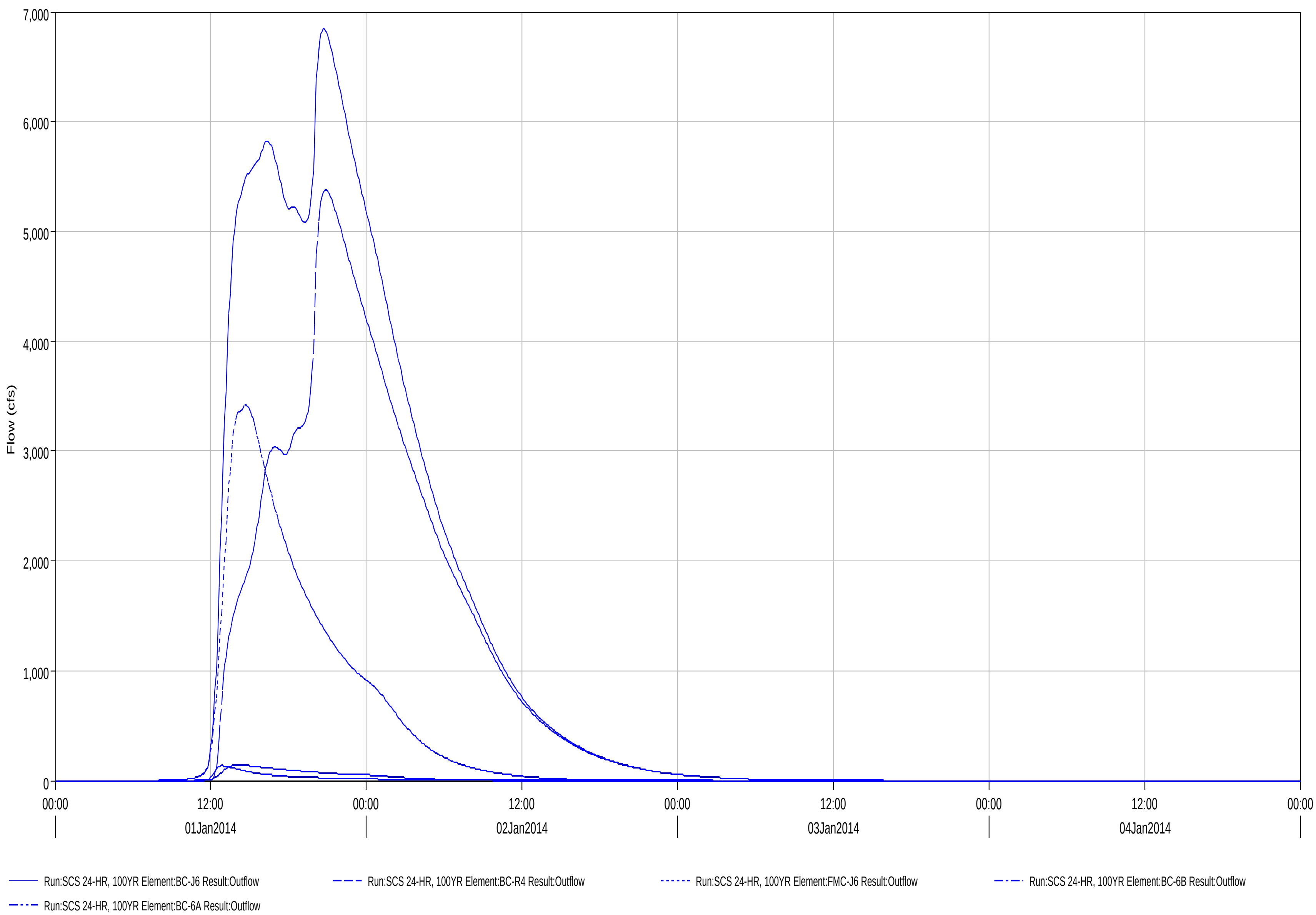


Figure B-11g - Hydrographs at Key Design Locations - Junction "BC-J6" - Confluence of Fourmile Creek and Boulder Creek Results for Run "SCS 24-HR, 100YR"



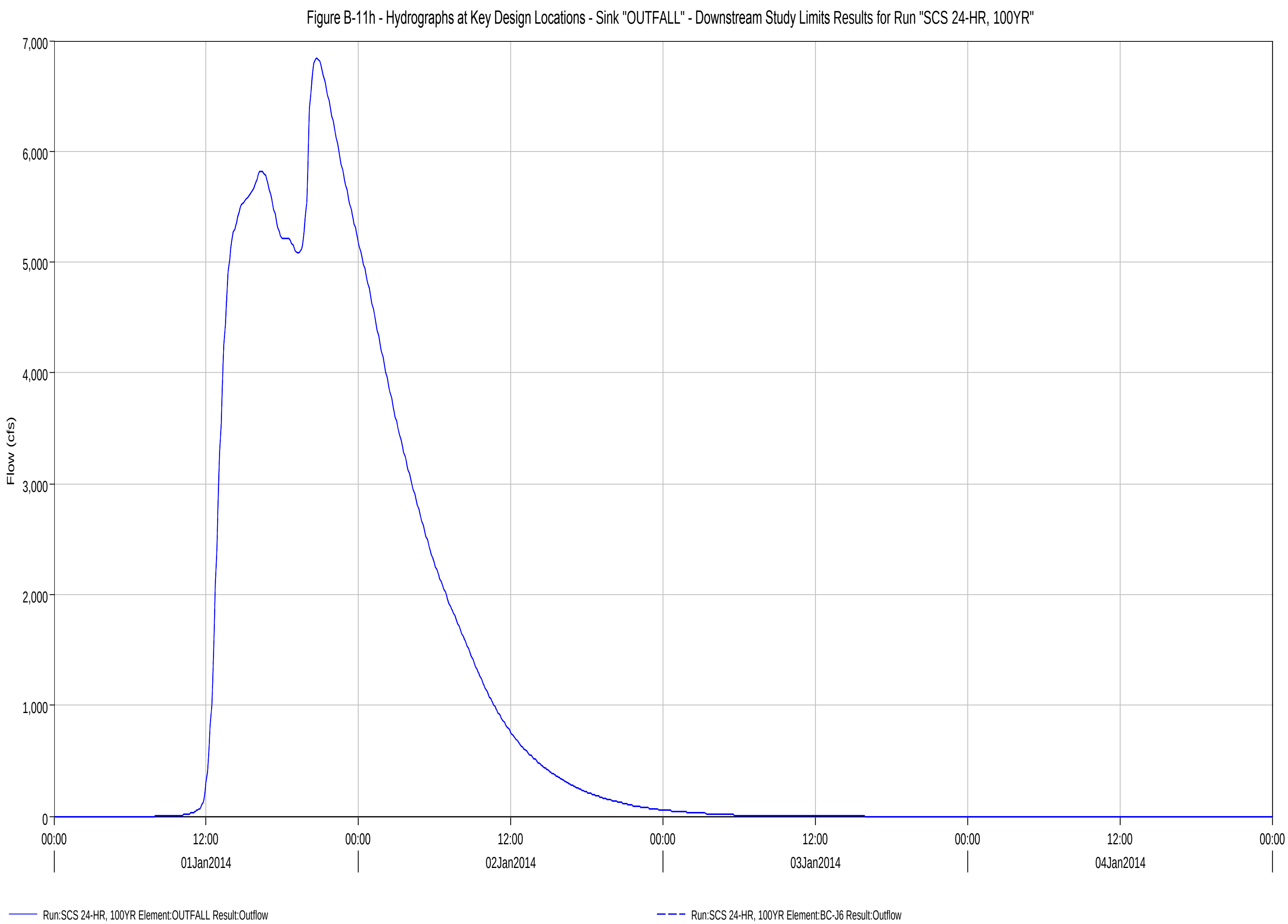


Figure B-11h - Hydrographs at Key Design Locations - Sink "OUTFALL" - Downstream Study Limits Results for Run "SCS 24-HR, 100YR"
Flow (cfs)
7,000
6,000
5,000
4,000
3,000
2,000
1,000
0
00:00
12:00
00:00
12:00
00:00
12:00
00:00
12:00
00:00
01Jan2014
02Jan2014
03Jan2014
04Jan2014
Run:SCS 24-HR, 100YR Element:OUTFALL Result:Outflow
Run:SCS 24-HR, 100YR Element:BC-J6 Result:Outflow

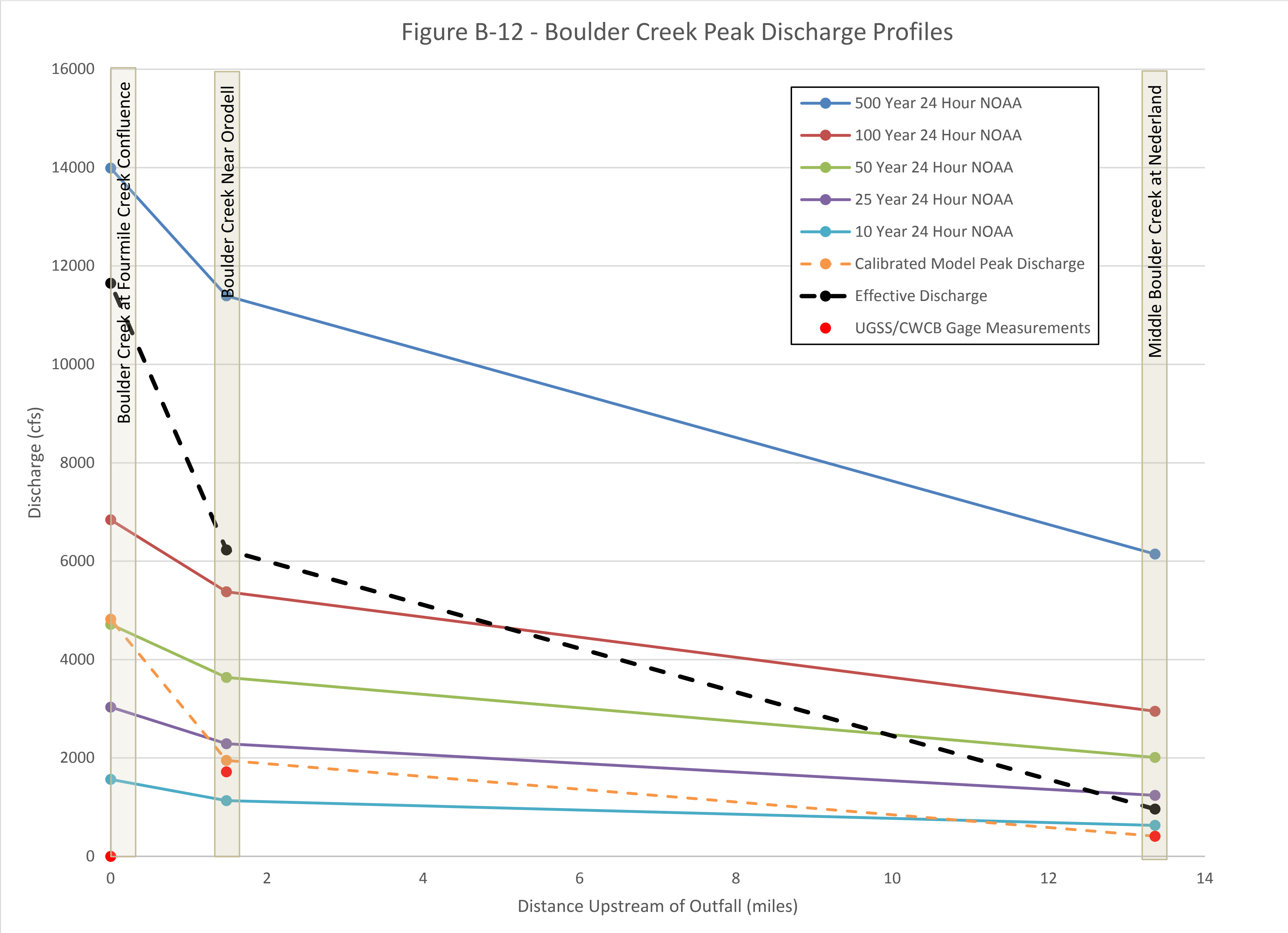


Figure B-12 - Boulder Creek Peak Discharge Profiles
Discharge (cfs)
Distance Upstream of Outfall (miles)
Boulder Creek at Fourmile Creek Confluence
Boulder Creek Near Orodell
Middle Boulder Creek at Nederland
500 Year 24 Hour NOAA
100 Year 24 Hour NOAA
50 Year 24 Hour NOAA
25 Year 24 Hour NOAA
10 Year 24 Hour NOAA
Calibrated Model Peak Discharge
Effective Discharge
UGSS/CWCB Gage Measurements
0
2000
4000
6000
8000
10000
12000
14000
16000
0
2
4
6
8
10
12
14

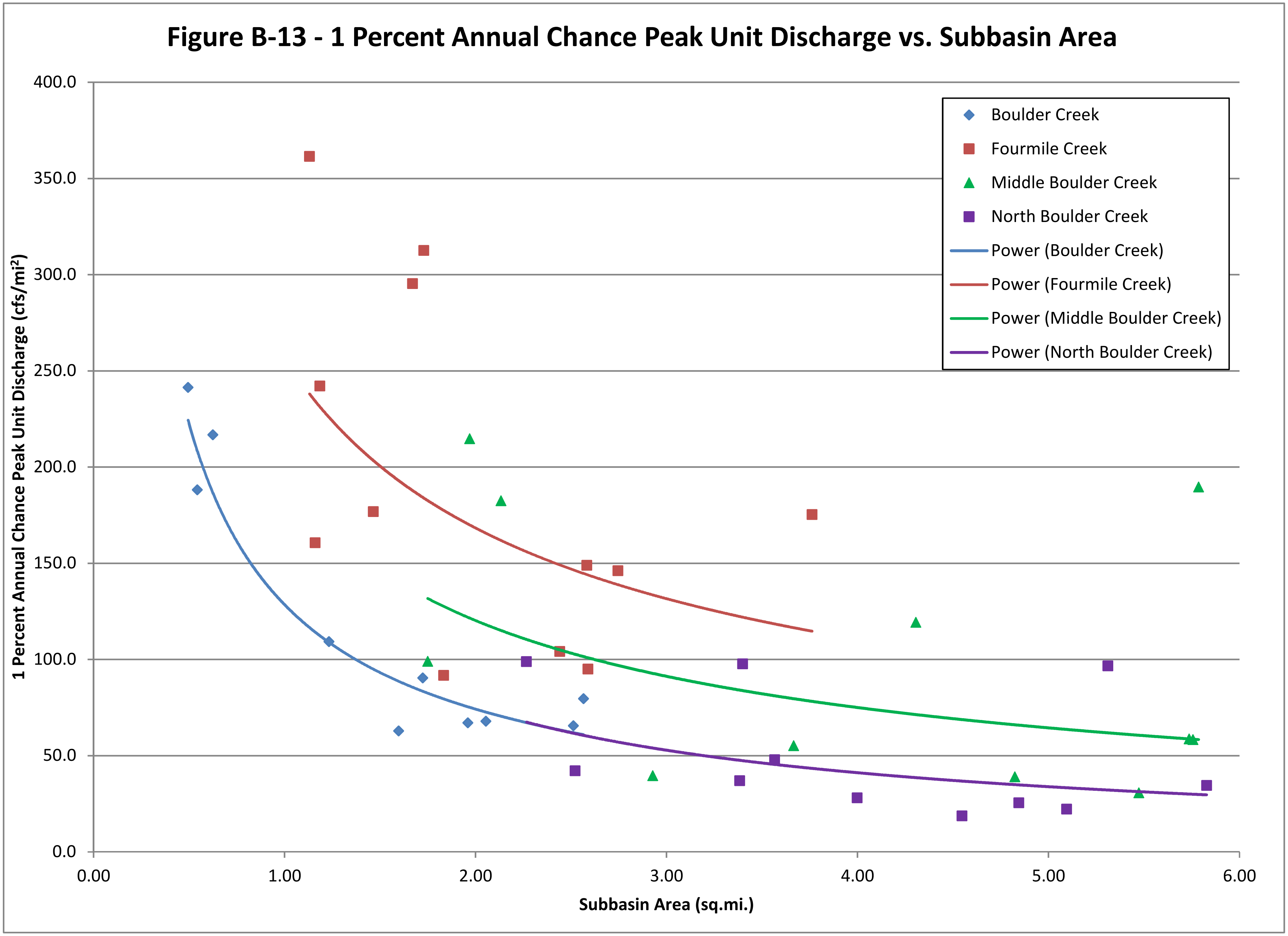


Figure B-13 - 1 Percent Annual Chance Peak Unit Discharge vs. Subbasin Area
1 Percent Annual Chance Peak Unit Discharge (cfs/mi²)
400.0
350.0
300.0
250.0
200.0
150.0
100.0
50.0
0.0
0.00
1.00
2.00
3.00
4.00
5.00
6.00
Subbasin Area (sq.mi.)
Boulder Creek
Fourmile Creek
Middle Boulder Creek
North Boulder Creek
Power (Boulder Creek)
Power (Fourmile Creek)
Power (Middle Boulder Creek)
Power (North Boulder Creek)

Appendix B
Hydrologic Analysis and Parameters

Tables

Table B-1 - Boulder Creek Sub-Basin Area

Basin ID	Area mi^2
BC-2A	1.2
BC-2B	2.5
BC-3A	0.5
BC-3B	0.5
BC-3C	2.0
BC-4	2.6
BC-5A	1.7
BC-5B	1.6
BC-6A	0.6
BC-6B	2.1
FMC-1	2.6
FMC-2A	2.4
FMC-2B	1.8
FMC-3A	3.8
FMC-3B	2.6
FMC-4A	2.7
FMC-4B	1.7
FMC-4C	1.2
FMC-5A	1.2
FMC-5B	1.5
FMC-6A	1.7
FMC-6B	1.1
MBC-1A	4.3
MBC-1B	1.8
MBC-2	5.8
MBC-3A	5.7
MBC-3B	5.8
MBC-4	4.8
MBC-5A	5.5
MBC-5B	2.9
MBC-6	2.1
MBC-7A	2.0
MBC-7B	3.7
NBC-1A	3.4
NBC-1B	5.3
NBC-2	5.1
NBC-3	4.8
NBC-4	4.5
NBC-5A	3.4
NBC-5B	4.0
NBC-5C	2.5
NBC-6A	5.8
NBC-6B	3.6
NBC-7	2.3

Table B-2 - Boulder Creek Rainfall Depths

		NOAA Atlas 14 - Rainfall Depths (in)					Predictive Model Adjusted Rainfall Depths (in)				
Basin ID	24 hour September 2013 Total Precip.	10 year 24 hr Precip.	25 year 24 hr Precip.	50 year 24 hr Precip.	100 year 24 hr Precip.	500 year 24 hr Precip.	10 year *	25 year*	50 year*	100 year*	500 year*
BC-2A	3.3	3.0	3.8	4.4	5.1	7.0	2.8	3.5	4.1	4.7	6.5
BC-2B	3.4	3.0	3.8	4.5	5.2	7.0	2.8	3.5	4.1	4.8	6.5
BC-3A	4.2	3.1	3.9	4.6	5.3	7.2	2.9	3.6	4.3	4.9	6.7
BC-3B	4.1	3.2	4.0	4.6	5.3	7.2	2.9	3.7	4.3	5.0	6.7
BC-3C	3.9	3.2	4.0	4.7	5.4	7.3	3.0	3.7	4.3	5.0	6.8
BC-4	3.4	3.0	3.7	4.4	5.1	6.9	2.8	3.5	4.1	4.7	6.4
BC-5A	3.8	3.1	3.9	4.6	5.3	7.2	2.9	3.6	4.3	4.9	6.7
BC-5B	3.9	3.2	4.1	4.7	5.5	7.3	3.0	3.8	4.4	5.1	6.8
BC-6A	3.9	3.2	4.0	4.7	5.4	7.3	3.0	3.7	4.4	5.0	6.8
BC-6B	3.9	3.3	4.1	4.8	5.5	7.4	3.0	3.8	4.4	5.1	6.9
FMC-1	2.0	2.7	3.4	4.0	4.6	6.4	2.5	3.1	3.7	4.3	6.0
FMC-2A	2.2	2.7	3.4	4.0	4.6	6.4	2.5	3.1	3.7	4.3	6.0
FMC-2B	2.1	2.6	3.3	3.9	4.5	6.3	2.5	3.1	3.6	4.2	5.9
FMC-3A	2.9	2.8	3.5	4.1	4.8	6.6	2.6	3.3	3.8	4.5	6.2
FMC-3B	2.0	2.7	3.5	4.1	4.7	6.5	2.5	3.2	3.8	4.4	6.1
FMC-4A	4.3	2.9	3.7	4.3	5.0	6.9	2.7	3.4	4.0	4.7	6.4
FMC-4B	3.7	2.9	3.7	4.3	5.0	6.9	2.7	3.4	4.0	4.7	6.4
FMC-4C	3.4	2.9	3.7	4.3	5.0	6.9	2.7	3.4	4.0	4.7	6.4
FMC-5A	4.6	3.0	3.8	4.5	5.2	7.1	2.8	3.6	4.2	4.8	6.6
FMC-5B	3.7	3.0	3.8	4.5	5.2	7.1	2.8	3.6	4.2	4.8	6.6
FMC-6A	4.4	3.2	4.0	4.7	5.4	7.3	2.9	3.7	4.3	5.0	6.8
FMC-6B	3.9	3.2	4.0	4.6	5.4	7.3	2.9	3.7	4.3	5.0	6.8
MBC-1A	1.0	2.6	3.4	4.0	4.8	6.9	2.5	3.1	3.7	4.4	6.4
MBC-1B	1.2	2.6	3.3	3.9	4.7	6.8	2.4	3.1	3.7	4.3	6.3
MBC-2	1.1	2.7	3.5	4.1	4.9	7.1	2.5	3.2	3.8	4.5	6.6
MBC-3A	1.8	2.7	3.3	4.0	4.7	6.8	2.5	3.1	3.7	4.4	6.3
MBC-3B	1.4	2.6	3.2	3.9	4.6	6.7	2.4	3.0	3.6	4.3	6.3
MBC-4	1.8	2.5	3.2	3.8	4.5	6.4	2.3	2.9	3.5	4.1	6.0
MBC-5A	1.9	2.6	3.2	3.8	4.5	6.5	2.4	3.0	3.6	4.2	6.1
MBC-5B	1.8	2.6	3.2	3.8	4.5	6.4	2.4	3.0	3.6	4.2	6.0
MBC-6	1.8	2.6	3.3	3.8	4.5	6.3	2.4	3.0	3.6	4.2	5.9
MBC-7A	2.3	2.7	3.4	4.0	4.7	6.4	2.5	3.2	3.7	4.3	6.0
MBC-7B	2.2	2.7	3.4	4.0	4.7	6.5	2.5	3.2	3.7	4.4	6.0
NBC-1A	1.5	2.8	3.5	4.2	5.0	7.1	2.6	3.3	3.9	4.6	6.6
NBC-1B	1.4	2.8	3.5	4.2	4.9	7.1	2.6	3.3	3.9	4.6	6.6
NBC-2	1.8	2.7	3.4	4.0	4.7	6.7	2.5	3.1	3.7	4.4	6.3
NBC-3	1.9	2.7	3.4	4.0	4.7	6.7	2.5	3.2	3.7	4.4	6.2
NBC-4	2.0	2.7	3.4	4.0	4.6	6.5	2.5	3.1	3.7	4.3	6.0
NBC-5A	2.0	2.6	3.3	3.8	4.5	6.2	2.4	3.0	3.6	4.2	5.8
NBC-5B	1.9	2.6	3.3	3.8	4.5	6.3	2.4	3.0	3.6	4.2	5.9
NBC-5C	1.8	2.6	3.2	3.8	4.5	6.3	2.4	3.0	3.5	4.1	5.8
NBC-6A	2.0	2.6	3.3	3.9	4.5	6.3	2.4	3.1	3.6	4.2	5.8
NBC-6B	2.0	2.6	3.3	3.9	4.5	6.3	2.5	3.1	3.6	4.2	5.8
NBC-7	2.9	2.8	3.6	4.2	4.9	6.7	2.6	3.3	3.9	4.5	6.2

* Depth Area Adjustment Factor of 0.93 was applied to NOAA Atlas 14 rainfall data. These depths were used in conjunction with the SCS Type II distribution in the predictive model.

Table B-3 - 5-minute Dimensionless NRCS Type II Cumulative Rainfall Distribution

Time Hours \ Minutes	0	5	10	15	20	25	30	35	40	45	50	55
0	0.000	0.001	0.001	0.002	0.003	0.004	0.005	0.006	0.007	0.008	0.009	0.010
1	0.011	0.012	0.013	0.014	0.015	0.016	0.017	0.018	0.019	0.020	0.021	0.022
2	0.023	0.024	0.025	0.026	0.027	0.028	0.029	0.030	0.031	0.032	0.033	0.034
3	0.035	0.036	0.037	0.038	0.039	0.040	0.041	0.042	0.043	0.044	0.045	0.047
4	0.048	0.049	0.051	0.052	0.053	0.055	0.056	0.057	0.059	0.060	0.061	0.063
5	0.064	0.065	0.067	0.068	0.069	0.071	0.072	0.073	0.075	0.076	0.077	0.079
6	0.080	0.082	0.083	0.085	0.087	0.088	0.090	0.092	0.093	0.095	0.097	0.098
7	0.100	0.102	0.103	0.105	0.107	0.108	0.110	0.112	0.113	0.115	0.117	0.118
8	0.120	0.122	0.124	0.126	0.128	0.131	0.133	0.135	0.138	0.140	0.142	0.145
9	0.147	0.150	0.152	0.155	0.158	0.160	0.163	0.166	0.169	0.172	0.175	0.178
10	0.181	0.184	0.188	0.191	0.195	0.199	0.203	0.208	0.213	0.218	0.224	0.230
11	0.236	0.243	0.250	0.257	0.266	0.274	0.283	0.318	0.352	0.387	0.479	0.571
12	0.663	0.678	0.692	0.707	0.716	0.726	0.735	0.743	0.750	0.758	0.764	0.770
13	0.776	0.781	0.786	0.791	0.795	0.800	0.804	0.808	0.811	0.815	0.818	0.822
14	0.825	0.828	0.831	0.834	0.837	0.839	0.842	0.844	0.847	0.849	0.851	0.854
15	0.856	0.858	0.861	0.863	0.865	0.867	0.869	0.871	0.873	0.875	0.877	0.879
16	0.881	0.883	0.885	0.887	0.889	0.891	0.893	0.895	0.896	0.898	0.900	0.901
17	0.903	0.905	0.906	0.908	0.910	0.911	0.913	0.915	0.916	0.918	0.919	0.921
18	0.922	0.923	0.925	0.926	0.927	0.929	0.930	0.931	0.933	0.934	0.935	0.937
19	0.938	0.939	0.941	0.942	0.943	0.945	0.946	0.947	0.949	0.950	0.951	0.952
20	0.953	0.954	0.955	0.956	0.957	0.958	0.959	0.960	0.961	0.962	0.963	0.964
21	0.965	0.966	0.967	0.968	0.969	0.970	0.971	0.972	0.973	0.974	0.975	0.976
22	0.977	0.978	0.979	0.980	0.981	0.982	0.983	0.984	0.985	0.986	0.987	0.988
23	0.989	0.990	0.991	0.992	0.993	0.994	0.995	0.996	0.997	0.998	0.999	0.999
24	1.000											

Table B-4 - Boulder Creek Lag Time Parameters

Basin ID	Kn	L *mi*	Lc *mi*	S *ft/mile*	TLAG *hours*
BC-2A	0.15	2.2	1.3	790	1.6
BC-2B	0.15	2.8	1.6	911	1.8
BC-3A	0.15	1.7	1.0	483	0.6
BC-3B	0.15	1.8	1.1	475	0.6
BC-3C	0.15	3.4	2.0	691	2.1
BC-4	0.15	3.1	1.5	48	2.9
BC-5A	0.15	3.0	2.0	515	2.1
BC-5B	0.15	3.1	1.8	667	2.0
BC-6A	0.15	1.9	1.3	379	0.9
BC-6B	0.15	2.7	1.5	803	1.8
FMC-1	0.15	3.2	1.7	853	1.9
FMC-2A	0.15	3.2	2.0	617	2.1
FMC-2B	0.15	3.0	2.0	493	2.2
FMC-3A	0.15	4.1	2.1	340	1.2
FMC-3B	0.15	3.8	2.1	313	1.3
FMC-4A	0.15	3.6	1.8	564	2.2
FMC-4B	0.15	3.8	2.3	372	1.0
FMC-4C	0.15	3.4	2.0	274	0.8
FMC-5A	0.15	2.3	1.4	57	2.5
FMC-5B	0.15	2.4	1.7	310	2.0
FMC-6A	0.15	3.2	2.4	315	1.2
FMC-6B	0.15	2.5	1.5	358	1.0
MBC-1A	0.15	3.9	2.2	516	2.4
MBC-1B	0.15	2.9	1.7	525	2.0
MBC-2	0.15	3.7	1.4	593	2.0
MBC-3A	0.15	4.9	2.5	841	2.5
MBC-3B	0.15	6.0	2.8	410	3.1
MBC-4	0.15	3.5	1.6	325	2.2
MBC-5A	0.15	5.6	3.2	452	3.1
MBC-5B	0.15	4.1	2.0	98	3.1
MBC-6	0.15	0.9	0.7	239	1.1
MBC-7A	0.15	6.3	3.4	169	0.5
MBC-7B	0.15	7.1	4.2	150	1.0
NBC-1A	0.15	5.1	2.5	429	2.8
NBC-1B	0.15	4.5	2.5	478	2.6
NBC-2	0.15	4.5	2.2	694	2.4
NBC-3	0.15	3.9	2.6	399	2.7
NBC-4	0.15	5.7	2.9	572	2.9
NBC-5A	0.15	4.5	2.4	565	2.5
NBC-5B	0.15	4.5	2.9	370	2.9
NBC-5C	0.15	4.0	1.6	303	2.4
NBC-6A	0.15	5.1	3.5	282	3.4
NBC-6B	0.15	4.4	2.1	137	3.1
NBC-7	0.15	2.7	1.8	272	2.2

	11-Sep	12-Sep	13-Sep	14-Sep	15-Sep	16-Sep	17-Sep	18-Sep
Gage Elevation (ft above reference)	121.7	123.18	125.96	128.72	130.61	132.27	132.27	132.27
Reservoir Elevation (ft)	8172.45	8173.93	8176.71	8179.47	8181.36	8183.02	8183.02	8183.02
Reservoir Volume Stored (AF)	9298.65	9562.85	10073.6	10595.1	10962.58	11288.56	11288.56	11288.56
Average Inflows (cfs)	80.4	153	320	188	205	172	132	124
Average Flow (cfs) to river incl. spillway	4.01	4.34	3.93	3.74	113.62	225.91	163.36	145.60

	19-Sep	20-Sep	21-Sep	22-Sep	23-Sep	24-Sep	25-Sep
Gage Elevation (ft above reference)	132.24	132.21	132.17	132.06	132.06	132.03	132.03
Reservoir Elevation (ft)	8182.99	8182.96	8182.92	8182.81	8182.81	8182.78	8182.78
Reservoir Volume Stored (AF)	11282.67	11276.77	11268.92	11247.32	11247.32	11241.43	11241.43
Average Inflows (cfs)	111	94.9	83.6	81.4	94.9	82.4	77.9
Average Flow (cfs) to river incl. spillway	110.57	77.19	60.63	62.03	74.82	53.07	49.50

TABLE B-5
Barker Reservoir Elevation-Storage Data During September 2013 High-flow Event
(Source: City of Boulder)
CDOT Flood Recovery Hydrologic Evaluation

Table B-6 - Boulder Creek Curve Numbers

Basin ID	Calibrated CN *AMC III*	Predictive CN *AMC II*
BC-2A	78	62
BC-2B	74	56
BC-3A	75	58
BC-3B	78	62
BC-3C	74	56
BC-4	80	64
BC-5A	78	61
BC-5B	73	54
BC-6A	80	64
BC-6B	72	53
FMC-1	81	66
FMC-2A	83	69
FMC-2B	82	67
FMC-3A	83	69
FMC-3B	83	67
FMC-4A	85	72
FMC-4B	86	74
FMC-4C	82	67
FMC-5A	87	75
FMC-5B	86	74
FMC-6A	88	77
FMC-6B	88	76
MBC-1A	72 *	72
MBC-1B	67 *	67
MBC-2	78 *	78
MBC-3A	77	61
MBC-3B	79	64
MBC-4	74	57
MBC-5A	74	56
MBC-5B	76	59
MBC-6	84	71
MBC-7A	78	62
MBC-7B	72	53
NBC-1A	81	69
NBC-1B	80	68
NBC-2	68	49
NBC-3	70	51
NBC-4	69	50
NBC-5A	74	57
NBC-5B	73	55
NBC-5C	75	58
NBC-6A	75	58
NBC-6B	78	61
NBC-7	81	66

* Note: AMC II Curve Numbers used for both Calibrated and Predictive Models

Table B-7 - Boulder Creek Land Use Conditions

Land Cover	TR-55 Classification	FMC	BC	NBC	MBC
11 - Open Water	Open Water	Fair	Fair	Fair	Fair
12, 41, 42, 43 - Deciduous Forest	Oak- Aspen	Poor	Fair	Fair	Fair
21- Developed Open Space	Developed Open Space, 2 Acre Lots	Fair	Fair	Fair	Fair
22 - Developed, Low Intensity	Developed Medium Intensity, 1/2 Acre Lots	Fair	Fair	Fair	Fair
23 - Developed, Medium Intensity	Developed Medium Intensity, 1/4 Acre Lots	Fair	Fair	Fair	Fair
31 - Barren Land	Barren Land	Fair	Fair	Fair	Fair
52 – Shrub/Brush	Shrub (Sagebrush for FMC & BC; Pinyon Pine for MBC; pasture NBC)	Fair	Fair	Fair	Fair
71, 81 - Grassland/Pasture	Grassland, pasture	Fair	Fair	Fair	Poor
90, 95 - Woody Wetlands, Herbaceous	Woody Wetlands, Herbaceous	Good	Good	Good	Good

Table B-8
Boulder Creek Hydrologic Modeling Detailed Results Summary

					NOAA Design Storms														
		Calibrated 24 hour			10-percent			4-percent			2-percent			1-percent			0.2-percent		
Hydrologic Element	Drainage Area (sq mi)	Peak Discharge (cfs)	Unit Peak Discharge (cfs/sq mi)	Volume (in)	Peak Discharge (cfs)	Unit Peak Discharge (cfs/sq mi)	Volume (in)	Peak Discharge (cfs)	Unit Peak Discharge (cfs/sq mi)	Volume (in)	Peak Discharge (cfs)	Unit Peak Discharge (cfs/sq mi)	Volume (in)	Peak Discharge (cfs)	Unit Peak Discharge (cfs/sq mi)	Volume (in)	Peak Discharge (cfs)	Unit Peak Discharge (cfs/sq mi)	Volume (in)
BC-2A	1.2	150	120	0.53	25	21	0.30	56	46	0.60	91	74	0.90	130	110	1.30	280	220	2.40
BC-2B	2.5	250	100	0.35	22	8.6	0.16	58	23	0.38	100	41	0.61	160	66	0.91	380	150	1.90
BC-3A	0.5	130	240	0.77	13	25	0.24	36	67	0.50	65	120	0.78	100	190	1.10	230	420	2.20
BC-3B	0.5	120	250	0.92	21	43	0.36	50	100	0.68	81	160	1.00	120	240	1.40	240	490	2.60
BC-3C	2.0	210	110	0.51	21	11	0.21	51	26	0.46	86	44	0.72	130	67	1.00	280	140	2.10
BC-4	2.6	230	88	0.68	46	18	0.38	93	36	0.70	140	56	1.00	200	80	1.40	400	150	2.60
BC-5A	1.7	210	120	0.72	31	18	0.32	67	39	0.63	110	62	0.94	160	90	1.30	310	180	2.50
BC-5B	1.6	180	110	0.46	14	8.6	0.17	37	23	0.40	64	40	0.64	100	63	0.95	220	140	1.90
BC-6A	0.63	120	200	0.92	30	48	0.46	61	98	0.82	95	150	1.20	140	220	1.60	260	410	2.90
BC-6B	2.1	230	110	0.44	18	8.8	0.17	50	24	0.39	88	43	0.64	140	68	0.94	310	150	1.90
FMC-1	2.6	130	50	0.16	51	20	0.32	110	41	0.60	170	64	0.89	250	95	1.30	510	200	2.40
FMC-2A	2.4	160	64	0.30	61	25	0.41	120	48	0.72	180	73	1.00	250	100	1.40	500	200	2.70
FMC-2B	1.8	99	54	0.23	37	20	0.35	75	41	0.64	120	63	0.93	170	92	1.30	340	180	2.50
FMC-3A	3.8	470	120	0.61	160	41	0.45	310	81	0.80	470	120	1.10	660	180	1.60	1300	340	2.80
FMC-3B	2.6	180	68	0.20	85	33	0.39	170	67	0.71	270	100	1.00	380	150	1.40	760	290	2.60
FMC-4A	2.7	430	160	1.70	120	42	0.64	210	75	1.10	290	110	1.50	400	150	2.00	720	260	3.40
FMC-4B	1.7	310	190	1.40	150	89	0.71	260	150	1.20	370	220	1.60	490	300	2.10	860	520	3.50
FMC-4C	1.2	210	180	0.82	63	53	0.45	130	110	0.80	200	170	1.10	290	240	1.60	550	470	2.80
FMC-5A	1.2	190	170	2.20	62	54	0.86	100	89	1.40	140	120	1.80	190	160	2.40	310	270	3.90
FMC-5B	1.5	210	140	1.30	83	56	0.78	140	95	1.30	190	130	1.70	260	180	2.20	440	300	3.70
FMC-6A	1.7	410	240	2.20	190	110	1.00	310	180	1.60	420	240	2.10	540	310	2.60	880	510	4.20
FMC-6B	1.1	270	240	1.60	140	120	0.95	230	200	1.50	310	280	2.00	410	360	2.50	670	600	4.00
MBC-1A	4.3	3.4	0.79	0.010	130	30	0.50	240	55	0.88	360	83	1.30	510	120	1.80	1000	240	3.40
MBC-1B	1.8	1.5	0.86	0.010	32	18	0.30	69	39	0.59	110	65	0.91	170	99	1.30	380	220	2.70
MBC-2	5.8	37	6.4	0.090	350	60	0.80	570	99	1.30	810	140	1.70	1100	190	2.30	2000	340	4.10
MBC-3A	5.7	110	20	0.030	47	8.3	0.18	120	20	0.39	210	36	0.65	340	59	0.99	810	140	2.20
MBC-3B	5.8	59	10	0.010	54	10	0.22	130	22	0.46	210	37	0.75	340	58	1.10	780	140	2.40
MBC-4	4.8	80	16	0.010	17	3.4	0.070	51	11	0.22	110	22	0.40	190	39	0.66	520	110	1.60
MBC-5A	5.5	81	15	0.010	17	3.1	0.070	50	9.1	0.22	97	18	0.40	170	31	0.66	460	84	1.60
MBC-5B	2.9	51	17	0.030	15	5.1	0.12	39	13	0.30	71	24	0.52	120	40	0.81	280	97	1.80
MBC-6	2.1	130	61	0.21	93	43	0.45	180	84	0.78	270	130	1.10	390	180	1.50	760	360	2.80
MBC-7A	2.0	210	110	0.16	57	29	0.24	150	77	0.48	270	140	0.74	420	210	1.10	940	480	2.10
MBC-7B	3.7	170	47	0.020	13	3.5	0.060	50	14	0.19	110	30	0.35	200	55	0.58	580	160	1.40
NBC-1A	3.4	62	18	0.060	82	24	0.47	150	45	0.82	230	68	1.20	330	98	1.70	660	190	3.20
NBC-1B	5.3	85	16	0.050	120	22	0.42	230	43	0.75	350	66	1.10	510	97	1.60	1000	200	3.00
NBC-2	5.1	48	9.4	0.00	6	1.2	0.020	25	4.9	0.11	57	11	0.24	110	22	0.44	370	73	1.20
NBC-3	4.8	64	13	0.00	9	1.9	0.040	32	6.5	0.15	66	14	0.30	120	25	0.52	360	75	1.30
NBC-4	4.5	59	13	0.00	6	1.2	0.020	22	4.7	0.11	46	10	0.24	85	19	0.42	260	57	1.10
NBC-5A	3.4	70	21	0.020	15	4.3	0.10	40	12	0.25	75	22	0.44	130	37	0.68	310	92	1.50
NBC-5B	4.0	67	17	0.010	11	2.7	0.060	33	8.2	0.19	64	16	0.36	110	28	0.59	300	75	1.40
NBC-5C	2.5	48	19	0.020	12	4.8	0.10	33	13	0.27	63	25	0.46	110	42	0.73	270	110	1.70
NBC-6A	5.8	120	20	0.040	28	4.9	0.12	71	12	0.29	130	22	0.50	200	34	0.76	470	81	1.70
NBC-6B	3.6	88	25	0.080	29	8.2	0.19	67	19	0.41	110	31	0.65	170	48	0.95	370	100	1.90
NBC-7	2.3	200	88	0.53	52	23	0.39	100	46	0.72	160	69	1.00	220	99	1.40	440	190	2.60
OUTFALL	128.7	4819	37.00	0.27	1564	12	0.29	3034	24	0.54	4716	37	0.82	6842	53	1.20	13990	110	2.30

Appendix C
Ayres Associates and CH2M HILL
Flood Frequency Analyses

HEC-SSP Output for USGS 06727000 / CDWR BOCOROCO Boulder Creek at Orodell Gage
HEC-SSP Output for USGS 06725500 / CDWR BOCOMIDCO Middle Boulder Creek at Nederland Gage

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Bulletin 17B Frequency Analysis
15 Aug 2014 04:03 PM

USGS 06727000 / CDWR BOCOROCO

Boulder Creek at Orodell Gage

--- Input Data ---

Analysis Name: 06727000 Bldr_Ck-ORO_2013 STA
Description: Copy of USGS 06727000 BOULDER CREEK NEAR ORODELL, CO.

Data Set Name: BOULDERCK2013-ORODELL, CO.-FLO
DSS File Name: H:\32-176904 Big Thompson Hydrology\Six_Rivers_HEC-SSP_FFA_Results\Six_Rivers\Six_Rivers.dss
DSS Pathname: /BOULDER CREEK/ORODELL, CO./FLOW-ANNUAL PEAK/01jan1900/IR-CENTURY/Save Data As: BOULDERCK2013-ORODELL, CO.-FLO/

Report File Name: H:\32-176904 Big Thompson Hydrology\Six_Rivers_HEC-SSP_FFA_Results\Six_Rivers\Bulletin17bResults\06727000_Bldr_Ck-ORO_2013_STA\06727000_Bldr_Ck-ORO_2013_STA.rpt
XML File Name: H:\32-176904 Big Thompson Hydrology\Six_Rivers_HEC-SSP_FFA_Results\Six_Rivers\Bulletin17bResults\06727000_Bldr_Ck-ORO_2013_STA\06727000_Bldr_Ck-ORO_2013_STA.xml

Start Date:
End Date:

Skew Option: Use Station Skew
Regional Skew: 0.459
Regional Skew MSE: 0.12

Plotting Position Type: Hazen

Upper Confidence Level: 0.05
Lower Confidence Level: 0.95
Use High Outlier Threshold
High Outlier Threshold: 2331.0

Use Historic Data
Historic Period Start Year: ---
Historic Period End Year: ---

Display ordinate values using 1 digits in fraction part of value

--- End of Input Data ---

--- Preliminary Results ---

<< Plotting Positions >>
BOULDERCK2013-ORODELL, CO.-FLO

Events Analyzed				Ordered Events			
Day	Mon	Year	FLOW CFS	Rank	Water Year	FLOW CFS	Hazen Plot Pos
01	Jul	1907	840.0	1	1921	2,500.0*	0.48
17	Jun	1908	465.0	2	2013	1,720.0	1.43
20	Jun	1909	875.0	3	1919	1,300.0	2.38
28	Jul	1910	324.0	4	1947	1,290.0	3.33
13	Jun	1911	469.0	5	2011	1,250.0	4.29
30	Jul	1912	880.0	6	1969	1,220.0	5.24
02	Jun	1913	366.0	7	1951	1,220.0	6.19

28 May 1914	840.0	8	1965	1,190.0	7.14	
29 Jun 1916	458.0	9	1952	1,180.0	8.10	
25 Jun 1917	545.0	10	1941	1,120.0	9.05	
22 Jun 1918	812.0	11	1935	1,060.0	10.00	
03 Aug 1919	1,300.0	12	2003	1,040.0	10.95	
10 Jun 1920	436.0	13	1957	1,010.0	11.90	
06 Jun 1921	2,500.0	14	1923	983.0	12.86	
16 Jun 1922	554.0	15	1949	965.0	13.81	
15 Jun 1923	983.0	16	2010	964.0	14.76	
14 Jun 1924	926.0	17	2009	932.0	15.71	
24 Jun 1925	374.0	18	1926	929.0	16.67	
08 Jun 1926	929.0	19	1924	926.0	17.62	
11 Jun 1927	672.0	20	1912	880.0	18.57	
02 Jun 1928	767.0	21	1909	875.0	19.52	
22 Jun 1929	548.0	22	1958	855.0	20.48	
14 Jun 1930	490.0	23	1914	840.0	21.43	
28 May 1931	535.0	24	1907	840.0	22.38	
26 Jun 1932	550.0	25	1997	830.0	23.33	
12 Jun 1933	480.0	26	1995	830.0	24.29	
31 May 1934	576.0	27	1983	830.0	25.24	
15 Jun 1935	1,060.0	28	1918	812.0	26.19	
19 Jun 1936	626.0	29	1938	802.0	27.14	
25 Jun 1937	455.0	30	1942	793.0	28.10	
22 Jun 1938	802.0	31	1953	786.0	29.05	
31 May 1939	425.0	32	1960	776.0	30.00	
21 Sep 1940	490.0	33	1928	767.0	30.95	
21 Jun 1941	1,120.0	34	1971	753.0	31.90	
12 Jun 1942	793.0	35	2012	723.0	32.86	
30 Jun 1943	634.0	36	2005	723.0	33.81	
22 Jun 1944	578.0	37	1948	712.0	34.76	
26 Jun 1945	617.0	38	2006	698.0	35.71	
18 Jun 1946	469.0	39	1927	672.0	36.67	
21 Jun 1947	1,290.0	40	1970	634.0	37.62	
07 Jun 1948	712.0	41	1961	634.0	38.57	
06 Jun 1949	965.0	42	1943	634.0	39.52	
16 Jun 1950	518.0	43	1996	626.0	40.48	
21 Jun 1951	1,220.0	44	1936	626.0	41.43	
07 Jun 1952	1,180.0	45	1986	617.0	42.38	
11 Jun 1953	786.0	46	1945	617.0	43.33	
20 May 1954	374.0	47	1973	610.0	44.29	
26 Jun 1955	436.0	48	1978	608.0	45.24	
23 May 1956	588.0	49	1959	602.0	46.19	
29 Jun 1957	1,010.0	50	1980	599.0	47.14	
06 Jun 1958	855.0	51	1967	594.0	48.10	
21 Jun 1959	602.0	52	1956	588.0	49.05	
16 Jun 1960	776.0	53	1979	582.0	50.00	
20 Jun 1961	634.0	54	1944	578.0	50.95	
01 Jul 1962	546.0	55	1934	576.0	51.90	
16 Jun 1963	328.0	56	1984	566.0	52.86	
29 Jun 1964	299.0	57	1922	554.0	53.81	
24 Jul 1965	1,190.0	58	1999	550.0	54.76	
26 May 1966	251.0	59	1932	550.0	55.71	
23 Jun 1967	594.0	60	1929	548.0	56.67	
23 Jun 1968	406.0	61	1962	546.0	57.62	
07 May 1969	1,220.0	62	1917	545.0	58.57	
25 May 1970	634.0	63	1931	535.0	59.52	
19 Jun 1971	753.0	64	1950	518.0	60.48	
06 Jun 1972	360.0	65	1982	510.0	61.43	
14 Jun 1973	610.0	66	1940	490.0	62.38	
21 Jun 1974	488.0	67	1930	490.0	63.33	
03 Jul 1975	460.0	68	1990	489.0	64.29	
03 Aug 1976	249.0	69	1974	488.0	65.24	
09 Jun 1977	290.0	70	1933	480.0	66.19	

25 Jun 1978	608.0	71	1946	469.0	67.14
01 Jul 1979	582.0	72	1911	469.0	68.10
02 Jul 1980	599.0	73	1908	465.0	69.05
04 Jun 1981	240.0	74	2004	461.0	70.00
02 Jul 1982	510.0	75	1975	460.0	70.95
28 Jun 1983	830.0	76	1916	458.0	71.90
02 Jul 1984	566.0	77	1937	455.0	72.86
10 Jun 1985	454.0	78	1985	454.0	73.81
20 Jun 1986	617.0	79	1988	440.0	74.76
10 Jun 1987	416.0	80	1955	436.0	75.71
22 Jun 1988	440.0	81	1920	436.0	76.67
30 Jul 1989	208.0	82	1993	428.0	77.62
12 Jun 1990	489.0	83	1991	428.0	78.57
18 Jun 1991	428.0	84	1939	425.0	79.52
21 May 1992	266.0	85	1987	416.0	80.48
18 Jun 1993	428.0	86	1968	406.0	81.43
02 Jun 1994	285.0	87	2008	393.0	82.38
21 Jun 1995	830.0	88	1954	374.0	83.33
22 Jun 1996	626.0	89	1925	374.0	84.29
07 Jun 1997	830.0	90	1913	366.0	85.24
02 Jul 1998	310.0	91	1972	360.0	86.19
23 Jun 1999	550.0	92	2000	341.0	87.14
09 Jun 2000	341.0	93	2001	330.0	88.10
08 Jun 2001	330.0	94	1963	328.0	89.05
03 Jun 2002	157.0	95	1910	324.0	90.00
01 Jun 2003	1,040.0	96	1998	310.0	90.95
10 Jun 2004	461.0	97	1964	299.0	91.90
25 Jun 2005	723.0	98	1977	290.0	92.86
09 Jul 2006	698.0	99	1994	285.0	93.81
30 Jun 2008	393.0	100	1992	266.0	94.76
27 Jun 2009	932.0	101	1966	251.0	95.71
07 Jun 2010	964.0	102	1976	249.0	96.67
13 Jul 2011	1,250.0	103	1981	240.0	97.62
07 Jul 2012	723.0	104	1989	208.0	98.57
13 Sep 2013	1,720.0	105	2002	157.0	99.52

* Outlier

<< Skew Weighting >>

Based on 105 events, mean-square error of station skew = 0.053
Mean-square error of regional skew = 0.12

<< Frequency Curve >>
BOULDERCK2013-ORODELL, CO.-FLO

Computed Curve FLOW, CFS	Expected Probability FLOW, CFS	Percent Chance Exceedance	Confidence Limits 0.05 FLOW, CFS	Confidence Limits 0.95 FLOW, CFS
2,340.3	2,433.3	0.2	2,844.8	1,996.7
2,019.0	2,079.6	0.5	2,412.4	1,745.6
1,788.0	1,830.0	1.0	2,107.1	1,562.4
1,566.4	1,594.0	2.0	1,819.1	1,384.2
1,285.5	1,299.6	5.0	1,462.1	1,153.8
1,079.3	1,086.8	10.0	1,207.0	980.8
874.3	877.5	20.0	960.8	804.0
586.1	586.1	50.0	632.6	543.0
394.5	393.1	80.0	429.1	358.9

321.3	319.1	90.0	353.5	287.4
271.4	268.5	95.0	302.1	238.8
198.1	193.8	99.0	226.2	168.6

<< Systematic Statistics >>
BOULDERCK2013-ORODELL, CO.-FLO

Log Transform: FLOW, CFS		Number of Events	
Mean	2.769	Historic Events	0
Standard Dev	0.205	High Outliers	0
Station Skew	0.036	Low Outliers	0
Regional Skew	0.459	Zero Events	0
Weighted Skew	0.165	Missing Events	0
Adopted Skew	0.036	Systematic Events	105

--- End of Preliminary Results ---

<< Low Outlier Test >>

Based on 105 events, 10 percent outlier test deviate K(N) = 3.033
Computed low outlier test value = 140.08

0 low outlier(s) identified below test value of 140.08

<< High Outlier Test >>

Based on 105 events, 10 percent outlier test deviate K(N) = 3.033
Computed high outlier test value = 2,466.49

1 high outlier(s) identified above input threshold of 2,331

```
* * * * * * * * * * * * * * * * * * * * * * * * * * * * * *
* Note - Collection of historical information and          *
*        comparison with similar data should be explored,  *
*        if not incorporated in this analysis.             *
* * * * * * * * * * * * * * * * * * * * * * * * * * * * * *
```

Statistics and frequency curve adjusted for 1 high outlier(s)

<< Systematic Statistics >>
BOULDERCK2013-ORODELL, CO.-FLO

Log Transform: FLOW, CFS		Number of Events	
Mean	2.769	Historic Events	0
Standard Dev	0.205	High Outliers	1
Station Skew	0.032	Low Outliers	0
Regional Skew	0.459	Zero Events	0
Weighted Skew	0.165	Missing Events	0

Adopted Skew	0.036	Systematic Events	105
		Historic Period	107

--- Final Results ---

<< Plotting Positions >>
BOULDERCK2013-ORODELL, CO.-FLO

Events Analyzed Day Mon Year	FLOW CFS	Ordered Events Rank	Water Year	FLOW CFS	Hazen Plot Pos
01 Jul 1907	840.0	1	1921	2,500.0*	0.47
17 Jun 1908	465.0	2	2013	1,720.0	1.41
20 Jun 1909	875.0	3	1919	1,300.0	2.36
28 Jul 1910	324.0	4	1947	1,290.0	3.32
13 Jun 1911	469.0	5	2011	1,250.0	4.27
30 Jul 1912	880.0	6	1969	1,220.0	5.22
02 Jun 1913	366.0	7	1951	1,220.0	6.17
28 May 1914	840.0	8	1965	1,190.0	7.13
29 Jun 1916	458.0	9	1952	1,180.0	8.08
25 Jun 1917	545.0	10	1941	1,120.0	9.03
22 Jun 1918	812.0	11	1935	1,060.0	9.98
03 Aug 1919	1,300.0	12	2003	1,040.0	10.94
10 Jun 1920	436.0	13	1957	1,010.0	11.89
06 Jun 1921	2,500.0	14	1923	983.0	12.84
16 Jun 1922	554.0	15	1949	965.0	13.79
15 Jun 1923	983.0	16	2010	964.0	14.75
14 Jun 1924	926.0	17	2009	932.0	15.70
24 Jun 1925	374.0	18	1926	929.0	16.65
08 Jun 1926	929.0	19	1924	926.0	17.60
11 Jun 1927	672.0	20	1912	880.0	18.56
02 Jun 1928	767.0	21	1909	875.0	19.51
22 Jun 1929	548.0	22	1958	855.0	20.46
14 Jun 1930	490.0	23	1914	840.0	21.41
28 May 1931	535.0	24	1907	840.0	22.37
26 Jun 1932	550.0	25	1997	830.0	23.32
12 Jun 1933	480.0	26	1995	830.0	24.27
31 May 1934	576.0	27	1983	830.0	25.22
15 Jun 1935	1,060.0	28	1918	812.0	26.18
19 Jun 1936	626.0	29	1938	802.0	27.13
25 Jun 1937	455.0	30	1942	793.0	28.08
22 Jun 1938	802.0	31	1953	786.0	29.03
31 May 1939	425.0	32	1960	776.0	29.99
21 Sep 1940	490.0	33	1928	767.0	30.94
21 Jun 1941	1,120.0	34	1971	753.0	31.89
12 Jun 1942	793.0	35	2012	723.0	32.85
30 Jun 1943	634.0	36	2005	723.0	33.80
22 Jun 1944	578.0	37	1948	712.0	34.75
26 Jun 1945	617.0	38	2006	698.0	35.70
18 Jun 1946	469.0	39	1927	672.0	36.66
21 Jun 1947	1,290.0	40	1970	634.0	37.61
07 Jun 1948	712.0	41	1961	634.0	38.56
06 Jun 1949	965.0	42	1943	634.0	39.51
16 Jun 1950	518.0	43	1996	626.0	40.47
21 Jun 1951	1,220.0	44	1936	626.0	41.42
07 Jun 1952	1,180.0	45	1986	617.0	42.37
11 Jun 1953	786.0	46	1945	617.0	43.32
20 May 1954	374.0	47	1973	610.0	44.28

26 Jun 1955	436.0	48	1978	608.0	45.23
23 May 1956	588.0	49	1959	602.0	46.18
29 Jun 1957	1,010.0	50	1980	599.0	47.13
06 Jun 1958	855.0	51	1967	594.0	48.09
21 Jun 1959	602.0	52	1956	588.0	49.04
16 Jun 1960	776.0	53	1979	582.0	49.99
20 Jun 1961	634.0	54	1944	578.0	50.94
01 Jul 1962	546.0	55	1934	576.0	51.90
16 Jun 1963	328.0	56	1984	566.0	52.85
29 Jun 1964	299.0	57	1922	554.0	53.80
24 Jul 1965	1,190.0	58	1999	550.0	54.75
26 May 1966	251.0	59	1932	550.0	55.71
23 Jun 1967	594.0	60	1929	548.0	56.66
23 Jun 1968	406.0	61	1962	546.0	57.61
07 May 1969	1,220.0	62	1917	545.0	58.56
25 May 1970	634.0	63	1931	535.0	59.52
19 Jun 1971	753.0	64	1950	518.0	60.47
06 Jun 1972	360.0	65	1982	510.0	61.42
14 Jun 1973	610.0	66	1940	490.0	62.37
21 Jun 1974	488.0	67	1930	490.0	63.33
03 Jul 1975	460.0	68	1990	489.0	64.28
03 Aug 1976	249.0	69	1974	488.0	65.23
09 Jun 1977	290.0	70	1933	480.0	66.18
25 Jun 1978	608.0	71	1946	469.0	67.14
01 Jul 1979	582.0	72	1911	469.0	68.09
02 Jul 1980	599.0	73	1908	465.0	69.04
04 Jun 1981	240.0	74	2004	461.0	69.99
02 Jul 1982	510.0	75	1975	460.0	70.95
28 Jun 1983	830.0	76	1916	458.0	71.90
02 Jul 1984	566.0	77	1937	455.0	72.85
10 Jun 1985	454.0	78	1985	454.0	73.80
20 Jun 1986	617.0	79	1988	440.0	74.76
10 Jun 1987	416.0	80	1955	436.0	75.71
22 Jun 1988	440.0	81	1920	436.0	76.66
30 Jul 1989	208.0	82	1993	428.0	77.62
12 Jun 1990	489.0	83	1991	428.0	78.57
18 Jun 1991	428.0	84	1939	425.0	79.52
21 May 1992	266.0	85	1987	416.0	80.47
18 Jun 1993	428.0	86	1968	406.0	81.43
02 Jun 1994	285.0	87	2008	393.0	82.38
21 Jun 1995	830.0	88	1954	374.0	83.33
22 Jun 1996	626.0	89	1925	374.0	84.28
07 Jun 1997	830.0	90	1913	366.0	85.24
02 Jul 1998	310.0	91	1972	360.0	86.19
23 Jun 1999	550.0	92	2000	341.0	87.14
09 Jun 2000	341.0	93	2001	330.0	88.09
08 Jun 2001	330.0	94	1963	328.0	89.05
03 Jun 2002	157.0	95	1910	324.0	90.00
01 Jun 2003	1,040.0	96	1998	310.0	90.95
10 Jun 2004	461.0	97	1964	299.0	91.90
25 Jun 2005	723.0	98	1977	290.0	92.86
09 Jul 2006	698.0	99	1994	285.0	93.81
30 Jun 2008	393.0	100	1992	266.0	94.76
27 Jun 2009	932.0	101	1966	251.0	95.71
07 Jun 2010	964.0	102	1976	249.0	96.67
13 Jul 2011	1,250.0	103	1981	240.0	97.62
07 Jul 2012	723.0	104	1989	208.0	98.57
13 Sep 2013	1,720.0	105	2002	157.0	99.52

Note: Plotting positions based on historic period (H) = 107
Number of historic events plus high outliers (Z) = 1
Weighting factor for systematic events (W) = 1.0192

* Outlier

<< Skew Weighting >>

Based on 107 events, mean-square error of station skew =	0.052
Mean-square error of regional skew =	0.12

<< Frequency Curve >>
BOULDERCK2013-ORODELL, CO.-FLO

Computed Curve FLOW, CFS	Expected Probability FLOW, CFS	Percent Chance Exceedance	Confidence Limits 0.05 FLOW, CFS	Confidence Limits 0.95 FLOW, CFS
2,332.2	2,424.5	0.2	2,833.7	1,990.4
2,013.1	2,073.3	0.5	2,404.6	1,741.0
1,783.7	1,825.4	1.0	2,101.4	1,559.0
1,563.3	1,590.8	2.0	1,815.1	1,381.7
1,283.7	1,297.8	5.0	1,459.8	1,152.4
1,078.3	1,085.8	10.0	1,205.7	979.9
873.9	877.0	20.0	960.3	803.6
586.1	586.1	50.0	632.6	543.0
394.6	393.2	80.0	429.1	359.0
321.3	319.2	90.0	353.5	287.4
271.4	268.5	95.0	302.1	238.8
198.0	193.7	99.0	226.1	168.5

<< Adjusted Statistics >>
BOULDERCK2013-ORODELL, CO.-FLO

Log Transform: FLOW, CFS		Number of Events	
Mean	2.769	Historic Events	0
Standard Dev	0.205	High Outliers	1
Station Skew	0.032	Low Outliers	0
Regional Skew	0.459	Zero Events	0
Weighted Skew	0.161	Missing Events	0
Adopted Skew	0.032	Systematic Events	105
		Historic Period	107

--- End of Analytical Frequency Curve ---

Bulletin 17B Frequency Analysis
08 Aug 2014 09:53 AM

USGS 06725500 / CDWR BOCOMIDCO

Middle Boulder Creek at Nederland Gage

--- Input Data ---

Analysis Name: BOCOMIDCO 17B
Description: 1908 to 2013

Data Set Name: BOCOMIDCO GAGE
DSS File Name: T:\481085-482330 CDOT Emergency Response Services\390_Design_Elements\Drainage\Hydrology\Phase 1\HEC-SSP\Boulder_Creek_Nederland\BOCOMIDCO\BOCOMIDCO.dss
DSS Pathname: ////01jan1900/IR-CENTURY//

Report File Name: T:\481085-482330 CDOT Emergency Response Services\390_Design_Elements\Drainage\Hydrology\Phase 1\HEC-SSP\Boulder_Creek_Nederland\BOCOMIDCO\Bulletin17bResults\BOCOMIDCO_17B\BOCOMIDCO_17B.rpt
XML File Name: T:\481085-482330 CDOT Emergency Response Services\390_Design_Elements\Drainage\Hydrology\Phase 1\HEC-SSP\Boulder_Creek_Nederland\BOCOMIDCO\Bulletin17bResults\BOCOMIDCO_17B\BOCOMIDCO_17B.xml

Start Date:
End Date:

Skew Option: Use Station Skew
Regional Skew: -0.501
Regional Skew MSE: 0.12

Plotting Position Type: Weibull

Upper Confidence Level: 0.05
Lower Confidence Level: 0.95

Display ordinate values using 3 digits in fraction part of value

--- End of Input Data ---

<< Low Outlier Test >>

Based on 105 events, 10 percent outlier test deviate K(N) = 3.033
Computed low outlier test value = 140.9028

0 low outlier(s) identified below test value of 140.9028

<< High Outlier Test >>

Based on 105 events, 10 percent outlier test deviate K(N) = 3.033

Computed high outlier test value = 1,144.1977

0 high outlier(s) identified above test value of 1,144.1977

--- Final Results ---

<< Plotting Positions >>
BOCOMIDCO GAGE

Events Analyzed			Ordered Events			
	FLOW			Water	FLOW	Weibull
Day Mon Year	cfs		Rank	Year	cfs	Plot Pos
12 Jun 1908	262.000		1	1914	811.000	0.94
19 Jun 1909	526.000		2	1951	800.000	1.89
03 Jun 1910	220.000		3	1957	745.000	2.83
27 Jun 1912	434.000		4	1953	730.000	3.77
31 May 1913	206.000		5	2011	697.000	4.72
02 Jun 1914	811.000		6	1949	674.000	5.66
20 Jun 1915	363.000		7	2003	662.000	6.60
19 Jun 1916	253.000		8	1918	651.000	7.55
17 Jun 1917	448.000		9	1952	648.000	8.49
14 Jun 1918	651.000		10	2010	642.000	9.43
28 May 1919	244.000		11	1965	640.000	10.38
08 Jun 1920	332.000		12	1921	624.000	11.32
15 Jun 1921	624.000		13	1958	622.000	12.26
14 Jun 1922	334.000		14	1995	593.000	13.21
16 Jun 1923	402.000		15	1997	582.000	14.15
14 Jun 1924	505.300		16	1983	579.000	15.09
29 May 1925	153.000		17	1972	550.000	16.04
06 Jun 1926	526.000		18	1991	540.000	16.98
14 Jun 1927	268.000		19	2009	535.000	17.92
25 May 1928	302.000		20	1956	528.000	18.87
08 Jun 1929	268.000		21	1935	528.000	19.81
13 Jun 1930	276.000		22	1926	526.000	20.75
07 Jun 1931	312.000		23	1909	526.000	21.70
28 Jun 1932	282.000		24	1978	507.000	22.64
21 Jun 1933	411.000		25	1924	505.300	23.58
11 May 1934	228.000		26	1980	504.000	24.53
14 Jun 1935	528.000		27	1971	503.000	25.47
31 May 1936	348.000		28	1996	501.000	26.42
26 Jun 1937	321.000		29	1999	498.000	27.36
22 Jun 1938	398.000		30	1985	496.000	28.30
01 Jun 1939	288.000		31	1975	496.000	29.25
02 Jun 1940	270.000		32	1945	491.000	30.19
13 May 1941	398.000		33	1984	490.000	31.13
07 Jun 1942	376.000		34	1959	480.000	32.08
02 Jun 1943	332.000		35	1973	478.000	33.02
10 Jun 1944	365.000		36	1990	471.000	33.96
25 Jun 1945	491.000		37	1962	470.000	34.91
17 Jun 1946	346.000		38	2013	469.000	35.85
21 Jun 1947	427.000		39	1977	469.000	36.79
08 Jun 1948	310.000		40	1981	463.000	37.74

13 Jun 1949	674.000	41	1960	460.000	38.68	
14 Jun 1950	414.000	42	2005	452.000	39.62	
18 Jun 1951	800.000	43	1969	448.000	40.57	
10 Jun 1952	648.000	44	1917	448.000	41.51	
13 Jun 1953	730.000	45	1970	445.000	42.45	
20 May 1954	208.000	46	2000	436.000	43.40	
13 Jun 1955	270.000	47	1974	434.000	44.34	
23 May 1956	528.000	48	1912	434.000	45.28	
29 Jun 1957	745.000	49	1947	427.000	46.23	
23 May 1958	622.000	50	1988	420.000	47.17	
14 Jun 1959	480.000	51	1986	415.000	48.11	
17 Jun 1960	460.000	52	1950	414.000	49.06	
02 Jun 1961	412.000	53	1961	412.000	50.00	
30 Jun 1962	470.000	54	1933	411.000	50.94	
16 Jun 1963	264.000	55	1982	406.000	51.89	
21 May 1964	292.000	56	1923	402.000	52.83	
24 Jul 1965	640.000	57	1941	398.000	53.77	
31 May 1966	158.000	58	1938	398.000	54.72	
20 Jun 1967	392.000	59	1979	393.000	55.66	
21 Jun 1968	392.000	60	1968	392.000	56.60	
30 May 1969	448.000	61	1967	392.000	57.55	
25 Jun 1970	445.000	62	2006	388.000	58.49	
19 Jun 1971	503.000	63	2008	385.000	59.43	
06 Jun 1972	550.000	64	1994	385.000	60.38	
10 Jun 1973	478.000	65	1942	376.000	61.32	
18 Jun 1974	434.000	66	1993	375.000	62.26	
08 Jun 1975	496.000	67	1944	365.000	63.21	
09 Jun 1976	357.000	68	1915	363.000	64.15	
06 Jun 1977	469.000	69	1998	357.000	65.09	
15 Jun 1978	507.000	70	1976	357.000	66.04	
13 Jun 1979	393.000	71	2007	351.000	66.98	
11 Jun 1980	504.000	72	1936	348.000	67.92	
09 Jun 1981	463.000	73	1946	346.000	68.87	
27 Jun 1982	406.000	74	2004	344.000	69.81	
10 Jul 1983	579.000	75	1987	341.000	70.75	
25 May 1984	490.000	76	1922	334.000	71.70	
08 Jun 1985	496.000	77	1943	332.000	72.64	
06 Jun 1986	415.000	78	1920	332.000	73.58	
09 Jun 1987	341.000	79	2001	325.000	74.53	
04 Jun 1988	420.000	80	1937	321.000	75.47	
11 Jun 1989	272.000	81	1931	312.000	76.42	
10 Jun 1990	471.000	82	1948	310.000	77.36	
01 Jun 1991	540.000	83	1928	302.000	78.30	
26 May 1992	269.000	84	1964	292.000	79.25	
18 Jun 1993	375.000	85	1939	288.000	80.19	
01 Jun 1994	385.000	86	1932	282.000	81.13	
15 Jun 1995	593.000	87	1930	276.000	82.08	
22 Jun 1996	501.000	88	1989	272.000	83.02	
07 Jun 1997	582.000	89	1955	270.000	83.96	
03 Jun 1998	357.000	90	1940	270.000	84.91	
23 Jun 1999	498.000	91	1992	269.000	85.85	
30 May 2000	436.000	92	1929	268.000	86.79	
15 May 2001	325.000	93	1927	268.000	87.74	
31 May 2002	222.000	94	1963	264.000	88.68	
30 May 2003	662.000	95	1908	262.000	89.62	
09 Jun 2004	344.000	96	1916	253.000	90.57	

23 May 2005	452.000	97	1919	244.000	91.51
06 Jun 2006	388.000	98	2012	234.000	92.45
20 May 2007	351.000	99	1934	228.000	93.40
03 Jun 2008	385.000	100	2002	222.000	94.34
26 Jun 2009	535.000	101	1910	220.000	95.28
07 Jun 2010	642.000	102	1954	208.000	96.23
12 Jul 2011	697.000	103	1913	206.000	97.17
06 Jul 2012	234.000	104	1966	158.000	98.11
11 Jun 2013	469.000	105	1925	153.000	99.06

<< Skew Weighting >>

Based on 105 events, mean-square error of station skew = 0.068
Mean-square error of regional skew = 0.12

<< Frequency Curve >>
BOCOMIDCO GAGE

Computed Curve FLOW, cfs	Expected Probability FLOW, cfs	Percent Chance Exceedance	Confidence Limits 0.05 FLOW, cfs	Confidence Limits 0.95 FLOW, cfs
937.488	954.901	0.2	1,061.172	846.939
871.826	884.601	0.5	978.820	792.559
819.140	828.943	1.0	913.378	748.561
763.261	770.408	2.0	844.645	701.496
683.033	687.338	5.0	747.322	633.077
615.635	618.161	10.0	667.002	574.661
539.222	540.439	20.0	577.889	507.068
409.726	409.726	50.0	433.369	387.579
302.528	301.653	80.0	321.537	282.527
255.153	253.680	90.0	273.806	234.946
220.300	218.240	95.0	238.911	199.949
164.683	161.211	99.0	182.984	144.771

<< Systematic Statistics >>
BOCOMIDCO GAGE

Log Transform: FLOW, cfs		Number of Events	
Mean	2.604	Historic Events	0
Standard Dev	0.150	High Outliers	0
Station Skew	-0.352	Low Outliers	0
Regional Skew	-0.501	Zero Events	0
Weighted Skew	-0.406	Missing Events	0
Adopted Skew	-0.352	Systematic Events	105

--- End of Analytical Frequency Curve ---

Appendix D
Project Correspondence and Response to Review Comments

Meeting Minutes
Response to CDOT and CWCB Review Comments (April 2014)
Response to Public Review Comments (August 2014)

Appendix D
Project Correspondence and Response to Review Comments

Meeting Minutes

Hydrology Weekly Meeting

ATTENDEES:

Keith Sheaffer
Steve Griffin
Steven Humphrey
Holly Linderholm
Cory Hooper
Heidi Schram
Will Carrier
Collin Haggerty
Bob Jarrett (PH)
John Hunt
Kevin Houck
Jim Wulliman
Derek Rapp

FROM: ICC OPS

DATE: January 9, 2014

The following is a summary of the Hydrology Weekly Meeting. Decisions are highlighted and are summarized in a table at the end of this document. Action Items are shown in bold type and are summarized in a table at the end of this document.

Preliminary Findings

The Consultant team memos regarding the preliminary findings are on track and will be delivered tomorrow Jan. 10th. Kevin Houck will combine into one memo presenting the preliminary findings of the Hydrology Team.

Current Progress and Findings

The Consultant teams are progressing well and have identified their additional needs recorded below.

Some questions that resulted from the discussion on progress are below:

- Should URS combine the gauge data of the two gauges from the South Platte in order to have a larger data set? Is that practice justifiable?
- How to handle skew and outliers? Should be answered by John Hunt and Bob Jarrett
- The Barker reservoir used as a volume calibration?

Steve Griffin has an unpublished HEC-HMS model that can be used and referenced in the memo.

It was determined that Bob has confidence in NRCS numbers and the consultants can include them in their analysis where they do not have numbers from Jarrett.

Kevin Houck brought up the importance of how the memo is messaged in order to reduce misinterpretation.

There was discussion on multiple parameters of the models. Specifics will not be provided here unless the Consultant teams would like to include any specifics.

Additional Data Needs

The Lake Estes dam release information has been requested from the Bureau of Reclamation. We are currently waiting to hear if we need to request the information through a FOIA. Keith Sheaffer will also inquire about the information along with the information on the Button Rock Dam with Jason Smith.

URS cannot complete their evaluation until Bob Jarrett is able to obtain the S. Platte data.

Still need to get the remainder of the rainfall run off data from AWA.

CH2MHill still needs numbers for Boulder Creek near Orodell.

Bob wants authorization to capture the flow estimate that the Jacobs team requested from the site south of Drake. Until the data is collected we will report a range for the findings. At this time Jacobs findings are reporting the additive value.

Additional information needed from Bob Jarrett:

- Points downs stream of critical confluence in the next 4 to 5 days downstream Drake on Big Thompson
- Lyons site – full survey .5 mile length to get longer reach length
- John Hunt will provide LIDAR to Bob
- Little Thompson natural flow estimate to use in the calibration of the model
- Atkins has comparative pre and post aerials (can ICC get these also)
- Bob plans to go out to the S. Platte next week and get data from the field offices the week after that.
- Kevin Houck would like to know whether he should use Jarrett or NRCS (Yokum's) numbers.
- The team would like to get Jarrett's opinion on using gauge analysis.

Project Schedule

Next meeting: Jan.16th 1 to 3pm

We will look at the working Models (not calibrated) in order to get questions answered and consistencies addressed.

S. Platte Extended Scope

Steven Humphrey explained the desire of evaluating the entire South Platte watershed all the way to the Nebraska border that came out of the Staff Bridge Meeting. The Consultants have been asked to provide a draft scope, schedule and cost for the additional effort to complete this additional evaluation. Preliminary limits of the scope are from Platteville to the Nebraska border. The proposal provided by the consultants should be submitted by COB on Friday, January 17th.

Discussion about the additional request resulted in using gauge data from USGS for the additional analysis.

For the additional effort the IC is interested in of the South Platte from Platteville to Nebraska there was discussion on the limits and structure of scope to be in the proposal. It was decided that it will most likely be a gauge study. What is the use of this analysis? Implications of use will likely be used for hydrology design. Will need to limit the scope to just the S. Platte not including any tributaries and a gauge analysis and a tributary chase for calcs gauge analysis

Action Item List

Action Item	Due	By
GIS Map Exhibit to accompany the Memo Deliverable		ICC – Ops Desk
Share all reports with the three consultant teams.		ICC- Ops Desk

Hydrology Weekly Meeting

ATTENDEES:

Keith Sheaffer
Steve Griffin
Steven Humphrey (PH)
Holly Linderholm
Cory Hooper (PH)
Heidi Schram
Will Carrier
Mike Tilko
Bob Jarrett
Morgan Lynch
Kevin Houck
Jim Wulliman
Derek Rapp
Gina DeRosa
Jeff Wulliman (PH)
Spence Kelly (PH)

FROM: ICC OPS

DATE: January 16, 2014

The following is a summary of the Hydrology Weekly Meeting. Decisions are highlighted and are summarized in a table at the end of this document. Action Items are shown in bold type and are summarized in a table at the end of this document.

Preliminary Findings

To finish up the preliminary findings memo these are the additional items needed:

- Bob to get the remaining East sites and visit the field offices to obtain data from the records
  - Ft. Lupton and Kersey are priority sites at US 85, US 34A and US 34D.
  - If Bob needs a survey team then he should contact Will Carrier to coordinate.
- Lake Estes Dam information is needed immediately, Holly to contact Kara at the Bureau of Reclamation to get an ETA of the information.

Kevin Houck and Bob Jarrett discussed presenting the results in a range or a specific number. It was decided that specific numbers will be reported with a note regarding the % uncertainty. Jim Wulliman added that since we reference the NRCS report within our data that we should know what their "fair" rating is so that we include their % uncertainty within ours.

Steve Griffin brought up the concern about timing of different audiences and how the memo is messaged. Right now gearing toward the upward audience and not the local agencies etc…. the dissemination of information should be a phased approach to ensure we keep our partners at the local agencies involved.

Kevin Houck would like to be able to present the preliminary findings to the Colorado Conservation Board on Tuesday the 28th and then to Water Congress that Thursday. Will the results be review and approved to be presented and does the team consider that appropriate timing of making the information public.

USGS is also analyzing the Storm Event, we should recognize their efforts and be aware of the timing of their release of information incase their findings are different than ours.

Bob and Kevin will get together about the areas in the memo where we are missing regulatory information and decide what to present in the Memo.

The team would like to have the memo and exhibits finalized by next Friday the 24th.

Current Progress and Findings

Models:

Bob Jarret asked that if the consultants can't get the model numbers close to his to let him know immediately so they can evaluate the model together. Still need the non-dam break/normal flow numbers from Bob Jarrett as well as confirmation of the Little Thompson River. Bob requested the max rainfall per hour in order to help with his confirmation.

As the teams calibrate their models there needs to be consistency as well as decisions on what the group is comfortable with and what/how they will defend their assumptions as they calibrate their models and find they have to use values outside the commonly accepted ranges.

It was decided to use the AMC 2 throughout the models and to not adjust it for the different time frames of the storm.

Need to be consistent through the analysis on all teams, URS will run a HEC HMS model also to confirm since they are currently using a gauge analysis for the S. Platte.

URS still needs the rainfall data from AWA.

Project Schedule

The next meeting will be held Thursday the 23rd from 1 to 3 pm the meeting after that will be Feb. 3rd or the 4th.

Action Item List

Action Item	Due	By
Get John Hunt's opinion on how to handle outliers and skew coefficients		Via email

Hydrology Weekly Meeting

ATTENDEES:

Keith Sheaffer
Steve Griffin
Steven Humphrey
Holly Linderholm
Heidi Schram
Will Carrier
John Hunt
Morgan Lynch
Kevin Houck
Jim Wulliman
Derek Rapp
Collin Haggerty (PH)
Cory Hooper (PH)

FROM: ICC OPS

DATE: January 23, 2014

The following is a summary of the Hydrology Weekly Meeting. Decisions are highlighted and are summarized in a table at the end of this document. Action Items are shown in bold type and are summarized in a table at the end of this document.

Peak Flow Estimate Memo

The draft memo was reviewed and approved by the IC, Johnny Olson. The ICC is comfortable with Kevin Houck of CWCB presenting the findings to his Board as well as the Water Congress the week of Jan. 27th.

This team would like to look at the results of the USGS study. Bob Kimbrough can provide the information to the ICC. We need to make sure to communicate with Josh Kiel about getting this info.

CWCB does not have a preference on how the memo is distributed to other agencies. It was decided that an effective method of distribution could be through email.

Review Modeling Efforts

Continue to review progress of the consultant's models and discuss consistencies to the teams approach.

Specific details on the modeling:

St. Vrain – the sensitivity of different parameters was analyzed.

- The model is mainly dependent on the curve number.
    - The range is from the mid to low 40's up to 60. The resulting average curve number is 56 between C & D

The consultants would like to have Bob Jarrett review the outcomes of the models to see if he is comfortable with the output.

Ask Bob about the 14 cfs/square mile discharge

James creek – the team has not been able to calibrate the model to some of the discharge outliers.

The team decided to have the rainfall consistent within basins but can change between basins. With this approach it was suggested that an analysis be done if there are differences between basins.

Ayers will have the rainfall runoff match flood frequency model. Are these just for analysis or should the models be calibrated to them?

ICC Ops to contact Bureau of Reclamation about the additional Lake Estes Dam information needed. The policy of the dam storage and handling of attenuation play into the calibration of the model

The model of Lefthand does not match the peak flow numbers at the top or bottom but does match in the middle.

There was concern expressed that the emergency reconstruction of roadways effected the high water marks and consequently the calculations of peak flows. Bob Jarrett was not present at the meeting but it was discussed that his methods take those variables into consideration and account for them in numerous ways.

The consultant teams will continue to collaborate about the models through email. **The ICC Ops will forward on the additional information provided by CH2MHill.**

Data Needs

The team still needs to know what to do about the skew coefficients and handling of outliers. Ayers suggested doing a skew analysis to provide new regional skew coefficients for this analysis.

There was discussion about using Bulletin 17B, the current standard, or the possibility of using the new “expected moments” approach that may be accepted soon by FEMA. There may be an opportunity to use a combination of the two approaches. The new approach includes additional outlier threshold equations. Kevin Houck will check with FEMA to see if they are planning on accepting the Expected Moments approach.

Need additional natural flows from Bob Jarrett.

URS is running a CUHP model on Coal Creek Canyon, they will also run a HEC-HMS to compare. URS still needs S. Platte information and bridge plans.

Project Schedule

The next meeting is scheduled for Monday February 3rd from 1 to 3 pm at the ICC.

Decision Register

Decision	Made By
CWCB approved to present findings to the Board and Water Congress	ICC- Johnny Olson
Email distribution of the Memo	Hydrology Team
Keep rainfall consistent within the sub basins but can vary between basins	Hydrology Team

Action Item List

Action Item	Due	By
Forward the information from CH2MHill to team		ICC Ops

Hydrology Weekly Meeting

ATTENDEES:

Steve Griffin
Steven Humphrey
Holly Linderholm
Heidi Schram
Will Carrier
Gina DeRosa
John Hunt
Morgan Lynch
Doug Stewart
John Hunt
Kevin Houck
Jim Wulliman
Naren Tayal (PH)
Cory Hooper (PH)

FROM: ICC OPS

DATE: February 3, 2014

The following is a summary of the Hydrology Weekly Meeting. Decisions are highlighted and are summarized in a table at the end of this document. Action Items are shown in bold type and are summarized in a table at the end of this document.

Peak Flow Estimate Memo

It seems that the memo was distributed in some fashion, now that it is public the team can provide to anyone who is asking for it. **ICC Ops will provide the most current version for the team to distribute.**

It is important to ensure that the local agencies understand that this is just the start of these efforts. CDOT will be collaborating with them throughout the rest of the process. This effort was completed to have a starting point for the future efforts that the Region and Local Agencies will complete in the future.

Lyons is particularly interested in the memo and the hydrology efforts, ICC Ops should ensure they received the memo and should start coordinating with them in these efforts.

The Drake numbers are a concern, there are no places that allow for attenuation so how is it possible that the flow is smaller downstream. Needs further analysis. At this time there is no way to explain these differences.

FEMA is starting to work on St. Vrain and Lefthand and looking at structure flow rates as they pertain to the Boulder County Structures (Apple Valley Road, Longmont Dam Road). There is work currently in these locations that CFL is performing. The results of FEMAs efforts will not impact the current work being completed. Naren Tayal from FEMA will attend these meetings in order to coordinate the two efforts.

Review Modeling Efforts

<u>Jacobs</u>

The best comparison was the discharge/max rainfall by square mile and the best fit curve number was 50.

Ran a comparison to some of the CH2MHill stuff and the results were pretty consistent.

The operation of the Lake Estes Dam is to pass the flows through so surface water doesn't rise or fall that much. It was asked if the dam operations waited until the water arrived in the reservoir or if they opened it up in anticipation of the higher flows.

So if the models won't match Jarrett's numbers should those values be abandoned?

All information related to this evaluation is in the email Jim Wulliman sent out.

CH2MHill

Orodell gauge and Bob Jarrett's peak flow estimate were very close, this time they calibrated the model to Jarrett's numbers.

They reduced the peaking coefficient to 0.1 and the generally accepted value is 0.4. If the parameter is changed back to 0.4 then the flows would raise but still not above the NOAA.

Barker Reservoir was completed in 1910 approx.10 years after data started being collected; so can be considered natural flows since the dam has been in place with similar operations for more than 50 years.

Is this how the team wants to treat the reservoir in this analysis? There needs to be a policy decision made.

An option would be to analyze when the peaks occurred and how that relates to the storage in the reservoir. Morgan will look into if the reservoir has any surface level or discharge information.

Andersons updated the 77 FIS model in 2012.

It was confirmed that the routing method being used is the Muskingum-Cunge.

Are we at the point on this that there needs to be a meeting with Anderson, Boulder and FEMA to discuss appropriate approach?

CH2MHill will re-run the model with the current parameters but with a full reservoir to further the analysis.

The email that Houck provided to the team expressed that there is presence of regulatory rates for the Little Thompson. However, the location that is referenced in the email is actually 10 miles downstream so the hydrology is different.

The Little Thompson model is calibrated to Bob Jarrett's natural flows only at this time.

Regional skew analysis efforts need to be completed in order to finish this analysis. John Hunt with Ayers will get costs to ICC Ops could come from remaining CH budget or ICC. The immediate priority is the new regional skew for mountain regions in order to apply to Orodell

URS

For Coal Creek Canyon the infiltration rate change is unjustifiable. In order to match flows had to increase the infiltration rate at first than decrease it later in the model to reach the design points.

What direction would CDOT want to go with this watershed? The URS recommendation would be to update the watershed to the NOAA Atlas 14.

Look at the Jefferson County recommendation/replacement memo and get the hydrology teams thoughts.

Deliverables

Provide recommendations of changing/updating the regulatory rate s to CWCB and CDOT to review by the end of Feb.

Format should follow closely to a FEMA submittal, CDOT and CWCB will coordinate on what they would like to see and get back to the Consultants.

Project Schedule

The next meeting is scheduled for Monday February 10th from 1 to 3 pm at the ICC.

Action Item List

Action Item	Due	By
Find out who F&A has distributed the memo to.		ICC Ops
Send a copy of the Phase I memo to Naren with FEMA		ICC Ops
URS needs S. Platte from Bob		Bob Jarrett
Find out if there are any videos at US 85.		Steve Griffin
Boulder Creek: Comparison with and without a full reservoir with the current parameters		CH2MHill
Big Thompson: compare sept. rainfall to NOAA rainfall, what affect it has, good with Lake Estes approach		Jacobs
St. Vrain: Updated flood frequency from Ayers (for Left hand also)		Jacobs
Coal Creek: Additional analysis just for fun, send data to Jacobs to add to the comparison analysis		URS
Regional skews (approach to be emailed and approved by CWCB and CDOT, hopefully have preliminary skews by Friday)		Ayers
Jacobs and CH2MHill to run aerial reduction		Jacobs and CH2Mhill
Format of recommendations on regulatory rates		CDOT and CWCB

Hydrology Weekly Meeting

ATTENDEES:

Steve Griffin
Steven Humphrey
Holly Linderholm
Heidi Schram
Will Carrier (PH)
Gina DeRosa (PH)
John Hunt
James Hitchenson
Morgan Lynch
Doug Stewart
John Hunt
Kevin Houck
Jim Wulliman
Naren Tayal
Cory Hooper
Derek Rapp
Bob Jarrett (PH)
Ed Tomlinson (PH)

FROM: ICC OPS

DATE: February 10, 2014

The following is a summary of the Hydrology Weekly Meeting. Decisions are highlighted and are summarized in a table at the end of this document. Action Items are shown in bold type and are summarized in a table at the end of this document.

US 36 CFL Project

The meeting began with the request of the peak flow numbers this team would like CFL to use in the existing hydrology model to make sure there are no fatal flaws in the current design. 3,400cfs will be used for the Little Thompson and the Jacobs team will need until COB to provide the number to be used for the N. St. Vrain.

FEMA

FEMA requested shape files for the CDOT structures, these can be provided by Staff Bridge.

FEMA will be continuing to participate in these meetings to ensure that CDOT and FEMA are aware of the efforts by both agencies.

Feedback and Historical Information

Kevin Houck then asked to add an agenda item. He would like Bob Jarrett to comment on the current feedback on memo, and specifically speak to the questions regarding the variance of flows on Boulder Creek.

It was mentioned that the hydrologic evaluations done back in ‘76 and ‘90 caused diverging opinion’s especially when it was found that on average the insurance floodplain was 60% larger than the analyzed gage’s 100yr data.

The resulting discussion concluded with an emphasis that this team is a technical group and to stay committed to what we are doing here and there will be other teams who will consider the other ramifications of this effort.

Bob Jarrett suggests that in order to support the technical expertise behind the analysis the team should do the best they can to quantify the uncertainty in the analysis. There was an expressed interest in what feedback has been received on the phase I memo.

The main feedback has been the question of how the flows decrease from 30,000 cfs to 15,000 cfs on the Big Thompson downstream of Drake? Along that stretch there isn't much opportunity for attenuation so hard to explain the large drop in flows. Bob Jarrett indicated that this was a location where he had used an additive method since he was unable to find a good location to collect data, he will try again to get data from this area. The only place where there may be some attenuation would be around Cedar Cove but not enough to justify the significant drop in estimates peak flows.

This team needs to be prepared to justify their assumptions and estimates especially since the USGS isn't currently sharing any information and their analysis is scheduled to come out shortly.

With additional information the Big Thompson below Drake data may change after further analysis.

The debris bulking and dam failures could potentially account for some of the attenuation as well as sediment. Obtaining the timing of the wave through Glen Haven would be beneficial in the analysis of this area.

Bob Jarrett would like the information provided on the Lake Estes dam releases. Bob is interested to see if there is any evidence of dam failures along Fish creek, would like any aerials that CDOT or the Consultants teams may have of this area.

The St. Vrain information at Lyons and I-25 were also questioned. Steve Griffin collected data at I-25 and with his available resources along with his conservative method to keep the resulting cfs numbers high; it is difficult to provide a rebuttal without more information regarding the USGS' "significantly higher" findings.

Team Efforts

<u>Gauge Analysis:</u>

Ayers has begun to developed regional skew estimate have not yet finalized, An example from the analysis resulted in a weighted average by drainage area of 0.46 which would have been -0.2 from 17B Map. Using the new skew analysis the Boulder Creek watershed would result in "100-year flood" cfs to between the "100 and 50-year flood"

For the St. Vrain the 100-year would be lower without proper use of outliers. Outliers get a much lower weighting.

Ayers analysis is complete however, they will confirm that Bob Jarrett supports the results and will then finish up and finalize. The final analysis will be provided in a memo and be distributed to the team. URS will send Ayers their Coal Creek gage analysis to include in the current analysis.

<u>Jacobs Modeling:</u>

The team changed the modeling approach to look at an adjusted 24-hr period of only the max rainfall. The team expressed concern with how the curve number method oversimplifies the model for timing and infiltration.

The timing of this event is what is causing the issues in the modeling efforts. What is the right way to proceed and which approach is this team going to move forward with as the "correct" approach? It was discussed and decided to move forward with the curve number approach and raise back up with a logical approach to get back to gages. Take the 24-hr max range and compare to the NOAA. (Jacobs team will send an example: of this in an email to the team). A memo will be generated to document the approach, and test in an alternate modeling approach such as Green-Ampt Infiltration Modeling

Next steps:

Complete the gage analysis, finalize the flood frequency of the following locations:

a. Big Thompson at the mouth Canyon
b. Big Thompson in Loveland
c. Big T confluence with Buckhorn Creek
d. North Fork of the Big Thompson
e. St. Vrain below the confluence
f. Boulder Creek at Orodell

Regional analysis is not applicable to the S. Platte, Ayers only did the mountain region at this time but will complete the analysis of the plains region if asked and have a contractual vehicle to use to do the work.

Additional Needs

URS needs As-builts for S. Platte River Bridges.

Steve Griffin has reports that Bob Jarrett requested if he still wants them.

The teams will communicate by email until the next meeting and send along results of the continued analysis.

ICC/CWCB needs to provide the Consultants expectations of the deliverable for Phase II. The audience for this will be two-fold, technical and a brief easy to understand executive summary that the general public can understand.

It was decided the meeting with City of Boulder should be postponed until the hydrology efforts are to a point that they can contribute value to the meeting.

Project Schedule

The next meeting is scheduled for Tuesday, February 25th from 1 to 4 pm at the ICC.

Hydrology Weekly Meeting

ATTENDEES:

Steve Griffin
Steven Humphrey
Holly Linderholm
Heidi Schram
Will Carrier
Gina DeRosa
Kevin Houck
Jim Wulliman
Naren Tayal
Doug Stewart
Cory Hooper
Derek Rapp

FROM: ICC OPS

DATE: March 11, 2014

The following is a summary of the Hydrology Weekly Meeting. Decisions are highlighted and are summarized in a table at the end of this document. Action Items are shown in bold type and are summarized in a table at the end of this document.

General

Concern about the USGS numbers that were presented at the CASFM event. Kevin Houck will schedule a meeting with Bob Jarrett and USGS to discuss the differing findings.

From the publicity recently it is even more important now that this team provides the same messaging of the information.

Steve Yokum would like the Big Thompson information, Steve Griffin to provide this to him.

For the stakeholder meetings regarding each of the watersheds, **the consultants will send their availability for the month of April and first week of May**. **The ICC will coordinate the meetings per watershed.** It is anticipated that these meetings will consist of a short presentation of our findings and model results in order to engage the coalitions in this effort as we now have a starting point.

Review of Reporting Efforts

<u>CH2M Hill</u>

It was confirmed that Boulder Creek will move forward with the 24hr storm with an AMC III for reporting instead of the 48hr storm.

A meeting with Boulder County and the City of Boulder will be scheduled hopefully before the 10th. This meeting is critical in moving forward as this watershed information needs to be incorporated into the remaining watersheds. This team would like to know where the regulatory rates are coming from.

<u>Jacobs</u>

Drafts will be ready for the next meeting.

URS

Drafts will be ready and the **team will check into the rumored 2006 Army Corps of Engineering model of the S. Platte Watershed**.

Final Draft for the next Meeting (3/21)

The final drafts of the reports will be provided in an electronic form with the modeling on a CD/DVD as well as 5 hard copies.

After submission, there will be a designated review and comment time frame. **The ICC OPS will combine and distribute all comments for the consultants to address.**

Ayers' contribution to the reports is still needed, ICC Ops to request from John Hunt.

The description of the process on how the presented results were reached only needs to be expressed qualitatively within the text.

Additional Hydrologic Services

The local watershed meetings will be added to the additional services scope.

AWA rainfall information will be used and requested. URS needs to indicate if AWA will need additional budget or time on their contract and include that in their task order amendment. The consultants should provide AWA with the additional sites they will want for the extended scope and if they will be providing additional flood frequency analysis. Along with this it needs to confirmed or denied that Ayers should complete the regional skew analysis for the plains region and if there needs to be contractual modifications associated with that.

As the teams start these additional efforts the **ICC will check for available LiDAR.**

Schedule

The next meeting is scheduled for 8 AM to 11 AM on March 21st at the Downtown Denver Jacobs Office.

Action Item List

Action Item	Due	By
Availability to meet with coalitions for the month of April and first week of May		Consultant Teams
Coordinate the meetings per watershed.		ICC OPS
2006 Army Corps of Engineering model of the S. Platte Watershed.		URS
Combine and distribute all comments for the consultants to address.		ICC OPS
Ayers' contribution to the draft reports.		ICC OPS
Additional available LiDAR		ICC OPS

Hydrology Weekly Meeting

ATTENDEES:

Steve Griffin
Steven Humphrey
Holly Linderholm
Heidi Schram
Will Carrier
Gina DeRosa
Kevin Houck
Jim Wulliman
Naren Tayal
Doug Stewart
Derek Rapp
John Hunt (PH)

FROM: ICC OPS

DATE: March 21, 2014

The following is a summary of the Hydrology Weekly Meeting. Decisions are highlighted and are summarized in a table at the end of this document. Action Items are shown in bold type and are summarized in a table at the end of this document.

General

The ICC leadership team currently does not share the team's perspective that teaming with the coalitions and bringing them into this effort now as valuable. This team agrees that it is worth an additional meeting with ICC leadership to convey the long term benefits of teaming with the local agencies and coalitions on the revised hydrology in the flood effected areas. **Steve Griffin, Kevin Houck and Steve Humphrey will meet with the ICC leadership the first week of April.**

The anticipated revisions to the Phase I memo can take place now. There will be a meeting with USGS regarding the discrepancy in reported peak flows on the St. Vrain Friday, March 28th at the Muller office in Lakewood.

The ICC DAR reports that are applicable to the studied watersheds will need a brief write up regarding the hydrology. **ICC OPS will send the template out to the consultants in order to facilitate the brief write up.**

Final Draft Review of Reporting Efforts

The consultant teams provided the draft reports in electronic and hard copy format.

Steve Griffin will provide a review comment template that will be used for the review process that will conclude Friday March 28th. At that time **ICC OPS will compile all the comments and distribute to the consultant teams.**

AWA Gridded Rainfall Data

Kevin Houck will follow up with Bill McCormick on what information is being requested.

Additional Hydrologic Services

Everything is in order to move forward with the amendments to the existing task order for the additional services. **Once URS receives the additional information from AWA they will need to resubmit their Task Order #2 Amendment.**

ICC Ops checked for new processed LiDAR of the extended scope areas but there hasn't been anything new posted. In order to request what is needed for this effort the **consultant teams should provide ICC Ops with a shape file of the limits of the additional study areas** so that **Ops can request specific tiles** in order to expedite the information transfer.

Schedule

Review comments should be in by Friday the 28th then will be combined and sent out to the Consultant teams.

The next meeting is scheduled for April 10th from 1-3 PM at the Flood Recovery Office, located at 1901 56th Ave., Greeley, CO.

Action Item List

Action Item	Due	By
FEMA acceptance of the 48-hr storm parameter on Boulder Creek	April 3rd AM	ICC OPS, CDOT & CWCB
DAR template for Hydrology summary		ICC OPS
Review Comments to the teams		ICC OPS
Revised Amendment to TO #2		URS
Shape files of extended study area limits		Consultant Teams
US34 Presentations to Jacobs team		ICC OPS
Consultants provide availability for April 21st through May 2nd for watershed meetings		Consultant Teams

COLORADO
Department of Transportation
Region 4

Flood Recovery Office
1901 56th Ave, Suite 110
Greeley, CO 80634

2013 Flood Hydrology Meeting

Attendees:

Steven Humphrey	Cory Hooper
Holly Linderholm	Morgan Lynch
Kevin Houck	Derek Rapp
Bob Jarrett (PH)	Jim Wulliman
Steve Griffin	Heidi Schram
Will Carrier (PH)	Naren Tayal
Ed Tomlinson	Doug Stewart (PH)

FROM: Flood Recovery Office

DATE: April 21, 2014

The following is a summary of the 2013 Flood Hydrology Meeting. Decisions are highlighted and are summarized in a table at the end of this document. Action Items are shown in bold type and are summarized in a table at the end of this document.

1. Introductions and General

N/A

2. Incorporation of Review Comments

The consultant teams have addressed most of the comments provided. There was discussion of sharing between the teams the responses to the general comments to ensure consistency in the responses. At this time CH2MHill delivered their revised draft reports, Jacobs will delivered once their executive summary has been reviewed in the next 24 hrs, and URS will deliver their revised reports on Thursday at the FRO.

There was discussion around the type of Executive Summary the team wants for these reports. It was settled that the summaries would be more technical in nature as typical in these reports. Every summary will include the standard language that was provided by Steven Humphrey and then the teams will include the information necessary per watershed. It was noted that each summary should include the tables of "modeled peak flows compared to current regulatory discharges" and the "Estimate of Sept. 2013 peak discharge recurrence interval."

The consultant teams should deliver 5 hard copies of the revised draft reports.

3. Scheduling of Meetings with the Local Jurisdictions

The team would like to complete all the local meetings by May 16th 2014.

In general, the information from this team will not be provided prior to the meetings but will be communicated along with the teams' process and intent at the meeting. The general structure of the meeting will be introductions, purpose and intent by Steve Griffin, Steven Humphrey or Kevin Houck followed by the study and results from the consultant teams. The consultant teams should use a method of communication that works best to walk the audience through the results and process.

The desired order of the meetings is:

- Big Thompson – week of 4/28
- St. Vrain / Lefthand Creek - TBD
- Boulder Creek - TBD
- Coal Creek - TBD
- Little Thompson – TBD

Houck and Griffin will check their schedules for available times and Steven Humphrey will engage PIO to ensure messaging and coordination is completed to CDOT's expectations.

CDOT to check into the requirements of the Open Records Department as they relate to this effort and these draft reports as we intend to share all this information with our local partners.

4. Additional Hydrologic Services

The task orders for the additional services are moving forward. The consultant teams who have not already, need to provide which LiDAR tiles they will need for the additional study areas. **Ed Tomlinson will get Bob Jarrett's most recent list of peak flow estimate locations** so that the consultants can check that against their desired locations in order to keep the additional locations to be evaluated to the 20 sites in the scope.

Steven Humphrey will provide the HEC-RAS model from RESPEC to Steven Griffin and Bob Jarrett.

5. Project Schedule

The next meeting will be held at the Jacobs Denver Office on May 7th from 9 am – 11 am in the Echo Lake Conference Room.

6. Action Item List

Action Item	Due	By
PIO involvement in the Local meetings		Steven Humphrey
Availability for Local meetings		Kevin Houck, Steve Griffin, Jacobs Team
Open records requirements		Steven Humphrey
Bob Jarrett's latest locations and estimates list		Ed Tomlinson
Consultants cross check Bob Jarrett's lists with their wish list of locations, then provide remaining desired additional sites.		Consultant Teams
HEC-RAS model to Bob Jarrett and Steve Griffin		Steven Humphrey

COLORADO
Department of Transportation
Region 4

Flood Recovery Office
1901 56th Ave, Suite 110
Greeley, CO 80634

2013 Flood Hydrology Meeting

Attendees:

Steven Humphrey
Holly Linderholm
Kevin Houck
Naren Tayal
Steve Griffin
Will Carrier
Cory Hooper (PH)
Morgan Lynch
Derek Rapp
Jim Wulliman
Heidi Schram

FROM: Flood Recovery Office

DATE: May 7, 2014

The following is a summary of the 2013 Flood Hydrology Meeting. Decisions are highlighted and are summarized in a table at the end of this document. Action Items are shown in bold type and are summarized in a table at the end of this document.

1. Introductions and General

N/A

2. Status of Phase 1 Hydrology Reports

The updated reports and models need to be posted to the CDOT FTP site. The consultant teams will be included in this distribution.

3. Little Thompson Meeting with DWR

Little Thompson DWR doesn't agree with the assumption of the dam failures and would like this team to remove the language from the reports. This team has agreed to remove the language but not change the model ect. The DWR report is anticipated to be public within 2 weeks and then the two teams can meet again.

Bob Jarret thinks he could get a new peak flow number of the main stem. This team would need very compelling evidence to change our numbers. So far our analysis still contains more data than the other analysis.

As we continue to encounter debate CDOT should strategize how they prefer to handle disagreements to our analysis in the future in order to be prepared.

4. I-25 Crossings

Steve Griffin will push on the email about the I-25 crossings. Will Carrier will coordinate with Bob Jarrett on what needs to be collected from the plains sites.

This team will move forward since the USGS is not ready for another meeting at this time. Additional analysis is warranted in this situation and there is potential to need additional survey data.

This team is in agreement that we will stick with our numbers at the St. Vrain.

5. Big Thompson Meeting

This meeting went very well and the presentation was excellent and delivered the intended amount of information. Any changes will come from the comments received from the meeting attendees.

6. St. Vrain, Left Hand and Boulder Creek Meeting

In order to prepare for this meeting the power point from the Big Thompson meeting will be distributed for the other watersheds to be adapted into the same format. The power points will be merged into one in order to reference more quickly during the Q&A section. The Q&A section will be held at the end for all watersheds. **CH2MHill will provide their slides to the Jacobs team to incorporate by Thursday the 8th.**

7. Additional Hydrologic Services

CWCB is being asked when the extended scope will be completed. At this time the team feels that Phase II will be complete in approx. 3 months after we collect all the data required.

8. Project Schedule

The next meeting will be held at the Flood Recovery Office in Greeley on May 28th from 9 am – 11 am.

9. Action Item List

Action Item	Due	By
Check on delivery of LOT 8 & 9 of the LiDAR		Steven Humphrey / Naren Tayal
Delivery of the Rainfall Data		Will Carrier / AWA
Data needed from plains as well as Bob Jarrett availability		Will Carrier

COLORADO
Department of Transportation
Region 4

Flood Recovery Office
1901 56th Ave, Suite 110
Greeley, CO 80634

2013 Flood Hydrology Meeting

Attendees:

Steven Humphrey
Holly Linderholm
Kevin Houck
Naren Tayal
Steve Griffin
Cory Hooper
Morgan Lynch
Derek Rapp
Jim Wulliman
Heidi Schram

FROM: Flood Recovery Office

DATE: May 28, 2014

The following is a summary of the 2013 Flood Hydrology Meeting. Decisions are highlighted and are summarized in a table at the end of this document. Action Items are shown in bold type and are summarized in a table at the end of this document.

1. Introductions and General

Kevin Houck inquired about the timeline of this effort in order to get an idea of the flood plain timeline that Lyons has asked about. The effected communities are more interested in the schedule of the revised flood plain mapping since that affects them more.

Confirmed that the review schedule of the different watersheds so that the teams are aware of the dates:

St. Vrain by Friday, June 6th
Left Hand Creek by Wednesday, June 18th
Boulder Creek by Thursday, July 3rd

The main push from the communities is for the new flood plain mapping so they can move forward with projects and policy.

2. Boulder County Meeting (May 12th)

The meeting went well. Longmont is concerned with their current design projects along the watershed.

3. Scheduling of Coal Creek Meeting

We would like to schedule the Coal Creek meeting within the next couple weeks. This team along with Region 1 will confirm who should attend this meeting. The attendees list needs to be confirmed for this meeting.

Holly Linderholm will get the updated reports posted to the CDOT FTP site.

4. Executive Summary of South Platte River

Still need an executive summary for the South Platte.

5. Little Thompson

Little Thompson is in a holding pattern but have decided to leave out the language about the dam failures**.**

Additionally, the St. Vrain at I-25 numbers are also on hold until the USGS ready.

Kevin Houck will check in with DWR to see if their report is ready.

6. Big Thompson Review and Comments

Loveland comments were sent electronically to Steve Griffin, he will forward along to the teams. Hard copies were reviewed briefly during this meeting.

Derek Rapp will email John Hunt and AWA about the rainfall information needed to address some of the comments.

Objective to this effort not go deep into tributaries but provide to the locals in order to get where they want.

7. Additional Hydrologic Services

Will Carrier to provide Bob Jarrett's availability and peak flows, what is his staffs' availability. From previous communication it sounds like Bob will not be available. The other teams will start identify staff and times that they can get high water marks. Steve Griffin will provide the list of models that CDOT has. The other teams will also check into who can offer survey or other people for high water marks if griffin can't get them in this week. The data needs to be collected quickly and we need to identify options outside of Bob Jarrett.

It may work out better for the schedule is the consultants collect data for their own watersheds. This has not been decided but considered in order to address the limited timeframe. If this is decided then there would need to be contract amendments to each consultant's scope and budget.

Steven Humphrey will talk with Will Carrier when he is back from vacation and then communicate if URS will collect all the data or if the other Consultants will be needed.

All LiDAR has come in and all the consultants have indicated they have what they need for now.

We will provide response to B.T. comments and collect the additional data and then see if the USGS would like to meet again.

8. Project Schedule

The next meeting will be held at the Jacobs Office in Denver on June 11th, from 9 am – 11 am.

9. Action Item List

Action Item	Due	By
Post updated reports to the FTP Site		Holly Linderholm
DWR Little Thompson report ready		Kevin Houck
Rainfall data from AWA		Derek Rapp

Appendix D
Project Correspondence and Response to Review Comments

Response to CDOT and CWCB Review Comments

Phase I Hydrology Response Letter

PREPARED FOR:	Colorado Department of Transportation
COPY TO:	Colorado Water Conservation Board
PREPARED BY:	Morgan Lynch, PE, CFM
DATE:	April 18, 2014
PROJECT NUMBER:	482330

General Comments

1. **Comment:** The following comment was appropriate for all six reports. Within the model calibration discussion, three concepts are being explained at the same time. One concept is the incorporation of actual September 2013 rainfall data into rainfall-runoff model. The second concept is the calibration of the outputs of that model to estimates of actual peak flows from September 2013 *(estimates usually made by Bob Jarrett)*. The third concept is the development via the calibrated model of various frequencies of rainfall hydrographs and resultant frequencies of peak flows, including those utilized by FEMA. The discussion could be edited to better clarify each of these three concepts. It appears that they represent the heart of this report and the other 5 reports, so it should be easy for the reader to distinguish the three concepts from each other and to follow how they tie together. The informed readers can then decide if they buy the reasoning *(i.e. "Does the set of assumptions modeled for the role of landslides make sense or not?")*
   Response: Additional language has been added to Section 2.4.1 to better define the models and subsequent sections.
2. **Comment:** This approach is dependent upon the fundamental assumption that the rainfall amounts used in these studies are accurate. One of the key problematic issues with rainfall-runoff modeling of actual storms is simulating with accurate rainfall depths. There are well-known issues with using NEXRAD estimates for rainfall depth estimates. These issues should be at least discussed in a brief literature review, so that readers are aware of the potential problems. These DRAFT reports do not introduce the potential sources of error in these values, leading readers to believe that they should be used without question.
   Response: Additional information on how the rainfall was analyzed has been included.
3. **Comment:** The NOAA precipitation depths have confidence intervals that express some of the expected uncertainty in the rainfall depths. This uncertainty was not addressed in the methods or mentioned as a caveat on the accuracy of the rainfall depth values used in the modeling.
   Response: Additional language has been added to Section 2.4.5 to better explain the inherent error with these depths.
4. **Comment:** A brief literature review should also be provided to discuss the appropriateness of the CN method for rainfall-runoff modeling in forested landscapes. In general, the selection of appropriate CN values in forested landscapes is problematic, though this may be less of a concern for large rain events (i.e. the Sept floods) and due to the calibration efforts implemented. Though these caveats should be discussed in each report.

Response: A discussion was included documenting why the curve number parameter was appropriate for calibration.

5. **Comment:** For reaches that have stream gages with a reasonable length of record, the frequency analysis of these gage data should be used to develop the recommended flow frequency. Actual data are preferred to the results of rainfall-runoff analyses. Is this planned but just unclear in the reports?
   Response: The flood frequency analysis was incorporated for comparison purposes only. For this analysis it was critical to be able to document flows in areas where gage information was not available.
6. **Comment:** I noticed that each report completed by separate agencies has a different way of phrasing the purpose of these studies. It seems to be, after reading them, that it would be best if each report had an identical statement of purpose and identification of the project sponsors. We could just copy the language verbatim from one report to the next.
   Response: Language has been standardized.

Little Thompson

1. **Comment:** I like that an Executive Summary has been placed at the beginning of the report. However, it is quite verbose for an Exec Summary and much of the information is more appropriately contained later in the report. I would recommend 1-2 paragraphs max. with the appropriate tables showing the new recommended regulatory numbers, 2013 flood peak estimate, and comparison with accepted hydrology.
   Response: The Executive Summary has been updated with standardized text provided by CDOT.
2. **Comment:** The site numbers won't hold any meaning for the reader, unless referred to a map.
   Response: Site numbers have been added to the figures.
3. **Comment:** I would recommend a different term instead of "Measured Peak". These discharges were reconstructed based on field observations, but were not actually "measured" using a flow meter or real-time river measurements during the flood event. The term might be confusing.
   Response: Has been updated to Observed Peak.
4. **Comment:** "…were then compared to concurrent alternative estimates of high-flow hydrology." This phrase is unclear.
   Response: This sentence has been rephrased.
5. **Comment:** Page 1-2 - Be careful to refer to "data" as a plural term.
   Response: Revised.
6. **Comment:** Page 1-2 - "The Little Thompson River has no record of flooding prior to September 2013." I would eliminate or rephrase. There are records of previous flooding on the Little Thompson.
   Response: Statement has been omitted.
7. **Comment:** There are slight differences in the predicted flows presented in Table 7 and Table 8.
   Response: These tables have been combined to omit confusion.
8. **Comment:** Dam Safety has just completed a hydrology analysis of the Little Thompson above 7 Bar Ranch using HEC-HMS, might be a useful for comparison.
   Response: This report is currently not available but will be considered in the next Phase of work.

9. **Comment:** In **Section 2.4.2**, is it possible to create a graphic of the rainfall over the 7 days simultaneously illustrating the ebbs and peaks of the streamflows? That way the reader understands more clearly why the choices about 24-hours vs. 7-days were made in the development of the calibrated model.
   Response: A graphic was added to the Appendix to show the rainfall event.
10. **Comment:** In **Section 2.4.5 – Rainfall Inputs subsection**, it would be helpful to have graphics of the actual rainfall distribution over the entire time and the 24-hour rainfall used in the model for the various sub-basins. The basic questions are, "*How well, in terms of rainfall input throughout the watershed, does the model represent what actually happened in September 2013?*" and "*Should we be persuaded or not?*" -
    Response: A graphic was added highlighting the 24-hour window used for the calibrated model.
11. **Comment:** In **Section 3.1**, it would be interesting to add one more table showing the actual 24-hour rainfall *(for the specific time period that was used to build the model)* at various points to the various frequencies of rainfall for each of those various points. That way, the conclusion later on in the report that the September 2013 peak flows in the Little Thompson were greater than a 500-year frequency flow, we can look at the estimated frequency of the rainfall that lead to those peak flows and decide if they make sense.
    Response: Table B-4 has been updated to show the rainfall for the September 2013 storm for each basin.
12. **Comment:** The conclusion in **Section 4.2** that the peak flows experienced in the study area in September 2013 were all greater than 500-year flows raises the question, *"So what happened on the Little Thompson downstream of Highway 36, all the way to Milliken, during that event?"* Although it is beyond the scope of this contract, the inclusion of a very short description of estimated peak flows, and, perhaps a brief discussion of some of the flood damages, in the more populated areas of the watershed downstream of Highway 36 would provide a useful context for this report's findings. A 500-year flood in a forested area with few inhabitants is too easily forgotten. Maybe CWCB can provide that information.
    Response: More on what happened downstream will be provided with the next phase of work. Some discussion on this item has been added to the conclusion.
13. **Comment:** The USGS collected 17 years of record at the Little Thompson River gaging station near Berthoud (06742000) before the station was discontinued in 1961. Apparently the station is now operated by the Colorado Division of Water Resources. If the total record at this station greatly exceeds 17 years, then frequency analyses at this gaging station could be used to evaluate the reasonableness of flood discharges in the upstream study reach.
    Response: This gage was referenced in the report. However, due the location relative to the study area was not utilized for this study but will be evaluated for the next phase of work.
14. **Comment:** The peak discharges for the September 2013 flood are referenced as being determined from "paleoflood methodology". Paleoflood methods use slackwater deposits, peak stage indicators and carbon dating of deposits for floods that occurred prior to systematic data collection. The peak discharges for September 2013 floods are based on recent high-water marks and channel geometry during the recent flood and should be referred to as indirect measurements (such as the slope-area method, critical depth computations, flow over the road computations, etc.).
    Response: More discussion was provided in Section 2.3 to document how the observed discharges were collected.
15. **Comment:** Evaluate if the large differences in 1-percent chance discharge between the Little Thompson River sub-watersheds and West Fork Little Thompson River sub-watersheds (shown

in Figure 1) are reasonable.

Response: More documentation was included on the differences in land use cover and soil types between the two watersheds. These differences lead us to conclude that the results are reasonable.

16. **Comment:** Determine if the 1-percent chance discharges for Little Thompson River are reasonable. The trend line through the 1-percent chance discharge is greater than 1 suggesting that the upstream 1-percent chance discharges may be too low relative to downstream areas.

    Response: The trendline for Little Thompson included a point that is downstream of the confluence at drainage area 43 sq. miles. This point was omitted from the trendline and this figure was added to the appendix.
17. **Comment:** The September 2013 was determined to be greater than a 500-year flood at all locations where the peak discharge of the September 2013 flood was available from indirect measurements. The study team should determine if this assessment is consistent with other nearby watersheds (e.g., Big Thompson River, St. Vrain, etc.) given the geographic distribution of rainfall for the September 2013 flood.

    Response: The Big Thompson generally had 100 year rainfall and 100 year discharge. We added 24 hour September 2013 precipitation totals to Table B-4 (Little Thompson River Rainfall Depths) to show the same correlation with 500 year rainfall and 500 year discharge.
18. **Comment:** Page 1-1: It is stated that LiDAR data includes changes in channel geometry. LiDAR does not penetrate water; in non low flow conditions and anything but riffle areas, LiDAR does not well define the channel bed. This has less significance for higher flows and it is not expected that this significantly impact results. This should simply be discussed as a dataset limitation.

    Response: This is correct and it was noted that the LiDAR documented horizontal changes.
19. **Comment:** At the calibration point, flow was reduced from the estimated peak flow of 12,300 cfs to 7800 cfs. How was this reduction performed? Details on how this lower value was obtained needs to be provided.

    Response: A clarification was provided in Section 2.3 documenting that the values were determined based on nearby sites and similar watersheds.

<u>Boulder Creek</u>

1. **Comment:** Section 2.4.2 under Calibration of Model to Entirety of September 2013 Event says that using the 7 day timeframe resulted in inappropriate model parameters and the methodology was rejected, but a summary of the model is still included in Appendix B. It seems confusing to leave those parameters in the report; the explanation was enough to show why it was rejected.

   Response: This information has been omitted from the reports.
2. **Comment:** Not sure if it is necessary to include the discussion of the calibration to the 48-hour storm. It seemed to work well, but was rejected because 48-hour is an unusual storm to report. Since the exercise didn't seem to affect the resulting model, maybe it can be left out of the report.

   Response: This information has been omitted from the reports.
3. **Comment:** Table 9 compares the predicted flows to other data sources, including the FIS discharges. I can't seem to match up the flows in Table 9 with the Summary of Discharges Table provided in the appendix. Were those FIS flows taken directly from the USACE model or report? An explanation of the data source and documentation should be included.

   Response: Additional documentation has been added to clarify the source of the table values.

4. **Comment:** In **Section 1.2**, "The watershed is generally bounded by…the City of Boulder to the ***east*** *(not the west)*…"
   Response: This has been updated.
5. **Comment:** In **Section 1.5.2**, is it possible to create a graphic of the rainfall over the 7 days simultaneously illustrating the ebbs and peaks of the streamflows? That way the reader understands more clearly why the choices about 24-hours vs. 7-days were made in the development of the calibrated model.
   Response: A graphic was added to the Appendix to show the rainfall event.
6. **Comment:** In **Section 2.4.2** the current final sentence reads, "*Therefore, this method was discarded in favor of calibration to the peak 24-hour event and use of the commonly accepted 24-hour design hyetograph.*" Having just read about how well the application of the peak 48-hour event worked, the reader is left wondering if the 24-hour event works well enough or not, or if it was used simply for convenience.
   Response: This discussion has been removed from the report per Comment 2.
7. **Comment:** In **Section 2.4.4** there is no mention of the 4-Mile Fire and its hydrologic impacts. I realize that complicates things, but wouldn't it be wise either to incorporate some representation of those impacts or to state explicitly that a conscious decision was made not to do so, for whatever reasons that decision might be made?
   Response: Additional discussion regarding the Four Mile burn area has been included in the report.
8. **Comment:** In **Section 2.4.5 – Rainfall Inputs subsection**, it would be helpful to have graphics of the actual rainfall distribution over the entire time and the 24-hour rainfall used in the model for the various sub-basins.
   Response: A graphic was added highlighting the 24-hour window used for the calibrated model.
9. **Comment:** In **Section 3.1**, it would be interesting to add one more table showing the actual 24-hour rainfall *(for the specific time period that was used to build the model)* at various points to the various frequencies of rainfall for each of those various points. That way, if the conclusion later on in the report is that the September 2013 peak flow was such and such frequency *(perhaps lower or higher than we might have anticipated)*, we can look at the estimated frequency of the rainfall that lead to that peak flow and decide if it makes sense.
   Response: Table B-4 has been updated to show the rainfall for the September 2013 storm for each basin.
10. **Comment:** In **Section 4.1** it would be helpful to provide a comparison of the proposed flows to the current design/regulatory flows. The reader should see immediately just how much of a change is recommended.
    Response: This information was provided in Table 9 and has been clarified with additional documentation in the report.
11. **Comment:** In **Section 4.2** there are some extremely sobering thoughts. I fear they may be lost. Is there a good way to give them a lot more punch? Maybe it could be done graphically???? There is a very big lesson here, but much of it could easily be lost.
    Response: Additional discussion was added to Section 4.2
12. **Comment:** Base flood estimate of Fourmile Creek near Orodell by the prediction model is approximately 55% of the effective estimate, which is based on an USGS 1977 analysis. Comparison of unit flow (cfs/sq mi.) with the other sites in Boulder Creek watershed indicates that the unit discharge at Fourmile Creek is 83% higher than the value of Middle Boulder Creek, which has the second highest unit discharge value. Impact of burned area in Fourmile Creek watershed is difficult to assess; however flood peaks of Sept 2013 event were estimated (measured) at several other locations in the watershed (Figure B-2), is it possible to use these estimates/measurements to further confirm the calibration?
    Response: Table 5 includes calibration points for Fourmile Creek.

13. **Comment:** Base flood of Boulder Creek at Orodell station estimated by the prediction model is 86% of the effective discharge. It is still a conservative estimate compared to the much lower estimate from gage frequency analysis. One of the reasons could be due to mixed population of peaks from rain-on-snow and storm events in the frequency analysis. Impact of Barker Reservoir could be another reason that modeled peak flow is on high side. Although the base flood estimate in this study is lower than the effective value, it is unlikely that the peak is underestimated.
    Response: Comment noted.
14. **Comment:** Gage 06725500, Middle Boulder Creek at Nederland has 87 year of record, with annual peak recorded from 1945 to 1995. Frequency curve from this station was not mentioned in the report. Is there any reason that the gage data are not suitable to use to calibrate the HMS model?
    Response: This gage has been added to the analysis and included in the report where applicable.
15. **Comment:** The source cited is from 1948, but contains data from 1969…? Double-check.
    Response: The source for the 1969 reference has been added.
16. **Comment:** May want to include additional background on how the Ayres stream gage analysis supplements the rainfall-runoff models.
    Response: Discussion was included and these points were used for comparison.
17. **Comment:** Table 5: The site numbers will not hold any significance for the reader unless shown on a map and referenced.
    Response: These locations were shown in the Appendix. A note has been added to direct the reader to the appendix.
18. **Comment:** Table 11: It is unclear here if the Annual Chance Peak Discharge numbers are the current regulatory numbers or a proposed set of numbers.
    Response: The headings and title of the table have been revised to help eliminate confusion.
19. **Comment:** See the comments for the Little Thompson for any text that was copied between the two reports.
    Response: Updated with the same responses for Little Thompson.

Appendix D
Project Correspondence and Response to Review Comments

Response to Public Review Comments

Phase I Hydrology Response Letter

PREPARED FOR: Colorado Department of Transportation

COPY TO: Colorado Water Conservation Board

PREPARED BY: CH2M HILL

DATE: August 8, 2014

PROJECT NUMBER: 482330

The Colorado Department of Transportation (CDOT) and the Colorado Water Conservation Board (CWCB) partnered with CH2M Hill to perform hydrologic analysis of the Boulder Creek watershed after the flooding of September 2013. The results of this analysis were published in the Draft report "*Boulder Creek Hydrologic Analysis*", April 2014. This report was distributed to interested agencies and communities for comments. The comments received are captured below with responses to how the comments were addressed.

Urban Drainage and Flood Control District Comments:

1. **Comment:** It is not clear in this report how the SCS 24-hr Type II rainfall distribution was selected. Shall the SCS 24-hr Type II rainfall distribution be also recommended for design flood predictions?
   Response: *See Page 2-9 of the April report, at the end of the "Rainfall Inputs" section: "Per the* Colorado Floodplain and Stormwater Criteria Manual *(CWCB, 2009), the standard NRCS 24-hour Type II rainfall distribution was used as the design hyetograph to distribute the 24-hour rainfall depths to generate hydrographs for the 10, 4, 2, 1, and 0.2 percent annual chance discharge."*
2. **Comment:** A design rainfall distribution shall be conservatively selected as the enveloping curves to the extreme rainfall cases (Guo and Harrigan 2009). To clarify how to select the design rainfall distribution, I suggest that this report may further provide a comparison between the middle 2-hour sharp rising curve in the SCS Type II rainfall distribution and the UDFCD's 100-yr 2-hr rainfall curve. If the difference is minimal, then the SCS Type II rainfall curve shall be acceptable for the predictive hydrologic models. Otherwise the SCS Type IIA rainfall curve may be a good substitute.
   Response: *The Type II NRCS Rainfall Distribution was selected per guidance in the* Colorado Floodplain and Stormwater Criteria Manual *(CWCB, 2009). In a review of a 57-year rainfall record at the Stapleton International Airport in Denver, CO, Guo (2008) recommended that a conservative rainfall distribution be developed "using the low enveloping curve for the leading portion, the high enveloping curve for the tail portion, and a sharp rise in between" and showed that the NRCS Type II rainfall distribution met this criteria for the analyzed rainfall record*[1]*. Given the proximity of Denver, CO to the study basin, the NRCS Type II rainfall distribution is appropriate for the Boulder Creek watershed as well. In reference to other hyetographs, the UDFCD's rainfall curves were developed in small, urbanized basins east of the foothills of the Front Range and were not considered representative for the much-larger and predominantly mountainous terrain of the study basin. The NRCS Type IIA rainfall distribution was not considered, as the Type IIA rainfall distribution was originally created for New Mexico, transferred to Colorado, and later discarded by the NRCS when NRCS concluded that the Type II storm yielded accurate results in Colorado (JR Engineering, LTD, unpublished response letter, September 4, 1992).*

[1] Guo, J.C.Y. (2008). *Design Rainfall Curve.* < *http://carbon.ucdenver.edu/~jguo/PaperWeb/(W2)RainDesignCurve.pdf* > *(August 5, 2014).*

3. **Comment:** It that model is used and having been involved in the development of design storms for UDFCD in the past, my recommendation would have been to use Type IIA storms instead.
   Response: *See response to Comment #2.*
4. **Comment:** As is common with modelling, the model was calibrated using the runoff rates of the most intense 24-hour precipitation period of the September 2013, an event that may, or may not be representative of much more intense, short duration storms like ones experienced along the front range foothills of Colorado.
   Response: *While intense, short-duration storms may cause extreme runoff in smaller basins near the foothills, a review of the flood history of Boulder Creek indicates that the September 2013 event is comparable to some of the largest flood events (1876, 1894, and 1921) along Boulder Creek: all the storms were large, general storms that lasted several days and spanned large portions of the Front Range such that the September 2013 storm is considered representative of extreme events along Boulder Creek. The report will be revised to include this discussion.*
5. **Comment:** Once saturated, something that I have observed to often occur between 1- to 2-inches of heavy precipitation, the surfaces acts as 100% impervious. Recognizing this and proper application of the Green-Ampt method can yield realistic runoff results.
   Response: *As discussed on Page 2-7 of the April report, an attempt to calibrate the model using the Green-Ampt method was made, but there was not a defensible way to assign Green-Ampt parameters based on soil data in the USDA Soil Survey that would result in modeled runoff volumes comparable to observed runoff measurements (modeled runoff was approximately an order-of-magnitude less than what was observed).*
6. **Comment:** Although the watershed parameters used in this computer model were calibrated by six stream gages along Boulder Creek during September 9th to 18th in 2013, the validity of this calibrated watershed model is only justified for this single event.
   Response: *Noted. While this is true for any hydrologic event, the calibrated model is considered representative of hydrologic conditions during extreme rainfall events; see response to Comment #4.*
7. **Comment:** Another point I would like to offer for your consideration is that the rainfall-runoff modeling for Boulder Creek used a 30-minute time step for the input of the Type II NRCS hyetograph.
   Response: *A 5-minute NRCS Type II hyetograph was used in the model; the report will be revised to clarify this.*
8. **Comment:** There is sufficient evidence that the current regulatory numbers are quite representative of what Boulder Creek is capable of producing and are inherently more protective of the public residing along it today and in the future.
   Response: *Noted. The intention of the report is to provide an improved estimate of the peak discharge-probability along Boulder Creek to accurately assess the recurrence interval of the September 2013 flood and limit the overdesign of planned CDOT improvements. While this analysis represents the most recent science and available data, the adoption and regulation of flow rates is a decision made by effected communities and regulatory agencies and is outside the purview of this report.*
9. **Comment:** The common practice when doing statistical analysis (e.g., Log Pearson) is that it is assumed that extreme event statistics are driven by the same population of meteorological and hydrologic events that drive smaller events. It is more than likely that the 1-percent and larger events may be a separate population of meteorological events.
   Response: *Noted. It is partially for this reason that little weight was given to the statistical gage analyses in calibrating the rainfall-runoff model or estimating the magnitude of extreme events.*

10. **Comment:** One of the other items described in the aforementioned report was the use of statistical analysis of the flow gage along Boulder Creek upstream of the City of Boulder. What struck me is that the two large floods, one in 1876 and another in 1894 (i.e., approaching 11,000 to 12,000 cfs), were not included in the Log Pearson analysis.

    Response: *There are two reasons these floods were not included in the statistical gage analysis: 1) the flows were recorded in Boulder, downstream of Orodell and thus inclusive of Fourmile Creek which is referenced in the FIS as the "primary source of flooding", and 2) these flows pre-date the construction of Barker Reservoir which, while not operated for flood control, has provided some flow attenuation since its construction. As a discussion point, the statistical gage analysis was re-run with a historic flow of 10,000 cfs occurring in 1894 (four times greater than the peak flow, 2,500 cfs, recorded at the Orodell gage in 1921) and the 100-year estimate increased to 3,182 cfs (Ayres Associates, e-mail correspondence, August 6, 2014). The report will be revised to indicate that historical flow estimates pre-dating the installation of the Orodell and Nederland gages do not exist.*

11. **Comment** Two calibrated and verified models have been in existence for number of years and it is my understanding that they were used by UDFCD in estimating the flows at the mouth of the canyon very shortly after the September flooding occurred.

    Response: *Based on e-mail conversations with UDFCD, there is no published documentation describing the use of these models to predict discharge-probability curves along Boulder Creek (Kevin Stewart, e-mail correspondence, May 29, 2014).*

12. **Comment:** In addition, UDFCD has 1-sq. km. pixel-by-pixel ground calibrated radar imagery virtual temporally dense rainfall depths for the entire watershed.

    Response: *Due to the resolution and rigorous QC procedure (described on page 2-8 of the April report, under "Rainfall Analysis"), the hyetographs generated by AWA will continue to be used for this study.*

<u>Boulder County Land Use Department Comments:</u>

13. **Comment**: The reference document was not provided. The technique to obtain the estimate was described as the Paleoflood method which appears to have mainly been a critical depth analysis. It is necessary to distinguish it from a full-scale paleoflood analysis which involved other observation and techniques.

    Response: *Section 2.3 of the report details the estimation of peak discharges; the report will be revised to remove ambiguity in other sections. Bob Jarrett's report describing the estimation of peak discharges will be included as an attachment.*

14. **Comment**: The effective peak flow at the outlet is significantly higher than the HMS estimated flow. For the calibrated model, the time to peak flow from Fourmile Creek is eight hours prior to the time to peak flow from and Boulder Creek including Middle and North Boulder Creek watersheds. Comparing the HMS model hydrographs and time to peak flow from the various sub watersheds with the 1977 model hydrographs and time to peaks may help better evaluate the HMS estimates.

    Response: *The peak discharges estimated by the calibrated HEC-HMS model occurred between 30 minutes prior to (Orodell) and 90 minutes following (Nederland) peak discharges measured at gage locations. In contrast, the 1977 USACE model was not calibrated, nor was it compared to actual gage measurements following rainfall events. The report will be revised to present and discuss the timing of computed peak discharges in relation to observations.*

15. **Comment**: A study contractor may conduct a critical storm analysis utilizing storm events of varying lengths to determine the most suitable precipitation parameters to use for peak discharge estimation.

Response: *See response to Comment #2.*

16. **Comment**: A noticeable difference between the USACE (Anderson) model and the CH2MHILL model is that a 6-hr storm event from NOAA 2 was used in the USACE (Anderson) model while, a 24-hr storm event from NOAA 14 was used in the CH2MHILL model. In their effort to match the results from the original 1977 USACE study, Anderson ran multiple scenarios, among them a modified USACE 6-hr Standard Project Storm and a variation of the 6-hr Southwestern Division Criteria Standard Project Storm. These two storm patterns produced relatively close 1-percent-annual-chance discharge estimates on Boulder Creek at Orodell (5230 cfs vs. 5910 cfs), but produced dramatically different estimates at the Boulder Creek Canyon mouth (5260 cfs vs. 9980 cfs). The Anderson evaluation concluded that the variation of the 6-hr Southwestern Division Criteria Standard Project Storm produced results that most closely aligned with the results from the original 1977 USACE study.

Response: *To evaluate the impact of differing storm durations and hyetographs, the Fourmile Creek hydrologic components of the calibrated HEC-HMS model were extracted to a separate HEC-HMS model and re-calibrated to a 6-hour event. Similar to the 24-hour calibration, the Fourmile Creek HEC-HMS model was calibrated by adjusting the CN to match peak flows; runoff due to rainfall that occurred prior to the calibration period was not considered such that calibrated CNs would be conservative (due to discounting the portion of the peak discharge that was attributable to rainfall that occurred prior to the calibration period). Initial abstraction was set to zero inches to reflect the effect of rainfall immediately prior to the calibration period. Following calibration of the Fourmile Creek model, the CNs were adjusted from AMCIII to AMCII to develop discharge-probability curves. Utilizing a 6-hour NRCS Type II hyetograph, the estimated 1 percent chance annual exceedance discharge was 3,630 cfs – a 6 percent increase over the 24-hour estimation. For comparison, an average CN of 93 would be needed to replicate the 6,230 cfs estimated at the mouth of Fourmile Creek by the 1977 USACE model. To further analyze the impacts of varying rainfall patterns, the 6-hour rainfall distribution used in the USACE 1977 study (referred to as the "modified 6-hour Southwestern Division Criteria" by Anderson) was evaluated as well; the estimated 1 percent chance annual exceedance discharge was slightly less than that estimated using the NRCS Type II hyetograph, showing a negligible sensitivity of the estimated peak discharges to rainfall duration and distribution. A discussion regarding the 6-hour storm event has been added to report.*

17. **Comment**: Run Fourmile with the 6-hour Southwestern Division Criteria Standard Project Storm.

Response: *See response to Comment #16.*

18. **Comment**: The calibration model should be improved to better match the volume of the 2013 storm event, or the study should clearly state that the model should be used only for the prediction of peak discharges. The peak of the computed [MBC @ Nederland] hydrograph is much narrower than that of the observed, resulting in a total volume for the computed hydrograph of 0.20 inches. This value is 0.31 inches less than the observed hydrograph of 0.51 inches. The calibration of the computed peak flow [at Orodell] of 1950 cfs matches the observed peak reasonably well; however the computed volume is 0.24 inches less than that of the observed hydrograph.

Response: *The volumes referred to above are over a 48-hour window that was selected to illustrate the recession limb of the modeled hydrograph that resulted from the 24-hour period of rainfall that was modeled. Comparing the modeled volume against the observed volume only over the 24-hour period that rainfall was modeled, the modeled and observed volumes are as follows:*

Modeled and Observed Volumes (24-hour Analysis Window)

Gage	Modeled Volume (watershed-inches)	Observed Volume (watershed-inches)	Difference (watershed-inches)
Middle Boulder Creek at Nederland	0.10	0.22	-0.12
Boulder Creek at Orodell	0.26	0.34	-0.08

While the modeled discharges are still less than the observed volumes, it should be noted that significant rainfall occurred prior to the analysis window. As the model does not account for runoff occurring from rainfall prior to the 24-hour analysis window, the observed hydrograph does; thus, due to the modeling methodology, the observed volumes are expected to be greater than the modeled volumes. Analyzing the Nederland gage record, runoff from rainfall preceding the analysis window could account for 35 to 65 percent of the observed volume. The report will be revised to report and discuss the modeled volumes in comparison to observed volumes.

19. **Comment**: The calibration focused on matching peaks using the CN value as the calibration parameter. Typically, CN values are most sensitive to hydrograph volumes, and routing parameters are better-suited to adjust the peaks.
Response: *As discussed on page 2-11 of the April report, the model was relatively insensitive to changes in routing parameters; halving or doubling the Manning's n value resulted in an approximate 5 percent change in the modeled peak discharge. Presumably, this is due to the steep slopes of the study basin channels. While the model was somewhat sensitive to subbasin lag time and Snyder's peaking factor, subbasin lag times were not calibrated as the modeled times-to-peak correlated well with observations and Snyder's peaking factors were not calibrated as a satisfactory calibration was achieved using C_p values within the range recommended in published literature.*

20. **Comment**: The model was calibrated using a storm that occurred at a dry time of year in Colorado which may have resulted in higher than normal loss rate. Design hydrographs generated from the calibrated model parameters may not be conservative. The model parameters should be modified to account for this or a discussion should be added to the report that indicates why the selected model parameters adequately account for this.
Response: *The 24-hour calibration period occurred several days into the storm event. Thus, at the start of the calibration period, the soils were likely partially- or fully-saturated, as evidenced by the observation that peak discharges occurred approximately a day after the peak rainfall, suggesting that the infiltration capacity of the Boulder Creek soils were largely expended prior to the calibration period. A brief discussion of this will be added to the revised report.*

21. **Comment**: The storm occurred after a prolonged dry period, meaning that the infiltration rates would be higher than at the normal condition. Loss rates are 90% or higher in sub-watersheds in North Boulder and Middle Boulder Creeks, which hardly reflect typical conditions.
Response: *See response to Comment #21.*

22. **Comment**: We have determined that the reported "Modeled Discharges" in Table 6 were not directly derived from the HEC-HMS model results, and, therefore, comparisons can't be verified. Any additional analysis or computations should be included in the report.
Response: *The calibration points were located approximately halfway between model junctions where peak discharges between the two junctions differed by 50 to 100 percent. Thus, the modeled peak discharge at these calibration points were estimated by interpolating between the two bounding model junctions based on contributing drainage area; discussion of this interpolation process will be provided in the revised report.*

23. **Comment**: The burn in the watershed was mentioned in the report but the size of the burned area was not clearly defined.

Response: *On Page 1-2 of the April report, the area of the Fourmile Canyon fire was identified as 10 square miles. Of this, 7.5 square miles was within the Fourmile Creek watershed and an additional 0.5 square miles elsewhere in the Boulder Creek watershed (above Orodell). The Fourmile Canyon Fire burn area will be added to the watershed overview figure.*

Appendix E
Digital Data

GIS Shapefiles
AWA Rainfall Data
HEC-HMS Calibrated Hydrologic Model
HEC-HMS Predictive Hydrologic Model