Hydrologic Evaluation of the St. Vrain Watershed

Post September 2013 Flood Event

Prepared for:

Colorado Department of Transportation
Region 4 Flood Recovery Office

Prepared by:

JACOBS

707 17th Street, Suite 2400
Denver, Colorado 80202

With Support from:

Muller Engineering Company, Inc.
Consulting Engineers

August 2014

August 29, 2014

We hereby affirm that this report and hydrologic analysis for the St. Vrain Watershed was prepared by us, or under our 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.

Signatures:

Heidi Schram
Jacobs Engineering Group Inc.
Registered Professional Engineer State of Colorado No. PE 39438

James T. Wulliman
Muller Engineering Company, Inc.
Registered Professional Engineer State of Colorado No. PE 20114

Derek N. Rapp
Muller Engineering Company, Inc.
Registered Professional Engineer State of Colorado No. PE 42209

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EXECUTIVE SUMMARY

In September 2013, the Colorado Front Range experienced an extensive rainstorm event spanning approximately ten days from September 9th to September 18th. 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 get critical travel corridors open again, and engage in assessments and analyses to guide longer term rebuilding efforts. As part of this effort, CDOT partnered 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 watersheds 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:

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 calibrated rainfall data representing the September rainstorm, and calibrate runoff 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]. Compare results to updated flood frequency analyses and unit discharge information and refine calibration as appropriate.

This report documents the hydrologic evaluation for the St. Vrain watershed.

Prior to September 2013, the last major flooding event on St. Vrain Creek in Lyons was in 1969, with the largest flood of record occurring in 1941. In 1977 and 1978, the effective regulatory flow rates documented by the Federal Emergency Management Agency (FEMA) in the 2012 Flood Insurance Study (FIS) were developed as part of two different studies. The effective peak discharges were developed based on a combination of flood frequency analysis for stream gage records and regression equations.

In the current evaluation, a rainfall-runoff model was developed to transform the recorded rainfall to stream discharge using the U.S. Army Corps of Engineers' HEC-HMS hydrologic model (USACE, 2010). The hydrologic model was calibrated through adjustment of model input parameters that represent land cover and soil conditions. The model was calibrated to provide a best fit with peak discharges estimated for the 2013 event at a number of locations in the watershed, including Button Rock Dam (Ralph Price Reservoir).

A systematic approach was taken in the calibration process to ensure a consistent method was used throughout all of the watersheds studied. The goal was to obtain the best overall fit to the majority of the peak discharge estimates rather than try to match them all at the expense of calibration parameters being pushed beyond a reasonable range. The systematic approach prevents individual basins in the model from being biased toward unique occurrences that may be associated with this particular storm event.

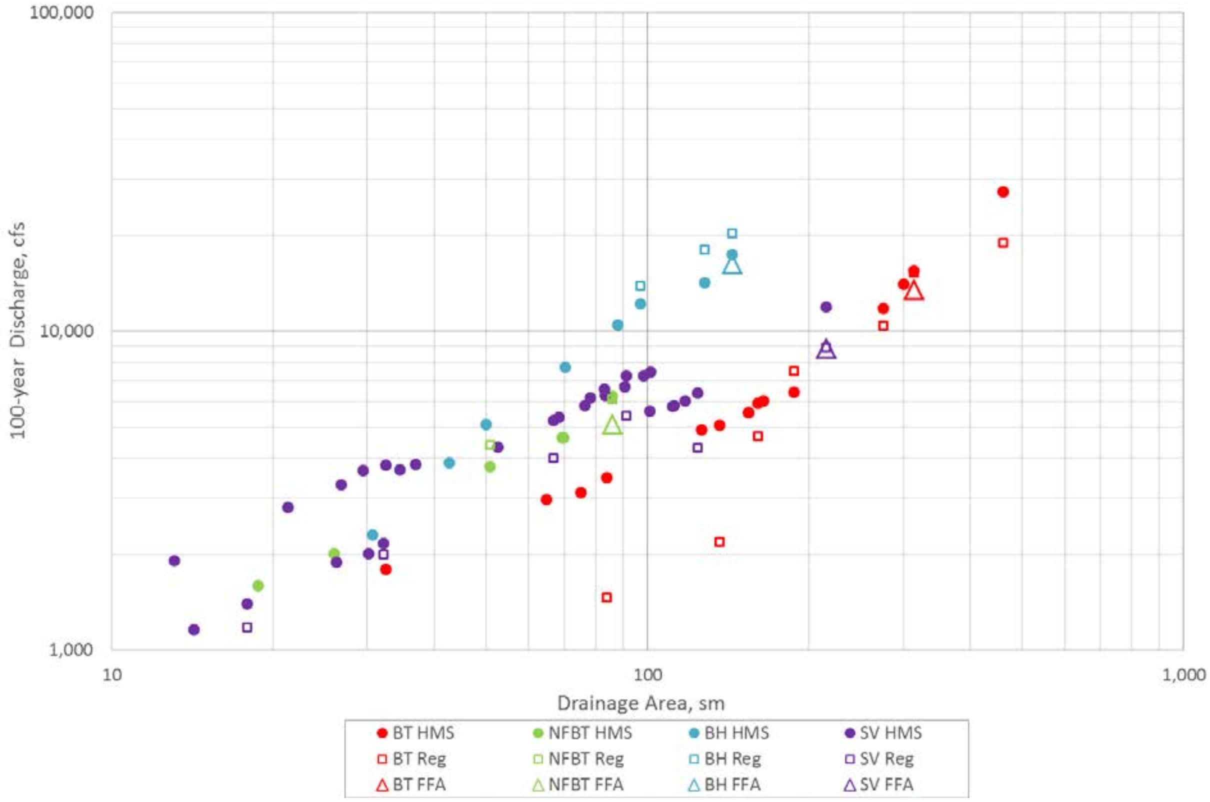
Loss parameters in the rainfall-runoff model were then uniformly adjusted to provide an overall best fit with the estimated September peak discharges based on the peak 24 hours of the September rainfall rather than the entire multi-day storm. Loss parameters were also adjusted to create the same overall ratio of runoff to rainfall during the peak 24-hours of rainfall as the multi-day event. The latter adjustment was used for developing predictive estimates of 10, 4, 2, 1, and 0.2 percent annual chance peak discharges (10-, 25-, 50-, 100-, and 500-year storm events) based on a 24-hour Soil Conservation Service (SCS) Type II storm distribution and the recently released 2014 National Oceanic and Atmospheric Administration (NOAA) Atlas 14 rainfall values. Since there is no regulatory flood control storage associated with Button Rock Dam, the model treats the reservoir as full at the start of the storm and disregards any flood storage behind the dam, but accounts for attenuation as the peak discharge passes through the emergency spillway. It should be noted that in general, the model focuses on peak discharge estimation along the main stem channels within relatively large watershed areas. Individual basins may produce greater discharges if divided into smaller areas or evaluated using shorter, more intense rainstorms. However, the larger basins and longer duration are appropriate for the major tributary peak discharges.

The resulting modeled peak discharges for the various return periods were compared to the results of an updated flood frequency analysis for St. Vrain Creek as well as to current regulatory discharges. The modeled peak discharges were compared on a unit discharge basis (in cfs per square mile of watershed area) against flood frequency results, current regulatory discharges, and modeled discharges in the Big Thompson, North Fork of the Big Thompson and Buckhorn Creek watersheds in addition to the St. Vrain watershed. These are shown in Figure ES-1. The information in Figure ES-1, including legend abbreviations, is discussed in detail in the body of the report; however, several observations can be made:

1. Compared to the modeled discharges, more scatter is associated with the current regulatory discharges for the design points shown.

2. Modeled discharges are generally higher than current regulatory discharges in the St. Vrain watershed.

Figure ES-1. Comparison of 100-year Discharges in the St. Vrain and Adjacent Big Thompson, North Fork of Big Thompson and Buckhorn Creek Watersheds



Current regulatory discharges in the St. Vrain watershed are primarily based on prior flood frequency analyses; however, it is possible that the gage analysis results, and therefore the regulatory discharges, may tend to be somewhat low, considering that three events have occurred during the period of record that are well in excess of the 100-year flow rate that is predicted using the flood frequency analysis. It is likely that the construction of Button Rock Dam has reduced some of the measured discharges that influence the prediction of 100-year flow rates.

Based on a review and evaluation of assumptions and limitations of the various hydrologic methodologies used, the results of the current rainfall-runoff model using the 24-hour NOAA rainfall are viewed as suitable for use by CDOT in the design of permanent roadway improvements in the St. Vrain watershed. It is recommended that local floodplain administrators consider using the results of this hydrologic analysis to update and revise current regulatory discharges in the St. Vrain watershed. Table ES-1 summarizes the predictive model results for the 100-year event compared to current regulatory discharges.

Table ES-1. 100-year Modeled Peak Flows Compared to Current Regulatory Discharges

Location	Current Regulatory Discharge (cfs)	Modeled Discharge (cfs)	Percent Difference
Middle St. Vrain Creek at confluence with South St. Vrain Creek	2,000	2,160	+8%
Middle St. Vrain Creek at Peaceful Valley (State Route 72 Bridge)	1,180	1,400	+19%
North St. Vrain Creek at confluence with St. Vrain Creek and South St. Vrain Creek	4,310	6,390	+48%
South St. Vrain Creek at confluence with St. Vrain Creek and North St. Vrain Creek	5,430	7,230	+33%
South St. Vrain Creek at confluence with Middle St. Vrain Creek	3,990	5,260	+32%
St. Vrain Creek Just downstream of confluence of North St. Vrain Creek and South St. Vrain Creek	8,880	11,910	+34%

Based on the modeled discharges for the return periods analyzed, the peak discharges observed along St. Vrain Creek during the September 2013 Flood event had an estimated recurrence interval ranging from approximately 1 percent annual peak discharge to the 0.2 percent annual peak discharge, or from a 100-year to a 500-year storm event. There are two exceptions to this where lower peak discharges were estimated. These results are shown in Table ES-2.

Table ES-2. Estimate of September 2013 Peak Discharge Recurrence Interval

Location	Measured Discharge (cfs)	Annual Chance Peak Discharge (cfs)					Estimated Recurrence Interval (yr)
		10%	4%	2%	1%	0.2%	
Middle St. Vrain Creek at Riverside	1,750	364	700	1,170	1,820	4,110	~ 100
South St. Vrain Creek below Middle St. Vrain	2,700	1,190	2,345	3,658	5,369	10,962	25 to 50
South St. Vrain Creek above Lyons	9,000	1,464	2,890	4,496	6,598	13,435	100 to 500
North St. Vrain Creek at Highway 7	450	963	1,785	2,667	3,799	7,423	< 10
North St. Vrain Creek below Button Rock Dam	10,000	1,502	3,108	5,002	7,472	16,002	100 to 500
North St. Vrain Creek above Lyons	12,300	1,056	2,299	3,804	5,842	13,100	100 to 500
St. Vrain Creek at Hwy 36 Bridge (D-15-I)	23,000	2,202	4,860	7,949	12,089	26,599	100 to 500

1.0 BACKGROUND

1.1 Purpose and Objective

In September 2013, the Colorado Front Range experienced an extensive rainstorm event spanning approximately ten days from September 9th to September 18th. 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.

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This report documents the hydrologic evaluation for the St. Vrain watershed.

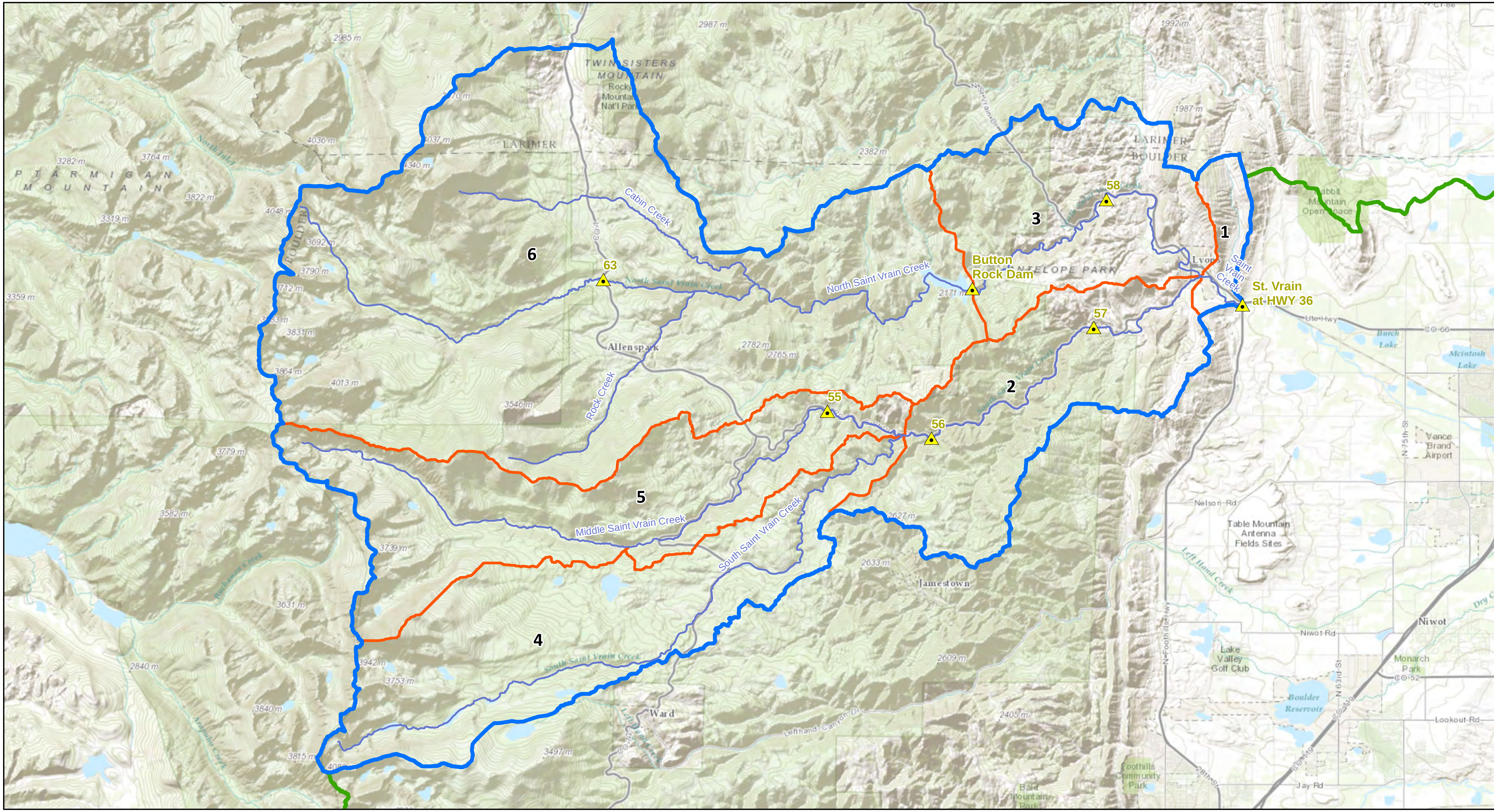
1.2 Project Area Description

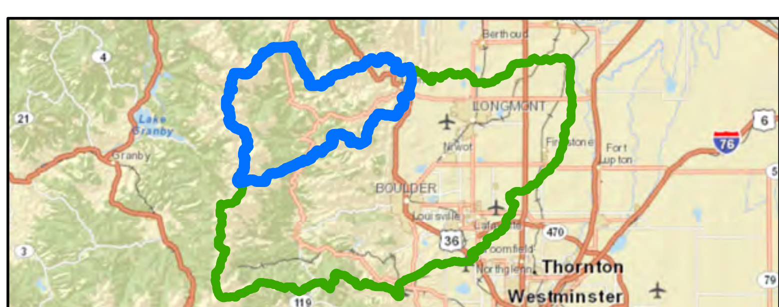
St. Vrain Creek is a perennial stream that drains the east slope of the Continental Divide by way of North, Middle and South St. Vrain Creeks. From the confluence of North and South St. Vrain Creeks at the Town of Lyons, St. Vrain Creek flows easterly through the City of Longmont, then northeasterly to the South Platte River. Dry Creek No. 1, Lefthand Creek, Spring Gulch, and Loomiller Basin join St. Vrain Creek within the City of Longmont. Downstream of Longmont, just before crossing I-25, Boulder Creek also joins St. Vrain Creek. Elevations in the watershed range from 4,900 feet in Longmont to more than 14,000 feet at Longs Peak. This study focuses on St. Vrain Creek from the headwaters at the Continental Divide to the U.S. Highway 36 Bridge (CDOT Structure D-15-I) just east of the Town of Lyons and includes a drainage area of approximately 218 square miles. Figure 1 provides an overview map of the study area within the St. Vrain Watershed.

The Middle St. Vrain Creek headwaters extend to the Continental Divide near Buchannan Pass. From there it flows east toward State Highway 72 near Peaceful Valley Campground. Middle St. Vrain Creek then parallels State Highway 72 and Riverside Drive down through Raymond to State Highway 7. It parallels State Highway 7 to its confluence with South St. Vrain Creek. Middle St. Vrain Creek has a drainage area of approximately 32 square miles upstream of the confluence with South St. Vrain Creek and has a length of approximately 15 miles.

The South St. Vrain Creek headwaters extend to the Continental Divide in the area of Brainard Lake. From there it flows east toward State Highway 72 and receives tributary runoff from Beaver Creek and the Beaver Reservoir. Beaver Reservoir has little to no effect on flood discharges downstream near Lyons. South St. Vrain Creek then flows in a northwesterly direction towards its confluence with Middle St. Vrain Creek at State Highway 7. South St. Vrain Creek has a drainage area of approximately 35 square miles upstream of the confluence with Middle St. Vrain Creek. From there, South St. Vrain Creek parallels State Highway 7 through the canyon narrows, enters Lyons near Fifth Avenue, and flows through residential land that is partially developed with single-family residences and mobile homes. South St. Vrain Creek has a drainage area of approximately 91 square miles upstream of the confluence with North St. Vrain Creek and has a total length of approximately 25 miles.

The North St. Vrain Creek headwaters extend to the Continental Divide in the Wild Basin section of Rocky Mountain National Park. From there it flows east toward State Highway 7 north of Allenspark picking up flow from several named tributaries including Hunters Creek which drains the southern side of Longs Peak. East of Highway 7, North St. Vrain Creek flows east and picks up several additional tributaries before flowing into Ralph Price Reservoir behind the Button Rock Dam. Some of the larger tributaries include Rock Creek draining from the south near Allenspark, Cabin Creek draining from the north near Meeker Park and the east side of Longs Peak, and Dry St. Vrain Creek from the south just above Ralph Price Reservoir. The tributary drainage area flowing into Ralph Price Reservoir is approximately 101 square miles.





St. Vrain Study Area

CDOT Flood Recovery Hydrologic Evaluation

0 1 2 3
Miles

Investigation Sites
Tributaries
St. Vrain Study Area
St. Vrain Major Basins
St. Vrain Watershed

Major Basins

1: St. Vrain Creek (From Confluence of North and South SVC to Hwy 36 Bridge)
2: South St. Vrain Creek (From Confluence with Middle SVC to Confluence with North SVC)
3: North St. Vrain Creek (Button Rock Dam to Confluence with South SVC)
4: South St. Vrain Creek (Headwaters to Confluence with Middle SVC)
5: Middle St. Vrain Creek (Headwaters to Confluence with South SVC)
6: North St. Vrain Creek (Headwaters to Button Rock Dam)

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Button Rock Dam was completed in 1969, six miles west of Lyons, to store municipal water supply. It was not designed to provide flood control, but can significantly impact smaller flood events and provides some attenuation to larger flood events passing through the emergency spillway. During the May 1969 flood, it reduced the magnitude of the discharge that could have inundated Longmont (2012 FIS). Downstream of Button Rock Dam, North St. Vrain Creek flows northeasterly through Longmont Reservoir (no significant impact on flood flows) to U.S. Highway 36. It then parallels U.S. Highway 36 and enters Lyons on vacant land near the northwestern corner of the community. Between Fifth Avenue and Second Avenue, the creek flows through a single-family residential area, north of the business community. North St. Vrain Creek has a drainage area of approximately 124 square miles upstream of the confluence with South St. Vrain Creek and has a length of approximately 31 miles.

1.3 Mapping

The United States Army Corps of Engineers (USACE) Hydrologic Engineering Center's Geospatial Hydrologic Modeling Extension (HEC-GeoHMS), version 10.1 was used as the primary tool for delineating basins within the target watershed. HEC-GeoHMS is a public domain extension to Esri's ArcGIS Software and the Spatial Analyst extension. HEC-GeoHMS is a geospatial hydrology toolkit that allows the user to visualize spatial information, document watershed characteristics, perform spatial analysis, delineate basins and streams, construct inputs to hydrologic models, and print reports. This tool was decided upon for use because of its integration with the Hydrologic Engineering Center's Hydrologic Modeling System (HEC-HMS) software and it was developed to use readily available digital geospatial information to construct hydrologic models more expediently than using manual methods.

HEC-GeoHMS was used to create background map files and basin model files. The basin model file contains hydrologic elements (basins) and their hydrologic connectivity (routing reaches). The basin area, length, length to centroid, and slope as well as the routing reach length and slope were determined using available geospatial data.

1.4 Data Collection

In order to facilitate the HEC-GeoHMS hydrologic modeling extension in Esri's ArcGIS software, several geospatial data sets were required. The HEC-GeoHMS extension uses a base digital surface elevation model to develop a series of raster data layers that are then used to delineate basin boundaries within the target watershed. A large amount of data is made available through the USDA/NRCS Geospatial Data Gateway (http://datagateway.nrcs.usda.gov/) and many of the necessary spatial data layers were downloaded from this website. Spatial data sets gathered from the USDA website included vector data files for 2013 Hydrologic Unit Code (HUC) boundaries, the 2012 National Hydrography Dataset (NHD), and the 2012 Gridded Soil Survey Geographic (gSSURGO) database. Raster data files were downloaded for Digital Line Graphs (DLG) and the 2001 National Land Cover Dataset. The base digital surface elevation model was created by the USGS as a 10 meter (1/3 arc second) Digital Elevation Model (DEM) shaded relief and Digital Raster Graphic (DRG) dataset. Raster and vector datasets for the study area were obtained through United States Geological Survey's (USGS's) National Map Seamless Server website, http://viewer.nationalmap.gov/viewer/. Roadway data sets developed by CDOT were also used. Digital aerial photography collected through the National Agriculture Imagery Program (NAIP) were downloaded and used for reference. The

National Flood Hazard layer for Boulder County was obtained through FEMA to depict flood mapping. All of the datasets were used in the HEC-GeoHMS ArcGIS extension to define the parameters and variables required to accurately define and depict the sub-basin geometry within the watershed.

1.5 Flood History

Unlike the September 2013 Flood, historical floods in Boulder County are due mainly to snowmelt combined with heavy rainfall, although heavy rainfall, especially in the form of cloudbursts, is also capable of causing flooding. A brief summary of the St. Vrain Creek flood history obtained from the 2012 Boulder County Flood Insurance Study (FIS) is provided here, for more detailed information please refer to the FIS.

Early records of floods in Lyons are fragmented and lacking in detail. Flooding occurred on St. Vrain Creek in 1864, 1876, 1894, 1919, 1941, 1949, 1951, 1957, and 1969. The floods of June 1864 and May 1876 were severe and much valley farmland was flooded. The flood of May 31, 1894, inundated the entire lower part of town. Although 20 homes at Lyons were washed away, no lives were lost. This flood had an estimated peak discharge of 9,800 cfs at Lyons, with most of the flow coming from South St. Vrain Creek.

In late July 1919, a series of severe thunderstorms caused flash flooding along St. Vrain Creek. The following is from the *Lyons Recorder*, dated August 2, 1919:

> *"The heaviest and most destructive cloudburst…in the memory of the oldest inhabitant, visited Lyons on Wednesday, July 30, between 2:30 and 3:45 P.M. It took out all bridges on the North St. Vrain for about 5 miles up and 5 miles downstream. The Longmont and Lyons water mains up the canyon were torn out along the narrow canyon. The people living…along the banks of the river were flooded out, and many abandoned their homes for higher ground and safety… homes (in the lower part of town)…were in a roaring sea of water 2 and 3 feet deep."*

Another crest on the following day flooded houses again in the lower areas of town and washed out 300 yards of railroad track east of Lyons. The peak discharge on July 30 was later computed to be 9,400 cfs. The right bank of North St. Vrain Creek was flooded to a width of 300 feet.

The largest peak discharge of record on St. Vrain Creek at Lyons was 10,500 cfs on June 22, 1941. This flood originated mostly on South St. Vrain Creek, and the creek peaked very rapidly with floodwaters receding quickly. It is assumed that an extremely localized cloudburst occurred over South St. Vrain Creek a short distance upstream from Lyons.

The effects of the June 4, 1949 flood were felt largely downstream of Lyons. Prolonged rainfall and heavy snowmelt kept St. Vrain Creek out of its banks in rural areas during most of the month of June. Bridges, roads, and irrigation head works were damaged.

Lyons received 6.3 inches of rain from a cloudburst storm that began at approximately 6 p.m. on August 3, 1951. This combined with generally heavy rains over the basin caused flooding from Lyons to the mouth of St. Vrain Creek. The flood lasted for less than 12 hours. Severe damage resulted to State Highway 7 along South St. Vrain Creek.

On May 8 and 9, 1957, approximately 3 to 5 inches of rain fell over the entire basin of St. Vrain Creek. The rain began at approximately 10 p.m. and stopped at approximately 6 a.m. On May 9, at approximately 1 a.m., St Vrain Creek peaked at Lyons at 3,060 cfs. The flood damaged and destroyed irrigation diversion works and bridges downstream from Lyons.

In 1969, heavy rainfall combined with snowmelt caused prolonged high flows on St. Vrain Creek. The worst flooding occurred on May 7 and 8 and from June 15 to June 21. Roads and bridges along the stream were extensively damaged, stream banks were eroded, and farmlands were flooded. On May 7, the peak discharge at Lyons was 2,900 cfs. Button Rock Dam, which was completed in the same year, inadvertently reduced the magnitude of the discharge that could have inundated Longmont (2012 FIS).

2.0 HYDROLOGIC ANALYSIS

2.1 Previous Studies

The effective Boulder County Flood Insurance Study (FIS) was published by the Federal Emergency Management Agency (FEMA) on December 18, 2012. Therefore, the information included in the FIS was up to date and there are no known relevant studies that occurred between the FIS effective date and the September 2013 flood event.

The hydrologic and hydraulic analyses for the original study for the unincorporated areas of Boulder County were performed by the U.S. Soil Conservation Service (SCS) in August 1974.

Frequency-discharge data for St. Vrain Creek in Longmont are based on information published in the June 1972 USACE Floodplain Information Reports Volume III for Lower St. Vrain. The 1-percent annual chance flood discharge on St. Vrain Creek is 10,200 cfs below Lyons, 11,200 cfs above the confluence with Lefthand Creek, and 13,200 cfs below the confluence with Lefthand Creek. The 0.2-percent annual chance flood discharges equal the discharge for the standard project flood (generally 40% to 60% of PMF) as published in the 1972 Floodplain Information Reports. This relationship is based on a log-Pearson Type II analysis of peak runoff data recorded at gages on St. Vrain Creek near Lyons and Platteville in accordance with U.S. Water Resources Council Bulletin 15. The years of record vary from 79 years at the Lyons gage to 47 years at the Platteville gage.

Frequency-discharge data for St. Vrain Creek in Lyons was initially based on information published in the September 1972 USACE Floodplain Information Reports Volume IV for Upper St. Vrain Creek. The 1-percent annual chance flood discharge on South St. Vrain Creek was 6,450 cfs, on North St. Vrain Creek it was 4,900 cfs, and on St. Vrain Creek below Lyons it was 10,200 cfs. The 0.2-percent annual chance flood discharges equal the discharge for the standard project flood (generally 40% to 60% of PMF) as published in the Floodplain Information Reports. This relationship was also based on a log-Pearson Type II analysis of peak runoff data recorded at gages on St. Vrain Creek near Lyons and Platteville in accordance with U.S. Water Resources Council Bulletin 15. These peak flows were subsequently updated in later studies.

The Lyons stream flow gage, located on the left bank of St. Vrain Creek 0.4 miles downstream from the confluence of North St. Vrain Creek and South St. Vrain Creek, has been in operation since 1895. The flows recorded are partly regulated by small diversions above the gage station. Significant peak flood discharges and stages recorded during this period are presented in Table 1.

Table 1 – Historic Flood Peak Discharges and Stages at Lyons Gage

Date	Stage (feet)	Maximum Discharge (cfs)
July 30, 1919	7.9	9,400
June 22, 1941	8.06	10,500
June 4, 1949	4.95	2,970
August 3, 1951	5.37	3,920
May 9, 1957	5.97	3,060
May 7, 1969	6.80	2,900

The subsequent hydrologic and hydraulic analyses for the Town of Lyons were performed by Howard, Needles, Tammen & Bergendorff in October 1977. The updated discharge-frequency relationships in the St. Vrain Creek basin at Lyons were based upon data generated for the June 1972 and September 1972 Floodplain Information Reports of Lower and Upper St. Vrain Creek by the USACE and on an updated statistical analysis of the stream gaging records of the St. Vrain Creek at Lyons. Synthetic unit hydrographs were developed for the St. Vrain Creek Basin and its sub-basins of North St. Vrain Creek and South St. Vrain Creek to help define the flow characteristics within the basin. The hydrographs were used for stream routing through Button Rock Dam to Lyons, and downstream from Lyons to determine the discharges throughout the length of the stream. Therefore, the current regulatory flows for North St. Vrain Creek include the impacts of Button Rock Dam.

Table 2 – Select Peak Discharge Values from 2012 FIS

Flooding Source and Location	Drainage Area (sq. mi.)	Peak Discharge (cfs)			
		10-yr	50-yr	100-yr	500-yr
Middle St. Vrain Creek					
at confluence with South St. Vrain Creek	32.4	590	1,430	2,000	4,070
at Peaceful Valley (State Route 72 Bridge)	18.7	470	860	1,180	2,320
North St. Vrain Creek					
at confluence with St. Vrain Creek and South St. Vrain Creek	125	1,000	2,850	4,310	10,630
South St. Vrain Creek					
at confluence with St. Vrain Creek and North St. Vrain Creek	92	1,400	3,750	5,430	11,900
at confluence with Middle St. Vrain Creek	66.7	1,220	2,790	3,990	8,560
St. Vrain Creek					
at Boulder-Weld County Line	351	5,520	10,950	14,850	28,670
at 85th Street	241	3,160	6,890	9,580	19,680
Just downstream of confluence of North St. Vrain Creek and South St. Vrain Creek	211	2,040	6,670	8,880	20,260

In 1978, Camp, Dresser & McKee Inc. developed a flood information report for South St. Vrain Creek and Middle St. Vrain Creek upstream of Lyons. The flood flow frequency data were based on regional relationships for statistical parameters of a log-Pearson Type III distribution. The regional relationships were developed through statistical analyses of stream flow records at ten USGS gaging stations located in the upper St. Vrain Creek and Big Thompson River basins. These relationships were used to develop peak flows at numerous locations along Middle St. Vrain Creek and South St. Vrain Creek.

2.2 September 2013 Peak Flow Estimates

Estimates of peak discharges associated with the September flood event based on field observations were undertaken by Bob Jarrett of Applied Weather Associates (AWA) as documented in the report *Peak Discharges for the September 2013 Flood in Selected Foothill Region Streams, South Platte River Basin, Colorado*. Over a long career with the USGS, Bob has developed techniques for making peak discharge estimates based on observations of high water marks and paleoflood evidence. Some of the important elements involved in making appropriate estimates include finding a suitable location on the river, accounting for the high hydraulic roughness that can develop during large floods, and factoring in the influence of sediment and debris. A brief description of the observation and discharge estimation techniques is included in Appendix A.

Key locations along the St. Vrain Watershed were identified, mapped, and prioritized for use by Bob in the field observations and discharge estimates. The discharge estimates provided by Bob Jarrett, as well as any other available discharge estimates in the watersheds, were compared to the current regulatory discharges to provide an initial assessment of the relative magnitude of the September floods. This information is documented in a memo entitled *CDOT/CWCB Hydrology Investigation Phase One – 2013 Flood Peak Flow Determinations*, dated January 21, 2014 which was later revised on July 16, 2014. This memo is included in Appendix A and the primary update to the memo regarding St. Vrain Creek was the updated peak discharge estimate in Lyons (23,000 cfs vs. 19,600 cfs). The increased peak discharge estimate was based on additional high water marks obtained by Bob Jarrett and a HEC-RAS analysis of the Highway 36 bridge crossing. Peak discharge estimates indicated in the July 16 memo are preliminary and subject to revision based on subsequent evaluations and comparisons. See Table 6 for a summary of the estimated 2013 peak flow discharges.

The US Geological Survey (USGS) has been engaged in preparing estimates of peak discharges associated the September 2013 flood event, including points within the St. Vrain watershed. Results of the USGS analysis have not been published as of the date of this report.

2.3 Updated Flood Frequency Analysis

Flood frequency analyses were performed to supplement the hydrologic evaluation of Saint Vrain Creek. The analyses followed the methods described in the document *"Guidelines for Determining Flood Flow Frequency"* published by the US Geological Survey on behalf of the Interagency Advisory Committee on Water Data, dated September 1981. This document is commonly known as *Bulletin 17B*.

Following the Bulletin 17B methods within the computer program HEC-SSP, Ayres Associates conducted the analyses using the annual peak flow records at the following stream flow gage:

St. Vrain Creek at Lyons

- USGS Gage 06724000 (1888 – 1998)
- CDWR Gage SVCLYOCO (1991 – 2012)

The Saint Vrain Creek gage record has 121 annual peaks from 1888 through 2012 with only a small gap between 1891 and 1895. The September 2013 flood was added to the data record with an estimated peak value of 23,300 cfs because the gage was destroyed during the flood and did not record a peak. The largest flood peak recorded at the gage is 10,500 cfs from 1941.

The hydrologic evaluation task force assembled by CDOT and CWCB for this effort conferred on the appropriate approach to take in the handling of stream flow gage data for flood frequency analysis. It was decided that to the extent practicable the methods recommended by Bulletin 17B should be followed. Stream gage analysis by Bulletin 17B methods requires as input the highest peak flow discharge for every year and the regional skew coefficient. The document recommends the use of a weighted skew coefficient that incorporates both the station skew and an appropriate general or regional skew. The regional skew coefficient has a strong influence on the resulting flood frequency relationship. It was agreed that the general skew coefficient map from Bulletin 17B would not be appropriate for this analysis because it is based on very old data. Therefore the approach initially taken (for the analyses reflected in the draft report) was to develop a regression equation for the regional skew coefficient derived from an analysis of 24 gage stations along the northern Front Range. The peak discharge from the 2013 flood had only been determined for a fraction of the gage locations that were included in the regional skew analysis. In order to incorporate a large number of regionally appropriate gages into the analysis, it was decided to incorporate many gages for which the 2013 peak flood discharge had not yet been determined. For the sake of consistency, the 1976 flood and 2013 flood were omitted from all gages for the regression analysis.

However, external review of the draft report led to comments that consideration should be given to revising the flood frequency analyses to simply use the station skew at each station rather than regionally weighting the skew coefficient. The comments arose from the observation that the analyses using the regional skew coefficients were yielding 100-year discharge values that were in some cases smaller than two or three of the flood peaks in the historical data. It was also observed that the difference between the station skew and regional skew coefficients exceeded 0.5 at some stations. Bulletin 17b warns that at such locations the regionally weighted skew approach can be inaccurate.

The detailed input to, and output from HEC-SSP for both gages using the revised approach based on station skew is included in Appendix B. The results are summarized in Table 2 below. Based on these results, the 2013 flood peak at Lyons significantly exceeded the 500-year event.

Table 3. Results of Flood Frequency Analysis for St. Vrain Creek at Lyons

Exceedence Recurrence Interval (years)	Discharge (cfs)
2	958
5	1,771
10	2,652
50	6,239
100	8,840
500	19,330

Although other gaging stations are located in the St. Vrain watershed (e.g. Middle St. Vrain Creek near Allenspark, South St. Vrain Creek near Ward, and North St. Vrain Creek at

Longmont Dam near Lyons), their relatively short period of record and the fact that they were discontinued well before the 2013 flood precluded their use in this study. Reliable flood-frequency relations are difficult to estimate when using short gage record lengths, particularly for semi-arid and arid basins in the western United States. The occurrence of high-outliers and low-outliers, mixed-population sources of flooding, non-stationarity (the effects of long-term variability on flood estimates), and other factors also contribute to uncertainty in flood-frequency estimates (Jarrett 2013).

2.4 Rainfall / Runoff Model for September, 2013 Event

2.4.1 Overall Modeling Approach

A hydrologic analysis was performed on the St. Vrain watershed to evaluate and attempt to replicate the September 2013 Flood event along the Front Range. The September 2013 flood event was modeled using the United States Army Corps of Engineers (USACE) Hydrologic Engineering Center's Hydrologic Modeling System (HEC-HMS) to calculate the peak runoff experienced during the flood within St. Vrain Creek, North St. Vrain Creek, South St. Vrain Creek and Middle St. Vrain Creek.

Of the various hydrologic models accepted by FEMA, HEC-HMS version 3.5 was determined to be the best suited for modeling the rural mountainous watersheds included in the CDOT scope of work. The primary reasons HEC-HMS was chosen are that it includes several different options to simulate the hydrologic response in a watershed including various infiltration loss methods (constant loss, exponential loss, CN method, Green-Ampt, Smith-Parlange, and soil moisture accounting), transform methods (kinematic wave and various unit hydrographs), and reach-routing methods (Modified Puls, Muskingum, Muskingum-Cunge, Lag, and Kinematic Wave). HEC-HMS also has a GIS interface (HEC-GeoHMS) which helped in obtaining the necessary model input parameters.

The Curve Number method was selected for infiltration losses due to its simplicity and the availability of soil and land cover data. However, as discussed later in this report, several other infiltration methods were evaluated to make sure the CN method was the most appropriate. For the transform method, the Snyder Unit Hydrograph was selected since it was developed in rural watersheds in the Appalachian Mountains and is also the basis of the Colorado Unit Hydrograph Procedure (CUHP). The two required input parameters for the Snyder UH are lag time (Tlag) and peaking coefficient (Cp). These parameters were initially estimated from the subcatchment length, length to centroid, and slope as outlined in the CWCB Floodplain and Stormwater Criteria Manual. For channel routing the Muskingum-Cunge method with an 8-point cross-section was selected due to the irregular shape of the channel cross-sections and the recommendations provided in the CWCB Floodplain and Stormwater Criteria Manual.

After initial working models were developed in HEC-HMS using HEC-GeoHMS, as discussed in the following sections, the models were then calibrated to the peak discharge estimates derived from field investigations of high water marks. Initially, Button Rock Dam was simply modeled as a junction with no accounting for storage or attenuation of runoff. During the calibration process, information on the stage-storage-discharge relationships for Button Rock Dam was incorporated.

The following sections discuss the steps undertaken during the rainfall/runoff modeling. Associated information is included in Appendix C, as described below.

2.4.2 Basin Delineation

The best available topographic data for watershed delineation were the 10-meter DEMs developed from USGS maps. DEMs are 3-D base maps, which HEC-GeoHMS uses to develop watershed boundaries and flow paths. Reaches were defined within the system based on a minimum tributary area of approximately two square miles. The upstream limits of the watershed are the Little Thompson River watershed to the north, the Continental Divide to the west, and the Lefthand Creek watershed to the south. With the downstream limit of the study set at the U.S. Highway 36 Bridge (CDOT Structure D-15-I) downstream of Lyons, basins were delineated around all reaches and confluences. The overall watershed was divided into 59 basins ranging from 0.25 square miles to 10 square miles. Basins were manually subdivided where necessary in order to compare peak discharge estimates at investigation sites with results from the hydrologic model. The seven peak discharge estimation locations are:

1. Middle St. Vrain Creek at Riverside
2. South St. Vrain Creek below Middle St. Vrain Creek
3. South St. Vrain Creek above Lyons
4. North St. Vrain Creek at Highway 7
5. North St. Vrain Creek below Button Rock Dam
6. North St. Vrain Creek above Lyons
7. St. Vrain Creek below Lyons at Highway 36 Bridge (D-15-I)

2.4.3 Basin Characterization

The St. Vrain basin is mountainous and mostly wooded with steep valley sides draining laterally toward central stream features. The basin is mostly rural with the Town of Lyons located at the eastern limit of the basin. Three major creeks divide the basin; North St. Vrain Creek, Middle St. Vrain Creek and South St. Vrain Creek. The total watershed for the study area is approximately 218 square miles.

The CN values used for the hydrologic analysis were obtained from the TR-55 manual for various soil groups and land cover types. The curve numbers represent the four (4) hydrologic soil groups (A, B, C, and D) for various land cover types including, but not limited to:, mixed forest, shrub/scrub, herbaceous grasslands, pasture, rock outcroppings, developed land, and water bodies. A hydrologic condition of “good” was initially applied to all CN values. These individual soil group and land cover types were then compiled to create a CN lookup table. The soil type and land cover datasets were then merged in GIS using the union tool to create a single layer with polygons representing the intersections of the two datasets. The “Generate CN Grid” tool in HEC-GeoHMS then utilizes the CN lookup table and the merged soil type/land cover polygon layer to generate a “CN” field in the soil type/land cover attribute table. The basin delineation boundaries were then overlaid with the soil type/land cover polygon layer to calculate area-weighted CN values for each basin. The resulting area-weighted CN values ranged from approximately 30 to as high as 90. The CN method impervious percentage input value for each basin was set to zero because all impervious areas were accounted for in the area-weighted CN.

The Snyder Unit hydrograph transform method was utilized to determine the shape and timing of runoff hydrographs for each basin. The Snyder Unit hydrograph transform method uses a peaking coefficient and the standard lag time as required input parameters. A default peaking coefficient of 0.4 was initially selected for all basins as being representative of mountain areas. The lag time was calculated using Equation CH9-510 and Table CH9-T505 in the CWCB Floodplain and Stormwater Criteria Manual. A default Kn value of 0.15 for evergreen forests was used for the basin roughness factor. The remaining input parameters for the lag time equation include basin length (miles), length to basin centroid (miles), and average basin slope (feet per mile). These parameters were acquired using the HEC-GeoHMS program and the project DEM and DRG datasets. Appendix C.6 summarizes the final model input parameters.

2.4.4 Hydrograph Routing

The Muskingum-Cunge routing method was used to route the runoff hydrographs generated from each basin. The required input parameters for this method included: channel length (feet), channel slope (feet/feet), an 8-point cross-section to represent the channel width and side slopes, and Manning's n values for the channel and overbank areas. The length, slope and 8-point cross-section station-elevation data of the channel reaches were acquired using the HEC-GeoHMS program and the 10-meter DEM and DRG datasets. The Manning's n values were initially set to a default of 0.05 for the channels and 0.10 for the overbank areas. Appendix C.6 summarizes the final model input parameters.

2.4.5 2013 Rainfall Information

The rainfall data required for the meteorological component of the HEC-HMS model were obtained for the September, 2013 storm from Applied Weather Associates (AWA). The Storm Precipitation Analysis System (SPAS) was used to analyze and calibrate the rainfall. SPAS uses a combination of climatological basemaps 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, SPAS through the use of climatological basemaps and weather radar data accounts for topography and locations of rain gages. For quality control, SPAS storm analyses have withheld some rain gages observations and run the rainfall analysis to see how well the magnitude and timing fit at the withheld rain gage locations. In almost all cases, the analyzed rainfall has been within five percent of the rain gage observations and usually within two 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. There was excellent weather radar coverage along with many rainfall observations with excellent overall spatial distributions at both low and high elevation locations. Another important point to note is that although convective rainfall estimated from NEXRAD can be questionable in the Colorado Front Range foothills, there are many papers in the literature on the good to excellent reliability of NEXRAD for frontal/upslope storms such as the September 2013 storm. Further information on SPAS can be found at the Applied Weather Associates website: http://www.appliedweatherassociates.com/spas-storm-analyses.html.

Basin shape files were provided to AWA to overlay on top of the gridded data. NEXRAD radar imagery utilized a best fit curve to break down the hourly storm increments into five minute increments at a grid spacing of one kilometer. The gridded rainfall information was then converted to an average rainfall hyetograph for each basin and imported into HEC-HMS as time series precipitation gage data. The hyetographs include 10 days of 5-minute incremental rainfall depths at the centroid of each basin.

The average 10-day cumulative rainfall depth for all of the basins was 10.99 inches, ranging from as low as 5.29 inches up to 16.13 inches for the individual basins. However, the majority of this rainfall fell within a 24-hour period starting around 1 A.M. on Thursday, September 12, 2013. The average 24-hour rainfall depth for all of the basins was 5.83 inches, ranging from 1.43 inches up to 9.55 inches for the individual basins. The average 24-hour rainfall depth of 5.83 inches roughly corresponds to a NOAA 200-year 24-hour rainfall depth.

Figure 2. September 2013 Rainfall Hyetograph upstream of Lyons on South St. Vrain Creek

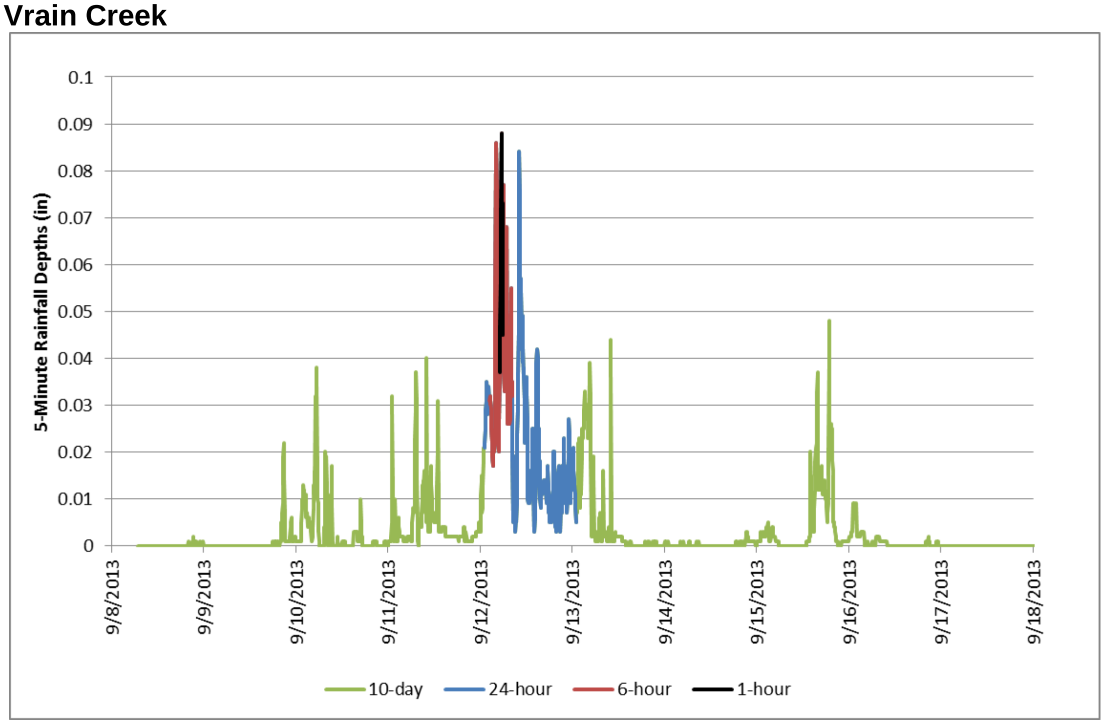


Figure 2 shows a hyetograph for Basin SV800 on South St. Vrain Creek just upstream of Lyons. The incremental depths are based on a 5-minute time step. As shown in Table 4, Basin SV800 experienced higher than average rainfall totals and intensities in the study area. The time of occurrence for maximum rainfall depth for various durations is shown on Figure 2 in different colors. It should be noted that the 10-day rainfall total exceeds a 1000-year event, the maximum 24-hour rainfall total is approximately a 500-year event, the maximum 6-hour rainfall total is approximately a

50-year event, and the maximum 1-hour rainfall total is only a 2-year event. This is a good indicator that although the total rainfall depth is an extremely rare event, the rainfall intensities for shorter durations were not that extreme.

The HEC-HMS model Control Specifications were set to coincide with the rainfall period start and end times. The background map for the model used the GIS basin delineations shapefile to provide spatial reference for the model components.

Table 4. Representative Rainfall Depths from September 2013 Flood and Associated NOAA Atlas 14 Recurrence Intervals

Location	Cabin Creek Headwaters (SV610)		Near Button Rock Dam (SV710)		South SVC above Lyons (SV800)		Rock Creek Headwaters (SV800)		South SVC Headwaters (SV1060)	
Duration	Rainfall (in)	NOAA RI (yr)	Rainfal l (in)	NOAA RI (yr)	Rainfall (in)	NOAA RI (yr)	Rainfall (in)	NOAA RI (yr)	Rainfall (in)	NOAA RI (yr)
10-day	10.40	100 to 200	16.13	> 1000	12.66	> 1000	10.94	500 to 1000	5.29	5
24-hour	5.62	100 to 200	9.55	> 1000	7.02	500	5.50	200	1.43	< 1
6-hour	2.56	50	4.37	500 to 1000	3.02	50	2.59	50	0.60	< 1
1-hour	0.57	1 to 2	1.15	10	0.72	2	0.28	< 1	0.12	< 1

2.4.6 Model Calibration and Validation

The first step in the model calibration process was calibrating the rainfall data from the 2013 storm to ground measurements, as discussed in the previous section. Once all required model input parameters were obtained and the rainfall data from the 2013 flood were incorporated, initial runs of the model were made to identify any potential errors in the setup. Once the base model was up and running correctly with the default input parameters, the second step was to begin calibrating the model to match the estimated peak discharges for the 2013 flood event.

Many of the model input parameters are physically based such as lengths and slopes of basins and channels. However, there are several input parameters that are empirical and can be used as calibration parameters. Four calibration parameters were evaluated to try and match the estimated peak discharge points from the 2013 Flood event including: Curve Number (CN), Peaking Coefficient (Cp), Basin Roughness (Kn), and Channel Roughness (Manning's n).

In order to determine the sensitivity of each of the four calibration parameters, attempts to calibrate the entire watershed using only one parameter at a time were conducted. From this analysis, it was determined that the peak flows and timing of peaks were most sensitive to the CN value selected for each basin.

Changing the CN value impacts the initial abstraction and the decaying infiltration rate which has the combined effect of reducing the total runoff volume over the 10-day period. More specifically, changing the CN value has noticeable effects on runoff volume during the first few days of the storm when the initial abstraction is being utilized, but then high peak discharges are still observed when the most intense part of the hyetograph occurs later.

Changing Cp and the Kn value in the lag time equation had some effect on localized basin peak discharges, but these effects did not translate downstream very far in the routing network. Changing the steepness of the hydrograph or the timing of the peak had little influence downstream because of the nature of this long duration storm with recurring periods of high rainfall. The individual basin runoff hydrographs typically had at least two peaks close together which regardless of small shifts in timing would still overlap with the peaks from adjacent basins as they are routed downstream.

Attempts to calibrate the model using the channel roughness alone did not produce noticeable impacts. Dramatic adjustments to the Manning's n value up or down had some minor effect on the timing of peaks but had no effect on the magnitude of the peak. Various cross-section shapes were also evaluated with little effect. After some additional research, it was concluded that the Muskingum-Cunge method, as well as several of the other HEC-HMS routing options, are highly sensitive to channel slope. The relatively steep mountain slopes within the study area were therefore the predominant factor in channel routing calculations and limited the effect of the roughness coefficient as a calibration parameter for adjusting travel times and coincidental peaks. Further review of literature, specifically reports by Jarrett (1985) and Barnes (1967) regarding the appropriate Manning's n values for mountain streams was conducted and it was determined that a default value of 0.15 was appropriate for the channels in this watershed.

After conducting the sensitivity analysis on the individual calibration parameters, additional attempts were made to get a best fit to the 2013 Flood peak discharge estimates by calibrating the CN, Cp, and Kn values simultaneously. However, it was subsequently determined that focusing the calibration effort on the CN value while holding the other parameters at reasonable default values was the most logical approach. This decision was supported by calibration efforts being performed concurrently in the Lefthand Creek Watershed and Big Thompson River Watershed. While the combined calibration approach was being conducted, the U.S. Bureau of Reclamation provided a stage-storage relationship for Lake Estes in the Big Thompson Watershed, along with stage-storage-discharge time-series data during the 2013 Flood event. This valuable information allowed better calibration and optimization routines to be run on the Big Thompson Watershed upstream of Lake Estes with respect to timing, volume and peak discharges based on a calculated inflow hydrograph to Lake Estes. The optimization results showed that the CN value was the dominating calibration factor. The Lake Estes optimization results for the Big Thompson watershed are included in Appendix C.5 for reference.

Calibrating the model to match the 2013 Flood peak discharge estimates was relatively straightforward at most locations. However, at a few locations, the peak discharge estimates were difficult to attain even when pushing the calibration parameters well beyond acceptable limits. In some cases runoff produced from a single basin prior to any channel routing would only be a small fraction of the peak discharge estimate at that same location. In these cases, all attempts were made to double check measured input parameters for errors including basin area, length, length to centroid, slope, and associated rainfall data.

There were locations were peak discharge estimates (and associated unit discharges cfs/sq.mi.) fluctuated up and down within short reaches when moving downstream through the watershed. Upon further discussion with the project team and review of available field data, it was hypothesized that several locations in the watershed experienced some form of a dam failure (possibly from woody debris dams, road-embankments, beaver dams, stock ponds, or landslides) that generated peak discharges significantly higher than the rainfall/runoff process alone would have produced. Evidence of these types of dam failures and associated surging flood pulses was documented in the USGS report (Godt et al., 2013).

Additional analysis was undertaken to develop expected unit discharges (cfs/sq.mi.) at the estimation locations for all watersheds being studied by CDOT. These unit discharges were then compared against one another as well as against model results throughout each of the study watersheds. In addition, unit discharges were also normalized with respect to the to the peak 1-hour rainfall experienced in the corresponding basins. Graphical curves were developed to provide a best-fit to this unit discharge data. This information and the best-fit curves helped to identify peak discharge estimates that were likely impacted by phenomenon other than the natural rainfall/runoff process. In these locations, attempts were made to calibrate the models while considering the "natural" flow that would be expected based on the unit discharge curves. After several iterations of calibrating the model, it was determined that a relatively good fit to the estimated peak discharges had been obtained. Calibration results for the 10-day 2013 Flood event are discussed in more detail in Section 3.0 of this report.

2.5 Rainfall / Runoff Model for Predictive Peak Discharges

2.5.1 Overall Modeling Approach

Once the rainfall-runoff model was calibrated to represent the September 2013 rainfall and peak runoff, the model was used to predict peak discharges based on NOAA rainfall for a number of return periods to help guide the design of permanent roadway improvements in the study watersheds. This analysis of NOAA rainfall data is referred to herein as the predictive model. Several additional calibration steps were involved in this process as described below.

2.5.2 Design Rainfall

The NOAA Atlas 14, Volume 8 was used to determine point precipitation frequency estimates. Isopluvials for 24-hour precipitation depths were overlaid with the basin delineation maps to determine the variation in rainfall depths within the watershed. Based on the isopluvials, the St. Vrain Watershed was broken into three raingage zones corresponding with basin boundaries. Latitude and Longitude values were determined for the centroid of each raingage zone in order to obtain precipitation frequency estimates. Table 6 shows the point precipitation values for the different rain gage zones and the basins included in each zone. Table 6 also shows the 90 percent confidence intervals which expresses some of the uncertainty. Zone 1 included 15 basins along the western side of the watershed from approximately the Peak-to-Peak Highway up to the headwaters. Zone 2 included 29 basins in the central part of the watershed. Zone 3 included 15 basins in the eastern part of the watershed near Lyons. The rainfall depths were applied to the standard 24-hour SCS Type II rainfall distribution. The 24-hour distributions were then incorporated into the HEC-HMS model to evaluate peak discharges for the predictive storms.

Table 5. St. Vrain Raingage Zones and Precipitation Depths

Zone	Zone 1 (West)	Zone 2 (Central)	Zone 3 (East)
Latitude	40.18365474	40.1761685003	40.21228738
Longitude	-105.602742	-105.4866579840	-105.3252132
Model Basins	SV990,SV1010,SV1060, SV1050, SV830, SV870, SV890, SV900, SV840, SV640, SV740, SV660, SV550, SV580, SV610,	SV1000, SV960, SV950, SV970, SV980, SV920, SV920A, SV1040, SV1020, SV1030, SV940, SV910A, SV740A, SV760, SV860, SV880, SV790, SV750, SV540, SV560, SV590, SV670, SV770, SV690, SV780, SV850, SV710, SV700, SV1070	SV910, SV930, SV800A, SV800, SV810, SV720, SV630, SV620, SV600A, SV600, SV570, SV650, SV730, SV680, SV820
10-yr, 24-hr	2.89 (2.35 – 3.52)	2.70 (2.19 – 3.29)	2.83 (2.31 – 3.47)
25-yr, 24-hr	3.65 (2.93 – 4.81)	3.42 (2.74 – 4.48)	3.62 (2.90 – 4.73)
50-yr, 24-hr	4.34 (3.38 – 5.78)	4.06 (3.15 – 5.37)	4.31 (3.35 – 5.68)
100-yr, 24-hr	5.11 (3.83 – 7.01)	4.77 (3.57 – 6.50)	5.07 (3.80 – 6.87)
500-yr, 24-hr	7.26 (5.00 – 10.7)	6.72 (4.62 – 9.77)	7.14 (4.91 – 10.3)

Due to the size of the St. Vrain watershed (approximately 218 square miles) it was necessary to consider area correction of the rainfall depths as described in NOAA Atlas 2. For the 24-hr storm duration, rainfall depths are reduced by as much as 8% depending on the drainage area. For tributary areas less than 10 square miles, no area correction was applied. Between 10 and 30 square miles, a 2% reduction was applied. Between 30 and 50 square miles, a 4% reduction was applied. Between 50 and 100 square miles, a 6% reduction was applied. For areas greater than 100 square miles, an 8% reduction was applied. To do this, the entire watershed was run with five different sets of rainfall depths for each return period corresponding to the different levels of area correction. The appropriate peak discharge result at each location in the watershed was then selected based on its relative location with respect to total tributary area. This results in unadjusted rainfall depths being used to generate peak flows in the headwater areas, while the area corrected rainfall depths are used as you move progressively downstream.

2.5.3 Model Calibration

Initial results from the NOAA rainfall predictive model produced peak discharges that were considerably lower than the current regulatory discharges and expected unit discharges. Further analysis of the predictive model results showed that a large percentage of the rainfall in the SCS 24-hour distribution was being removed by the initial abstraction component of the CN infiltration method. This large initial abstraction was resulting in limited rainfall becoming runoff. This raised questions regarding the differences between the SCS 24-hr rainfall distribution and the 2013 storm event which had a long duration with a lower intensity. After some consideration, it became apparent that the calibrated CN values for the 10-day storm were highly dependent on the rainfall early in the storm that saturates the soil prior to the peak rainfall occurring. This also raised some concerns about the applicability of the CN infiltration method. Known weaknesses of the CN infiltration method are that rainfall intensity is not considered and the default initial abstraction does not depend upon storm characteristics or timing. Therefore, three other infiltration options in

HEC-HMS (constant loss, exponential loss, and Green-Ampt) were also evaluated to see if they responded differently to the 10-day vs. 24-hr rainfall duration.

In order to most efficiently evaluate the different infiltration methods, the optimization routines in HEC-HMS were utilized in the 10-day model representing the September 2013 storm. The optimization feature allows the user to specify which model input parameters will be optimized in an attempt to produce runoff that matches an observed hydrograph. Unfortunately, there were no observed hydrographs in the St. Vrain watershed during the 2013 Flood event. Electricity was knocked out at Button Rock Dam during the flood disabling any ability to record discharges from the outlet structure or spillway. The USGS gage in Lyons was also destroyed during the storm and no information was recorded.

However, since the Big Thompson watershed had available time-series data at Lake Estes from the 2013 Flood, an inflow hydrograph to Lake Estes was developed based on the observed stage-storage and stage-discharge information provided by the U.S. Bureau of Reclamation. Therefore, the Big Thompson 10-day model was used to test the various infiltration methods. Within HEC-HMS, the Nedler and Mead search method was utilized with a Peak Weighted Root Mean Square objective function. This means that the infiltration parameters for basins upstream of Lake Estes were iteratively adjusted in an attempt to match the above average peak flow values in the observed hydrograph. The parameters were iteratively adjusted using a scaling factor so that all basin parameters were affected in a consistent manner. Several optimization scenarios were run for the different infiltration methods including:

- Constant Loss Method – optimizing Initial Loss and Constant Loss
- CN Method – optimizing CN value and Initial Abstraction
- CN Method – optimizing CN value only
- Exponential Loss Method – optimizing Initial Range, Initial Coeff, Coeff Ratio, and Exponent
- Exponential Loss Method – optimizing Initial Range, Initial Coeff, and Coeff Ratio
- Green-Ampt – optimizing Initial Loss, Moisture Defecit, Wettting Front Suction, and Hydraulic Conductivity

After reviewing results for the optimization scenarios outlined above (included in Appendix C.5 for reference), it was apparent that the CN Method was actually able to produce the best fit to the observed inflow hydrograph at Lake Estes. Although the CN method has its weaknesses, it is suitable for large return period storm events. Additionally, since it is being used as a calibration parameter, the actual selection of a default value for forested areas is not critical. To further support the continued use of the CN method, the other infiltration methods had their own weaknesses which deterred their use for this project.

After deciding to stay with the CN Method for all watersheds being studied, it was still necessary to address the 10-day storm vs. NOAA 24-hour rainfall duration. Therefore, it was decided to extract the maximum 24-hour period of rainfall from the 10-day period of data and re-calibrate the model. The goal was to determine what adjustment in CN values was necessary to match the estimated 2013 Flood peak discharges using only the maximum 24-hour period of rainfall. At a conceptual level, the idea of adjusting the CN values for all basins in the St. Vrain Watershed to

Antecedent Runoff Condition (ARC) 3 seemed like a good starting point in the calibration process since the early wetting period of the storm had been removed. Chapter 10 of the National Engineering Handbook Part 630 was used to determine the ARC 3 CN value for each basin.

For ARC 3, the average CN value for the watershed (average of all individual basin CN values) increased from 59 for the 10-day model to 76 for the Max24hr model. The model results after adjusting the CN value to ARC 3 produced peak discharges that were almost identical to the estimated 2013 Flood peak discharges and the 10-day model results. However, when initial attempts to use the Max24hr CN values with the SCS 24-hour rainfall distributions were made, the resulting peak discharges were extremely high and did not agree with expected unit discharges or the updated flood frequency analysis. Further investigation revealed that the average 24-hour maximum rainfall for the St. Vrain watershed was a smaller percentage of the average 10-day rainfall than in the Big Thompson watershed and thus curve numbers calibrated for the 24-hour rainfall would have to be inordinately high to compensate for the lower rainfall. The difference between the average 10-day rainfall (10.99 inches) and the average 24-hour maximum rainfall (5.83 inches) for the St. Vrain Watershed was 5.16 inches. Therefore, it should be expected that the high CN values from ARC 3 would be necessary to produce the same peak discharges when only using roughly half of the rainfall total.

This information made it apparent that in order to develop a calibrated model based on the maximum 24-hour rainfall period, it was necessary to consider the percentage of rainfall that becomes runoff during the peak of the storm for both the 10-day model and the Max24hr model. Therefore, a ratio of total runoff (inches) divided by total rainfall (inches) was determined for each individual basin in the 10-day model. These ratios were then multiplied by the maximum 24-hour rainfall depths for each basin to determine the corresponding runoff depth expected for each basin during the 24-hour period of maximum rainfall. The goal was to maintain consistency between the amount of rainfall that infiltrated and the amount that became runoff during the most intense period of the 2013 Flood event. The final step was to iteratively determine the CN values necessary to produce the expected runoff depths for each individual basin. The end result was an average CN value of 63 for the watershed with individual basin CN values ranging from 46 to 81. Appendices C.1 through C.4 include the model results for the Max24hr rainfall period utilizing the ARC 3 CN values as well as the runoff/rainfall ratio determined CN values. The peak discharges for the runoff/rainfall ratio determined CN values are approximately 30% lower than for the ARC 3 CN values.

Using the calibrated Max24hr runoff/rainfall ratio model, the NOAA 24-hour rainfall depths and SCS Type 2 storm distributions were applied for each of the return periods. As a reasonableness check, the predictive model results were compared to expected unit discharges and the updated flood frequency analysis at the Lyons stream gage that was described in Section II.C. These reasonableness checks served to further validate that the CN values from the calibrated Max24hr rainfall model were better able to reflect the difference between the rainfall distributions from the 2013 Flood and the SCS 24-hr storm distributions. Results from the predictive models are discussed in more detail in Section 3.0 of this report.

3.0 HYDROLOGIC MODEL RESULTS

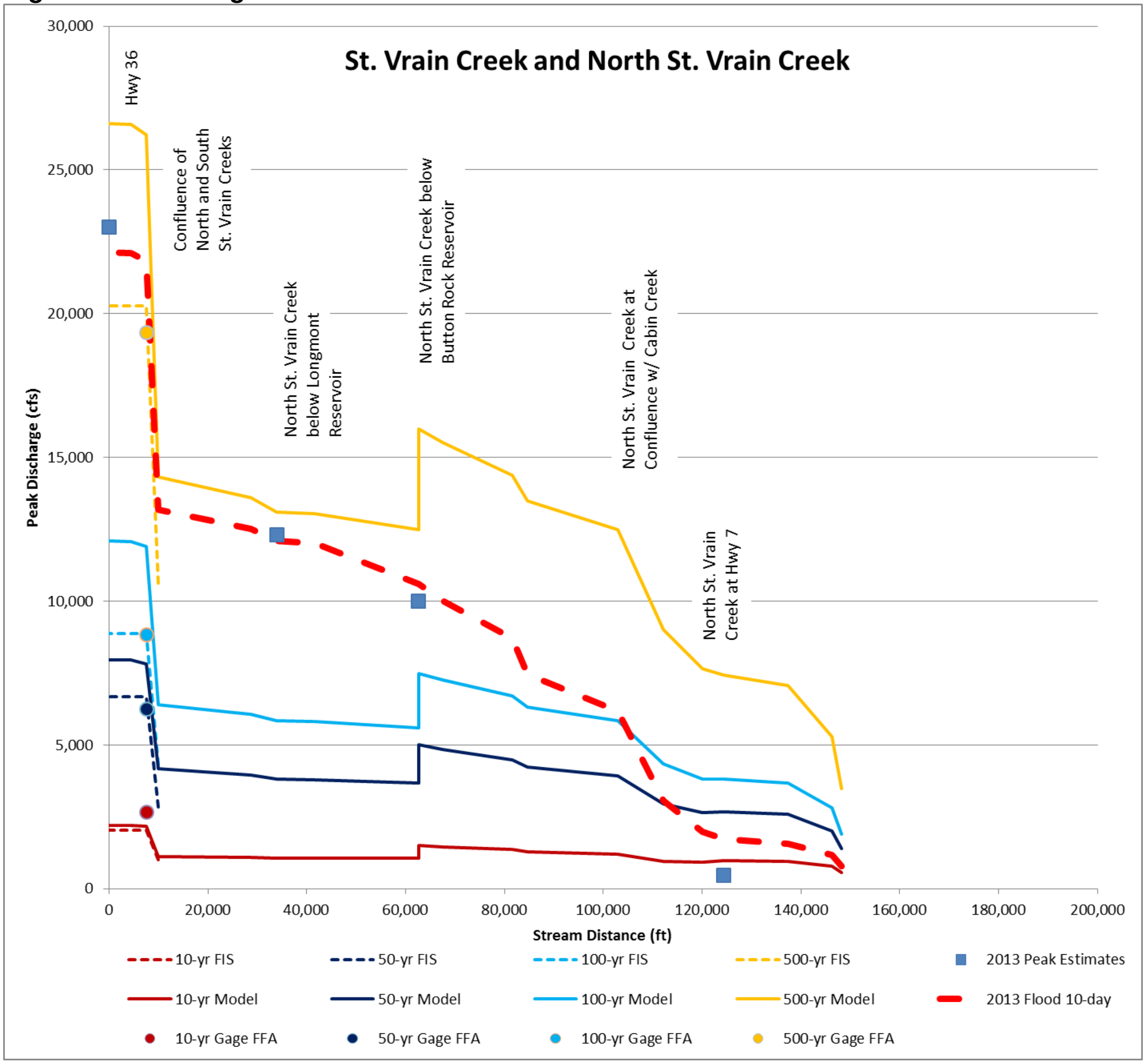
Table 6 (below) and the expanded table in Appendix C.1 show peak discharge results at selected locations along St. Vrain Creek, North St. Vrain Creek, South St. Vrain Creek and Middle St. Vrain Creek. Location descriptions and tributary drainage areas are provided for each location. The table in Appendix C.1 also includes approximate river stationing and the corresponding model node for each location. Estimated peak discharge values from the 2013 Flood were developed by Bob Jarrett and are provided at a few locations. The next column presents the calibrated model results for the full 10-day rainfall period. The calibrated Max24hr model results are presented in Appendix C.1. The last five columns present the NOAA 24-hour Type II distribution storms with area correction for the 10-, 25-, 50-, 100- and 500-year recurrence intervals. The expanded table in Appendix C.1 also includes the 2012 Effective FIS peak discharges at corresponding locations for the 10-, 50-, 100- and 500-year recurrence intervals. It should be noted that effective peak discharge locations were matched as close as possible to the model locations, but in some instances they may be a fair distance apart. Refer to Table 2 for the actual location descriptions and tributary drainage areas for the FIS peak discharges. The expanded table in Appendix C.1 also includes the updated Flood frequency analysis results by Ayres Associates for the 10-, 50-, 100-, and 500-year recurrence intervals.

Table 6. Hydrologic Model Peak Discharge Results

Description	Drainage Area (sq. mi.)	2013 Flood Estimated Peak Discharge (cfs)	2013 Flood 10-day Period Calibrated (cfs)	NOAA Design Storms (Depth-Area Adjusted) 10-yr (cfs)	25-yr (cfs)	50-yr (cfs)	100-yr (cfs)	500-yr (cfs)
Headwaters Middle SVC	14		526	243	497	783	1,162	2,423
Camp Dick on Middle SVC	18		762	279	584	935	1,399	2,966
Middle SVC at Raymond	26		1,588	352	761	1,240	1,882	4,077
Middle SVC at Riverside (Jarrett #55)	30	**1,750**	**1,996**	**364**	**799**	**1,315**	**2,011**	**4,421**
Middle SVC above confluence with South SVC	32		2,430	394	862	1,415	2,162	4,741
Brainard Lake (South SVC headwaters)	9		389	495	835	1,183	1,603	2,883
South SVC at Hwy 72	27		1,556	914	1,628	2,374	3,292	6,132
South SVC above confluence with Middle SVC	35		2,402	993	1,792	2,636	3,679	6,938
Confluence of Middle and South SVC	67		4,525	1,169	2,300	3,585	5,258	10,716
South SVC (Jarrett #56)	68	**2,700**	**4,777**	1,190	2,345	3,658	5,369	10,962
South SVC at Big Narrows	78		6,572	1,376	2,712	4,220	6,189	12,597
South SVC at Little Narrows (Jarrett #57)	83	**9,000**	**7,518**	**1,464**	**2,890**	**4,496**	**6,598**	**13,435**
South SVC above confluence with North SVC	91		8,886	1,605	3,168	4,933	7,234	14,748
North SVC headwaters	13		773	563	972	1,390	1,906	3,482
North SVC at confluence with Cony Creek	21		1,178	768	1,375	2,009	2,807	5,297
North SVC at Copeland Falls	29		1,551	954	1,747	2,590	3,662	7,059
North SVC at Hwy 7 (Jarrett #63)	33	**450**	**1,713**	**963**	**1,785**	**2,667**	**3,799**	**7,423**
North SVC at confluence with Horse Creek below Hwy 7	37		1,972	920	1,737	2,656	3,819	7,636
North SVC at confluence with Rock Creek	53		3,061	952	1,872	2,943	4,330	9,016
North SVC at confluence with Cabin Creek	76		6,162	1,198	2,446	3,921	5,843	12,487
North SVC at Coulson Gulch confluence	83		7,441	1,279	2,627	4,222	6,303	13,499
North SVC at confluence with Dry SVC	91		8,706	1,351	2,786	4,486	6,704	14,371
North SVC inflow to Button Rock Reservoir	98		10,007	1,457	3,013	4,850	7,247	15,522
North SVC inflow to Button Rock Reservoir	101	**10,000**	**10,591**	**1,502**	**3,108**	**5,002**	**7,472**	**16,002**
Discharge from Button Rock Reservoir	101		**10,591**	**1,059**	**2,221**	**3,674**	**5,603**	**12,490**
North SVC below Longmont Reservoir at Hwy 36	111		12,023	1,054	2,289	3,788	5,818	13,049
North SVC (Jarrett #58)	112	**12,300**	**12,094**	**1,056**	**2,299**	**3,804**	**5,842**	**13,100**
North SVC at Apple Valley Road	118		12,501	1,081	2,377	3,938	6,052	13,599
North SVC above confluence with South SVC	124		13,182	1,123	2,502	4,160	6,386	14,329
Confluence of North and South SVC	215		21,827	2,178	4,786	7,828	11,910	26,222
St Vrain Creek at confluence with Stone Canyon	218		22,102	2,202	4,857	7,943	12,080	26,581
Outlet - St. Vrain Creek at Hwy 36 downstream of Lyons	218	**23,000**	**22,127**	**2,202**	**4,860**	**7,949**	**12,089**	**26,599**

Three peak discharge profile plots are also provided in Figures 3, 4 and 5 for St. Vrain Creek and North St. Vrain Creek (combined), South St. Vrain Creek, and Middle St. Vrain Creek, respectively. The Effective FIS peak discharges are plotted as thin dashed lines. The corresponding predictive model results for the NOAA 24-hr Type II distribution storms are plotted as solid lines in the same color as the FIS discharges. The thick dashed red line is the calibrated 2013 Flood model using the full 10-day rainfall period. The estimated peak discharges and flood-frequency results are plotted as points on the profile plots.

Figure 3. Discharge Profile Plot for St. Vrain Creek and North St. Vrain Creek



On St. Vrain Creek in Lyons, the 10-day calibrated model was able to match the estimated peak discharge within 4% (22,130 cfs vs. 23,000 cfs). On North St. Vrain Creek upstream of Apple Valley Road, the 10-day calibrated model was able to match the estimated peak discharge within 2% (12,100 cfs vs. 12,300 cfs). Further upstream at Button Rock Dam, the 10-day calibrated model was able to match the estimated peak discharge within 6% (10,590 cfs vs. 10,000 cfs). It should be noted that the effects of Button Rock Dam were not modeled for the 2013 Flood event because by the time the peak discharge occurred, the reservoir was already filled to capacity and spilling through the emergency spillway. Therefore, it was decided that any attenuation in this particular event was minimal. Further upstream where North St. Vrain Creek crosses Highway 7, a peak discharge of 450 cfs was estimated, however the model was unable to produce a peak discharge this low and still match the peak discharge estimates further downstream.

A concerted effort was made not to over calibrate the model to match all peak discharge estimates. Instead, a systematic approach was taken in the calibration process to ensure a consistent method was used throughout all of the watersheds studied. The goal was to obtain the best overall fit to the majority of the peak discharge estimates rather than try to match them all at the expense of calibration parameters being pushed beyond a reasonable range. The systematic approach prevents individual basins in the model from being biased toward unique occurrences associated with this particular storm event. Although the model has been calibrated to the 2013 Flood event, the end goal is to develop a hydrologic model capable of representing storms of various magnitudes.

The calibrated model results for the NOAA 24-hour predictive storms are also shown on the profile plots in Figures 3 through 5. The model results compared reasonably well with the existing regulatory flows and the updated flood-frequency analysis (FFA).

On North St. Vrain Creek, the only Effective FIS peak discharges are located just upstream of the confluence with South St. Vrain Creek in Lyons. However, the Effective FIS accounts for routing of peak flow hydrographs through Button Rock Dam (2012 FIS). Following discussions with CWCB, it was decided that the model would include attenuation effects of the emergency spillway but would not include any storage of flood flows. This was achieved by assuming Ralph Price Reservoir was completely filled to the elevation of the emergency spillway at the start of the storm. Above this elevation, a stage-area relationship was developed for the reservoir. The emergency spillway was then modeled using the standard broad-crested weir equation. This provided some attenuation of the design storms as shown in Figure 3. However, this approach still resulted in peak discharges that are approximately 12% to 48% higher than the Effective FIS discharges on North St. Vrain Creek upstream of Lyons. Downstream of the confluence on St. Vrain Creek, the model produced peak discharges that are approximately 8% to 36% higher than the Effective FIS discharges.

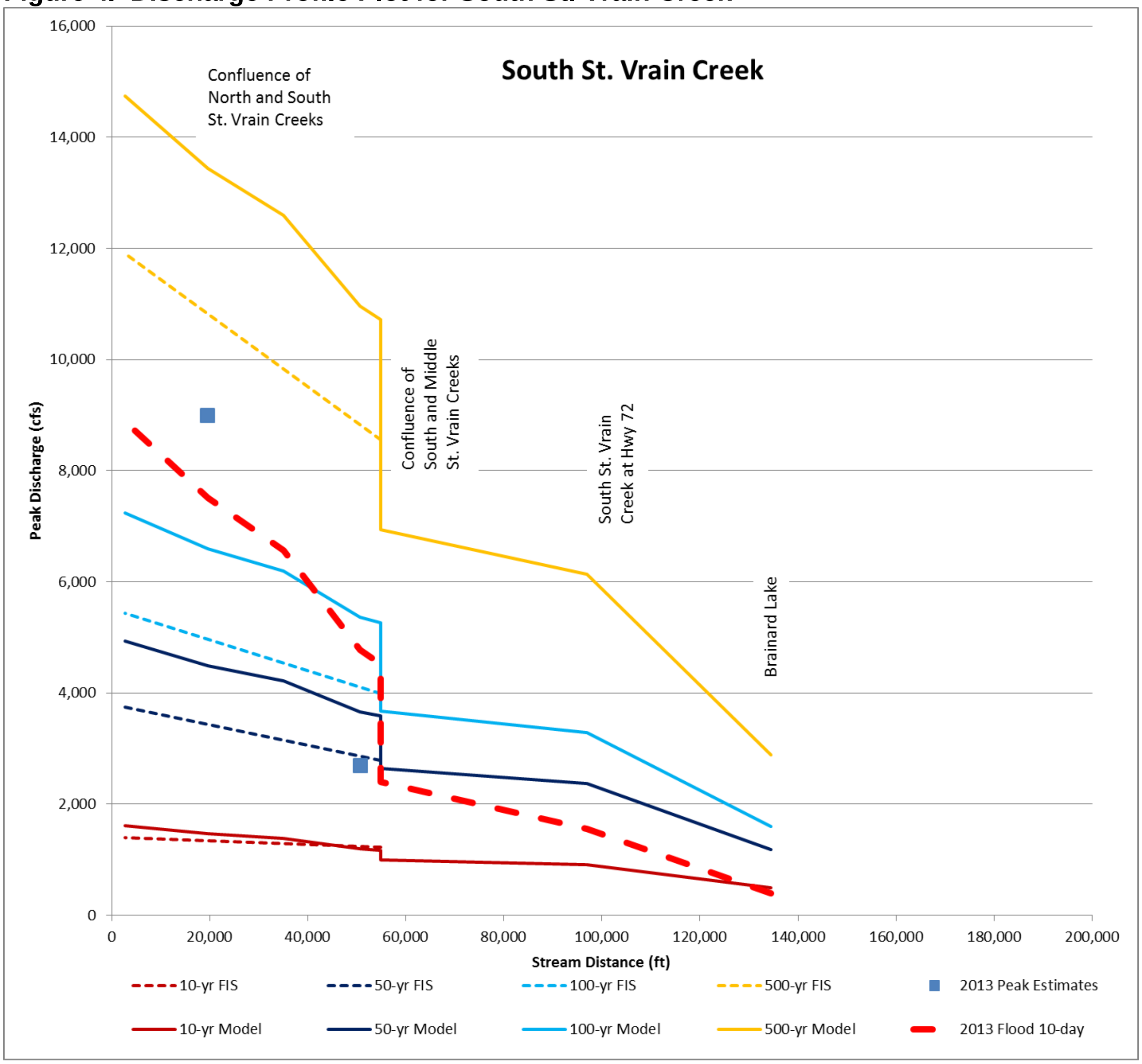
This initially raised some questions into the accuracy of the model and the FIS discharges. Review of the updated Flood-Frequency Analysis by Ayres Associates showed that the FFA produced results for St. Vrain Creek that were slightly lower than the Effective FIS discharges. However, further research into the flood history for St. Vrain Creek, review of the St. Vrain Creek gage data in Lyons, review of the North St. Vrain Creek gage data (27 years), and release information for Button Rock Dam since its construction, it was determined that the reservoir has a significant effect on the updated FFA as well as the previous FFA used to develop the Effective FIS discharges.

Over the course of approximately 30 years (1984 to 2005), the largest peak discharge from Button Rock Dam was approximately 800 cfs. The largest measured peak flow in St. Vrain Creek at the Lyons gage during this same 30-year time period was 4,200 cfs on May 29, 1995. Of this peak flow, only 190 cfs came from the Button Rock outlet works (no discharge was measured through the emergency spillway within a month of that event).

The largest peak flow measured on the North St. Vrain gage was 1,630 cfs in 1941 (period of record was 1926 to 1953). However, the 2012 FIS states that this storm which produced the largest peak discharge on record at the Lyons gage (10,200 cfs), "*originated mostly on South St. Vrain Creek…and it is assumed that an extremely localized cloudburst occurred over South St. Vrain Creek a short distance upstream of Lyons*."

This information indicates that Button Rock Dam has a pronounced effect on peak discharges for the more frequently occurring storms. This in turn affects the flood frequency analysis which is dominated by the smaller events on St. Vrain Creek, many of them likely related to snowmelt events. Therefore, in order to maintain the conservative approach of assuming the reservoir is full when a large storm occurs, the higher peak discharges on North St. Vrain Creek and St. Vrain Creek are justified.

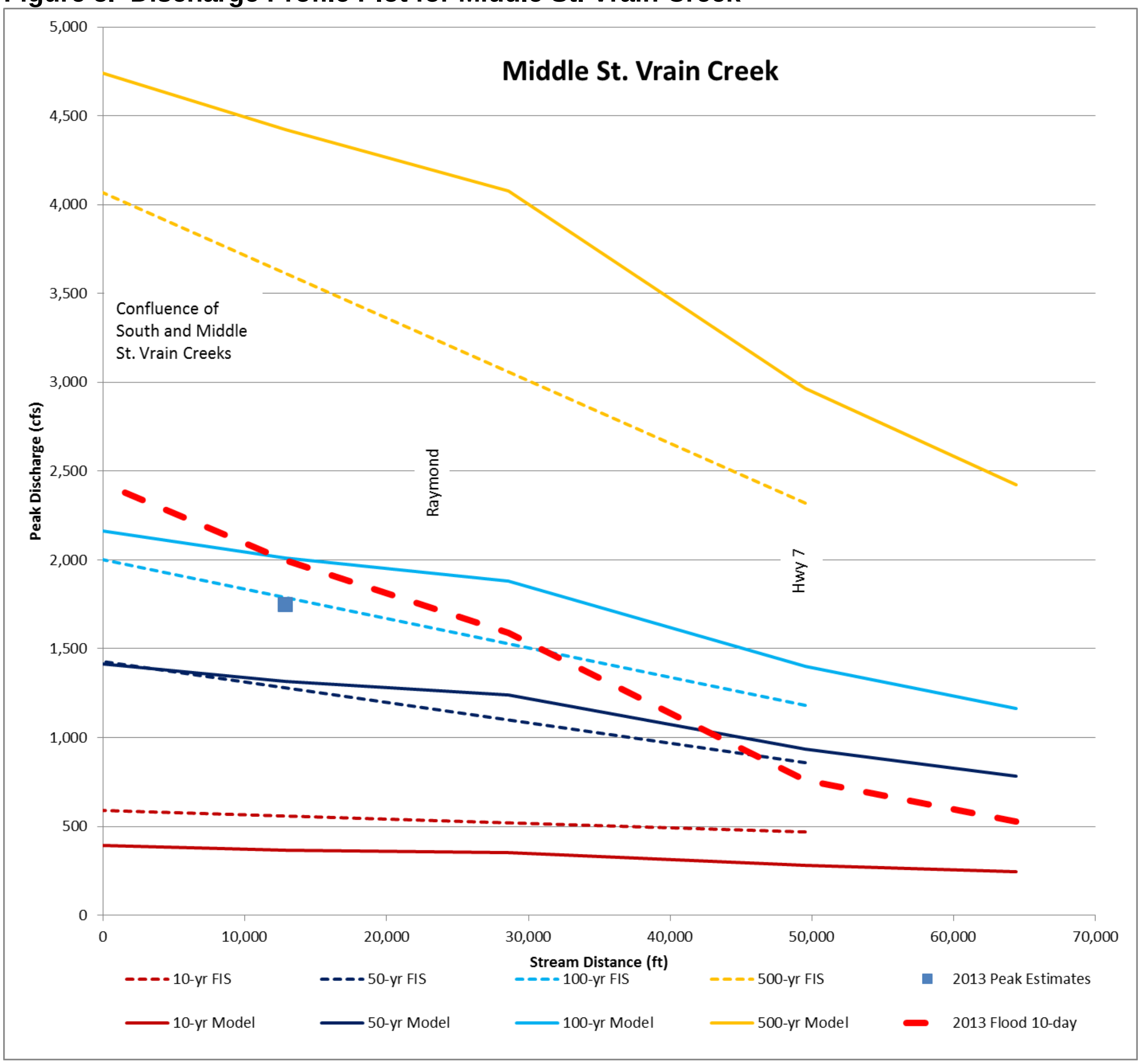
Figure 4. Discharge Profile Plot for South St. Vrain Creek



On South St. Vrain Creek (Figure 4), the two peak discharge estimate locations were not consistent with each other. Just downstream of the confluence with Middle St. Vrain Creek the peak discharge estimate was 2,700 cfs, whereas just a little further downstream the estimate was 9,000 cfs. There is no significant tributary between these two locations, so it was assumed that one or both of these peak discharge estimates may have been influenced by landslides, debris dams, scour and/or sediment deposition. The 10-day calibrated model focused on the higher downstream estimate because it was more in line with expected unit discharges and the other estimates upstream on Middle St. Vrain Creek and downstream in Lyons. On Middle St. Vrain Creek, the 10-day calibrated model was approximately 14% higher than the estimated peak discharge. Downstream on South St. Vrain Creek, the 10-day calibrated model was approximately 15% lower than the estimated peak discharge. These two locations were balanced are within the range of hydrologic uncertainty (+/- 20%) for the estimates.

On South St. Vrain Creek, it can be seen that the predictive storms produced peak discharge values approximately 4% to 33% larger than the Effective FIS discharge values. At the confluence with the North St. Vrain in Lyons, the 100-year peak discharge was 33% higher than the Effective FIS value. Similarly, at the confluence of South and Middle St. Vrain Creeks, the 100-year model results were approximately 32% higher than the Effective FIS discharge.

Figure 5. Discharge Profile Plot for Middle St. Vrain Creek

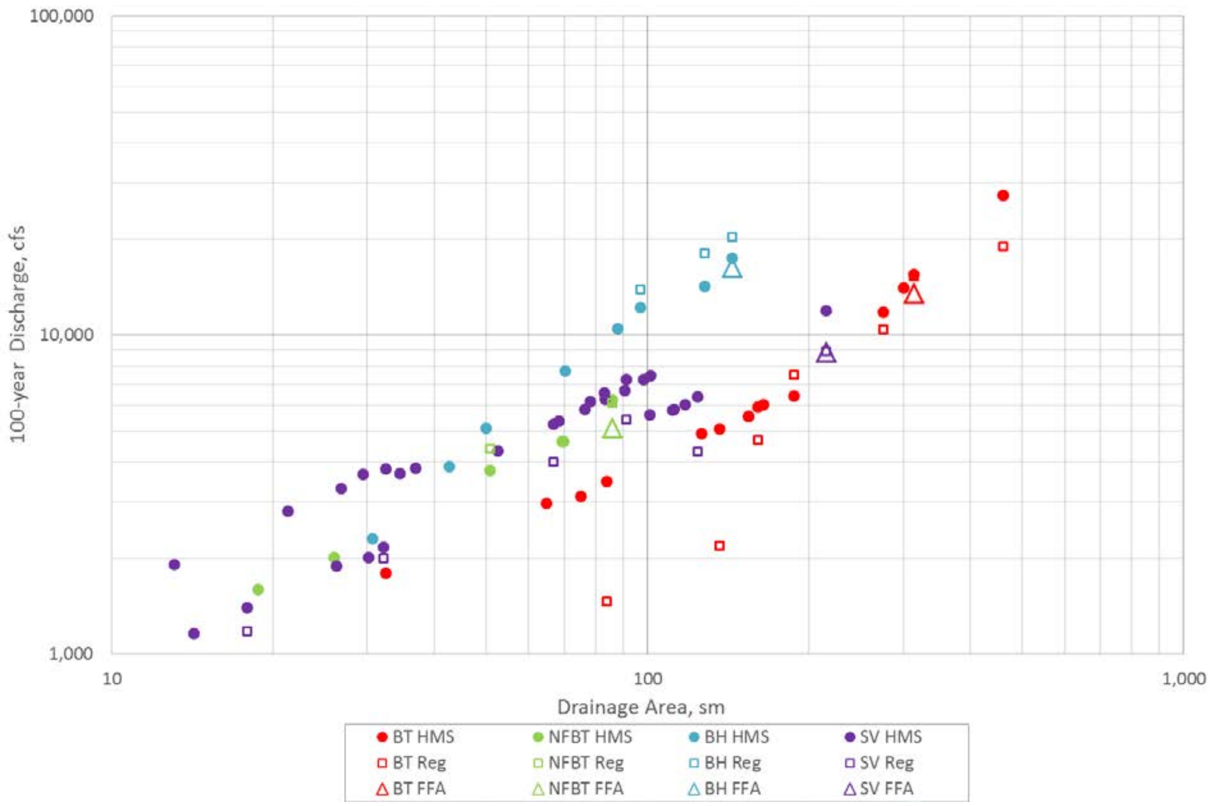


On Middle St. Vrain Creek (Figure 5), it can be seen that the 50-year and 100-year storms matched very closely with the Effective FIS discharge values. The 500-year model results were approximately 5% to 15% higher than the Effective FIS discharge values. The 10-year model results were approximately 30% to 40% lower than Effective FIS discharge values.

The resulting modeled peak discharges for the various return periods were compared to the results of an updated flood frequency analysis for St. Vrain Creek as well as to current regulatory discharges. The modeled peak discharges were compared on a unit discharge basis (in cfs per square mile of watershed area) against flood frequency results, current regulatory discharges, and modeled discharges in the Big Thompson, North Fork of the Big Thompson and Buckhorn Creek watersheds in addition to the St. Vrain watershed. This information is shown in Figure 6 below. Several observations can be made:

1. Compared to the modeled discharges, more scatter is associated with the current regulatory discharges for the design points shown.
2. Modeled discharges are generally higher than current regulatory discharges in the St. Vrain watershed.

Figure 6. Comparison of 100-year Discharges in the St. Vrain and Adjacent Big Thompson, North Fork of Big Thompson and Buckhorn Creek Watersheds



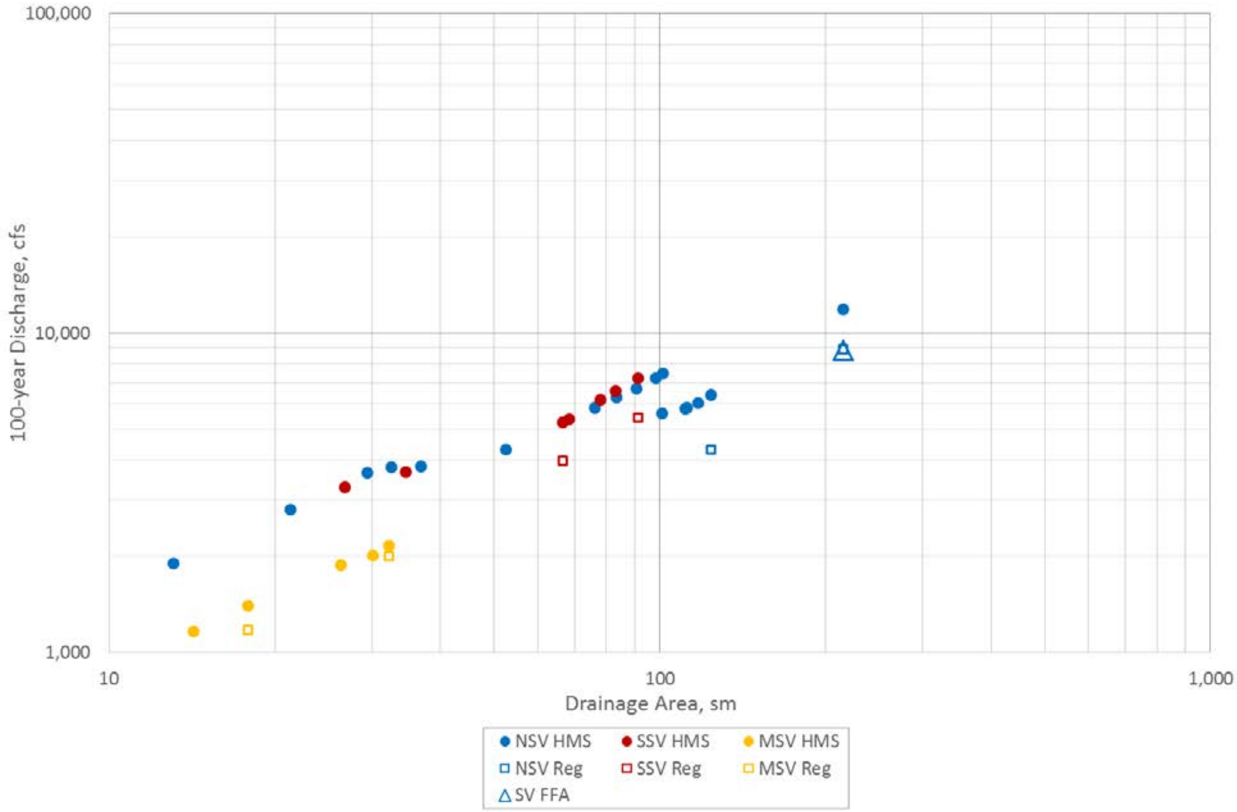
Watershed (color):
BT = Big Thompson River (red)
NFBT = North Fork Big Thompson (green)
BH = Buckhorn Creek (light blue)
SV = St. Vrain Creek (dark blue)

Analysis Method/Data Source (marker shape):
FFA = Flood Frequency Analysis (triangle)
Reg = FIS Regulatory Peak Discharge (square)
HMS = HEC-HMS Calibrated Model (circle)

Several data points are included in Figure 6 above. Therefore a summary of the abbreviations used in the figure legend is provided. Each watershed is indicated by a single color and each method is indicated by a specific marker shape:

For purposes of clarity, Figure 6 has been reproduced as Figure 7 below with all watersheds removed except the St. Vrain Creek Watershed. The St. Vrain Creek watershed was also split into the various branches (North, South, and Middle).

Figure 7. Comparison of 100-year Discharges in the St. Vrain Creek Watershed



Current regulatory discharges in the St. Vrain watershed are primarily based on prior flood frequency analyses; however, it is possible that the gage analysis results, and therefore the regulatory discharges, may tend to be somewhat low, considering that three events have occurred during the period of record that are well in excess of the 100-year flow rate that is predicted using the flood frequency analysis. It is likely that the construction of Button Rock Dam has reduced some of the measured discharges that influence the prediction of 100-year flow rates.

Based on a review and evaluation of assumptions and limitations of the various hydrologic methodologies used, the results of the current rainfall-runoff model using the 24-hour NOAA rainfall are viewed as suitable for use by CDOT in the design of permanent roadway improvements in the St. Vrain watershed. It is recommended that local floodplain administrators consider using the results of this hydrologic analysis to update and revise current regulatory discharges in the St. Vrain watershed. Table 8, below, summarizes the predictive model results for the 100-year event compared to current regulatory discharges.

4.0 CONCLUSIONS AND RECOMMENDATIONS

This report documents a hydrologic investigation of Saint Vrain Creek associated with the extreme flood event of September, 2013. Peak discharges experienced during the flood were estimated and compared to current regulatory discharges as discussed in Appendix A. A summary of the peak discharge estimates are shown in Table 7 below. Comparisons of the 2012 Effective FIS discharges with the measured flood estimates indicate that the September 2013 Flood ranged from a 50-year event to greater than a 500-year event in some locations.

Table 7. Comparison of Peak Discharge Estimates

	2013 Effective FIS Peak Discharge				Ayres 2013 Updated				2013 Flood	2013 Flood
	Approximate Location for Comparison				Flood Frequency Analysis				Estimated	Estimated
Description	**10-yr (cfs)**	**50-yr (cfs)**	**100-yr (cfs)**	**500-yr (cfs)**	**10-yr (cfs)**	**50-yr (cfs)**	**100-yr (cfs)**	**500-yr (cfs)**	**Peak Discharge (cfs)**	**Recurrence Interval (yrs)**
Camp Dick on Middle SVC	470	860	1,180	2,320						
Middle SVC at Riverside (Jarrett #55)									1,750	100 Year
Middle SVC above confluence with South SVC	590	1,430	2,000	4,070						
Confluence of Middle and South SVC	1,220	2,790	3,990	8,560						
South SVC (Jarrett #56)									2,700	50 Year
South SVC at Little Narrows (Jarrett #57)									9,000	100-500 Year
South SVC above confluence with North SVC	1,400	3,750	5,430	11,900						
North SVC at Hwy 7 (Jarrett #63)									450	--
North SVC inflow to Button Rock Reservoir									10,000	> 500 Year
North SVC (Jarrett #58)									12,300	> 500 Year
North SVC above confluence with South SVC	1,000	2,850	4,310	10,630						
Confluence of North and South SVC	2,040	6,670	8,880	20,260	2,652	6,239	8,840	19,330		
St. Vrain Creek at Hwy 36 below Lyons	2,040	6,670	8,880	20,260					23,000	> 500 Year

An updated flood frequency analysis was performed to reflect annual peak flows that have occurred since prior gage analyses, including estimated discharges during the 2013 Flood. Detailed findings from the gage analysis for the St. Vrain Creek gage in Lyons are provided in Appendix B. Table 7 shows a summary of the updated flood frequency analysis for St. Vrain Creek (analysis includes 2013 Flood event in the record). The FFA results indicate slightly lower peak discharges than the current regulatory peak discharges.

A HEC-HMS rainfall/runoff model was developed and calibrated to match the peak discharge estimates obtained for the 2013 flood event. The first step in this process was to calibrate rainfall information representing the September storm to match available ground data throughout the study watersheds. This is described in Section 2.4.5. The rainfall data was incorporated as 5-minute incremental rainfall hyetographs for a ten-day period representing the 2013 storm. The second step was to calibrate the model using the Curve Number as a calibration parameter to obtain a best fit of the model results to the peak discharge estimates for the September 2013 event. This model was calibrated to the full 10-day period. The third step was to apply NOAA point precipitation depths for various recurrence intervals using a 24-hour SCS Type II rainfall distribution to develop predictive peak discharges. To better represent a 24-hour storm as opposed to the long duration September event, the model was re-calibrated for the maximum 24-hour period of rainfall based on the ratio of runoff to rainfall from the full ten-day 2013 flood event. Once the curve numbers were adjusted to generate the same ratio of runoff to rainfall for the maximum 24-hour rainfall as the full ten day event, the design rainfall was applied. The results of this predictive model are summarized in Table 6 and in Appendix C.

Based on a review and evaluation of assumptions and limitations of the various hydrologic methodologies used, the results of the current rainfall-runoff model using the 24-hour NOAA rainfall are viewed as suitable for use by CDOT in the design of permanent roadway improvements in the St. Vrain watershed. It is recommended that local floodplain administrators consider using the results of this hydrologic analysis to update and revise current regulatory discharges in the St. Vrain watershed. Table 8 summarizes the predictive model results for the 100-year event compared to current regulatory discharges.

Table 8. 100-year Modeled Peak Flows Compared to Current Regulatory Discharges

Location	Current Regulatory Discharge (cfs)	Modeled Discharge (cfs)	Percent Difference
Middle St. Vrain Creek at confluence with South St. Vrain Creek	2,000	2,160	+8%
Middle St. Vrain Creek at Peaceful Valley (State Route 72 Bridge)	1,180	1,400	+19%
North St. Vrain Creek at confluence with St. Vrain Creek and South St. Vrain Creek	4,310	6,390	+48%
South St. Vrain Creek at confluence with St. Vrain Creek and North St. Vrain Creek	5,430	7,230	+33%
South St. Vrain Creek at confluence with Middle St. Vrain Creek	3,990	5,260	+32%
St. Vrain Creek Just downstream of confluence of North St. Vrain Creek and South St. Vrain Creek	8,880	11,910	+34%

With these recommendations, the peak discharges observed in the St. Vrain Watershed during the September 2013 Flood event had an estimated recurrence interval ranging from approximately the 1 percent annual peak discharge to the 0.2 percent annual peak discharge, or from a 100-year to a 500-year storm event. There are two exceptions to this where lower peak discharges were estimated.

Table 9. Estimate of September 2013 Peak Discharge Recurrence Interval based on Model Results

Location	Measured Discharge (cfs)	Annual Chance Peak Discharge (cfs)					Estimated Recurrence Interval (yr)
		10%	4%	2%	1%	0.2%	
Middle St. Vrain Creek at Riverside	1,750	364	700	1,170	1,820	4,110	~ 100
South St. Vrain Creek below Middle St. Vrain	2,700	1,190	2,345	3,658	5,369	10,962	25 to 50
South St. Vrain Creek above Lyons	9,000	1,464	2,890	4,496	6,598	13,435	100 to 500
North St. Vrain Creek at Highway 7	450	963	1,785	2,667	3,799	7,423	< 10
North St. Vrain Creek below Button Rock Dam	10,000	1,502	3,108	5,002	7,472	16,002	100 to 500
North St. Vrain Creek above Lyons	12,300	1,056	2,299	3,804	5,842	13,100	100 to 500
St. Vrain Creek at Hwy 36 Bridge (D-15-I)	23,000	2,202	4,860	7,949	12,089	26,599	100 to 500

5.0 REFERENCES

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TECHNICAL APPENDICES

Appendix A
2013 Discharge Estimates in Comparison to Current Regulatory Flows

Flood and Paleoflood Methodologies for the September 2013 Flood Area

For Colorado Department of Transportation

Robert D. Jarrett

December 17, 2013

Flood Methods

Although flood measurements were made by the U.S. Geological Survey at many of their streamflow-gaging stations located in the September 2013 flood area in the Northern Colorado Front Range and downstream locations, there are other sites where flood data are needed such as for determining design floods for bridges affected by the flood. Post-flood, or indirect, methods are used to estimate peak discharges at ungaged sites or gaged sites that were inaccessible due to hazardous conditions, washed out bridges from which direct (current meter) measurements often are made, or other factors. Various indirect methods such as the slope-area, step-backwater, contracted-opening, and flow over a highway embankment are commonly used to compute flood discharge using standard hydraulic computational methods. The critical-depth method increasingly is being used on streams with channel gradients exceeding 0.005 to 0.01 ft/ft (~25 to 50 ft/mi) and has been validated to be within about 15 percent of discharge measured with current meter (Jarrett and England, 2002); this field documentation study of 212 stream sites in the western US for floods ranging from about the 2 year to 10,000 year recurrence interval (average of about the 75-year flood) confirms the theoretical reliability of the critical-depth method in higher gradient channels (Grant, 1997). Most streams within the 2013 flood area have gradients exceeding 0.005 ft/ft making them conducive for application of the critical-depth method. In addition, because of the extensive channel erosion and deposition, finding sufficient reach length for application of the other indirect methods is extremely problematic. Thus, the critical-depth method is very applicable in short, relatively straight but un-eroded sections of channel. Several channel cross sections are made in these relatively stable (in many cases, bedrock reaches can be located in mountain channels). An important benefit of using the critical-depth method is that discharge is not a function of channel roughness (e.g., Manning's n value); rather discharge is solely a function of channel geometry. Peak discharge calculations are made directly from channel cross-section data and associated high-water marks (HWMs). Peak discharge is estimated to be the average of the values at each cross section (typically 2-4 per site). An approximation of the peak-discharge uncertainty at a site can be made from the individual estimates and the average peak-discharge value.

The primary benefits of the critical-depth method are their cost effectiveness (about a tenth the cost of a standard indirect method referenced above) and how rapidly data can be provided from beginning of fieldwork to completion of the summary table (about two weeks for the requested sites, weather permitting). For September 2013 flood site visits, appropriate data reduction, computations, and quality assurance will be included. Photographs at all sites (on CD-ROM by site) and the site description (including latitude and longitude) will be provided in table form (Excel spreadsheet) for use by the Colorado Department of Transportation.

Paleoflood Method

In the past two decades, there has been growing interest by dam-safety officials and floodplain managers to incorporate risk-based analyses for design-flood hydrology. Extreme or rare floods, with recurrence intervals exceeding the 50-year flood to about the 10,000-year flood (annual exceedence probabilities, AEPs, in the range of about 0.02 to 10^{-4} chance of occurrence per year), are of increasing interest to the hydrologic and engineering communities for the purposes of planning, design, and maintenance of structures such as dams and levees. Flood-frequency analysis is a major component of flood-risk assessment. Reliable flood-frequency relations are difficult to estimate when using short gage record lengths typical of streamflow-gaging stations in the United States, particularly for semi-arid and arid basins in the western United States. The occurrence of high-outliers and low-outliers, mixed-population sources of flooding, non-stationarity (the effects of long-term variability on flood estimates), and other factors also contribute to uncertainty in flood-frequency estimates. Reliable flood-frequency estimates are needed as input to risk assessments for determining appropriate levels of public safety, prioritizing projects, and allocating limited resources in a wide range of water-resources investigations such as dam safety, flood-plain management, and design of infrastructure such as bridges located in floodplains.

Because of the important role of paleoflood hydrology, it has increasingly been used in a range of water-resources investigations over the past 20 years. The American Society of Civil Engineers (ASCE) is also assessing the use of paleoflood hydrology as it relates to dam safety and risk-based assessments as well as better use of historical data and paleoflood data in many water-resources investigations. One ASCE focus area emphasized the need to develop standard protocols for using paleoflood techniques for applications by practicing hydrologists, engineers, and scientists in related fields. Paleoflood hydrology can provide useful information to assist the Colorado Department of Transportation and floodplain managers in their assessments of the probability of large floods. Documenting maximum paleofloods combined with regional analyses of contemporary extreme rainfall and floods help provide reliable flood-frequency estimates. Current regional flood-frequency methods available for eastern Colorado – defined as streams below about 8,000 feet and eastward) have uncertainties exceeding 100 percent. A CDOT-USGS eastern Colorado paleoflood study is underway to help reduce these uncertainties; I am providing field training in paleoflood methods for USGS and CDOT engineers. I collected substantial amounts of paleoflood data in the September 2013 flood area with the assistance of graduate students before I retired. They need only to be compiled from published papers, theses/dissertations, and field notebooks.

Paleoflood hydrology is the science of reconstructing the magnitude and estimating the frequency of large floods using geological evidence and a variety of interdisciplinary techniques. Although most paleoflood studies involve prehistoric floods, the methodology is applicable to historic or modern floods at gaged and ungaged sites (Jarrett and Tomlinson, 2000). Paleoflood studies to obtain data for contemporary floods (about 150 years ago to the present) also are used to complement short gage records and can be used to estimate flood-frequency relations at sites with limited gage data (Jarrett and Tomlinson, 2000).

Floods leave distinctive sedimentary deposits, along with botanical, erosional features on channel margins, and modifications of geomorphic surfaces by floodwaters in channels and on floodplains. These features, termed paleostage indicators (PSIs - PSIs can be thought of like old flood high-water marks, but with less reliability), can be used to infer the stage of past floods. In paleoflood studies, the most commonly used PSIs are slack-water deposits (SWDs) of silt and sand rapidly deposited from suspension in sediment-laden waters where velocities are minimal during the time that inundation occurs. SWDs are most commonly found in streams in the deserts of the south-western US. Another type of PSI used in paleoflood studies, particularly in mountain streams, is flood bars (FBs) of sand, gravel, cobble, and boulder deposits. A difference in studies that use SWDs and FBs is that SWDs can provide evidence for multiple (20-30) distinct floods that can be dated with ^{14}C, whereas coarse grained sediments in FBs (gravel, cobble, and boulders) can make it difficult to excavate a deposit to ascertain more than a few floods. The important factor for paleoflood studies is that the largest flood in a defined time scale is the primary flood documented. Another difference is most paleoflood studies are very detailed at a specific site, whereas the methods I developed are for documenting the largest paleoflood and discharge bounds on non-inundation surfaces (NISs) at many sites (50 to 200) along streams and their tributaries in a hydrologically homogeneous study region using relative dating methods for PSIs and NISs (e.g., Jarrett and Tomlinson, 2000).

When discharges are large enough, streambed and bank materials are mobilized and transported (Jarrett and England, 2002). These can be observed throughout the September 2013 flood area. When stream velocity, depth, and slope decrease, flowing water often is no longer competent to transport sediments, which are then deposited as slack-water deposits on the floodplain and flood bars in the channel. The types of sites where flood deposits commonly are found and studied include: (1) locations of rapid energy dissipation, where transported sediments would be deposited, such as tributary junctions, reaches of decreased channel gradient, abrupt channel expansions, or reaches of increased flow depth; (2) locations along the sides of valleys in wide, expanding reaches where fine-grained sediments or slack-water deposits would likely be deposited; (3) ponded areas upstream from channel contractions; (4) the inside of bends or overbank areas on the outside of bends, and; (5) locations at and downstream from terminal moraines across valley floors where floods would likely deposit sediments eroded from the moraines.

Flood-transported sediments and woody debris can scar trees, yielding an approximate flood height. Most commonly, trees along the main flow channel are scarred, whereas, trees protected by upstream trees and those in the margin of a floodplain may not have flood scars. Scars from older floods may have healed since the flood. Systematic coring on the upstream and streamward sides of trees can identify old scars. A lack of scarring at multiple sites in a reach is an indicator that substantial flooding has not occurred since establishment of trees on the floodplain. Use of multiple types of flood evidence at numerous sites for a stream and regional increases confidence for determining paleoflood magnitude and ages as well as ascertaining approximate levels of uncertainty.

The geomorphic evidence of floods in steep mountain basins (Jarrett and Tomlinson, 2000; the 2013 flood) is unequivocal. Paleoflood evidence in higher gradient streams is relatively easy to recognize and long lasting (tens of thousands of years) because of the quantity, morphology, structure, and size of sediments deposited by floods. In paleoflood investigations, lack of physical evidence of the occurrence of flooding is as important as discovering tangible on-site evidence of such floods (Jarrett and Costa, 1988; Jarrett and Tomlinson, 2000). Jarrett and Costa (1988) used PSIs and the lack of evidence of flooding (e.g., relatively undisturbed terminal moraines in stream valleys) to help understand the spatial variability of the maximum flooding throughout the Big Thompson River basin in Colorado. A paleohydrologic bound is a time interval since a particular discharge has not been exceeded. These bounds or non-inundation surfaces (NIS) have no fluvial erosional or depositional evidence and are determined to be stable surfaces with the age estimated such as by ^{14}C dating and relative-dating methods such soil-profile development.

Estimating paleoflood discharge using SWDs and PSIs is similar to estimating peak discharge using recent HWMs with step-backwater analysis, the slope-area, critical-depth, and slope-conveyance methods. Paleoflood discharge is reconstructed from estimates of flood width and depth corresponding to the elevation of the top of flood-deposited sediments (or new PSIs) and channel slope obtained during on-site visits to streams. Flood depth is estimated by using the PSIs in the channel or on the floodplain above the channel-bed elevation. Using the estimated flood depth and channel geometry, the mean depth, width, and cross-sectional area below the PSI elevation is determined. For streams that have higher gradient channels where slope exceeds 0.005 to 0.01 ft/ft, which are common in mountainous basins, flood and paleoflood discharge can be estimated using the critical-depth method, particularly for large floods (Jarrett and England, 2002). The slope-conveyance method can be used for relatively uniform channels (Jarrett and England, 2002) in the 2013 flooded area. Flow-resistance coefficients for these channels can be estimated from analysis of data for Colorado streams (Jarrett, 1985).

STATE OF COLORADO

Colorado Water Conservation Board
Department of Natural Resources
1313 Sherman Street, Room 721
Denver, Colorado 80203
Phone: (303) 866-3441
Fax: (303) 866-4474
www.cwcb.state.co.us

TO: Johnny Olson
CDOT Incident Command

FROM: Kevin Houck, P.E.
Chief, CWCB Watershed & Flood Protection Section

DATE: January 21, 2014
REVISED AND UPDATED JULY16, 2014

SUBJECT: **CDOT/CWCB Hydrology Investigation**
Phase One – 2013 Flood Peak Flow Determinations

As you are aware, northern Colorado experienced one of its worst flood disasters in state history in September 2013. This flood damaged or destroyed numerous state highways and bridges, primarily in the South Platte River basin. In addition, this flood destroyed numerous streamgauges and other measuring devices and created significant erosion and stream movement, which made measurement of flood flows extremely difficult.

The Colorado Department of Transportation (CDOT), in partnership with the Colorado Water Conservation Board (CWCB), has undertaken a significant effort to measure peak flows from the 2013 flood and to investigate an update of hydrologic models for watersheds that experienced significant damage. This memorandum summarizes the initial findings for peak flows during the flood. The effort is currently underway to reevaluate basin hydrology for the affected watersheds. Results from that effort will be summarized in a future memorandum.

Currently, best available information is being used for comparison to peak flood discharges. This comparison involves matching the peak flow rates from the 2013 flood to the regulatory discharges published in the Flood Insurance Study (FIS) for each county, as prepared by the Federal Emergency Management Agency (FEMA). When the new hydrologic models for each watershed are completed and approved, an updated comparison to peak flowrates from the 2013 flood will be made. This may result in a different peak flow frequency for some of the watersheds. While it is my belief that the updated information will yield a better overall estimate, this information is not yet available at this time. As such, <u>the estimated flood frequencies presented in this memorandum is based on the best available information as of this date, but should be treated as provisional and subject to change.</u>

The watersheds studied during this analysis include the South Platte River, Coal Creek, Boulder Creek, Lefthand Creek, the St. Vrain River, the Little Thompson River, and the Big Thompson River.

A summary of peak flood discharges from the 2013 flood, a comparison to regulatory flows, and an estimate of the observed flood frequency is presented in the table below. A discussion of the process will follow this table. In addition, Figures 1-4 present location maps of the various watersheds.

TABLE 1 – SUMMARY OF OBSERVED DISCHARGES AND FREQUENCY ESTIMATES

Location	Drainage Area (sq. mi.)	Regulatory Discharges (cfs)				2013 Peak Discharge Estimate (cfs)	2013 Estimated Frequency
		10-Year	50-Year	100-year	500-Year		
South Platte River							
South Platte River at Fort Lupton	5,043	10,000	22,000	29,000	52,000	10,100	10-Year
South Platte River at Kersey	9,659	11,000	24,500	32,500	57,500	55,000[1]	500 Year[1]
Coal Creek[2]							
Coal Creek at SH72 Near Wondervu	10.3	77	1,580	2,930	5,240	1,110	25-50 Year
Coal Creek Near Plainview Road	15.1	67	1,690	3,340	6,260	3,900	>100 Yr
Boulder Creek							
Boulder Creek near Orodell[3]	102	1,520	5,270	6,920	12,360	2,020	> 10 Year
Boulder Creek at 28th Street	136	2,200	7,800	8,000	20,600	5,300	25 Year
St. Vrain River Watershed							
Middle St. Vrain River above S. St. Vrain	32.4	590	1,430	2,000	4,070	1,750	50-100 Yr
South St. Vrain River at Middle St. Vrain	66.7	1,220	2,790	3,990	8,560	2,700	50-Year
South St. Vrain above confluence N. St. Vrain	92	1,400	3,750	5,430	11,900	9,000	<500 Year
North St. Vrain above confluence S. St. Vrain	125	1,000	2,850	4,310	10,630	12,300	>500 Year
St. Vrain below confluence N and S branches	211	2,040	6,670	8,890	20,260	23,300[4]	<500 Year
St. Vrain River at Interstate 25[5]	854	5,950	12,850	16,700	41,960	18,000[5]	>100 Year
Lefthand Creek upstream of US36[6]	47.2[6]	1,035	4,145	6,700	14,990	3,520[6]	50-Year
Little James Creek at Confl. James Creek	1.8	109	544	970	2,690	1,050	100 Year
James Creek above Little James Creek	8.9	200	1,190	2,140	6,010	2,900	>100 Year
James Creek at X/S A (d/s of Main Street)	14.5	355	2,180	3,930	10,880	3,300	50-100 Yr
Little Thompson River[7]							
Little Thompson River above West Fork	13.8	170	280	340	490	2,680	>500-Year
Little Thompson River below West Fork	43.2	775	2,166	2,585	N/A	12,300	>500-Year
Little Thompson River at Interstate 25[5]	170	5,535	12,723	14,728	19,923	14,500[5]	100 Year
Big Thompson River Watershed							
Big Thompson at Loveland Heights	156	2,250	3,800	4,700	7,200	9,300	>500-Year
Big Thompson at Drake Above North Fork	191	2,750	5,700	7,500	13,600	12,500	500 Year
Big Thompson below Drake	274	3,700	7,850	10,400	19,200	14,800[4]	>100 Year
Big Thompson at CR 29	314	3,800	10,500	15,300	37,000	15,500	100 Year
Big Thompson River at Interstate 25[5]	515	4,300	8,800	11,500	21,000	19,000	<500 Year
North Fork Big Thompson River at Drake	83	1,500	4,100	6,100	14,100	5,900[4,8]	100-Yr
Buckhorn Creek at Masonville above Redstone	92	4,674	10,321	13,862	24,000	7,700[4]	25-Year
Buckhorn Cr. at Confluence w/ Big Thompson	142.9	6,844	15,090	20,244	36,000	11,200	25-Year

[1]Discharge estimates from direct measurements below Fort Lupton not yet available. Hydrology team used values from other flood sites and professional judgment to estimate flow at Kersey, but this is not a direct measurement.

[2]Coal Creek regulatory values have been submitted to and approved by FEMA, but not yet published in Flood Insurance Study.

[3]Per Upper Boulder Creek & Fourmile Creek Floodplain Information Report (Gingery and Associates, 1981)

[4]Revision to a previous estimate.

[5]Information at Interstate 25 provided by Steve Griffin, Region 4 Hydraulics. See Peak Flow Hydrology Investigation for the September 2013 Flood at Interstate 25, dated January 7, 2014.

[6]Regulatory discharge values for Lefthand Creek are not available upstream of Longmont in the 2012 FIS. Values reported in the table above represent the discharges at Highway 36 provided by Boulder County from the 1983 Simons Li report for Upper Lefthand Creek, which are presented for comparison, but they do not directly correspond to the location of the observed flood peak, which is further upstream of US36. Professional judgment was used to estimate the observed frequency based on available information.

[7]No regulatory discharge values are available for the Little Thompson River. "Regulatory discharges" presented in the table above are from a hydrologic model developed by CDOT (courtesy Steve Griffin, Region 4 Hydraulics) or from regression equations (Capesius and Stephen, 2009). This represents the best available information, but it is not regulatory.

[8]Measurement at Drake listed. NRCS established an estimate of 18,400 cfs at a location 4.5 miles upstream of Drake. The larger value is judged to be a result of a natural dambreak whose flows were quickly attenuated downstream.

STUDY DESCRIPTION AND BACKGROUND

Following the September 2013 flood event, it became immediately apparent by State leaders in various departments that updated floodplain information would be needed for the purposes of infrastructure repair and land use decisions. Put simply, current regulatory information no longer applied in many areas, although it still represented the only information available following the flood. As such, CDOT and CWCB began a massive effort to update the hydrology and hydraulics of many of the watersheds affecting CDOT infrastructure damaged by the 2013 floods. This effort is being phased to develop information for various steps of the analysis.

The first phase, described here, involves an initial analysis of the 2013 flood to determine which frequencies may have occurred for six key watersheds. This enables CDOT and other land use agencies to determine how infrastructure performed during a flood of a particular magnitude. This memorandum summarizes the preliminary information obtained during this phase.

The second phase will involve update and redevelopment of the hydrologic models for the same six watersheds. In some cases, this will be the first major update to the regulatory watershed in over thirty years (see below).

Ultimately, the CWCB resolves to utilize updated topographic information to develop new hydraulic information. CDOT would be able to use this information for infrastructure design decisions, and CWCB plans to use this information to update regulatory floodplains.

HYDROLOGY

Hydrology involves the computation of design flow rates expected to occur at various locations for various design frequencies (i.e. 10-year or 100-year). It is a complex modeling effort involving rainfall, infiltration, soil types, land uses, and other watershed characteristics such as slope and imperviousness. Detention and reservoir storage can be incorporated into the modeling, but it is a state and federal requirement that attenuation from storage components can only be considered in areas where dedicated flood storage is set aside that cannot be used for other purposes, such as water supply. For cases such as Barker Reservoir on Boulder Creek, flood flows may be incidentally detained in less-than-full reservoirs (as happened during this event since it was well past the spring season, when reservoirs are typically filled), but if this storage cannot be relied upon during a flood event, it is typically ignored.

In practical uses, it is not desirable to update hydrology on a frequent basis. Floodplain studies and maps, and the modeling behind them, are expensive to update, and there are important and sometimes controversial land use impacts associated with changing floodplain maps often. Any time hydrology is updated for a watershed, all floodplain maps must generally be changed to reflect this new hydrology. Practically speaking, large scale hydrology has not been updated for many of the watersheds in over twenty or thirty years.

However, the circumstances that exist now render the creation of new hydrology to be a uniquely appropriate effort at this time. There are many reasons for this:

- Because of stream erosion and movement, the hydraulic characteristics of many large rivers are vastly different than what they were just ten months ago. For this reason, it is assumed that floodplains associated with many reaches of these large watersheds will need to be updated in any case to reflect new hydraulic conditions.
- The National Oceanic and Atmospheric Administration (NOAA) updated design rainfall information for the first time in forty years in 2013. Prior to the new information becoming available, design rainfall was still based on documents released in 1973. The new information incorporates an additional forty years of data and underwent heavy peer review prior to being published, and it is widely regarded as far superior to previous information.
- This flood represents a unique opportunity for hydrologic reevaluation because it occurred in an area with a large volume of data available (including detailed gridded rainfall, sufficient soils and land use information,

reservoir releases during the flood, newly obtained LIDAR topography, and ample direct and indirect flow measurements). This provides a one-time opportunity for a recorded event to calibrate the models to.

- Perhaps most important, there is increased political and public support for updating information used for recovery activities for the express purpose of mitigating future flood threats.

For these reasons, the hydrology team agreed that this is an appropriate time to restudy basin hydrology at the watershed level. This process has already begun, but it is a rigorous and detailed process, and no preliminary results are available at this time.

STUDY PROCESS AND KEY ASSUMPTIONS/CAVEATS

As mentioned above, many measurement devices failed during the September 2013 flood, rendering the need for indirect analysis to determine flow rates that occurred during the flood. For this study, field measurements were taken at key locations in an effort to estimate these flow rates forensically (indirect post-flood determinations). Locations were chosen based on need, accessibility, and site conditions, with surveys taking place in November and December 2013. Fieldwork involved determination of high water marks and development of new rating curves based on updated topography, which in many cases was vastly different than what existed prior to the flood.

It is important to note that there is a degree of subjectivity and professional judgment necessary for these indirect peak flow calculations. In many cases, it is a challenge to determine what the stream looked like at the moment of peak flow, especially as streams continued to migrate or erode following the peak of the flow. As such, a certain amount of statistical uncertainty is inherent in developing measurements of this type. The team estimates that the uncertainty in some cases can be as high as +/- 20%. While this envelope of uncertainty will not, in most cases, affect the stated frequency, this range should nonetheless, we factored into consideration when viewing measured discharges in Table 1. Finally, the results presented herein will undergo subsequent review and may be revised. However, I am quite confident that the computed flow rates using indirect methods presented in this memorandum are as good as can be obtained anywhere.

It is known by the hydrology team that others have undertaken similar efforts, but to the team's knowledge, no results have yet been released. One such effort has been undertaken by the United States Geological Survey (USGS). The USGS took field measurements within the first two months following the flood. However, as of the date of this memorandum, nothing has been made publicly available. While I am confident that the measurements presented in this memorandum will stand up under comparison, it should be emphasized that due to the inherent uncertainties referenced above, it is likely that small deviations would be present when comparing these results to eventual results from others.

These computed flow rates were then compared to currently published regulatory flow values for the purpose of assigning flood frequencies. In most cases, this regulatory information can be obtained from FEMA's Flood Insurance Studies. This is the source of this regulatory information in all cases from Table 1 unless otherwise noted. Regulatory information from the FIS generally includes 10-year, 50-year, 100-year, and 500-year values.

It is also important to note that the locations for field measurements were not always exactly in the same locations as design hydrological points from the FIS. However, unless specifically noted otherwise, the observed flows can generally be compared to the regulatory flows as they are proximate in location and generally do not represent a hydrologic departure (for example, without intervening tributaries).

Perhaps most importantly, it is critical to understand that these computed flow rates are being compared to established regulatory floodplain information that was developed prior to the flood. This simply represents the best available information that can currently be used. As noted above, there are plans to conduct an updated comparison based on results from the hydrologic analysis developed during the second phase of this study. It is extremely likely that somewhat different results will be obtained during this reanalysis. As such, <u>comparisons and flood frequencies presented in this memorandum should be treated as provisional based on the best information available at this time and subject to revision</u>.

Appendix B
Flood Frequency Analysis at Stream Flow Gages

Bulletin 17B Frequency Analysis

St. Vrain Creek at Lyons

USGS Gage 06724000 (1888 – 1998)

CDWR Gage SVCLYOCO (1991 – 2012)

Bulletin 17B Frequency Analysis
21 Aug 2014 01:46 PM

--- Input Data ---

Analysis Name: 06724000 St_V AT LYONS STA REV
Description: USGS 06724000 ST. VRAIN CREEK AT LYONS, CO. With Peak Flow of 23,300 cfs for 2013 flood

Data Set Name: ST. VRAIN CK-LYONS 2013_Q23300
DSS File Name: H:\32-176904 Big Thompson Hydrology\Six_Rivers_HEC-SSP_FFA_Results\Six_Rivers\Six_Rivers.dss
DSS Pathname: /ST. VRAIN CREEK/LYONS, CO./FLOW-ANNUAL PEAK/01jan1900/IR-CENTURY/USGS/

Report File Name: H:\32-176904 Big Thompson Hydrology\Six_Rivers_HEC-SSP_FFA_Results\Six_Rivers\Bulletin17bResults\06724000_St_V_AT_LYONS_STA_REV\06724000_St_V_AT_LYONS_STA_REV.rpt
XML File Name: H:\32-176904 Big Thompson Hydrology\Six_Rivers_HEC-SSP_FFA_Results\Six_Rivers\Bulletin17bResults\06724000_St_V_AT_LYONS_STA_REV\06724000_St_V_AT_LYONS_STA_REV.xml

Start Date:
End Date:

Skew Option: Use Station Skew
Regional Skew: 0.608
Regional Skew MSE: 0.12

Plotting Position Type: Median

Upper Confidence Level: 0.05
Lower Confidence Level: 0.95
Use High Outlier Threshold
High Outlier Threshold: 8515.0

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

Display ordinate values using 0 digits in fraction part of value

--- End of Input Data ---

--- Preliminary Results ---

<< Plotting Positions >>
ST. VRAIN CK-LYONS 2013_Q23300

Events Analyzed		Ordered Events			
Day Mon Year	FLOW CFS	Rank	Water Year	FLOW CFS	Median Plot Pos
19 Jun 1888	535	1	2013	23,300*	0.57
28 May 1889	548	2	1941	10,500*	1.39
02 Jun 1890	675	3	1919	9,400*	2.21
27 May 1891	1,400	4	1995	4,200	3.02
16 Jun 1895	1,130	5	1951	3,920	3.84
18 Aug 1896	1,500	6	1957	3,060	4.66
18 May 1897	1,020	7	1949	2,970	5.47
17 Jun 1898	603	8	1969	2,900	6.29
20 Jun 1899	1,180	9	1961	2,540	7.11
29 Apr 1900	918	10	1947	2,360	7.92
23 Jun 1901	857	11	1935	2,340	8.74
09 Jun 1902	514	12	1980	2,330	9.56
23 Jun 1903	1,710	13	1924	2,230	10.38
20 Jun 1904	850	14	1946	2,140	11.19
09 Jun 1905	1,660	15	1921	2,050	12.01
13 Jun 1906	1,170	16	1930	2,040	12.83
02 Jul 1907	1,120	17	1967	2,010	13.64
30 Jul 1908	650	18	1999	1,880	14.46

04 Jul 1909	1,150	19	1965	1,840	15.28
03 Jun 1910	465	20	1971	1,760	16.09
09 Jun 1911	660	21	1903	1,710	16.91
25 Jun 1912	1,150	22	1918	1,700	17.73
11 Jun 1913	490	23	1923	1,670	18.55
02 Jun 1914	1,540	24	1905	1,660	19.36
20 Jun 1915	955	25	1938	1,650	20.18
20 Jun 1916	620	26	1997	1,640	21.00
23 Jun 1917	1,240	27	1952	1,610	21.81
22 Jun 1918	1,700	28	1982	1,600	22.63
30 Jul 1919	9,400	29	1978	1,560	23.45
26 May 1920	733	30	2010	1,550	24.26
07 Jun 1921	2,050	31	1914	1,540	25.08
14 Jun 1922	574	32	1942	1,510	25.90
09 Jun 1923	1,670	33	1896	1,500	26.72
14 Jun 1924	2,230	34	1983	1,470	27.53
02 Jun 1925	410	35	1931	1,450	28.35
09 Jun 1926	1,100	36	1891	1,400	29.17
29 Jun 1927	604	37	1973	1,360	29.98
31 May 1928	1,010	38	1984	1,340	30.80
03 Jul 1929	765	39	1963	1,300	31.62
10 Aug 1930	2,040	40	1958	1,290	32.43
16 Jul 1931	1,450	41	1991	1,280	33.25
18 Jun 1932	854	42	1917	1,240	34.07
20 Jun 1933	1,130	43	1943	1,230	34.89
10 May 1934	628	44	1937	1,230	35.70
27 May 1935	2,340	45	2003	1,220	36.52
16 Jun 1936	832	46	1966	1,210	37.34
25 Jun 1937	1,230	47	1899	1,180	38.15
02 Sep 1938	1,650	48	1906	1,170	38.97
30 Aug 1939	978	49	2005	1,160	39.79
27 May 1940	675	50	1912	1,150	40.60
21 Jun 1941	10,500	51	1909	1,150	41.42
02 Aug 1942	1,510	52	2011	1,140	42.24
29 May 1943	1,230	53	1962	1,140	43.06
18 May 1944	962	54	1933	1,130	43.87
25 Jun 1945	1,000	55	1895	1,130	44.69
18 Jul 1946	2,140	56	1996	1,120	45.51
17 Jun 1947	2,360	57	1986	1,120	46.32
10 Jun 1948	820	58	1907	1,120	47.14
04 Jun 1949	2,970	59	1926	1,100	47.96
12 Jun 1950	712	60	1987	1,080	48.77
03 Aug 1951	3,920	61	1979	1,050	49.59
07 Jun 1952	1,610	62	1985	1,040	50.41
13 Jun 1953	970	63	1897	1,020	51.23
20 May 1954	285	64	1928	1,010	52.04
23 Jul 1955	680	65	1945	1,000	52.86
02 Jun 1956	749	66	1989	998	53.68
09 May 1957	3,060	67	1939	978	54.49
08 May 1958	1,290	68	1953	970	55.31
15 Jun 1959	857	69	1944	962	56.13
18 Jun 1960	717	70	1970	958	56.94
03 Jun 1961	2,540	71	1915	955	57.76
30 Jun 1962	1,140	72	1972	940	58.58
16 Jun 1963	1,300	73	1975	922	59.40
27 May 1964	458	74	1900	918	60.21
17 Jun 1965	1,840	75	1990	908	61.03
20 Jul 1966	1,210	76	2009	890	61.85
30 Aug 1967	2,010	77	1994	874	62.66
21 Jun 1968	636	78	1959	857	63.48
07 May 1969	2,900	79	1901	857	64.30
29 Jun 1970	958	80	1932	854	65.11
25 Apr 1971	1,760	81	1904	850	65.93
04 Jun 1972	940	82	1976	835	66.75
11 Jun 1973	1,360	83	1936	832	67.57
18 Jun 1974	641	84	1948	820	68.38
09 Jun 1975	922	85	1993	818	69.20
01 Aug 1976	835	86	2006	808	70.02
24 Jul 1977	732	87	1929	765	70.83
17 May 1978	1,560	88	1956	749	71.65
15 Jun 1979	1,050	89	1920	733	72.47
30 Apr 1980	2,330	90	1977	732	73.28
04 Jun 1981	418	91	2004	722	74.10
27 Jul 1982	1,600	92	1960	717	74.92

19 Jun 1983	1,470	93	1950	712	75.74
01 Aug 1984	1,340	94	2000	688	76.55
09 Jun 1985	1,040	95	1955	680	77.37
19 Jun 1986	1,120	96	1940	675	78.19
09 Jun 1987	1,080	97	1890	675	79.00
12 Jun 1988	568	98	1998	662	79.82
03 Jun 1989	998	99	1911	660	80.64
12 Jun 1990	908	100	1908	650	81.45
21 Jun 1991	1,280	101	1974	641	82.27
12 Jun 1992	548	102	1968	636	83.09
17 Jun 1993	818	103	1934	628	83.91
10 Aug 1994	874	104	1916	620	84.72
29 May 1995	4,200	105	1927	604	85.54
26 May 1996	1,120	106	1898	603	86.36
07 Jun 1997	1,640	107	1922	574	87.17
04 Jun 1998	662	108	1988	568	87.99
30 Apr 1999	1,880	109	2008	564	88.81
30 May 2000	688	110	1992	548	89.62
18 May 2001	400	111	1889	548	90.44
01 Jun 2002	190	112	1888	535	91.26
30 May 2003	1,220	113	1902	514	92.08
01 Jul 2004	722	114	1913	490	92.89
03 Jun 2005	1,160	115	1910	465	93.71
09 Jul 2006	808	116	1964	458	94.53
25 Jun 2008	564	117	1981	418	95.34
27 Jun 2009	890	118	1925	410	96.16
06 Jun 2010	1,550	119	2001	400	96.98
09 Jul 2011	1,140	120	2012	347	97.79
07 Jul 2012	347	121	1954	285	98.61
13 Sep 2013	23,300	122	2002	190	99.43

* Outlier

<< Skew Weighting >>

Based on 122 events, mean-square error of station skew =	0.151
Mean-square error of regional skew =	0.12

<< Frequency Curve >>

ST. VRAIN CK-LYONS 2013_Q23300

Computed Curve FLOW, CFS	Expected Probability FLOW, CFS	Percent Chance Exceedance	Confidence Limits 0.05 FLOW, CFS	Confidence Limits 0.95 FLOW, CFS
19,945	22,201	0.2	28,554	14,877
12,748	13,767	0.5	17,356	9,898
9,025	9,551	1.0	11,828	7,223
6,341	6,600	2.0	8,001	5,230
3,914	4,001	5.0	4,701	3,354
2,670	2,705	10.0	3,096	2,349
1,777	1,787	20.0	1,999	1,597
958	958	50.0	1,058	865
625	624	80.0	698	553
534	532	90.0	601	467
483	480	95.0	546	419
424	421	99.0	483	363

<< Systematic Statistics >>

ST. VRAIN CK-LYONS 2013_Q23300

Log Transform: FLOW, CFS		Number of Events	
Mean	3.039	Historic Events	0
Standard Dev	0.289	High Outliers	0
Station Skew	1.234	Low Outliers	0
Regional Skew	0.608	Zero Events	0

Weighted Skew	0.886	Missing Events	0
Adopted Skew	1.234	Systematic Events	122

--- End of Preliminary Results ---

<< High Outlier Test >>

Based on 122 events, 10 percent outlier test deviate K(N) = 3.083
Computed high outlier test value = 8,515.4

3 high outlier(s) identified above input threshold of 8,515

* 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 3 high outlier(s)

<< Systematic Statistics >>
ST. VRAIN CK-LYONS 2013_Q23300

Log Transform: FLOW, CFS		Number of Events	
Mean	3.038	Historic Events	0
Standard Dev	0.287	High Outliers	3
Station Skew	1.217	Low Outliers	0
Regional Skew	0.608	Zero Events	0
Weighted Skew	0.886	Missing Events	0
Adopted Skew	1.234	Systematic Events	122
		Historic Period	126

<< Low Outlier Test >>

Based on 126 events, 10 percent outlier test deviate K(N) = 3.095
Computed low outlier test value = 140.9

0 low outlier(s) identified below test value of 140.9

--- Final Results ---

<< Plotting Positions >>
ST. VRAIN CK-LYONS 2013_Q23300

Events Analyzed		Ordered Events			
Day Mon Year	FLOW CFS	Rank	Water Year	FLOW CFS	Median Plot Pos
19 Jun 1888	535	1	2013	23,300*	0.55
28 May 1889	548	2	1941	10,500*	1.34
02 Jun 1890	675	3	1919	9,400*	2.14
27 May 1891	1,400	4	1995	4,200	2.94
16 Jun 1895	1,130	5	1951	3,920	3.76
18 Aug 1896	1,500	6	1957	3,060	4.58
18 May 1897	1,020	7	1949	2,970	5.39
17 Jun 1898	603	8	1969	2,900	6.21
20 Jun 1899	1,180	9	1961	2,540	7.03
29 Apr 1900	918	10	1947	2,360	7.85
23 Jun 1901	857	11	1935	2,340	8.66

09 Jun 1902	514	12	1980	2,330	9.48
23 Jun 1903	1,710	13	1924	2,230	10.30
20 Jun 1904	850	14	1946	2,140	11.12
09 Jun 1905	1,660	15	1921	2,050	11.94
13 Jun 1906	1,170	16	1930	2,040	12.75
02 Jul 1907	1,120	17	1967	2,010	13.57
30 Jul 1908	650	18	1999	1,880	14.39
04 Jul 1909	1,150	19	1965	1,840	15.21
03 Jun 1910	465	20	1971	1,760	16.02
09 Jun 1911	660	21	1903	1,710	16.84
25 Jun 1912	1,150	22	1918	1,700	17.66
11 Jun 1913	490	23	1923	1,670	18.48
02 Jun 1914	1,540	24	1905	1,660	19.30
20 Jun 1915	955	25	1938	1,650	20.11
20 Jun 1916	620	26	1997	1,640	20.93
23 Jun 1917	1,240	27	1952	1,610	21.75
22 Jun 1918	1,700	28	1982	1,600	22.57
30 Jul 1919	9,400	29	1978	1,560	23.38
26 May 1920	733	30	2010	1,550	24.20
07 Jun 1921	2,050	31	1914	1,540	25.02
14 Jun 1922	574	32	1942	1,510	25.84
09 Jun 1923	1,670	33	1896	1,500	26.65
14 Jun 1924	2,230	34	1983	1,470	27.47
02 Jun 1925	410	35	1931	1,450	28.29
09 Jun 1926	1,100	36	1891	1,400	29.11
29 Jun 1927	604	37	1973	1,360	29.93
31 May 1928	1,010	38	1984	1,340	30.74
03 Jul 1929	765	39	1963	1,300	31.56
10 Aug 1930	2,040	40	1958	1,290	32.38
16 Jul 1931	1,450	41	1991	1,280	33.20
18 Jun 1932	854	42	1917	1,240	34.01
20 Jun 1933	1,130	43	1943	1,230	34.83
10 May 1934	628	44	1937	1,230	35.65
27 May 1935	2,340	45	2003	1,220	36.47
16 Jun 1936	832	46	1966	1,210	37.29
25 Jun 1937	1,230	47	1899	1,180	38.10
02 Sep 1938	1,650	48	1906	1,170	38.92
30 Aug 1939	978	49	2005	1,160	39.74
27 May 1940	675	50	1912	1,150	40.56
21 Jun 1941	10,500	51	1909	1,150	41.37
02 Aug 1942	1,510	52	2011	1,140	42.19
29 May 1943	1,230	53	1962	1,140	43.01
18 May 1944	962	54	1933	1,130	43.83
25 Jun 1945	1,000	55	1895	1,130	44.64
18 Jul 1946	2,140	56	1996	1,120	45.46
17 Jun 1947	2,360	57	1986	1,120	46.28
10 Jun 1948	820	58	1907	1,120	47.10
04 Jun 1949	2,970	59	1926	1,100	47.92
12 Jun 1950	712	60	1987	1,080	48.73
03 Aug 1951	3,920	61	1979	1,050	49.55
07 Jun 1952	1,610	62	1985	1,040	50.37
13 Jun 1953	970	63	1897	1,020	51.19
20 May 1954	285	64	1928	1,010	52.00
23 Jul 1955	680	65	1945	1,000	52.82
02 Jun 1956	749	66	1989	998	53.64
09 May 1957	3,060	67	1939	978	54.46
08 May 1958	1,290	68	1953	970	55.28
15 Jun 1959	857	69	1944	962	56.09
18 Jun 1960	717	70	1970	958	56.91
03 Jun 1961	2,540	71	1915	955	57.73
30 Jun 1962	1,140	72	1972	940	58.55
16 Jun 1963	1,300	73	1975	922	59.36
27 May 1964	458	74	1900	918	60.18
17 Jun 1965	1,840	75	1990	908	61.00
20 Jul 1966	1,210	76	2009	890	61.82
30 Aug 1967	2,010	77	1994	874	62.63
21 Jun 1968	636	78	1959	857	63.45
07 May 1969	2,900	79	1901	857	64.27
29 Jun 1970	958	80	1932	854	65.09
25 Apr 1971	1,760	81	1904	850	65.91
04 Jun 1972	940	82	1976	835	66.72
11 Jun 1973	1,360	83	1936	832	67.54
18 Jun 1974	641	84	1948	820	68.36
09 Jun 1975	922	85	1993	818	69.18

01 Aug 1976	835	86	2006	808	69.99
24 Jul 1977	732	87	1929	765	70.81
17 May 1978	1,560	88	1956	749	71.63
15 Jun 1979	1,050	89	1920	733	72.45
30 Apr 1980	2,330	90	1977	732	73.27
04 Jun 1981	418	91	2004	722	74.08
27 Jul 1982	1,600	92	1960	717	74.90
19 Jun 1983	1,470	93	1950	712	75.72
01 Aug 1984	1,340	94	2000	688	76.54
09 Jun 1985	1,040	95	1955	680	77.35
19 Jun 1986	1,120	96	1940	675	78.17
09 Jun 1987	1,080	97	1890	675	78.99
12 Jun 1988	568	98	1998	662	79.81
03 Jun 1989	998	99	1911	660	80.63
12 Jun 1990	908	100	1908	650	81.44
21 Jun 1991	1,280	101	1974	641	82.26
12 Jun 1992	548	102	1968	636	83.08
17 Jun 1993	818	103	1934	628	83.90
10 Aug 1994	874	104	1916	620	84.71
29 May 1995	4,200	105	1927	604	85.53
26 May 1996	1,120	106	1898	603	86.35
07 Jun 1997	1,640	107	1922	574	87.17
04 Jun 1998	662	108	1988	568	87.98
30 Apr 1999	1,880	109	2008	564	88.80
30 May 2000	688	110	1992	548	89.62
18 May 2001	400	111	1889	548	90.44
01 Jun 2002	190	112	1888	535	91.26
30 May 2003	1,220	113	1902	514	92.07
01 Jul 2004	722	114	1913	490	92.89
03 Jun 2005	1,160	115	1910	465	93.71
09 Jul 2006	808	116	1964	458	94.53
25 Jun 2008	564	117	1981	418	95.34
27 Jun 2009	890	118	1925	410	96.16
06 Jun 2010	1,550	119	2001	400	96.98
09 Jul 2011	1,140	120	2012	347	97.80
07 Jul 2012	347	121	1954	285	98.62
13 Sep 2013	23,300	122	2002	190	99.43

Note: Plotting positions based on historic period (H) = 126
Number of historic events plus high outliers (Z) = 3
Weighting factor for systematic events (W) = 1.0336

* Outlier

<< Skew Weighting >>

Based on 126 events, mean-square error of station skew = 0.144
Mean-square error of regional skew = 0.12

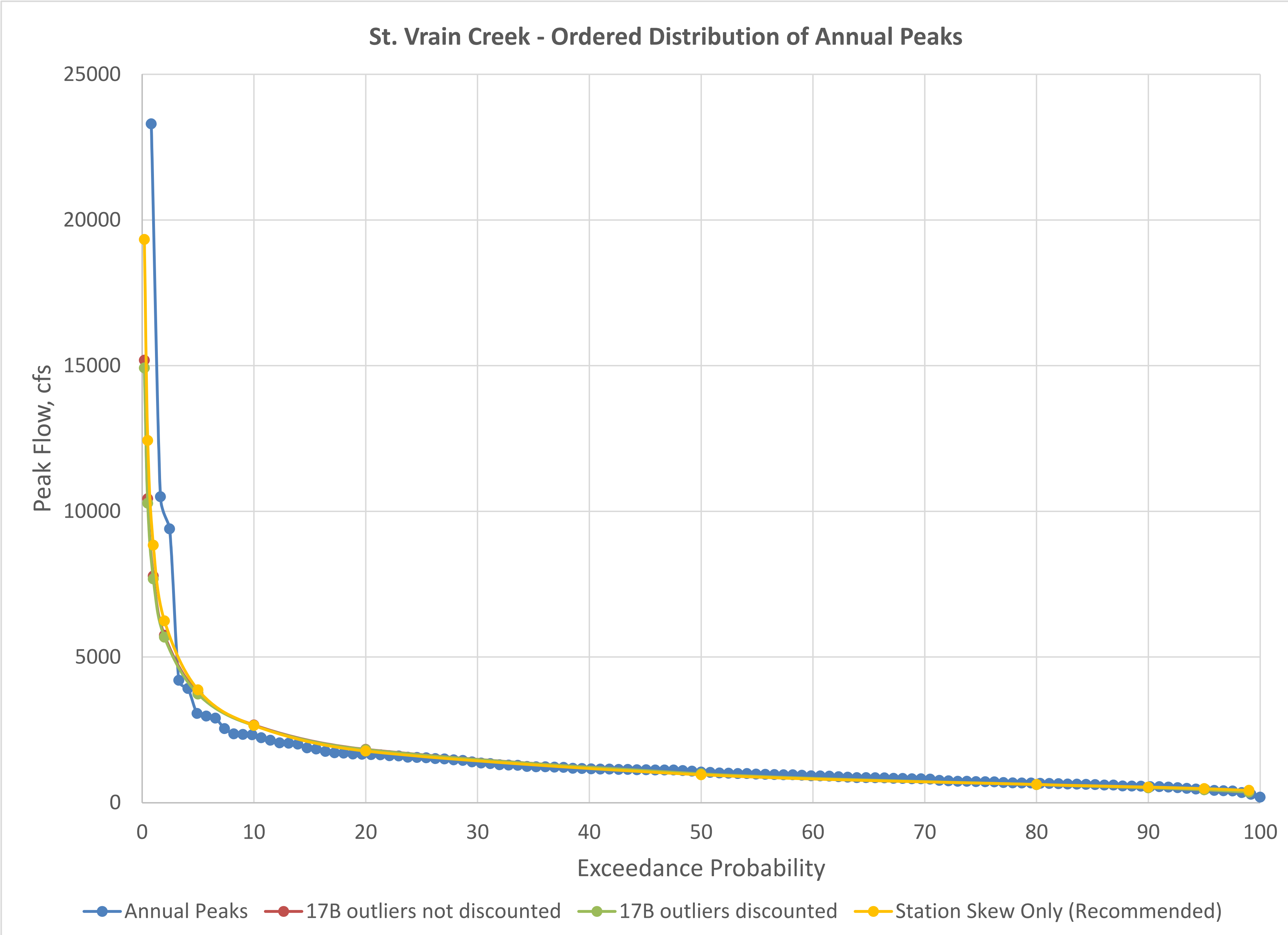
<< Frequency Curve >>
ST. VRAIN CK-LYONS 2013_Q23300

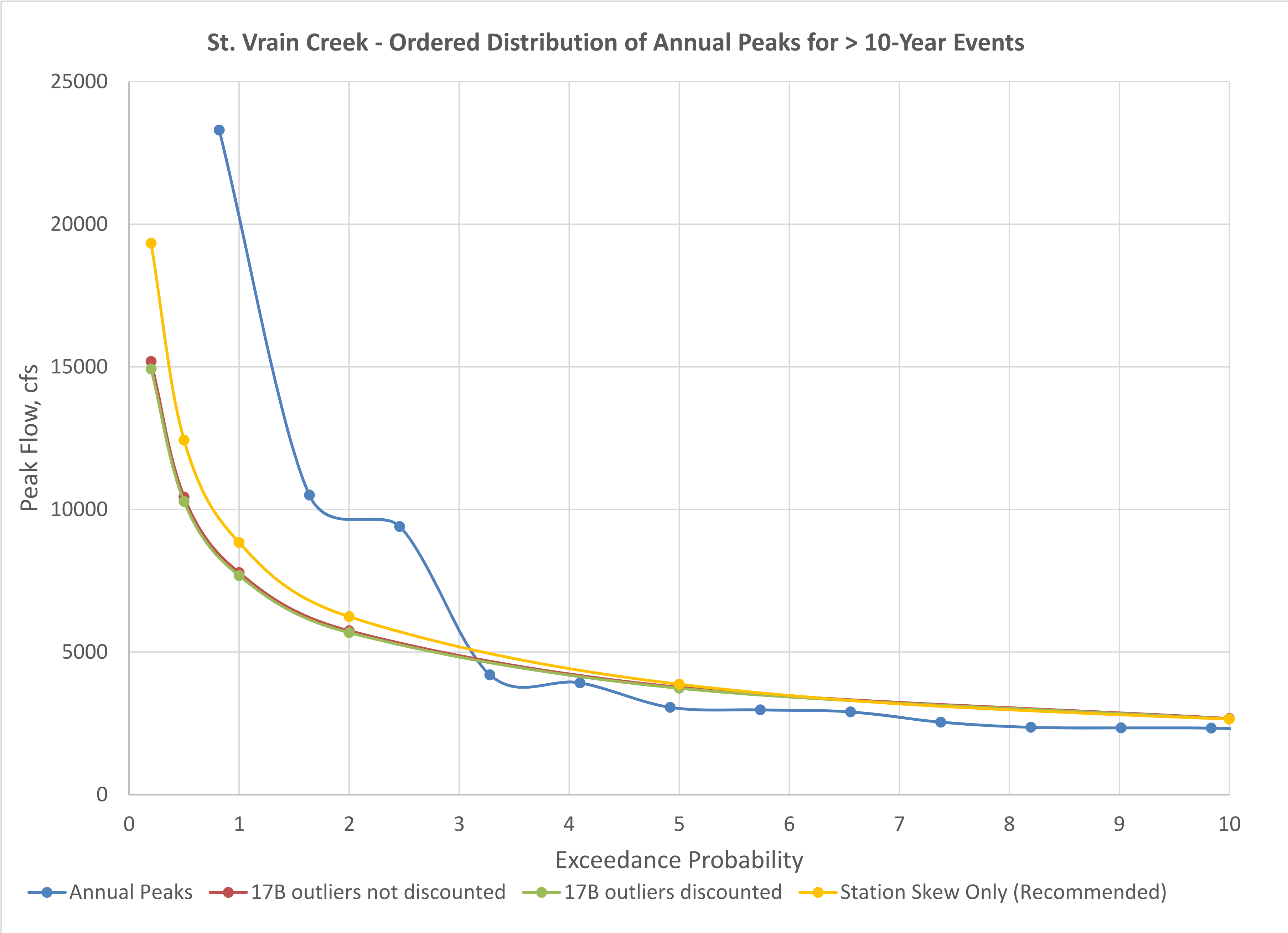
Computed Curve FLOW, CFS	Expected Probability FLOW, CFS	Percent Chance Exceedance	Confidence Limits 0.05 FLOW, CFS	Confidence Limits 0.95 FLOW, CFS
19,330	21,484	0.2	27,577	14,459
12,430	13,410	0.5	16,877	9,673
8,840	9,348	1.0	11,559	7,088
6,239	6,490	2.0	7,858	5,152
3,872	3,958	5.0	4,646	3,322
2,652	2,686	10.0	3,072	2,335
1,771	1,782	20.0	1,991	1,593
958	958	50.0	1,058	866
625	624	80.0	698	554
534	532	90.0	600	467
482	480	95.0	545	418
422	419	99.0	481	362

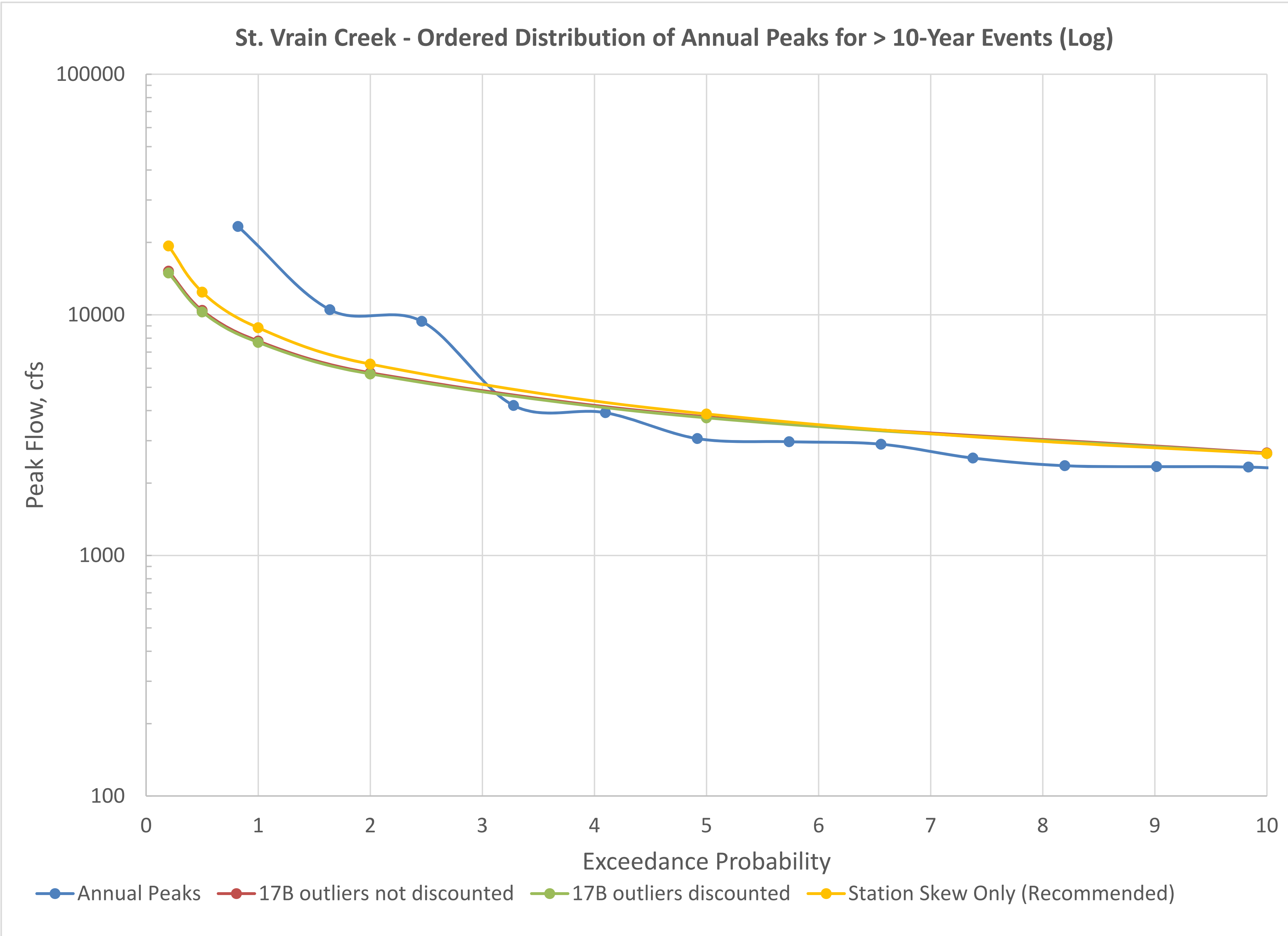
<< Adjusted Statistics >>
ST. VRAIN CK-LYONS 2013_Q23300

Log Transform: FLOW, CFS		Number of Events	
Mean	3.038	Historic Events	0
Standard Dev	0.287	High Outliers	3
Station Skew	1.217	Low Outliers	0
Regional Skew	0.608	Zero Events	0
Weighted Skew	0.885	Missing Events	0
Adopted Skew	1.217	Systematic Events	122
		Historic Period	126

--- End of Analytical Frequency Curve ---

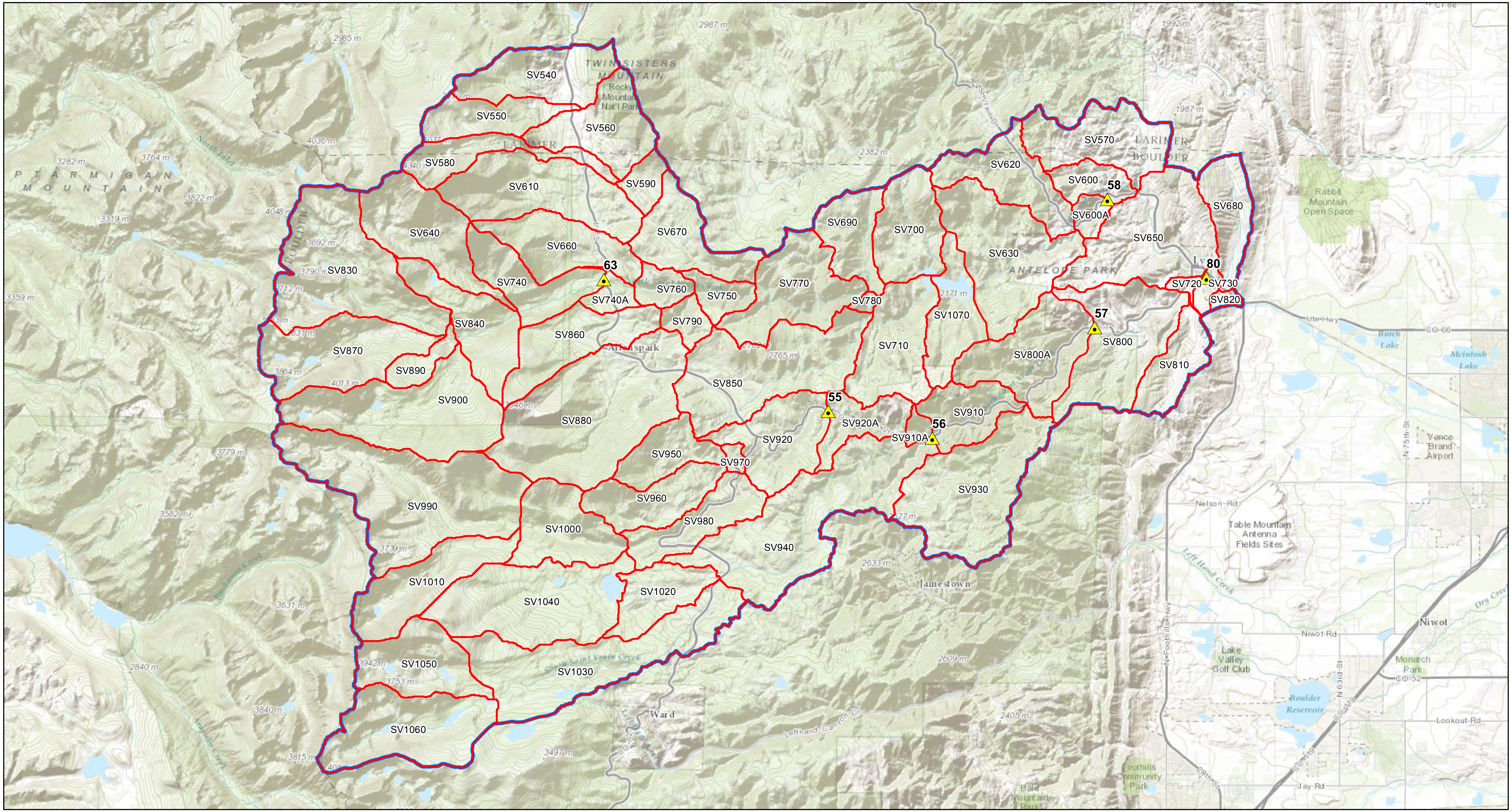

St. Vrain Creek - Ordered Distribution of Annual Peaks
Peak Flow, cfs
25000
20000
15000
10000
5000
0
0
10
20
30
40
50
60
70
80
90
100
Exceedance Probability
Annual Peaks
17B outliers not discounted
17B outliers discounted
Station Skew Only (Recommended)


St. Vrain Creek - Ordered Distribution of Annual Peaks for > 10-Year Events
Peak Flow, cfs
25000
20000
15000
10000
5000
0
0
1
2
3
4
5
6
7
8
9
10
Exceedance Probability
Annual Peaks
17B outliers not discounted
17B outliers discounted
Station Skew Only (Recommended)



St. Vrain Creek - Ordered Distribution of Annual Peaks for > 10-Year Events (Log)
100000
10000
1000
100
Peak Flow, cfs
0
1
2
3
4
5
6
7
8
9
10
Exceedance Probability
Annual Peaks
17B outliers not discounted
17B outliers discounted
Station Skew Only (Recommended)

Appendix C
Rainfall / Runoff Modeling



St. Vrain Watershed

CDOT Flood Recovery Hydrologic Evaluation

0 1 2 3
Miles

Investigation Sites
St. Vrain SubBasins
St. Vrain Watershed Boundary

Site	Stream and Location	Peak Discharge	Tributary Area
55	Middle St Vrain Creek at Riverside	1750	37.3
56	South St Vrain Creek d/s Middle St Vrain Creek	2700	70.4
57	South St Vrain Creek abv Lyons	9000	85.0
58	North St Vrain Creek abv Lyons	12300	112.0
63	North St Vrain at Hwy 7 south of Estes Park	450	32.6
80	St Vrain Creek downstream from Lyons	does not exceed ~21300 cfs	217.2

JACOBS

Appendix C.1

St. Vrain Creek Watershed

Design Point	Description	Drainage Area (sq. mi.)	2013 Flood Estimated Peak Discharge (cfs)	2013 Flood 10-day Period Calibrated (cfs)	2013 Flood Max 24hr Period Calibrated (cfs)	2013 Flood Max 24hr Period Runoff/Rainfall Ratio Adjusted (cfs)	NOAA 24-hr Type II Predictive Storms (Depth-Area Adjusted) 10-yr (cfs)	25-yr (cfs)	50-yr (cfs)	100-yr (cfs)	500-yr (cfs)	Effective FIS Peak Discharge Approximate Location for Comparison 10-yr (cfs)	50-yr (cfs)	100-yr (cfs)	500-yr (cfs)	Ayres 2013 Updated Flood Frequency Analysis 10-yr (cfs)	50-yr (cfs)	100-yr (cfs)	500-yr (cfs)
SV990	Buchanan Pass (Middle SVC headwaters)	10.21		430	485	345	201	396	611	891	1,802								
SV1010	Coney Creek (Middle SVC headwaters)	4.03		97	87	59	46	107	184	288	657								
J184	Headwaters Middle SVC	14.24		526	504	350	243	497	783	1,162	2,423								
R450	Middle SVC at headwaters	14.24		526	504	350	243	497	783	1,162	2,422								
SV1000	Middle SVC area above Camp Dick	3.66		290	330	241	41	103	179	284	654								
J176	Camp Dick on Middle SVC	17.89		762	772	539	279	584	935	1,399	2,966	470	860	1,180	2,320				
R460	Middle SVC along Hwy 72	17.89		762	772	539	279	584	934	1,399	2,965								
SV960	Park Creek Trib to Middle SVC	3.00		318	366	273	27	70	124	198	463								
SV950	Cave Creek Trib to Middle SVC	2.25		290	315	244	23	60	108	174	410								
J196	Cave and Park Creek Tribs on Middle SVC	5.25		596	680	517	50	130	230	370	867								
R400	Cave and Park Creek Trib to Middle SVC	5.25		596	680	517	50	130	230	370	867								
SV970	Ironclads trib area to Middle SVC	0.28		51	49	38	2	7	15	28	77								
SV980	Middle SVC area around Hwy 72	2.90		328	374	283	32	75	127	197	439								
J191	Middle SVC at Raymond	26.32		1,588	1,753	1,264	352	761	1,240	1,882	4,077								
R410	Middle SVC between Raymond and Riverside	26.32		1,588	1,752	1,263	352	761	1,239	1,882	4,075								
SV920	Middle SVC area above Riverside	3.85		547	633	421	13	43	86	152	410								
J201A	**Middle SVC at Riverside (Jarrett #55)**	**30.18**	**1750**	**1,996**	**2,218**	**1,622**	**364**	**799**	**1,315**	**2,011**	**4,421**								
R410A	Middle SVC above confluence with South SVC	30.18		1,996	2,218	1,621	364	799	1,314	2,011	4,419								
SV920A	Middle SVC area above confluence with South SVC	2.02		505	464	341	49	100	157	229	462								
J201B	Middle SVC above confluence with South SVC	32.19		2,430	2,481	1,840	394	862	1,415	2,162	4,741	590	1,430	2,000	4,070				
SV1060	Long Lake (South SVC headwaters)	5.62		216	202	140	269	459	655	894	1,626								
SV1050	Mitchell Lake (South SVC headwaters)	3.73		173	177	117	228	379	532	716	1,273								
J171	Brainard Lake (South SVC headwaters)	9.35		389	377	256	495	835	1,183	1,603	2,883								
R520	South SVC headwaters to Hwy 72	9.35		389	377	256	495	834	1,182	1,602	2,882								
SV1040	Beaver Reservoir trib area (South SVC)	7.14		529	548	413	270	493	725	1,012	1,899								
J490	Beaver Reservoir (South SVC)	7.14		529	548	413	270	493	725	1,012	1,899								
R490	Beaver Creek (South SVC)	7.14		529	548	413	270	493	725	1,012	1,898								
SV1020	Beaver Creek area tributary to South SVC	2.52		296	326	244	63	128	201	293	592								
SV1030	South SVC area upstream of Hwy 72	7.78		457	460	334	154	289	433	614	1,188								
J179	South SVC at Hwy 72	26.78		1,556	1,578	1,149	914	1,628	2,374	3,292	6,132								
R480	South SVC from Hwy 72 to confluence with Middle SVC	26.78		1,556	1,577	1,126	914	1,627	2,372	3,289	6,128								
SV940	South SVC area between Hwy 72 and Middle SVC	7.75		944	964	749	86	176	278	410	846								
J201C	South SVC above confluence with Middle SVC	34.53		2,402	2,478	1,804	993	1,792	2,636	3,679	6,938								
J201	Confluence of Middle and South SVC	66.72		4,525	4,833	3,547	1,169	2,300	3,585	5,258	10,716	1,220	2,790	3,990	8,560				
R370A	South SVC below confluence with Middle SVC	66.72		4,524	4,832	3,547	1,169	2,300	3,585	5,257	10,713								
SV910A	Long Gulch Trib to South SVC below confluence with Middle SVC	1.72		453	467	343	45	96	154	228	471								
J204A	**South SVC at Discharge Estimation Point (Jarrett #56)**	**68.45**	**2700**	**4,777**	**5,007**	**3,695**	**1,190**	**2,345**	**3,658**	**5,369**	**10,962**								
R370	South SVC above Big Narrows	68.45		4,777	5,006	3,695	1,190	2,344	3,657	5,368	10,957								
SV910	South SVC trib area above Big Narrows	2.50		691	692	525	109	205	303	424	794								
SV930	Central Gulch Trib to South SVC at Big Narrows	7.22		1,549	1,476	1,014	200	374	554	776	1,459								
J204	South SVC at Big Narrows	78.17		6,572	6,330	4,822	1,376	2,712	4,220	6,189	12,597								
R350A	South SVC below Big and Little Narrows	78.17		6,571	6,329	4,821	1,376	2,711	4,219	6,187	12,594								
SV800A	Coffintop Gulch trib to South SVC between Big and Little Narrows	4.89		959	995	667	170	324	483	679	1,286								
J204B	**South SVC at Little Narrows (Jarrett #57)**	**83.06**	**9000**	**7,518**	**6,865**	**5,269**	**1,464**	**2,890**	**4,496**	**6,598**	**13,435**								
R350	South SVC below Little Narrows past Hall Ranch	83.06		7,516	6,862	5,267	1,461	2,886	4,492	6,587	13,421								
SV800	South SVC trib area at Hall Ranch	5.67		1,044	1,051	712	176	332	493	692	1,306								
SV810	Red Hill Gulch Trib to South SVC above Lyons	2.28		360	354	232	94	173	253	350	645								
SV720	Indian Lookout Mountain Trib Area to South SVC	0.26		56	53	35	41	67	91	119	199								
J234	South SVC above confluence with North SVC	91.27		8,886	7,670	5,937	1,605	3,168	4,933	7,234	14,748	1,400	3,750	5,430	11,900				
R190	South SVC above confluence with North SVC	91.27		8,886	7,669	5,937	1,605	3,167	4,933	7,230	14,745								
SV830	North SVC headwaters	7.95		413	399	285	333	577	830	1,139	2,097								
SV870	Ouzel Creek Trib to North SVC headwaters	5.14		361	330	229	261	438	620	839	1,508								
J219	North SVC headwaters	13.08		773	728	511	563	972	1,390	1,906	3,482								
R320	North SVC near Ouzel Falls	13.08		773	728	511	563	972	1,389	1,906	3,481								
SV890	North SVC trib area near Calypso Cascades	1.01		34	45	31	9	26	51	87	224								
SV900	Cony Creek Trib area to North SVC	7.24		379	393	307	211	398	604	862	1,697								
J211	North SVC at confluence with Cony Creek	21.33		1,178	1,075	838	768	1,375	2,009	2,807	5,297								
R310	North SVC above Copeland Falls in Wild Basin	21.33		1,177	1,075	838	768	1,375	2,009	2,807	5,295								
SV840	Sandbeach Creek Trib to North SVC in Wild Basin	3.64		179	216	160	47	121	217	352	839								
SV640	Hunters Creek Trib to North SVC in Wild Basin	4.50		228	236	181	152	276	410	575	1,101								
J227	North SVC at Copeland Falls	29.47		1,551	1,495	1,152	954	1,747	2,590	3,662	7,059								
R240	North SVC above Hwy 7	29.47		1,550	1,493	1,150	953	1,745	2,587	3,658	7,048								
SV740	Campers Creek Trib to North SVC at Hwy 7	3.05		180	230	159	13	43	87	155	425								
J252A	**North SVC at Hwy 7 (Jarrett #63)**	**32.52**	**450**	**1,713**	**1,686**	**1,279**	**963**	**1,785**	**2,667**	**3,799**	**7,423**								
R240A	North SVC below Hwy 7	32.52		1,713	1,686	1,279	963	1,785	2,667	3,798	7,421								
SV740A	North SVC trib area at Hwy 7	0.78		69	83	62	10	28	51	84	202								
SV660	Horse Creek Trib to North SVC below Hwy 7	3.57		205	270	188	12	40	81	145	403								
J252	North SVC at confluence with Horse Creek below Hwy 7	36.87		1,972	1,982	1,481	920	1,737	2,656	3,819	7,636								
R170	North SVC between Horse Creek and Rock Creek	36.87		1,971	1,981	1,481	920	1,737	2,656	3,819	7,633								
SV760	North SVC trib area between Horse Creek and Rock Creek	1.01		146	169	119	2	10	23	47	150								
SV860	Willow Creek Tributary to Rock Creek and North SVC near Allenspark	3.75		291	345	256	29	75	134	216	513								
SV880	Rock Creek Trib to North SVC at Ferncliff	10.10		673	846	586	24	80	164	292	810								
J216	Rock Creek Trib to North SVC at Ferncliff	13.85		960	1,188	839	47	144	284	488	1,289								
R290	Rock Creek Trib to North SVC	13.85		960	1,187	839	47	144	284	488	1,288								
SV790	Rock creek trib area at confluence with North SVC	0.90		106	135	99	1	6	14	30	105								
J239	North SVC at confluence with Rock Creek	52.63		3,061	3,330	2,418	952	1,872	2,943	4,330	9,016								
R200	North SVC between Rock Creek and Cabin Creek tribs	52.63		3,060	3,330	2,418	952	1,872	2,943	4,329	9,012								
SV750	North SVC trib area above Cabin Creek Confluence	1.15		178	213	153	1	6	14	31	110								
SV540	Inn Brook Trib at Longs Peak above North SVC	3.82		516	609	462	40	106	191	309	730								
SV550	Alpine Brook Trib at Longs Peak above North SVC	2.46		211	241	174	58	121	194	289	608								
J298	Confluence of Inn Brook and Alpine Brook tributary to North SVC	6.28		711	841	636	97	227	384	597	1,335								
R40	Tahosa Creek between Roaring Fork and Alpine Brook tribs	6.28		710	841	636	97	227	384	597	1,335								
SV560	Tahosa Valley upstream of Roaring Fork trib in North SVC area	3.68		572	658	417	32	88	161	264	638								
SV580	Roaring Fork Trib to Tahosa Creek in North SVC area	2.36		184	193	134	61	118	180	259	517								
J291	Tahosa Valley above Cabin Creek in North SVC area	12.32		1,443	1,659	1,158	176	405	683	1,058	2,365								
R70	Tahosa Creek above Cabin Creek in North SVC area	12.32		1,443	1,659	1,157	176	405	683	1,058	2,364								
SV590	Tahosa Creek trib area upstream of Cabin Creek in North SVC area	0.97		272	256	178	11	32	61	102	252								
SV610	Cabin Creek Trib area to North SVC	5.79		672	708	493	143	281	436	634	1,284								
J283	Cabin Creek and Tahosa Creek confluence in North SVC area	19.08		2,303	2,578	1,731	315	693	1,139	1,736	3,776								
R120	Cabin Creek trib to North SVC	19.08		2,303	2,577	1,731	315	693	1,139	1,736	3,775								
SV670	Cabin Creek Trib area at confluence with North SVC	3.38		671	699	475	36	85	143	221	491								
J249	North SVC at confluence with Cabin Creek	76.25		6,162	6,565	4,649	1,198	2,446	3,921	5,843	12,487								
R250	North SVC below confluence with Cabin Creek	76.25		6,161	6,564	4,647	1,198	2,445	3,920	5,841	12,479								
SV770	North SVC trib area below confluence with Cabin Creek	4.56		1,093	1,033	745	66	146	240	364	783								
SV690	Coulson Gulch trib to North SVC	2.51		642	611	368	50	112	184	279	596								
J244	North SVC at Coulson Gulch confluence	83.31		7,441	7,951	5,335	1,279	2,627	4,222	6,303	13,499								
R260	North SVC above confluence with Dry SVC	83.31		7,441	7,951	5,334	1,279	2,626	4,222	6,303	13,495								
SV780	North SVC area below Coulson Gulch confluence	0.21		82	85	56	11	26	43	65	140								
SV850	Dry SVC trib to North SVC	7.24		1,241	1,302	932	88	190	308	463	984								
J224	North SVC at confluence with Dry SVC	90.76		8,706	9,276	6,139	1,351	2,786	4,486	6,704	14,371								
R270	North SVC below confluence with Dry SVC	90.76		8,705	9,274	6,138	1,351	2,785	4,483	6,699	14,363								
SV710	North SVC trib area upstream of Button Rock Reservoir	4.20		981	985	704	57	126	206	311	667								
SV700	Rattlesnake Gulch Trib to North SVC	3.48		1,017	937	574	134	257	389	554	1,073								
J261	North SVC inflow to Button Rock Reservoir	98.44		10,007	10,612	6,997	1,457	3,013	4,850	7,247	15,522								
R3250	North SVC through Button Rock Reservoir	98.44		10,006	10,612	6,996	1,457	3,013	4,849	7,246	15,522								
SV1070	Long Gulch trib to North SVC at Button Rock Reservoir	2.88		796	783	608	93	187	291	423	845								
J168	**North SVC inflow to Button Rock Reservoir**	**101.32**	**10000**	**10,591**	**11,112**	**7,389**	**1,502**	**3,108**	**5,002**	**7,472**	**16,002**								
Button Rock	**Discharge from Button Rock Reservoir**	**101.00**	**10000**	**10,591**	**11,112**	**7,389**	**1,059**	**2,221**	**3,674**	**5,603**	**12,490**								
R180	North SVC below Button Rock Reservoir	101.32		10,588	11,110	7,387	978	2,090	3,459	5,318	11,927								
SV630	North SVC throught Longmont Reservoir below Button Rock	6.50		1,039	1,042	768	146	291	447	641	1,258								
SV620	North SVC trib area from Hwy 36 at north end	3.51		635	696	574	75	158	251	368	748								
J278	North SVC below Longmont Reservoir at Hwy 36	111.33		12,023	12,365	8,240	1,054	2,289	3,788	5,818	13,049								
R80A	North SVC along upper part of Hwy 36	111.33		12,021	12,363	8,238	1,054	2,289	3,787	5,817	13,047								
SV600A	North SVC trib area above peak discharge estimation point	0.66		107	101	70	53	97	142	195	356								
J286A	**North SVC at Peak Discharge Estimation Point (Jarrett #58)**	**111.99**	**12300**	**12,094**	**12,405**	**8,270**	**1,056**	**2,299**	**3,804**	**5,842**	**13,100**								
R80	North SVC above Apple Valley Road	111.99		12,090	12,403	8,268	1,056	2,299	3,803	5,841	13,098								
SV600	North SVC trib area at Apple Valley Road	1.40		161	167	108	59	115	176	250	482								
SV570	Spring Gulch Trib to North SVC at Apple Valley Road	4.14		445	533	386	46	110	186	287	629								
J286	North SVC at Apple Valley Road	117.54		12,501	12,752	8,529	1,081	2,377	3,938	6,052	13,599								
R110	North SVC above confluence with South SVC	117.54		12,487	12,742	8,523	1,081	2,376	3,937	6,049	13,590								
SV650	North SVC trib area above confluence with South SVC	6.43		712	693	546	210	387	570	793	1,476								
J260	North SVC above confluence with South SVC	123.97		13,182	13,196	8,952	1,123	2,502	4,160	6,386	14,329	1,000	2,850	4,310	10,630				
J258	Confluence of North and South SVC	215.24		21,827	20,639	14,879	2,178	4,786	7,828	11,910	26,222	2,040	6,670	8,880	20,260	2,622	5,542	7,446	14,250
R140	St Vrain Creek through Lyons	215.24		21,819	20,631	14,873	2,177	4,785	7,826	11,905	26,209								
SV730	Lyons trib area to St. Vrain Creek	0.47		68	67	41	35	62	89	120	214								
SV680	Stone Canyon Trib to St Vrain Creek at Lyons	2.43		234	236	191	119	206	293	397	705								
J255	St Vrain Creek at confluence with Stone Canyon	218.14		22,102	20,771	15,016	2,202	4,857	7,943	12,080	26,581								
R210	St Vrain Creek below Lyons	218.14		22,098	20,767	15,013	2,202	4,856	7,942	12,078	26,576								
SV820	St. Vrain Creek trib area downstream of Lyons	0.25		45	44	30	36	58	77	100	164								
Outlet1	**Outlet - St. Vrain Creek at Hwy 36 downstream of Lyons**	**218.39**	**23000**	**22,127**	**20,782**	**15,024**	**2,202**	**4,860**	**7,949**	**12,089**	**26,599**	2,040	6,670	8,880	20,260				

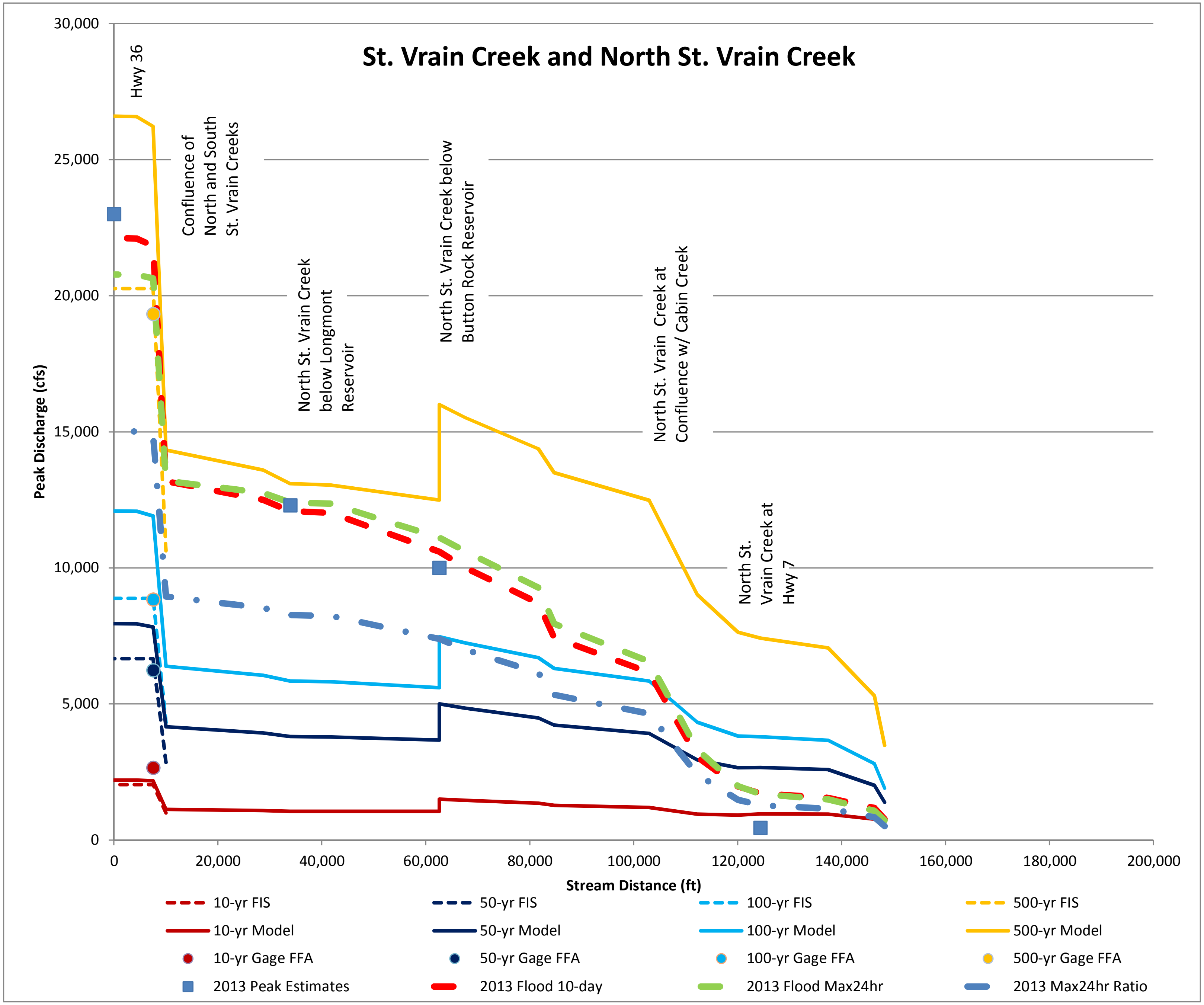
Appendix C.1 (continued)

Condensed for Profiles

ST. VRAIN WATERSHED

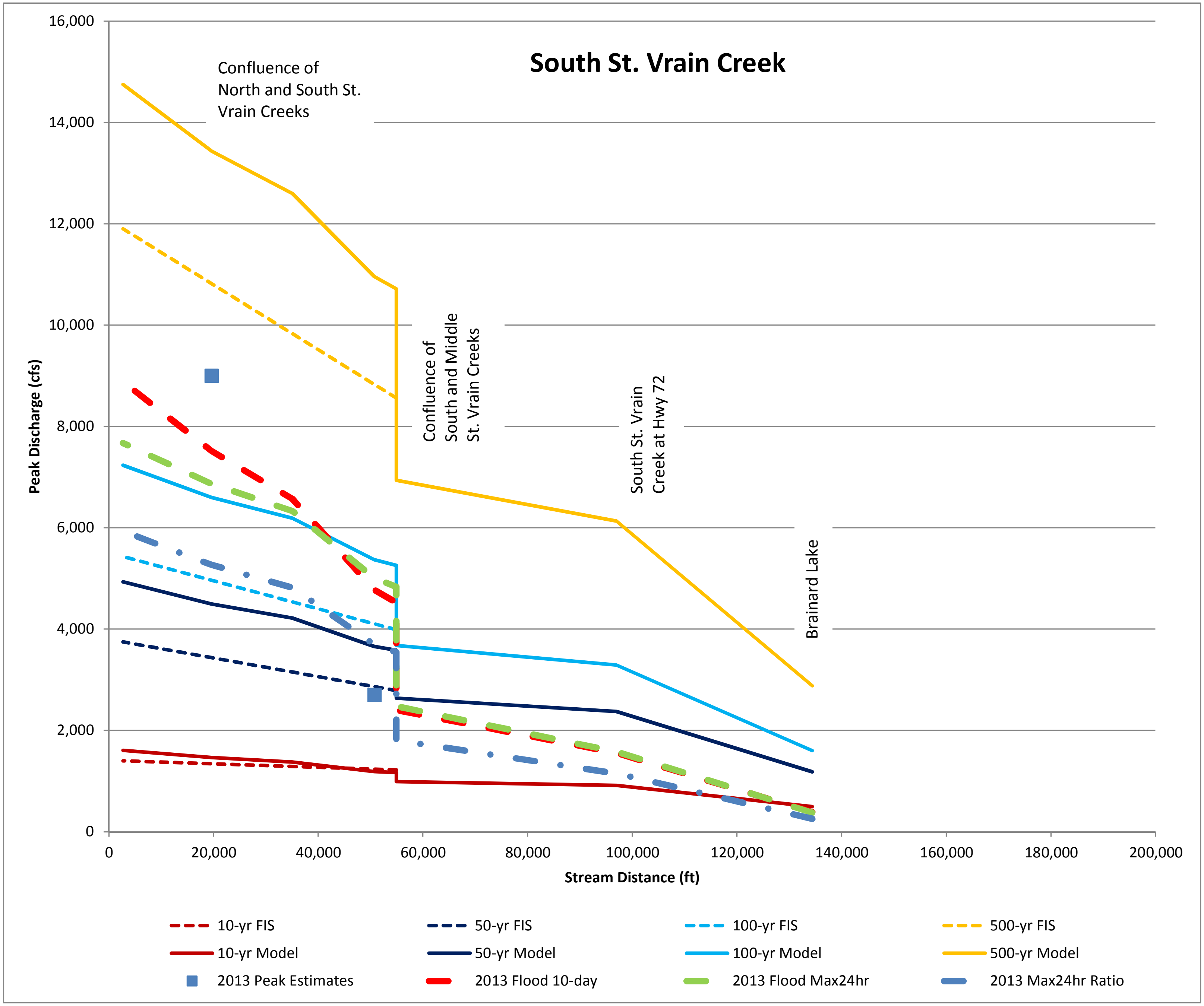
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
		Approx. Station	Drainage Area	2013 Flood Estimated	2013 Flood 10-day Period Calibrated	2013 Flood Max 24hr Period Calibrated	2013 Flood Max 24hr Period Rainfall/Runoff Ratio Adjusted	NOAA Design Storms (Depth-Area Adjusted)					Effective FIS Peak Discharge				Ayres 2013 Flood Frequency Analysis			
								10-yr	25-yr	50-yr	100-yr	500-yr	10-yr	50-yr	100-yr	500-yr	10-yr	50-yr	100-yr	500-yr
HEC-HMS Design Point	Description	(ft)	(sq. mi.)	Peak Discharge (cfs)	(cfs)	(cfs)	(cfs)	(cfs)	(cfs)	(cfs)	(cfs)	(cfs)	(cfs)	(cfs)	(cfs)	(cfs)	(cfs)	(cfs)	(cfs)	(cfs)
J184	Headwaters Middle SVC	64,375	14		526	504	350	243	497	783	1,162	2,423								
J176	Camp Dick on Middle SVC	49,524	18		762	772	539	279	584	935	1,399	2,966	470	860	1,180	2,320				
J191	Middle SVC at Raymond	28,604	26		1,588	1,753	1,264	352	761	1,240	1,882	4,077								
J201A	**Middle SVC at Riverside (Dischage Estimation Point #55 by Bob Jarrett)**	12,864	30	**1,750**	**1,996**	**2,218**	**1,622**	**364**	**799**	**1,315**	**2,011**	**4,421**								
J201B	Middle SVC above confluence with South SVC	0	32		2,430	2,481	1,840	394	862	1,415	2,162	4,741	590	1,430	2,000	4,070				
J171	Brainard Lake (South SVC headwaters)	134,386	9		389	377	256	495	835	1,183	1,603	2,883								
J179	South SVC at Hwy 72	96,994	27		1,556	1,578	1,149	914	1,628	2,374	3,292	6,132								
J201C	South SVC above confluence with Middle SVC	54,933	35		2,402	2,478	1,804	993	1,792	2,636	3,679	6,938								
J201	Confluence of Middle and South SVC	54,933	67		4,525	4,833	3,547	1,169	2,300	3,585	5,258	10,716	1,220	2,790	3,990	8,560				
J204A	**South SVC at Discharge Estimation Point #56 by Bob Jarrett**	50,712	68	**2,700**	**4,777**	**5,007**	**3,695**	1,190	2,345	3,658	5,369	10,962								
J204	South SVC at Big Narrows	35,070	78		6,572	6,330	4,822	1,376	2,712	4,220	6,189	12,597								
J204B	**South SVC at Little Narrows (Peak Discharge Estimate Point #57 by Bob Jarrett)**	19,616	83	**9,000**	**7,518**	**6,865**	**5,269**	**1,464**	**2,890**	**4,496**	**6,598**	**13,435**								
J234	South SVC above confluence with North SVC	2,692	91		8,886	7,670	5,937	1,605	3,168	4,933	7,234	14,748	1,400	3,750	5,430	11,900				
J219	North SVC headwaters	148,267	13		773	728	511	563	972	1,390	1,906	3,482								
J211	North SVC at confluence with Cony Creek	146,337	21		1,178	1,075	838	768	1,375	2,009	2,807	5,297								
J227	North SVC at Copeland Falls	137,427	29		1,551	1,495	1,152	954	1,747	2,590	3,662	7,059								
J252A	**North SVC at Hwy 7 (Peak Estimation Point #63 by Bob Jarrett)**	124,396	33	**450**	**1,713**	**1,686**	**1,279**	**963**	**1,785**	**2,667**	**3,799**	**7,423**								
J252	North SVC at confluence with Horse Creek below Hwy 7	120,085	37		1,972	1,982	1,481	920	1,737	2,656	3,819	7,636								
J239	North SVC at confluence with Rock Creek	112,223	53		3,061	3,330	2,418	952	1,872	2,943	4,330	9,016								
J249	North SVC at confluence with Cabin Creek	102,962	76		6,162	6,565	4,649	1,198	2,446	3,921	5,843	12,487								
J244	North SVC at Coulson Gulch confluence	84,708	83		7,441	7,951	5,335	1,279	2,627	4,222	6,303	13,499								
J224	North SVC at confluence with Dry SVC	81,656	91		8,706	9,276	6,139	1,351	2,786	4,486	6,704	14,371								
J261	North SVC inflow to Button Rock Reservoir	67,599	98		10,007	10,612	6,997	1,457	3,013	4,850	7,247	15,522								
J168	**North SVC inflow to Button Rock Reservoir**	62,608	101	**10,000**	**10,591**	**11,112**	**7,389**	**1,502**	**3,108**	**5,002**	**7,472**	**16,002**								
Button Rock	**Discharge from Button Rock Reservoir**	62,608	101		**10,591**	**11,112**	**7,389**	**1,059**	**2,221**	**3,674**	**5,603**	**12,490**								
J278	North SVC below Longmont Reservoir at Hwy 36	41,695	111		12,023	12,365	8,240	1,054	2,289	3,788	5,818	13,049								
J286A	**North SVC at Peak Discharge Estimation Point #58 by Bob Jarrett**	33,900	112	**12,300**	**12,094**	**12,405**	**8,270**	**1,056**	**2,299**	**3,804**	**5,842**	**13,100**								
J286	North SVC at Apple Valley Road	28,711	118		12,501	12,752	8,529	1,081	2,377	3,938	6,052	13,599								
J260	North SVC above confluence with South SVC	10,000	124		13,182	13,196	8,952	1,123	2,502	4,160	6,386	14,329	1,000	2,850	4,310	10,630				
J258	Confluence of North and South SVC	7,559	215		21,827	20,639	14,879	2,178	4,786	7,828	11,910	26,222	2,040	6,670	8,880	20,260	2,652	6,239	8,840	19,330
J255	St Vrain Creek at confluence with Stone Canyon	4,401	218		22,102	20,771	15,016	2,202	4,857	7,943	12,080	26,581								
Outlet1	**Outlet - St. Vrain Creek at Hwy 36 downstream of Lyons**	0	218	**23,000**	**22,127**	**20,782**	**15,024**	**2,202**	**4,860**	**7,949**	**12,089**	**26,599**	2,040	6,670	8,880	20,260				

Appendix C.2

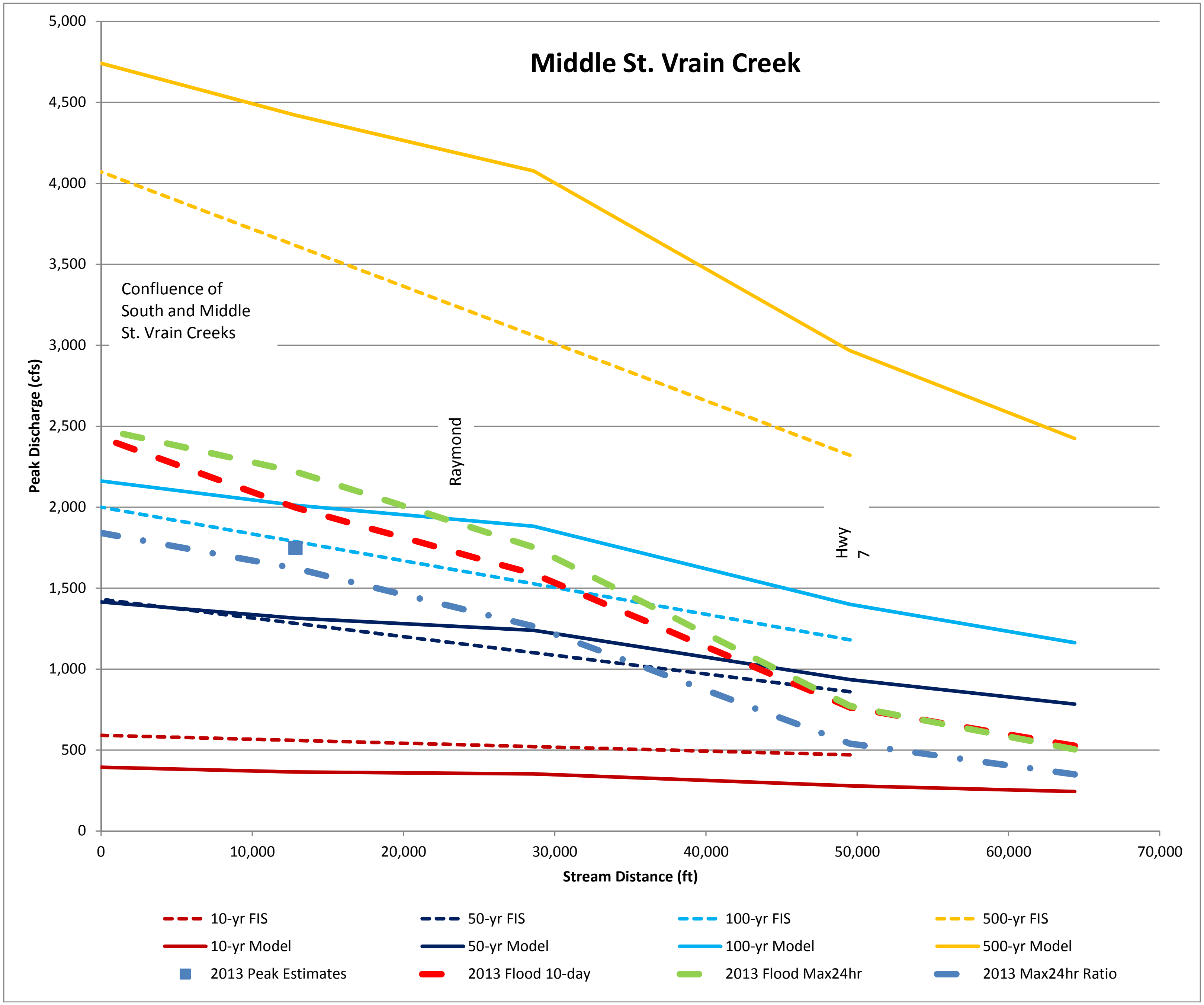


St. Vrain Creek and North St. Vrain Creek
Peak Discharge (cfs)
30,000
25,000
20,000
15,000
10,000
5,000
0
Hwy 36
Confluence of North and South St. Vrain Creeks
North St. Vrain Creek below Longmont Reservoir
North St. Vrain Creek below Button Rock Reservoir
North St. Vrain Creek at Confluence w/ Cabin Creek
North St. Vrain Creek at Hwy 7
0
20,000
40,000
60,000
80,000
100,000
120,000
140,000
160,000
180,000
200,000
Stream Distance (ft)
10-yr FIS
50-yr FIS
100-yr FIS
500-yr FIS
10-yr Model
50-yr Model
100-yr Model
500-yr Model
10-yr Gage FFA
50-yr Gage FFA
100-yr Gage FFA
500-yr Gage FFA
2013 Peak Estimates
2013 Flood 10-day
2013 Flood Max24hr
2013 Max24hr Ratio

Appendix C.3


South St. Vrain Creek
Confluence of North and South St. Vrain Creeks
Confluence of South and Middle St. Vrain Creeks
South St. Vrain Creek at Hwy 72
Brainard Lake
Peak Discharge (cfs)
16,000
14,000
12,000
10,000
8,000
6,000
4,000
2,000
0
Stream Distance (ft)
0
20,000
40,000
60,000
80,000
100,000
120,000
140,000
160,000
180,000
200,000
10-yr FIS
50-yr FIS
100-yr FIS
500-yr FIS
10-yr Model
50-yr Model
100-yr Model
500-yr Model
2013 Peak Estimates
2013 Flood 10-day
2013 Flood Max24hr
2013 Max24hr Ratio

Appendix C.4



Middle St. Vrain Creek
Peak Discharge (cfs)
5,000
4,500
4,000
3,500
3,000
2,500
2,000
1,500
1,000
500
0
Confluence of
South and Middle
St. Vrain Creeks
Raymond
Hwy
7
0
10,000
20,000
30,000
40,000
50,000
60,000
70,000
Stream Distance (ft)
10-yr FIS
50-yr FIS
100-yr FIS
500-yr FIS
10-yr Model
50-yr Model
100-yr Model
500-yr Model
2013 Peak Estimates
2013 Flood 10-day
2013 Flood Max24hr
2013 Max24hr Ratio

Big Thompson - Curve Number Optimizatio

Appendix C.5

Project: Big Thompson Calibrated   Optimization Trial: BT CN Optimization

Start of Trial:	09Sep2013, 00:00	Basin Model:	Big Thompson Calibrated
End of Trial:	15Sep2013, 23:45	Meteorologic Model:	BigThompson 2013 Flood
Compute Time:	12Feb2014, 20:21:51	Control Specifications:	Big Thompson - Lake Estes

Objective Function at Basin Element "J4055"

Start of Function :	09Sep2013, 00:00	Type :	Peak-Weighted RMS Error
End of Function :	15Sep2013, 23:45	Value :	742.0

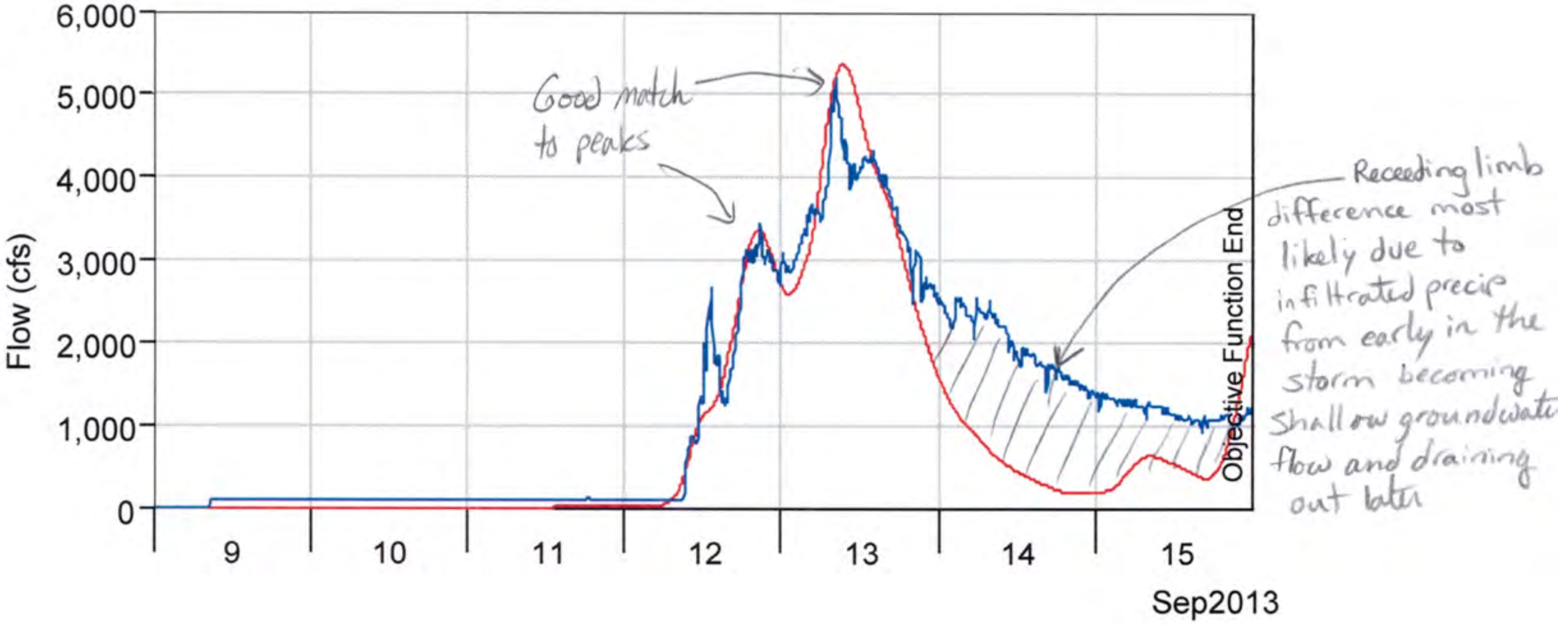
Volume Units: IN

Measure	Simulated	Observed	Difference	Percent Difference
Volume (IN)	1.45	1.98	-0.53	-26.80
Peak Flow (CFS)	5347.3	5162.4	184.8	3.6
Time of Peak	13Sep2013, 09:15	13Sep2013, 08:15		
Time of Center of Mass	13Sep2013, 14:26	13Sep2013, 19:10		

Model optimization involved changing the initial abstraction (in) and the Curve Number to acheive a best fit to the Inflow hydrograph for Lake Estes

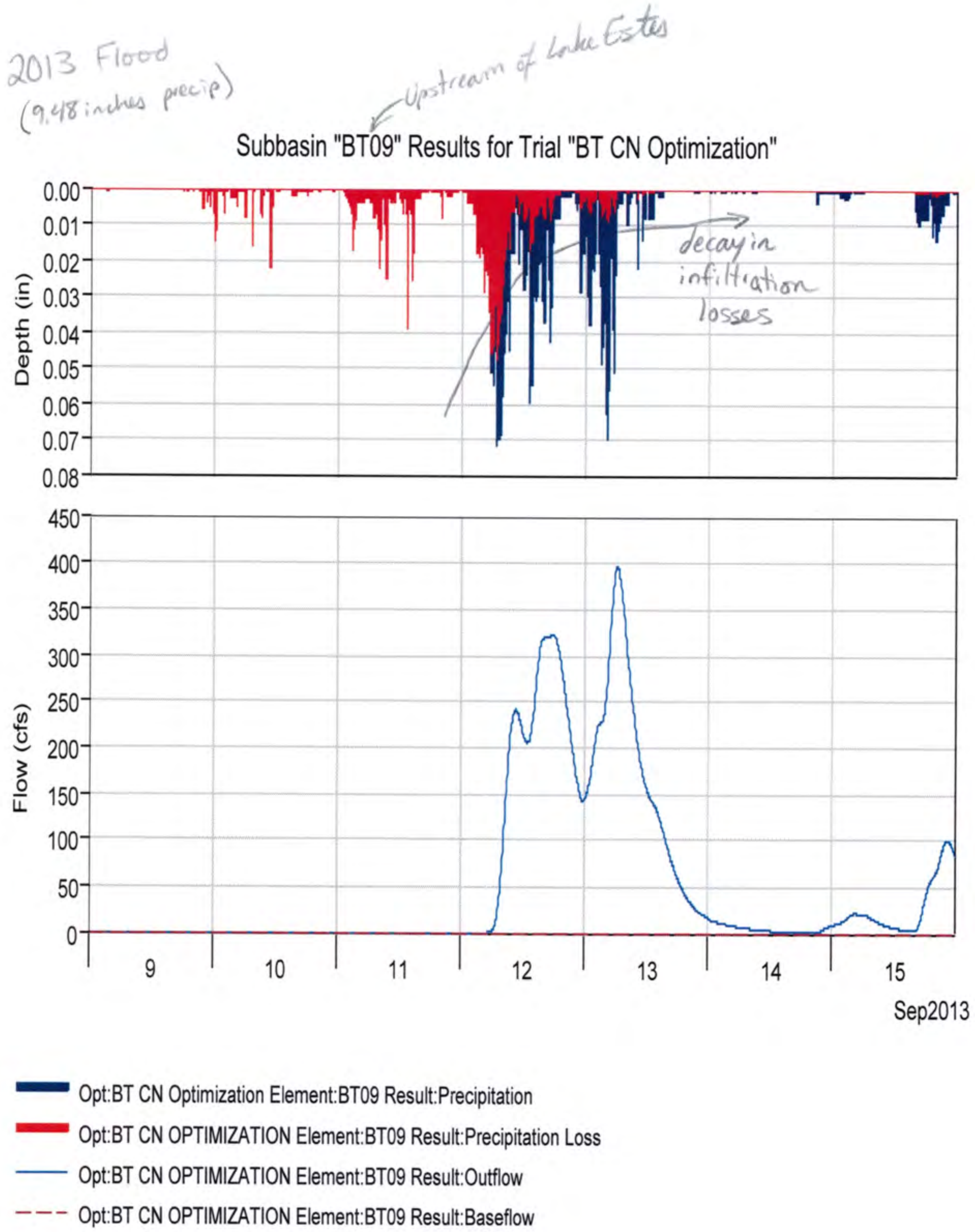
Curve Numbers increased by 12% over previously calibrated model
Initial Abstraction doubled ($I_a \approx 0.45$)

Lake Estes Inflow Hydrograph Comparison



Opt:BT CN Optimization Element:J4055 Result:Outflow

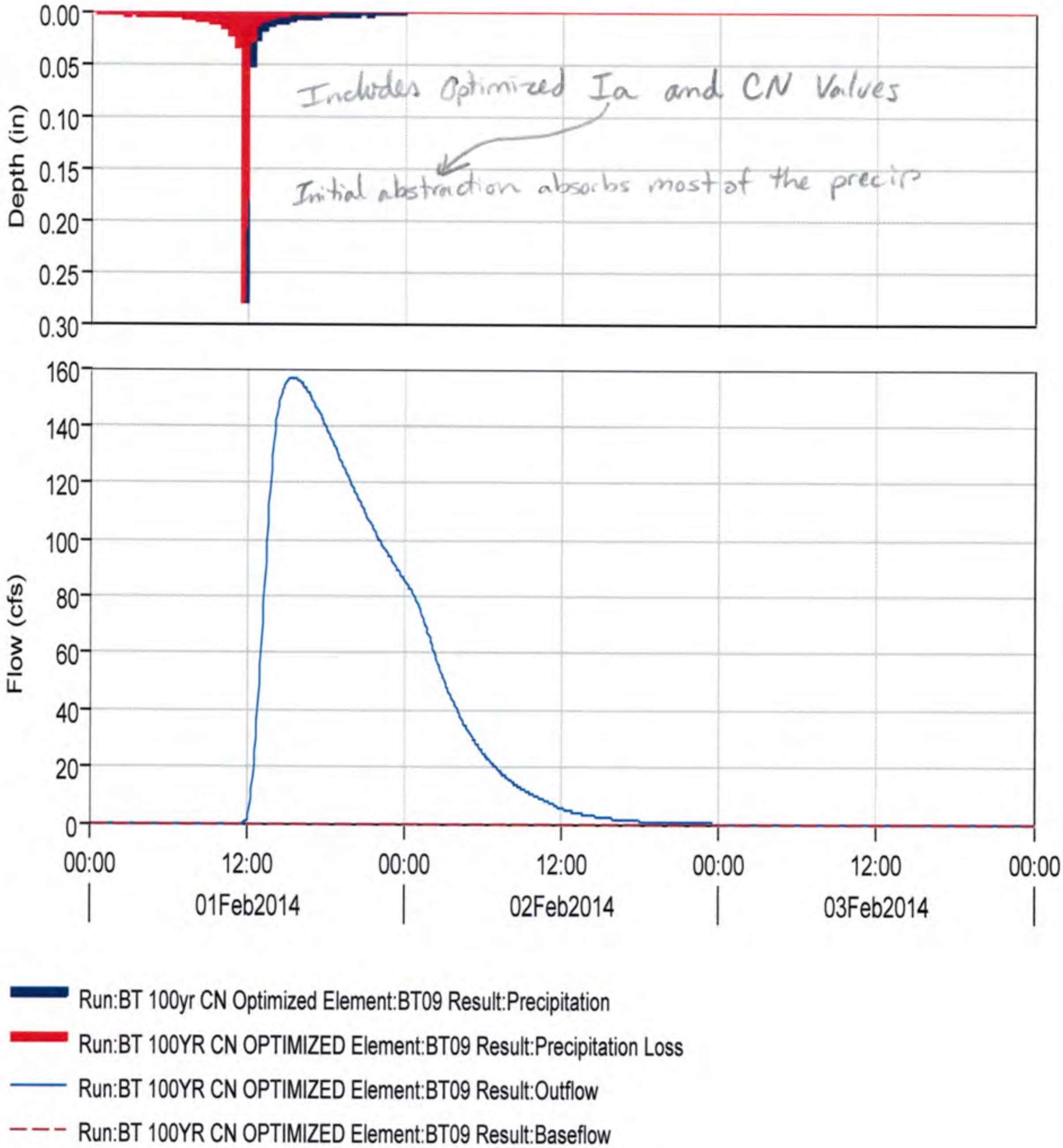
Opt:BT CN OPTIMIZATION Element:J4055 Result:Observed Flow


2013 Flood
(9.48 inches precip)
Upstream of Lake Estes
Subbasin "BT09" Results for Trial "BT CN Optimization"
Depth (in)
0.00
0.01
0.02
0.03
0.04
0.05
0.06
0.07
0.08
decay in infiltration losses
Flow (cfs)
450
400
350
300
250
200
150
100
50
0
9
10
11
12
13
14
15
Sep2013
Opt:BT CN Optimization Element:BT09 Result:Precipitation
Opt:BT CN OPTIMIZATION Element:BT09 Result:Precipitation Loss
Opt:BT CN OPTIMIZATION Element:BT09 Result:Outflow
Opt:BT CN OPTIMIZATION Element:BT09 Result:Baseflow

NOAA 100-yr 24hr Storm
(4.42 inches Precip)

Upstream of Lake Estes

Subbasin "BT09" Results for Run "BT 100yr CN Optimized"

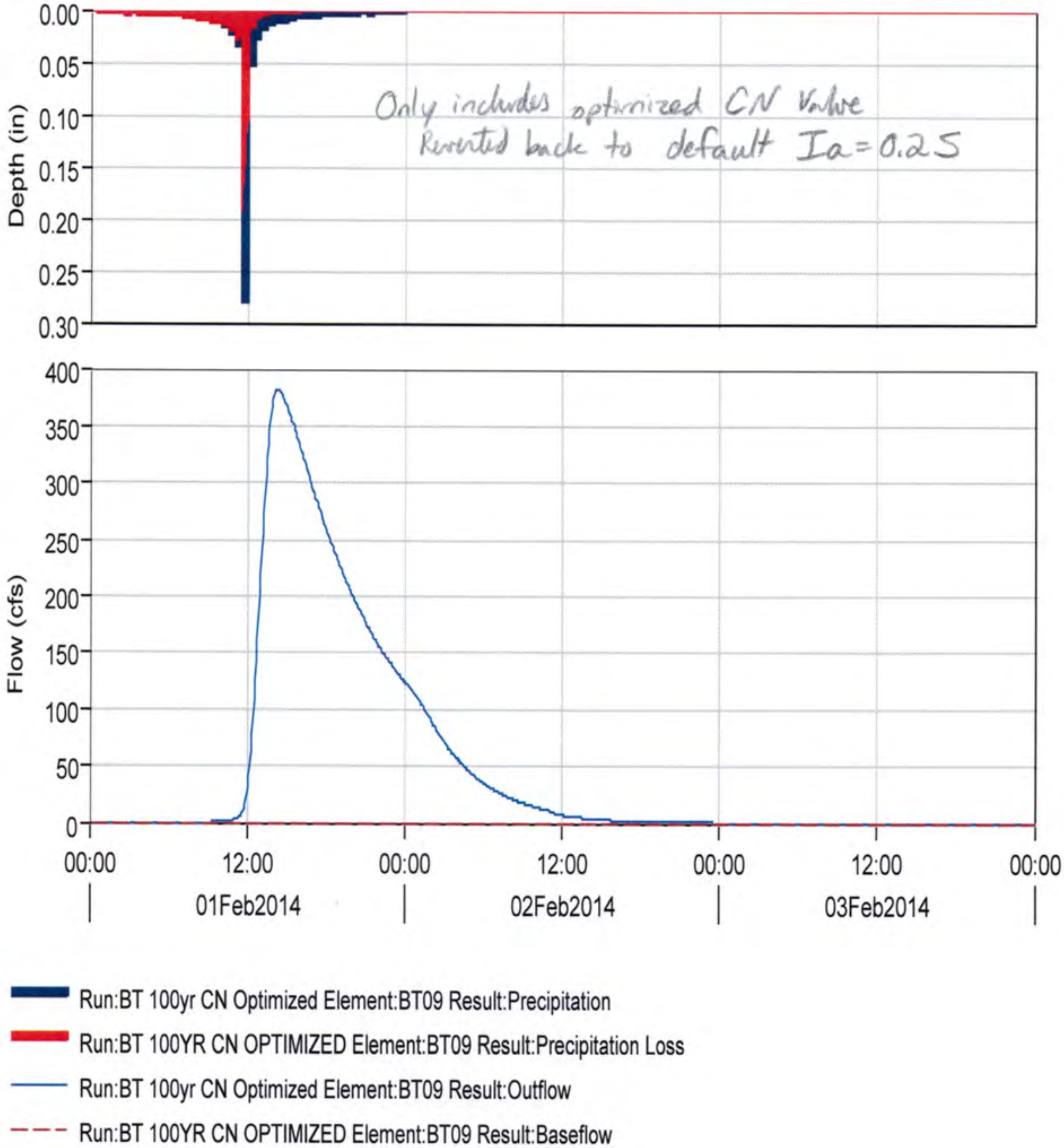


NOAA 100-yr 24 hr Storm

(4.42 inches precip)

upstream of Lake Estes

Subbasin "BT09" Results for Run "BT 100yr CN Optimized"



Big Thompson - Initial + Constant Loss Method

Project: Big Thompson Calibrated   Optimization Trial: BT Constant Optimization

Start of Trial: 09Sep2013, 00:00   Basin Model: BT Constant Loss
End of Trial: 15Sep2013, 23:45   Meteorologic Model: BigThompson 2013 Flood
Compute Time: 12Feb2014, 18:19:07   Control Specifications: Big Thompson - Lake Estes

Objective Function at Basin Element "J4055"

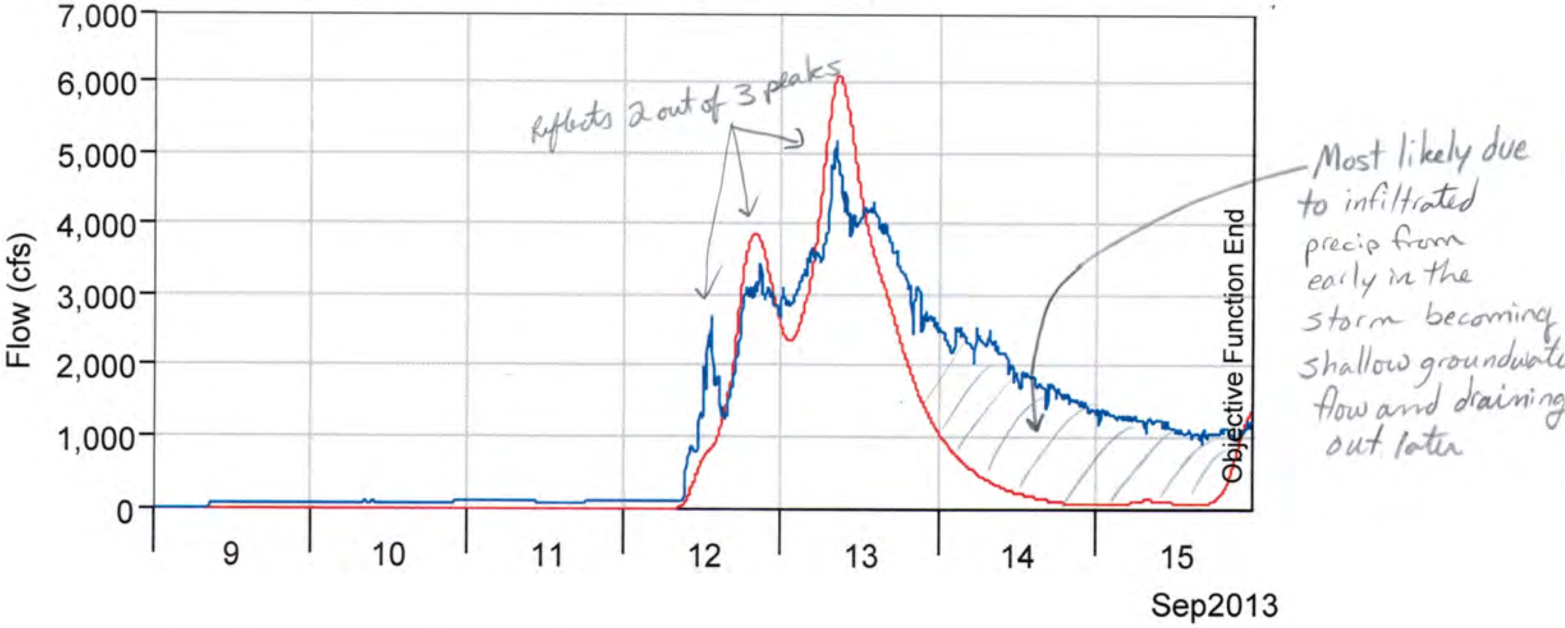
Start of Function : 09Sep2013, 00:00   Type : Peak-Weighted RMS Error
End of Function : 15Sep2013, 23:45   Value : 994.3

Volume Units: IN

Measure	Simulated	Observed	Difference	Percent Difference
Volume (IN)	1.23	1.98	-0.75	-37.74
Peak Flow (CFS)	6088.4	5162.4	926.0	17.9
Time of Peak	13Sep2013, 08:40	13Sep2013, 08:15		
Time of Center of Mass	13Sep2013, 10:16	13Sep2013, 19:10		

Model Optimization involved changing Initial Loss (in) and Constant Infiltration rate (fc) to acheive a best fit to the Inflow Hydrograph for Lake Estes.

Lake Estes Inflow Hydrograph Comparison



Opt:BT Constant Optimization Element:J4055 Result:Outflow

Opt:BT CONSTANT OPTIMIZATION Element:J4055 Result:Observed Flow

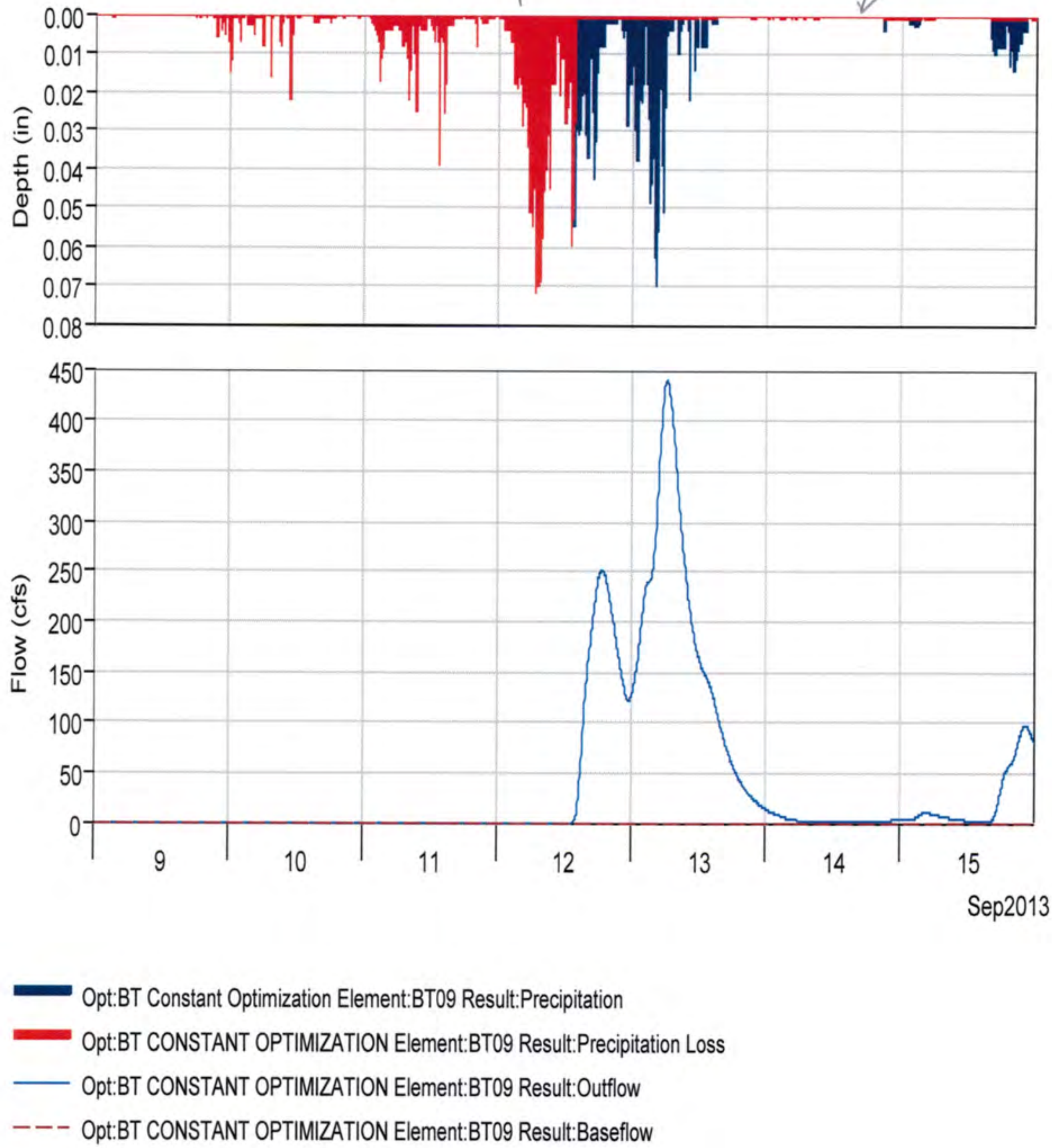
2013 Flood (9.48 inches precip)

upstream of Lake Estes

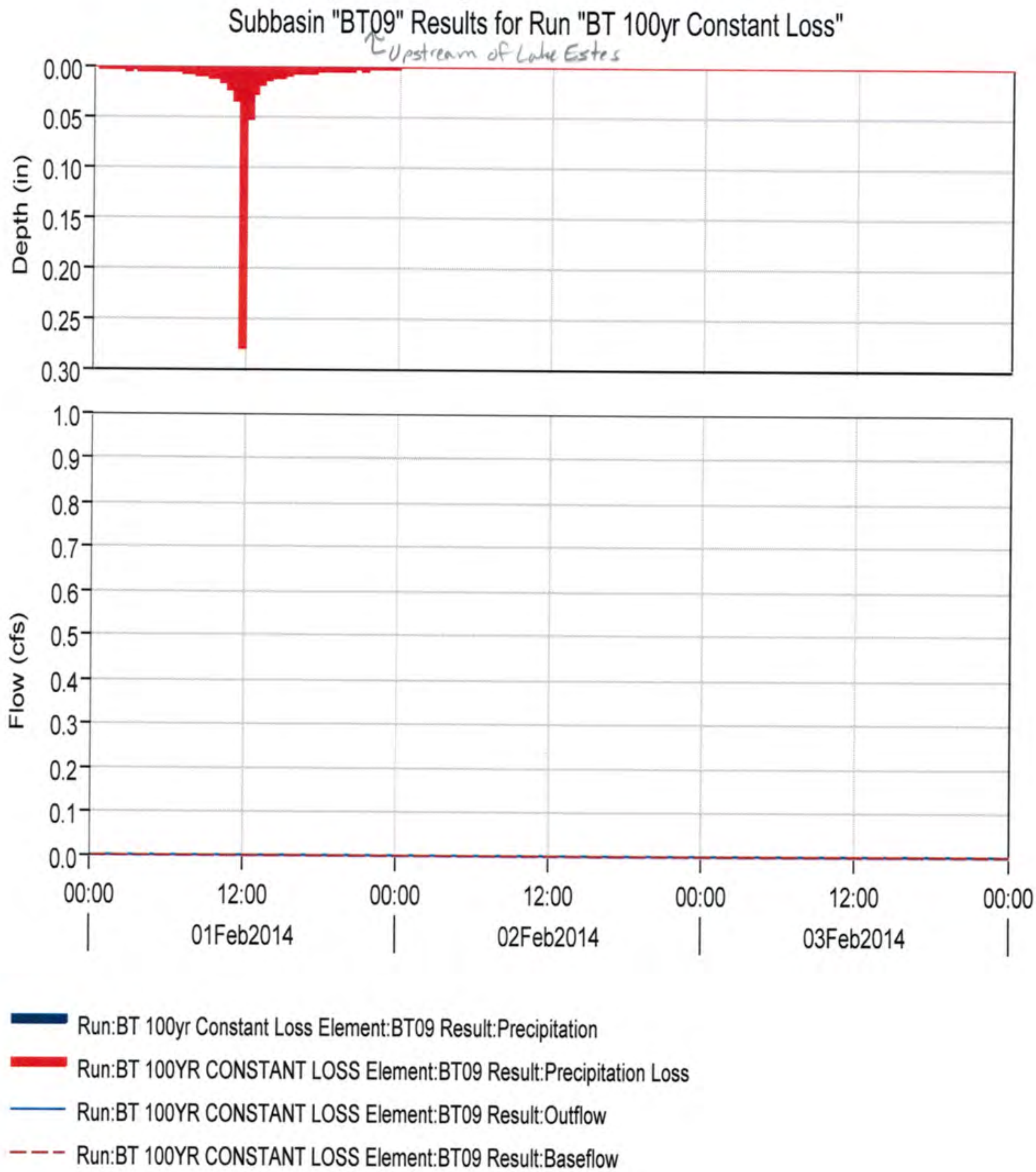
Optimization dominated by Initial loss

Constant infiltration rate is very low

Subbasin "BT09" Results for Trial "BT Constant Optimization"



100yr
NOAA 24-hr Storm
(4.42 inches)



Big Thompson - Green Ampt Optimization

Project: Big Thompson Calibrated   Optimization Trial: Green Ampt Optimization

Start of Trial: 09Sep2013, 00:00   Basin Model: BT GreenAmpt Loss
End of Trial: 15Sep2013, 23:45   Meteorologic Model: BigThompson 2013 Flood
Compute Time: 12Feb2014, 17:31:26   Control Specifications: Big Thompson - Lake Estes

Objective Function at Basin Element "J4055"

Start of Function : 09Sep2013, 00:00   Type : Peak-Weighted RMS Error
End of Function : 15Sep2013, 23:45   Value : 1411.3

Volume Units: IN

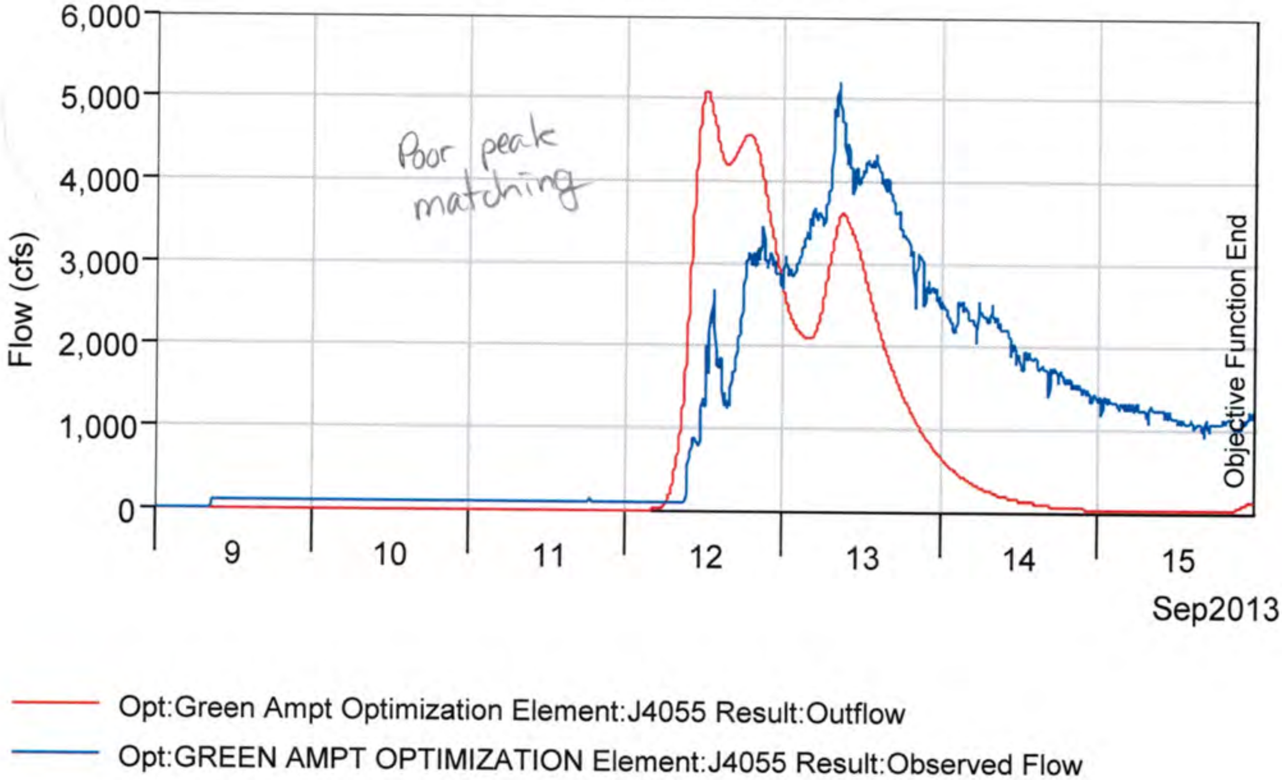
Measure	Simulated	Observed	Difference	Percent Difference
Volume (IN)	1.20	1.98	-0.78	-39.42
Peak Flow (CFS)	5061.0	5162.4	-101.4	-2.0
Time of Peak	12Sep2013, 12:05	13Sep2013, 08:15		
Time of Center of Mass	13Sep2013, 01:37	13Sep2013, 19:10		

Model optimization involved changing:

- Initial Water Content
- Saturated Water Content
- Wetting Front Suction
- Hydraulic Conductivity

to acheive a best fit to the inflow hydrograph for Lake Estes

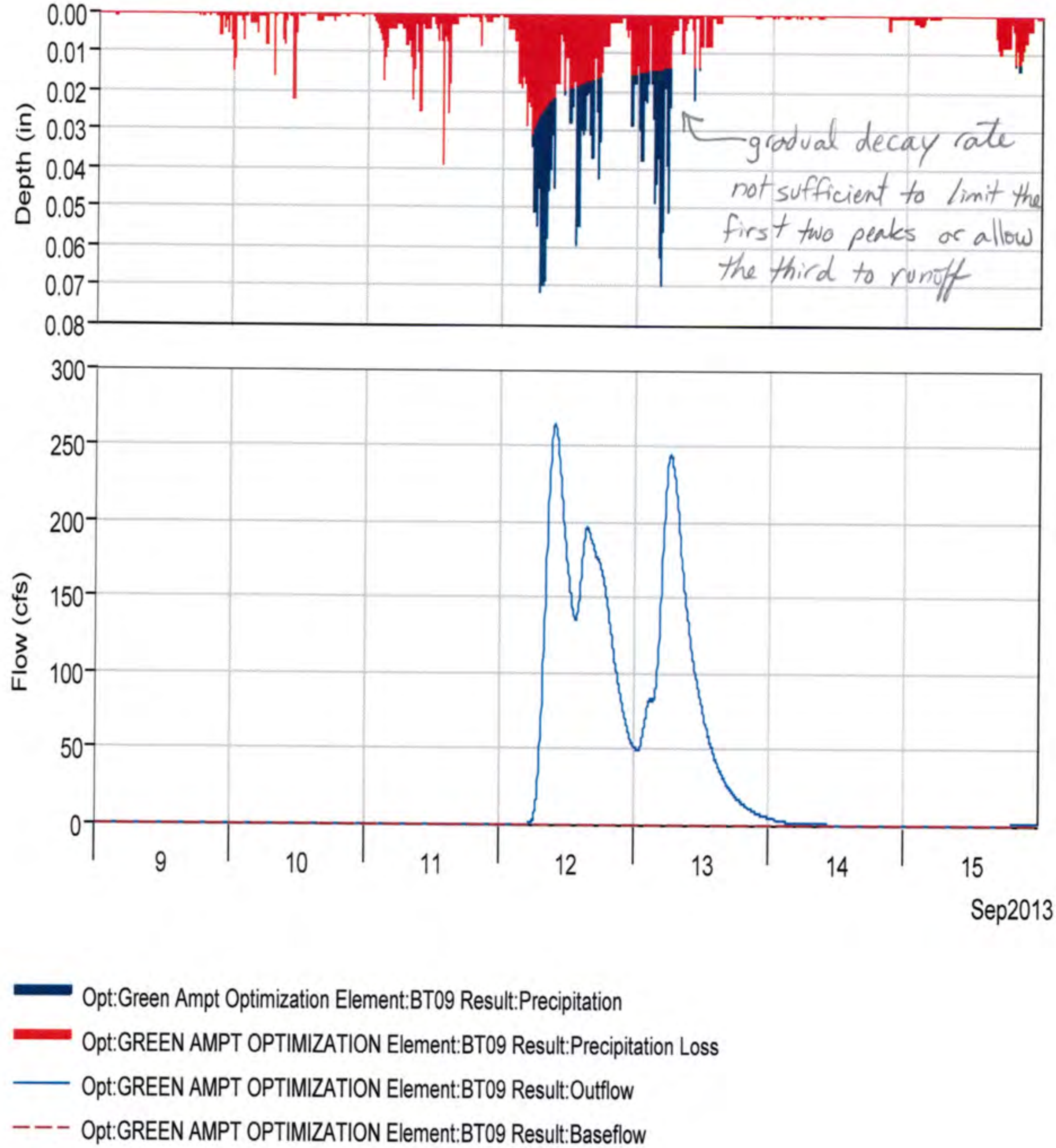
Lake Estes Inflow Hydrograph Comparison



2013 Flood
(9.48 inches precip)

Upstream of Lake Estes

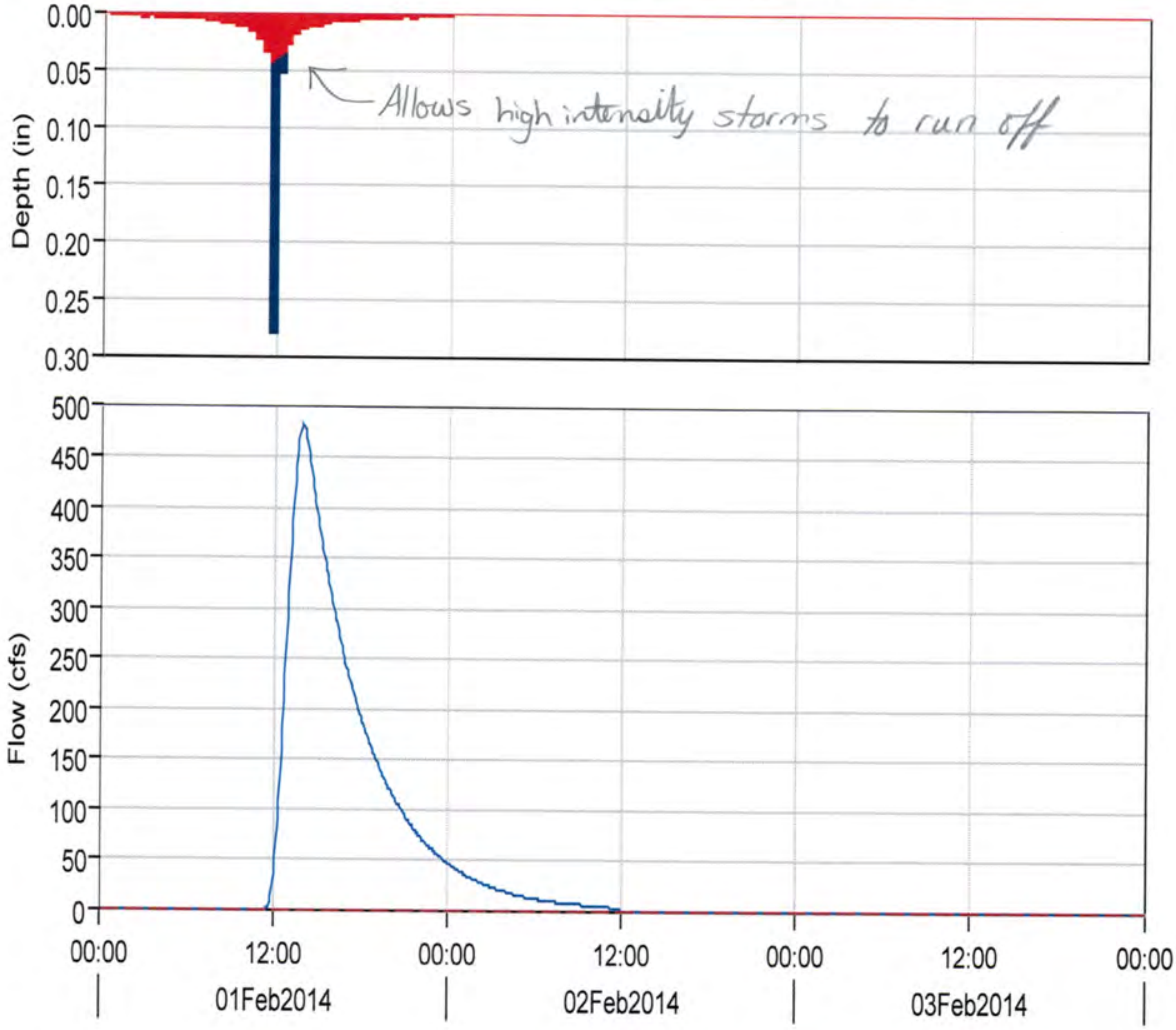
Subbasin "BT09" Results for Trial "Green Ampt Optimization"



NOAA 100-yr 24 hr Storm
(4.42 inches precip)

Upstream of Lake Estes

Subbasin "BT09" Results for Run "BT 100yr GreenAmpt"



Run:BT 100yr GreenAmpt Element:BT09 Result:Precipitation

Run:BT 100YR GREENAMPT Element:BT09 Result:Precipitation Loss

Run:BT 100YR GREENAMPT Element:BT09 Result:Outflow

Run:BT 100YR GREENAMPT Element:BT09 Result:Baseflow

Big Thompson - Exponential Loss Optimization

Project: Big Thompson Calibrated   Optimization Trial: BT Exponential Optimization

Start of Trial:	09Sep2013, 00:00	Basin Model:	BT Exponential Loss
End of Trial:	15Sep2013, 23:45	Meteorologic Model:	BigThompson 2013 Flood
Compute Time:	12Feb2014, 18:45:36	Control Specifications:	Big Thompson - Lake Estes

Objective Function at Basin Element "J4055"

Start of Function :	09Sep2013, 00:00	Type :	Peak-Weighted RMS Error
End of Function :	15Sep2013, 23:45	Value :	971.4

Volume Units: IN

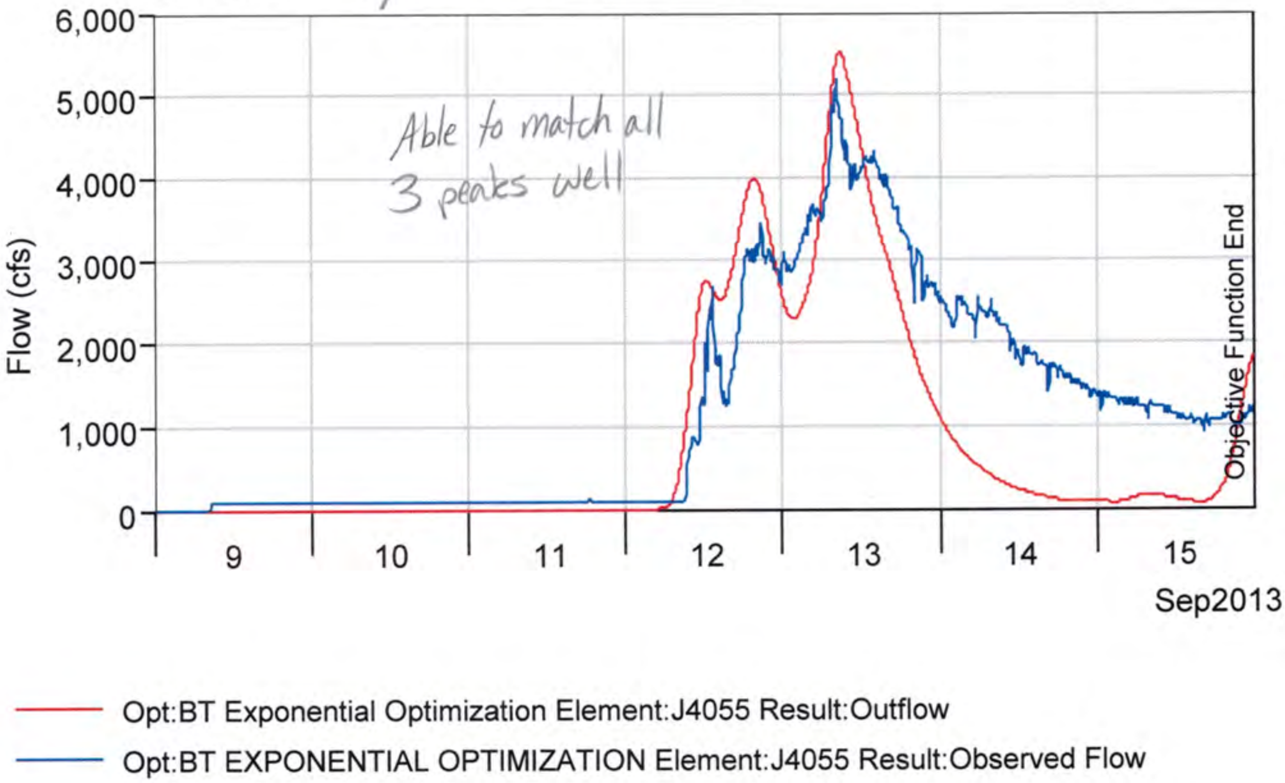
Measure	Simulated	Observed	Difference	Percent Difference
Volume (IN)	1.35	1.98	-0.63	-31.94
Peak Flow (CFS)	5498.0	5162.4	335.6	6.5
Time of Peak	13Sep2013, 08:55	13Sep2013, 08:15		
Time of Center of Mass	13Sep2013, 08:54	13Sep2013, 19:10		

Model optimization involved changing:

- Initial Range
- Initial Loss Rate Coefficient
- Coefficient Ratio

to acheive a best fit to the inflow hydrograph for Lake Estes

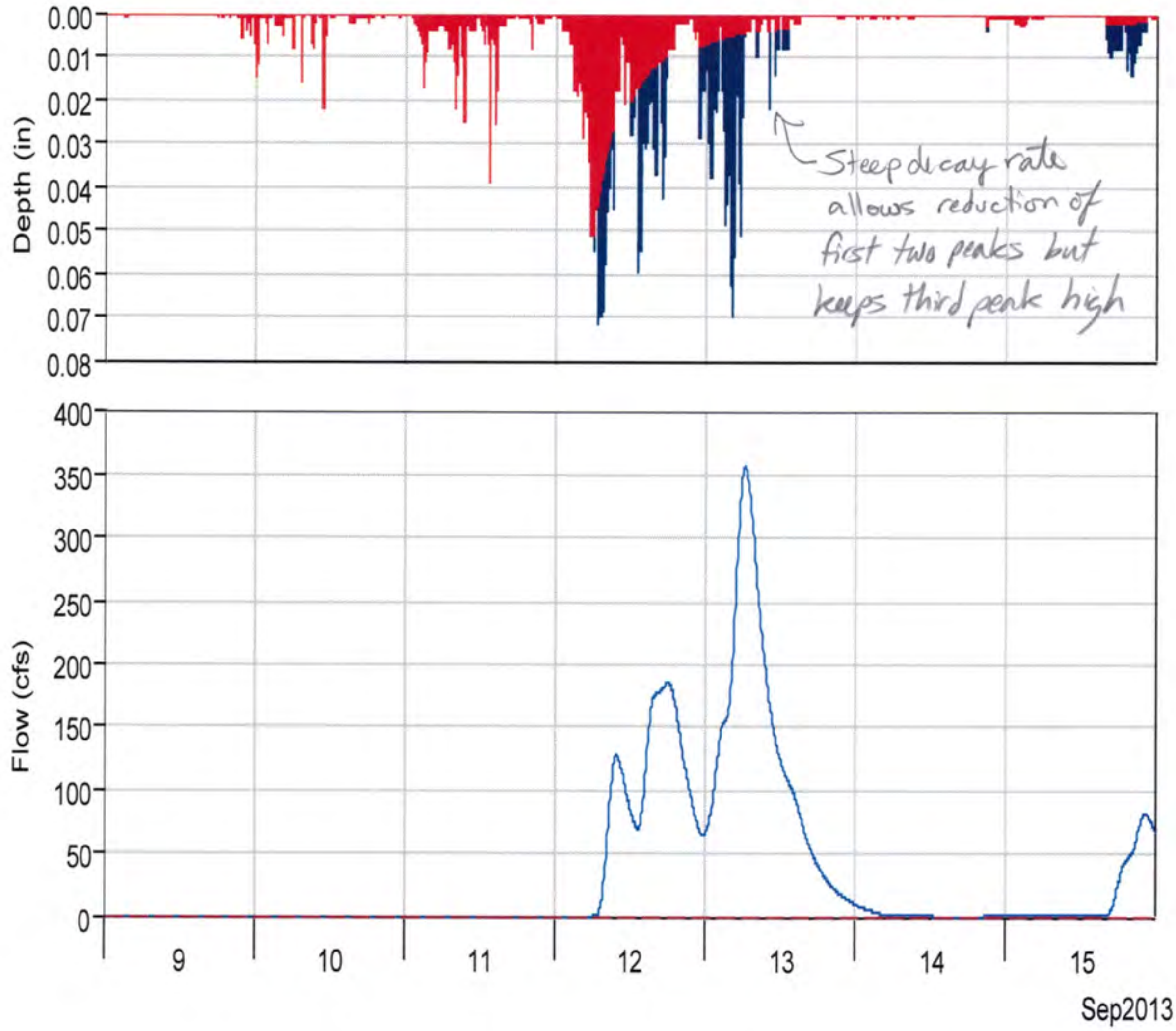
Lake Estes Inflow Hydrograph Comparison



2013 Flood
(9.48 inches Precip)

Upstream of Lake Estes

Subbasin "BT09" Results for Trial "BT Exponential Optimization"



Opt:BT Exponential Optimization Element:BT09 Result:Precipitation

Opt:BT EXPONENTIAL OPTIMIZATION Element:BT09 Result:Precipitation Loss

Opt:BT EXPONENTIAL OPTIMIZATION Element:BT09 Result:Outflow

Opt:BT EXPONENTIAL OPTIMIZATION Element:BT09 Result:Baseflow

Project: Big Thompson Calibrated
Simulation Run: BT Exponential Loss Junction: J4055

Start of Run:	09Sep2013, 00:00	Basin Model:	BT Exponential Loss
End of Run:	15Sep2013, 23:45	Meteorologic Model:	BigThompson 2013 Flood
Compute Time:	12Feb2014, 19:26:35	Control Specifications:	Big Thompson - Lake Estes

Volume Units: IN

vs. 5498 cfs for Optimization Routine

Computed Results

Peak Outflow :	4424.0 (CFS)	Date/Time of Peak Outflow :	13Sep2013, 08:50
Total Outflow :	1.02 (IN)		

vs. 1.35 inches for Optimization Routine

Observed Hydrograph at Gage Lake Estes Inflow Shifted

Peak Discharge :	5162.44 (CFS)	Date/Time of Peak Discharge :	13Sep2013, 08:15
Avg Abs Residual :	635.67 (CFS)		
Total Residual :	-0.96 (IN)	Total Obs Q :	1.98 (IN)

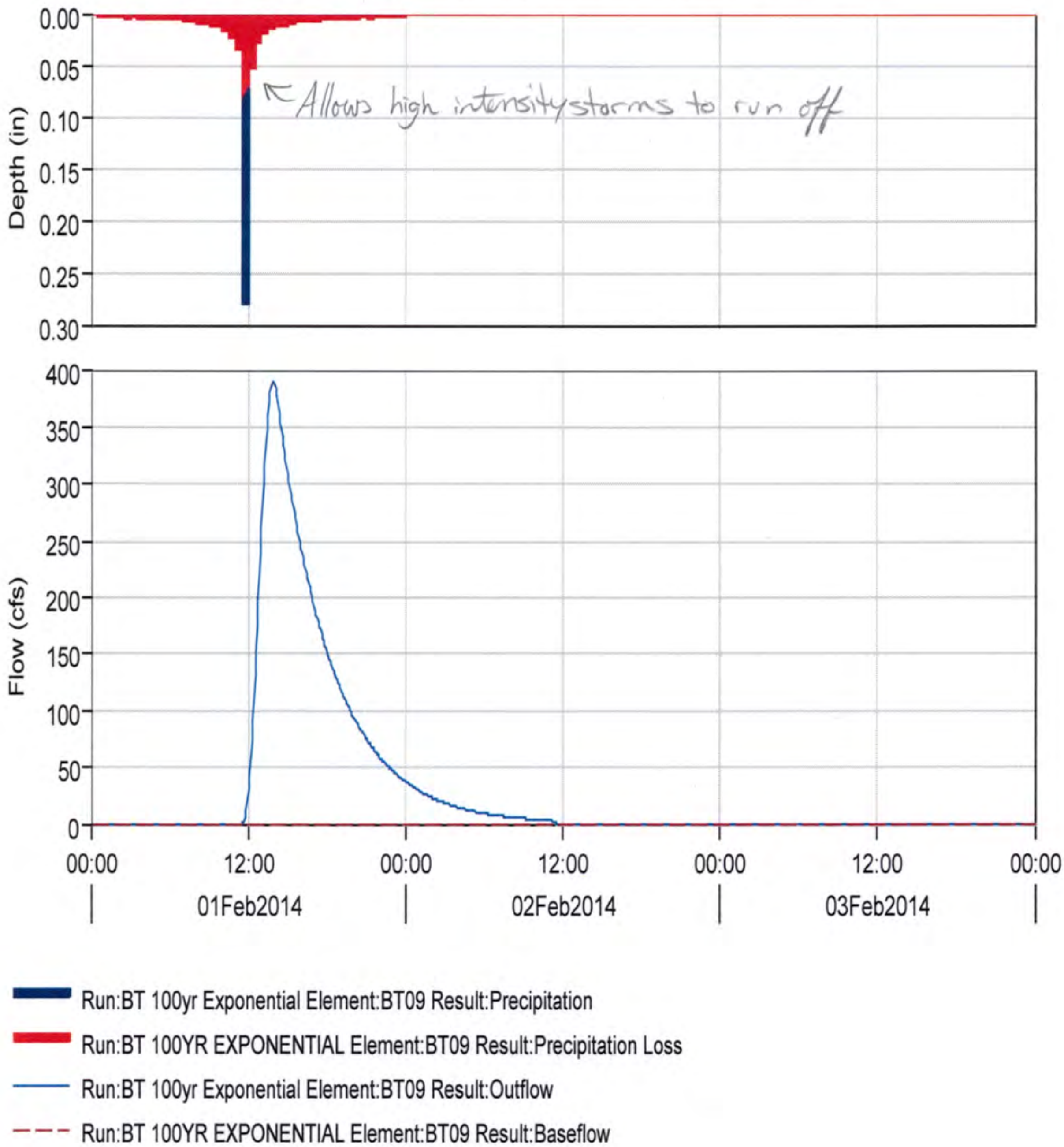
When the optimized values for:
- Initial Range
- Initial Loss Rate Coefficient
- Coefficient Ratio

are plugged back into the model as hardwired inputs, they do not produce the same results as the optimization routine. This was checked several times and may be an issue with the program.

NOAA 100yr 24hr Storm
(4.42 inches precip)

upstream of Lake Estes

Subbasin "BT09" Results for Run "BT 100yr Exponential"



Big Thompson - Curve Number Optimization for Max 24-hr Rainfall Period

Project: Big Thompson Calibrated Optimization Trial: BT CN Optimization Max24hr

Start of Trial:	12Sep2013, 04:15	Basin Model:	Big Thompson Calibrated
End of Trial:	15Sep2013, 04:15	Meteorologic Model:	Big Thompson Max 24hr
Compute Time:	12Feb2014, 21:31:54	Control Specifications:	Big Thompson Max 24hr

Objective Function at Basin Element "J4055"

Start of Function :	12Sep2013, 04:15	Type :	Peak-Weighted RMS Error
End of Function :	15Sep2013, 04:15	Value :	906.8

Volume Units: IN

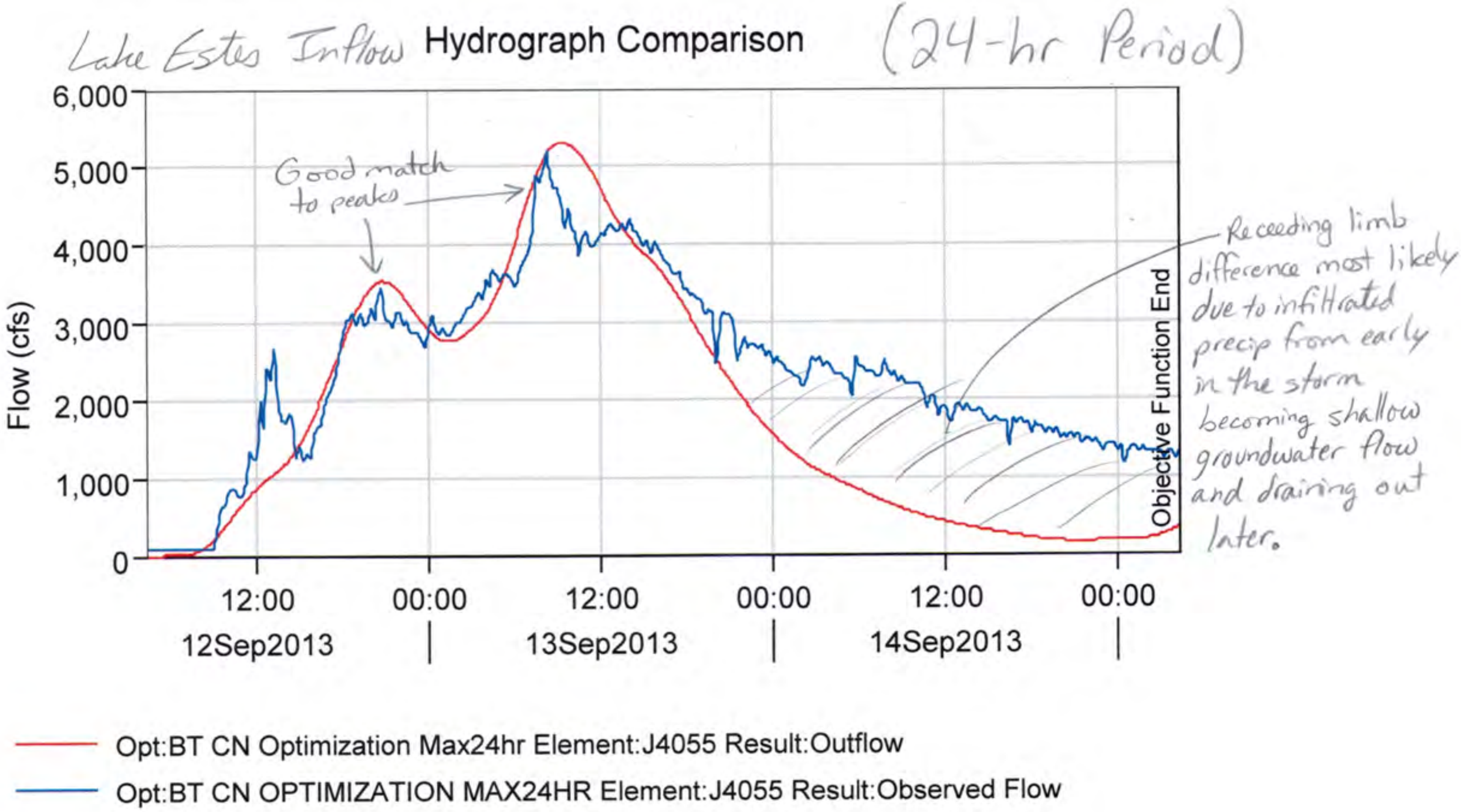
Measure	Simulated	Observed	Difference	Percent Difference
Volume (IN)	1.30	1.71	-0.41	-23.81
Peak Flow (CFS)	5270.9	5162.4	108.5	2.1
Time of Peak	13Sep2013, 09:20	13Sep2013, 08:15		
Time of Center of Mass	13Sep2013, 09:39	13Sep2013, 15:56		

} even better fit

Model optimization involved changing the initial abstraction (in) and the Curve Number to acheive a best fit to the inflow hydrograph for Lake Estes during the 24-hr period of maximum rainfall.

Curve numbers only decreased by 1.4%

Initial abstraction was reduced by 30% ($I_a = 0.14S$)

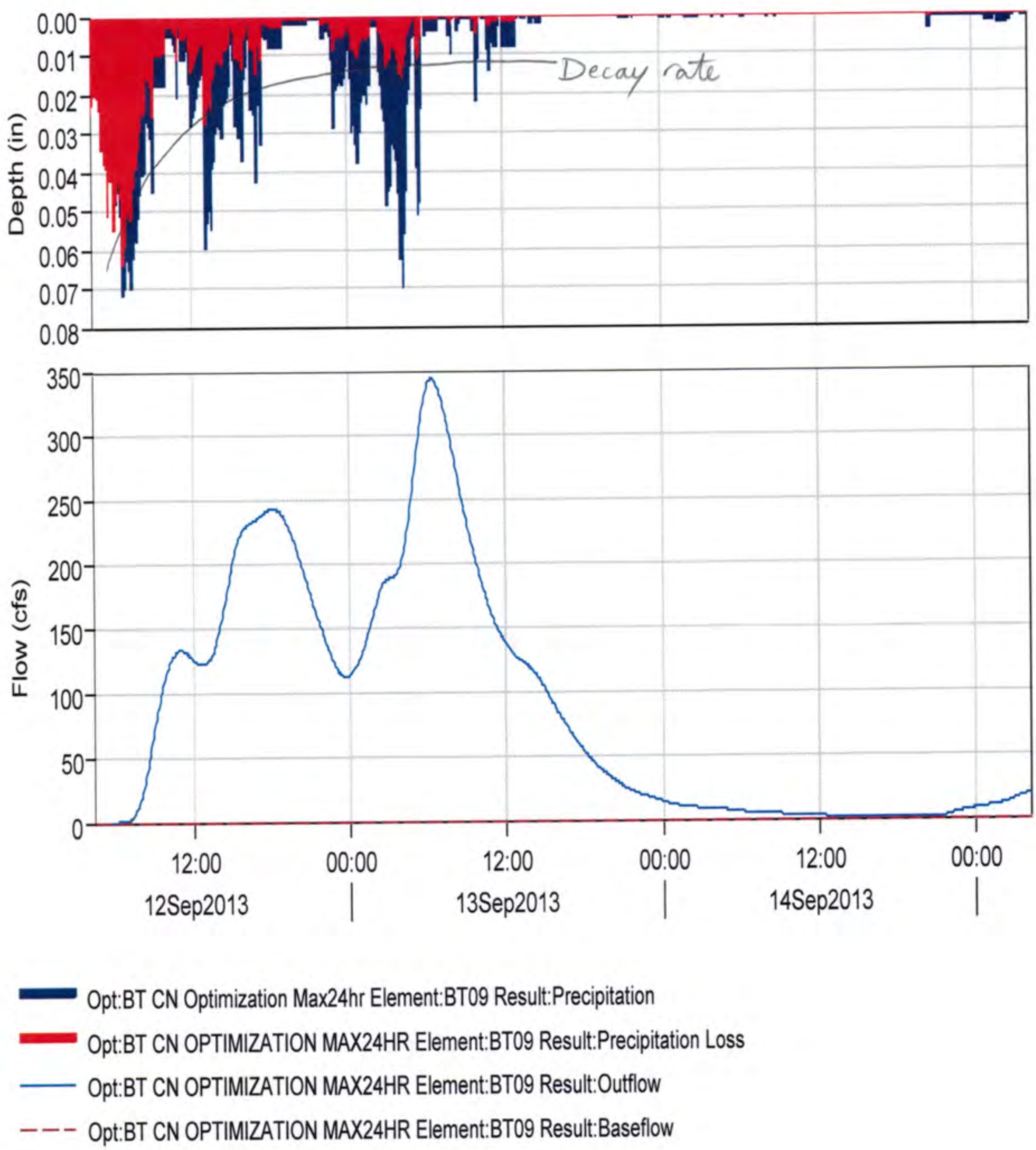

Lake Estes Inflow Hydrograph Comparison (24-hr Period)
6,000
5,000
4,000
3,000
2,000
1,000
0
Flow (cfs)
Good match to peaks
Receeding limb difference most likely due to infiltrated precip from early in the storm becoming shallow groundwater flow and draining out later.
Objective Function End
12:00
00:00
12:00
00:00
12:00
00:00
12Sep2013
13Sep2013
14Sep2013
Opt:BT CN Optimization Max24hr Element:J4055 Result:Outflow
Opt:BT CN OPTIMIZATION MAX24HR Element:J4055 Result:Observed Flow

2013 Flood

(7.18 inches precip in 24-hr period)

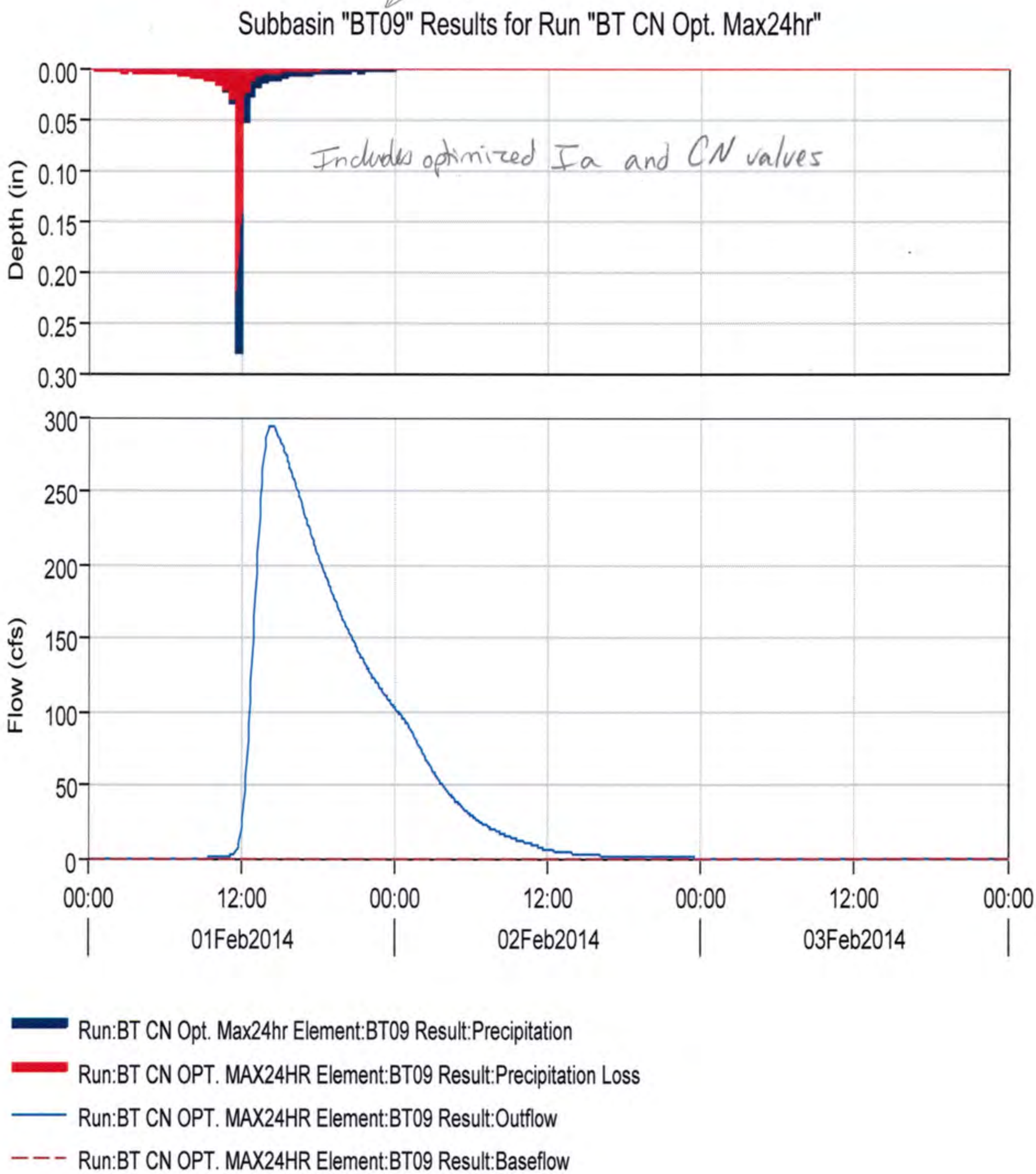
upstream of Lake Estes

Subbasin "BT09" Results for Trial "BT CN Optimization Max24hr"



NOAA 100-yr 24-hr Storm
(4.42 inches Precip)

upstream of Lake Estes



Appendix C.6

St. Vrain Watershed - HEC-HMS Model Inputs

Model ID	Description	Area (sq.mi.)	CN (10-day)	CN (24-hr)	Cp	Kn	L (mi)	Lc (mi)	S (ft/mi)	Lag Time (hr)	L (ft)	S (ft/ft)	n Channel	n Left OB	n Right OB
SV990	Buchanan Pass (Middle SVC headwaters)	10.2	54.8	65	0.4	0.15	6.2	2.75	403.22581	3.14					
SV1010	Coney Creek (Middle SVC headwaters)	4.0	47.0	58	0.4	0.15	4.12	2.12	388.34951	2.53					
J184	Headwaters Middle SVC														
R450	Middle SVC at headwaters										14851	0.043	0.15	0.15	0.15
SV1000	Middle SVC area above Camp Dick	3.7	50.4	59	0.4	0.15	2.79	1.75	645.16129	1.92					
J176	Camp Dick on Middle SVC														
R460	Middle SVC along Hwy 72										20920	0.038	0.15	0.15	0.15
SV960	Park Creek Trib to Middle SVC	3.0	53.3	58	0.4	0.15	3.5	1.7	457.14286	2.17					
SV950	Cave Creek Trib to Middle SVC	2.3	52.9	58	0.4	0.15	2.52	1.5	674.60317	1.75					
J196	Cave and Park Creek Tribs on Middle SVC														
R400	Cave and Park Creek Trib to Middle SVC										3357	0.050	0.15	0.15	0.15
SV970	Ironclads trib area to Middle SVC	0.3	50.1	54	0.4	0.15	0.77	0.35	649.35065	0.74					
SV980	Middle SVC area around Hwy 72	2.9	56.1	60	0.4	0.15	3.61	1.8	221.60665	2.52					
J191	Middle SVC at Raymond														
R410	Middle SVC between Raymond and Riverside										15740	0.028	0.15	0.15	0.15
SV920	Middle SVC area above Riverside	3.9	46.2	52	0.4	0.15	3.29	1.5	243.16109	2.27					
J201A	Middle SVC at Riverside (Dischage Estimation Point #55 by Bob Jarrett)														
R410A	Middle SVC above confluence with South SVC										12864	0.031	0.15	0.15	0.15
SV920A	Middle SVC area above confluence with South SVC	2.0	64.7	66	0.4	0.15	2.7	1.7	370.37037	2.07					
J201B	Middle SVC above confluence with South SVC														
SV1060	Long Lake (South SVC headwaters)	5.6	62.4	73	0.4	0.15	4.09	2	391.19804	2.48					
SV1050	Mitchell Lake (South SVC headwaters)	3.7	66.7	75	0.4	0.15	3.54	1.75	508.47458	2.16					
J171	Brainard Lake (South SVC headwaters)														
R520	South SVC headwaters to Hwy 72										37392	0.048	0.15	0.15	0.15
SV1040	Beaver Reservoir trib area (South SVC)	7.1	62.7	71	0.4	0.15	3.87	1.75	620.15504	2.16					
J490	Beaver Reservoir (South SVC)														
R490	Beaver Creek (South SVC)										13357	0.048	0.15	0.15	0.15
SV1020	Beaver Creek area tributary to South SVC	2.5	63.7	66	0.4	0.15	2.45	1.5	285.71429	2.00					
SV1030	South SVC area upstream of Hwy 72	7.8	59.5	68	0.4	0.15	7.2	3.7	305.55556	3.81					
J179	South SVC at Hwy 72														
R480	South SVC from Hwy 72 to confluence with Middle SVC										42061	0.037	0.15	0.15	0.15
SV940	South SVC area between Hwy 72 and Middle SVC	7.8	60.3	63	0.4	0.15	8.62	4.5	208.81671	4.59					
J201C	South SVC above confluence with Middle SVC														
J201	Confluence of Middle and South SVC														
R370A	South SVC below confluence with Middle SVC										4221	0.036	0.15	0.15	0.15
SV910A	Long Gulch Trib to South SVC below confluence with Middle SVC	1.7	62.0	65	0.4	0.15	2.36	1	508.47458	1.57					
J204A	South SVC at Discharge Estimation Point #56 by Bob Jarrett														
R370	South SVC above Big Narrows										15642	0.042	0.15	0.15	0.15
SV910	South SVC trib area above Big Narrows	2.5	68.6	70	0.4	0.15	2.94	1.5	612.2449	1.88					
SV930	Central Gulch Trib to South SVC at Big Narrows	7.2	68.3	69	0.4	0.15	5.43	3	331.49171	3.20					
J204	South SVC at Big Narrows														
R350A	South SVC below Big and Little Narrows										15454	0.036	0.15	0.15	0.15
SV800A	Coffintop Gulch trib to South SVC between Big and Little Narrows	4.9	67.9	69	0.4	0.15	3.78	1.8	423.28042	2.30					
J204B	South SVC at Little Narrows (Peak Discharge Estimate Point #57 by Bob Jarrett)														
R350	South SVC below Little Narrows past Hall Ranch										16924	0.014	0.15	0.15	0.15
SV800	South SVC trib area at Hall Ranch	5.7	67.5	69	0.4	0.15	4.59	2.25	359.47712	2.71					
SV810	Red Hill Gulch Trib to South SVC above Lyons	2.3	67.4	71	0.4	0.15	3.22	1.72	295.03106	2.28					
SV720	Indian Lookout Mountain Trib Area to South SVC	0.3	79.3	79	0.4	0.15	0.79	0.4	506.32911	0.81					
J234	South SVC above confluence with North SVC														
R190	South SVC above confluence with North SVC										2692	0.016	0.15	0.15	0.15
SV830	North SVC headwaters	7.9	63.7	72	0.4	0.15	4.94	2.5	566.80162	2.67					
SV870	Ouzel Creek Trib to North SVC headwaters	5.1	66.7	74	0.4	0.15	4.39	2.25	501.13895	2.53					
J219	North SVC headwaters														
R320	North SVC near Ouzel Falls										1930	0.083	0.15	0.15	0.15
SV890	North SVC trib area near Calypso Cascades	1.0	42.4	54	0.4	0.15	1.77	1	1016.9492	1.28					
SV900	Cony Creek Trib area to North SVC	7.2	56.9	67	0.4	0.15	4.96	2	504.03226	2.53					
J211	North SVC at confluence with Cony Creek														
R310	North SVC above Copeland Falls in Wild Basin										8910	0.058	0.15	0.15	0.15
SV840	Sandbeach Creek Trib to North SVC in Wild Basin	3.6	45.3	57	0.4	0.15	3.23	0.75	712.0743	1.50					
SV640	Hunters Creek Trib to North SVC in Wild Basin	4.5	60.6	69	0.4	0.15	4.58	2.75	676.8559	2.61					
J227	North SVC at Copeland Falls														
R240	North SVC above Hwy 7										13031	0.015	0.15	0.15	0.15
SV740	Campers Creek Trib to North SVC at Hwy 7	3.1	41.8	51	0.4	0.15	3.23	1.4	619.19505	1.89					
J252A	North SVC at Hwy 7 (Peak Estimation Point #63 by Bob Jarrett)														
R240A	North SVC below Hwy 7										4311	0.076	0.15	0.15	0.15
SV740A	North SVC trib area at Hwy 7	0.8	49.8	58	0.4	0.15	1.29	0.6	503.87597	1.09					
SV660	Horse Creek Trib to North SVC below Hwy 7	3.6	41.1	50	0.4	0.15	3.64	2.1	521.97802	2.31					
J252	North SVC at confluence with Horse Creek below Hwy 7														
R170	North SVC between Horse Creek and Rock Creek										7862	0.038	0.15	0.15	0.15
SV760	North SVC trib area between Horse Creek and Rock Creek	1.0	44.5	49	0.4	0.15	1.22	0.7	696.72131	1.07					
SV860	Willow Creek Tributary to Rock Creek and North SVC near Allenspark	3.7	49.0	57	0.4	0.15	4.1	2.2	609.7561	2.38					
SV880	Rock Creek Trib to North SVC at Ferncliff	10.1	42.5	51	0.4	0.15	5.66	2.75	565.37102	2.88					
J216	Rock Creek Trib to North SVC at Ferncliff														
R290	Rock Creek Trib to North SVC										6941	0.042	0.15	0.15	0.15
SV790	Rock creek trib area at confluence with North SVC	0.9	41.1	47	0.4	0.15	1.54	0.7	584.41558	1.19					
J239	North SVC at confluence with Rock Creek														
R200	North SVC between Rock Creek and Cabin Creek tribs										9261	0.031	0.15	0.15	0.15
SV750	North SVC trib area above Cabin Creek Confluence	1.2	42.7	46	0.4	0.15	1.86	0.9	483.87097	1.42					
SV540	Inn Brook Trib at Longs Peak above North SVC	3.8	56.3	58	0.4	0.15	2.59	1	501.9305	1.63					
SV550	Alpine Brook Trib at Longs Peak above North SVC	2.5	59.0	63	0.4	0.15	3.08	1.75	714.28571	1.95					
J298	Confluence of Inn Brook and Alpine Brook tributary to North SVC														
R40	Tahosa Creek between Roaring Fork and Alpine Brook tribs in North SVC area										10990	0.042	0.15	0.15	0.15
SV560	Tahosa Valley trib area upstream of Roaring Fork trib in North SVC area	3.7	53.9	57	0.4	0.15	2.44	1.35	532.78689	1.74					
SV580	Roaring Fork Trib to Tahosa Creek in North SVC area	2.4	61.0	66	0.4	0.15	4.76	2.75	693.27731	2.63					
J291	Tahosa Valley above Cabin Creek in North SVC area														
R70	Tahosa Creek above Cabin Creek in North SVC area										5716	0.030	0.15	0.15	0.15
SV590	Tahosa Creek trib area upstream of Cabin Creek in North SVC area	1.0	54.4	57	0.4	0.15	1.3	0.5	538.46154	1.02					
SV610	Cabin Creek Trib area to North SVC	5.8	60.2	65	0.4	0.15	4.64	2.5	797.41379	2.47					
J283	Cabin Creek and Tahosa Creek confluence in North SVC area														
R120	Cabin Creek trib to North SVC										19910	0.043	0.15	0.15	0.15
SV670	Cabin Creek Trib area at confluence with North SVC	3.4	59.5	60	0.4	0.15	3.83	2.5	339.42559	2.67					
J249	North SVC at confluence with Cabin Creek														
R250	North SVC below confluence with Cabin Creek										18254	0.033	0.15	0.15	0.15
SV770	North SVC trib area below confluence with Cabin Creek	4.6	60.6	62	0.4	0.15	3.94	2	431.47208	2.41					
SV690	Coulson Gulch trib to North SVC	2.5	59.5	63	0.4	0.15	2.25	1	311.11111	1.68					
J244	North SVC at Coulson Gulch confluence														
R260	North SVC above confluence with Dry SVC										3052	0.035	0.15	0.15	0.15
SV780	North SVC area below Coulson Gulch confluence	0.2	61.4	64	0.4	0.15	0.44	0.2	1590.9091	0.44					
SV850	Dry SVC trib to North SVC	7.2	59.0	62	0.4	0.15	5.62	3.25	355.87189	3.28					
J224	North SVC at confluence with Dry SVC														
R270	North SVC below confluence with Dry SVC										14057	0.018	0.15	0.15	0.15
SV710	North SVC trib area upstream of Button Rock Reservoir	4.2	58.2	62	0.4	0.15	4.1	2.2	304.87805	2.67					
SV700	Rattlesnake Gulch Trib to North SVC	3.5	67.2	69	0.4	0.15	2.25	1.1	444.44444	1.63					
J261	North SVC inflow to Button Rock Reservoir														
R3250	North SVC through Button Rock Reservoir										4991	0.007	0.15	0.01	0.15
SV1070	Long Gulch trib to North SVC at Button Rock Reservoir	2.9	63.0	67	0.4	0.15	2.46	1.15	711.38211	1.58					
J168	North SVC outflow from Button Rock Reservoir														
R180	North SVC below Button Rock Reservoir										20913	0.030	0.15	0.15	0.15
SV630	North SVC throught Longmont Reservoir below Button Rock Reservoir	6.5	63.5	66	0.4	0.15	4.37	2.5	240.2746	2.95					
SV620	North SVC trib area from Hwy 36 at north end	3.5	64.1	64	0.4	0.15	4.35	2	551.72414	2.39					
J278	North SVC below Longmont Reservoir at Hwy 36														
R80A	North SVC along upper part of Hwy 36										7795	0.019	0.15	0.15	0.15
SV600A	North SVC trib area above peak discharge estimation point #58 by Bob Jarrett	0.7	69.5	72	0.4	0.15	1.07	0.7	654.20561	1.03					
J286A	North SVC at Peak Discharge Estimation Point #58 by Bob Jarrett														
R80	North SVC above Apple Valley Road										5189	0.012	0.15	0.15	0.15
SV600	North SVC trib area at Apple Valley Road	1.4	62.8	68	0.4	0.15	2.32	0.85	366.37931	1.57					
SV570	Spring Gulch Trib to North SVC at Apple Valley Road	4.1	56.4	59	0.4	0.15	4.41	2.25	272.10884	2.80					
J286	North SVC at Apple Valley Road														
R110	North SVC above confluence with South SVC										21152	0.010	0.15	0.15	0.15
SV650	North SVC trib area above confluence with South SVC	6.4	68.1	70	0.4	0.15	3.62	2.25	165.74586	2.85					
J260	North SVC above confluence with South SVC														
J258	Confluence of North and South SVC														
R140	St Vrain Creek through Lyons										3158	0.007	0.15	0.15	0.15
SV730	Lyons trib area to St. Vrain Creek	0.5	73.5	74	0.4	0.15	1.44	0.67	173.61111	1.40					
SV680	Stone Canyon Trib to St Vrain Creek at Lyons	2.4	70.7	74	0.4	0.15	3.32	1.75	195.78313	2.48					
J255	St Vrain Creek at confluence with Stone Canyon														
R210	St Vrain Creek below Lyons										4401	0.010	0.15	0.15	0.15
SV820	St. Vrain Creek trib area downstream of Lyons	0.3	80.6	81	0.4	0.15	1.33	0.53	385.71429	1.11					
Outlet1	Outlet - St. Vrain Creek at Hwy 36 downstream of Lyons														

Appendix C.6 (cont.)

Time		(Cumulative Precipitation)/(Total Storm Precipitation)			
Hours	t/T	Type 1 Storm	Type 1A Storm	Type II Storm	Type III Storm
0	0.000	0.000	0.000	0.000	0.000
0.5	0.021	0.008	0.010	0.005	0.005
1	0.042	0.017	0.020	0.011	0.010
1.5	0.063	0.026	0.035	0.016	0.015
2	0.083	0.035	0.050	0.022	0.020
2.5	0.104	0.045	0.067	0.028	0.025
3	0.125	0.055	0.082	0.035	0.031
3.5	0.146	0.065	0.098	0.041	0.037
4	0.167	0.076	0.116	0.048	0.043
4.5	0.188	0.087	0.135	0.056	0.050
5	0.208	0.099	0.156	0.063	0.057
5.5	0.229	0.112	0.180	0.071	0.064
6	0.250	0.126	0.206	0.080	0.072
6.5	0.271	0.140	0.237	0.089	0.081
7	0.292	0.156	0.268	0.098	0.091
7.5	0.313	0.174	0.310	0.109	0.102
8	0.333	0.194	0.425	0.120	0.114
8.5	0.354	0.219	0.480	0.133	0.128
9	0.375	0.254	0.520	0.147	0.146
9.5	0.396	0.303	0.550	0.163	0.166
10	0.417	0.515	0.577	0.181	0.189
10.5	0.438	0.583	0.601	0.204	0.217
11	0.458	0.624	0.624	0.235	0.250
11.5	0.479	0.655	0.645	0.283	0.298
12	0.500	0.682	0.664	0.663	0.500
12.5	0.521	0.706	0.683	0.735	0.702
13	0.542	0.728	0.701	0.772	0.750
13.5	0.563	0.748	0.719	0.799	0.784
14	0.583	0.766	0.736	0.820	0.811
14.5	0.604	0.783	0.753	0.838	0.834
15	0.625	0.799	0.769	0.854	0.854
15.5	0.646	0.815	0.785	0.868	0.872
16	0.667	0.830	0.800	0.880	0.886
16.5	0.688	0.844	0.815	0.891	0.898
17	0.708	0.857	0.830	0.902	0.910
17.5	0.729	0.870	0.844	0.912	0.919
18	0.750	0.882	0.858	0.921	0.928
18.5	0.771	0.893	0.871	0.929	0.936
19	0.792	0.905	0.884	0.937	0.943
19.5	0.813	0.916	0.896	0.945	0.950
20	0.833	0.926	0.908	0.952	0.957
20.5	0.854	0.936	0.920	0.959	0.963
21	0.875	0.946	0.932	0.965	0.969
21.5	0.896	0.956	0.944	0.972	0.975
22	0.917	0.965	0.956	0.978	0.981
22.5	0.938	0.974	0.967	0.984	0.986
23	0.958	0.983	0.978	0.989	0.991
23.5	0.979	0.991	0.989	0.995	0.996
24	1.000	1.000	1.000	1.000	1.000

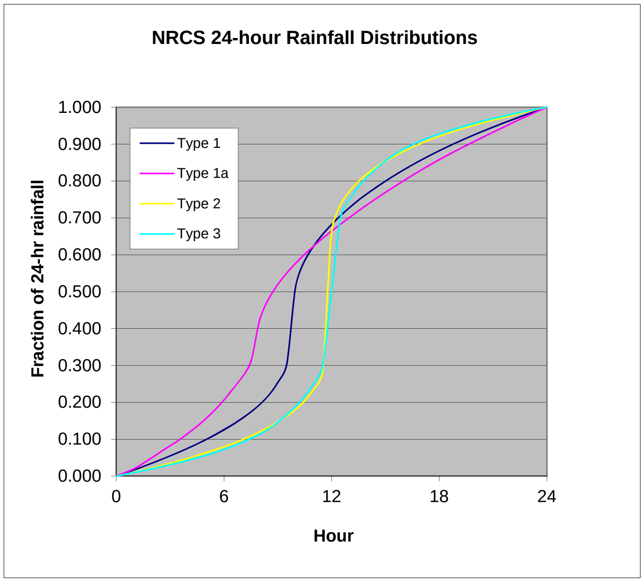
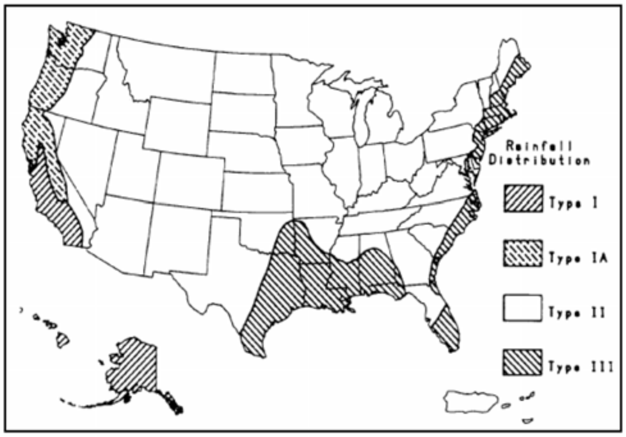


Figure 1: Geographic boundaries for the NRCS rainfall distributions



St. Vrain Creek

Appendix C.6 (continued)

	Raingage Zones		
	Zone 1 (West)	**Zone 2 (Central)**	**Zone 3 (East)**
Lat	40.18365474	40.1761685003	40.21228738
Long	-105.602742	-105.4866579840	-105.3252132
max 100-yr 1-hr Precip	2.06	1.93	2.05
10-yr, 24-hr	2.89	2.7	2.83
25-yr, 24-hr	3.65	3.42	3.62
50-yr, 24-hr	4.34	4.06	4.31
100-yr, 24-hr	5.11	4.77	5.07
500-yr, 24-hr	7.26	6.72	7.14
	SV990	SV1000	SV910
	SV1010	SV960	SV930
	SV1060	SV950	SV800A
	SV1050	SV970	SV800
	SV830	SV980	SV810
	SV870	SV920	SV720
	SV890	SV920A	SV630
	SV900	SV1040	SV620
	SV840	SV1020	SV600A
	SV640	SV1030	SV600
	SV740	SV940	SV570
	SV660	SV910A	SV650
	SV550	SV740A	SV730
	SV580	SV760	SV680
	SV610	SV860	SV820
		SV880	
		SV790	
		SV750	
		SV540	
		SV560	
		SV590	
		SV670	
		SV770	
		SV690	
		SV780	
		SV850	
		SV710	
		SV700	
		SV1070	

Unadjusted NOAA Rainfall

Basin	10-yr	25-yr	50-yr	100-yr	500-yr
SV1000	2.7	3.42	4.06	4.77	6.72
SV1010	2.89	3.65	4.34	5.11	7.26
SV1020	2.7	3.42	4.06	4.77	6.72
SV1030	2.7	3.42	4.06	4.77	6.72
SV1040	2.7	3.42	4.06	4.77	6.72
SV1050	2.89	3.65	4.34	5.11	7.26
SV1060	2.89	3.65	4.34	5.11	7.26
SV1070	2.7	3.42	4.06	4.77	6.72
SV540	2.7	3.42	4.06	4.77	6.72
SV550	2.89	3.65	4.34	5.11	7.26
SV560	2.7	3.42	4.06	4.77	6.72
SV570	2.83	3.62	4.31	5.07	7.14
SV580	2.89	3.65	4.34	5.11	7.26
SV590	2.7	3.42	4.06	4.77	6.72
SV600	2.83	3.62	4.31	5.07	7.14
SV600A	2.83	3.62	4.31	5.07	7.14
SV610	2.89	3.65	4.34	5.11	7.26
SV620	2.83	3.62	4.31	5.07	7.14
SV630	2.83	3.62	4.31	5.07	7.14
SV640	2.89	3.65	4.34	5.11	7.26
SV650	2.83	3.62	4.31	5.07	7.14
SV660	2.89	3.65	4.34	5.11	7.26
SV670	2.7	3.42	4.06	4.77	6.72
SV680	2.83	3.62	4.31	5.07	7.14
SV690	2.7	3.42	4.06	4.77	6.72
SV700	2.7	3.42	4.06	4.77	6.72
SV710	2.7	3.42	4.06	4.77	6.72
SV720	2.83	3.62	4.31	5.07	7.14
SV730	2.83	3.62	4.31	5.07	7.14
SV740	2.89	3.65	4.34	5.11	7.26
SV740A	2.7	3.42	4.06	4.77	6.72
SV750	2.7	3.42	4.06	4.77	6.72
SV760	2.7	3.42	4.06	4.77	6.72
SV770	2.7	3.42	4.06	4.77	6.72
SV780	2.7	3.42	4.06	4.77	6.72
SV790	2.7	3.42	4.06	4.77	6.72
SV800	2.83	3.62	4.31	5.07	7.14
SV800A	2.83	3.62	4.31	5.07	7.14
SV810	2.83	3.62	4.31	5.07	7.14
SV820	2.83	3.62	4.31	5.07	7.14
SV830	2.89	3.65	4.34	5.11	7.26
SV840	2.89	3.65	4.34	5.11	7.26
SV850	2.7	3.42	4.06	4.77	6.72
SV860	2.7	3.42	4.06	4.77	6.72
SV870	2.89	3.65	4.34	5.11	7.26
SV880	2.7	3.42	4.06	4.77	6.72
SV890	2.89	3.65	4.34	5.11	7.26
SV900	2.89	3.65	4.34	5.11	7.26
SV910	2.83	3.62	4.31	5.07	7.14
SV910A	2.7	3.42	4.06	4.77	6.72
SV920	2.7	3.42	4.06	4.77	6.72
SV920A	2.7	3.42	4.06	4.77	6.72
SV930	2.83	3.62	4.31	5.07	7.14
SV940	2.7	3.42	4.06	4.77	6.72
SV950	2.7	3.42	4.06	4.77	6.72
SV960	2.7	3.42	4.06	4.77	6.72
SV970	2.7	3.42	4.06	4.77	6.72
SV980	2.7	3.42	4.06	4.77	6.72
SV990	2.89	3.65	4.34	5.11	7.26

St. Vrain Creek

NOAA Aerial Reduction (98% - 10 to 30 sq.mi.)

Basin	10-yr	25-yr	50-yr	100-yr	500-yr
SV1000	2.65	3.35	3.98	4.67	6.59
SV1010	2.83	3.58	4.25	5.01	7.11
SV1020	2.65	3.35	3.98	4.67	6.59
SV1030	2.65	3.35	3.98	4.67	6.59
SV1040	2.65	3.35	3.98	4.67	6.59
SV1050	2.83	3.58	4.25	5.01	7.11
SV1060	2.83	3.58	4.25	5.01	7.11
SV1070	2.65	3.35	3.98	4.67	6.59
SV540	2.65	3.35	3.98	4.67	6.59
SV550	2.83	3.58	4.25	5.01	7.11
SV560	2.65	3.35	3.98	4.67	6.59
SV570	2.77	3.55	4.22	4.97	7.00
SV580	2.83	3.58	4.25	5.01	7.11
SV590	2.65	3.35	3.98	4.67	6.59
SV600	2.77	3.55	4.22	4.97	7.00
SV600A	2.77	3.55	4.22	4.97	7.00
SV610	2.83	3.58	4.25	5.01	7.11
SV620	2.77	3.55	4.22	4.97	7.00
SV630	2.77	3.55	4.22	4.97	7.00
SV640	2.83	3.58	4.25	5.01	7.11
SV650	2.77	3.55	4.22	4.97	7.00
SV660	2.83	3.58	4.25	5.01	7.11
SV670	2.65	3.35	3.98	4.67	6.59
SV680	2.77	3.55	4.22	4.97	7.00
SV690	2.65	3.35	3.98	4.67	6.59
SV700	2.65	3.35	3.98	4.67	6.59
SV710	2.65	3.35	3.98	4.67	6.59
SV720	2.77	3.55	4.22	4.97	7.00
SV730	2.77	3.55	4.22	4.97	7.00
SV740	2.83	3.58	4.25	5.01	7.11
SV740A	2.65	3.35	3.98	4.67	6.59
SV750	2.65	3.35	3.98	4.67	6.59
SV760	2.65	3.35	3.98	4.67	6.59
SV770	2.65	3.35	3.98	4.67	6.59
SV780	2.65	3.35	3.98	4.67	6.59
SV790	2.65	3.35	3.98	4.67	6.59
SV800	2.77	3.55	4.22	4.97	7.00
SV800A	2.77	3.55	4.22	4.97	7.00
SV810	2.77	3.55	4.22	4.97	7.00
SV820	2.77	3.55	4.22	4.97	7.00
SV830	2.83	3.58	4.25	5.01	7.11
SV840	2.83	3.58	4.25	5.01	7.11
SV850	2.65	3.35	3.98	4.67	6.59
SV860	2.65	3.35	3.98	4.67	6.59
SV870	2.83	3.58	4.25	5.01	7.11
SV880	2.65	3.35	3.98	4.67	6.59
SV890	2.83	3.58	4.25	5.01	7.11
SV900	2.83	3.58	4.25	5.01	7.11
SV910	2.77	3.55	4.22	4.97	7.00
SV910A	2.65	3.35	3.98	4.67	6.59
SV920	2.65	3.35	3.98	4.67	6.59
SV920A	2.65	3.35	3.98	4.67	6.59
SV930	2.77	3.55	4.22	4.97	7.00
SV940	2.65	3.35	3.98	4.67	6.59
SV950	2.65	3.35	3.98	4.67	6.59
SV960	2.65	3.35	3.98	4.67	6.59
SV970	2.65	3.35	3.98	4.67	6.59
SV980	2.65	3.35	3.98	4.67	6.59
SV990	2.83	3.58	4.25	5.01	7.11

NOAA Aerial Reduction (96% -30 to 50 sq.mi.)

Basin	10-yr	25-yr	50-yr	100-yr	500-yr
SV1000	2.59	3.28	3.90	4.58	6.45
SV1010	2.77	3.50	4.17	4.91	6.97
SV1020	2.59	3.28	3.90	4.58	6.45
SV1030	2.59	3.28	3.90	4.58	6.45
SV1040	2.59	3.28	3.90	4.58	6.45
SV1050	2.77	3.50	4.17	4.91	6.97
SV1060	2.77	3.50	4.17	4.91	6.97
SV1070	2.59	3.28	3.90	4.58	6.45
SV540	2.59	3.28	3.90	4.58	6.45
SV550	2.77	3.50	4.17	4.91	6.97
SV560	2.59	3.28	3.90	4.58	6.45
SV570	2.72	3.48	4.14	4.87	6.85
SV580	2.77	3.50	4.17	4.91	6.97
SV590	2.59	3.28	3.90	4.58	6.45
SV600	2.72	3.48	4.14	4.87	6.85
SV600A	2.72	3.48	4.14	4.87	6.85
SV610	2.77	3.50	4.17	4.91	6.97
SV620	2.72	3.48	4.14	4.87	6.85
SV630	2.72	3.48	4.14	4.87	6.85
SV640	2.77	3.50	4.17	4.91	6.97
SV650	2.72	3.48	4.14	4.87	6.85
SV660	2.77	3.50	4.17	4.91	6.97
SV670	2.59	3.28	3.90	4.58	6.45
SV680	2.72	3.48	4.14	4.87	6.85
SV690	2.59	3.28	3.90	4.58	6.45
SV700	2.59	3.28	3.90	4.58	6.45
SV710	2.59	3.28	3.90	4.58	6.45
SV720	2.72	3.48	4.14	4.87	6.85
SV730	2.72	3.48	4.14	4.87	6.85
SV740	2.77	3.50	4.17	4.91	6.97
SV740A	2.59	3.28	3.90	4.58	6.45
SV750	2.59	3.28	3.90	4.58	6.45
SV760	2.59	3.28	3.90	4.58	6.45
SV770	2.59	3.28	3.90	4.58	6.45
SV780	2.59	3.28	3.90	4.58	6.45
SV790	2.59	3.28	3.90	4.58	6.45
SV800	2.72	3.48	4.14	4.87	6.85
SV800A	2.72	3.48	4.14	4.87	6.85
SV810	2.72	3.48	4.14	4.87	6.85
SV820	2.72	3.48	4.14	4.87	6.85
SV830	2.77	3.50	4.17	4.91	6.97
SV840	2.77	3.50	4.17	4.91	6.97
SV850	2.59	3.28	3.90	4.58	6.45
SV860	2.59	3.28	3.90	4.58	6.45
SV870	2.77	3.50	4.17	4.91	6.97
SV880	2.59	3.28	3.90	4.58	6.45
SV890	2.77	3.50	4.17	4.91	6.97
SV900	2.77	3.50	4.17	4.91	6.97
SV910	2.72	3.48	4.14	4.87	6.85
SV910A	2.59	3.28	3.90	4.58	6.45
SV920	2.59	3.28	3.90	4.58	6.45
SV920A	2.59	3.28	3.90	4.58	6.45
SV930	2.72	3.48	4.14	4.87	6.85
SV940	2.59	3.28	3.90	4.58	6.45
SV950	2.59	3.28	3.90	4.58	6.45
SV960	2.59	3.28	3.90	4.58	6.45
SV970	2.59	3.28	3.90	4.58	6.45
SV980	2.59	3.28	3.90	4.58	6.45
SV990	2.77	3.50	4.17	4.91	6.97

St. Vrain Creek Appendix C.6 (continued)

NOAA Aerial Reduction (94% - 50 to 100 sq.mi.)

Basin	10-yr	25-yr	50-yr	100-yr	500-yr
SV1000	2.54	3.21	3.82	4.48	6.32
SV1010	2.72	3.43	4.08	4.80	6.82
SV1020	2.54	3.21	3.82	4.48	6.32
SV1030	2.54	3.21	3.82	4.48	6.32
SV1040	2.54	3.21	3.82	4.48	6.32
SV1050	2.72	3.43	4.08	4.80	6.82
SV1060	2.72	3.43	4.08	4.80	6.82
SV1070	2.54	3.21	3.82	4.48	6.32
SV540	2.54	3.21	3.82	4.48	6.32
SV550	2.72	3.43	4.08	4.80	6.82
SV560	2.54	3.21	3.82	4.48	6.32
SV570	2.66	3.40	4.05	4.77	6.71
SV580	2.72	3.43	4.08	4.80	6.82
SV590	2.54	3.21	3.82	4.48	6.32
SV600	2.66	3.40	4.05	4.77	6.71
SV600A	2.66	3.40	4.05	4.77	6.71
SV610	2.72	3.43	4.08	4.80	6.82
SV620	2.66	3.40	4.05	4.77	6.71
SV630	2.66	3.40	4.05	4.77	6.71
SV640	2.72	3.43	4.08	4.80	6.82
SV650	2.66	3.40	4.05	4.77	6.71
SV660	2.72	3.43	4.08	4.80	6.82
SV670	2.54	3.21	3.82	4.48	6.32
SV680	2.66	3.40	4.05	4.77	6.71
SV690	2.54	3.21	3.82	4.48	6.32
SV700	2.54	3.21	3.82	4.48	6.32
SV710	2.54	3.21	3.82	4.48	6.32
SV720	2.66	3.40	4.05	4.77	6.71
SV730	2.66	3.40	4.05	4.77	6.71
SV740	2.72	3.43	4.08	4.80	6.82
SV740A	2.54	3.21	3.82	4.48	6.32
SV750	2.54	3.21	3.82	4.48	6.32
SV760	2.54	3.21	3.82	4.48	6.32
SV770	2.54	3.21	3.82	4.48	6.32
SV780	2.54	3.21	3.82	4.48	6.32
SV790	2.54	3.21	3.82	4.48	6.32
SV800	2.66	3.40	4.05	4.77	6.71
SV800A	2.66	3.40	4.05	4.77	6.71
SV810	2.66	3.40	4.05	4.77	6.71
SV820	2.66	3.40	4.05	4.77	6.71
SV830	2.72	3.43	4.08	4.80	6.82
SV840	2.72	3.43	4.08	4.80	6.82
SV850	2.54	3.21	3.82	4.48	6.32
SV860	2.54	3.21	3.82	4.48	6.32
SV870	2.72	3.43	4.08	4.80	6.82
SV880	2.54	3.21	3.82	4.48	6.32
SV890	2.72	3.43	4.08	4.80	6.82
SV900	2.72	3.43	4.08	4.80	6.82
SV910	2.66	3.40	4.05	4.77	6.71
SV910A	2.54	3.21	3.82	4.48	6.32
SV920	2.54	3.21	3.82	4.48	6.32
SV920A	2.54	3.21	3.82	4.48	6.32
SV930	2.66	3.40	4.05	4.77	6.71
SV940	2.54	3.21	3.82	4.48	6.32
SV950	2.54	3.21	3.82	4.48	6.32
SV960	2.54	3.21	3.82	4.48	6.32
SV970	2.54	3.21	3.82	4.48	6.32
SV980	2.54	3.21	3.82	4.48	6.32
SV990	2.72	3.43	4.08	4.80	6.82

NOAA Aerial Reduction (92% - Greater than 100 sq.mi.)

Basin	10-yr	25-yr	50-yr	100-yr	500-yr
SV1000	2.48	3.15	3.74	4.39	6.18
SV1010	2.66	3.36	3.99	4.70	6.68
SV1020	2.48	3.15	3.74	4.39	6.18
SV1030	2.48	3.15	3.74	4.39	6.18
SV1040	2.48	3.15	3.74	4.39	6.18
SV1050	2.66	3.36	3.99	4.70	6.68
SV1060	2.66	3.36	3.99	4.70	6.68
SV1070	2.48	3.15	3.74	4.39	6.18
SV540	2.48	3.15	3.74	4.39	6.18
SV550	2.66	3.36	3.99	4.70	6.68
SV560	2.48	3.15	3.74	4.39	6.18
SV570	2.60	3.33	3.97	4.66	6.57
SV580	2.66	3.36	3.99	4.70	6.68
SV590	2.48	3.15	3.74	4.39	6.18
SV600	2.60	3.33	3.97	4.66	6.57
SV600A	2.60	3.33	3.97	4.66	6.57
SV610	2.66	3.36	3.99	4.70	6.68
SV620	2.60	3.33	3.97	4.66	6.57
SV630	2.60	3.33	3.97	4.66	6.57
SV640	2.66	3.36	3.99	4.70	6.68
SV650	2.60	3.33	3.97	4.66	6.57
SV660	2.66	3.36	3.99	4.70	6.68
SV670	2.48	3.15	3.74	4.39	6.18
SV680	2.60	3.33	3.97	4.66	6.57
SV690	2.48	3.15	3.74	4.39	6.18
SV700	2.48	3.15	3.74	4.39	6.18
SV710	2.48	3.15	3.74	4.39	6.18
SV720	2.60	3.33	3.97	4.66	6.57
SV730	2.60	3.33	3.97	4.66	6.57
SV740	2.66	3.36	3.99	4.70	6.68
SV740A	2.48	3.15	3.74	4.39	6.18
SV750	2.48	3.15	3.74	4.39	6.18
SV760	2.48	3.15	3.74	4.39	6.18
SV770	2.48	3.15	3.74	4.39	6.18
SV780	2.48	3.15	3.74	4.39	6.18
SV790	2.48	3.15	3.74	4.39	6.18
SV800	2.60	3.33	3.97	4.66	6.57
SV800A	2.60	3.33	3.97	4.66	6.57
SV810	2.60	3.33	3.97	4.66	6.57
SV820	2.60	3.33	3.97	4.66	6.57
SV830	2.66	3.36	3.99	4.70	6.68
SV840	2.66	3.36	3.99	4.70	6.68
SV850	2.48	3.15	3.74	4.39	6.18
SV860	2.48	3.15	3.74	4.39	6.18
SV870	2.66	3.36	3.99	4.70	6.68
SV880	2.48	3.15	3.74	4.39	6.18
SV890	2.66	3.36	3.99	4.70	6.68
SV900	2.66	3.36	3.99	4.70	6.68
SV910	2.60	3.33	3.97	4.66	6.57
SV910A	2.48	3.15	3.74	4.39	6.18
SV920	2.48	3.15	3.74	4.39	6.18
SV920A	2.48	3.15	3.74	4.39	6.18
SV930	2.60	3.33	3.97	4.66	6.57
SV940	2.48	3.15	3.74	4.39	6.18
SV950	2.48	3.15	3.74	4.39	6.18
SV960	2.48	3.15	3.74	4.39	6.18
SV970	2.48	3.15	3.74	4.39	6.18
SV980	2.48	3.15	3.74	4.39	6.18
SV990	2.66	3.36	3.99	4.70	6.68

Appendix C.6 (cont)

St. Vrain Creek

HEC-HMS Design Point	Location Description	Area (sq. mi.)	Rainfall Depth-Area Reduction %
SV990	Buchanan Pass (Middle SVC headwaters)	10.21	98%
SV1010	Coney Creek (Middle SVC headwaters)	4.03	100%
J184	Headwaters Middle SVC	14.24	98%
R450	Middle SVC at headwaters	14.24	98%
SV1000	Middle SVC area above Camp Dick	3.66	100%
J176	Camp Dick on Middle SVC	17.89	98%
R460	Middle SVC along Hwy 72	17.89	98%
SV960	Park Creek Trib to Middle SVC	3.00	100%
SV950	Cave Creek Trib to Middle SVC	2.25	100%
J196	Cave and Park Creek Tribs on Middle SVC	5.25	100%
R400	Cave and Park Creek Trib to Middle SVC	5.25	100%
SV970	Ironclads trib area to Middle SVC	0.28	100%
SV980	Middle SVC area around Hwy 72	2.90	100%
J191	Middle SVC at Raymond	26.32	98%
R410	Middle SVC between Raymond and Riverside	26.32	98%
SV920	Middle SVC area above Riverside	3.85	100%
J201A	Middle SVC at Riverside (Dischage Estimation Point #55 by Bob Jarrett)	30.18	98%
R410A	Middle SVC above confluence with South SVC	30.18	98%
SV920A	Middle SVC area above confluence with South SVC	2.02	100%
J201B	Middle SVC above confluence with South SVC	32.19	98%
SV1060	Long Lake (South SVC headwaters)	5.62	100%
SV1050	Mitchell Lake (South SVC headwaters)	3.73	100%
J171	Brainard Lake (South SVC headwaters)	9.35	100%
R520	South SVC headwaters to Hwy 72	9.35	100%
SV1040	Beaver Reservoir trib area (South SVC)	7.14	100%
J490	Beaver Reservoir (South SVC)	7.14	100%
R490	Beaver Creek (South SVC)	7.14	100%
SV1020	Beaver Creek area tributary to South SVC	2.52	100%
SV1030	South SVC area upstream of Hwy 72	7.78	100%
J179	South SVC at Hwy 72	26.78	98%
R480	South SVC from Hwy 72 to confluence with Middle SVC	26.78	98%
SV940	South SVC area between Hwy 72 and Middle SVC	7.75	100%
J201C	South SVC above confluence with Middle SVC	34.53	98%
J201	Confluence of Middle and South SVC	66.72	94%
R370A	South SVC below confluence with Middle SVC	66.72	94%
SV910A	Long Gulch Trib to South SVC below confluence with Middle SVC	1.72	100%
J204A	South SVC at Discharge Estimation Point #56 by Bob Jarrett	68.45	94%
R370	South SVC above Big Narrows	68.45	94%
SV910	South SVC trib area above Big Narrows	2.50	100%
SV930	Central Gulch Trib to South SVC at Big Narrows	7.22	100%
J204	South SVC at Big Narrows	78.17	94%
R350A	South SVC below Big and Little Narrows	78.17	94%
SV800A	Coffintop Gulch trib to South SVC between Big and Little Narrows	4.89	100%
J204B	South SVC at Little Narrows (Peak Discharge Estimate Point #57 by Bob Jarret	83.06	94%
R350	South SVC below Little Narrows past Hall Ranch	83.06	94%
SV800	South SVC trib area at Hall Ranch	5.67	100%
SV810	Red Hill Gulch Trib to South SVC above Lyons	2.28	100%
SV720	Indian Lookout Mountain Trib Area to South SVC	0.26	100%
J234	South SVC above confluence with North SVC	91.27	94%
R190	South SVC above confluence with North SVC	91.27	94%
SV830	North SVC headwaters	7.95	100%
SV870	Ouzel Creek Trib to North SVC headwaters	5.14	100%
J219	North SVC headwaters	13.08	98%
R320	North SVC near Ouzel Falls	13.08	98%
SV890	North SVC trib area near Calypso Cascades	1.01	100%
SV900	Cony Creek Trib area to North SVC	7.24	100%
J211	North SVC at confluence with Cony Creek	21.33	98%
R310	North SVC above Copeland Falls in Wild Basin	21.33	98%
SV840	Sandbeach Creek Trib to North SVC in Wild Basin	3.64	100%
SV640	Hunters Creek Trib to North SVC in Wild Basin	4.50	100%
J227	North SVC at Copeland Falls	29.47	98%
R240	North SVC above Hwy 7	29.47	98%
SV740	Campers Creek Trib to North SVC at Hwy 7	3.05	100%
J252A	North SVC at Hwy 7 (Peak Estimation Point #63 by Bob Jarrett)	32.52	98%
R240A	North SVC below Hwy 7	32.52	98%
SV740A	North SVC trib area at Hwy 7	0.78	100%
SV660	Horse Creek Trib to North SVC below Hwy 7	3.57	100%
J252	North SVC at confluence with Horse Creek below Hwy 7	36.87	96%
R170	North SVC between Horse Creek and Rock Creek	36.87	96%
SV760	North SVC trib area between Horse Creek and Rock Creek	1.01	100%
SV860	Willow Creek Tributary to Rock Creek and North SVC near Allenspark	3.75	100%
SV880	Rock Creek Trib to North SVC at Ferncliff	10.10	98%
J216	Rock Creek Trib to North SVC at Ferncliff	13.85	98%
R290	Rock Creek Trib to North SVC	13.85	98%
SV790	Rock creek trib area at confluence with North SVC	0.90	100%
J239	North SVC at confluence with Rock Creek	52.63	96%
R200	North SVC between Rock Creek and Cabin Creek tribs	52.63	96%
SV750	North SVC trib area above Cabin Creek Confluence	1.15	100%
SV540	Inn Brook Trib at Longs Peak above North SVC	3.82	100%
SV550	Alpine Brook Trib at Longs Peak above North SVC	2.46	100%
J298	Confluence of Inn Brook and Alpine Brook tributary to North SVC	6.28	100%
R40	Tahosa Creek between Roaring Fork and Alpine Brook tribs in North SVC area	6.28	100%
SV560	Tahosa Valley trib area upstream of Roaring Fork trib in North SVC area	3.68	100%
SV580	Roaring Fork Trib to Tahosa Creek in North SVC area	2.36	100%
J291	Tahosa Valley above Cabin Creek in North SVC area	12.32	98%
R70	Tahosa Creek above Cabin Creek in North SVC area	12.32	98%
SV590	Tahosa Creek trib area upstream of Cabin Creek in North SVC area	0.97	100%
SV610	Cabin Creek Trib area to North SVC	5.79	100%
J283	Cabin Creek and Tahosa Creek confluence in North SVC area	19.08	98%
R120	Cabin Creek trib to North SVC	19.08	98%
SV670	Cabin Creek Trib area at confluence with North SVC	3.38	100%
J249	North SVC at confluence with Cabin Creek	76.25	94%
R250	North SVC below confluence with Cabin Creek	76.25	94%
SV770	North SVC trib area below confluence with Cabin Creek	4.56	100%
SV690	Coulson Gulch trib to North SVC	2.51	100%
J244	North SVC at Coulson Gulch confluence	83.31	94%
R260	North SVC above confluence with Dry SVC	83.31	94%
SV780	North SVC area below Coulson Gulch confluence	0.21	100%
SV850	Dry SVC trib to North SVC	7.24	100%
J224	North SVC at confluence with Dry SVC	90.76	94%
R270	North SVC below confluence with Dry SVC	90.76	94%
SV710	North SVC trib area upstream of Button Rock Reservoir	4.20	100%
SV700	Rattlesnake Gulch Trib to North SVC	3.48	100%
J261	North SVC inflow to Button Rock Reservoir	98.44	94%
R3250	North SVC through Button Rock Reservoir	98.44	94%
SV1070	Long Gulch trib to North SVC at Button Rock Reservoir	2.88	100%
J168	North SVC inflow to Button Rock Reservoir	101.32	94%
Button Rock	Discharge from Button Rock Reservoir	101.00	94%
R180	North SVC below Button Rock Reservoir	101.32	92%
SV630	North SVC throught Longmont Reservoir below Button Rock Reservoir	6.50	100%
SV620	North SVC trib area from Hwy 36 at north end	3.51	100%
J278	North SVC below Longmont Reservoir at Hwy 36	111.33	92%
R80A	North SVC along upper part of Hwy 36	111.33	92%
SV600A	North SVC trib area above peak discharge estimation point #58 by Bob Jarrett	0.66	100%
J286A	North SVC at Peak Discharge Estimation Point #58 by Bob Jarrett	111.99	92%
R80	North SVC above Apple Valley Road	111.99	92%
SV600	North SVC trib area at Apple Valley Road	1.40	100%
SV570	Spring Gulch Trib to North SVC at Apple Valley Road	4.14	100%
J286	North SVC at Apple Valley Road	117.54	92%
R110	North SVC above confluence with South SVC	117.54	92%
SV650	North SVC trib area above confluence with South SVC	6.43	100%
J260	North SVC above confluence with South SVC	123.97	92%
J258	Confluence of North and South SVC	215.24	92%
R140	St Vrain Creek through Lyons	215.24	92%
SV730	Lyons trib area to St. Vrain Creek	0.47	100%
SV680	Stone Canyon Trib to St Vrain Creek at Lyons	2.43	100%
J255	St Vrain Creek at confluence with Stone Canyon	218.14	92%
R210	St Vrain Creek below Lyons	218.14	92%
SV820	St. Vrain Creek trib area downstream of Lyons	0.25	100%
Outlet1	Outlet - St. Vrain Creek at Hwy 36 downstream of Lyons	218.39	92%

HEC-HMS Rainfall Depth-Area Reduction Zones	NOAA Atlas 2 Curves	
	Area (sq. mi.)	Rainfall Depth-Area Reduction %
0-10 mi^2 100%	0	100.0%
	5	99.0%
	10	98.5%
10-30 mi^2 98%	15	98.0%
	20	97.2%
30-50 mi^2 96%	30	96.5%
	40	95.8%
	50	95.2%
50-100 mi^2 94%	75	94.0%
	100	93.5%
100-400 mi^2 92%	125	93.0%
	150	92.5%
	200	92.0%
	250	91.7%
	300	91.4%
	350	91.1%
	400	90.8%
> 400 mi^2	> 400	N/A

Application of Rainfall Depth-Area Reduction for HEC-HMS Model

In order to evaluate the impacts of the NOAA Atlas 2 rainfall depth-area reduction factors on the Lefthand Creek watershed, several model scenarios were run using different rainfall depths. The three different scenarios included the unadjusted NOAA rainfall depth and two levels of reduced NOAA rainfall depths (98% and 96%). The results from each rainfall depth scenario were saved to a spreadsheet and the appropriate value at any given design point was determined based on the tributary area to that design point as shown in the table to the left. The steps to do this in HEC-HMS are described below.

1. Open the Basin Model "LH Max24hr Calibrated".
2. Open the Meteorological Model for the design storm of interest (e.g. NOAA 100-yr DARF) and select the "specified hyetograph".
3. Copy and Paste the desired rainfall depths (based on both design storm and depth-area reduction level) from the *LH Raingage Zones.xls* spreadsheet into the column for "Total Depth (in)" in the HEC-HMS user interface.
4. Run the HEC-HMS model and save the global summary results table to a summary spreadsheet.
5. Repeat Steps 3 and 4 with a different set of rainfall depths from the *LH Raingage Zones.xls* spreadsheet. This process must be repeated up to fifteen times to develop peak discharges for all five design storms and all three levels of rainfall depth-area reduction.
6. Once all of the model results have been produced, the summary spreadsheet can be used to determine the appropriate peak discharge at each design point using the table to the left.