# Hydrologic Evaluation of the Big Thompson Watershed

## Post September 2013 Flood Event

**Prepared for:**

**Colorado Department of Transportation**
**Region 4 Flood Recovery Office**

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**August 2014**

August 29, 2014

We hereby affirm that this report and hydrologic analysis for the Big Thompson 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.

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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.

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| • 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 Big Thompson watershed.

Prior to September 2013, the last major flooding event on the Big Thompson River upstream of Loveland was the infamous 1976 Big Thompson Flood. In 1981, the effective regulatory flow rates documented by the Federal Emergency Management Agency (FEMA) in the 2013 Flood Insurance Study (FIS) were developed. The effective peak discharges were developed based on a combination of gage records and regression equations.

In the current evaluation, a rainfall-runoff model was developed to transform ground-calibrated rainfall information for the September storm 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. A primary basis of calibration was a discharge hydrograph at Lake Estes provided by the U.S Bureau of Reclamation. This information was useful in calibration of the model because it provided peak discharge and volume accounting in real-time.

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 individually 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 such as debris dam breaches, discussed further in the body of the report, that are 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. This was to prepare the model 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. The model disregards any flood attenuation in Lake Estes for these discharge estimates, since there is no regulatory flood control storage associated with this reservoir. 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 the Big Thompson River, North Fork Big Thompson River, Buckhorn Creek and adjacent St. Vrain watershed, 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 and current regulatory discharges to get a sense for how the different sources of discharge estimates compare. This information is shown in Figure ES-1. The figure, 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, particularly on the Big Thompson River.
2. The regulatory discharges for the Big Thompson River upstream of Lake Estes (less than 154 square miles on chart) appear low relative to the model results.
3. Current 100-year regulatory discharges for Buckhorn Creek appear slightly high compared to the flood frequency results and the predictive model results. The Buckhorn Creek gage only had 30 years of data but included three historic peaks of around 10,000 cfs. The FFA is problematic as indicated by the large 5% and 95% confidence limits (6,500 to 62,100 cfs) for the 100-year peak discharge and is therefore not being relied on as a point of calibration.

The assumptions and limitations of the various methodologies were closely reviewed, compared, and contrasted. Based on this evaluation, 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 Big Thompson Watershed. In addition, the results of this modeling effort will be made available to local agencies for their consideration in revising discharges currently used for regulatory purposes.

**Figure ES-1. Comparison of 100-year Unit Discharges in the Big Thompson River, North Fork of Big Thompson and Buckhorn Creek**

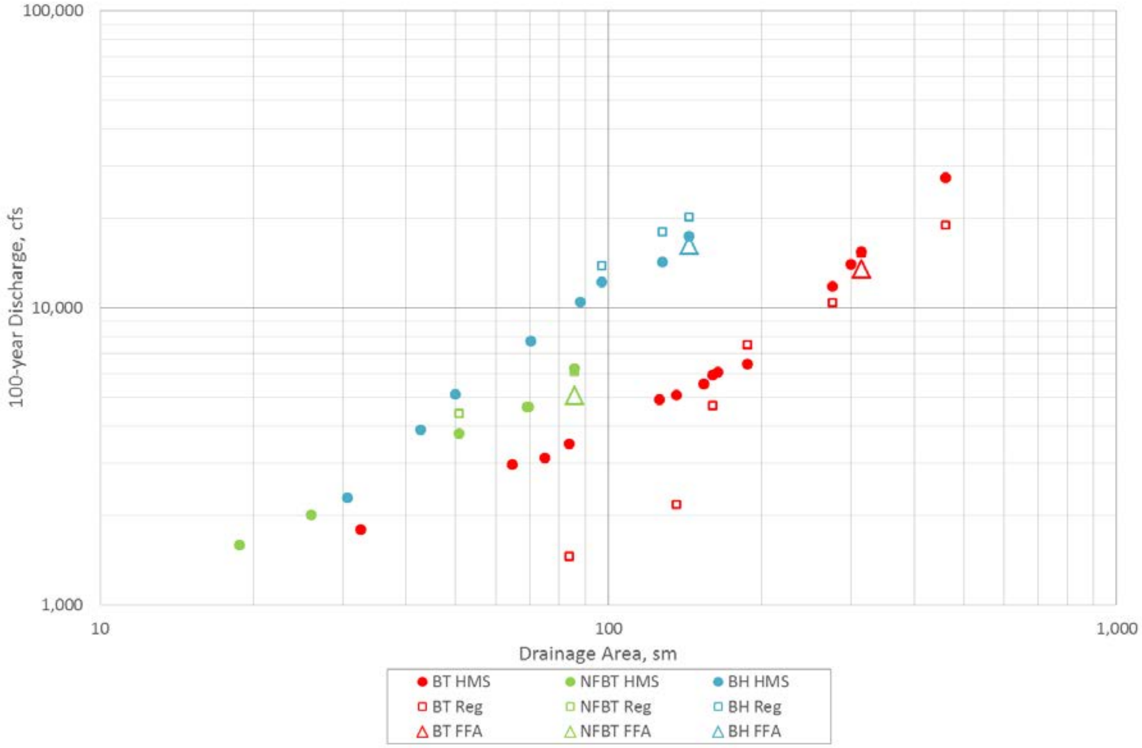

Table ES-1 summarizes the predictive model results for the 100-year event compared to current regulatory discharges. Significant differences are noted at two of these design points. The predictive discharge at the confluence of the Big Thompson and Buckhorn Creek is provisional and subject to change based on anticipated extension of the NOAA Atlas 2 rainfall depth-area reduction curves beyond 400-square miles. Local floodplain administrators may consider using the results of this hydrologic analysis to update and revise current regulatory discharges in the Big Thompson watershed. At a minimum, it is recommended that the current regulatory discharges be revised on the Big Thompson River upstream of Lake Estes.

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

| Location | Current Regulatory Discharge (cfs) | Modeled Discharge (cfs) | Percent Difference |
|---|---|---|---|
| Lake Estes | 2,180 | 5,550 | +155% |
| Big Thompson above Drake | 7,500 | 6,450 | -14% |
| Big Thompson below Drake | 10,400 | 11,800 | +13% |
| Big Thompson at Mouth of Canyon | 15,300 | 15,450 | +1% |
| Big Thompson at Buckhorn Creek [1] | 19,000 | 27,440 [1] | +44% [1] |
| North Fork BT above Drake | 6,100 | 6,240 | +2% |
| Buckhorn Creek at Masonville | 13,862 | 12,200 | -12% |
| Buckhorn Creek at Confl. w/ Redstone Ck. | 18,059 | 14,220 | -21% |
| Buckhorn at County Rd. 24H, CDWR Gage | 20,244 | 17,410 | -14% |

[1] Provisional and subject to change based on future extension of NOAA Atlas 2 rainfall area reduction curves.

Based on the modeled discharges for the return periods analyzed, the peak discharges observed along the Big Thompson River during the September 2013 flood event had an estimated recurrence interval ranging from approximately 4 percent annual peak discharge to greater than the 0.2 percent annual peak discharge, or from a 25-year to greater than a 500-year storm event. These results are shown in Table ES-2.

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

| Location | Estimated Discharge (cfs) | Annual Chance Peak Discharge (cfs) | | | | | Estimated Recurrence Interval (yr) |
|---|---|---|---|---|---|---|---|
| | | 10% | 4% | 2% | 1% | 0.2% | |
| BT at Lake Estes | 5,330 | 850 | 1,980 | 3,420 | 5,550 | 13,370 | ~ 100 |
| BT at Loveland Heights | 9,300 | 940 | 2,180 | 3,750 | 6,060 | 14,520 | 100 to 500 |
| BT above Drake | 12,500 | 960 | 2,280 | 3,960 | 6,450 | 15,690 | 100 to 500 |
| BT below Drake | 14,800 | 2,120 | 4,540 | 7,500 | 11,800 | 26,990 | 100 to 500 |
| BT at Mouth of Canyon | 15,500 | 3,040 | 6,250 | 10,050 | 15,450 | 34,000 | ~ 100 |
| BT at Buckhorn Creek [1] | 19,000 | 7,170 | 12,840 | 19,050 | 27,440 | 59,360 | ~ 50 [1] |
| NFBT Headwaters | 1,700 | 470 | 800 | 1,150 | 1,590 | 2,950 | ~ 100 |
| NFBT 4.5 miles above Drake | 18,400 | 1,110 | 2,090 | 3,200 | 4,640 | 9,500 | > 500 |
| NFBT at Drake | 5,900 | 1,540 | 2,870 | 4,340 | 6,240 | 12,600 | ~ 100 |
| Buckhorn at Stove Prairie Ck. | 4,400 | 1,310 | 2,410 | 3,590 | 5,110 | 9,960 | 50 to 100 |
| Buckhorn above Masonville | 11,000 | 2,970 | 5,220 | 7,520 | 10,460 | 19,620 | ~ 100 |
| Buckhorn above Redstone Ck. | 7,700 | 3,570 | 6,180 | 8,830 | 12,200 | 22,590 | 25 to 50 |
| Buckhorn at CR 24H | 11,200 | 4,850 | 8,700 | 12,590 | 17,410 | 32,500 | 25 to 50 |
| Redstone Ck. at Masonville | 1,400 | 560 | 1,210 | 1,930 | 2,880 | 6,060 | 25 to 50 |

[1] Provisional and subject to change based on future extension of NOAA Atlas 2 rainfall area reduction curves.

## 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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Compare results to updated flood frequency analyses and unit discharge information and calibrate as appropriate.

This report documents the hydrologic evaluation for the Big Thompson watershed.

### 1.2 Project Area Description

The Big Thompson River originates in the Rocky Mountains, and the basin extends west to the Continental Divide at an elevation of 14,250 feet on Long's Peak. The Big Thompson River flows in an easterly direction through the southern part of Larimer County to the South Platte River in Weld County. Figure 1 provides an overview map of the study area within the Big Thompson watershed. The studied section of the Big Thompson River is approximately 42 miles long and extends from the headwaters down to the confluence with Buckhorn Creek, approximately 5 miles west of Loveland. The study area encompasses approximately 460 square miles. Considerable residential development has taken place along the riverbanks, especially in the narrow canyon area. Channel slopes range from approximately 0.3 percent in the area near Loveland to 2.5 percent through the narrows. Numerous small tributaries were included in this study. The stream channels are narrow and some have slopes averaging 7.6 percent. There are no structures along the Big Thompson River or its tributaries that provide a major reduction in flood flows. Lake Estes is not designed for flood control and is operated to try and pass flood flows through the outlet structure with very little attenuation.

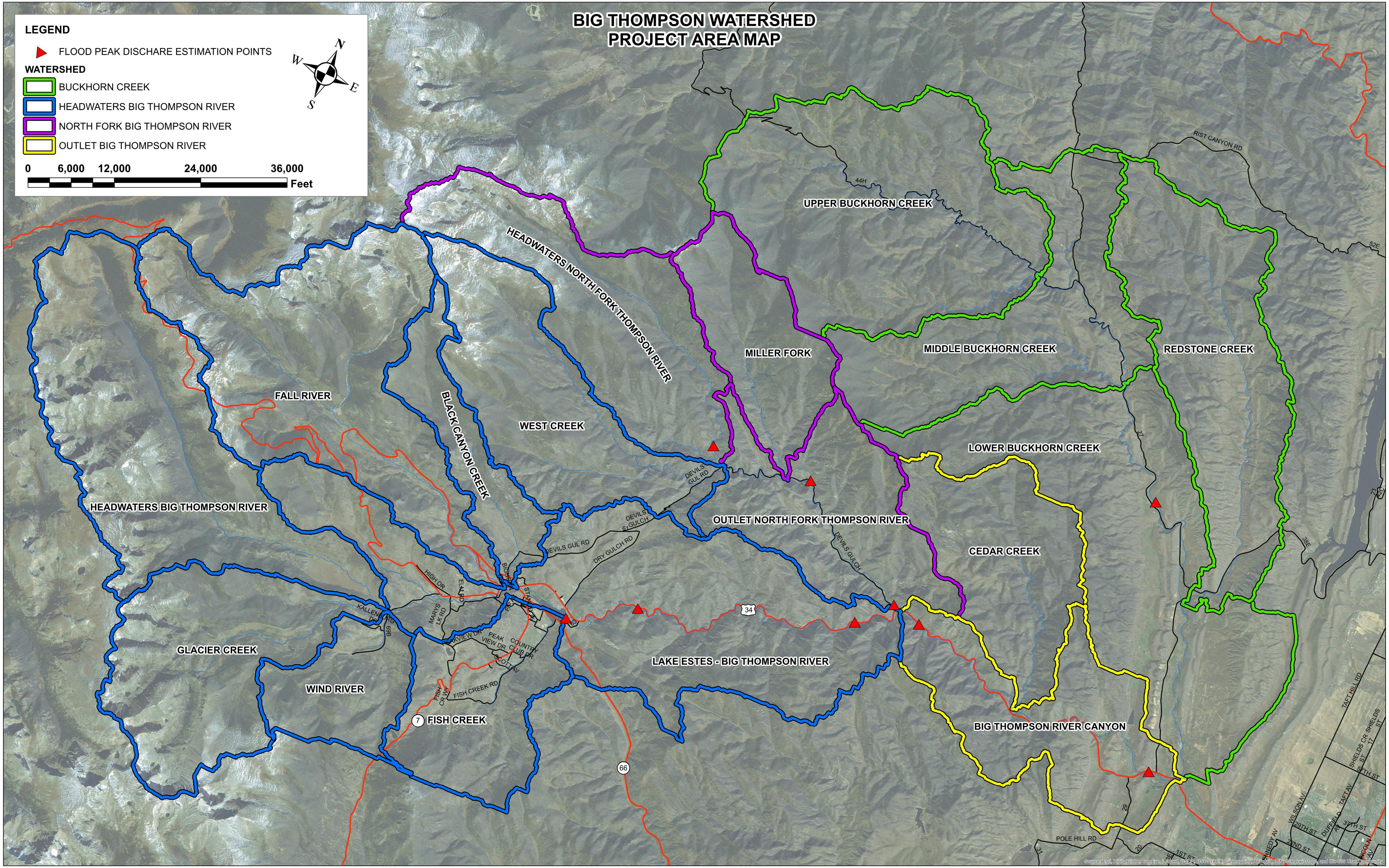
Fish Creek flows north through Larimer County to its confluence with the Big Thompson River at Lake Estes in the Town of Estes Park. Fall River flows southeast through Larimer County and joins the Big Thompson River in Estes Park. The Town of Estes Park is located in the southwest corner of Larimer County and is situated in an upland valley at an elevation of 7,500 feet. The town's central business district consists of numerous retail and novelty shops located near the confluence of the Big Thompson and Fall Rivers.

The total tributary area to Lake Estes is approximately 154 square miles. Downstream of Lake Estes, the Big Thompson River flows northeast for approximately 13.5 miles, paralleling U.S. Highway 34 toward Drake and its confluence with the North Fork Big Thompson. Upstream of the confluence, the Big Thompson has a tributary drainage area of approximately 190 square miles.

The North Fork Big Thompson River is approximately 9.8 miles long, with the lower limit being at the confluence with the Big Thompson River at Drake. The tributary area of the North Fork at Drake is approximately 86 square miles. The average channel width through this reach is 25 feet, and the channel slope averages 2.5 percent. Two of the larger tributaries to the North Fork Big Thompson River, West Creek and Devils Gulch, join near Glen Haven. West Creek and Devils Gulch have average channel widths of 25 feet, and their slopes are 1.7 percent and 7.6 percent, respectively.

At Drake, downstream of the confluence of the Big Thompson River and the North Fork Big Thompson, the drainage area is approximately 276 square miles. From Drake, the Big Thompson River continues to flow east, paralleling U.S. Highway 34 for approximately 11 miles to the mouth of the canyon and then another mile to the confluence with Buckhorn Creek. Upstream of Buckhorn Creek, the Big Thompson drainage area is approximately 316 square miles.

# BIG THOMPSON WATERSHED
# PROJECT AREA MAP



Source: Esri, DigitalGlobe, GeoEye, i-cubed, USDA, USGS, AEX, Getmapping, Aerogrid, IGN, IGP, swisstopo, and the GIS User Community

Buckhorn Creek is approximately 23 miles long and flows east and south through Larimer County and joins the Big Thompson River approximately 5 miles west of Loveland. Redstone Creek flows south on the east side of Buckhorn Creek basin and joins Buckhorn Creek at Masonville. Buckhorn Creek has a tributary area of approximately 144 square miles at the confluence with the Big Thompson River. Development in the two basins is confined to those areas where the valley width permits it, and consists mostly of farming units. The channel slope of Buckhorn Creek is approximately 1.1 percent, and the Redstone Creek channel slope averages approximately 3.5 percent.

### 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. The 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/. Street 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 Larimer 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 boundaries within the watershed.

## 1.5 Flood History

Unlike the September 2013 flood, historical floods on the Big Thompson River have typically been caused by intense rainfall from localized thunderstorms. These types of floods are typically characterized by high peak discharges of short duration. Historical flooding has also occurred as a result of rapid spring snowmelt which typically has a longer duration. A brief summary of the Big Thompson River flood history obtained from the 2013 Larimer County Flood Insurance Study (FIS) is provided here, for more detailed information please refer to the FIS.

The largest recorded flood on the Big Thompson River occurred from July 31st to Aug 1st, 1976. This flood was one of the worst natural disasters in the history of the State of Colorado. Intense precipitation over an approximate 60-square mile area between Lake Estes and Drake, with rainfall depths up to 12 inches, generated a flood discharge of approximately 31,200 cfs at the mouth of the canyon. This flood is known to have taken 139 lives. Property damage was estimated at $16.5 million, while hundreds of people were left homeless. Over 200 residential structures were damaged or destroyed by the flood, while nearly 1,200 land parcels were adversely affected.

Approximately 13 floods have occurred in Loveland on the Big Thompson River since 1864. These floods occurred in 1864, 1894, 1906, 1919 (8,000 cfs), 1921, 1923 (7,000 cfs), 1938, 1941, 1942, 1945 (7,600 cfs), 1949 (7,750 cfs), 1951, and 1976. All but the 1919 flood did damage to crops, homes and businesses in the Loveland area.

On June 9, 1921, the Colorado and Southern Railroad Bridge was destroyed due to heavy rains on June 2nd through 7th, 1921. On June 4th through 7th, 1949, heavy rains in the headwaters area of the Big Thompson River basin caused a flood with a magnitude of 7,750 cfs. Although considerably lower than the regulatory 100-year flood discharge of 19,000 cfs, lowland areas just west of Loveland were damaged.

The largest floods recorded at Loveland have also been the most recent ones. On August 2nd and 3rd, 1951, intense rains over much of the Big Thompson River basin caused a dam to break on Buckhorn Creek on August 3rd. This caused severe flooding from the mouth of Buckhorn Creek to the mouth of the Big Thompson River, especially through the Loveland area. Approximately 1 mile of US Highway 34 was destroyed just west of Loveland. Irrigation works were destroyed, crop loss was heavy, and much sediment and erosion damage occurred. The lives of four people were lost and many were left homeless. Total damages from the flood were estimated at $602,000. The estimated discharge from this flood was 22,000 cfs at Loveland, larger than the 1-percent annual chance flood discharge of 19,000 cfs. Buckhorn Creek has flooded on several other occasions, the largest floods were in 1923 (10,500 cfs), 1938 (10,200 cfs), and 1948 (5,750 cfs). Documentation of floods on Redstone Creek is relatively sparse. However, an intense rainstorm on September 10, 1938, caused flooding in some of the lower areas of the floodplain.

Fish Creek and Fall River have not often been subject to major flooding, although the Fall River did overflow its banks in 1965 and cause some damage. In July 1982, extensive damage occurred throughout the Town of Estes Park because of the failure of Lawn Lake Dam located in the headwaters of the Fall River. On July 15, 1982, the Lawn Lake Dam on the Roaring River failed. According to <u>Rocky Mountain News</u>, this catastrophic failure sent “a 30-foot wall of water down Roaring River…The water swept into Fall River…At about 8 A.M., it slammed into resorts perched on the river's banks at the west end of Estes Park." The Lawn Lake Dam failure caused property damage estimated at $20 to $30 million, and the loss of several lives. The flooding from this event was more extensive than that which would have been caused by the 0.2-percent annual chance flood.

The Town of Estes Park has not frequently been subject to damaging flood flows however, the flood of 1965 demonstrated the potential for flooding that exists, particularly in areas where buildings encroach upon the riverbanks. The 1965 flood was the result of a combination of heavy rain and rapid snowmelt on a warm day in June. Rainfall depth over a 2-day period was approximately 1.9 inches. The peak in the Big Thompson River near Lake Estes was approximately double the normal flow. The 1965 peak of 1,640 cfs was the most damaging flow in recent history, although flows of this magnitude were also recorded in 1949, 1951, 1953, and 1957. Damage from the 1965 event was the result of continued encroachment upon the river channel banks and blockage of the Fall River culvert at Elkhorn Avenue that diverted flows through the center of town.

## 2.0 HYDROLOGIC ANALYSIS

### 2.1 Previous Studies

The effective Larimer County FIS was published by the Federal Emergency Management Agency (FEMA) on February 6, 2013. 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. A summary of peak discharges from the FIS is shown in Table 1.

In 1971, the USACE presented flood flow frequencies for the lower portion of the Big Thompson River near Loveland based on statistical analysis of USGS gage data. Those flood frequencies were verified and used for the hydraulic study by Resource Consultants, Inc., which became effective in 1981.

The effective regulatory discharges on the Big Thompson River, the North Fork Big Thompson River, and their major tributaries were developed based upon a combination of gage records and regression equations contained in the CWCB Technical Manual No. 1, prepared by the USGS. The locations of the stream gages analyzed and their respective years of record at the time of the study were as follows: Drake gage located on the Big Thompson River near the mouth of the canyon (47 years), Big Thompson River below Lake Estes (17 years), Big Thompson River above Lake Estes (27 years), and North Fork Big Thompson River at Drake (30 years). The gage records were analyzed using the log-Pearson Type III distribution as recommended in U.S. Water Resources Council Bulletin 17, and the discharges were adjusted as recommended in Technical Manual No. 1.

The EPA Storm Water Management Model (SWMM) was used to determine discharges on drainage basins that are representative of the smaller Big Thompson River and North Fork Big Thompson River tributaries. These discharges were plotted on semi-log paper to develop discharge-drainage area curves for the region. These curves were entered with the drainage areas of the smaller tributaries, and the appropriate discharges were tabulated.

For purposes of a 2005 study revision, the flood flow frequencies presented in the USACE study were further verified by augmenting the stream flow data with entries from the intervening period of record. An updated flood frequency relationship was developed in 2005 by Ayres Associates in accordance with criteria outlined in Bulletin 17B, Guidelines for Determining Flood Flow Frequencies with the aid of the flood-frequency analysis program HEC-FFA. The updated flood frequency analysis used a systematic record of 80 years. Comparison showed that the effective flood discharges were higher than those from the updated flood frequency but typically plotted within the 90% confidence interval. The effective flood discharges were therefore adopted for the 2013 FIS instead of the updated flood frequency results.

The discharges for Buckhorn Creek, Redstone Creek, and Black Canyon Creek were calculated based upon the regression equations found in Technical Manual No. 1. Parameters needed for the regression equations were taken from USGS topographic maps at a scale of 1:250,000, SCS County Soil Maps, and County Land Use Maps. For Buckhorn Creek and Redstone Creek, discharges for each design point were calculated for the portions of the basin above 7,500 feet and below 7,500 feet, and the largest discharge at each point was used. It should be noted that the regulatory 100-year peak discharge for Buckhorn Creek (20,244 cfs) is larger than the 100-year peak discharge for the entire Big Thompson watershed upstream of Loveland including Buckhorn Creek (19,000 cfs). This raises concerns regarding the accuracy of the Buckhorn Creek peak discharge as will be discussed later in this report.

Discharges for Fish Creek and Fall River were computed based upon records of stream gages located on the two streams. The Fish Creek gage had 30 years of record, and the Fall River gage had 9 years of record. These records were analyzed using a log-Pearson Type III distribution as recommended in U.S. Water Resources Council Bulletin 17. These discharges were weighted with those obtained using regression equations from the CWCB's Technical Manual No. 1.

## 2.2 September 2013 Peak Discharge 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 Big Thompson Watershed were identified, mapped, and prioritized for use by Bob Jarrett 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 and revised on July 16, 2014. This memo is included in Appendix A. Peak discharge estimates indicated in the July 16 memo are preliminary and subject to revision based on subsequent evaluations and comparisons.

**Table 1. Select Peak Discharge Values from 2013 FIS**

| Flooding Source and Location | Drainage Area (sq. mi.) | Peak Discharge (cfs) | | | |
|---|---|---|---|---|---|
| | | 10-yr | 50-yr | 100-yr | 500-yr |
| **Big Thompson River** | | | | | |
| At Railroad Avenue | 515 | 4,700 | 12,300 | 19,000 | 44,000 |
| At Mouth of Canyon (Drake Gage) | 314 | 3,800 | 10,500 | 15,300 | 37,000 |
| At Drake Below North Fork | 274 | 3,700 | 7,850 | 10,400 | 19,200 |
| At Drake Above North Fork | 191 | 2,750 | 5,700 | 7,500 | 13,600 |
| At Lake Estes Below Dry Gulch | 156 | 2,250 | 3,800 | 4,700 | 7,200 |
| At Lake Estes | 137.5 | 1,510 | 1,990 | 2,180 | 2,600 |
| At St. Vrain Avenue | 136.9 | 1,510 | 1,990 | 2,180 | 2,600 |
| At Confluence with Fall River | 87.1 | 980 | 1,340 | 1,460 | 1,760 |
| At Crags Drive in Estes Park | 87 | 980 | 1,340 | 1,460 | 1,760 |
| **Black Canyon Creek** | | | | | |
| At Confluence with Big Thompson River | 10 | 130 | 200 | 230 | 310 |
| **Buckhorn Creek** | | | | | |
| At Confluence with Big Thompson River | 142.9 | 6,844 | 15,090 | 20,244 | 36,000 |
| At Masonville Below Redstone Creek | 122.5 | 6,321 | 13,593 | 18,059 | 32,000 |
| At Masonville Above Redstone Creek | 92 | 4,674 | 10,321 | 13,862 | 24,000 |
| **Cedar Creek** | | | | | |
| At Confluence with Big Thompson River | 19.75 | 2,460 | 6,530 | 9,400 | 20,000 |
| **Devils Gulch** | | | | | |
| At Confluence with West Creek | 0.91 | 540 | 900 | 1,200 | 1,800 |
| **Fall River** | | | | | |
| At Confluence with Big Thompson River | 39.9 | 450 | 610 | 680 | 830 |
| **Fish Creek** | | | | | |
| At Lake Estes | 16 | 105 | 280 | 400 | 840 |
| **Fox Creek** | | | | | |
| At Confluence with North Fork Big Thompson River | 7.35 | 1,200 | 2,200 | 2,750 | 4,800 |
| **Miller Fork** | | | | | |
| At Confluence with North Fork Big Thompson River | 13.67 | 1,350 | 2,650 | 3,350 | 6,300 |
| **North Fork Big Thompson River** | | | | | |
| At Drake Road | 83 | 1,500 | 4,100 | 6,100 | 14,100 |
| At Glen Haven Below Devils Gulch | 51 | 1,450 | 3,400 | 4,400 | 11,500 |
| **Redstone Creek** | | | | | |
| At Confluence with Buckhorn Creek | 30.5 | 4,187 | 9,217 | 12,370 | 22,500 |
| **West Creek** | | | | | |
| At Confluence with North Fork Big Thompson River | 24.6 | 1,500 | 3,100 | 4,000 | 8,000 |

Some of the discharge estimates were greater than what would be expected given the tributary drainage basin characteristics, rainfall amounts and rainfall intensities measured during the storm. This information along with field observations by Bob Jarrett have led us to the conclusion that dam failures (including woody debris dams, road-embankments, beaver dams, stock ponds, and landslides) played a major role in this flood. Post-flood aerial imagery showed evidence of dam failures, mostly from debris flows, associated temporary debris dams, and catastrophic/sudden failures including the release of groundwater in landslides. These various dam failures resulted in dramatic peak flows, but because these dams have so little volume, attenuation of these peak flows downstream can also be dramatic. A USGS report (Godt et al., 2013) discussing landslides caused by the 2013 rainfall states that:

> *"debris flows exacerbated flooding by supplying sediment to stream valleys. This sediment was mobilized by floods and in some cases caused surging flood pulses that destroyed buildings and infrastructure."*

### 2.3 Updated Flood Frequency Analyses

Flood frequency analyses were performed to supplement the hydrologic evaluation of the Big Thompson River. 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 gages:

| | |
|---|---|
| Big Thompson River at Mouth of Canyon near Drake | |
| • USGS Gage 06738000 | (1888 – 2007 broken) |
| • CDWR Gage BTCANYCO | (1991 – 2012) |
| North Fork Big Thompson River at Drake | |
| • USGS Gage 06736000 | (1947 – 1976) |
| • CDWR Gage BTNFDRCO | (1991 – 2012) |
| Buckhorn Creek near Masonville | |
| • USGS Gage 06739500 | (1947 – 1955) |
| • CDWR Gage BUCRMVCO | (1993 – 2012) |

The Big Thompson River gage record has 89 annual peak flows. The earliest is from 1888 and the latest is from 2012. Gaps in the record exist between 1903 and 1927 and between 1933 and 1938. Also no peak flood value is recorded for 1950. For the purposes of this study, peak values from another gage nearby were added for 1908 through 1911 simply to supplement the record. The September 2013 flood was added to the data record with a peak value of 15,500 cfs which was estimated independently by both Ayres Associates and Bob Jarrett from analysis of high water marks. The largest peak discharge recorded at this gage is 31,200 cfs from the infamous 1976 flood. The 2013 flood peak is the second largest.

An important factor in analyzing this gage is the introduction of Olympus Dam forming Lake Estese in Estes Park. The dam began regulating flows in 1950. The flood frequency analysis at the gage was performed in three ways to determine how best to account for the regulation of flows by the dam. The first analysis incorporated all annual peaks up to 1950 (pre-dam). The second used the data after 1950 (post-dam). The third analysis incorporated all of the data. The pre-dam analysis produced results very similar to the analysis incorporating the entire period of record. The post-dam analysis produced lower discharges for each recurrence interval. Based on that comparison it was decided to use the entire period of record, since this would provide the greatest degree of confidence in the flood frequency estimates.

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 in the Big Thompson.

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 all three gages in the Big Thompson watershed based on the revised approach using station skew are included in Appendix B. The results are summarized in Table 2 below.

**Table 2. Results of Flood Frequency Analysis for Big Thompson River at the Mouth of the Canyon**

| Exceedence Recurrence Interval (years) | Big Thompson at Mouth of Canyon (cfs) | North Fork Big Thompson at Drake (cfs) | Buckhorn Creek near Masonville (cfs) |
|---|---|---|---|
| 2 | 920 | 190 | 290 |
| 5 | 1,970 | 460 | 1,300 |
| 10 | 3,210 | 820 | 2,810 |
| 50 | 8,940 | 2,990 | 10,360 |
| 100 | 13,530 | 5,100 | 16,230 |
| 500 | 34,140 | 17,120 | 39,510 |

Based on these results, the 2013 flood was slightly larger than a 100-year event at the mouth of Big Thompson Canyon and on the North Fork Big Thompson at Drake, whereas the 1976 flood was slightly below the 500-year event at the mouth of the canyon. Because of the relatively short period of record and large confidence bands for the Buckhorn gage, the results of the FFA for Buckhorn were not relied on as a point of calibration. 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 Big Thompson 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 the Big Thompson River, North Fork Big Thompson River, and Buckhorn 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, CN method, Green-Ampt, etc.), transform methods (unit hydrograph, kinematic wave, etc.), and reach-routing methods (Modified Puls, Muskingum-Cunge, etc.). 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, Lake Estes 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 Lake Estes 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 Cache la Poudre watershed to the north, the Continental Divide to the west, and the St. Vrain and Little Thompson watersheds to the south. With the downstream limit of the study set at the confluence with Buckhorn Creek, basins were delineated around all reaches and confluences. The overall watershed was divided into 50 basins ranging from 0.25 square miles to 30 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 fifteen peak discharge estimation locations used for comparison include:

1. Big Thompson River at Lake Estes (USBR)
2. Big Thompson River at Loveland Heights (Jarrett)
3. Big Thompson River at Mountain Shadows Land u/s Drake (Jarrett)
4. Big Thompson River d/s of Drake (Jarrett)
5. Big Thompson River u/s River Rim Rd in Loveland (Jarrett and Ayres)
6. Big Thompson River at downstream study limit (Ayres)
7. North Fork Big Thompson River Headwaters (NRCS)
8. North Fork Big Thompson River 3.5 miles upstream of Drake (NRCS)
9. North Fork Big Thompson River at Drake (Jarrett)
10. Buckhorn Creek at Confluence with Stove Prairie Creek (Jarrett)
11. Buckhorn Creek 3.5 miles upstream of Masonville (NRCS)
12. Buckhorn Creek at Masonville (Jarrett)
13. Buckhorn Creek at County Road 24H near CDWR Gage (Jarrett)
14. Redstone Creek Headwaters (NRCS)
15. Redstone Creek at Masonville (Jarrett)

### 2.4.3 Basin Characterization

The basin characteristics of the Big Thompson watershed consist mainly of undeveloped, rural, mountainous terrain with some developed urban areas within the town of Estes Park. The watershed topography generally slopes west to east with slopes that range from mild to steep. The individual basin slopes range from approximately 7 percent to as steep as 58 percent depending on the spatial location within the watershed. Three major creeks divide the study area; the Big Thompson River, North Fork Big Thompson River, and Buckhorn Creek. The total watershed area is approximately 460 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. Default Kn values of 0.15 for evergreen forests and 0.10 for agriculture and heavy shrub/brush were 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.

### 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 and slope of the channel reaches were acquired using the HEC-GeoHMS program and the 10-meter DEM and DRG datasets. Initially, a generic cross-section was used for all reaches in the model, with the intention of going back and replacing the cross-sections with site-specific station-elevation data once higher resolution topography was obtained. However, as will be discussed later in this report, the routing component of the model is not very sensitive and has very little effect on peak flows or attenuation due to the steep slope and relatively narrow width of the mountain channels. Therefore, the generic cross-section was used for all reaches and consists of a 20 feet bottom width, channel side slopes of 3:1 transitioning to 4:1 in the overbank areas. The Manning's n values were initially set to a default of 0.05 for the channels and 0.20 for the overbank areas.

### 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 in most places. There was excellent weather radar coverage along with many rainfall observations with excellent overall spatial distributions at both low and high elevation locations. The exception to this was in the headwater areas of the North Fork Big Thompson and Buckhorn Creek. 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 8.85 inches, ranging from as low as 3.92 inches up to 13.22 inches for the individual basins. However, the majority of this rainfall fell within a 24-hour period starting around 4 A.M. on Thursday, September 12, 2013. The average 24-hour rainfall depth for all of the basins was 5.26 inches, ranging from 2.00 inches up to 8.02 inches for the individual basins. The average 24-hour rainfall depth of 5.26 inches roughly corresponds to a NOAA 100-year rainfall depth. Table 3 shows the September 2013 rainfall depths for various durations in five representative basins from the study area. It also shows the associated NOAA Atlas 14 recurrence interval for each depth-duration pair.

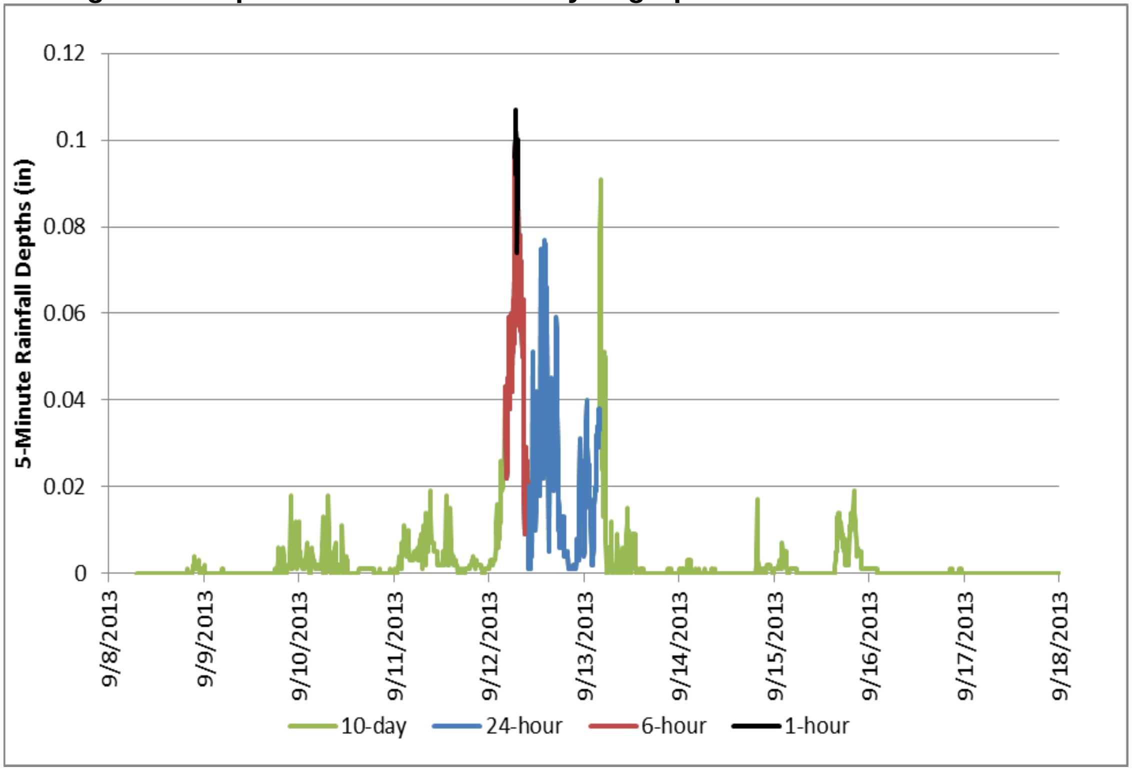
Figure 2 shows a hyetograph for the Fish Creek basin which drains directly to Lake Estes. The incremental depths are based on a 5-minute time step. As shown in Table 3, Fish Creek experienced some of the highest rainfall totals and intensities in the study area. The time of occurrence for maximum rainfall depth for various durations is shown on Figure 2 in different colors.

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 3. Representative Rainfall Depths from September 2013 Flood and Associated NOAA Atlas 14 Recurrence Interval**

| Location | BT Headwaters (BT18) | | Fish Creek (BT05) | | Fox Creek (BT30) | | Cedar Creek (BT33) | | Redstone Creek (BH16) | |
|---|---|---|---|---|---|---|---|---|---|---|
| Duration | Rainfall (in) | NOAA RI (yr) | Rainfall (in) | NOAA RI (yr) | Rainfall (in) | NOAA RI (yr) | Rainfall (in) | NOAA RI (yr) | Rainfall (in) | NOAA RI (yr) |
| 10-day | 3.92 | 2 to 5 | 12.36 | >1000 | 8.70 | 100 to 200 | 13.22 | >1000 | 9.60 | 200 to 500 |
| 24-hour | 2.00 | 5 | 8.02 | >1000 | 5.36 | 200 to 500 | 7.98 | 500 to 1000 | 4.82 | 50 to 100 |
| 6-hour | 1.20 | 2 to 5 | 3.77 | 100 to 200 | 2.33 | 25 to 50 | 3.08 | 25 to 50 | 2.07 | 5 to 10 |
| 1-hour | 0.36 | < 1 | 1.11 | 10 to 25 | 0.58 | 1 | 0.90 | 2 to 5 | 0.55 | < 1 |

**Figure 2. September 2013 Rainfall Hyetograph for Fish Creek Basin**



## 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 as explained below.

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 event 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 for channel reaches 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 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 justifiable method. During this combined calibration process, the U.S. Bureau of Reclamation provided a stage-storage relationship for Estes Park, along with Stage-Storage-Discharge time-series data during the 2013 flood event. This valuable information provided an additional peak discharge estimation point as well as allowed better calibration of the watershed upstream of Lake Estes with respect to timing, volume and peak discharges based on a calculated inflow hydrograph to Lake Estes. Similarly, the Colorado Division of Water Resources (CDWR) stream gage on Buckhorn Creek near County Road 24H (BUCRMVCO) recorded stage data throughout the 2013 flood event and provided information on timing of the peak discharge for Buckhorn Creek.

Calibrating the model to match the 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.

Attempts were also made to maximize peak discharges by raising composite CN values to 98, increasing the peaking coefficient and shortening the lag time. Even with all of these calibration parameters maximized, the modeled peak discharges were often still not close to the estimated peak discharge. There were also 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, and landslides) that generated peak discharges significantly higher than the rainfall/runoff process alone would have produced. Evidence of these types of dam failures and resulting high, short peak discharges was documented by 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 Big Thompson watershed was broken into four raingage zones corresponding with basin boundaries. Latitude and Longitude values were determined for the centroid of each raingage zone in order to obtain the point precipitation frequency estimates. Table 4 below and Appendix C.6 show the point precipitation values for the different raingage zones and the basins included in each zone. Table 4 also shows the 90 percent confidence intervals on the rainfall depths which expresses some of the uncertainty. Zone 1 included a single basin in the southwest corner of the watershed near Longs Peak. Zone 2 included 28 basins along the western side of the watershed from approximately Drake to the headwaters. Zone 3 included 14 basins in the central part of the watershed. Zone 4 included 7 basins in the eastern part of the watershed near Loveland. 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 4. Big Thompson Raingage Zones and Precipitation Depths**

| Zone | Zone 1 (Southwest) | Zone 2 (West) | Zone 3 (Central) | Zone 4 (East) |
|---|---|---|---|---|
| **Latitude** | 40.2920 | 40.4275 | 40.5173 | 40.4711 |
| **Longitude** | -105.6392 | -105.5556 | -105.3296 | -105.2161 |
| **Model Basins** | BT14 | BT18, BT17, BT16, BT15, BT13, BT12, BT10, BT19, BT09, BT21, BT22, BT20, BT23, BT05, BT06, BT07, BT03B, BT03A, BT27, BT28, BT26, BT30, BT31, BT25, BT32, BT24A, BH12, BH13 | BT03, BT24, BT02, BT33, BH11, BH10, BH09, BH14, BH08, BH07, BH06, BH05, BH04A, BH16 | BT01A, BT01, BH15, BH04, BH02, BH03, BH01 |
| **Point Precipitation Frequency Estimates with 90% Confidence Intervals (inches)** | | | | |
| **10-yr, 24-hr** | 2.95 (2.35 – 3.70) | 2.39 (1.91 – 2.99) | 2.86 (2.27 – 3.60) | 3.17 (2.54 – 3.93) |
| **25-yr, 24-hr** | 3.72 (2.94 – 5.01) | 3.06 (2.45 – 4.18) | 3.70 (2.93 – 5.03) | 4.09 (3.24 – 5.45) |
| **50-yr, 24-hr** | 4.42 (3.40 – 6.00) | 3.69 (2.86 – 5.07) | 4.46 (3.42 – 6.12) | 4.92 (3.78 – 6.60) |
| **100-yr, 24-hr** | 5.22 (3.88 – 7.27) | 4.42 (3.30 – 6.24) | 5.33 (3.95 – 7.50) | 5.84 (4.34 – 8.04) |
| **500-yr, 24-hr** | 7.48 (5.14 – 11.0) | 6.50 (4.48 – 9.78) | 7.77 (5.34 – 11.6) | 8.39 (5.76 – 12.2) |

Due to the size of the Big Thompson watershed (approximately 460 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 10% 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. Between 100 and 400 square miles in size, an 8% reduction was applied. For areas greater than 400 square miles, which exceeds the graph limit in NOAA Atlas 2, a 10% reduction was applied. However, this 10% reduction is probably not enough to realistically reflect convective storm behavior over such a large area and more research is being conducted on how to extend the NOAA Atlas 2 curves beyond 400 square miles. Appendix C.6 shows the reduction at each design point in the model.

To evaluate the area corrections, the entire watershed was run with six 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 discharges in the headwater areas, while the area corrected rainfall depths are used as the design points move progressively downstream. This is described in more detail in Appendix C.6.

In addition to the 24-hour storm duration, a 6-hour storm duration was also evaluated. Often times, in smaller smaller basins the shorter, more intense design storms produce larger peak discharges. However, due to the large size of the basins tributary to key design points and the fact that rainfall area corrections are more significant for 6-hour storms, the peak discharges were typically at or below the 24-hour peak discharges. Therefore, results for the 6-hour storm duration are not included in this report.

### 2.5.3 Model Calibration

Initial model results 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. For the Big Thompson watershed, an inflow hydrograph to Lake Estes was developed based on the observed stage-storage and observed stage-discharge information provided by the USBR for the 2013 flood event. 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 are iteratively adjusted in an attempt to match the above average peak flow values in the observed hydrograph. The parameters are iteratively adjusted using a scaling factor so that all basin parameters are adjusted 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 which are included in Appendix C.5, 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 the primary 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, the next problem was addressing the 10-day storm vs. SCS 24-hr 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 to see what magnitude of adjusted CNs would result in a best fit of the maximum 24-hour rainfall to the estimated 2013 flood peaks.

The “Max24hr” period of rainfall was then input into the meteorologic component of the model and the CN values for basins upstream of Lake Estes were optimized again to match the corresponding 24-hour inflow hydrograph at Lake Estes. The optimization run resulted in a CN scaling factor of 5%, which means that all CN values for basins upstream of Lake Estes were increased by 5% to achieve the best fit to the inflow hydrograph. This 5% scaling factor was then applied to the rest of the basins in the Big Thompson watershed. However, this adjustment was not sufficient to match the combined peak discharges further downstream in the watershed. Therefore, at a conceptual level, the idea of adjusting the CN values for downstream basins to Antecedent Runoff Condition (ARC) 3 seemed like a good check on the upper boundary limits 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 value for each basin. The model results after adjusting the CN value to ARC 3 produced peak discharges much higher than the estimated peak discharges from the 2013 flood. Therefore, the CN adjustment was scaled back between ARC 2 and ARC 3 to produce the same results that the 10-day model produced, in an attempt to match the estimated peak discharges from the 2013 flood. On a basin-wide average, the 10-day calibrated model had an average CN value of 58. The Max24hr calibrated model had a basin wide average CN value of 69 to generate peak discharges providing the best fit to the September 2013 event. Calibration results for the Max24hr event are discussed further in Section 3.0.

Using the calibrated Max24hr rainfall model matching the September 2013 event, the NOAA 24-hour SCS Type 2 storm distributions were input for a number of return periods. As a reasonableness check, the revised predictive model results were compared to expected unit discharges and the updated flood frequency analysis at the Big Thompson gage near the mouth of the canyon. 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 distributions. Results from the predictive models are discussed in more detail in Section 3.0 of this report.

## 3.0 HYDROLOGIC MODEL RESULTS

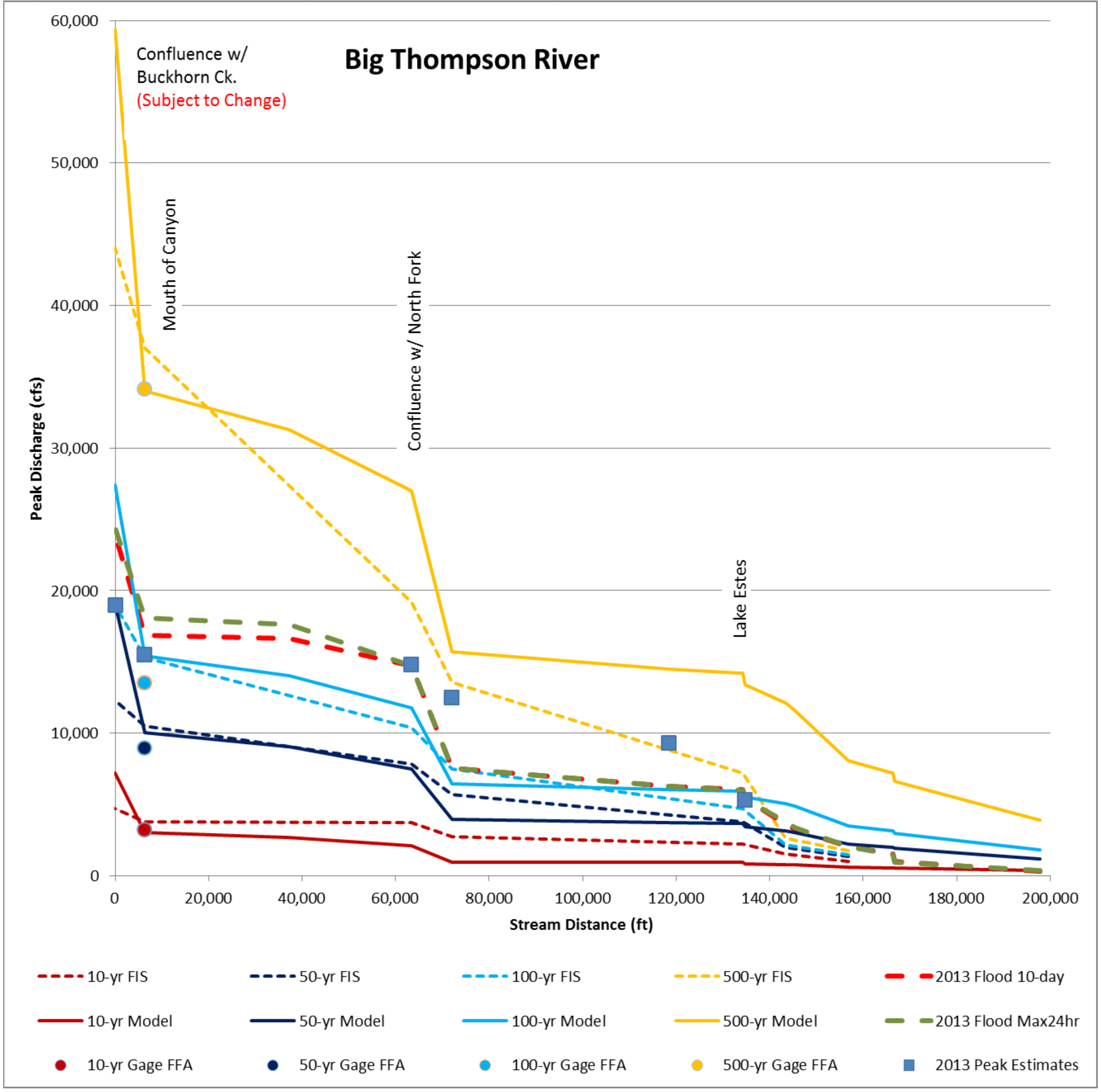
Table 5 below and the expanded table in Appendix C.1 show results at selected locations along the main stem of the Big Thompson River, the North Fork Big Thompson and Buckhorn Creek. Location descriptions and tributary drainage areas are provided for each location.

**Table 5. Hydrologic Model Peak Discharge Results**

| | Drainage | 2013 Flood | 2013 Flood | 2013 Flood | NOAA 24-hr Type II Predictive Storms | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | Area | Estimated | 10-day Period | Max 24hr Period | (Depth-Area Ajdusted) | | | | |
| **Location Description** | **(sq. mi.)** | **Peak Discharge (cfs)** | **Calibrated (cfs)** | **Calibrated (cfs)** | **10-yr (cfs)** | **25-yr (cfs)** | **50-yr (cfs)** | **100-yr (cfs)** | **500-yr (cfs)** |
| BT at confluence with Fern Creek in RMNP | 33 | | 329 | 394 | 354 | 737 | 1,183 | 1,793 | 3,893 |
| BT at Confluence of Glacier Creek | 65 | | 1,020 | 958 | 557 | 1,177 | 1,923 | 2,959 | 6,650 |
| BT at confluence with Wind River upstream of Estes Park | 75 | | 1,514 | 1,460 | 558 | 1,204 | 2,000 | 3,124 | 7,216 |
| BT at confluence with Beaver Brook | 84 | | 2,032 | 2,029 | 609 | 1,328 | 2,221 | 3,482 | 8,089 |
| BT at confluence with Fall River | 126 | | 3,274 | 3,398 | 786 | 1,794 | 3,056 | 4,896 | 11,580 |
| BT at confluence with Black Canyon Creek | 136 | | 3,639 | 3,773 | 794 | 1,834 | 3,148 | 5,074 | 12,118 |
| BT inflow to Lake Estes | 154 | | 5,415 | 5,342 | 846 | 1,980 | 3,424 | 5,548 | 13,370 |
| **Lake Estes (Olympus Dam)** | **154** | **5,327** | **5,327** | **5,327** | **846** | **1,980** | **3,424** | **5,548** | **13,370** |
| BT at confluence with Dry Gulch below Lake Estes | 160 | | 6,023 | 6,003 | 923 | 2,142 | 3,683 | 5,942 | 14,219 |
| **BT at Loveland Heights (Jarrett Estimate #62)** | **164** | **9,300** | **6,269** | **6,252** | **936** | **2,176** | **3,748** | **6,055** | **14,520** |
| **BT at Mountain Shadows Lane (Jarrett Estimate #65)** | **188** | **12,500** | **7,566** | **7,534** | **960** | **2,278** | **3,961** | **6,453** | **15,686** |
| **Confluence of BT and NFBT at Drake (Jarrett Estimate #76)** | **276** | **14,800** | **14,731** | **14,728** | **2,116** | **4,538** | **7,495** | **11,803** | **26,983** |
| BT at confluence with Cedar Creek | 300 | | 16,632 | 17,624 | 2,693 | 5,582 | 9,048 | 14,020 | 31,273 |
| **BT near Mouth of Canyon (Jarrett Estimate #66)** | **314** | **15,500** | **16,876** | **18,106** | **3,041** | **6,249** | **10,054** | **15,449** | **34,002** |
| BT confluence with Buckhorn | 461 | | 23,957 | 24,406 | 7,174 | 12,838 | 19,051 | 27,437 | 59,360 |
| **BT downstream study limit** | **461** | **19,000** | **23,957** | **24,406** | **7,174** | **12,838** | **19,051** | **27,437** | **59,360** |
| **Headwaters of North Fork Big Thompson (NRCS Estimate)** | **19** | **1,700** | **1,302** | **1,297** | **473** | **804** | **1,154** | **1,588** | **2,954** |
| NFBT upstream of Glen Haven | 26 | | 1,913 | 1,902 | 554 | 975 | 1,432 | 2,010 | 3,870 |
| NFBT at Glen Haven | 51 | | 4,004 | 3,980 | 971 | 1,764 | 2,640 | 3,767 | 7,464 |
| NFBT at confluence with Miller Fork | 69 | | 5,570 | 5,546 | 1,108 | 2,083 | 3,184 | 4,625 | 9,460 |
| **NFBT 4.5 miles above Drake (NRCS Peak Estimation Point)** | **70** | **18,400** | **5,596** | **5,570** | **1,111** | **2,091** | **3,197** | **4,644** | **9,502** |
| **NFBT at Drake (Jarrett Estimate #81)** | **86** | **5,900** | **7,723** | **7,706** | **1,539** | **2,868** | **4,336** | **6,240** | **12,599** |
| Buckorn Creek at confluence with Twin Cabin Gulch | 31 | | 2,412 | 2,395 | 495 | 986 | 1,553 | 2,296 | 4,797 |
| Buckhorn at confluence with Sheep Creek | 43 | | 3,522 | 3,486 | 927 | 1,766 | 2,683 | 3,875 | 7,740 |
| **Buckhorn at Confl. w/ Stove Prarie Creek (Jarrett #106)** | **50** | **4,400** | **4,205** | **4,199** | **1,307** | **2,410** | **3,591** | **5,109** | **9,964** |
| Buckhorn at Fish Creek confluence | 70 | | 6,356 | 6,294 | 2,023 | 3,709 | 5,465 | 7,733 | 14,931 |
| **Buckhorn 3.5 miles above Masonville (NRCS Estimation Point)** | **88** | **11,000** | **8,115** | **7,929** | **2,972** | **5,218** | **7,519** | **10,459** | **19,622** |
| **Buckhorn at Masonville above Redstone Creek (Jarrett #108)** | **97** | **7,700** | **8,962** | **8,676** | **3,574** | **6,178** | **8,834** | **12,198** | **22,587** |
| Buckhorn at confluence with Redstone Creek | 128 | | 10,531 | 10,253 | 3,796 | 6,900 | 10,125 | 14,218 | 27,154 |
| **Buckhorn at County Rd. 24H, CDWR Gage (Jarrett #111)** | **144** | **11,200** | **11,136** | **10,878** | **4,850** | **8,695** | **12,591** | **17,408** | **32,501** |

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 are shown in the next column and were developed by Bob Jarrett, Ayres Associates, the NRCS and the USBR. The next two columns present the calibrated model results for the full 10-day rainfall period and the maximum 24-hour rainfall period, respectively. 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 2013 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 1 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 at three locations for the 10-, 50-, 100-, and 500-year recurrence intervals.

**Figure 3. Peak Discharge Profile for the Big Thompson River**



As shown on Figures 3 through 5, the calibrated 2013 flood model results for the 10-day rainfall period and the maximum 24-hour rainfall period are almost identical. The CN values were increased by 11 on average to produce results similar to the peak discharge estimates from the 2013 flood. When comparing the calibrated model results with the estimated peak discharges there are some locations that match closely and others that differ significantly, as discussed below.

Provided in Appendix C.5 are the Lake Estes Optimization results for the different infiltration methods. There are handwritten notes in Appendix C.5 to identify the key points for each infiltration method. Ultimately, it was decided to stay with the CN method for calibration and development of predictive storm peak discharges.

At Lake Estes, the optimized model results produce a very similar inflow hydrograph to the observed hydrograph as shown in Appendix C.5. The calibrated model discharge from Lake Estes matches the observed discharge exactly because it has been built into the model. Lake Estes was considered to be one of the most reliable peak discharge estimation points in the Big Thompson watershed because stage data were recorded throughout the 10-day storm event and used to develop a full discharge hydrograph. The discharge from Lake Estes also did not exhibit any surges in the peak because any flood waves from upstream dam failures (e.g. Fish Creek) would be attenuated through the reservoir. This is in comparison to the various methods used to estimate a single peak discharge value several days to months after the storm event occurred.

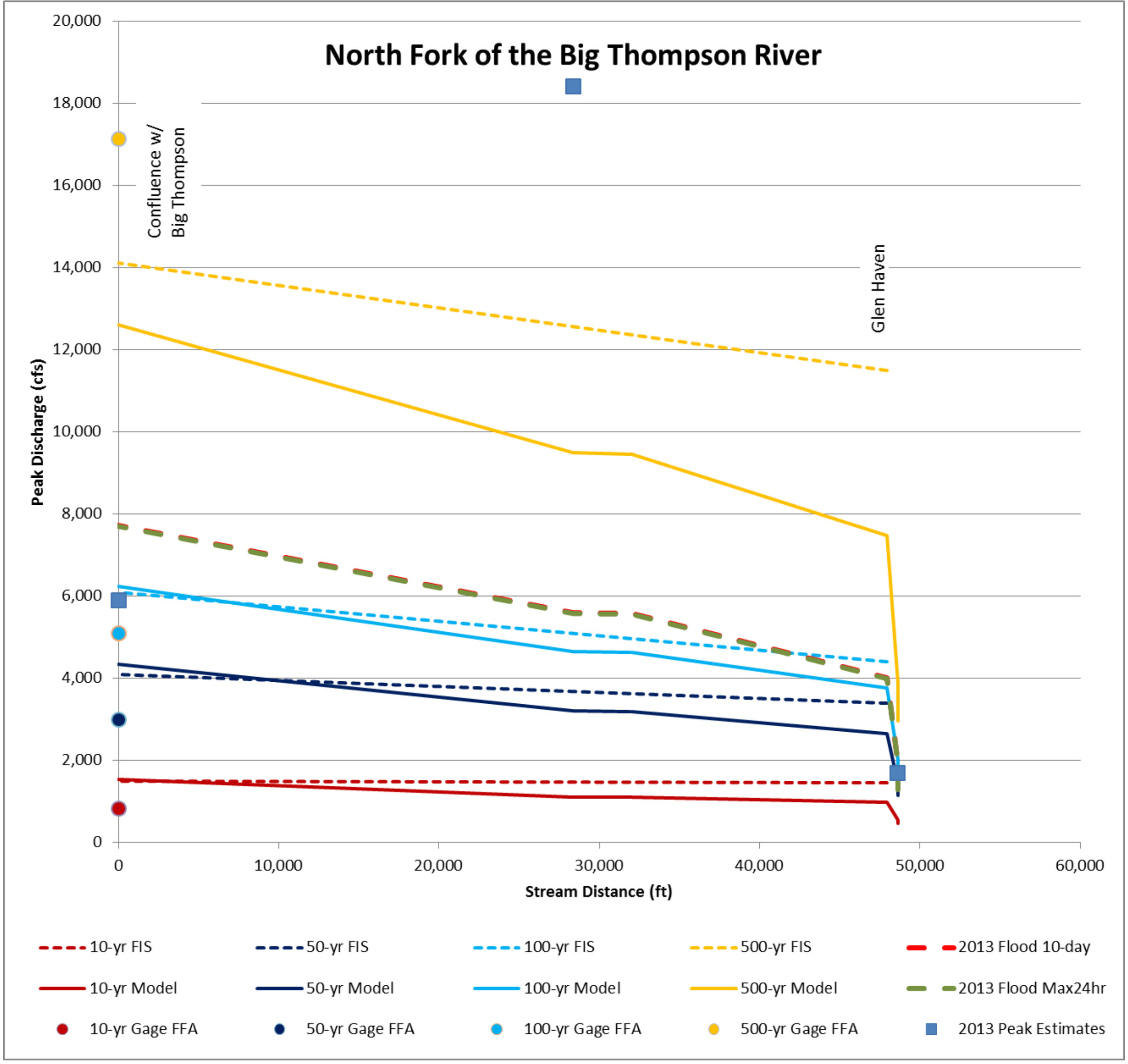
Downstream of Lake Estes, the calibrated model did not match the higher peak discharge estimates provided by Bob Jarrett (6,300cfs vs. 9,300 cfs at Loveland Heights and 7,600 cfs vs. 12,500 cfs at Mountain Shadows Lane). The primary reason the model did not match these peak discharges was because the model calibration in this reach was more heavily weighted to reflect the reliable Lake Estes discharge hydrograph. The relatively limited drainage area contributing runoff downstream of Lake Estes was insufficient to increase the peak discharges from the reservoir enough to match the other two estimates. However, further downstream, below the confluence with the North Fork Big Thompson at Drake, the calibrated model was able to match Bob Jarrett’s estimate of 14,800 cfs within 1 percent.

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.

With this systematic calibration approach in mind, and because the peak discharges at Lake Estes and below Drake closely matched the peak discharge estimates, further attempts to match the two estimates in between would only cause peak discharges further downstream to exceed the estimates at those locations. Something else to consider regarding the two peak discharge estimates between Lake Estes and Drake, is the number of local access bridges in this reach that failed during the 2013 flood event. These local bridges most likely acted as small dams during the flood prior to failing, but once they failed, created a surge in the peak discharge for a short distance downstream. Often these bridges fail in a cascade pattern, increasing the downstream peak discharge with a cumulative effect.

An example of the effect of bridge failures can be seen on Fish Creek, which enters Lake Estes from the south. The NRCS estimated the peak discharge from Fish Creek at 6,900 cfs (442 cfs/sq.mi.). Other tributaries near Fish Creek in Estes Park had peak discharges of 30 to 40 cfs/sq.mi. (Jarrett 2013). Drainage area differences, basin slopes, and even modest differences in rainfall cannot explain these differences in peak discharge (or unit discharge) for these tributaries. Several locations were noted in upper Fish Creek where bridge failures occurred that substantially exacerbated peak discharges. The calibrated rainfall/runoff model for Fish Creek only produced a peak discharge of 2,000 cfs, compared to the NRCS estimate of 6,900 cfs.

**Figure 4. Peak Discharge Profile for the North Fork of the Big Thompson River**



Similarly, the calibrated model discharge of 5,600 cfs (80 cfs/sq.mi.) on the North Fork Big Thompson 4.5 miles upstream of Drake was considerably lower than NRCS peak discharge estimate of 18,400 cfs (263 cfs/sq.mi.). In contrast, the calibrated model produced a peak discharge of 7,700 cfs (90 cfs/sq.mi.) 4.5 miles downstream on the North Fork Big Thompson at Drake, compared to Bob Jarrett's estimate of 5,900 cfs (69 cfs/sq.mi.). The large difference in peak discharge estimates is most likely due to attenuation of debris dam failures as the peak discharge left the relatively narrow canyon near the NRCS estimate location into the wider valley near Drake. The small volume associated with the debris dam failure would be conducive to rapid attenuation. The substantial amount of sediment deposition near Drake is evidence that the velocity of peak flows from the North Fork Big Thompson decreased significantly.

To help provide more perspective, the NRCS peak discharge estimate on the North Fork Big Thompson upstream of Glen Haven was 1,700 cfs (93 cfs/sq.mi.). Since the 2013 rainfall event was not convective, substantial differences in rainfall rates/amounts are not expected. This was verified by reviewing the AWA rainfall data for the North Fork Big Thompson basins. Therefore, it is extremely unlikely that the unit discharge would vary significantly between the North Fork Big Thompson tributaries either. Yet the adjacent tributaries of Fox Creek and West Creek upstream of Glen Haven had NRCS peak discharge estimates of 3,500 cfs (486 cfs/sq.mi.) and 11,000 cfs (477 cfs/sq.mi.). This significant difference in unit discharges is indicative of mechanisms other than just the rainfall/runoff process producing the increased peak discharges.

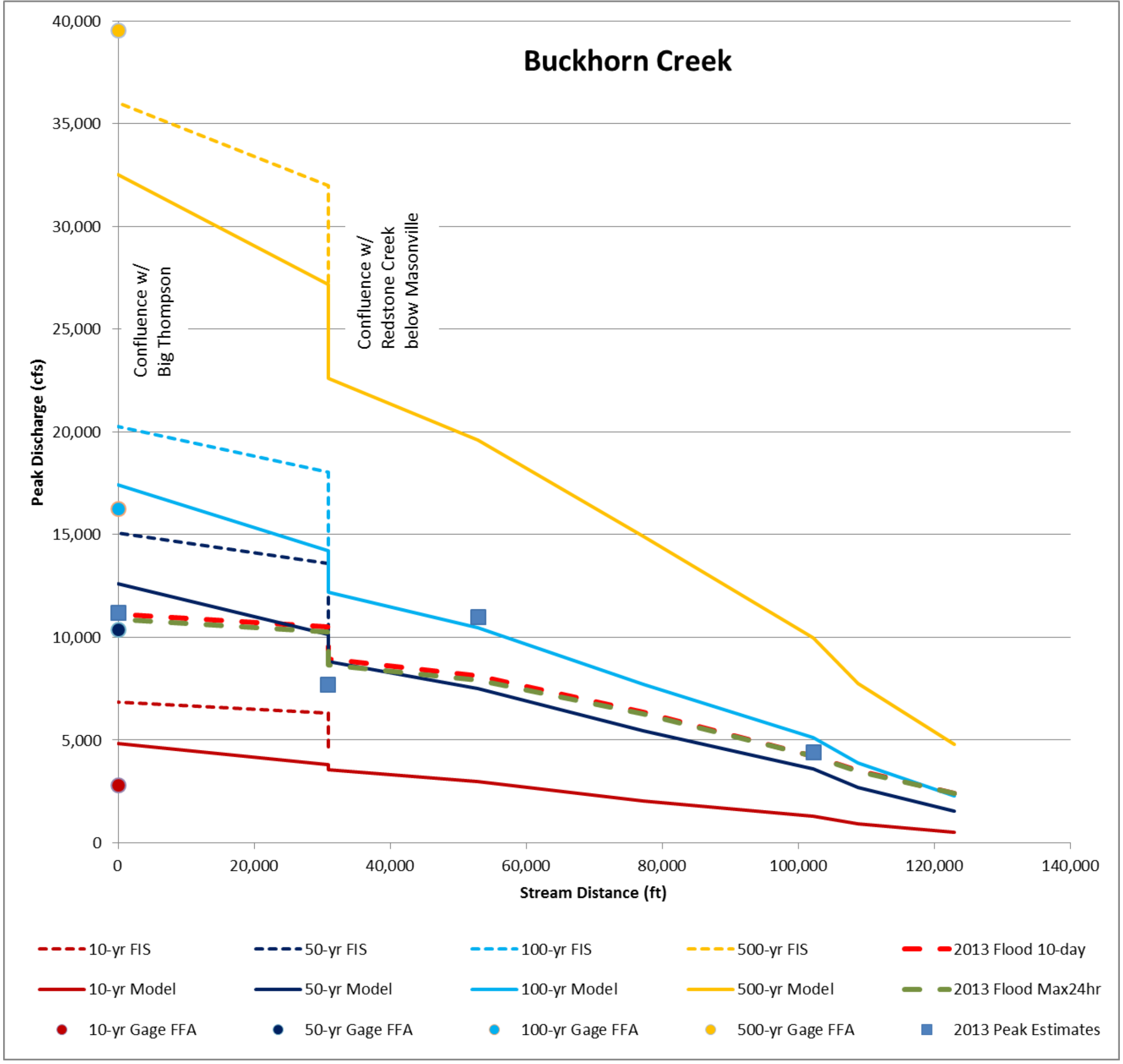
Downstream of Drake, near the mouth of the Canyon, the calibrated model discharge (16,900 cfs) was approximately 9% higher than the estimated peak discharge of 15,500 cfs by Bob Jarrett (well within the 15 to 25 percent range of hydrologic uncertainty associated with the estimates). The model discharge was only 4% higher than the USGS estimate of 16,200 cfs at the mouth of the canyon.

On Buckhorn Creek, approximately 12.5 miles upstream of Masonville, the calibrated model discharge (4,200 cfs) was within approximately 4% of the estimated peak discharge of 4,400 cfs by Bob Jarrett. Nine miles further downstream (approximately 3.5 miles upstream of Masonville), the calibrated model discharge (8,100 cfs) was approximately 26% lower than the NRCS estimate of 11,000 cfs. However, at Masonville above the confluence with Redstone Creek, the calibrated model discharge (9,000 cfs) was approximately 16% higher than the estimate of 7,700 cfs by Bob Jarrett. This fluctuation in peak discharge estimates was mentioned in correspondence with Bob Jarrett where he stated that between his upper site and the NRCS site, he noted extensive woody debris along the channel and several locations where woody debris dams (and subsequent failure) may have increased peak discharge. In addition, he noted at least three major culvert crossings upstream from the NRCS site that likely accumulated woody debris and may have failed, also potentially adding to the peak discharge. As stated in the NRCS report, substantial portions of the upper catchment burned during the High Park Fire in 2012, which most likely increased peak flow during this event. It is estimated that burn areas can produce significantly higher runoff peaks (up to 100 times) until vegetation is re-established (DeBano et.al., 1998 and DeBano et.al., 2005). Burn impacts were not accounted for in the hydrologic models because their impacts typically only last for a few years, but the burn area may have contributed some of the woody debris noted by Bob Jarrett. Therefore, due to the potential of such transitory waves to increase peak discharges over short reaches, the calibrated model appears to fit the upper reaches of Buckhorn Creek fairly well.

Redstone Creek joins Buckhorn Creek just downstream from Masonville. The calibrated model discharge (1,600 cfs) above the confluence was approximately 13% higher than the estimated peak discharge of 1,400 cfs by Bob Jarrett, well within the range of hydrologic uncertainty.

Further downstream on Buckhorn Creek at County Road 24H, near the CDWR stream gage, the calibrated model discharge (11,100 cfs) was within 1% of the estimated peak discharge of 11,200 cfs by Bob Jarrett. The CDWR stream gage recorded stage data during the 2013 flood event with a peak stage of 14.82 feet occurring on September 13, 2013 at 3:15AM. Bob Jarrett noted that the high water marks he measured in the field were within a few tenths of a foot of this elevation. The hydrologic model was also calibrated to match the timing of the peak discharge with the peak stage recorded at the CDWR stream gage, to ensure that the peak discharge at the confluence of Buckhorn Creek and the Big Thompson aligned correctly.

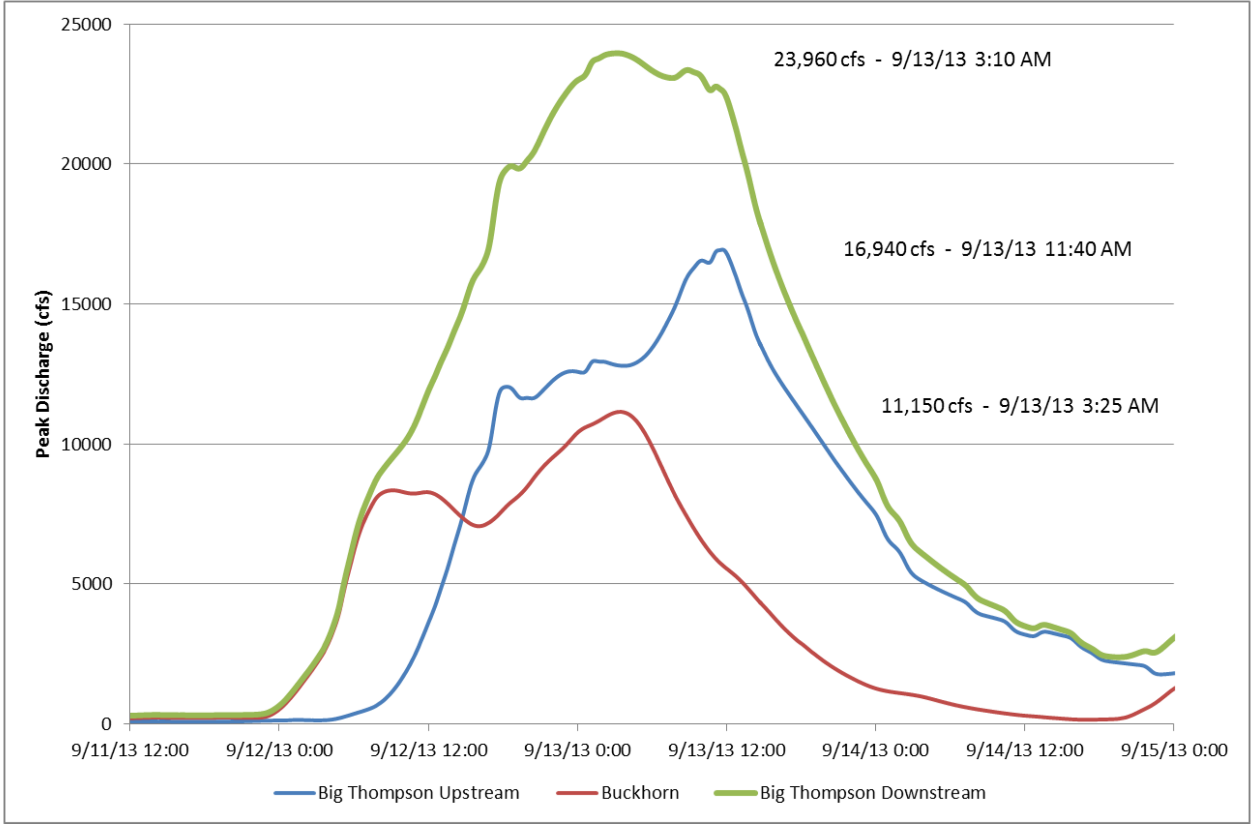
**Figure 5. Peak Discharge Profile for Buckhorn Creek**



At the confluence of the Big Thompson River and Buckhorn Creek, the calibrated model discharge (24,000 cfs) was approximately 26% higher than the estimated peak discharge of 19,000 cfs determined by Ayres Associates (at the upper limit of the 15% to 25% range of hydrologic uncertainty associated with the estimates). Upstream of the confluence on the Big

Thompson River, the calibrated model peak discharge of 16,900 cfs was only 9% greater than the estimated peak discharge of 15,500 cfs. On Buckhorn Creek, the calibrated model peak discharge (11,100 cfs) was within 1% of the estimated peak discharge of 11,200 cfs and the timing of the peak discharge matched the CDWR stream gage. Therefore, the initial thought was that the calibrated model peak discharge on the Big Thompson River was occurring too early, causing the hydrographs to overlap too much and resulting in a higher combined peak discharge downstream. The upstream hydrographs and the combined downstream hydrograph are shown in Figure 6.

**Figure 6. Peak Discharge Hydrographs for Big Thompson River and Buckhorn Creek**



The calibrated model peak discharge on Buckhorn Creek occurred approximately 8 hours before the peak discharge on the Big Thompson River upstream of the confluence. However, due to the shape of the hydrographs with multiple peaks over the course of the long duration storm, the combined peak discharge downstream was higher than the estimated peak discharge by 26%. In order to check the timing of the peak discharge on the Big Thompson River, the travel time from Lake Estes down to the confluence with Buckhorn Creek (25.5 miles) was determined to be approximately 3.75 hours, with average channel velocities ranging between 9 and 13 feet per second. The peak discharge from Lake Estes occurred at approximately 8:15 AM. When accounting for the travel time determined above, the peak would reach the confluence with Buckhorn Creek at noon. Considering that the peak discharge from the North Fork Big Thompson occurs earlier than the peak from Lake Estes, the combined peak discharge occurring slightly earlier than noon (at 11:40 AM) seems appropriate. Figure 6 above shows that the modeled combined flow at the confluence of the Big Thompson and Buckhorn Creek was in the 23,000 cfs to 24,000 cfs range for approximately 12 hours and therefore would not have been very sensitive to changes in timing from the two separate hydrographs. For example, the hydrograph for the Big Thompson River would need to be delayed by an additional

15 hours in order for the combined peak discharge to be only 19,000 cfs. Therefore, the timing of the peak discharges is generally viewed as representative for the 2013 flood Event.

Another possible explanation for the difference between the calibrated model peak discharge and the estimated peak discharge is the attenuation that occurs on the Big Thompson River as it leaves the steep Canyon Narrows and flattens out for the last 3.5 miles to the confluence with Buckhorn Creek. This reach of channel also includes the Loveland Water Storage Reservoir, several offline gravel pit ponds, and at least five large irrigation ditch head gates which would result in losses from the river. All of these factors may have reduced the peak discharge on the Big Thompson River prior to the confluence with Buckhorn Creek. However, for flood control planning purposes, these diversion losses are assumed negligible and they were not included in the hydrologic model to ensure that the predictive model provides appropriately conservative results. Therefore, the calibration results were assumed adequate to proceed with the analysis of the predictive storms, although results would continue to be evaluated for reasonableness.

The calibrated model results for the NOAA 24-hour predictive storms are shown on the profile plots in Figures 3 through 5. The predictive model peak discharges for the various return periods were compared to the results from the updated flood frequency analysis for the Big Thompson River, North Fork Big Thompson River and Buckhorn Creek as well as to current regulatory discharges. The model results compared well with the existing regulatory flows and the updated flood-frequency analysis (FFA).

On the Big Thompson River (Figure 3), it can be seen that at the mouth of the canyon, the model results closely matched the FFA results for the 10-year (5%) and 500-year (1%) storms. The model results were slightly higher than the FFA results for the 50-year (12%) and 100-year (14%) storms. However, it should be noted that the FFA results by Ayres which are presented in this report used only the station skew as opposed to a weighted skew (station skew and regional skew). It was decided that only the station skew would be used based on review comments provided on a draft version of the report. A separate FFA prepared by the NRCS at the Mouth of Canyon which used a weighted skew (included the 2013 peak discharge estimate for 11 stations in the regional skew coefficient) resulted in a 50-year peak discharge of 9,530 cfs and a 100-year peak discharge of 14,500 cfs. The calibrated model peak discharges were only 5% and 7% higher than these FFA results, respectively.

Upstream of Lake Estes, the predictive model peak discharges are well above the Effective FIS values with the exception of the 10-year storm, which is most likely because the smaller design storms are driven by combined rain and snowmelt events as opposed to just a rainfall event. The 10-year predictive peak discharges are less than the effective FIS peak discharges from Lake Estes down to the mouth of the canyon, again probably due to combined rain and snowmelt events. The 50-year and 100-year predictive model peak discharges tend to straddle the Effective FIS peak discharges within 20% from Lake Estes to the mouth of the canyon. The 500-year predictive peak discharges are higher than the effective FIS peak discharges from Lake Estes to Drake but are closer near the mouth of the canyon. Downstream of the confluence with Buckhorn Creek, the predictive model peak discharges are significantly higher than the Effective FIS peak discharges. These predictive model estimates are provisional and subject to change based on the anticipated extension of the NOAA Atlas 2 rainfall depth-area reduction curves beyond 400-square miles.

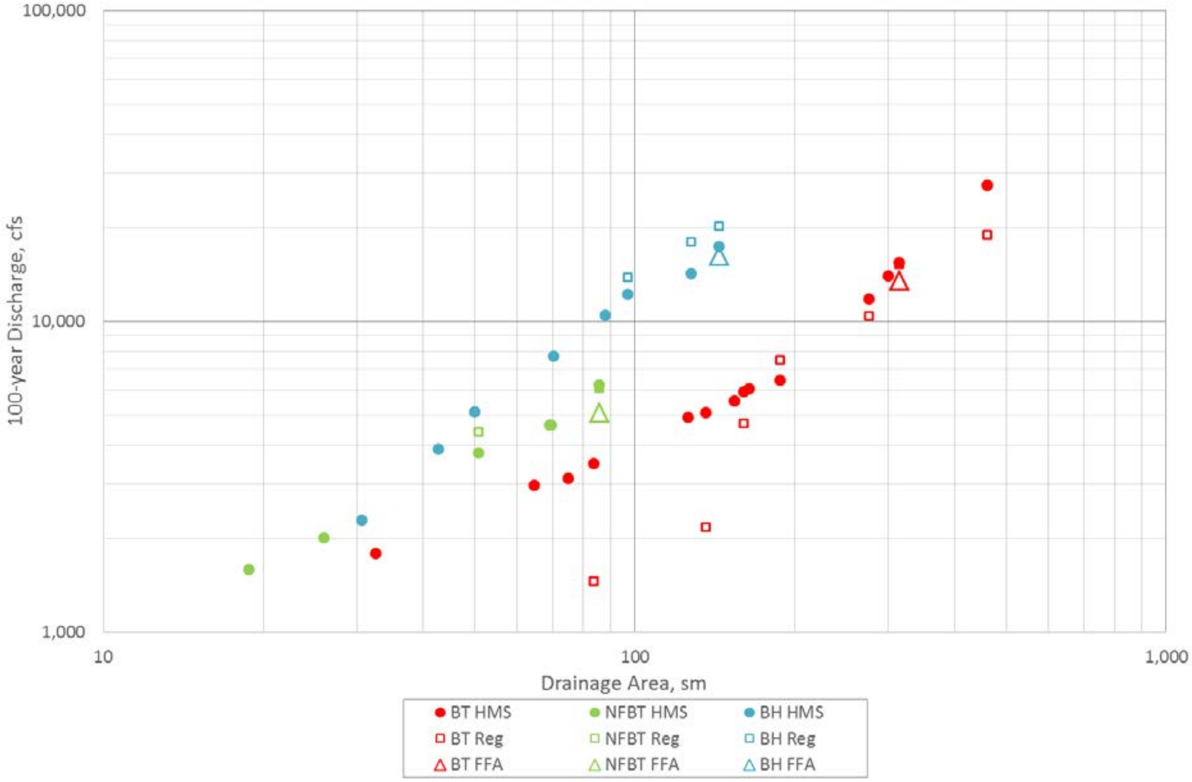
On the North Fork Big Thompson (Figure 4), the predictive peak discharges are approximately equal to the Effective FIS discharges at Drake for the 10-year, 50-year, and 100-year storms. For the 500-year storm, the predictive peak discharge is approximately 11% lower than the

Effective FIS result at Drake. Upstream in Glen Haven, the predictive model results are less than the Effective FIS results for all design storms by approximately 15% to 30%. For the 10-year storm, this may be due to combined rain/snowmelt events. When compared to the FFA results prepared by Ayres for the gage at Drake (52 years), the predictive model peaks were higher than the FFA 10-year (87%), 50-year (45%), and 100-year (22%) results. The predictive model 500-year peak discharge was approximately 26% less than the FFA results. However, when comparing against the FFA prepared by the NRCS (weighted skew), the predictive peak discharges are only 15% higher than the FFA results for the 100-year storm.

On Buckhorn Creek (Figure 5), the calibrated model produces peak discharges approximately 10% to 30% lower than the Effective FIS discharges. However, it should be noted that the Effective FIS discharges were based on regression equations for above and below 7,500 feet with the most conservative value being selected. Another interesting point to note is that the 100-year discharge on Buckhorn Creek from the Effective FIS is 20,244 cfs, however the combined Buckhorn and Big Thompson 100-year regulatory discharge downstream is only 19,000 cfs. The updated FFA for Buckhorn Creek resulted in a 100-year peak discharge of 16,200 cfs and a 500-year peak discharge of 39,500 cfs (greater than the infamous 1976 Big Thompson Flood). As noted previously though, the 5% and 95% confidence limits are extremely wide for the 100-year peak discharge (6,500 cfs to 62,100 cfs). The 100-year predictive peak discharge was within 7% of the updated FFA results.

The predictive peak discharges were also compared on a unit discharge basis (in cfs per square mile of watershed area) against flood frequency results and current regulatory discharges to get a sense for how the different sources of discharge estimates compare. This information is shown in Figure 7. Below Figure 7 is a summary of the abbreviations used in the figure legend.

**Figure 7. Comparison of 100-year Unit Discharges in the Big Thompson River, North Fork of Big Thompson and Buckhorn Creek**



Watershed (color):
BT = Big Thompson River (red)
NFBT = N. Fork Big Thompson River (green)
BH = Buckhorn Creek (blue)

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

The following observations can be made from Figure 7:

1. Compared to the modeled discharges, more scatter is associated with the current regulatory discharges, particularly on the Big Thompson River.
2. The regulatory discharges for the Big Thompson River upstream of Lake Estes appear low relative to the predictive model results.
3. Current 100-year regulatory discharges for Buckhorn Creek appear slightly high compared to the flood frequency results and the predictive model results. The Buckhorn Creek gage only had 30 years of data but included three historic peaks of around 10,000 cfs. The FFA is problematic as indicated by the large 5% and 95% confidence limits (6,500 to 62,100 cfs) for the 100-year peak discharge and is therefore not being relied on as a point of calibration.

## 4.0 CONCLUSIONS AND RECOMMENDATIONS

This report documents a hydrologic investigation of the Big Thompson River 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 6 below. Comparisons of the 2013 Effective FIS discharges with the flood discharge estimates indicate that the September 2013 flood ranged from a 50-year event to greater than a 500-year event in some locations.

An updated flood frequency analysis was also performed as part of this study to reflect annual peak flows that have occurred since prior gage analyses, including estimated peak discharges from the 2013 Flood. Backup information associated with the gage analyses for the Big Thompson gage at the mouth of the canyon is provided in Appendix B. Table 6 below shows a summary of the updated flood frequency analysis for the Big Thompson River. The flood frequency analysis results indicate lower peak discharges than the current regulatory peak discharges. A flood frequency analysis was conducted on the stream gage record for Buckhorn Creek also. However, due to the short period of record and the extremely wide confidence limits on the 100-year and 500-year peak discharge estimates, this gage was not relied on as a point of calibration.

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 10-day period around the 2013 flood event. 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. 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 based on the maximum 24-hour period of rainfall from the 2013 flood event. Once the curve numbers were adjusted to provide a best fit with the 2013 peak discharge estimates, the design rainfall was applied. The results of this predictive model are summarized in Table 4 and in Appendix C.

**Table 6. 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 (years)** |
| BT at confluence with Beaver Brook | 980 | 1,340 | 1,460 | 1,760 | | | | | | |
| BT at confluence with Black Canyon Creek | 1,510 | 1,990 | 2,180 | 2,600 | | | | | | |
| Lake Estes (Olympus Dam) | | | | | | | | | 5,327 | > 100 Year |
| BT at confluence with Dry Gulch below Lake Estes | 2,250 | 3,800 | 4,700 | 7,200 | | | | | | |
| BT at Loveland Heights | | | | | | | | | 9,300 | > 500 Year |
| BT at Mountain Shadows Lane above Drake | 2,750 | 5,700 | 7,500 | 13,600 | | | | | 12,500 | 500 Year |
| Confluence of BT and NFBT at Drake | 3,700 | 7,850 | 10,400 | 19,200 | | | | | 14,800 | 100-500 Yr |
| BT at Mouth of Canyon | 3,800 | 10,500 | 15,300 | 37,000 | 3,208 | 8,942 | 13,533 | 34,145 | 15,500 | 100 Year |
| BT confluence with Buckhorn | 4,700 | 12,300 | 19,000 | 44,000 | | | | | 19,000 | 100 Year |
| NFBT at Glen Haven | 1,450 | 3,400 | 4,400 | 11,500 | | | | | | |
| NFBT 4.5 miles above Drake (NRCS) | | | | | | | | | 18,400 | > 500 Year |
| NFBT at Drake | 1,500 | 4,100 | 6,100 | 14,100 | 823 | 2,987 | 5,096 | 17,122 | 5,900 | 100 Year |
| Buckhorn Creek At Stove Prairie Creek | | | | | | | | | 4,400 | N/A |
| Buckhorn 3.5 miles above Masonville | | | | | | | | | 11,000 | N/A |
| Buckhorn at Masonville above Redstone Ck. | 4,674 | 10,321 | 13,862 | 24,000 | | | | | 7,700 | 10-50 Yr |
| Buckhorn at confluence with Redstone Creek | 6,321 | 13,593 | 18,059 | 32,000 | | | | | | |
| Buckhorn upstream of confluence with BT | 6,844 | 15,090 | 20,244 | 36,000 | 2,807 | 10,362 | 16,233 | 39,513 | 11,200 | 10-50 Yr |

For the Big Thompson River at the mouth of the canyon, the predictive model results matched the FFA results for the 10-year (5%), 50-year (12%), 100-year (14%) and 500-year (1%) storms. A separate FFA prepared by the NRCS at the Mouth of Canyon, which included the 2013 peak discharge estimates in the weighted skew coefficient, resulted in a 50-year peak discharge of 9,530 cfs and a 100-year peak discharge of 14,500 cfs. The calibrated model peak discharges were only 5% and 7% higher than these FFA results, respectively.

Table 7 compares the predictive peak discharges from this modeling effort to current regulatory discharges for the 100-year event. Since the rainfall/runoff model results are relatively consistent with the updated flood frequency analysis, because they are more consistent in terms of unit discharge than current regulatory flows in Big Thompson upstream of Lake Estes, in the North Fork of the Big Thompson, and in Buckhorn Creek, and because the current model provides peak discharge information throughout the watershed, it is recommended that the model results be considered for adoption as the updated regulatory peak discharges.

**Table 7. 100-year Modeled Peak Flows Compared to Current Regulatory Discharges**

| Location | Current Regulatory Discharge (cfs) | Modeled Discharge (cfs) | Percent Difference |
|---|---|---|---|
| Big Thompson above Lake Estes | 2,180 | 5,074 | +133% |
| Big Thompson below Lake Estes | 4,700 | 5,942 | +26% |
| Big Thompson above Drake | 7,500 | 6,450 | -14% |
| Big Thompson below Drake | 10,400 | 11,800 | +13% |
| Big Thompson at Mouth of Canyon | 15,300 | 15,450 | +1% |
| Big Thompson at Buckhorn Creek [1] | 19,000 | 27,440 [1] | +44% [1] |
| North Fork BT at Glen Haven | 4,400 | 3,770 | -14% |
| North Fork BT at Drake | 6,100 | 6,240 | +2% |
| Buckhorn Creek at Masonville | 13,862 | 12,200 | -12% |
| Buckhorn Creek at Confl. with Redstone Creek | 18,059 | 14,220 | -21% |
| Buckhorn Creek at County Road 24H, CDWR Gage | 20,244 | 17,410 | -14% |

[1] Provisional and subject to change based on future extension of NOAA Atlas 2 rainfall area reduction curves.

Based on the modeled discharges for the return periods analyzed, as shown in Table 8 below, the peak discharges observed along the Big Thompson River during the September 2013 flood event had an estimated recurrence interval ranging from approximately 4 percent annual peak discharge to greater than the 0.2 percent annual peak discharge, or from a 25-year to greater than a 500-year storm event.

**Table 8. Estimate of September 2013 Peak Discharge Recurrence Interval**

| Location | Estimated Discharge (cfs) | Annual Chance Peak Discharge (cfs) | | | | | Estimated Recurrence Interval (yr) |
|---|---|---|---|---|---|---|---|
| | | 10% | 4% | 2% | 1% | 0.2% | |
| Lake Estes | 5,330 | 850 | 1,980 | 3,420 | 5,550 | 13,370 | ~ 100 |
| Big Thompson at Loveland Heights | 9,300 | 940 | 2,180 | 3,750 | 6,060 | 14,520 | 100 to 500 |
| Big Thompson above Drake | 12,500 | 960 | 2,280 | 3,960 | 6,450 | 15,690 | 100 to 500 |
| Big Thompson below Drake | 14,800 | 2,120 | 4,540 | 7,500 | 11,800 | 26,990 | 100 to 500 |
| Big Thompson at Mouth of Canyon | 15,500 | 3,040 | 6,250 | 10,050 | 15,450 | 34,000 | ~ 100 |
| Big Thompson at Buckhorn Creek [1] | 19,000 | 7,170 | 12,840 | 19,050 | 27,440 | 59,360 | ~50 [1] |
| North Fork BT Headwaters | 1,700 | 470 | 800 | 1,150 | 1,590 | 2,950 | ~100 |
| North Fork BT 4.5 miles above Drake | 18,400 | 1,100 | 2,090 | 3,200 | 4,640 | 9,500 | > 500 |
| North Fork BT at Drake | 5,900 | 1,540 | 2,870 | 4,340 | 6,240 | 12,600 | ~ 100 |
| Buckhorn at Stove Prairie Creek | 4,400 | 1,310 | 2,410 | 3,590 | 5,110 | 9,960 | 50 to 100 |
| Buckhorn 3.5 miles above Masonville | 11,000 | 2,970 | 5,220 | 7,520 | 10,460 | 19,620 | ~ 100 |
| Buckhorn above Redstone Creek | 7,700 | 3,570 | 6,180 | 8,830 | 12,200 | 22,590 | 25 to 50 |
| Buckhorn at County Road 24H | 11,200 | 4,850 | 8,700 | 12,590 | 17,410 | 32,500 | 25 to 50 |
| Redstone Creek above Masonville | 1,400 | 560 | 1,210 | 1,930 | 2,880 | 6,060 | 25 to 50 |

[1] Provisional and subject to change based on future extension of NOAA Atlas 2 rainfall area reduction curves.

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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

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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, 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.

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.

**Interstate & Federal • Watershed & Flood Protection • Stream & Lake Protection • Finance**
**Water Information • Water Conservation & Drought Planning • Water Supply Planning**

# 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, 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.

# Appendix B
# Flood Frequency Analysis at Stream Flow Gages

# Bulletin 17B Frequency Analysis

# Big Thompson River at Mouth of Canyon near Drake

## USGS Gage 06738000 (1888 – 2007 broken)

## CDWR Gage BTCANYCO (1991 – 2012)

```
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Bulletin 17B Frequency Analysis
    29 Jul 2014   11:23 AM
-------------------------------


--- Input Data ---

Analysis Name: 06738000 BT-MOUTH ALL2013 STA
Description: USGS 06738000 BIG THOMPSON RIVER AT MOUTH OF CANYON NR DRAKE, CO (Using Station Skew
Only)

Data Set Name: BT RIVER-MO ALL 2013
DSS File Name: H:\32-176904 Big Thompson
Hydrology\Six_Rivers_HEC-SSP_FFA_Results\Six_Rivers\Six_Rivers.dss
DSS Pathname: /BIG THOMPSON RIVER/MOUTH OF CANYON NR DRAKE, CO/FLOW-ANNUAL
PEAK/01jan1900/IR-CENTURY/Save Data As: BT RIVER-MO ALL/

Report File Name: H:\32-176904 Big Thompson
Hydrology\Six_Rivers_HEC-SSP_FFA_Results\Six_Rivers\Bulletin17bResults\06738000_BT-MOUTH_ALL2013_
STA\06738000_BT-MOUTH_ALL2013_STA.rpt
XML File Name: H:\32-176904 Big Thompson
Hydrology\Six_Rivers_HEC-SSP_FFA_Results\Six_Rivers\Bulletin17bResults\06738000_BT-MOUTH_ALL2013_
STA\06738000_BT-MOUTH_ALL2013_STA.xml

Start Date:
End Date:

Skew Option: Use Station Skew
Regional Skew: 0.643
Regional Skew MSE: 0.12

Plotting Position Type: Hazen

Upper Confidence Level: 0.05
Lower Confidence Level: 0.95
Use High Outlier Threshold
High Outlier Threshold: 13791.0

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

Display ordinate values using 1 digits in fraction part of value

--- End of Input Data ---


--- Preliminary Results ---

<< Plotting Positions >>
BT RIVER-MO ALL 2013
-------------------------------------------------------------------
|     Events Analyzed        |           Ordered Events            |
|                   FLOW     |             Water        FLOW   Hazen |
| Day Mon Year       CFS     |   Rank      Year          CFS  Plot Pos |
|----------------------------|-------------------------------------|
|   18 Jun 1888       889.0  |     1       1976    31,200.0*   0.53   |
|   30 Jul 1895     1,900.0  |     2       2013    15,500.0*   1.60   |
|   30 May 1896     1,010.0  |     3       1945     7,600.0    2.66   |
|   11 Jun 1897     1,060.0  |     4       1908     6,620.0    3.72   |
|   11 Jul 1898     1,360.0  |     5       1980     6,150.0    4.79   |
|   20 Jun 1899     1,920.0  |     6       1938     5,600.0    5.85   |
|   10 Jun 1902       773.0  |     7       1941     4,690.0    6.91   |
|   18 Jun 1903     1,300.0  |     8       1942     3,730.0    7.98   |
|   07 Jul 1908     6,620.0  |     9       1951     3,530.0    9.04   |
|   20 Jun 1909     1,180.0  |    10       1949     3,330.0   10.11   |
|   03 Jun 1910       630.0  |    11       1995     2,740.0   11.17   |
|   18 Jun 1911       710.0  |    12       1999     2,460.0   12.23   |
|   28 Jun 1927     1,060.0  |    13       1947     2,320.0   13.30   |
|   31 May 1928     1,800.0  |    14       1983     2,250.0   14.36   |
|   28 Jul 1929     1,600.0  |    15       1965     2,220.0   15.43   |
|   14 Aug 1930     1,590.0  |    16       1957     2,040.0   16.49   |
|   07 Jun 1931     1,190.0  |    17       1899     1,920.0   17.55   |
```

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|  28 Jun 1932       928.0  |   18      1895     1,900.0   18.62    |
|  14 Jun 1933     1,460.0  |   19      1969     1,800.0   19.68    |
|  01 Sep 1938     5,600.0  |   20      1928     1,800.0   20.74    |
|  31 May 1939       923.0  |   21      1946     1,680.0   21.81    |
|  02 Jun 1940       839.0  |   22      1978     1,670.0   22.87    |
|  22 Jun 1941     4,690.0  |   23      1929     1,600.0   23.94    |
|  07 Jun 1942     3,730.0  |   24      1930     1,590.0   25.00    |
|  23 Jun 1943     1,330.0  |   25      1953     1,500.0   26.06    |
|  11 Jun 1944     1,260.0  |   26      1952     1,500.0   27.13    |
|  19 Jul 1945     7,600.0  |   27      1933     1,460.0   28.19    |
|  18 Jul 1946     1,680.0  |   28      1979     1,450.0   29.26    |
|  21 Jun 1947     2,320.0  |   29      1898     1,360.0   30.32    |
|  03 Jun 1948     1,300.0  |   30      1943     1,330.0   31.38    |
|  04 Jun 1949     3,330.0  |   31      1948     1,300.0   32.45    |
|  03 Aug 1951     3,530.0  |   32      1903     1,300.0   33.51    |
|  07 Jun 1952     1,500.0  |   33      1944     1,260.0   34.57    |
|  14 Jun 1953     1,500.0  |   34      1982     1,220.0   35.64    |
|  21 May 1954       390.0  |   35      2010     1,200.0   36.70    |
|  24 Jul 1955       495.0  |   36      2003     1,190.0   37.77    |
|  03 Jun 1956       608.0  |   37      1931     1,190.0   38.83    |
|  09 May 1957     2,040.0  |   38      1973     1,180.0   39.89    |
|  27 May 1958       900.0  |   39      1909     1,180.0   40.96    |
|  21 Jun 1959       680.0  |   40      1997     1,170.0   42.02    |
|  18 Jun 1960       504.0  |   41      1961     1,140.0   43.09    |
|  03 Jun 1961     1,140.0  |   42      1927     1,060.0   44.15    |
|  02 Jul 1962       735.0  |   43      1897     1,060.0   45.21    |
|  16 Jun 1963       610.0  |   44      2011     1,050.0   46.28    |
|  21 May 1964       274.0  |   45      1984     1,030.0   47.34    |
|  16 Jun 1965     2,220.0  |   46      1896     1,010.0   48.40    |
|  20 Jul 1966       840.0  |   47      1986     1,000.0   49.47    |
|  21 Jun 1967       544.0  |   48      1932       928.0   50.53    |
|  21 Jun 1968       517.0  |   49      2008       923.0   51.60    |
|  07 May 1969     1,800.0  |   50      1939       923.0   52.66    |
|  24 Jun 1970       715.0  |   51      1958       900.0   53.72    |
|  26 Jun 1971       815.0  |   52      1888       889.0   54.79    |
|  15 Jun 1972       492.0  |   53      1991       842.0   55.85    |
|  27 Jun 1973     1,180.0  |   54      1966       840.0   56.91    |
|  13 Jul 1974       660.0  |   55      1940       839.0   57.98    |
|  03 Jul 1975       560.0  |   56      1971       815.0   59.04    |
|  31 Jul 1976    31,200.0  |   57      1996       814.0   60.11    |
|  24 Jul 1977       262.0  |   58      1902       773.0   61.17    |
|  17 May 1978     1,670.0  |   59      1993       738.0   62.23    |
|  15 Jun 1979     1,450.0  |   60      1987       738.0   63.30    |
|  30 Apr 1980     6,150.0  |   61      1962       735.0   64.36    |
|  12 Jul 1981       419.0  |   62      1988       730.0   65.43    |
|  13 Sep 1982     1,220.0  |   63      1970       715.0   66.49    |
|  20 Jun 1983     2,250.0  |   64      1911       710.0   67.55    |
|  02 Jul 1984     1,030.0  |   65      2012       708.0   68.62    |
|  09 Jun 1985       708.0  |   66      1985       708.0   69.68    |
|  06 Jul 1986     1,000.0  |   67      1998       701.0   70.74    |
|  30 Apr 1987       738.0  |   68      2004       694.0   71.81    |
|  18 Jun 1988       730.0  |   69      1959       680.0   72.87    |
|  20 Jun 1989       615.0  |   70      1974       660.0   73.94    |
|  13 Jun 1990       564.0  |   71      1910       630.0   75.00    |
|  12 Jun 1991       842.0  |   72      1989       615.0   76.06    |
|  16 May 1992       386.0  |   73      1963       610.0   77.13    |
|  18 Jun 1993       738.0  |   74      2005       609.0   78.19    |
|  14 May 1994       244.0  |   75      1956       608.0   79.26    |
|  30 May 1995     2,740.0  |   76      1990       564.0   80.32    |
|  02 Jul 1996       814.0  |   77      1975       560.0   81.38    |
|  09 Jun 1997     1,170.0  |   78      1967       544.0   82.45    |
|  12 Jul 1998       701.0  |   79      2000       532.0   83.51    |
|  30 Apr 1999     2,460.0  |   80      1968       517.0   84.57    |
|  30 May 2000       532.0  |   81      2009       507.0   85.64    |
|  18 May 2001       440.0  |   82      1960       504.0   86.70    |
|  31 May 2002       266.0  |   83      1955       495.0   87.77    |
|  31 May 2003     1,190.0  |   84      1972       492.0   88.83    |
|  25 Jul 2004       694.0  |   85      2006       456.0   89.89    |
|  03 Jun 2005       609.0  |   86      2001       440.0   90.96    |
|  20 May 2006       456.0  |   87      1981       419.0   92.02    |
|  29 May 2007       338.0  |   88      1954       390.0   93.09    |
|  05 Jun 2008       923.0  |   89      1992       386.0   94.15    |
|  26 Jun 2009       507.0  |   90      2007       338.0   95.21    |
|  12 Jun 2010     1,200.0  |   91      1964       274.0   96.28    |
```

```
|  07 Jun 2011     1,050.0  |   92      2002       266.0   97.34   |
|  07 Jul 2012       708.0  |   93      1977       262.0   98.40   |
|  13 Sep 2013    15,500.0  |   94      1994       244.0   99.47   |
|---------------------------|---------------------------------------|
                                                          * Outlier



<< Skew Weighting >>
-----------------------------------------------------------------
Based on 94 events, mean-square error of station skew =     0.174
Mean-square error of regional skew =                         0.12
-----------------------------------------------------------------



<< Frequency Curve >>
BT RIVER-MO ALL 2013
-------------------------------------------------------------------
|  Computed    Expected   |   Percent    |    Confidence Limits    |
|    Curve    Probability |   Chance     |        0.05        0.95 |
|        FLOW, CFS        | Exceedance   |        FLOW, CFS        |
|-------------------------|--------------|-------------------------|
|    43,287.9    51,678.6 |       0.2    |     73,371.0    28,471.7 |
|    24,574.1    27,903.8 |       0.5    |     38,689.6    17,112.2 |
|    15,873.2    17,427.6 |       1.0    |     23,631.0    11,539.7 |
|    10,153.1    10,845.7 |       2.0    |     14,294.4     7,702.7 |
|     5,509.6     5,713.3 |       5.0    |      7,213.6     4,414.3 |
|     3,391.5     3,464.8 |      10.0    |      4,215.2     2,821.8 |
|     2,022.3     2,042.2 |      20.0    |      2,403.0     1,733.2 |
|       921.2       921.2 |      50.0    |      1,063.7       793.9 |
|       533.7       531.7 |      80.0    |        625.4       446.0 |
|       435.9       433.4 |      90.0    |        516.5       358.1 |
|       382.6       379.6 |      95.0    |        457.1       310.5 |
|       322.9       320.0 |      99.0    |        390.3       257.7 |
|-------------------------|--------------|-------------------------|


<< Systematic Statistics >>
BT RIVER-MO ALL 2013
------------------------------------------------------------------
|        Log Transform:        |                                |
|          FLOW, CFS           |        Number of Events        |
|------------------------------|--------------------------------|
|  Mean                3.037   |  Historic Events           0   |
|  Standard Dev        0.368   |  High Outliers          0      |
|  Station Skew        1.220   |  Low Outliers           0      |
|  Regional Skew       0.643   |  Zero Events            0      |
|  Weighted Skew       0.879   |  Missing Events         0      |
|  Adopted Skew        1.220   |  Systematic Events        94   |
|------------------------------|--------------------------------|

--- End of Preliminary Results ---




-----------------------
<< High Outlier Test >>
-----------------------
 Based on 94 events, 10 percent outlier test deviate K(N) = 2.996
                     Computed high outlier test value = 13,791.04

     2 high outlier(s) identified above input threshold of 13,791

   * * * * * * * * * * * * * * * * * * * * * * * * * * * * * *
   * 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 2 high outlier(s)


<< Systematic Statistics >>
```

```
BT RIVER-MO ALL 2013
----------------------------------------------------------------
|        Log Transform:          |                              |
|          FLOW, CFS             |       Number of Events       |
|--------------------------------|------------------------------|
|  Mean                  3.030   |  Historic Events          0  |
|  Standard Dev          0.355   |  High Outliers         2     |
|  Station Skew          1.124   |  Low Outliers          0     |
|  Regional Skew         0.643   |  Zero Events           0     |
|  Weighted Skew         0.879   |  Missing Events        0     |
|  Adopted Skew          1.220   |  Systematic Events       94  |
|                                |  Historic Period        126  |
|--------------------------------|------------------------------|


----------------------
<< Low Outlier Test >>
----------------------
Based on 126 events, 10 percent outlier test deviate K(N) = 3.095
                          Computed low outlier test value = 85.34

            0 low outlier(s) identified below test value of 85.34




--- Final Results ---

<< Plotting Positions >>
BT RIVER-MO ALL 2013
--------------------------------------------------------------------
|     Events Analyzed        |            Ordered Events            |
|                     FLOW   |               Water        FLOW   Hazen |
| Day Mon Year         CFS   |   Rank        Year         CFS  Plot Pos |
|----------------------------|--------------------------------------|
|  18 Jun 1888       889.0  |    1       1976    31,200.0*   0.40   |
|  30 Jul 1895     1,900.0  |    2       2013    15,500.0*   1.19   |
|  30 May 1896     1,010.0  |    3       1945     7,600.0    2.12   |
|  11 Jun 1897     1,060.0  |    4       1908     6,620.0    3.19   |
|  11 Jul 1898     1,360.0  |    5       1980     6,150.0    4.26   |
|  20 Jun 1899     1,920.0  |    6       1938     5,600.0    5.33   |
|  10 Jun 1902       773.0  |    7       1941     4,690.0    6.40   |
|  18 Jun 1903     1,300.0  |    8       1942     3,730.0    7.47   |
|  07 Jul 1908     6,620.0  |    9       1951     3,530.0    8.54   |
|  20 Jun 1909     1,180.0  |   10       1949     3,330.0    9.61   |
|  03 Jun 1910       630.0  |   11       1995     2,740.0   10.68   |
|  18 Jun 1911       710.0  |   12       1999     2,460.0   11.75   |
|  28 Jun 1927     1,060.0  |   13       1947     2,320.0   12.82   |
|  31 May 1928     1,800.0  |   14       1983     2,250.0   13.89   |
|  28 Jul 1929     1,600.0  |   15       1965     2,220.0   14.96   |
|  14 Aug 1930     1,590.0  |   16       1957     2,040.0   16.03   |
|  07 Jun 1931     1,190.0  |   17       1899     1,920.0   17.10   |
|  28 Jun 1932       928.0  |   18       1895     1,900.0   18.17   |
|  14 Jun 1933     1,460.0  |   19       1969     1,800.0   19.24   |
|  01 Sep 1938     5,600.0  |   20       1928     1,800.0   20.31   |
|  31 May 1939       923.0  |   21       1946     1,680.0   21.38   |
|  02 Jun 1940       839.0  |   22       1978     1,670.0   22.45   |
|  22 Jun 1941     4,690.0  |   23       1929     1,600.0   23.52   |
|  07 Jun 1942     3,730.0  |   24       1930     1,590.0   24.59   |
|  23 Jun 1943     1,330.0  |   25       1953     1,500.0   25.66   |
|  11 Jun 1944     1,260.0  |   26       1952     1,500.0   26.73   |
|  19 Jul 1945     7,600.0  |   27       1933     1,460.0   27.80   |
|  18 Jul 1946     1,680.0  |   28       1979     1,450.0   28.86   |
|  21 Jun 1947     2,320.0  |   29       1898     1,360.0   29.93   |
|  03 Jun 1948     1,300.0  |   30       1943     1,330.0   31.00   |
|  04 Jun 1949     3,330.0  |   31       1948     1,300.0   32.07   |
|  03 Aug 1951     3,530.0  |   32       1903     1,300.0   33.14   |
|  07 Jun 1952     1,500.0  |   33       1944     1,260.0   34.21   |
|  14 Jun 1953     1,500.0  |   34       1982     1,220.0   35.28   |
|  21 May 1954       390.0  |   35       2010     1,200.0   36.35   |
|  24 Jul 1955       495.0  |   36       2003     1,190.0   37.42   |
|  03 Jun 1956       608.0  |   37       1931     1,190.0   38.49   |
|  09 May 1957     2,040.0  |   38       1973     1,180.0   39.56   |
```

```
|  27 May 1958       900.0  |   39      1909      1,180.0   40.63  |
|  21 Jun 1959       680.0  |   40      1997      1,170.0   41.70  |
|  18 Jun 1960       504.0  |   41      1961      1,140.0   42.77  |
|  03 Jun 1961     1,140.0  |   42      1927      1,060.0   43.84  |
|  02 Jul 1962       735.0  |   43      1897      1,060.0   44.91  |
|  16 Jun 1963       610.0  |   44      2011      1,050.0   45.98  |
|  21 May 1964       274.0  |   45      1984      1,030.0   47.05  |
|  16 Jun 1965     2,220.0  |   46      1896      1,010.0   48.12  |
|  20 Jul 1966       840.0  |   47      1986      1,000.0   49.19  |
|  21 Jun 1967       544.0  |   48      1932        928.0   50.26  |
|  21 Jun 1968       517.0  |   49      2008        923.0   51.33  |
|  07 May 1969     1,800.0  |   50      1939        923.0   52.40  |
|  24 Jun 1970       715.0  |   51      1958        900.0   53.47  |
|  26 Jun 1971       815.0  |   52      1888        889.0   54.54  |
|  15 Jun 1972       492.0  |   53      1991        842.0   55.61  |
|  27 Jun 1973     1,180.0  |   54      1966        840.0   56.68  |
|  13 Jul 1974       660.0  |   55      1940        839.0   57.75  |
|  03 Jul 1975       560.0  |   56      1971        815.0   58.82  |
|  31 Jul 1976    31,200.0  |   57      1996        814.0   59.89  |
|  24 Jul 1977       262.0  |   58      1902        773.0   60.96  |
|  17 May 1978     1,670.0  |   59      1993        738.0   62.03  |
|  15 Jun 1979     1,450.0  |   60      1987        738.0   63.10  |
|  30 Apr 1980     6,150.0  |   61      1962        735.0   64.16  |
|  12 Jul 1981       419.0  |   62      1988        730.0   65.23  |
|  13 Sep 1982     1,220.0  |   63      1970        715.0   66.30  |
|  20 Jun 1983     2,250.0  |   64      1911        710.0   67.37  |
|  02 Jul 1984     1,030.0  |   65      2012        708.0   68.44  |
|  09 Jun 1985       708.0  |   66      1985        708.0   69.51  |
|  06 Jul 1986     1,000.0  |   67      1998        701.0   70.58  |
|  30 Apr 1987       738.0  |   68      2004        694.0   71.65  |
|  18 Jun 1988       730.0  |   69      1959        680.0   72.72  |
|  20 Jun 1989       615.0  |   70      1974        660.0   73.79  |
|  13 Jun 1990       564.0  |   71      1910        630.0   74.86  |
|  12 Jun 1991       842.0  |   72      1989        615.0   75.93  |
|  16 May 1992       386.0  |   73      1963        610.0   77.00  |
|  18 Jun 1993       738.0  |   74      2005        609.0   78.07  |
|  14 May 1994       244.0  |   75      1956        608.0   79.14  |
|  30 May 1995     2,740.0  |   76      1990        564.0   80.21  |
|  02 Jul 1996       814.0  |   77      1975        560.0   81.28  |
|  09 Jun 1997     1,170.0  |   78      1967        544.0   82.35  |
|  12 Jul 1998       701.0  |   79      2000        532.0   83.42  |
|  30 Apr 1999     2,460.0  |   80      1968        517.0   84.49  |
|  30 May 2000       532.0  |   81      2009        507.0   85.56  |
|  18 May 2001       440.0  |   82      1960        504.0   86.63  |
|  31 May 2002       266.0  |   83      1955        495.0   87.70  |
|  31 May 2003     1,190.0  |   84      1972        492.0   88.77  |
|  25 Jul 2004       694.0  |   85      2006        456.0   89.84  |
|  03 Jun 2005       609.0  |   86      2001        440.0   90.91  |
|  20 May 2006       456.0  |   87      1981        419.0   91.98  |
|  29 May 2007       338.0  |   88      1954        390.0   93.05  |
|  05 Jun 2008       923.0  |   89      1992        386.0   94.12  |
|  26 Jun 2009       507.0  |   90      2007        338.0   95.19  |
|  12 Jun 2010     1,200.0  |   91      1964        274.0   96.26  |
|  07 Jun 2011     1,050.0  |   92      2002        266.0   97.33  |
|  07 Jul 2012       708.0  |   93      1977        262.0   98.40  |
|  13 Sep 2013    15,500.0  |   94      1994        244.0   99.47  |
|---------------------------|---------------------------------------|
|      Note: Plotting positions based on historic period (H) = 126 |
|             Number of historic events plus high outliers (Z) = 2 |
|              Weighting factor for systematic events (W) = 1.3478 |
--------------------------------------------------------------------
                                                        * Outlier



<< Skew Weighting >>
-----------------------------------------------------------------
Based on 126 events, mean-square error of station skew =    0.127
Mean-square error of regional skew =                         0.12
-----------------------------------------------------------------

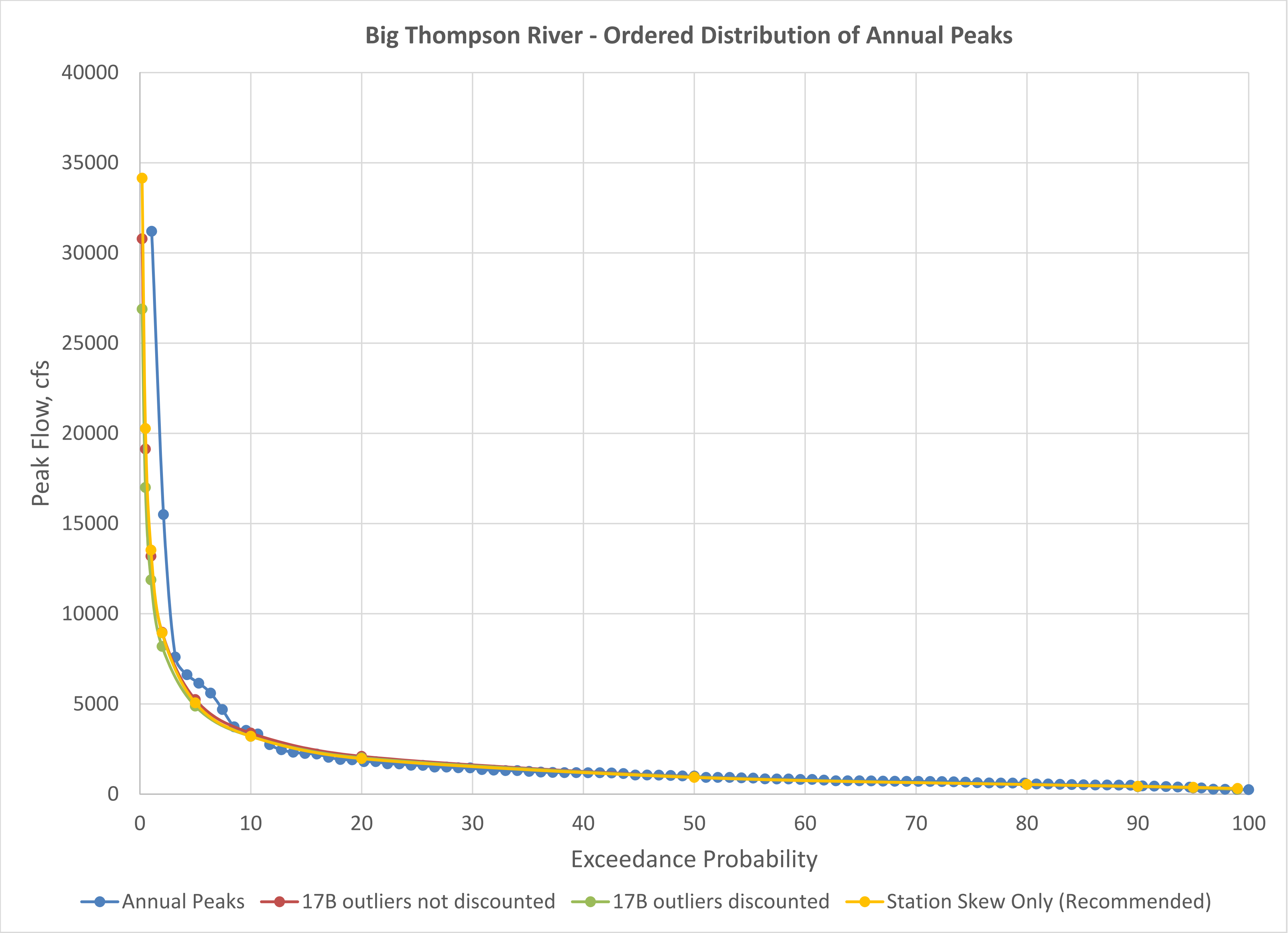


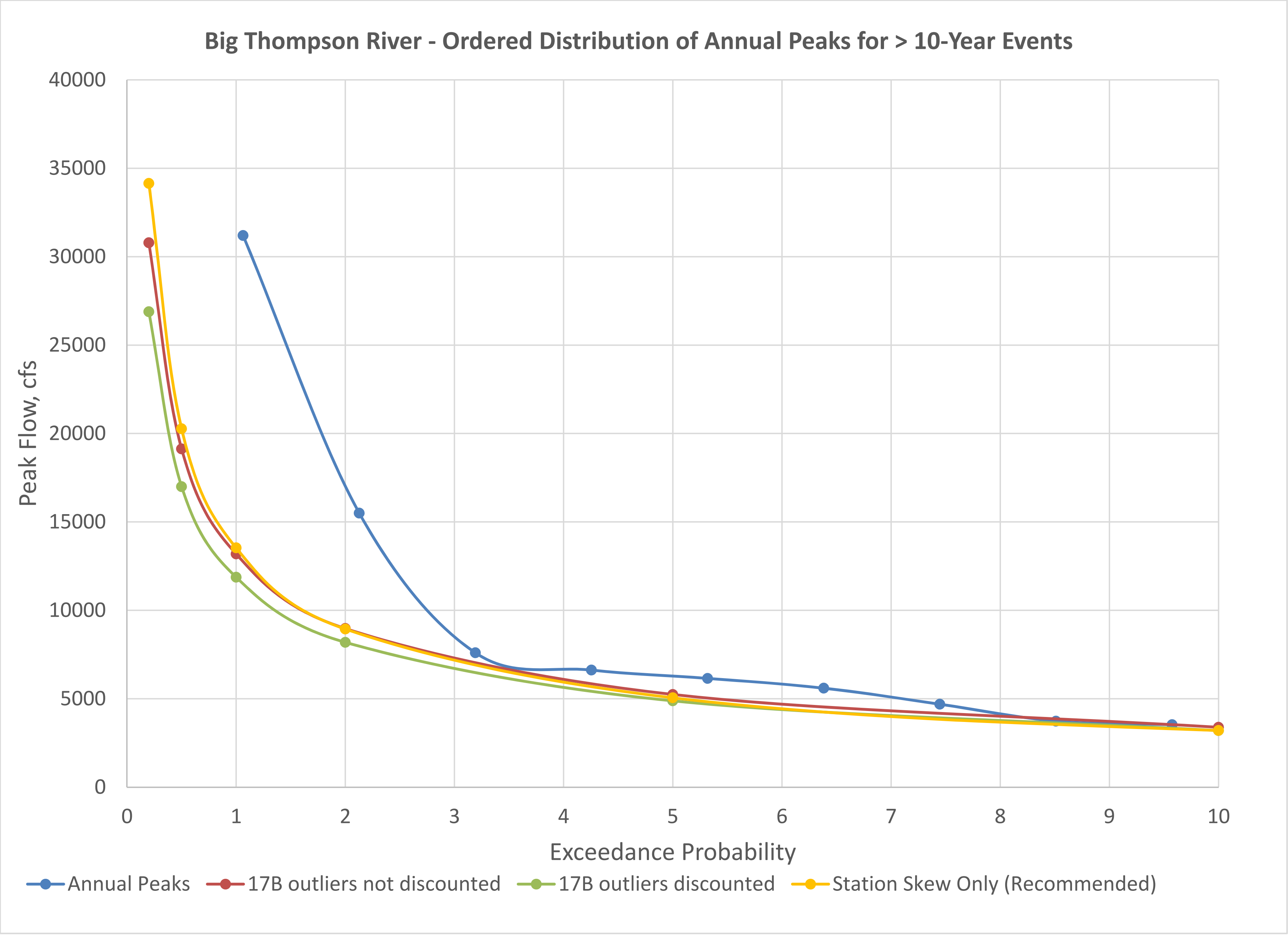
<< Frequency Curve >>
BT RIVER-MO ALL 2013
```

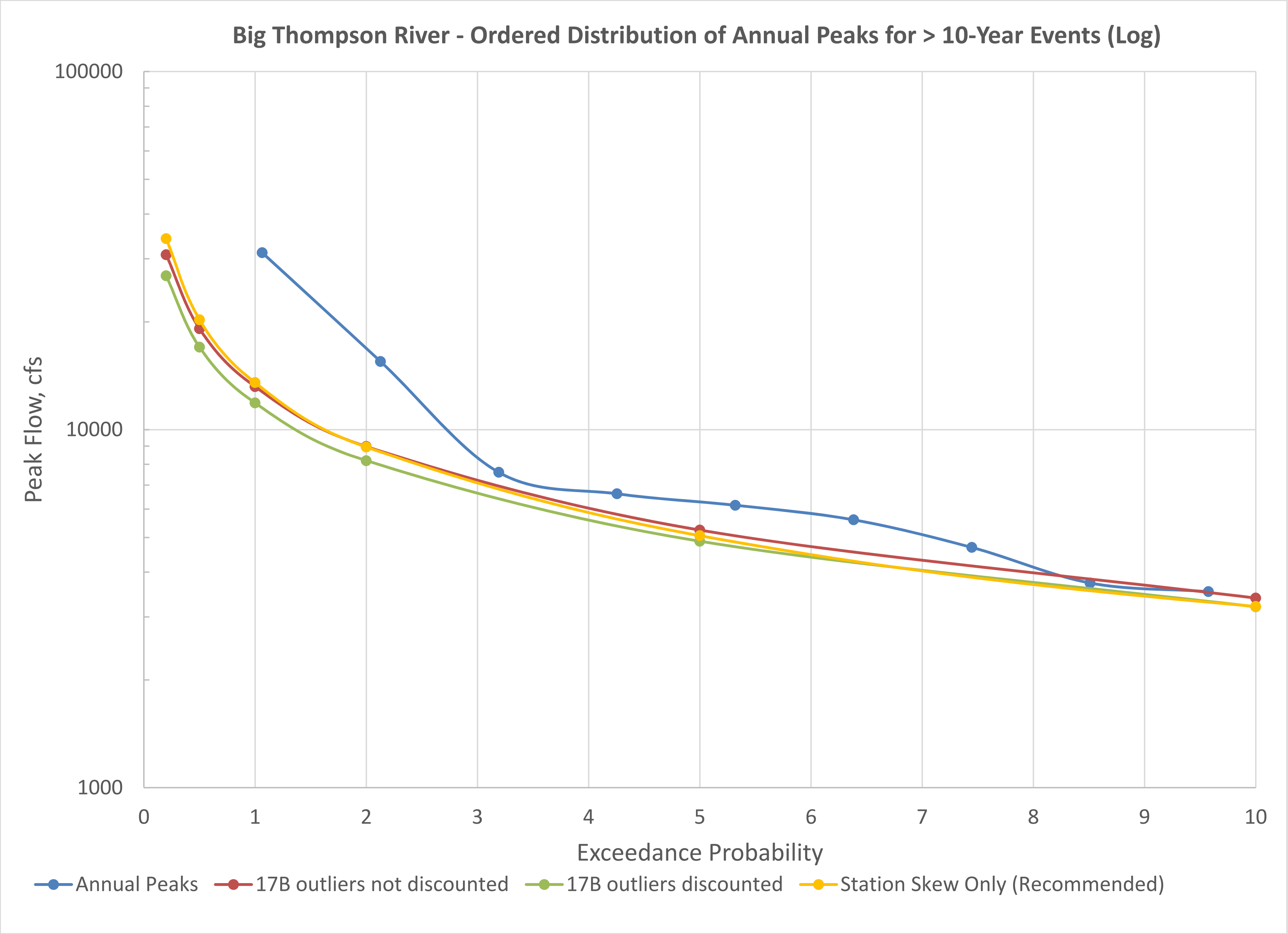
```
-------------------------------------------------------------------
|  Computed    Expected   |   Percent   |    Confidence Limits    |
|    Curve    Probability |   Chance    |        0.05        0.95 |
|        FLOW, CFS        | Exceedance  |        FLOW, CFS        |
|-------------------------|-------------|-------------------------|
|    34,144.9    40,180.9 |      0.2    |    56,135.6    23,003.4 |
|    20,267.7    22,784.7 |      0.5    |    31,136.5    14,388.9 |
|    13,532.5    14,752.8 |      1.0    |    19,744.5     9,995.9 |
|     8,941.5     9,505.7 |      2.0    |    12,389.6     6,870.1 |
|     5,057.8     5,232.3 |      5.0    |     6,550.8     4,088.1 |
|     3,207.8     3,272.9 |     10.0    |     3,957.0     2,686.0 |
|     1,966.5     1,984.9 |     20.0    |     2,324.5     1,693.8 |
|       922.6       922.6 |     50.0    |     1,059.9       799.5 |
|       536.2       534.1 |     80.0    |       625.0       450.7 |
|       435.2       432.6 |     90.0    |       513.2       359.4 |
|       379.0       375.8 |     95.0    |       450.9       309.0 |
|       313.9       310.6 |     99.0    |       378.5       251.1 |
|-------------------------|-------------|-------------------------|


<< Adjusted Statistics >>
BT RIVER-MO ALL 2013
----------------------------------------------------------------
|        Log Transform:        |                               |
|          FLOW, CFS           |       Number of Events        |
|------------------------------|-------------------------------|
|  Mean                 3.030  |  Historic Events          0  |
|  Standard Dev         0.355  |  High Outliers         2     |
|  Station Skew         1.124  |  Low Outliers          0     |
|  Regional Skew        0.643  |  Zero Events           0     |
|  Weighted Skew        0.876  |  Missing Events        0     |
|  Adopted Skew         1.124  |  Systematic Events       94  |
|                              |  Historic Period        126  |
|------------------------------|-------------------------------|

--- End of Analytical Frequency Curve ---
```


Big Thompson River - Ordered Distribution of Annual Peaks
Peak Flow, cfs
40000
35000
30000
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)


Big Thompson River - Ordered Distribution of Annual Peaks for > 10-Year Events
40000
35000
30000
25000
20000
15000
10000
5000
0
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)


Big Thompson River - Ordered Distribution of Annual Peaks for > 10-Year Events (Log)
100000
10000
1000
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)

# Bulletin 17B Frequency Analysis

# North Fork Big Thompson River at Drake

## USGS Gage 06736000 (1947 – 1976)

## CDWR Gage BTNFDRCO (1991 – 2012)

```
-------------------------------
Bulletin 17B Frequency Analysis
    10 Jul 2014   01:03 PM
-------------------------------


--- Input Data ---

Analysis Name: NORTH FORK BIG T_R_ST_H_OUT
Description:

Data Set Name: NORTH FORK BIG THOMPSON RIVER-DRAKE, CO.-FLOW-ANNUAL PEAK
DSS File Name: H:\32-176904 Big Thompson
Hydrology\North_Fork_Big_Thompson\North_Fork_Big_Thompson.dss
DSS Pathname: /NORTH FORK BIG THOMPSON RIVER/DRAKE, CO./FLOW-ANNUAL
PEAK/01jan1900/IR-CENTURY/USGS/

Report File Name: H:\32-176904 Big Thompson
Hydrology\North_Fork_Big_Thompson\Bulletin17bResults\NORTH_FORK_BIG_T_R_ST_H_OUT\NORTH_FORK_BIG_T
_R_ST_H_OUT.rpt
XML File Name: H:\32-176904 Big Thompson
Hydrology\North_Fork_Big_Thompson\Bulletin17bResults\NORTH_FORK_BIG_T_R_ST_H_OUT\NORTH_FORK_BIG_T
_R_ST_H_OUT.xml

Start Date:
End Date:

Skew Option: Use Station Skew
Regional Skew: -Infinity
Regional Skew MSE: -Infinity

Plotting Position Type: Median

Upper Confidence Level: 0.05
Lower Confidence Level: 0.95
Use High Outlier Threshold
High Outlier Threshold: 3787.5

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 >>
NORTH FORK BIG THOMPSON RIVER-DRAKE, CO.-FLOW-ANNUAL PEAK
--------------------------------------------------------------------
|     Events Analyzed       |            Ordered Events            |
|                     FLOW  |          Water        FLOW   Median  |
| Day Mon Year         CFS  |  Rank     Year         CFS  Plot Pos |
|---------------------------|--------------------------------------|
|  21 Jun 1947         410  |    1      1976       8,710*   1.34   |
|  11 Jun 1948         166  |    2      2013       5,900*   3.24   |
|  04 Jun 1949         820  |    3      1965       1,290    5.15   |
|  10 Jul 1950         450  |    4      1957         850    7.06   |
|  19 Jun 1951         232  |    5      1949         820    8.97   |
|  05 Jun 1952         283  |    6      1969         800   10.88   |
|  13 Jun 1953         223  |    7      1966         584   12.79   |
|  27 Jun 1954          47  |    8      1995         572   14.69   |
|  14 Aug 1955         114  |    9      2010         463   16.60   |
|  21 May 1956         228  |   10      1950         450   18.51   |
|  29 Jul 1957         850  |   11      1997         425   20.42   |
|  24 May 1958         295  |   12      1947         410   22.33   |
|  20 Jun 1959         153  |   13      1973         398   24.24   |
|  18 Jun 1960         120  |   14      1999         318   26.15   |
|  03 Jun 1961         275  |   15      1958         295   28.05   |
|  12 Jul 1962         138  |   16      1952         283   29.96   |
|  16 Jun 1963         157  |   17      2005         276   31.87   |
|  08 Jun 1964          84  |   18      1961         275   33.78   |
```

```
|  16 Jun 1965       1,290 |   19      1970         251   35.69    |
|  20 Jul 1966         584 |   20      2004         249   37.60    |
|  21 Jun 1967         148 |   21      1975         245   39.50    |
|  12 Aug 1968         156 |   22      1951         232   41.41    |
|  07 May 1969         800 |   23      2011         229   43.32    |
|  24 Jun 1970         251 |   24      1956         228   45.23    |
|  19 Jun 1971         227 |   25      1971         227   47.14    |
|  04 Jun 1972         170 |   26      1953         223   49.05    |
|  11 Jun 1973         398 |   27      1991         215   50.95    |
|  17 Jun 1974         184 |   28      1993         211   52.86    |
|  18 Jun 1975         245 |   29      2003         196   54.77    |
|  31 Jul 1976       8,710 |   30      1996         190   56.68    |
|  03 Jun 1991         215 |   31      1974         184   58.59    |
|  25 Jun 1992         100 |   32      1972         170   60.50    |
|  17 Jun 1993         211 |   33      1948         166   62.40    |
|  14 May 1994         131 |   34      2008         160   64.31    |
|  30 May 1995         572 |   35      2001         158   66.22    |
|  15 Jun 1996         190 |   36      1963         157   68.13    |
|  09 Jun 1997         425 |   37      1968         156   70.04    |
|  21 May 1998         155 |   38      1998         155   71.95    |
|  30 Apr 1999         318 |   39      1959         153   73.85    |
|  30 May 2000          80 |   40      1967         148   75.76    |
|  16 Aug 2001         158 |   41      1962         138   77.67    |
|  04 Jun 2002          49 |   42      1994         131   79.58    |
|  29 May 2003         196 |   43      1960         120   81.49    |
|  23 Jul 2004         249 |   44      2006         115   83.40    |
|  24 Jul 2005         276 |   45      1955         114   85.31    |
|  09 Jul 2006         115 |   46      1992         100   87.21    |
|  05 Jun 2008         160 |   47      2009          94   89.12    |
|  02 Jun 2009          94 |   48      1964          84   91.03    |
|  11 Jun 2010         463 |   49      2000          80   92.94    |
|  12 Jul 2011         229 |   50      2012          51   94.85    |
|  07 Jul 2012          51 |   51      2002          49   96.76    |
|  13 Sep 2013       5,900 |   52      1954          47   98.66    |
|--------------------------|---------------------------------------|
                                                        * Outlier


<< Skew Weighting >>
-----------------------------------------------------------------
Based on 52 events, mean-square error of station skew =     0.348
Mean-square error of regional skew =                           -?
-----------------------------------------------------------------


<< Frequency Curve >>
NORTH FORK BIG THOMPSON RIVER-DRAKE, CO.-FLOW-ANNUAL PEAK
-------------------------------------------------------------------
|  Computed    Expected   |   Percent    |    Confidence Limits    |
|    Curve    Probability |   Chance     |        0.05        0.95 |
|        FLOW, CFS        | Exceedance   |        FLOW, CFS        |
|-------------------------|--------------|-------------------------|
|      24,736      38,397 |      0.2     |      62,793      12,534 |
|      11,666      15,937 |      0.5     |      25,741       6,528 |
|       6,564       8,234 |      1.0     |      13,032       3,956 |
|       3,666       4,294 |      2.0     |       6,556       2,376 |
|       1,671       1,819 |      5.0     |       2,613       1,187 |
|         907         953 |     10.0     |       1,290         685 |
|         480         491 |     20.0     |         631         379 |
|         192         192 |     50.0     |         240         151 |
|         108         108 |     80.0     |         138          81 |
|          90          89 |     90.0     |         116          66 |
|          81          80 |     95.0     |         105          58 |
|          71          71 |     99.0     |          94          51 |
|-------------------------|--------------|-------------------------|


<< Systematic Statistics >>
NORTH FORK BIG THOMPSON RIVER-DRAKE, CO.-FLOW-ANNUAL PEAK
------------------------------------------------------------------
|        Log Transform:           |                              |
|          FLOW, CFS              |       Number of Events       |
|---------------------------------|------------------------------|
```

```
|  Mean                 2.387  |  Historic Events           0  |
|  Standard Dev         0.428  |  High Outliers          0     |
|  Station Skew         1.518  |  Low Outliers           0     |
|  Regional Skew          ---  |  Zero Events            0     |
|  Weighted Skew          ---  |  Missing Events         0     |
|  Adopted Skew         1.518  |  Systematic Events        52  |
|------------------------------|-------------------------------|

--- End of Preliminary Results ---




-----------------------
<< High Outlier Test >>
-----------------------
 Based on 52 events, 10 percent outlier test deviate K(N) = 2.783
                       Computed high outlier test value = 3,787.5

    2 high outlier(s) identified above input threshold of 3,787.5

   * * * * * * * * * * * * * * * * * * * * * * * * * * * * * *
   * 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 2 high outlier(s)


<< Systematic Statistics >>
NORTH FORK BIG THOMPSON RIVER-DRAKE, CO.-FLOW-ANNUAL PEAK
----------------------------------------------------------------
|        Log Transform:         |                               |
|          FLOW, CFS            |       Number of Events        |
|------------------------------|-------------------------------|
|  Mean                 2.374  |  Historic Events           0  |
|  Standard Dev         0.405  |  High Outliers          2     |
|  Station Skew         1.432  |  Low Outliers           0     |
|  Regional Skew          ---  |  Zero Events            0     |
|  Weighted Skew          ---  |  Missing Events         0     |
|  Adopted Skew         1.518  |  Systematic Events        52  |
|                              |  Historic Period          67  |
|------------------------------|-------------------------------|


----------------------
<< Low Outlier Test >>
----------------------
 Based on 67 events, 10 percent outlier test deviate K(N) = 2.877
                           Computed low outlier test value = 16.2

             0 low outlier(s) identified below test value of 16.2





--- Final Results ---

<< Plotting Positions >>
NORTH FORK BIG THOMPSON RIVER-DRAKE, CO.-FLOW-ANNUAL PEAK
--------------------------------------------------------------------
|     Events Analyzed        |            Ordered Events          |
|                     FLOW   |          Water        FLOW   Median |
| Day Mon Year         CFS   |  Rank     Year         CFS  Plot Pos |
|---------------------------|--------------------------------------|
|  21 Jun 1947         410   |    1      1976       8,710*   1.04   |
|  11 Jun 1948         166   |    2      2013       5,900*   2.52   |
|  04 Jun 1949         820   |    3      1965       1,290    4.23   |
|  10 Jul 1950         450   |    4      1957         850    6.16   |
|  19 Jun 1951         232   |    5      1949         820    8.09   |
|  05 Jun 1952         283   |    6      1969         800   10.01   |
|  13 Jun 1953         223   |    7      1966         584   11.94   |
```

```
|  27 Jun 1954          47  |    8      1995         572   13.87   |
|  14 Aug 1955         114  |    9      2010         463   15.80   |
|  21 May 1956         228  |   10      1950         450   17.73   |
|  29 Jul 1957         850  |   11      1997         425   19.66   |
|  24 May 1958         295  |   12      1947         410   21.59   |
|  20 Jun 1959         153  |   13      1973         398   23.52   |
|  18 Jun 1960         120  |   14      1999         318   25.45   |
|  03 Jun 1961         275  |   15      1958         295   27.37   |
|  12 Jul 1962         138  |   16      1952         283   29.30   |
|  16 Jun 1963         157  |   17      2005         276   31.23   |
|  08 Jun 1964          84  |   18      1961         275   33.16   |
|  16 Jun 1965       1,290  |   19      1970         251   35.09   |
|  20 Jul 1966         584  |   20      2004         249   37.02   |
|  21 Jun 1967         148  |   21      1975         245   38.95   |
|  12 Aug 1968         156  |   22      1951         232   40.88   |
|  07 May 1969         800  |   23      2011         229   42.80   |
|  24 Jun 1970         251  |   24      1956         228   44.73   |
|  19 Jun 1971         227  |   25      1971         227   46.66   |
|  04 Jun 1972         170  |   26      1953         223   48.59   |
|  11 Jun 1973         398  |   27      1991         215   50.52   |
|  17 Jun 1974         184  |   28      1993         211   52.45   |
|  18 Jun 1975         245  |   29      2003         196   54.38   |
|  31 Jul 1976       8,710  |   30      1996         190   56.31   |
|  03 Jun 1991         215  |   31      1974         184   58.23   |
|  25 Jun 1992         100  |   32      1972         170   60.16   |
|  17 Jun 1993         211  |   33      1948         166   62.09   |
|  14 May 1994         131  |   34      2008         160   64.02   |
|  30 May 1995         572  |   35      2001         158   65.95   |
|  15 Jun 1996         190  |   36      1963         157   67.88   |
|  09 Jun 1997         425  |   37      1968         156   69.81   |
|  21 May 1998         155  |   38      1998         155   71.74   |
|  30 Apr 1999         318  |   39      1959         153   73.66   |
|  30 May 2000          80  |   40      1967         148   75.59   |
|  16 Aug 2001         158  |   41      1962         138   77.52   |
|  04 Jun 2002          49  |   42      1994         131   79.45   |
|  29 May 2003         196  |   43      1960         120   81.38   |
|  23 Jul 2004         249  |   44      2006         115   83.31   |
|  24 Jul 2005         276  |   45      1955         114   85.24   |
|  09 Jul 2006         115  |   46      1992         100   87.17   |
|  05 Jun 2008         160  |   47      2009          94   89.09   |
|  02 Jun 2009          94  |   48      1964          84   91.02   |
|  11 Jun 2010         463  |   49      2000          80   92.95   |
|  12 Jul 2011         229  |   50      2012          51   94.88   |
|  07 Jul 2012          51  |   51      2002          49   96.81   |
|  13 Sep 2013       5,900  |   52      1954          47   98.74   |
|---------------------------|--------------------------------------|
|       Note: Plotting positions based on historic period (H) = 67 |
|             Number of historic events plus high outliers (Z) = 2 |
|                 Weighting factor for systematic events (W) = 1.3 |
--------------------------------------------------------------------
                                                        * Outlier



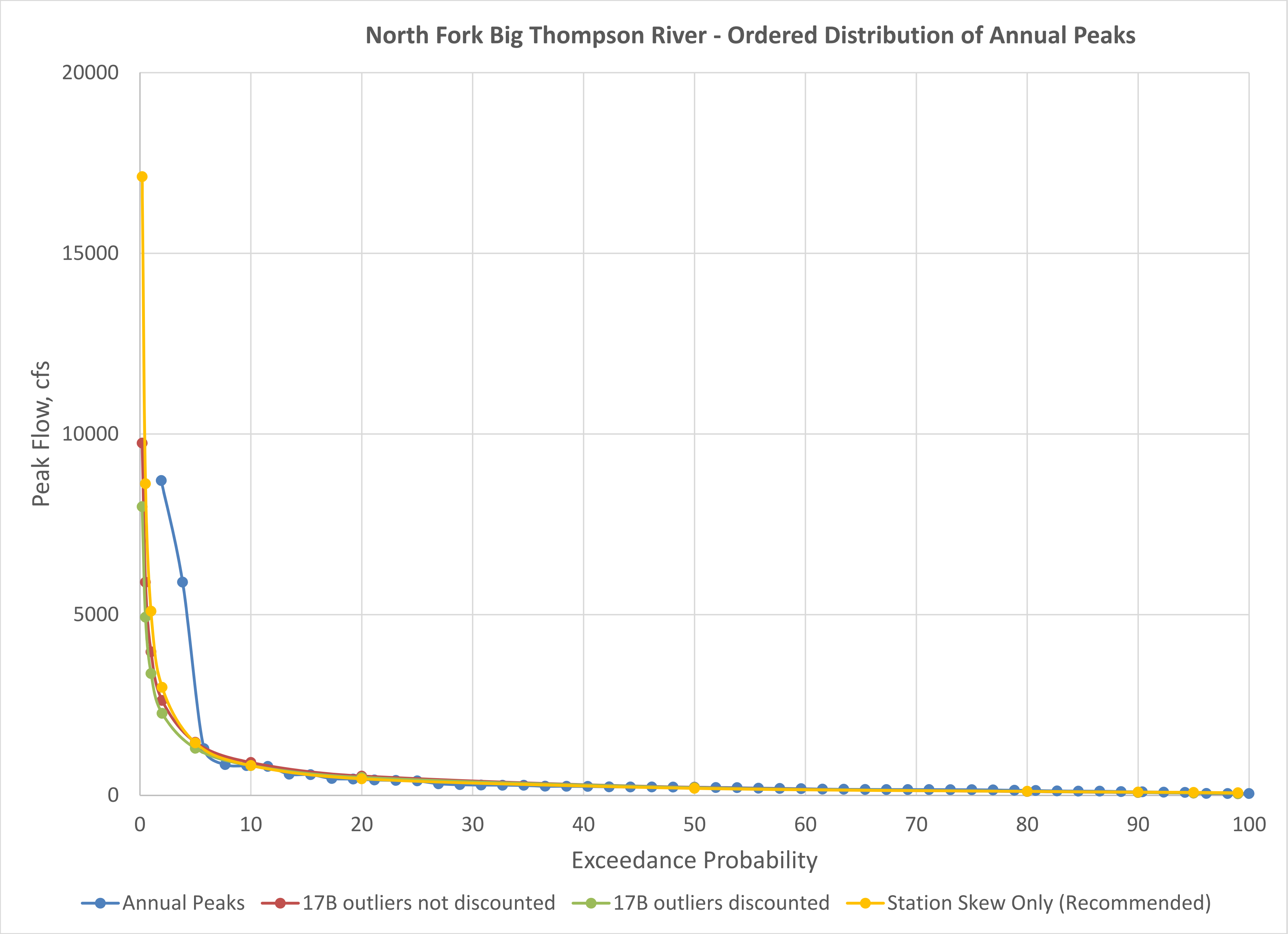
<< Skew Weighting >>
-----------------------------------------------------------------
Based on 67 events, mean-square error of station skew =     0.276
Mean-square error of regional skew =                           -?
-----------------------------------------------------------------

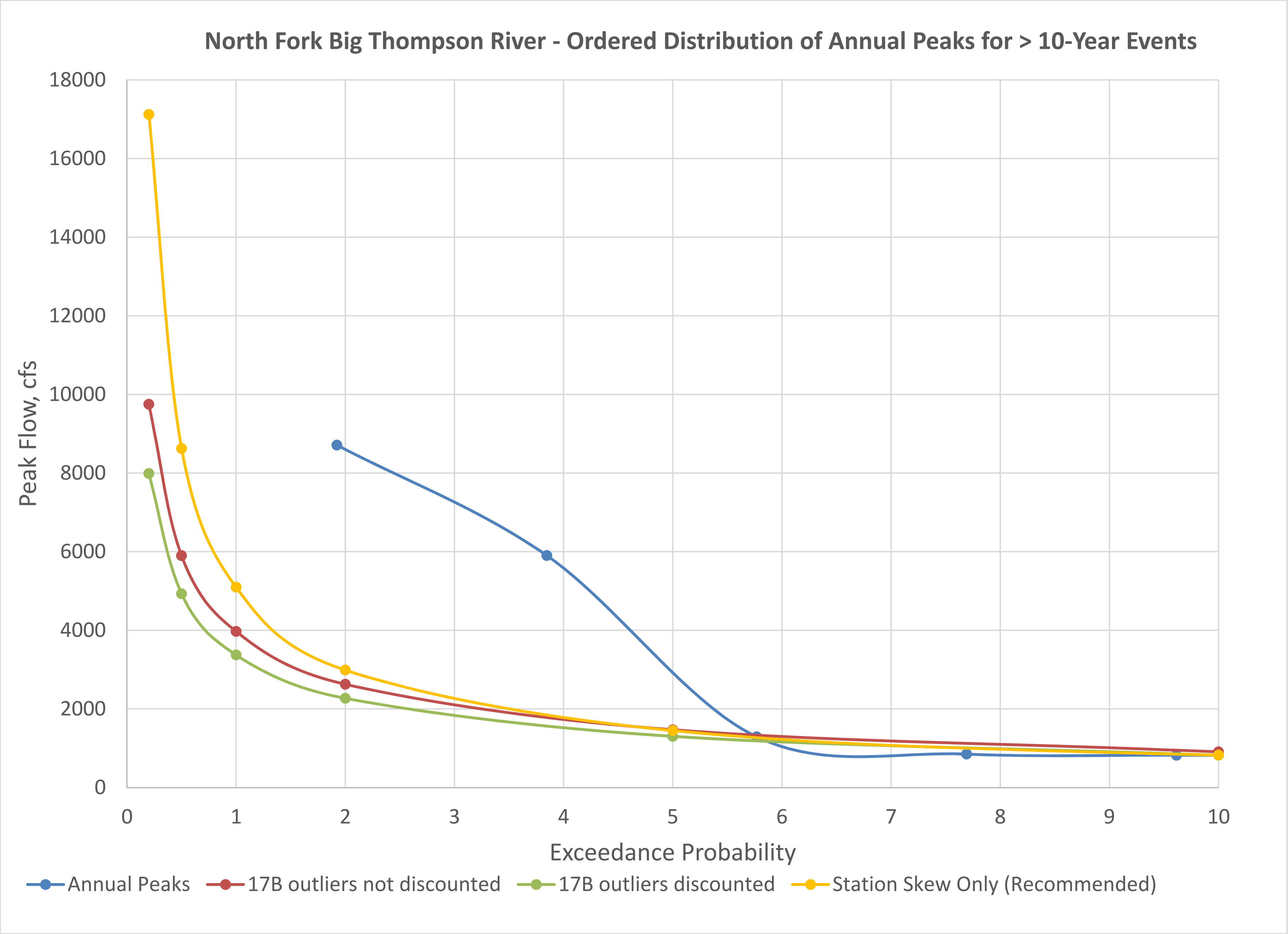

<< Frequency Curve >>
NORTH FORK BIG THOMPSON RIVER-DRAKE, CO.-FLOW-ANNUAL PEAK
-------------------------------------------------------------------
|  Computed    Expected   |   Percent   |    Confidence Limits    |
|    Curve    Probability |   Chance    |        0.05        0.95 |
|        FLOW, CFS        | Exceedance  |        FLOW, CFS        |
|-------------------------|-------------|-------------------------|
|      17,122      25,556 |       0.2   |      40,656       9,106 |
|       8,623      11,464 |       0.5   |      18,021       5,020 |
|       5,096       6,270 |       1.0   |       9,670       3,174 |
|       2,987       3,453 |       2.0   |       5,151       1,988 |
|       1,449       1,567 |       5.0   |       2,209       1,049 |
|         823         861 |      10.0   |       1,149         630 |
```

```
|         455         464 |     20.0    |         590         364 |
|         191         191 |     50.0    |         236         153 |
|         109         108 |     80.0    |         137          83 |
|          90          89 |     90.0    |         115          67 |
|          80          79 |     95.0    |         103          59 |
|          70          70 |     99.0    |          92          51 |
|-------------------------|-------------|-------------------------|


<< Adjusted Statistics >>
NORTH FORK BIG THOMPSON RIVER-DRAKE, CO.-FLOW-ANNUAL PEAK
----------------------------------------------------------------
|        Log Transform:          |                                |
|          FLOW, CFS             |        Number of Events        |
|--------------------------------|--------------------------------|
|  Mean                 2.374    |  Historic Events            0  |
|  Standard Dev         0.405    |  High Outliers           2     |
|  Station Skew         1.432    |  Low Outliers            0     |
|  Regional Skew          ---    |  Zero Events             0     |
|  Weighted Skew          ---    |  Missing Events          0     |
|  Adopted Skew         1.432    |  Systematic Events         52  |
|                                |  Historic Period           67  |
|--------------------------------|--------------------------------|

--- End of Analytical Frequency Curve ---
```


North Fork Big Thompson River - Ordered Distribution of Annual Peaks
Peak Flow, cfs
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)


North Fork Big Thompson River - Ordered Distribution of Annual Peaks for > 10-Year Events
Peak Flow, cfs
18000
16000
14000
12000
10000
8000
6000
4000
2000
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)


North Fork Big Thompson River - 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)

# Bulletin 17B Frequency Analysis

# Buckhorn Creek near Masonville

## USGS Gage 06739500 (1947 – 1955)

## CDWR Gage BUCRMVCO (1993 – 2012)

```
-------------------------------
Bulletin 17B Frequency Analysis
    31 Jul 2014   10:32 AM
-------------------------------


--- Input Data ---

Analysis Name: 06739500 BKHRN CK 2013 allSTA
Description: Copy of 1951 DB removed, 1923 and 1928 Historic Peaks

Data Set Name: BUCKHORN CREEK 2013
DSS File Name: H:\32-176904 Big Thompson
Hydrology\Six_Rivers_HEC-SSP_FFA_Results\Six_Rivers\Six_Rivers.dss
DSS Pathname: /BUCKHORN CREEK/MASONVILLE, CO/FLOW-ANNUAL PEAK/01jan1900/IR-CENTURY/Save Data As:
BUCKHORN CREEK 2013/

Report File Name: H:\32-176904 Big Thompson
Hydrology\Six_Rivers_HEC-SSP_FFA_Results\Six_Rivers\Bulletin17bResults\06739500_BKHRN_CK_2013_all
STA\06739500_BKHRN_CK_2013_allSTA.rpt
XML File Name: H:\32-176904 Big Thompson
Hydrology\Six_Rivers_HEC-SSP_FFA_Results\Six_Rivers\Bulletin17bResults\06739500_BKHRN_CK_2013_all
STA\06739500_BKHRN_CK_2013_allSTA.xml

Start Date:
End Date:

Skew Option: Use Station Skew
Regional Skew: 0.384
Regional Skew MSE: 0.12

Plotting Position Type: Median

Upper Confidence Level: 0.05
Lower Confidence Level: 0.95

Use Historic Data
Historic Period Start Year: 1922
Historic Period End Year: 1946
Year: 1923   Value: 10,500
Year: 1938   Value: 10,200

Display ordinate values using 1 digits in fraction part of value

--- End of Input Data ---


--- Preliminary Results ---

<< Plotting Positions >>
BUCKHORN CREEK 2013
--------------------------------------------------------------------
|     Events Analyzed        |            Ordered Events           |
|                      FLOW  |           Water         FLOW   Median |
| Day Mon Year          CFS  |  Rank     Year           CFS  Plot Pos |
|----------------------------|-------------------------------------- |
|  22 Jun 1947       324.0   |    1       2013    11,000.0    2.46   |
|  30 May 1948     5,750.0   |    2       1948     5,750.0    5.99   |
|  04 Jun 1949     3,740.0   |    3       1949     3,740.0    9.51   |
|  28 Jul 1950       104.0   |    4       1999     2,480.0   13.03   |
|  23 May 1952       355.0   |    5       1995     2,030.0   16.55   |
|  20 May 1953        49.0   |    6       1954     1,520.0   20.07   |
|  20 Jul 1954     1,520.0   |    7       1994     1,040.0   23.59   |
|  26 Aug 1955       544.0   |    8       2011       920.0   27.11   |
|  03 Jun 1993        79.0   |    9       1997       689.0   30.63   |
|  10 Aug 1994     1,040.0   |   10       1955       544.0   34.15   |
|  30 May 1995     2,030.0   |   11       2012       423.0   37.68   |
|  27 May 1996       117.0   |   12       2003       393.0   41.20   |
|  27 Jul 1997       689.0   |   13       1952       355.0   44.72   |
|  06 May 1998       180.0   |   14       1947       324.0   48.24   |
|  30 Apr 1999     2,480.0   |   15       2010       266.0   51.76   |
|  25 May 2000        17.6   |   16       2005       250.0   55.28   |
|  05 May 2001       151.0   |   17       1998       180.0   58.80   |
|  28 May 2002         7.0   |   18       2001       151.0   62.32   |
```

```
|  18 Jun 2003       393.0  |   19      1996       117.0   65.85   |
|  19 Aug 2004        73.8  |   20      2008       110.0   69.37   |
|  04 Jun 2005       250.0  |   21      1950       104.0   72.89   |
|  10 Apr 2006         6.1  |   22      1993        79.0   76.41   |
|  05 Jun 2008       110.0  |   23      2004        73.8   79.93   |
|  25 Apr 2009        40.5  |   24      1953        49.0   83.45   |
|  04 Jul 2010       266.0  |   25      2009        40.5   86.97   |
|  12 Jul 2011       920.0  |   26      2000        17.6   90.49   |
|  07 Jul 2012       423.0  |   27      2002         7.0   94.01   |
|  13 Sep 2013    11,000.0  |   28      2006         6.1   97.54   |
|---------------------------|--------------------------------------|


<< Skew Weighting >>
-----------------------------------------------------------------
Based on 28 events, mean-square error of station skew =     0.189
Mean-square error of regional skew =                         0.12
-----------------------------------------------------------------


<< Frequency Curve >>
BUCKHORN CREEK 2013
-------------------------------------------------------------------
|  Computed    Expected   |   Percent    |    Confidence Limits    |
|    Curve    Probability |   Chance     |        0.05        0.95 |
|        FLOW, CFS        | Exceedance   |        FLOW, CFS        |
|-------------------------|-------------|-------------------------|
|    45,174.8    76,479.9 |      0.2    |   225,825.0    15,463.5 |
|    27,425.5    41,020.7 |      0.5    |   120,328.7    10,147.6 |
|    18,069.0    24,831.7 |      1.0    |    71,226.1     7,120.9 |
|    11,388.1    14,490.5 |      2.0    |    39,981.8     4,799.5 |
|     5,634.6     6,569.6 |      5.0    |    16,701.3     2,611.5 |
|     2,981.4     3,285.3 |     10.0    |     7,663.0     1,490.0 |
|     1,359.5     1,430.8 |     20.0    |     2,993.3       730.1 |
|       289.5       289.5 |     50.0    |       527.5       159.5 |
|        58.1        54.9 |     80.0    |       108.0        26.5 |
|        24.5        21.9 |     90.0    |        49.3         9.4 |
|        11.9         9.9 |     95.0    |        26.1         3.9 |
|         2.9         2.0 |     99.0    |         7.9         0.7 |
|-------------------------|-------------|-------------------------|


<< Systematic Statistics >>
BUCKHORN CREEK 2013
----------------------------------------------------------------
|        Log Transform:         |                               |
|          FLOW, CFS            |       Number of Events        |
|------------------------------|-------------------------------|
|  Mean                 2.443  |  Historic Events           0  |
|  Standard Dev         0.814  |  High Outliers          0     |
|  Station Skew        -0.134  |  Low Outliers           0     |
|  Regional Skew        0.384  |  Zero Events            0     |
|  Weighted Skew        0.183  |  Missing Events         0     |
|  Adopted Skew        -0.134  |  Systematic Events        28  |
|------------------------------|-------------------------------|

--- End of Preliminary Results ---



Note: High outlier threshold is set to lowest historic value.



----------------------
<< Low Outlier Test >>
----------------------
 Based on 28 events, 10 percent outlier test deviate K(N) = 2.534
                            Computed low outlier test value = 2.4

              0 low outlier(s) identified below test value of 2.4
```

```
-----------------------
<< High Outlier Test >>
-----------------------
 Based on 28 events, 10 percent outlier test deviate K(N) = 2.534
                    Computed high outlier test value = 32,108.47

     1 high outlier(s) identified above input threshold of 10,200

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

    Statistics and frequency curve adjusted for 1 high outlier(s)
                                             and 2 historic event(s)


<< Systematic Statistics >>
BUCKHORN CREEK 2013
----------------------------------------------------------------
|        Log Transform:         |                               |
|          FLOW, CFS            |       Number of Events        |
|-------------------------------|-------------------------------|
|  Mean                 2.438   |  Historic Events           2  |
|  Standard Dev         0.799   |  High Outliers          1     |
|  Station Skew        -0.145   |  Low Outliers           0     |
|  Regional Skew        0.384   |  Zero Events            0     |
|  Weighted Skew        0.183   |  Missing Events         0     |
|  Adopted Skew        -0.134   |  Systematic Events        28  |
|                               |  Historic Period          92  |
|-------------------------------|-------------------------------|




--- Final Results ---

<< Plotting Positions >>
BUCKHORN CREEK 2013
--------------------------------------------------------------------
|     Events Analyzed          |          Ordered Events             |
|                     FLOW     |           Water        FLOW   Median |
| Day Mon Year         CFS     |  Rank      Year         CFS  Plot Pos |
|------------------------------|-------------------------------------|
|  01 Jan 1923    10,500.0     |    1       2013    11,000.0*   0.76   |
|  01 Jan 1938    10,200.0     |    2       1923    10,500.0    1.84   |
|  22 Jun 1947       324.0     |    3       1938    10,200.0    2.92   |
|  30 May 1948     5,750.0     |    4       1948     5,750.0    5.25   |
|  04 Jun 1949     3,740.0     |    5       1949     3,740.0    8.81   |
|  28 Jul 1950       104.0     |    6       1999     2,480.0   12.38   |
|  23 May 1952       355.0     |    7       1995     2,030.0   15.95   |
|  20 May 1953        49.0     |    8       1954     1,520.0   19.52   |
|  20 Jul 1954     1,520.0     |    9       1994     1,040.0   23.08   |
|  26 Aug 1955       544.0     |   10       2011       920.0   26.65   |
|  03 Jun 1993        79.0     |   11       1997       689.0   30.22   |
|  10 Aug 1994     1,040.0     |   12       1955       544.0   33.79   |
|  30 May 1995     2,030.0     |   13       2012       423.0   37.35   |
|  27 May 1996       117.0     |   14       2003       393.0   40.92   |
|  27 Jul 1997       689.0     |   15       1952       355.0   44.49   |
|  06 May 1998       180.0     |   16       1947       324.0   48.06   |
|  30 Apr 1999     2,480.0     |   17       2010       266.0   51.62   |
|  25 May 2000        17.6     |   18       2005       250.0   55.19   |
|  05 May 2001       151.0     |   19       1998       180.0   58.76   |
|  28 May 2002         7.0     |   20       2001       151.0   62.33   |
|  18 Jun 2003       393.0     |   21       1996       117.0   65.89   |
|  19 Aug 2004        73.8     |   22       2008       110.0   69.46   |
|  04 Jun 2005       250.0     |   23       1950       104.0   73.03   |
|  10 Apr 2006         6.1     |   24       1993        79.0   76.60   |
|  05 Jun 2008       110.0     |   25       2004        73.8   80.16   |
|  25 Apr 2009        40.5     |   26       1953        49.0   83.73   |
|  04 Jul 2010       266.0     |   27       2009        40.5   87.30   |
|  12 Jul 2011       920.0     |   28       2000        17.6   90.86   |
```

```
|  07 Jul 2012       423.0  |   29      2002         7.0   94.43   |
|  13 Sep 2013    11,000.0  |   30      2006         6.1   98.00   |
|---------------------------|--------------------------------------|
|       Note: Plotting positions based on historic period (H) = 92 |
|             Number of historic events plus high outliers (Z) = 3 |
|              Weighting factor for systematic events (W) = 3.2963 |
--------------------------------------------------------------------
                                                        * Outlier

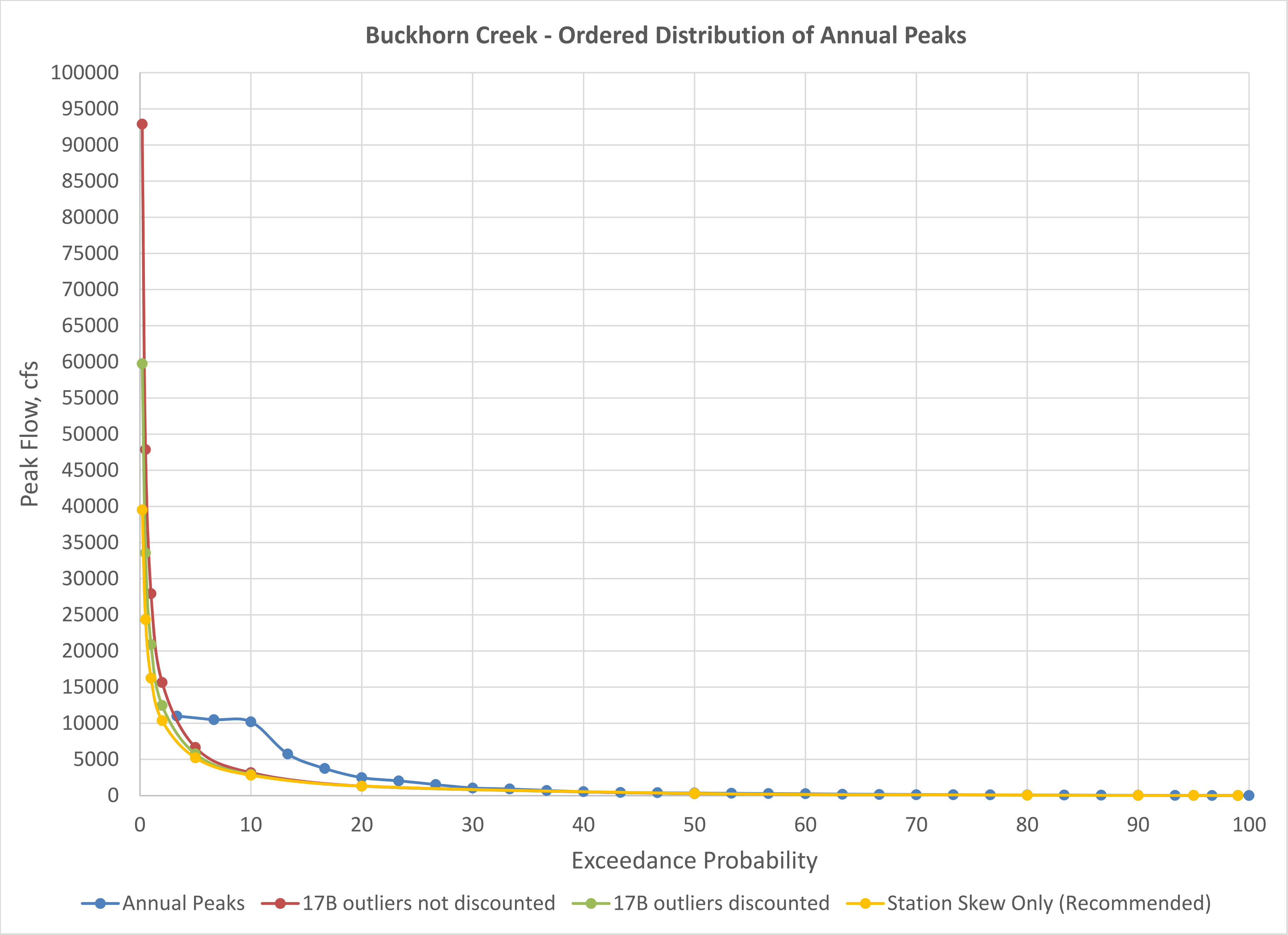


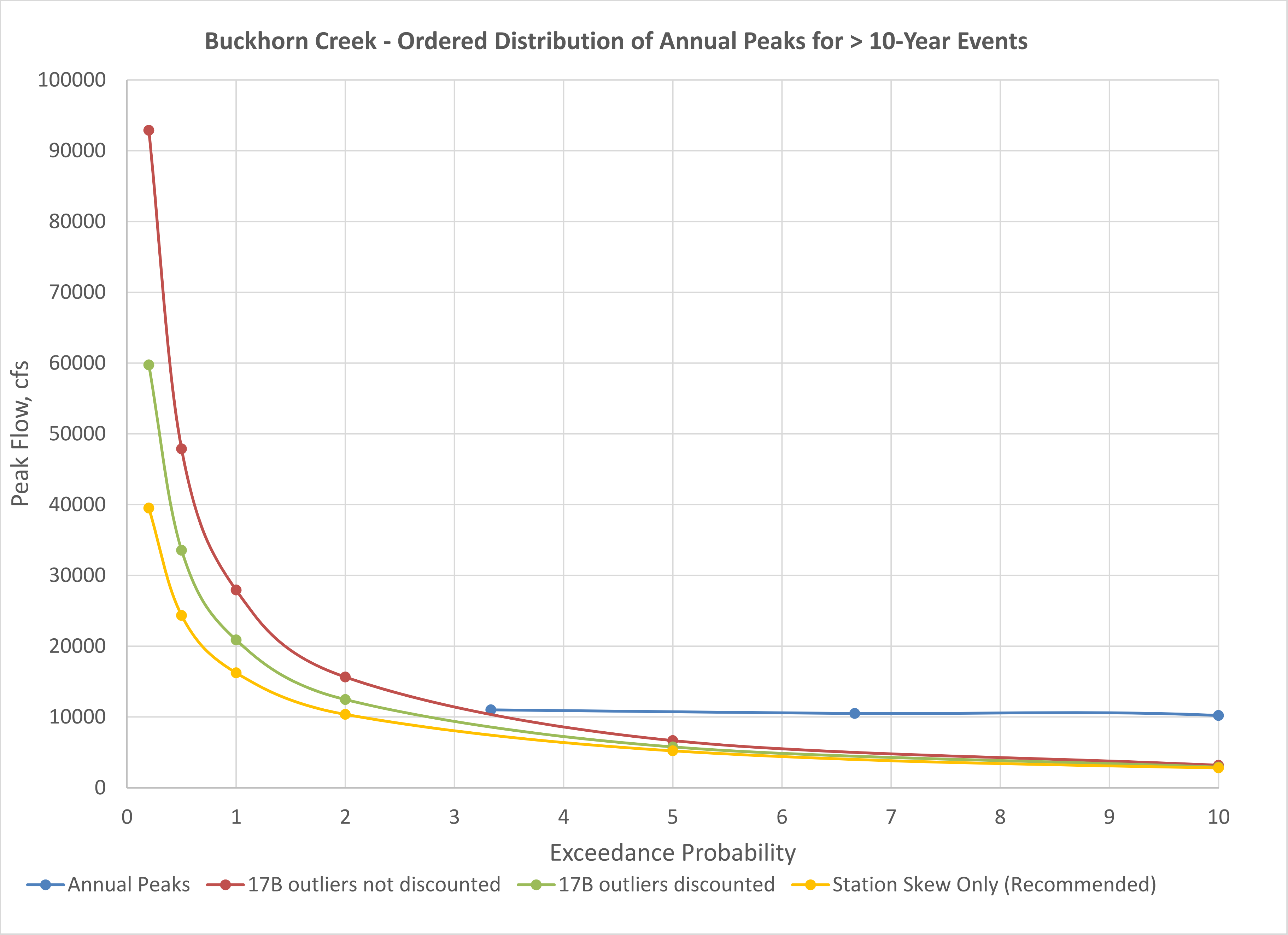
<< Skew Weighting >>
-----------------------------------------------------------------
Based on 92 events, mean-square error of station skew =     0.065
Mean-square error of regional skew =                         0.12
-----------------------------------------------------------------

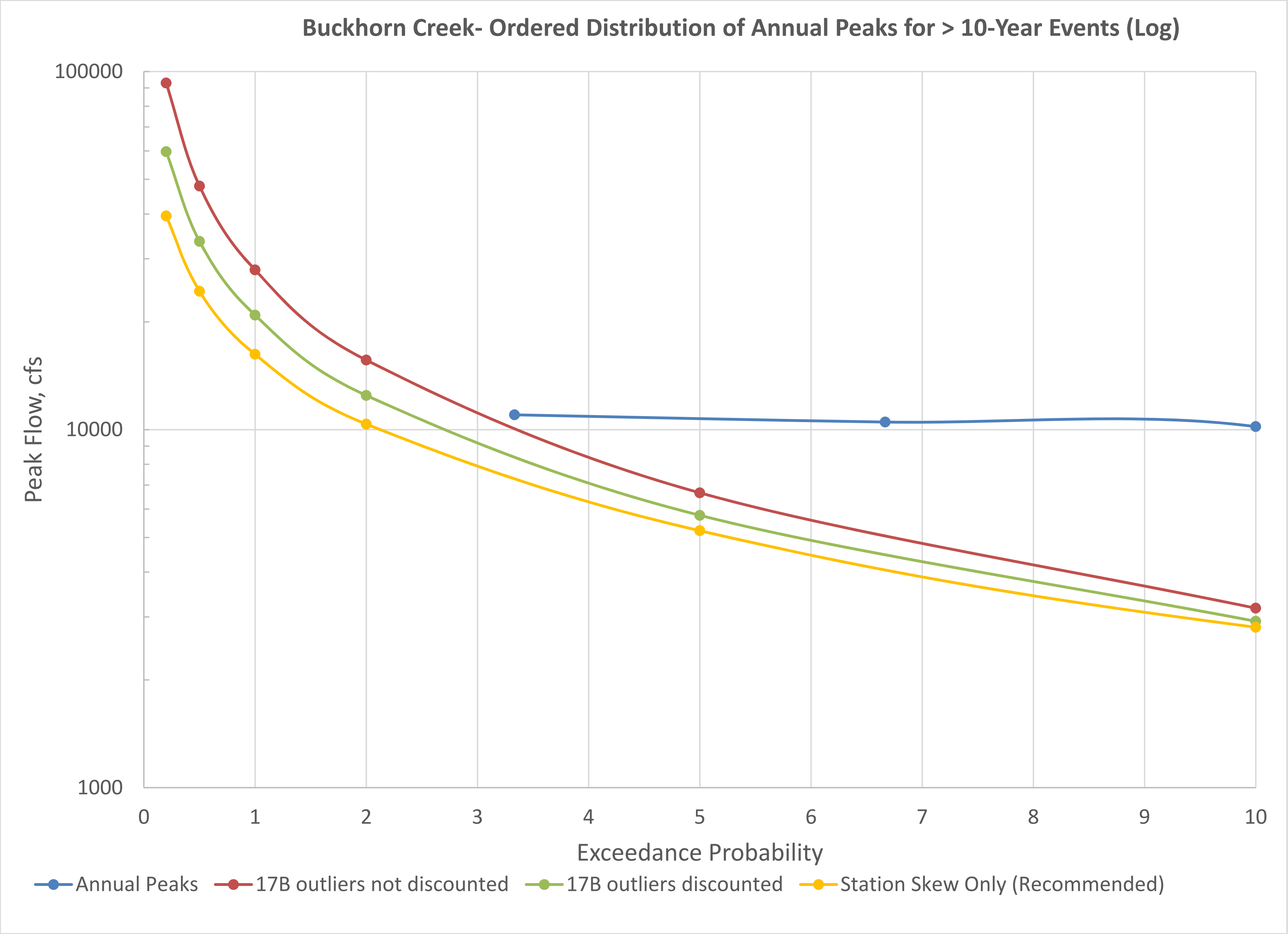

<< Frequency Curve >>
BUCKHORN CREEK 2013
-------------------------------------------------------------------
|  Computed    Expected   |   Percent   |    Confidence Limits    |
|    Curve    Probability |   Chance    |        0.05        0.95 |
|        FLOW, CFS        | Exceedance  |        FLOW, CFS        |
|-------------------------|-------------|-------------------------|
|    39,513.2    65,807.6 |      0.2    |   190,375.4    13,855.7 |
|    24,346.9    35,982.8 |      0.5    |   103,366.7     9,206.2 |
|    16,233.1    22,106.9 |      1.0    |    62,114.6     6,525.5 |
|    10,361.7    13,097.5 |      2.0    |    35,428.6     4,445.8 |
|     5,221.9     6,064.5 |      5.0    |    15,142.4     2,457.5 |
|     2,806.5     3,085.3 |     10.0    |     7,082.6     1,421.5 |
|     1,303.1     1,369.9 |     20.0    |     2,827.2       708.1 |
|       286.4       286.4 |     50.0    |       516.2       159.7 |
|        59.1        55.9 |     80.0    |       108.6        27.4 |
|        25.3        22.6 |     90.0    |        50.2         9.9 |
|        12.4        10.4 |     95.0    |        26.8         4.1 |
|         3.1         2.1 |     99.0    |         8.2         0.7 |
|-------------------------|-------------|-------------------------|


<< Adjusted Statistics >>
BUCKHORN CREEK 2013
----------------------------------------------------------------
|        Log Transform:        |                               |
|          FLOW, CFS           |       Number of Events        |
|------------------------------|-------------------------------|
|  Mean                 2.438  |  Historic Events          2   |
|  Standard Dev         0.799  |  High Outliers         1      |
|  Station Skew        -0.145  |  Low Outliers          0      |
|  Regional Skew        0.384  |  Zero Events           0      |
|  Weighted Skew        0.040  |  Missing Events        0      |
|  Adopted Skew        -0.145  |  Systematic Events       28  |
|                              |  Historic Period         92  |
|------------------------------|-------------------------------|

--- End of Analytical Frequency Curve ---
```


Buckhorn Creek - Ordered Distribution of Annual Peaks
Peak Flow, cfs
100000
95000
90000
85000
80000
75000
70000
65000
60000
55000
50000
45000
40000
35000
30000
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)


Buckhorn Creek - Ordered Distribution of Annual Peaks for > 10-Year Events
Peak Flow, cfs
100000
90000
80000
70000
60000
50000
40000
30000
20000
10000
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)


Buckhorn Creek- Ordered Distribution of Annual Peaks for > 10-Year Events (Log)
100000
10000
1000
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

# BIG THOMPSON WATERSHED

# Appendix C.1

**Big Thompson River 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) | NOAA 24-hr Type II Predictive Storms (Depth-Area Adjusted) |  |  |  |  | Effective FIS Peak Discharge Approximate Location for Comparison |  |  |  | Ayres 2013 Updated Flood Frequency Analysis |  |  |  |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
|  |  |  |  |  |  | 10-yr (cfs) | 25-yr (cfs) | 50-yr (cfs) | 100-yr (cfs) | 500-yr (cfs) | 10-yr (cfs) | 50-yr (cfs) | 100-yr (cfs) | 500-yr (cfs) | 10-yr (cfs) | 50-yr (cfs) | 100-yr (cfs) | 500-yr (cfs) |
| BT18 | Big Thompson River Headwaters Area | 29.56 |  | 304 | 365 | 361 | 730 | 1,160 | 1,729 | 3,676 |  |  |  |  |  |  |  |  |
| BT17 | Fern Creek Trib to BT in RMNP | 2.95 |  | 41 | 48 | 20 | 55 | 103 | 174 | 446 |  |  |  |  |  |  |  |  |
| J4026 | BT at confluence with Fern Creek in RMNP | 32.51 |  | 329 | 394 | 354 | 737 | 1,183 | 1,793 | 3,893 |  |  |  |  |  |  |  |  |
| R400 | BT below confluence with Fern Creek in RMNP | 32.51 |  | 329 | 394 | 354 | 737 | 1,183 | 1,792 | 3,890 |  |  |  |  |  |  |  |  |
| BT16 | BT area above and through Moraine Park | 7.55 |  | 304 | 328 | 21 | 64 | 129 | 232 | 649 |  |  |  |  |  |  |  |  |
| BT15 | Mill Creek Trib to BT in RMNP | 5.42 |  | 87 | 70 | 0 | 10 | 30 | 67 | 259 |  |  |  |  |  |  |  |  |
| BT14 | Glacier Creek Trib to BT in RMNP | 18.73 |  | 365 | 306 | 241 | 479 | 744 | 1,102 | 2,303 |  |  |  |  |  |  |  |  |
| J4032 | Confluence of Glacier Creek and Mill Creek in RMNP | 24.15 |  | 449 | 372 | 241 | 483 | 766 | 1,160 | 2,546 |  |  |  |  |  |  |  |  |
| R410 | Glacier Creek Trib to BT at Moraine Park | 24.15 |  | 449 | 372 | 241 | 483 | 766 | 1,160 | 2,546 |  |  |  |  |  |  |  |  |
| BT13 | BT area near confluence with Glacier Creek | 0.59 |  | 48 | 51 | 1 | 4 | 11 | 23 | 80 |  |  |  |  |  |  |  |  |
| J4040 | BT at Confluence of Glacier Creek | 64.79 |  | 1,020 | 958 | 557 | 1,177 | 1,923 | 2,959 | 6,650 |  |  |  |  |  |  |  |  |
| R380 | BT above confluence with Wind River | 64.79 |  | 1,019 | 957 | 557 | 1,177 | 1,923 | 2,959 | 6,650 |  |  |  |  |  |  |  |  |
| BT12 | Wind River Trib to BT | 10.25 |  | 593 | 578 | 8 | 42 | 102 | 209 | 705 |  |  |  |  |  |  |  |  |
| J4037 | BT at confluence with Wind River upstream of Estes Park | 75.04 |  | 1,514 | 1,460 | 558 | 1,204 | 2,000 | 3,124 | 7,216 |  |  |  |  |  |  |  |  |
| R390 | BT below confluence with Wind River | 75.04 |  | 1,513 | 1,460 | 558 | 1,203 | 1,999 | 3,123 | 7,215 |  |  |  |  |  |  |  |  |
| BT10 | BT area upstream of confluence with Beaver Brook | 1.26 |  | 143 | 155 | 12 | 32 | 60 | 100 | 253 |  |  |  |  |  |  |  |  |
| BT19 | Beaver Brook Trib to BT | 7.50 |  | 451 | 488 | 57 | 136 | 238 | 383 | 913 |  |  |  |  |  |  |  |  |
| J4047 | BT at confluence with Beaver Brook | 83.81 |  | 2,032 | 2,029 | 609 | 1,328 | 2,221 | 3,482 | 8,089 | 980 | 1,340 | 1,460 | 1,760 |  |  |  |  |
| R360 | BT upstream of confluence with Fall River | 83.81 |  | 2,031 | 2,028 | 609 | 1,328 | 2,220 | 3,481 | 8,084 |  |  |  |  |  |  |  |  |
| BT09 | BT area upstream of confluence with Fall River | 2.67 |  | 327 | 363 | 65 | 130 | 205 | 305 | 638 |  |  |  |  |  |  |  |  |
| BT21 | Fall River Headwaters | 12.86 |  | 270 | 307 | 107 | 247 | 421 | 663 | 1,536 |  |  |  |  |  |  |  |  |
| BT22 | Roaring River Trib to Fall River | 12.26 |  | 389 | 456 | 112 | 255 | 434 | 681 | 1,566 |  |  |  |  |  |  |  |  |
| J4070 | Fall River confluence with Roaring River | 25.12 |  | 658 | 763 | 219 | 502 | 855 | 1,343 | 3,100 |  |  |  |  |  |  |  |  |
| R310 | Fall River Trib to BT | 25.12 |  | 657 | 762 | 219 | 502 | 855 | 1,343 | 3,098 |  |  |  |  |  |  |  |  |
| BT20 | Lower Fall River Trib Area | 14.51 |  | 444 | 455 | 32 | 98 | 191 | 333 | 900 |  |  |  |  |  |  |  |  |
| **J4050** | **Fall River Trib to BT (NRCS Peak Estimation Point)** | **39.63** | **3800** | **1,093** | **1,211** | **248** | **593** | **1,039** | **1,669** | **3,990** | 450 | 610 | 680 | 830 |  |  |  |  |
| J4052 | BT at confluence with Fall River | 126.10 |  | 3,274 | 3,398 | 786 | 1,794 | 3,056 | 4,896 | 11,580 |  |  |  |  |  |  |  |  |
| R300 | BT below confluence with Fall River | 126.10 |  | 3,273 | 3,398 | 786 | 1,793 | 3,056 | 4,896 | 11,579 |  |  |  |  |  |  |  |  |
| BT23 | Black Canyon Creek Trib to BT | 10.17 |  | 378 | 385 | 18 | 62 | 127 | 232 | 666 | 130 | 200 | 230 | 310 |  |  |  |  |
| J4061 | BT at confluence with Black Canyon Creek | 136.27 |  | 3,639 | 3,773 | 794 | 1,834 | 3,148 | 5,074 | 12,118 | 1,510 | 1,990 | 2,180 | 2,600 |  |  |  |  |
| R330 | BT upstream of Lake Estes | 136.27 |  | 3,633 | 3,765 | 793 | 1,831 | 3,143 | 5,064 | 12,094 |  |  |  |  |  |  |  |  |
| **BT05** | **Fish Creek Trib to Lake Estes (NRCS Peak Estimation Point)** | **16.72** | **6900** | **1,994** | **1,718** | 48 | 143 | 281 | 496 | 1,352 | 105 | 280 | 400 | 840 |  |  |  |  |
| BT06 | Trib area on North side of Lake Estes | 1.12 |  | 161 | 180 | 88 | 138 | 189 | 249 | 430 |  |  |  |  |  |  |  |  |
| J4055 | BT inflow to Lake Estes | 154.12 |  | 5,415 | 5,342 | 846 | 1,980 | 3,424 | 5,548 | 13,370 |  |  |  |  |  |  |  |  |
| **Lake Estes** | **Lake Estes (Olympus Dam)** | **154.12** | **5327** | **5,327** | **5,327** | **846** | **1,980** | **3,424** | **5,548** | **13,370** |  |  |  |  |  |  |  |  |
| R340 | BT below Lake Estes | 154.12 |  | 5,324 | 5,324 | 846 | 1,980 | 3,424 | 5,548 | 13,370 |  |  |  |  |  |  |  |  |
| BT07 | Dry Gulch Trib to BT below Lake Estes | 6.30 |  | 755 | 732 | 140 | 267 | 410 | 598 | 1,216 | 1,200 | 2,150 | 2,600 | 4,100 |  |  |  |  |
| J4058 | BT at confluence with Dry Gulch below Lake Estes | 160.42 |  | 6,023 | 6,003 | 923 | 2,142 | 3,683 | 5,942 | 14,219 | 2,250 | 3,800 | 4,700 | 7,200 |  |  |  |  |
| R358 | BT below confluence with Dry Gulch | 160.42 |  | 5,993 | 5,974 | 923 | 2,141 | 3,682 | 5,939 | 14,211 |  |  |  |  |  |  |  |  |
| BT03B | BT upstream of Loveland Heights | 3.91 |  | 348 | 349 | 19 | 52 | 99 | 169 | 437 |  |  |  |  |  |  |  |  |
| **ICC_62** | **BT at Loveland Heights (Jarrett #62)** | **164.32** | **9300** | **6,269** | **6,252** | **936** | **2,176** | **3,748** | **6,055** | **14,520** |  |  |  |  |  |  |  |  |
| R355 | BT below Loveland Heights | 164.32 |  | 6,253 | 6,237 | 935 | 2,175 | 3,746 | 6,052 | 14,515 |  |  |  |  |  |  |  |  |
| BT03A | BT area at Mountain Shadows Lane upstream of Drake | 23.27 |  | 1,506 | 1,478 | 38 | 133 | 273 | 490 | 1,389 |  |  |  |  |  |  |  |  |
| **ICC_65** | **BT at Mountain Shadows Lane above Drake (Jarrett #65)** | **187.59** | **12500** | **7,566** | **7,534** | **960** | **2,278** | **3,961** | **6,453** | **15,686** | 2,750 | 5,700 | 7,500 | 13,600 |  |  |  |  |
| R350 | BT above Drake | 187.59 |  | 7,562 | 7,529 | 960 | 2,277 | 3,961 | 6,453 | 15,685 |  |  |  |  |  |  |  |  |
| BT03 | BT area above Drake | 2.08 |  | 149 | 151 | 2 | 13 | 33 | 71 | 254 |  |  |  |  |  |  |  |  |
| BT27 | Cow Creek Trib to NFBT | 9.78 |  | 836 | 836 | 174 | 333 | 513 | 750 | 1,532 |  |  |  |  |  |  |  |  |
| BT28 | West Creek Trib to NFBT | 12.24 |  | 1,011 | 1,003 | 350 | 608 | 885 | 1,235 | 2,339 |  |  |  |  |  |  |  |  |
| **J4093** | **West Creek upstream of Devils Gulch in NFBT (NRCS Estimation)** | **22.02** | **11000** | **1,847** | **1,839** | **495** | **898** | **1,343** | **1,908** | **3,744** | 1,500 | 3,100 | 4,000 | 8,000 |  |  |  |  |
| R160 | West Creek above Glen Haven in NFBT | 22.02 |  | 1,847 | 1,839 | 495 | 898 | 1,342 | 1,907 | 3,742 |  |  |  |  |  |  |  |  |
| BT26 | Devils Gulch Trib to NFBT | 2.82 |  | 331 | 327 | 29 | 72 | 129 | 211 | 511 | 540 | 900 | 1,200 | 1,800 |  |  |  |  |
| **BT30** | **Fox Creek Trib to NFBT (NRCS Estimation)** | **7.23** | **3500** | **614** | **609** | **87** | **180** | **292** | **443** | **962** | 1,200 | 2,200 | 2,750 | 4,800 |  |  |  |  |
| **BT31** | **Headwaters of North Fork Big Thompson River (NRCS Estimation)** | **18.80** | **1700** | **1,302** | **1,297** | **473** | **804** | **1,154** | **1,588** | **2,954** |  |  |  |  |  |  |  |  |
| J4103 | NFBT upstream of Glen Haven | 26.03 |  | 1,913 | 1,902 | 554 | 975 | 1,432 | 2,010 | 3,870 |  |  |  |  |  |  |  |  |
| R130 | NFBT upstream of Glen Haven | 26.03 |  | 1,913 | 1,902 | 554 | 975 | 1,432 | 2,009 | 3,870 |  |  |  |  |  |  |  |  |
| J4098 | NFBT at Glen Haven | 50.87 |  | 4,004 | 3,980 | 971 | 1,764 | 2,640 | 3,767 | 7,464 | 1,450 | 3,400 | 4,400 | 11,500 |  |  |  |  |
| R140 | NFBT below Glen Haven | 50.87 |  | 4,003 | 3,979 | 971 | 1,764 | 2,640 | 3,766 | 7,462 |  |  |  |  |  |  |  |  |
| BT25 | NFBT area below Glen Haven | 4.19 |  | 482 | 474 | 52 | 118 | 201 | 315 | 721 |  |  |  |  |  |  |  |  |
| BT32 | Miller Fork Trib to NFBT | 14.18 |  | 1,217 | 1,231 | 113 | 258 | 439 | 690 | 1,592 | 1,350 | 2,650 | 3,350 | 6,300 |  |  |  |  |
| J4106 | NFBT at confluence with Miller Fork | 69.24 |  | 5,570 | 5,546 | 1,108 | 2,083 | 3,184 | 4,625 | 9,460 |  |  |  |  |  |  |  |  |
| R185 | NFBT below confluence with Miller Fork | 69.24 |  | 5,570 | 5,546 | 1,107 | 2,083 | 3,184 | 4,624 | 9,459 |  |  |  |  |  |  |  |  |
| BT24A | Trib area to NFBT at NRCS peak estimation point | 0.38 |  | 75 | 73 | 10 | 24 | 40 | 64 | 146 |  |  |  |  |  |  |  |  |
| **ICC_78** | **NFBT 4.5 miles above Drake (NRCS Peak Estimation Point)** | **69.62** | **18400** | **5,596** | **5,570** | **1,111** | **2,091** | **3,197** | **4,644** | **9,502** |  |  |  |  |  |  |  |  |
| R180 | NFBT above confluence with BT | 69.62 |  | 5,595 | 5,569 | 1,111 | 2,090 | 3,196 | 4,642 | 9,498 |  |  |  |  |  |  |  |  |
| BT24 | NFBT area above confluence with BT | 16.22 |  | 2,358 | 2,389 | 525 | 945 | 1,375 | 1,914 | 3,593 |  |  |  |  |  |  |  |  |
| **J4080b** | **NFBT at Drake (Jarrett #81)** | **85.84** | **5900** | **7,723** | **7,706** | **1,539** | **2,868** | **4,336** | **6,240** | **12,599** | **1,500** | **4,100** | **6,100** | **14,100** | **823** | **2,987** | **5,096** | **17,122** |
| **J4080** | **Confluence of BT and NFBT at Drake (Jarrett #76)** | **275.51** | **14800** | **14,731** | **14,728** | **2,116** | **4,538** | **7,495** | **11,803** | **26,983** | 3,700 | 7,850 | 10,400 | 19,200 |  |  |  |  |
| R240 | BT below Drake | 275.51 |  | 14,716 | 14,714 | 2,115 | 4,537 | 7,493 | 11,801 | 26,979 |  |  |  |  |  |  |  |  |
| BT02 | BT area below Drake | 5.92 |  | 588 | 843 | 278 | 483 | 693 | 952 | 1,741 |  |  |  |  |  |  |  |  |
| BT33 | Cedar Creek Trib to BT | 18.97 |  | 1,804 | 2,807 | 767 | 1,240 | 1,698 | 2,253 | 3,901 | 2,460 | 6,530 | 9,400 | 20,000 |  |  |  |  |
| J4083 | BT at confluence with Cedar Creek | 300.40 |  | 16,632 | 17,624 | 2,693 | 5,582 | 9,048 | 14,020 | 31,273 |  |  |  |  |  |  |  |  |
| R265 | BT below confluence with Cedar Creek | 300.40 |  | 16,614 | 17,606 | 2,691 | 5,580 | 9,045 | 14,015 | 31,263 |  |  |  |  |  |  |  |  |
| BT01A | BT area at Mouth of Canyon | 13.63 |  | 812 | 675 | 812 | 1,280 | 1,733 | 2,259 | 3,786 |  |  |  |  |  |  |  |  |
| **ICC_66** | **BT near Mouth of Canyon (Jarrett #66)** | **314.03** | **15500** | **16,876** | **18,106** | **3,041** | **6,249** | **10,054** | **15,449** | **34,002** | **3,800** | **10,500** | **15,300** | **37,000** | **3,208** | **8,942** | **13,533** | **34,145** |
| R260 | BT upstream of Buckhorn Gulch confluence | 314.03 |  | 16,866 | 18,093 | 3,038 | 6,245 | 10,049 | 15,443 | 33,989 |  |  |  |  |  |  |  |  |
| BT01 | BT area near confluence with Buckhorn | 2.39 |  | 326 | 134 | 210 | 333 | 451 | 588 | 982 |  |  |  |  |  |  |  |  |
| BH12 | Buckhorn Creek Headwaters | 26.77 |  | 2,108 | 2,066 | 415 | 822 | 1,291 | 1,907 | 3,985 |  |  |  |  |  |  |  |  |
| BH13 | Twin Cabin Gulch Trib to Buckhorn Creek | 3.88 |  | 365 | 366 | 101 | 206 | 328 | 490 | 1,034 |  |  |  |  |  |  |  |  |
| J4029 | Buckorn Creek at confluence with Twin Cabin Gulch | 30.65 |  | 2,412 | 2,395 | 495 | 986 | 1,553 | 2,296 | 4,797 |  |  |  |  |  |  |  |  |
| R20 | Buckhorn Creek Headwaters | 30.65 |  | 2,411 | 2,395 | 495 | 986 | 1,553 | 2,295 | 4,795 |  |  |  |  |  |  |  |  |
| BH11 | Buckhorn Creek area above Sheep Creek confluence | 4.32 |  | 524 | 522 | 427 | 719 | 1,009 | 1,360 | 2,406 |  |  |  |  |  |  |  |  |
| BH10 | Sheep Creek Trib to Buckhorn Creek | 7.66 |  | 735 | 696 | 260 | 482 | 716 | 1,012 | 1,942 |  |  |  |  |  |  |  |  |
| J4130 | Buckhorn at confluence with Sheep Creek | 42.64 |  | 3,522 | 3,486 | 927 | 1,766 | 2,683 | 3,875 | 7,740 |  |  |  |  |  |  |  |  |
| R30 | Buckhorn Creek upstream of Stove Prarie Creek confluence | 42.64 |  | 3,521 | 3,486 | 927 | 1,765 | 2,682 | 3,874 | 7,739 |  |  |  |  |  |  |  |  |
| BH09 | Buckhorn Area above confluence with Stove Prarie Creek | 0.75 |  | 125 | 101 | 152 | 242 | 328 | 429 | 722 |  |  |  |  |  |  |  |  |
| BH14 | Stove Prarie Creek Trib to Buckhorn Gulch | 6.55 |  | 699 | 703 | 431 | 731 | 1,034 | 1,402 | 2,509 |  |  |  |  |  |  |  |  |
| **J4133** | **Buckhorn Creek at Confl. w/ Stove Prarie Creek (Jarrett #106)** | **49.94** | **4400** | **4,205** | **4,199** | **1,307** | **2,410** | **3,591** | **5,109** | **9,964** |  |  |  |  |  |  |  |  |
| R40 | Buckhorn Creek upstream of confluence with Fish Creek | 49.94 |  | 4,204 | 4,197 | 1,303 | 2,408 | 3,590 | 5,107 | 9,960 |  |  |  |  |  |  |  |  |
| BH08 | Buckhorn area upstream of confluence with Fish Creek | 4.67 |  | 461 | 462 | 236 | 442 | 659 | 933 | 1,788 |  |  |  |  |  |  |  |  |
| BH07 | Upper North Fork Fish Creek Trib to Buckhorn | 8.85 |  | 922 | 894 | 416 | 711 | 1,009 | 1,376 | 2,486 |  |  |  |  |  |  |  |  |
| BH06 | Fish Creek Trib to Buckhorn | 6.25 |  | 821 | 784 | 322 | 552 | 785 | 1,071 | 1,937 |  |  |  |  |  |  |  |  |
| J4122 | Confluence of North Fork Fish Creek and Fish Creek | 15.10 |  | 1,742 | 1,678 | 702 | 1,214 | 1,725 | 2,355 | 4,272 |  |  |  |  |  |  |  |  |
| R50 | Fish Creek Trib to Buckhorn | 15.10 |  | 1,742 | 1,677 | 702 | 1,213 | 1,724 | 2,354 | 4,271 |  |  |  |  |  |  |  |  |
| BH05 | Buckhorn area near Fish Creek confluence | 0.58 |  | 77 | 72 | 80 | 131 | 180 | 240 | 413 |  |  |  |  |  |  |  |  |
| J4125 | Buckhorn at Fish Creek confluence | 70.27 |  | 6,356 | 6,294 | 2,023 | 3,709 | 5,465 | 7,733 | 14,931 |  |  |  |  |  |  |  |  |
| R95 | Buckhorn Creek above NRCS Estimation Point | 70.27 |  | 6,354 | 6,292 | 2,022 | 3,708 | 5,463 | 7,731 | 14,926 |  |  |  |  |  |  |  |  |
| BH04A | Buckhorn area upstream of NRCS Estimation Point | 17.75 |  | 1,771 | 1,651 | 1,089 | 1,705 | 2,291 | 2,988 | 5,028 |  |  |  |  |  |  |  |  |
| **ICC_79** | **Buckhorn 3.5 miles above Masonville (NRCS Estimation Point)** | **88.02** | **11000** | **8,115** | **7,929** | **2,972** | **5,218** | **7,519** | **10,459** | **19,622** |  |  |  |  |  |  |  |  |
| R90 | Buckhorn Creek upstream of Redstone Creek | 88.02 |  | 8,111 | 7,925 | 2,968 | 5,214 | 7,514 | 10,452 | 19,607 |  |  |  |  |  |  |  |  |
| BH04 | Buckhorn Area upstream of confluence with Redstone Creek | 8.49 |  | 1,166 | 902 | 1,019 | 1,520 | 1,991 | 2,524 | 4,028 |  |  |  |  |  |  |  |  |
| **J4119b** | **Buckhorn at Masonville upstream of Redstone Creek (Jarrett #108)** | 96.51 | **7700** | 8,962 | 8,676 | 3,574 | 6,178 | 8,834 | 12,198 | 22,587 | 4,674 | 10,321 | 13,862 | 24,000 |  |  |  |  |
| **BH16** | **Redstone Creek Headwaters (NRCS Estimation)** | **17.46** | **1200** | **889** | **985** | **319** | **694** | **1,119** | **1,688** | **3,603** |  |  |  |  |  |  |  |  |
| J4121 | Redstone Creek NRCS Peak Estimate Location | 17.46 |  | 889 | 985 | 319 | 694 | 1,119 | 1,688 | 3,603 |  |  |  |  |  |  |  |  |
| R100 | Redstone Creek upstream of confluence with Buckhorn | 17.46 |  | 888 | 984 | 319 | 693 | 1,117 | 1,684 | 3,591 |  |  |  |  |  |  |  |  |
| BH15 | Redstone Creek area near confluence with Buckhorn | 13.60 |  | 744 | 670 | 256 | 535 | 850 | 1,256 | 2,591 |  |  |  |  |  |  |  |  |
| **J4120** | **Redstone Creek U/S of Confl. w/ Buckhorn (Jarrett #109)** | **31.06** | **1400** | **1,585** | **1,581** | **564** | **1,205** | **1,930** | **2,882** | **6,059** | **4,187** | **9,217** | **12,370** | **22,500** |  |  |  |  |
| J4119 | Buckhorn at confluence with Redstone Creek | 127.57 |  | 10,531 | 10,253 | 3,796 | 6,900 | 10,125 | 14,218 | 27,154 | 6,321 | 13,593 | 18,059 | 32,000 |  |  |  |  |
| R190 | Buckhorn downstream of Confluence with Redstone Creek | 127.57 |  | 10,525 | 10,248 | 3,780 | 6,886 | 10,107 | 14,189 | 27,107 |  |  |  |  |  |  |  |  |
| BH02 | Buckhorn area below confluence with Redstone Creek | 8.34 |  | 721 | 487 | 1,069 | 1,544 | 1,983 | 2,475 | 3,851 |  |  |  |  |  |  |  |  |
| **BH03** | **Indian Creek Tributary to Buckhorn (Jarrett #110)** | **7.93** | **100** | **624** | **374** | **1,111** | **1,588** | **2,026** | **2,516** | **3,883** |  |  |  |  |  |  |  |  |
| **J4088** | **Buckhorn at County Rd. 24H, CDWR Gage (Jarrett #111)** | **143.84** | **11200** | **11,136** | **10,878** | **4,850** | **8,695** | **12,591** | **17,408** | **32,501** | **6,844** | **15,090** | **20,244** | **36,000** | **2,807** | **10,362** | **16,233** | **39,513** |
| R230 | Buckhorn Creek upstream of confluence with BT | 143.84 |  | 11,134 | 10,877 | 4,843 | 8,681 | 12,579 | 17,394 | 32,478 |  |  |  |  |  |  |  |  |
| BH01 | Buckhorn area at BT | 0.88 |  | 112 | 48 | 194 | 273 | 346 | 427 | 651 |  |  |  |  |  |  |  |  |
| J4077 | BT confluence with Buckhorn [1] | 461.14 |  | 23,957 | 24,406 | 7,174 | 12,838 | 19,051 | 27,437 | 59,360 | 4,700 | 12,300 | 19,000 | 44,000 |  |  |  |  |
| R220 | BT downstream of confluence with Buckhorn [1] | 461.14 |  | 23,957 | 24,406 | 7,174 | 12,838 | 19,051 | 27,437 | 59,360 |  |  |  |  |  |  |  |  |
| **Outlet_BT-BH** | **BT downstream study limit (Ayres Estimate)** [1] | **461.14** | **19000** | **23,957** | **24,406** | **7,174** | **12,838** | **19,051** | **27,437** | **59,360** |  |  |  |  |  |  |  |  |

[1] - Predictive peak discharges at confluence of Big Thompson and Buckhorn are provisional and subject to change.

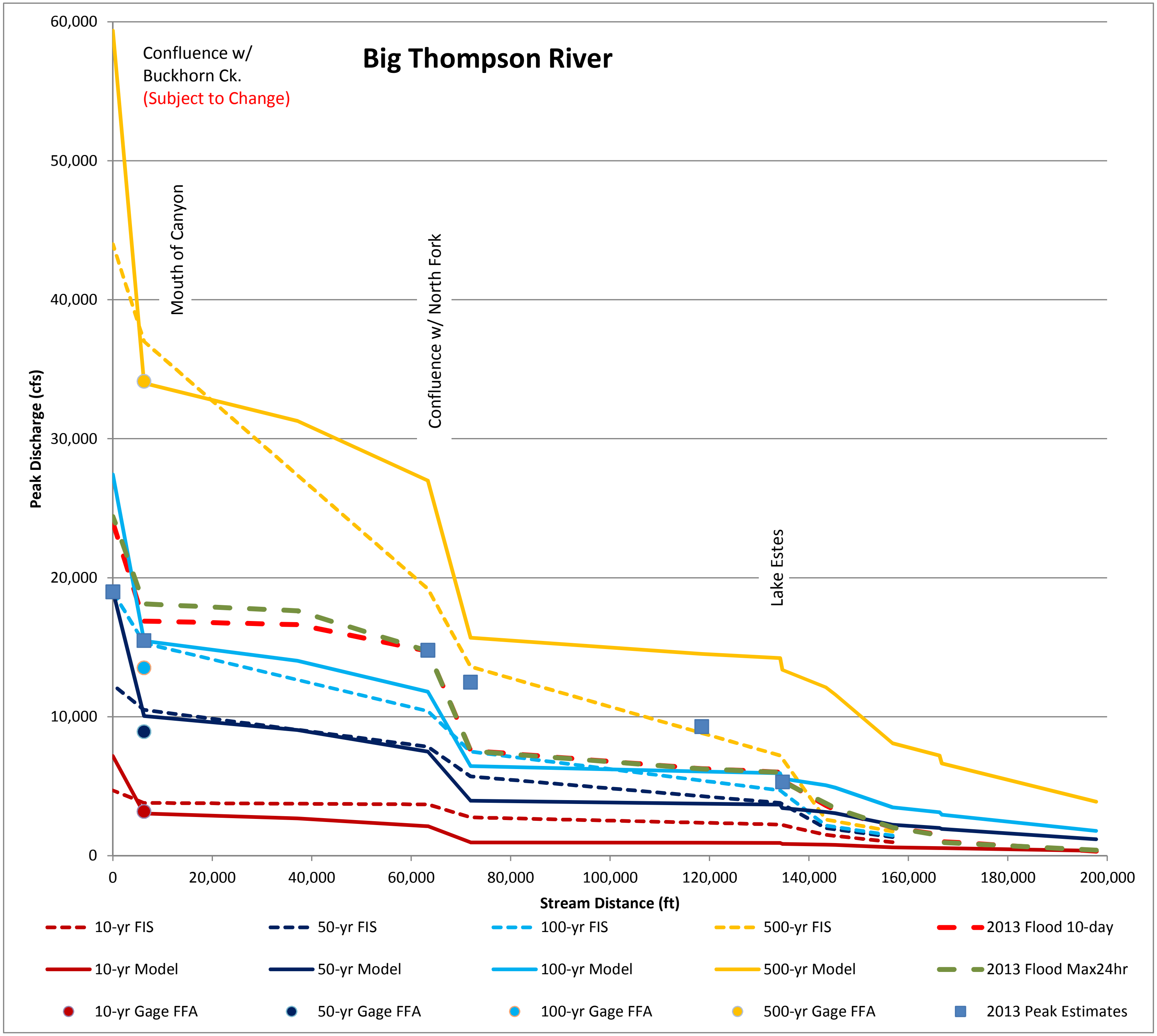
# Appendix C.1 (continued)
# Condensed for Profiles

**BIG THOMPSON RIVER WATERSHED**

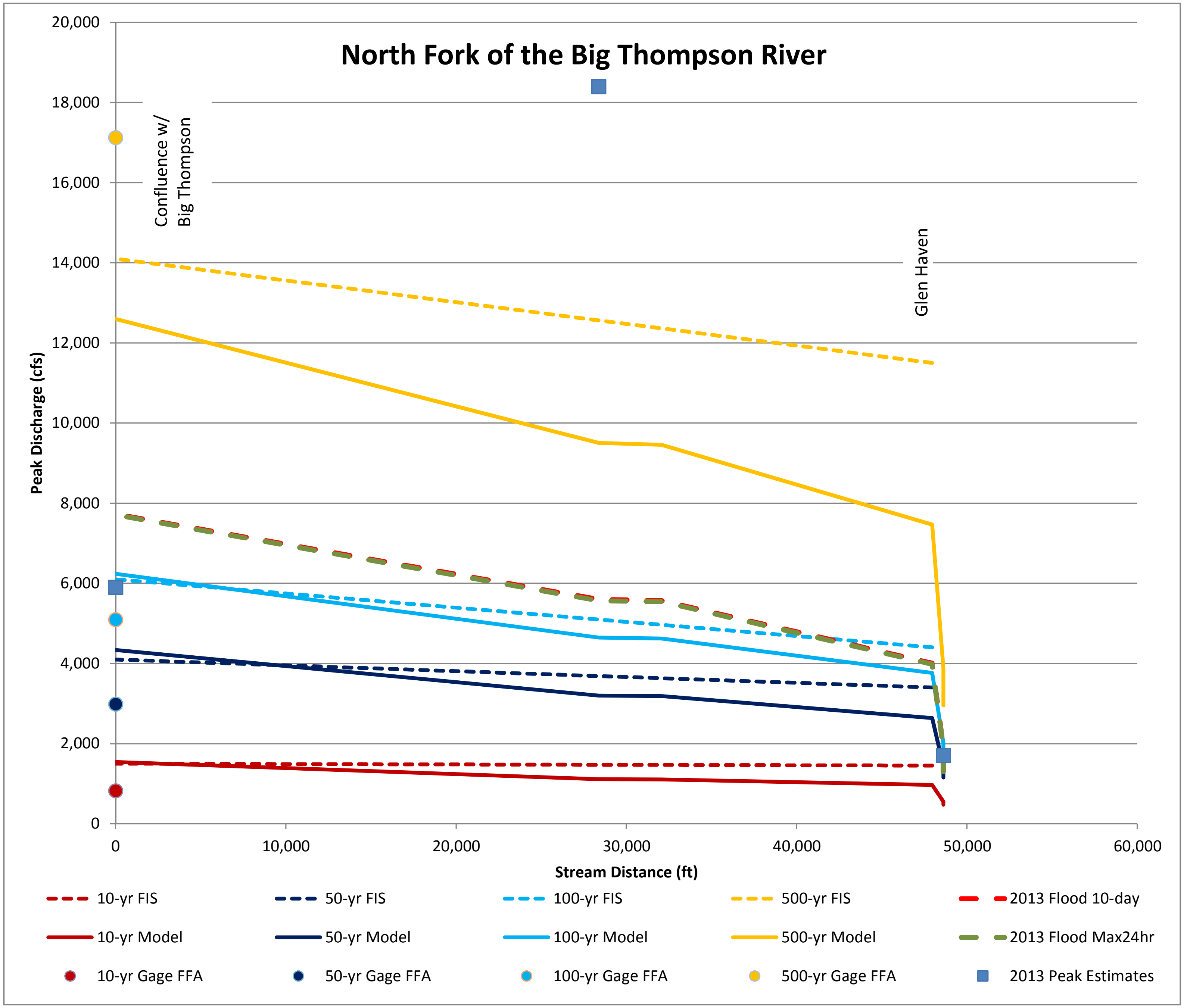
| 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **HEC-HMS Design Point** | **Description** | **Approx. Station (ft)** | **Drainage Area (sq. mi.)** | **2013 Flood Estimated Peak Discharge (cfs)** | **2013 Flood 10-day Period Calibrated (cfs)** | **2013 Flood Max 24hr Period Calibrated (cfs)** | **NOAA 24-hr Type II Predictive Storms (Depth-Area Ajdusted)** | | | | | **Effective FIS Peak Discharge Approximate Location for Comparison** | | | | **Ayres 2013 Updated Flood Frequency Analysis** | | | |
| | | | | | | | **10-yr (cfs)** | **25-yr (cfs)** | **50-yr (cfs)** | **100-yr (cfs)** | **500-yr (cfs)** | **10-yr (cfs)** | **50-yr (cfs)** | **100-yr (cfs)** | **500-yr (cfs)** | **10-yr (cfs)** | **50-yr (cfs)** | **100-yr (cfs)** | **500-yr (cfs)** |
| J4026 | BT at confluence with Fern Creek in RMNP | 197,791 | 33 | | 329 | 394 | 354 | 737 | 1,183 | 1,793 | 3,893 | | | | | | | | |
| J4040 | BT at Confluence of Glacier Creek | 166,727 | 65 | | 1,020 | 958 | 557 | 1,177 | 1,923 | 2,959 | 6,650 | | | | | | | | |
| J4037 | BT at confluence with Wind River upstream of Estes Park | 166,288 | 75 | | 1,514 | 1,460 | 558 | 1,204 | 2,000 | 3,124 | 7,216 | | | | | | | | |
| J4047 | BT at confluence with Beaver Brook | 156,868 | 84 | | 2,032 | 2,029 | 609 | 1,328 | 2,221 | 3,482 | 8,089 | 980 | 1,340 | 1,460 | 1,760 | | | | |
| J4052 | BT at confluence with Fall River | 145,353 | 126 | | 3,274 | 3,398 | 786 | 1,794 | 3,056 | 4,896 | 11,580 | | | | | | | | |
| J4061 | BT at confluence with Black Canyon Creek | 143,406 | 136 | | 3,639 | 3,773 | 794 | 1,834 | 3,148 | 5,074 | 12,118 | 1,510 | 1,990 | 2,180 | 2,600 | | | | |
| J4055 | BT inflow to Lake Estes | 134,698 | 154 | | 5,415 | 5,342 | 846 | 1,980 | 3,424 | 5,548 | 13,370 | | | | | | | | |
| **Lake Estes** | **Lake Estes (Olympus Dam)** | **134,698** | **154** | **5,327** | **5,327** | **5,327** | **846** | **1,980** | **3,424** | **5,548** | **13,370** | | | | | | | | |
| J4058 | BT at confluence with Dry Gulch below Lake Estes | 134,222 | 160 | | 6,023 | 6,003 | 923 | 2,142 | 3,683 | 5,942 | 14,219 | 2,250 | 3,800 | 4,700 | 7,200 | | | | |
| **ICC_62** | **BT at Loveland Heights (Jarrett Estimate #62)** | **118,462** | **164** | **9,300** | **6,269** | **6,252** | **936** | **2,176** | **3,748** | **6,055** | **14,520** | | | | | | | | |
| **ICC_65** | **BT at Mountain Shadows Lane (Jarrett Estimate #65)** | **71,968** | **188** | **12,500** | **7,566** | **7,534** | **960** | **2,278** | **3,961** | **6,453** | **15,686** | **2,750** | **5,700** | **7,500** | **13,600** | | | | |
| **J4080** | **Confluence of BT and NFBT at Drake (Jarrett Estimate #76)** | **63,392** | **276** | **14,800** | **14,731** | **14,728** | **2,116** | **4,538** | **7,495** | **11,803** | **26,983** | **3,700** | **7,850** | **10,400** | **19,200** | | | | |
| J4083 | BT at confluence with Cedar Creek | 37,172 | 300 | | 16,632 | 17,624 | 2,693 | 5,582 | 9,048 | 14,020 | 31,273 | | | | | | | | |
| **ICC_66** | **BT near Mouth of Canyon (Jarrett Estimate #66)** | **6,280** | **314** | **15,500** | **16,876** | **18,106** | **3,041** | **6,249** | **10,054** | **15,449** | **34,002** | **3,800** | **10,500** | **15,300** | **37,000** | **3,208** | **8,942** | **13,533** | **34,145** |
| J4077 | BT confluence with Buckhorn [1] | 21 | 461 | | 23,957 | 24,406 | 7,174 | 12,838 | 19,051 | 27,437 | 59,360 | 4,700 | 12,300 | 19,000 | 44,000 | | | | |
| **Outlet_BT-BH** | **BT downstream study limit [1]** | **0** | **461** | **19,000** | **23,957** | **24,406** | **7,174** | **12,838** | **19,051** | **27,437** | **59,360** | | | | | | | | |
| **BT31** | **Headwaters of North Fork Big Thompson (NRCS Estimate)** | **48,614** | **19** | **1,700** | **1,302** | **1,297** | **473** | **804** | **1,154** | **1,588** | **2,954** | | | | | | | | |
| J4103 | NFBT upstream of Glen Haven | 48,614 | 26 | | 1,913 | 1,902 | 554 | 975 | 1,432 | 2,010 | 3,870 | | | | | | | | |
| J4098 | NFBT at Glen Haven | 47,955 | 51 | | 4,004 | 3,980 | 971 | 1,764 | 2,640 | 3,767 | 7,464 | 1,450 | 3,400 | 4,400 | 11,500 | | | | |
| J4106 | NFBT at confluence with Miller Fork | 32,065 | 69 | | 5,570 | 5,546 | 1,108 | 2,083 | 3,184 | 4,625 | 9,460 | | | | | | | | |
| **ICC_78** | **NFBT 4.5 miles above Drake (NRCS Peak Estimation Point)** | **28,368** | **70** | **18,400** | **5,596** | **5,570** | **1,111** | **2,091** | **3,197** | **4,644** | **9,502** | | | | | | | | |
| **J4080b** | **NFBT at Drake (Jarrett Estimate #81)** | **0** | **86** | **5,900** | **7,723** | **7,706** | **1,539** | **2,868** | **4,336** | **6,240** | **12,599** | **1,500** | **4,100** | **6,100** | **14,100** | **823** | **2,987** | **5,096** | **17,122** |
| J4029 | Buckorn Creek at confluence with Twin Cabin Gulch | 122,878 | 31 | | 2,412 | 2,395 | 495 | 986 | 1,553 | 2,296 | 4,797 | | | | | | | | |
| J4130 | Buckhorn at confluence with Sheep Creek | 108,712 | 43 | | 3,522 | 3,486 | 927 | 1,766 | 2,683 | 3,875 | 7,740 | | | | | | | | |
| **J4133** | **Buckhorn at Confl. w/ Stove Prarie Creek (Jarrett #106)** | **102,179** | **50** | **4,400** | **4,205** | **4,199** | **1,307** | **2,410** | **3,591** | **5,109** | **9,964** | | | | | | | | |
| J4125 | Buckhorn at Fish Creek confluence | 77,194 | 70 | | 6,356 | 6,294 | 2,023 | 3,709 | 5,465 | 7,733 | 14,931 | | | | | | | | |
| **ICC_79** | **Buckhorn 3.5 miles above Masonville (NRCS Estimation Point)** | **52,899** | **88** | **11,000** | **8,115** | **7,929** | **2,972** | **5,218** | **7,519** | **10,459** | **19,622** | | | | | | | | |
| **J4119b** | **Buckhorn at Masonville above Redstone Creek (Jarrett #108)** | **30,896** | **97** | **7,700** | **8,962** | **8,676** | **3,574** | **6,178** | **8,834** | **12,198** | **22,587** | **4,674** | **10,321** | **13,862** | **24,000** | | | | |
| J4119 | Buckhorn at confluence with Redstone Creek | 30,896 | 128 | | 10,531 | 10,253 | 3,796 | 6,900 | 10,125 | 14,218 | 27,154 | 6,321 | 13,593 | 18,059 | 32,000 | | | | |
| **J4088** | **Buckhorn at County Rd. 24H, CDWR Gage (Jarrett #111)** | **0** | **144** | **11,200** | **11,136** | **10,878** | **4,850** | **8,695** | **12,591** | **17,408** | **32,501** | **6,844** | **15,090** | **20,244** | **36,000** | **2,807** | **10,362** | **16,233** | **39,513** |

[1] - Predictive peak discharges at confluence of Big Thompson and Buckhorn are provisional and subject to change.

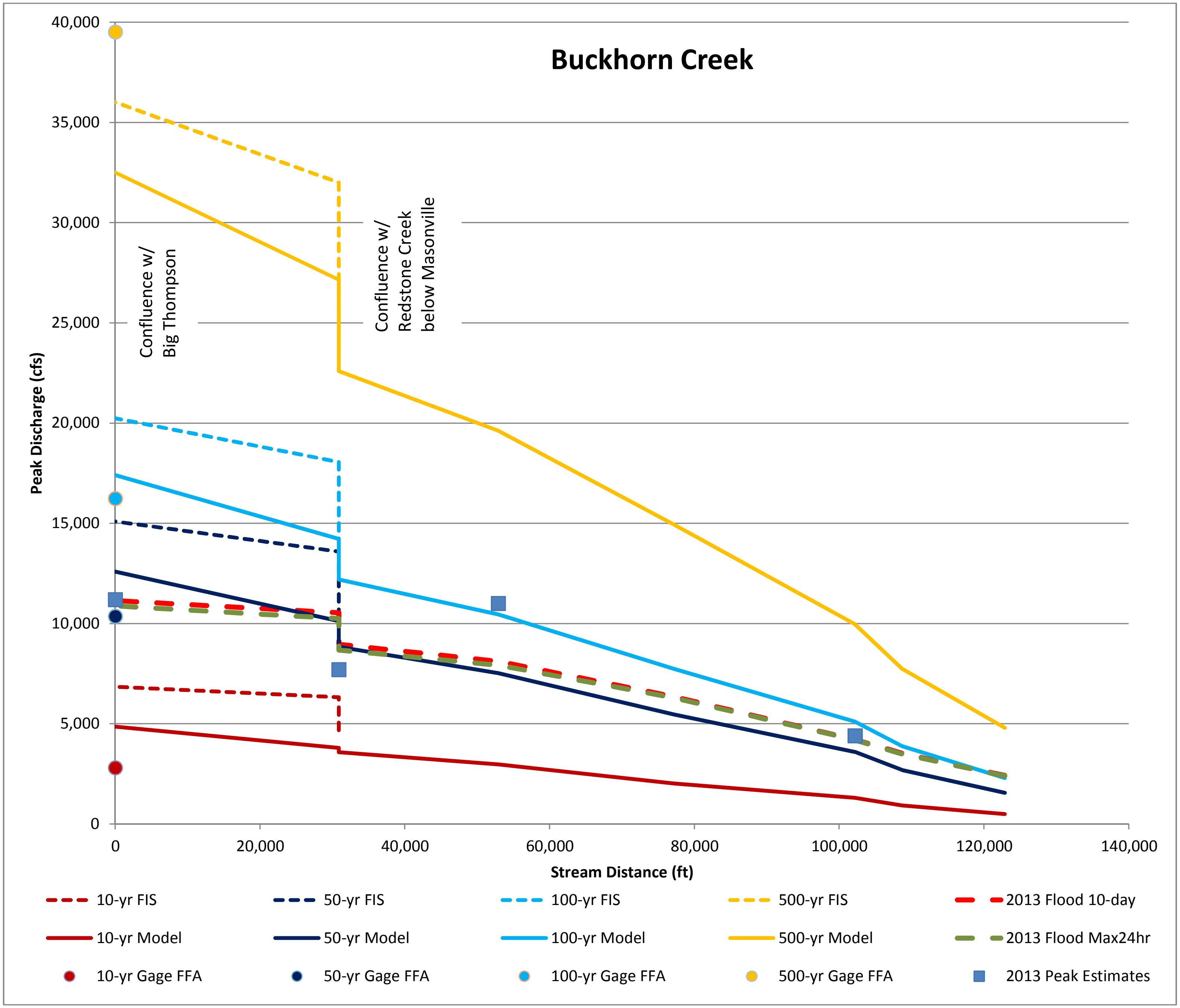
# Appendix C.2


Big Thompson River
Confluence w/
Buckhorn Ck.
(Subject to Change)
Mouth of Canyon
Confluence w/ North Fork
Lake Estes
Peak Discharge (cfs)
60,000
50,000
40,000
30,000
20,000
10,000
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
2013 Flood 10-day
10-yr Model
50-yr Model
100-yr Model
500-yr Model
2013 Flood Max24hr
10-yr Gage FFA
50-yr Gage FFA
100-yr Gage FFA
500-yr Gage FFA
2013 Peak Estimates

# Appendix C.3


North Fork of the Big Thompson River
Peak Discharge (cfs)
20,000
18,000
16,000
14,000
12,000
10,000
8,000
6,000
4,000
2,000
0
Confluence w/
Big Thompson
Glen Haven
0
10,000
20,000
30,000
40,000
50,000
60,000
Stream Distance (ft)
10-yr FIS
50-yr FIS
100-yr FIS
500-yr FIS
2013 Flood 10-day
10-yr Model
50-yr Model
100-yr Model
500-yr Model
2013 Flood Max24hr
10-yr Gage FFA
50-yr Gage FFA
100-yr Gage FFA
500-yr Gage FFA
2013 Peak Estimates

# Appendix C.4


Buckhorn Creek
Peak Discharge (cfs)
40,000
35,000
30,000
25,000
20,000
15,000
10,000
5,000
0
Stream Distance (ft)
0
20,000
40,000
60,000
80,000
100,000
120,000
140,000
Confluence w/ Big Thompson
Confluence w/ Redstone Creek below Masonville
10-yr FIS
50-yr FIS
100-yr FIS
500-yr FIS
2013 Flood 10-day
10-yr Model
50-yr Model
100-yr Model
500-yr Model
2013 Flood Max24hr
10-yr Gage FFA
50-yr Gage FFA
100-yr Gage FFA
500-yr Gage FFA
2013 Peak Estimates

# 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

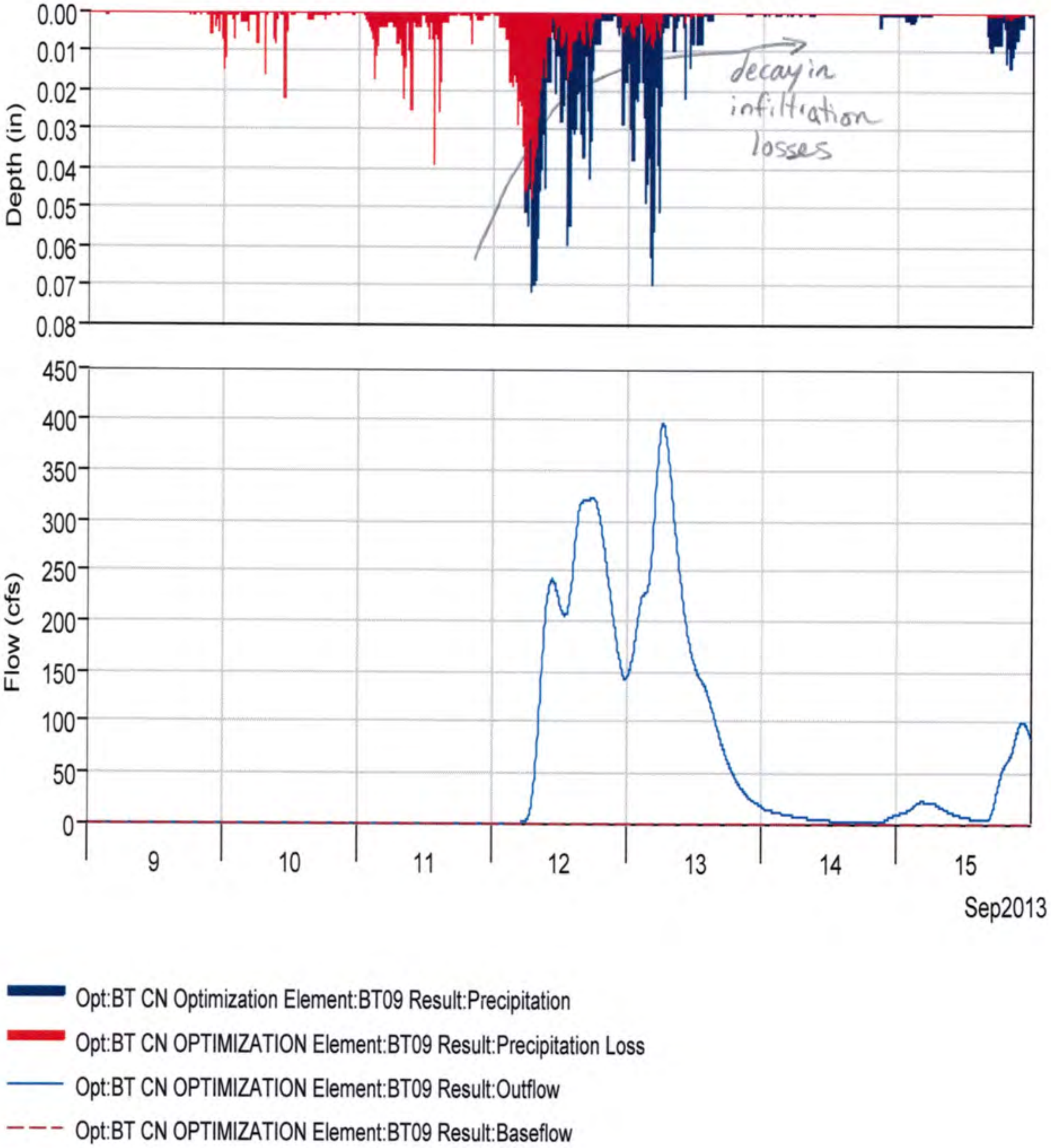
Good match to peaks

Receeding limb difference most likely due to infiltrated precip from early in the storm becoming shallow groundwat flow and draining out later

2013 Flood
(9.48 inches precip)

Upstream of Lake Estes

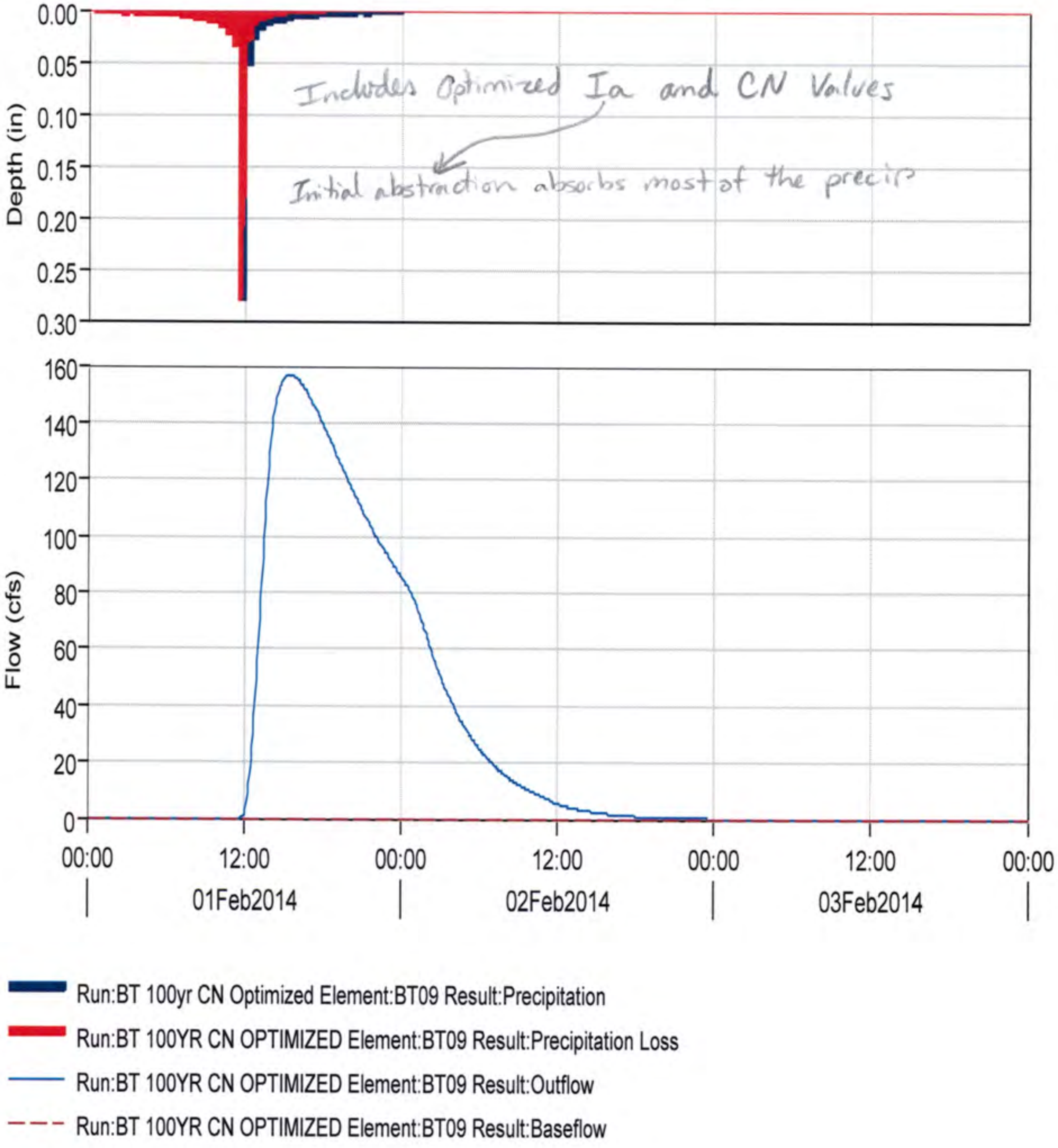
Subbasin "BT09" Results for Trial "BT CN Optimization"


decay in infiltration losses

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

Upstream of Lake Estes

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



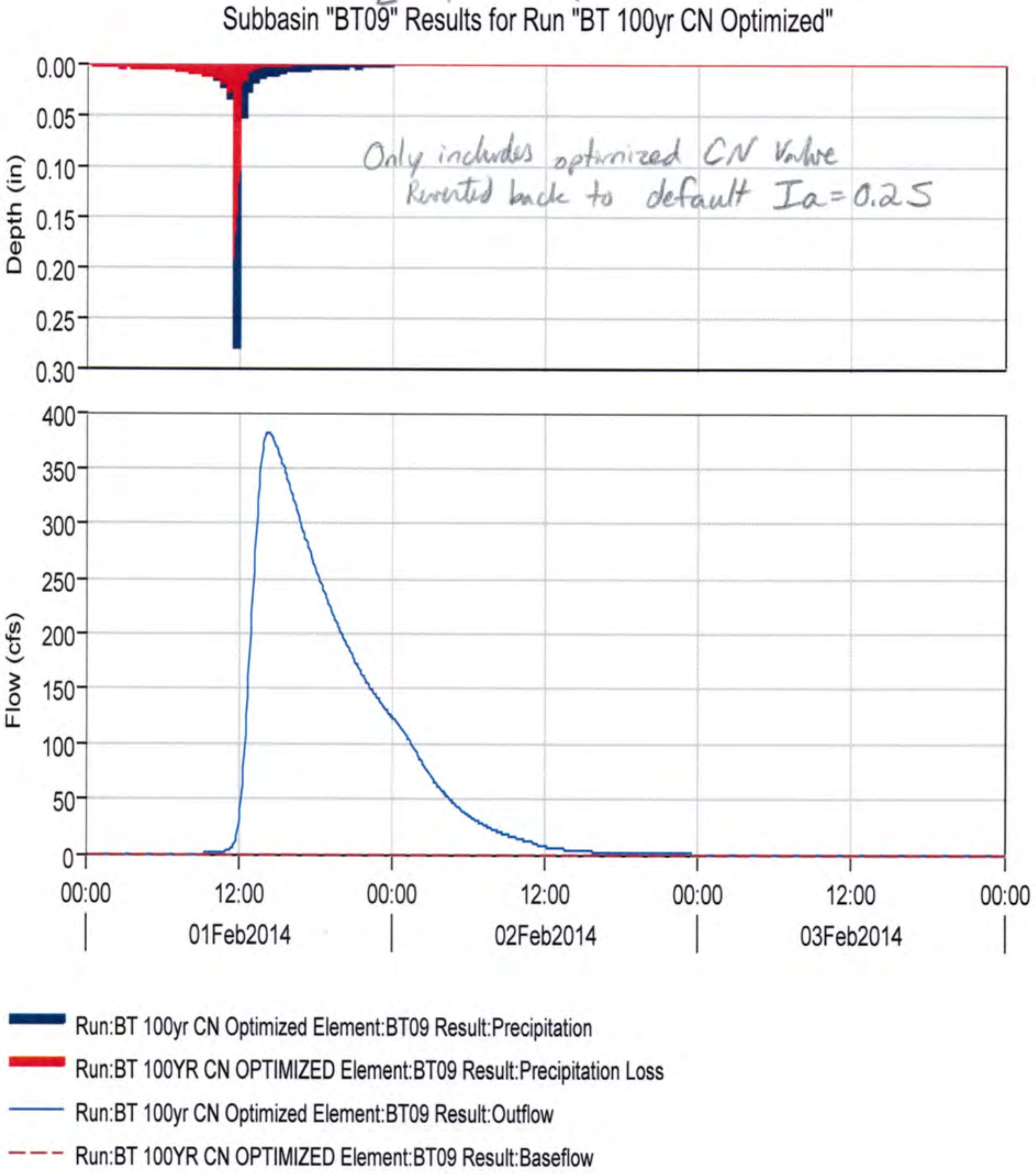
Includes Optimized Ia and CN Values

Initial abstraction absorbs most of the precip

NOAA 100-yr 24 hr Storm

(4.42 inches precip)

← upstream of Lake Estes



Only includes optimized CN Value
Reverted back to default Ia = 0.25

# 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"

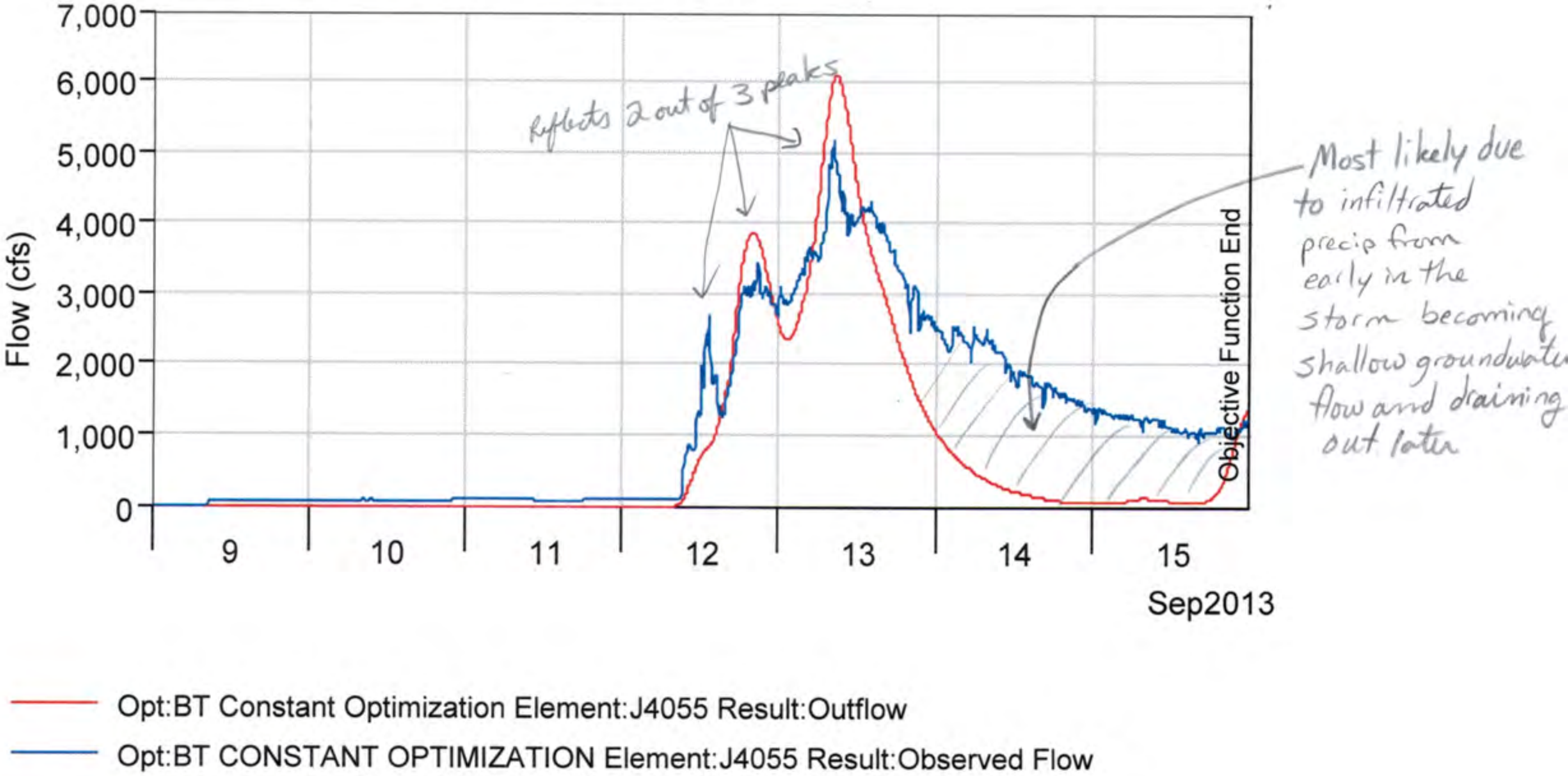
Start of Function : 09Sep2013, 00:00    Type : Peak-Weighted RMS Error
End of Function : 15Sep2013, 23:45    Value : 994.3

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



Reflects 2 out of 3 peaks

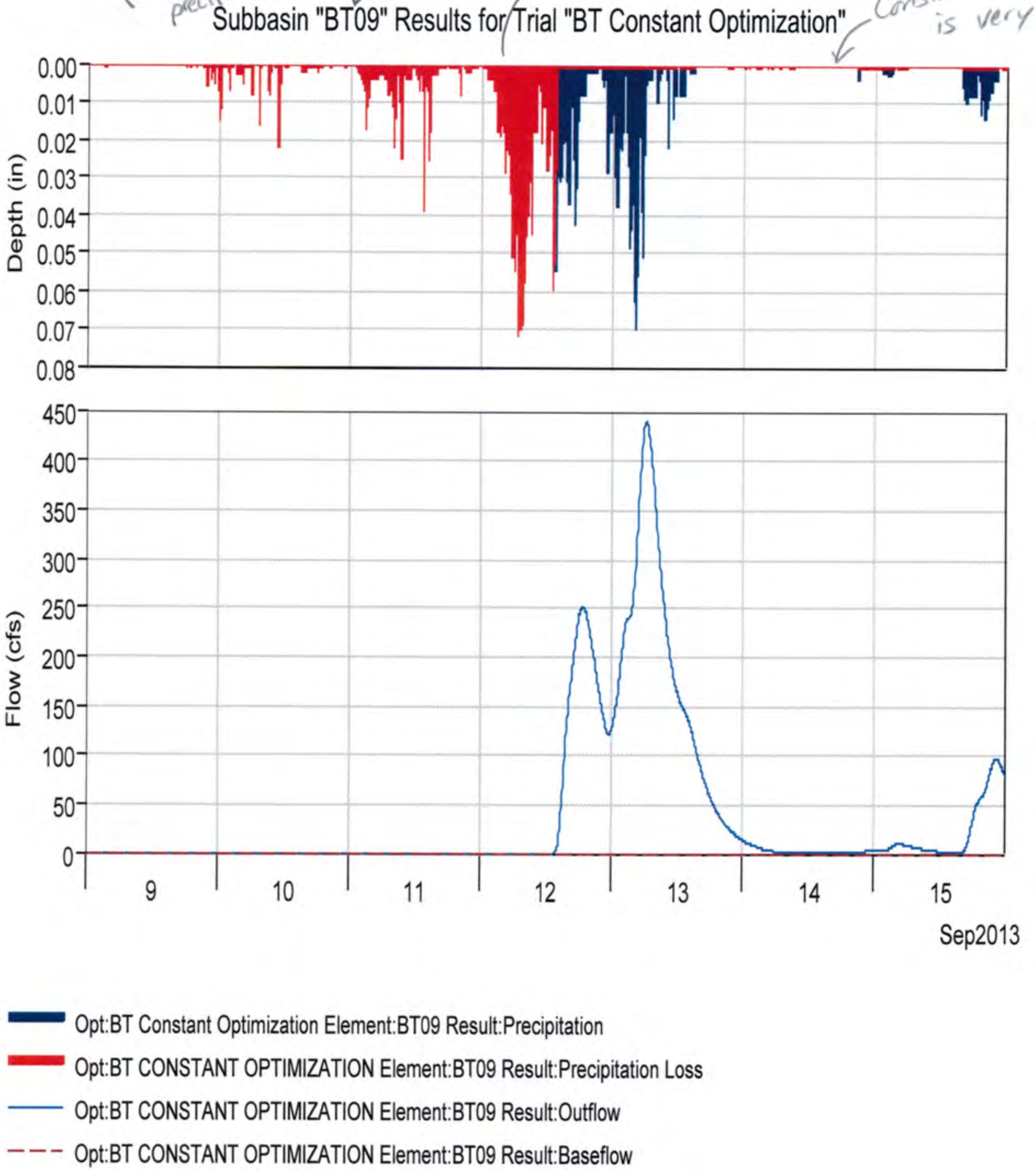
Most likely due to infiltrated precip from early in the storm becoming shallow groundwate flow and draining out later

2013 Flood
(9.48 inches precip)

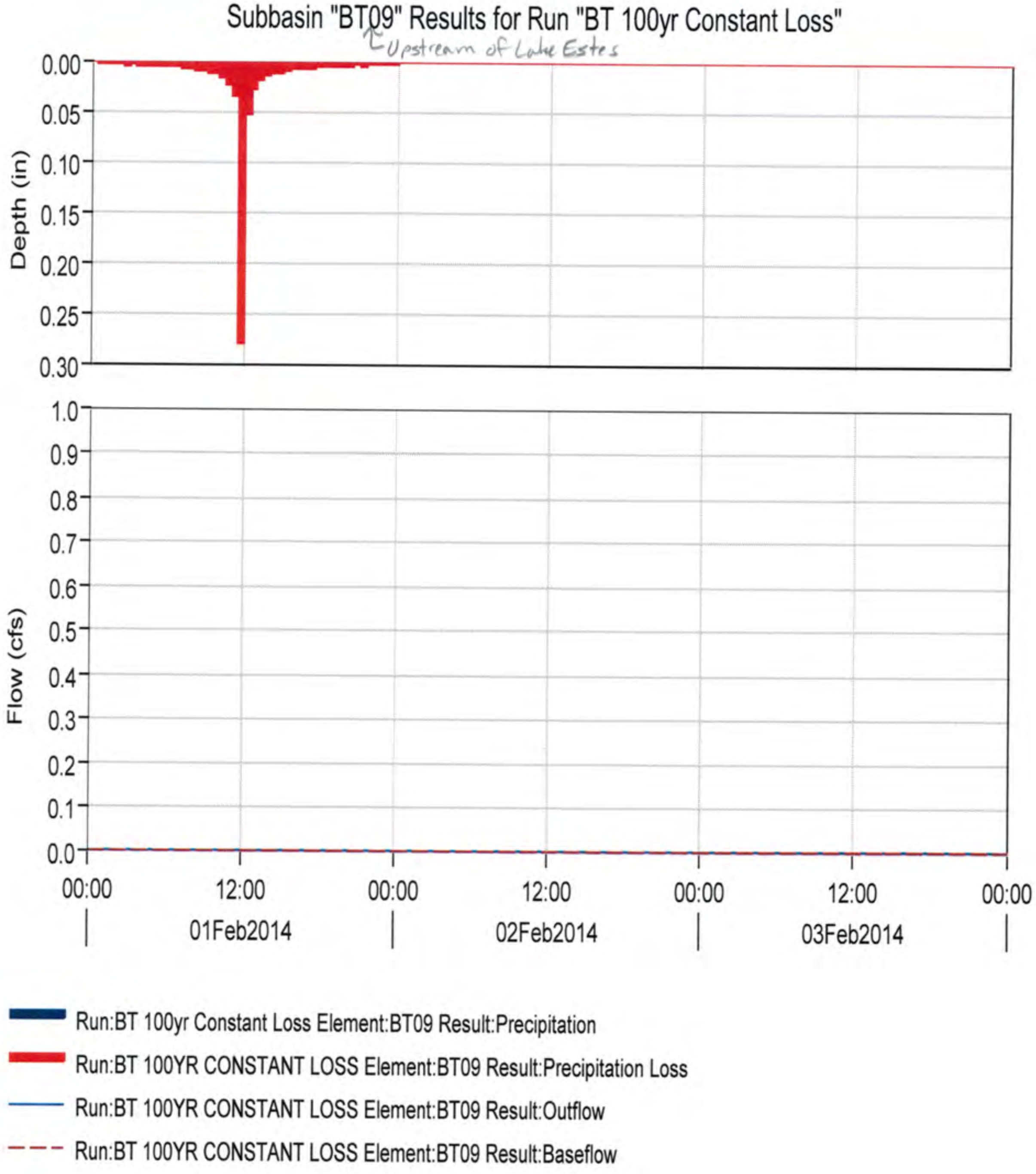
upstream of Lake Estes

Optimization dominated by Initial loss

Constant infiltration rate is very low



NOAA 100yr 24-hr Storm
(4.42 inches)



Subbasin "BT09" Results for Run "BT 100yr Constant Loss"

↑Upstream of Lake Estes

# 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

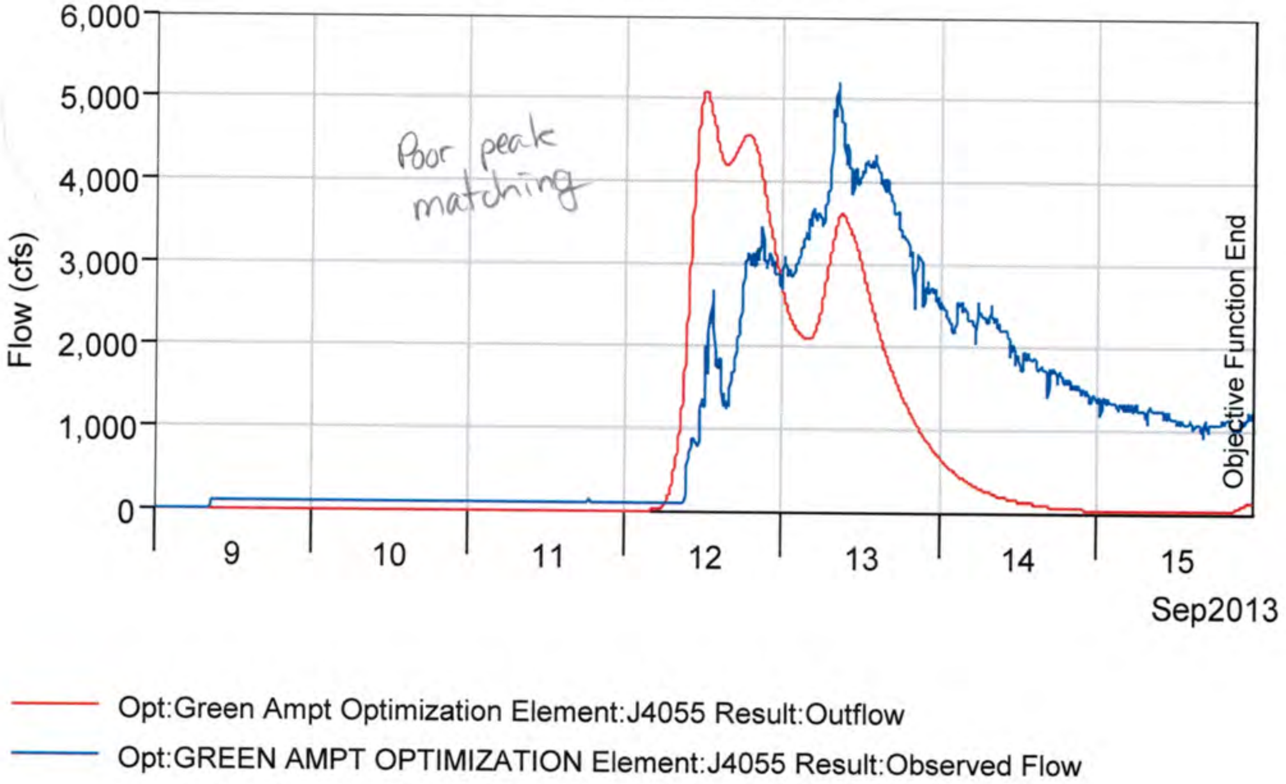
| Measure | Simulated | Observed | Difference | Percent Difference |
|---|---|---|---|---|
| Volume (IN) | 1.20 | 1.98 | -0.78 | -39.42 |
| Peak Flow (CFS) | 5061.0 | 5162.4 | -101.4 | -2.0 |
| Time of Peak | 12Sep2013, 12:05 | 13Sep2013, 08:15 | | |
| Time of Center of Mass | 13Sep2013, 01:37 | 13Sep2013,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

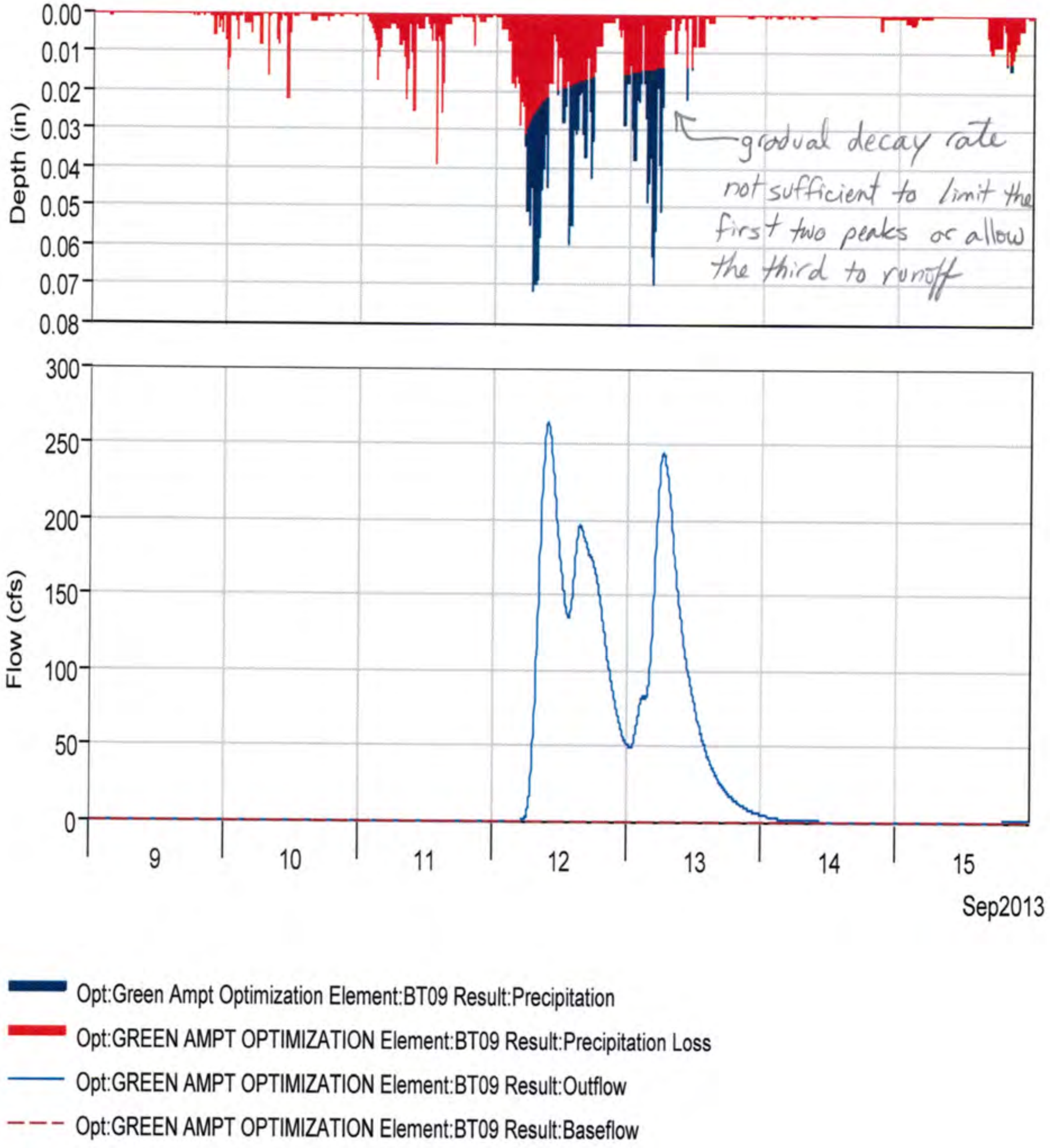


Poor peak matching

2013 Flood
(9.48 inches precip)

Upstream of Lake Estes

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

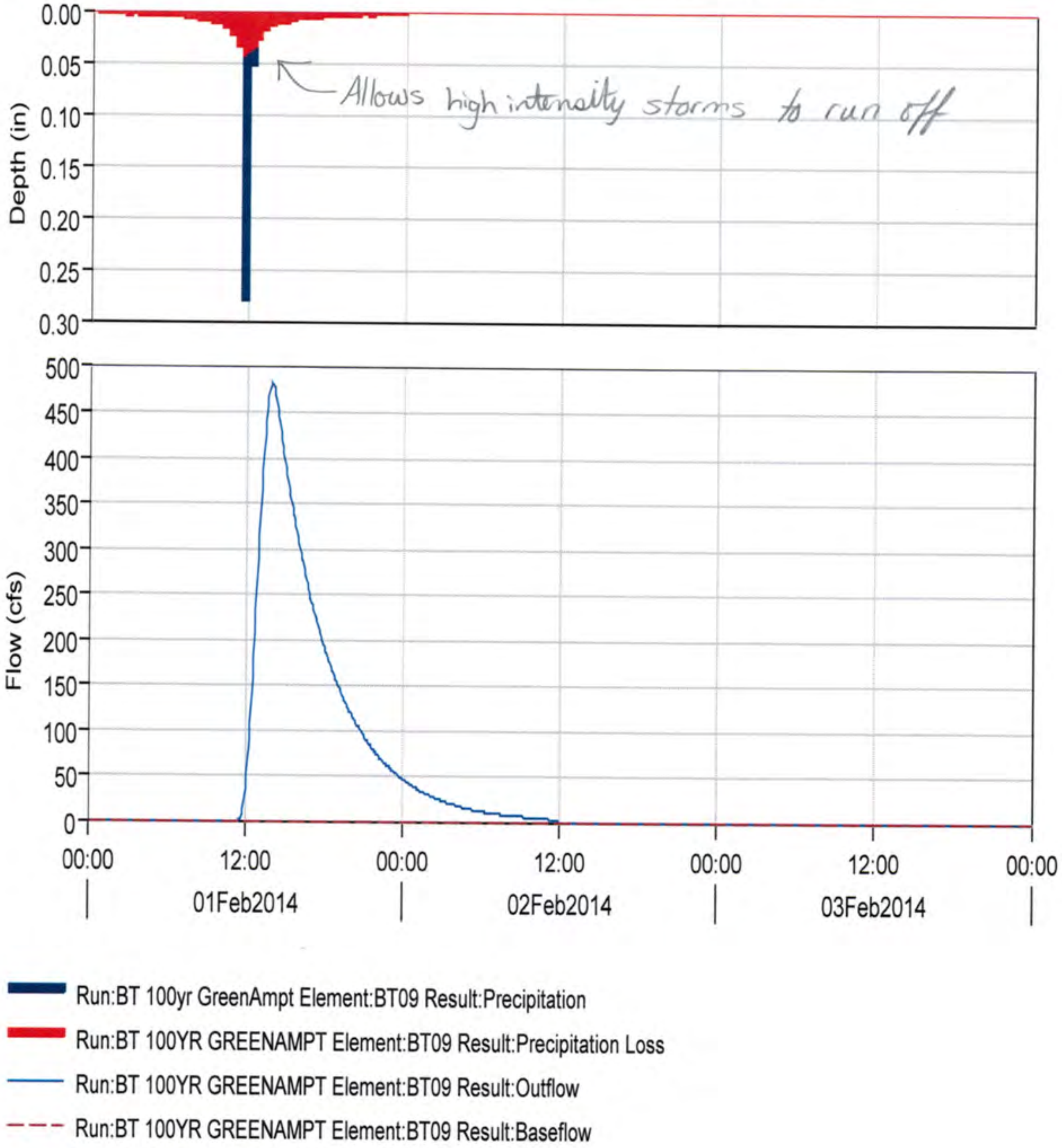


gradual decay rate not sufficient to limit the first two peaks or allow the third to runoff

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

Upstream of Lake Estes

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



# 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

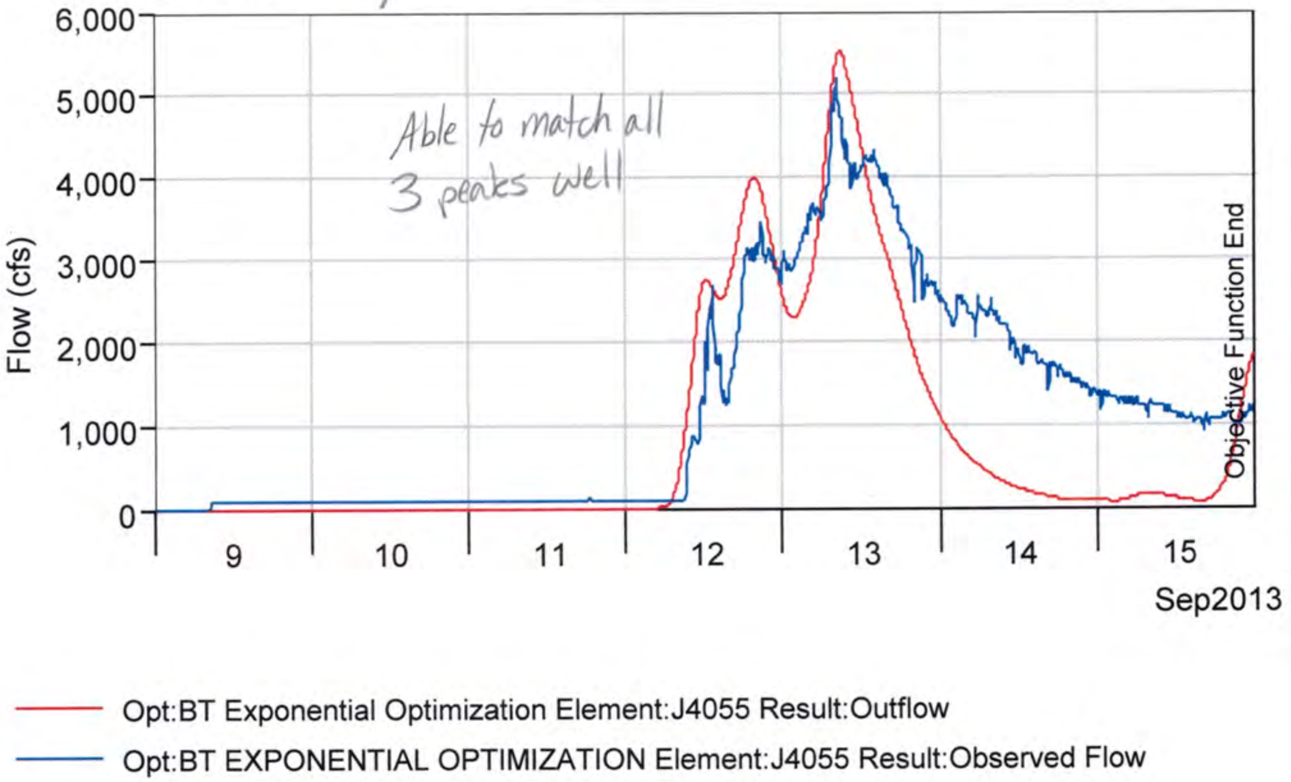
| Measure | Simulated | Observed | Difference | Percent Difference |
|---|---|---|---|---|
| Volume (IN) | 1.35 | 1.98 | -0.63 | -31.94 |
| Peak Flow (CFS) | 5498.0 | 5162.4 | 335.6 | 6.5 |
| Time of Peak | 13Sep2013, 08:55 | 13Sep2013, 08:15 | | |
| Time of Center of Mass | 13Sep2013, 08:54 | 13Sep2013,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

Model optimization involved changing:

- Initial Range
- Initial Loss Rate Coefficient
- Coefficient Ratio

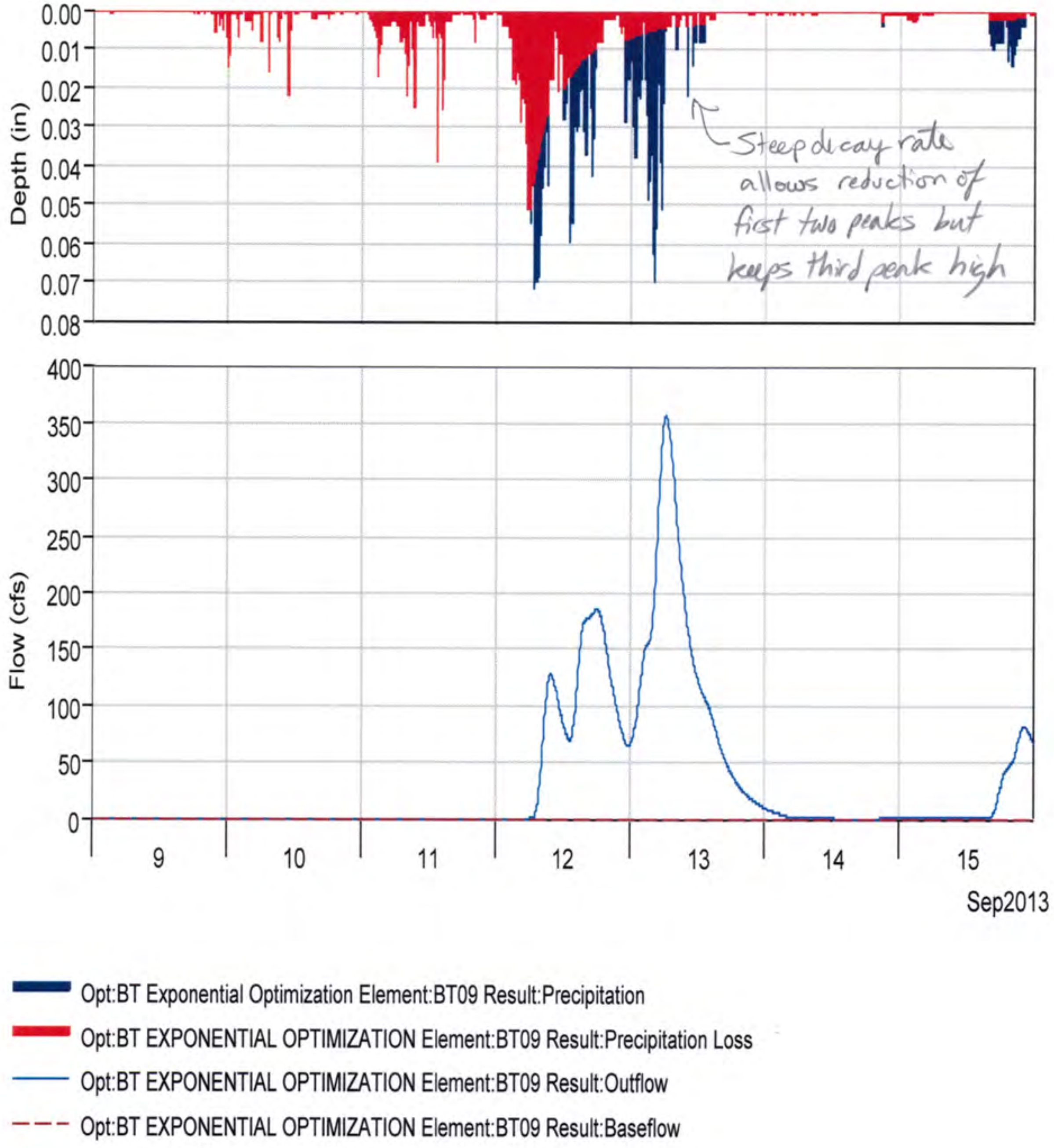
to acheive a best fit to the inflow hydrograph for Lake Estes

## Lake Estes Inflow Hydrograph Comparison



Able to match all
3 peaks well

2013 Flood
(9.48 inches Precip)



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

Upstream of Lake Estes

Steep decay rate allows reduction of first two peaks but keeps third peak high

```
                    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:

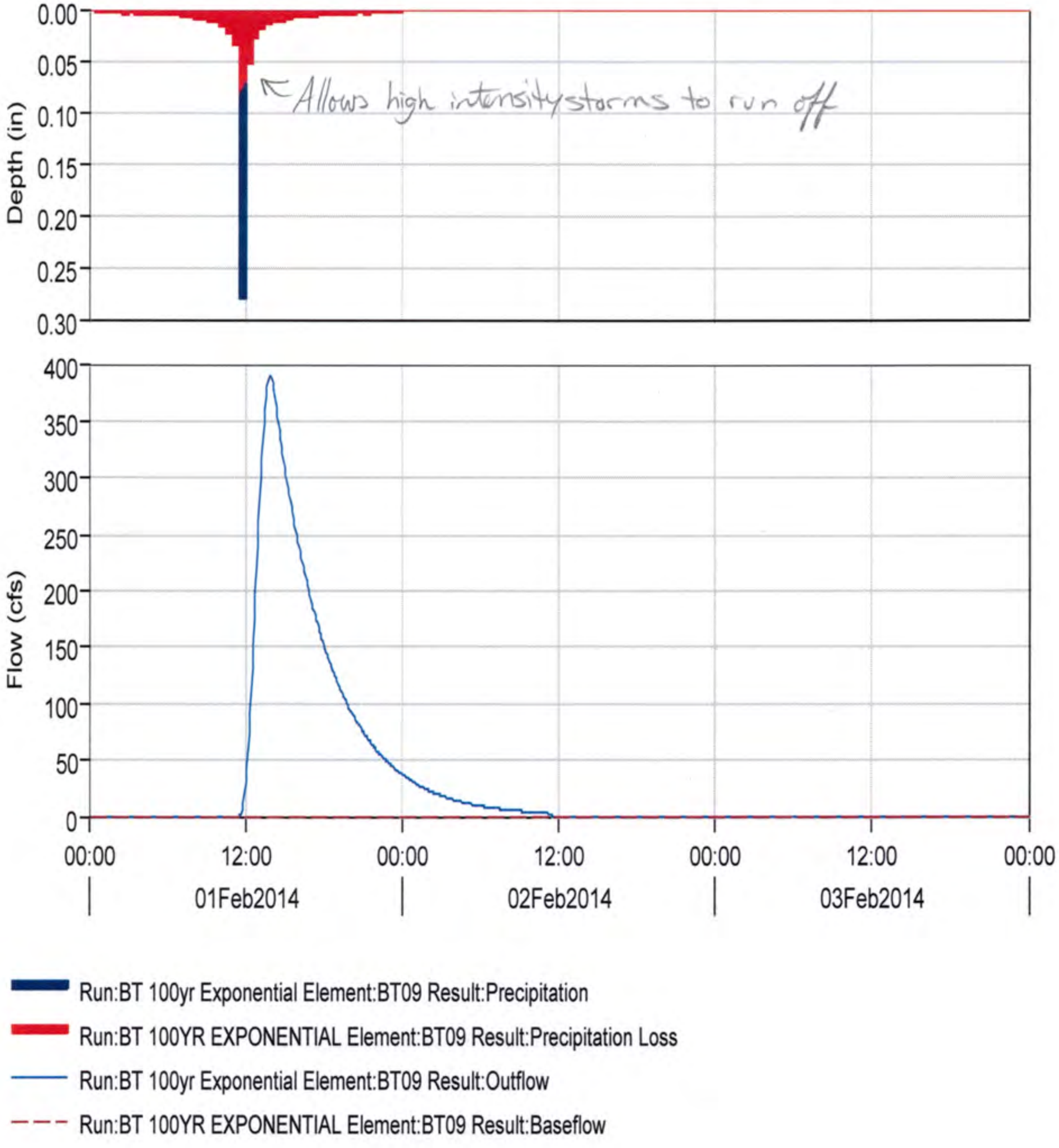
- Initial Range
- Initial Loss Rate Coefficient
- Coefficient Ratio

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"



Allows high intensity storms to run off

# 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 | | |

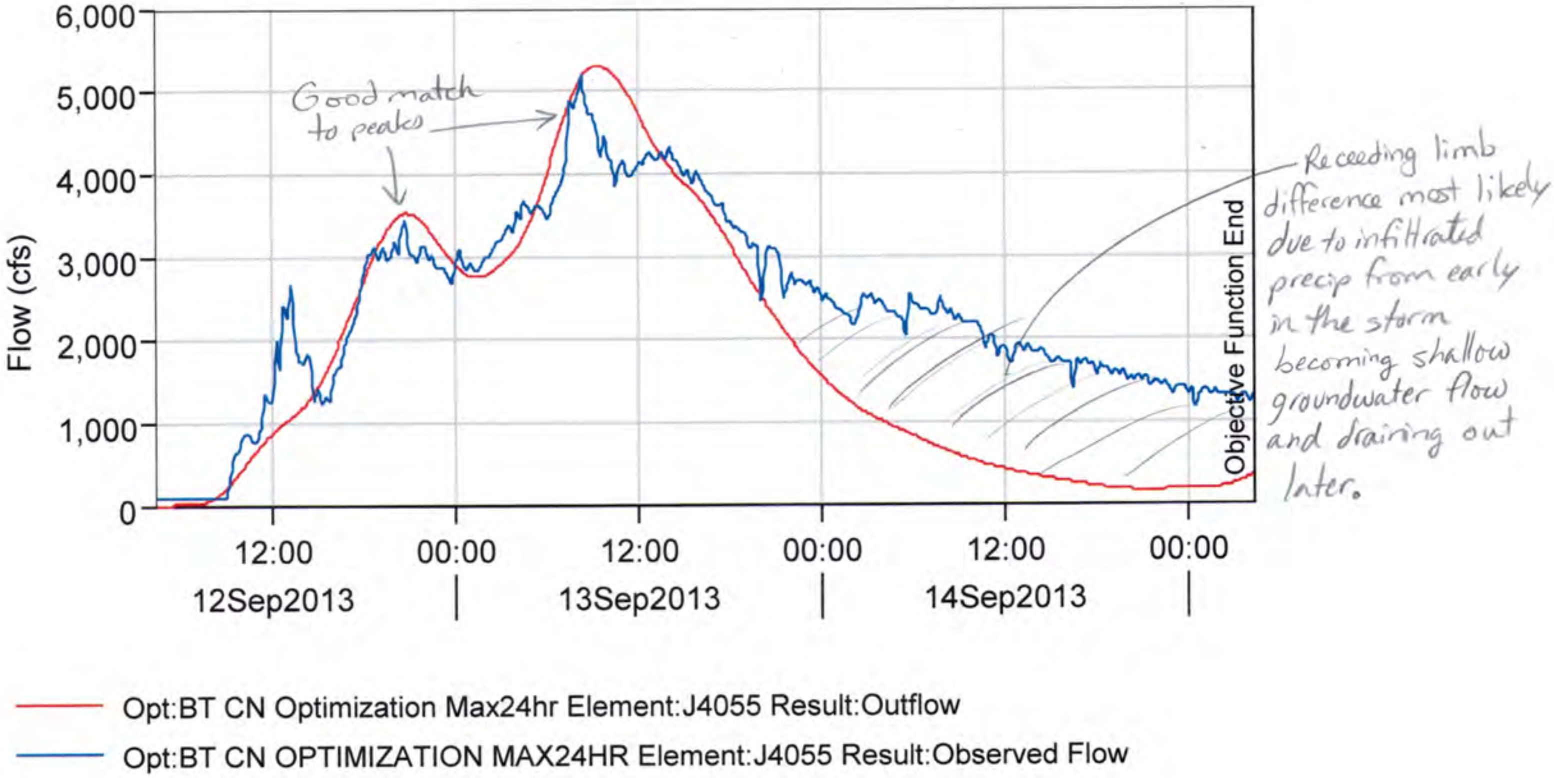
} even better fit

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)



Good match to peaks

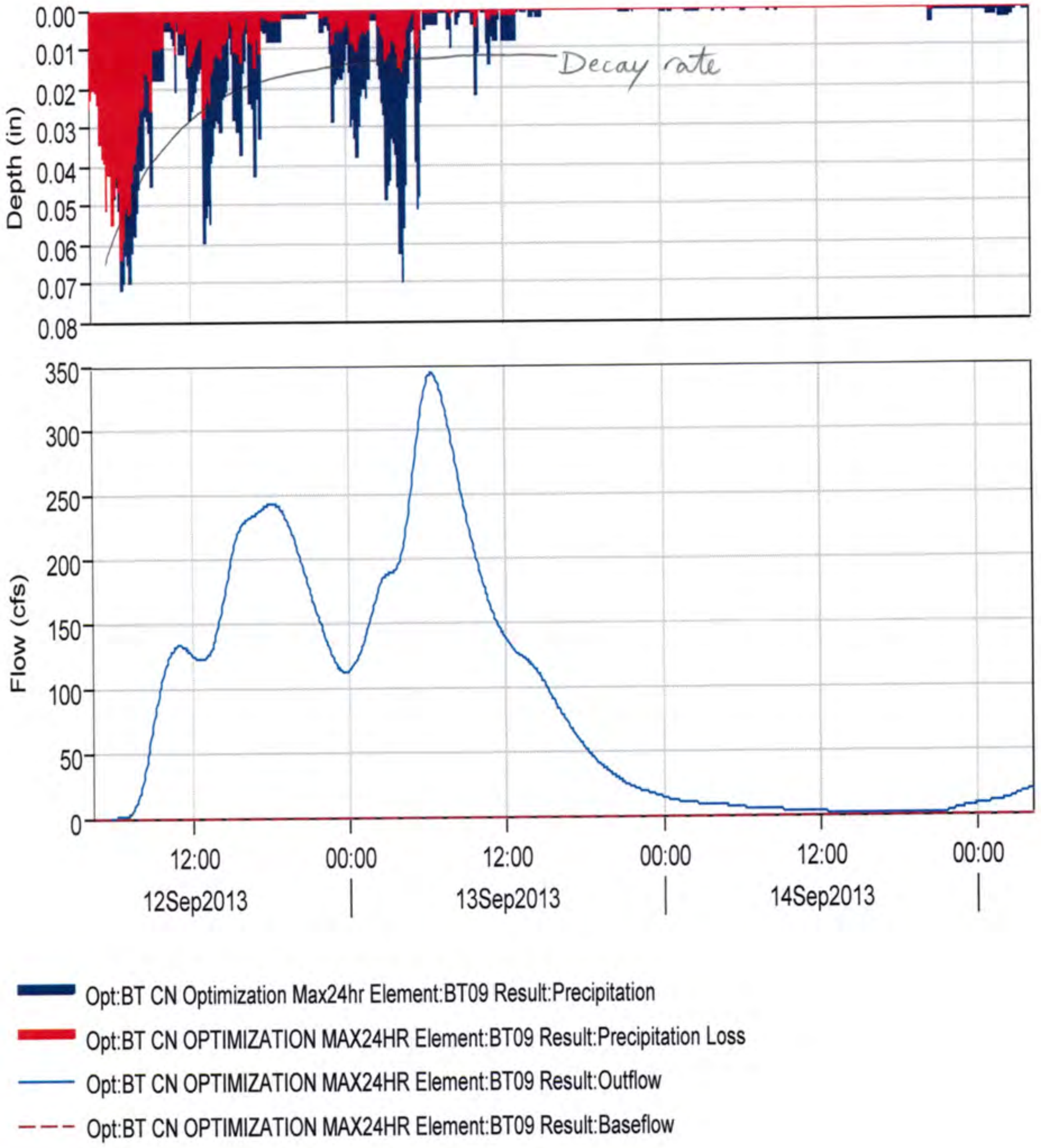
Receding limb difference most likely due to infiltrated precip from early in the storm becoming shallow groundwater flow and draining out later.

2013 Flood

(7.18 inches precip in 24-hr period)

upstream of Lake Estes

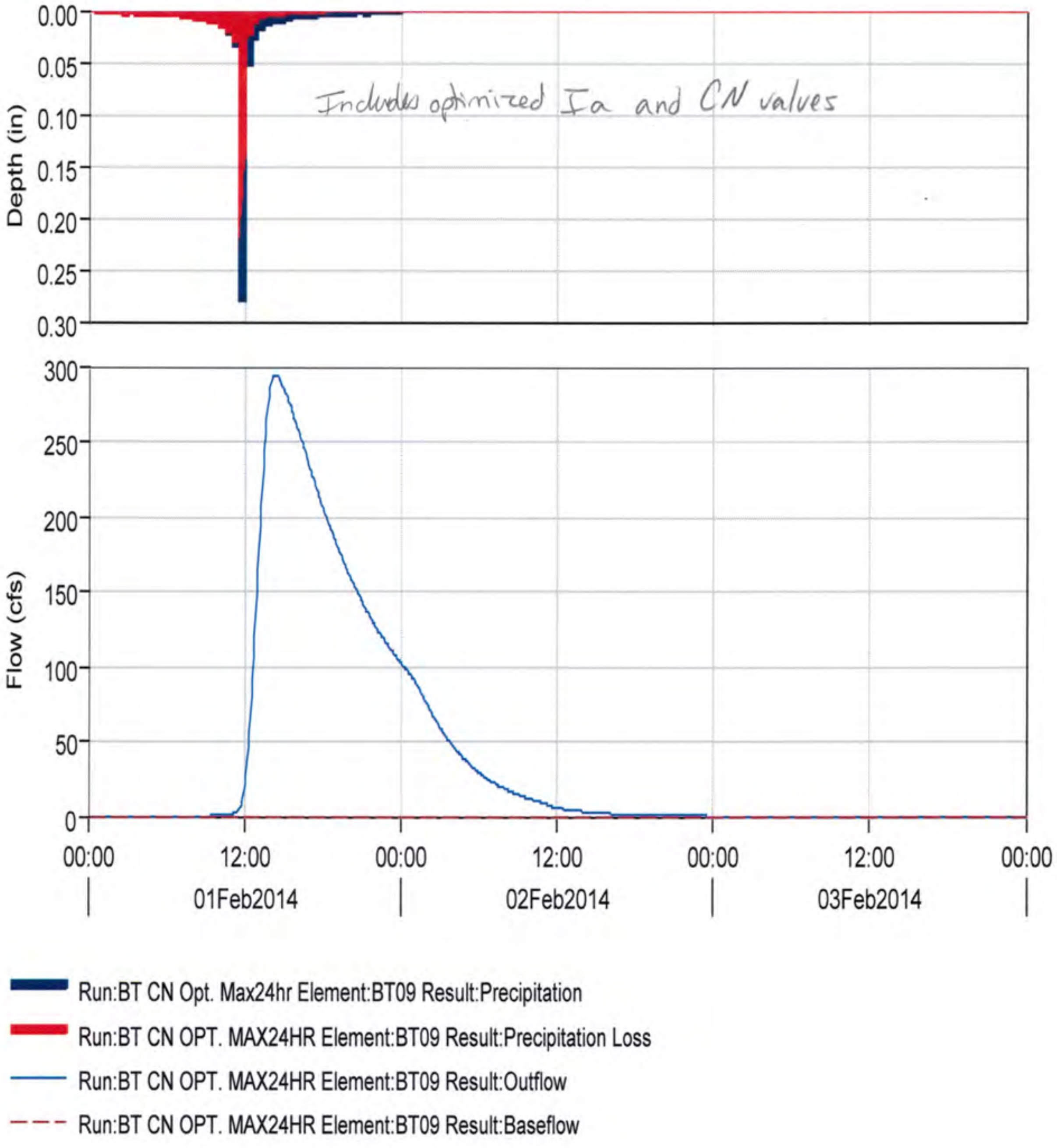
Subbasin "BT09" Results for Trial "BT CN Optimization Max24hr"



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

upstream of Lake Estes

Subbasin "BT09" Results for Run "BT CN Opt. Max24hr"



Includes optimized Ia and CN values

# Appendix C.6

## Big Thompson 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) | ag Time (hr | L (ft) | S (ft/ft) | n Channel | n Left OB | n Right OB |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| BT18 | Big Thompson River Headwaters Area | 29.6 | 56.9 | 68.6 | 0.4 | 0.15 | 10.55 | 4.60 | 371 | 4.50 | | | | | |
| BT17 | Fern Creek Trib to BT in RMNP | 3.0 | 49.6 | 59.9 | 0.4 | 0.15 | 4.39 | 2.20 | 870 | 2.29 | | | | | |
| J4026 | BT at confluence with Fern Creek in RMNP | | | | | | | | | | | | | | |
| R400 | BT below confluence with Fern Creek in RMNP | | | | | | | | | | 31064 | 0.019 | 0.15 | 0.15 | 0.15 |
| BT16 | BT area above and through Moraine Park | 7.5 | 45.7 | 55.1 | 0.4 | 0.15 | 7.25 | 3.67 | 525 | 3.48 | | | | | |
| BT15 | Mill Creek Trib to BT in RMNP | 5.4 | 38.0 | 45.8 | 0.4 | 0.15 | 7.47 | 3.25 | 559 | 3.34 | | | | | |
| BT14 | Glacier Creek Trib to BT in RMNP | 18.7 | 51.8 | 62.5 | 0.4 | 0.15 | 10.39 | 6.24 | 478 | 4.75 | | | | | |
| J4032 | Confluence of Glacier Creek and Mill Creek in RMNP | | | | | | | | | | | | | | |
| R410 | Glacier Creek Trib to BT at Moraine Park | | | | | | | | | | 7276 | 0.049 | 0.15 | 0.15 | 0.15 |
| BT13 | BT area near confluence with Glacier Creek | 0.6 | 42.5 | 51.3 | 0.4 | 0.15 | 1.78 | 0.78 | 469 | 1.34 | | | | | |
| J4040 | BT at Confluence of Glacier Creek | | | | | | | | | | | | | | |
| R380 | BT above confluence with Wind River | | | | | | | | | | 439 | 0.027 | 0.15 | 0.15 | 0.15 |
| BT12 | Wind River Trib to BT | 10.2 | 41.2 | 49.7 | 0.4 | 0.15 | 6.50 | 2.82 | 625 | 2.99 | | | | | |
| J4037 | BT at confluence with Wind River upstream of Estes Park | | | | | | | | | | | | | | |
| R390 | BT below confluence with Wind River | | | | | | | | | | 9420 | 0.016 | 0.15 | 0.15 | 0.15 |
| BT10 | BT area upstream of confluence with Beaver Brook | 1.3 | 50.7 | 61.2 | 0.4 | 0.15 | 2.47 | 1.14 | 436 | 1.71 | | | | | |
| BT19 | Beaver Brook Trib to BT | 7.5 | 51.6 | 62.2 | 0.4 | 0.15 | 6.96 | 3.64 | 465 | 3.50 | | | | | |
| J4047 | BT at confluence with Beaver Brook | | | | | | | | | | | | | | |
| R360 | BT upstream of confluence with Fall River | | | | | | | | | | 11515 | 0.009 | 0.15 | 0.15 | 0.15 |
| BT09 | BT area upstream of confluence with Fall River | 2.7 | 58.4 | 70.4 | 0.4 | 0.15 | 3.79 | 1.57 | 389 | 2.23 | | | | | |
| BT21 | Fall River Headwaters | 12.9 | 53.0 | 64.0 | 0.4 | 0.15 | 8.22 | 3.80 | 458 | 3.76 | | | | | |
| BT22 | Roaring River Trib to Fall River | 12.3 | 53.4 | 64.5 | 0.4 | 0.15 | 7.84 | 3.77 | 583 | 3.54 | | | | | |
| J4070 | Fall River confluence with Roaring River | | | | | | | | | | | | | | |
| R310 | Fall River Trib to BT | | | | | | | | | | 43695 | 0.024 | 0.15 | 0.15 | 0.15 |
| BT20 | Lower Fall River Trib Area | 14.5 | 46.0 | 55.6 | 0.4 | 0.15 | 12.38 | 6.13 | 334 | 5.30 | | | | | |
| J4050 | Fall River Trib to BT (NRCS Peak Estimation Point) | | | | | | | | | | | | | | |
| J4052 | BT at confluence with Fall River | | | | | | | | | | | | | | |
| R300 | BT below confluence with Fall River | | | | | | | | | | 1947 | 0.010 | 0.15 | 0.15 | 0.15 |
| BT23 | Black Canyon Creek Trib to BT | 10.2 | 44.2 | 53.4 | 0.4 | 0.15 | 11.06 | 4.98 | 508 | 4.45 | | | | | |
| J4061 | BT at confluence with Black Canyon Creek | | | | | | | | | | | | | | |
| R330 | BT upstream of Lake Estes | | | | | | | | | | 8708 | 0.003 | 0.15 | 0.15 | 0.15 |
| BT05 | Fish Creek Trib to Lake Estes | 16.7 | 53.1 | 55.7 | 0.4 | 0.15 | 8.46 | 3.94 | 380 | 3.96 | | | | | |
| BT06 | Trib area on North side of Lake Estes | 1.1 | 69.7 | 84.1 | 0.4 | 0.15 | 2.38 | 1.13 | 118 | 2.09 | | | | | |
| J4055 | BT inflow to Lake Estes | | | | | | | | | | | | | | |
| Lake Estes | Lake Estes (Olympus Dam) | | | | | | | | | | | | | | |
| R340 | BT below Lake Estes | | | | | | | | | | 476 | 0.106 | 0.15 | 0.15 | 0.15 |
| BT07 | Dry Gulch Trib to BT below Lake Estes | 6.3 | 68.3 | 71.7 | 0.4 | 0.15 | 5.60 | 2.35 | 262 | 3.10 | | | | | |
| J4058 | BT at confluence with Dry Gulch below Lake Estes | | | | | | | | | | | | | | |
| R358 | BT below confluence with Dry Gulch | | | | | | | | | | 15760 | 0.009 | 0.15 | 0.15 | 0.15 |
| BT03B | BT upstream of Loveland Heights | 3.9 | 51.5 | 58.5 | 0.4 | 0.15 | 4.92 | 2.83 | 292 | 3.10 | | | | | |
| ICC_62 | BT at Loveland Heightes (Peak Discharge Point #62) | | | | | | | | | | | | | | |
| R355 | BT below Loveland Heights | | | | | | | | | | 46494 | 0.019 | 0.15 | 0.15 | 0.15 |
| BT03A | BT area at Mountain Shadows Lane upstream of Drake | 23.3 | 46.9 | 54.0 | 0.4 | 0.15 | 11.76 | 4.21 | 215 | 4.95 | | | | | |
| ICC_65 | BT at Mountain Shadows Lane above Drake | | | | | | | | | | | | | | |
| R350 | BT above Drake | | | | | | | | | | 8576 | 0.028 | 0.15 | 0.15 | 0.15 |
| BT03 | BT area above Drake | 2.1 | 38.9 | 45.0 | 0.4 | 0.15 | 2.65 | 1.26 | 749 | 1.65 | | | | | |
| BT27 | Cow Creek Trib to NFBT | 9.8 | 63.5 | 71.0 | 0.4 | 0.15 | 8.87 | 4.03 | 464 | 3.92 | | | | | |
| BT28 | West Creek Trib to NFBT | 12.2 | 68.8 | 76.5 | 0.4 | 0.15 | 8.34 | 4.15 | 516 | 3.81 | | | | | |
| J4093 | West Creek upstream of Devils Gulch in NFBT | | | | | | | | | | | | | | |
| R160 | West Creek above Glen Haven in NFBT | | | | | | | | | | 16517 | 0.024 | 0.15 | 0.15 | 0.15 |
| BT26 | Devils Gulch Trib to NFBT | 2.8 | 57.4 | 62.5 | 0.4 | 0.15 | 3.50 | 1.22 | 272 | 2.12 | | | | | |
| BT30 | Fox Creek Trib to NFBT | 7.2 | 60.0 | 67.0 | 0.4 | 0.15 | 8.59 | 4.62 | 490 | 4.02 | | | | | |
| BT31 | Headwaters of North Fork Big Thompson River | 18.8 | 69.0 | 78.0 | 0.4 | 0.15 | 13.50 | 5.20 | 435 | 4.95 | | | | | |
| J4103 | NFBT upstream of Glen Haven | | | | | | | | | | | | | | |
| R130 | NFBT upstream of Glen Haven | | | | | | | | | | 659 | 0.031 | 0.15 | 0.15 | 0.15 |
| J4098 | NFBT at Glen Haven | | | | | | | | | | | | | | |
| R140 | NFBT below Glen Haven | | | | | | | | | | 15890 | 0.021 | 0.15 | 0.15 | 0.15 |
| BT25 | NFBT area below Glen Haven | 4.2 | 59.6 | 65.0 | 0.4 | 0.15 | 4.79 | 2.10 | 427 | 2.61 | | | | | |
| BT32 | Miller Fork Trib to NFBT | 14.2 | 55.5 | 64.0 | 0.4 | 0.15 | 8.66 | 4.43 | 427 | 4.07 | | | | | |
| J4106 | NFBT at confluence with Miller Fork | | | | | | | | | | | | | | |
| R185 | NFBT below confluence with Miller Fork | | | | | | | | | | 3697 | 0.025 | 0.15 | 0.15 | 0.15 |
| BT24A | Trib area to NFBT at NRCS peak estimation point | 0.4 | 63.3 | 66.4 | 0.4 | 0.15 | 1.38 | 0.51 | 812 | 0.98 | | | | | |
| ICC_78 | NFBT above Drake (NRCS Peak Estimation Point) | | | | | | | | | | | | | | |
| R180 | NFBT above confluence with BT | | | | | | | | | | 28368 | 0.023 | 0.15 | 0.15 | 0.15 |
| BT24 | NFBT area above confluence with BT | 16.2 | 64.6 | 73.0 | 0.4 | 0.15 | 8.51 | 3.63 | 422 | 3.79 | | | | | |
| J4080b | NFBT at Drake (Jarrett Estimation Point #81) | | | | | | | | | | | | | | |
| J4080 | Confluence of BT and NFBT at Drake | | | | | | | | | | | | | | |
| R240 | BT below Drake | | | | | | | | | | 26220 | 0.022 | 0.15 | 0.15 | 0.15 |
| BT02 | BT area below Drake | 5.9 | 47.0 | 75.0 | 0.4 | 0.15 | 5.83 | 2.69 | 494 | 2.96 | | | | | |
| BT33 | Cedar Creek Trib to BT | 19.0 | 46.0 | 80.0 | 0.4 | 0.15 | 11.70 | 6.09 | 330 | 5.20 | | | | | |
| J4083 | BT at confluence with Cedar Creek | | | | | | | | | | | | | | |
| R265 | BT below confluence with Cedar Creek | | | | | | | | | | 30892 | 0.015 | 0.15 | 0.15 | 0.15 |
| BT01A | BT area at Mouth of Canyon | 13.6 | 46.0 | 80.0 | 0.4 | 0.15 | 8.19 | 3.72 | 261 | 4.09 | | | | | |
| ICC_66 | BT at Mouth of Canyon (Jarrett Estimation point #66) | | | | | | | | | | | | | | |
| R260 | BT upstream of Buckhorn Gulch confluence | | | | | | | | | | 6259 | 0.006 | 0.15 | 0.15 | 0.15 |
| BT01 | BT area near confluence with Buckhorn | 2.4 | 76.2 | 80.0 | 0.4 | 0.15 | 4.21 | 1.36 | 142 | 2.60 | | | | | |
| BH12 | Buckhorn Creek Headwaters | 26.8 | 56.4 | 70.0 | 0.4 | 0.1 | 13.02 | 6.74 | 281 | 3.82 | | | | | |
| BH13 | Twin Cabin Gulch Trib to Buckhorn Creek | 3.9 | 59.6 | 70.0 | 0.4 | 0.1 | 5.56 | 2.76 | 554 | 1.92 | | | | | |
| J4029 | Buckorn Creek at confluence with Twin Cabin Gulch | | | | | | | | | | | | | | |
| R20 | Buckhorn Creek Headwaters | | | | | | | | | | 14166 | 0.026 | 0.15 | 0.15 | 0.15 |
| BH11 | Buckhorn Creek area above Sheep Creek confluence | 4.3 | 69.4 | 78.0 | 0.4 | 0.1 | 3.77 | 1.50 | 415 | 1.45 | | | | | |
| BH10 | Sheep Creek Trib to Buckhorn Creek | 7.7 | 59.3 | 71.0 | 0.4 | 0.1 | 9.92 | 5.72 | 403 | 3.11 | | | | | |
| J4130 | Buckhorn at confluence with Sheep Creek | | | | | | | | | | | | | | |
| R30 | Buckhorn Creek upstream of Stove Prarie Creek confluence | | | | | | | | | | 6533 | 0.020 | 0.15 | 0.15 | 0.15 |
| BH09 | Buckhorn Area above confluence with Stove Prarie Creek | 0.7 | 73.2 | 82.0 | 0.4 | 0.1 | 1.86 | 0.64 | 782 | 0.78 | | | | | |
| BH14 | Stove Prarie Creek Trib to Buckhorn Gulch | 6.6 | 66.6 | 77.0 | 0.4 | 0.1 | 6.07 | 3.05 | 293 | 2.27 | | | | | |
| J4133 | Buckhorn Creek at Confl. w/ Stove Prarie Creek (Jarrett #106) | | | | | | | | | | | | | | |
| R40 | Buckhorn Creek upstream of confluence with Fish Creek | | | | | | | | | | 24985 | 0.017 | 0.15 | 0.15 | 0.15 |
| BH08 | Buckhorn area upstream of confluence with Fish Creek | 4.7 | 65.7 | 71.5 | 0.4 | 0.1 | 5.41 | 2.04 | 335 | 1.87 | | | | | |
| BH07 | Upper North Fork Fish Creek Trib to Buckhorn | 8.8 | 62.2 | 76.0 | 0.4 | 0.1 | 10.28 | 5.84 | 352 | 3.25 | | | | | |
| BH06 | Fish Creek Trib to Buckhorn | 6.3 | 62.3 | 76.0 | 0.4 | 0.1 | 9.28 | 4.73 | 384 | 2.88 | | | | | |
| J4122 | Confluence of North Fork Fish Creek and Fish Creek | | | | | | | | | | | | | | |
| R50 | Fish Creek Trib to Buckhorn | | | | | | | | | | 9138 | 0.042 | 0.15 | 0.15 | 0.15 |
| BH05 | Buckhorn area near Fish Creek confluence | 0.6 | 68.6 | 80.0 | 0.4 | 0.1 | 2.18 | 1.06 | 365 | 1.10 | | | | | |
| J4125 | Buckhorn at Fish Creek confluence | | | | | | | | | | | | | | |
| R95 | Buckhorn Creek above NRCS Estimation Point | | | | | | | | | | 24295 | 0.020 | 0.15 | 0.15 | 0.15 |
| BH04A | Buckhorn area upstream of NRCS Estimation Point | 17.7 | 70.4 | 83.0 | 0.4 | 0.1 | 13.59 | 6.80 | 313 | 3.81 | | | | | |
| ICC_79 | Buckhorn 3.5 miles above Masonville (NRCS estimation point) | | | | | | | | | | | | | | |
| R90 | Buckhorn Creek upstream of Redstone Creek | | | | | | | | | | 22003 | 0.010 | 0.15 | 0.15 | 0.15 |
| BH04 | Buckhorn Area upstream of confluence with Redstone Creek | 8.5 | 76.2 | 85.0 | 0.4 | 0.1 | 6.33 | 3.97 | 333 | 2.46 | | | | | |
| J4119b | Buckhorn at Masonville U/S of Redstone Creek (Jarrett #108) | | | | | | | | | | | | | | |
| BH16 | Redstone Creek Headwaters (NRCS Estimation Point) | 17.5 | 46.8 | 64.0 | 0.4 | 0.1 | 9.29 | 3.81 | 257 | 2.87 | | | | | |
| J4121 | Redstone Creek NRCS Peak Estimate Location | | | | | | | | | | | | | | |
| R100 | Redstone Creek upstream of confluence with Buckhorn | | | | | | | | | | 45523 | 0.014 | 0.15 | 0.15 | 0.15 |
| BH15 | Redstone Creek area near confluence with Buckhorn | 13.6 | 50.0 | 62.0 | 0.4 | 0.1 | 10.81 | 5.27 | 207 | 3.48 | | | | | |
| J4120 | Redstone Creek U/S of Confl. w/ Buckhorn (Jarrett #109) | | | | | | | | | | | | | | |
| J4119 | Buckhorn at confluence with Redstone Creek | | | | | | | | | | | | | | |
| R190 | Buckhorn downstream of Confluence with Redstone Creek | | | | | | | | | | 24786 | 0.007 | 0.15 | 0.15 | 0.15 |
| BH02 | Buckhorn area below confluence with Redstone Creek | 8.3 | 70.0 | 88.0 | 0.4 | 0.1 | 7.15 | 4.24 | 257 | 2.73 | | | | | |
| BH03 | Indian Creek Tributary to Buckhorn (Jarrett #110) | 7.9 | 70.0 | 89.0 | 0.4 | 0.1 | 6.83 | 3.26 | 195 | 2.58 | | | | | |
| J4088 | Buckhorn at County Road 24H (CDWR Gage, Jarrett #111) | | | | | | | | | | | | | | |
| R230 | Buckhorn Creek upstream of confluence with BT | | | | | | | | | | 6110 | 0.006 | 0.15 | 0.15 | 0.15 |
| BH01 | Buckhorn area at BT | 0.9 | 77.5 | 90.0 | 0.4 | 0.1 | 2.81 | 1.60 | 175 | 1.55 | | | | | |
| J4077 | BT confluence with Buckhorn | | | | | | | | | | | | | | |
| R220 | BT downstream of confluence with Buckhorn | | | | | | | | | | 21 | 0.050 | 0.15 | 0.15 | 0.15 |
| Outlet_BT-BH | BT downstream study limit | | | | | | | | | | | | | | |

# 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 |

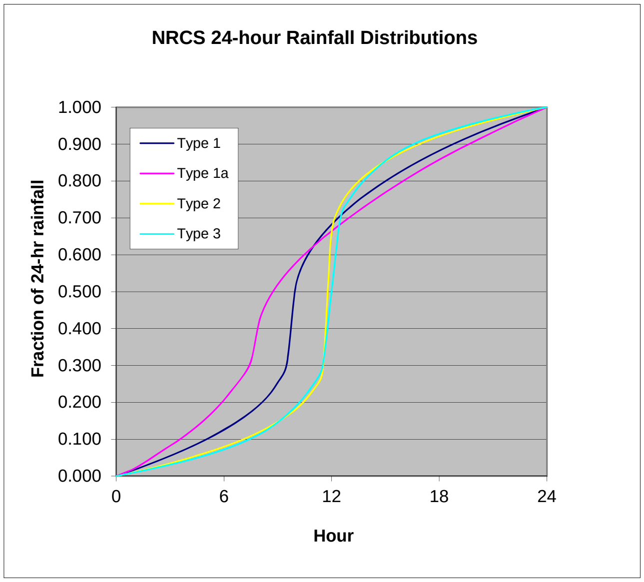
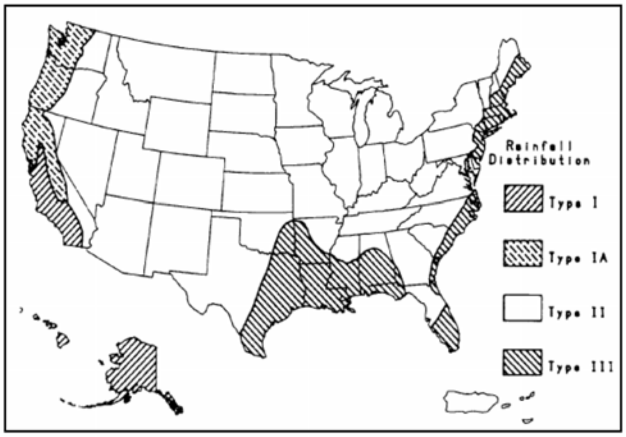

NRCS 24-hour Rainfall Distributions

**Figure 1:** Geographic boundaries for the NRCS rainfall distributions



**Big Thompson River**

Appendix C.6 (continued)

|  | Raingage Zones |  |  |  |
|---|---|---|---|---|
|  | **Zone 1 (Southwest)** | **Zone 2 (West)** | **Zone 3 (Central)** | **Zone 4 (East)** |
| **Lat** | 40.29203442120 | 40.42754844160 | 40.51726900460 | 40.47105144940 |
| **Long** | -105.63919893300 | -105.55558840800 | -105.32955527300 | -105.21613280200 |
| **max 100-yr 1-hr Precip** | 2.11 | 1.79 | 2.15 | 2.36 |
| **10-yr, 24-hr** | 2.95 | 2.39 | 2.86 | 3.17 |
| **25-yr, 24-hr** | 3.72 | 3.06 | 3.7 | 4.09 |
| **50-yr, 24-hr** | 4.42 | 3.69 | 4.46 | 4.92 |
| **100-yr, 24-hr** | 5.22 | 4.42 | 5.33 | 5.84 |
| **500-yr, 24-hr** | 7.48 | 6.5 | 7.77 | 8.39 |
|  | BT14 | BT18 | BT03 | BT01A |
|  |  | BT17 | BT24 | BT01 |
|  |  | BT16 | BT02 | BH15 |
|  |  | BT15 | BT33 | BH04 |
|  |  | BT13 | BH11 | BH02 |
|  |  | BT12 | BH10 | BH03 |
|  |  | BT10 | BH09 | BH01 |
|  |  | BT19 | BH14 |  |
|  |  | BT09 | BH08 |  |
|  |  | BT21 | BH07 |  |
|  |  | BT22 | BH06 |  |
|  |  | BT20 | BH05 |  |
|  |  | BT23 | BH04A |  |
|  |  | BT05 | BH16 |  |
|  |  | BT06 |  |  |
|  |  | BT07 |  |  |
|  |  | BT03B |  |  |
|  |  | BT03A |  |  |
|  |  | BT27 |  |  |
|  |  | BT28 |  |  |
|  |  | BT26 |  |  |
|  |  | BT30 |  |  |
|  |  | BT31 |  |  |
|  |  | BT25 |  |  |
|  |  | BT32 |  |  |
|  |  | BT24A |  |  |
|  |  | BH12 |  |  |
|  |  | BH13 |  |  |

**Big Thompson River** Appendix C.6 (continued)

Unadjusted NOAA Rainfall

| **Basin** | **10-yr** | **25-yr** | **50-yr** | **100-yr** | **500-yr** |
|---|---|---|---|---|---|
| BH01 | 3.17 | 4.09 | 4.92 | 5.84 | 8.39 |
| BH02 | 3.17 | 4.09 | 4.92 | 5.84 | 8.39 |
| BH03 | 3.17 | 4.09 | 4.92 | 5.84 | 8.39 |
| BH04 | 3.17 | 4.09 | 4.92 | 5.84 | 8.39 |
| BH04A | 2.86 | 3.7 | 4.46 | 5.33 | 7.77 |
| BH05 | 2.86 | 3.7 | 4.46 | 5.33 | 7.77 |
| BH06 | 2.86 | 3.7 | 4.46 | 5.33 | 7.77 |
| BH07 | 2.86 | 3.7 | 4.46 | 5.33 | 7.77 |
| BH08 | 2.86 | 3.7 | 4.46 | 5.33 | 7.77 |
| BH09 | 2.86 | 3.7 | 4.46 | 5.33 | 7.77 |
| BH10 | 2.86 | 3.7 | 4.46 | 5.33 | 7.77 |
| BH11 | 2.86 | 3.7 | 4.46 | 5.33 | 7.77 |
| BH12 | 2.39 | 3.06 | 3.69 | 4.42 | 6.5 |
| BH13 | 2.39 | 3.06 | 3.69 | 4.42 | 6.5 |
| BH14 | 2.86 | 3.7 | 4.46 | 5.33 | 7.77 |
| BH15 | 3.17 | 4.09 | 4.92 | 5.84 | 8.39 |
| BH16 | 2.86 | 3.7 | 4.46 | 5.33 | 7.77 |
| BT01 | 3.17 | 4.09 | 4.92 | 5.84 | 8.39 |
| BT01A | 3.17 | 4.09 | 4.92 | 5.84 | 8.39 |
| BT02 | 2.86 | 3.7 | 4.46 | 5.33 | 7.77 |
| BT03 | 2.86 | 3.7 | 4.46 | 5.33 | 7.77 |
| BT03A | 2.39 | 3.06 | 3.69 | 4.42 | 6.5 |
| BT03B | 2.39 | 3.06 | 3.69 | 4.42 | 6.5 |
| BT05 | 2.39 | 3.06 | 3.69 | 4.42 | 6.5 |
| BT06 | 2.39 | 3.06 | 3.69 | 4.42 | 6.5 |
| BT07 | 2.39 | 3.06 | 3.69 | 4.42 | 6.5 |
| BT09 | 2.39 | 3.06 | 3.69 | 4.42 | 6.5 |
| BT10 | 2.39 | 3.06 | 3.69 | 4.42 | 6.5 |
| BT12 | 2.39 | 3.06 | 3.69 | 4.42 | 6.5 |
| BT13 | 2.39 | 3.06 | 3.69 | 4.42 | 6.5 |
| BT14 | 2.95 | 3.72 | 4.42 | 5.22 | 7.48 |
| BT15 | 2.39 | 3.06 | 3.69 | 4.42 | 6.5 |
| BT16 | 2.39 | 3.06 | 3.69 | 4.42 | 6.5 |
| BT17 | 2.39 | 3.06 | 3.69 | 4.42 | 6.5 |
| BT18 | 2.39 | 3.06 | 3.69 | 4.42 | 6.5 |
| BT19 | 2.39 | 3.06 | 3.69 | 4.42 | 6.5 |
| BT20 | 2.39 | 3.06 | 3.69 | 4.42 | 6.5 |
| BT21 | 2.39 | 3.06 | 3.69 | 4.42 | 6.5 |
| BT22 | 2.39 | 3.06 | 3.69 | 4.42 | 6.5 |
| BT23 | 2.39 | 3.06 | 3.69 | 4.42 | 6.5 |
| BT24 | 2.86 | 3.7 | 4.46 | 5.33 | 7.77 |
| BT24A | 2.39 | 3.06 | 3.69 | 4.42 | 6.5 |
| BT25 | 2.39 | 3.06 | 3.69 | 4.42 | 6.5 |
| BT26 | 2.39 | 3.06 | 3.69 | 4.42 | 6.5 |
| BT27 | 2.39 | 3.06 | 3.69 | 4.42 | 6.5 |
| BT28 | 2.39 | 3.06 | 3.69 | 4.42 | 6.5 |
| BT30 | 2.39 | 3.06 | 3.69 | 4.42 | 6.5 |
| BT31 | 2.39 | 3.06 | 3.69 | 4.42 | 6.5 |
| BT32 | 2.39 | 3.06 | 3.69 | 4.42 | 6.5 |
| BT33 | 2.86 | 3.7 | 4.46 | 5.33 | 7.77 |

**Big Thompson River** Appendix C.6 (continued)

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

| **Basin** | **10-yr** | **25-yr** | **50-yr** | **100-yr** | **500-yr** |
|---|---|---|---|---|---|
| BH01 | 3.11 | 4.01 | 4.82 | 5.72 | 8.22 |
| BH02 | 3.11 | 4.01 | 4.82 | 5.72 | 8.22 |
| BH03 | 3.11 | 4.01 | 4.82 | 5.72 | 8.22 |
| BH04 | 3.11 | 4.01 | 4.82 | 5.72 | 8.22 |
| BH04A | 2.80 | 3.63 | 4.37 | 5.22 | 7.61 |
| BH05 | 2.80 | 3.63 | 4.37 | 5.22 | 7.61 |
| BH06 | 2.80 | 3.63 | 4.37 | 5.22 | 7.61 |
| BH07 | 2.80 | 3.63 | 4.37 | 5.22 | 7.61 |
| BH08 | 2.80 | 3.63 | 4.37 | 5.22 | 7.61 |
| BH09 | 2.80 | 3.63 | 4.37 | 5.22 | 7.61 |
| BH10 | 2.80 | 3.63 | 4.37 | 5.22 | 7.61 |
| BH11 | 2.80 | 3.63 | 4.37 | 5.22 | 7.61 |
| BH12 | 2.34 | 3.00 | 3.62 | 4.33 | 6.37 |
| BH13 | 2.34 | 3.00 | 3.62 | 4.33 | 6.37 |
| BH14 | 2.80 | 3.63 | 4.37 | 5.22 | 7.61 |
| BH15 | 3.11 | 4.01 | 4.82 | 5.72 | 8.22 |
| BH16 | 2.80 | 3.63 | 4.37 | 5.22 | 7.61 |
| BT01 | 3.11 | 4.01 | 4.82 | 5.72 | 8.22 |
| BT01A | 3.11 | 4.01 | 4.82 | 5.72 | 8.22 |
| BT02 | 2.80 | 3.63 | 4.37 | 5.22 | 7.61 |
| BT03 | 2.80 | 3.63 | 4.37 | 5.22 | 7.61 |
| BT03A | 2.34 | 3.00 | 3.62 | 4.33 | 6.37 |
| BT03B | 2.34 | 3.00 | 3.62 | 4.33 | 6.37 |
| BT05 | 2.34 | 3.00 | 3.62 | 4.33 | 6.37 |
| BT06 | 2.34 | 3.00 | 3.62 | 4.33 | 6.37 |
| BT07 | 2.34 | 3.00 | 3.62 | 4.33 | 6.37 |
| BT09 | 2.34 | 3.00 | 3.62 | 4.33 | 6.37 |
| BT10 | 2.34 | 3.00 | 3.62 | 4.33 | 6.37 |
| BT12 | 2.34 | 3.00 | 3.62 | 4.33 | 6.37 |
| BT13 | 2.34 | 3.00 | 3.62 | 4.33 | 6.37 |
| BT14 | 2.89 | 3.65 | 4.33 | 5.12 | 7.33 |
| BT15 | 2.34 | 3.00 | 3.62 | 4.33 | 6.37 |
| BT16 | 2.34 | 3.00 | 3.62 | 4.33 | 6.37 |
| BT17 | 2.34 | 3.00 | 3.62 | 4.33 | 6.37 |
| BT18 | 2.34 | 3.00 | 3.62 | 4.33 | 6.37 |
| BT19 | 2.34 | 3.00 | 3.62 | 4.33 | 6.37 |
| BT20 | 2.34 | 3.00 | 3.62 | 4.33 | 6.37 |
| BT21 | 2.34 | 3.00 | 3.62 | 4.33 | 6.37 |
| BT22 | 2.34 | 3.00 | 3.62 | 4.33 | 6.37 |
| BT23 | 2.34 | 3.00 | 3.62 | 4.33 | 6.37 |
| BT24 | 2.80 | 3.63 | 4.37 | 5.22 | 7.61 |
| BT24A | 2.34 | 3.00 | 3.62 | 4.33 | 6.37 |
| BT25 | 2.34 | 3.00 | 3.62 | 4.33 | 6.37 |
| BT26 | 2.34 | 3.00 | 3.62 | 4.33 | 6.37 |
| BT27 | 2.34 | 3.00 | 3.62 | 4.33 | 6.37 |
| BT28 | 2.34 | 3.00 | 3.62 | 4.33 | 6.37 |
| BT30 | 2.34 | 3.00 | 3.62 | 4.33 | 6.37 |
| BT31 | 2.34 | 3.00 | 3.62 | 4.33 | 6.37 |
| BT32 | 2.34 | 3.00 | 3.62 | 4.33 | 6.37 |
| BT33 | 2.80 | 3.63 | 4.37 | 5.22 | 7.61 |

**Big Thompson River** Appendix C.6 (continued)

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

| Basin | 10-yr | 25-yr | 50-yr | 100-yr | 500-yr |
|---|---|---|---|---|---|
| BH01 | 3.04 | 3.93 | 4.72 | 5.61 | 8.05 |
| BH02 | 3.04 | 3.93 | 4.72 | 5.61 | 8.05 |
| BH03 | 3.04 | 3.93 | 4.72 | 5.61 | 8.05 |
| BH04 | 3.04 | 3.93 | 4.72 | 5.61 | 8.05 |
| BH04A | 2.75 | 3.55 | 4.28 | 5.12 | 7.46 |
| BH05 | 2.75 | 3.55 | 4.28 | 5.12 | 7.46 |
| BH06 | 2.75 | 3.55 | 4.28 | 5.12 | 7.46 |
| BH07 | 2.75 | 3.55 | 4.28 | 5.12 | 7.46 |
| BH08 | 2.75 | 3.55 | 4.28 | 5.12 | 7.46 |
| BH09 | 2.75 | 3.55 | 4.28 | 5.12 | 7.46 |
| BH10 | 2.75 | 3.55 | 4.28 | 5.12 | 7.46 |
| BH11 | 2.75 | 3.55 | 4.28 | 5.12 | 7.46 |
| BH12 | 2.29 | 2.94 | 3.54 | 4.24 | 6.24 |
| BH13 | 2.29 | 2.94 | 3.54 | 4.24 | 6.24 |
| BH14 | 2.75 | 3.55 | 4.28 | 5.12 | 7.46 |
| BH15 | 3.04 | 3.93 | 4.72 | 5.61 | 8.05 |
| BH16 | 2.75 | 3.55 | 4.28 | 5.12 | 7.46 |
| BT01 | 3.04 | 3.93 | 4.72 | 5.61 | 8.05 |
| BT01A | 3.04 | 3.93 | 4.72 | 5.61 | 8.05 |
| BT02 | 2.75 | 3.55 | 4.28 | 5.12 | 7.46 |
| BT03 | 2.75 | 3.55 | 4.28 | 5.12 | 7.46 |
| BT03A | 2.29 | 2.94 | 3.54 | 4.24 | 6.24 |
| BT03B | 2.29 | 2.94 | 3.54 | 4.24 | 6.24 |
| BT05 | 2.29 | 2.94 | 3.54 | 4.24 | 6.24 |
| BT06 | 2.29 | 2.94 | 3.54 | 4.24 | 6.24 |
| BT07 | 2.29 | 2.94 | 3.54 | 4.24 | 6.24 |
| BT09 | 2.29 | 2.94 | 3.54 | 4.24 | 6.24 |
| BT10 | 2.29 | 2.94 | 3.54 | 4.24 | 6.24 |
| BT12 | 2.29 | 2.94 | 3.54 | 4.24 | 6.24 |
| BT13 | 2.29 | 2.94 | 3.54 | 4.24 | 6.24 |
| BT14 | 2.83 | 3.57 | 4.24 | 5.01 | 7.18 |
| BT15 | 2.29 | 2.94 | 3.54 | 4.24 | 6.24 |
| BT16 | 2.29 | 2.94 | 3.54 | 4.24 | 6.24 |
| BT17 | 2.29 | 2.94 | 3.54 | 4.24 | 6.24 |
| BT18 | 2.29 | 2.94 | 3.54 | 4.24 | 6.24 |
| BT19 | 2.29 | 2.94 | 3.54 | 4.24 | 6.24 |
| BT20 | 2.29 | 2.94 | 3.54 | 4.24 | 6.24 |
| BT21 | 2.29 | 2.94 | 3.54 | 4.24 | 6.24 |
| BT22 | 2.29 | 2.94 | 3.54 | 4.24 | 6.24 |
| BT23 | 2.29 | 2.94 | 3.54 | 4.24 | 6.24 |
| BT24 | 2.75 | 3.55 | 4.28 | 5.12 | 7.46 |
| BT24A | 2.29 | 2.94 | 3.54 | 4.24 | 6.24 |
| BT25 | 2.29 | 2.94 | 3.54 | 4.24 | 6.24 |
| BT26 | 2.29 | 2.94 | 3.54 | 4.24 | 6.24 |
| BT27 | 2.29 | 2.94 | 3.54 | 4.24 | 6.24 |
| BT28 | 2.29 | 2.94 | 3.54 | 4.24 | 6.24 |
| BT30 | 2.29 | 2.94 | 3.54 | 4.24 | 6.24 |
| BT31 | 2.29 | 2.94 | 3.54 | 4.24 | 6.24 |
| BT32 | 2.29 | 2.94 | 3.54 | 4.24 | 6.24 |
| BT33 | 2.75 | 3.55 | 4.28 | 5.12 | 7.46 |

**Big Thompson River** Appendix C.6 (continued)

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

| **Basin** | **10-yr** | **25-yr** | **50-yr** | **100-yr** | **500-yr** |
|---|---|---|---|---|---|
| BH01 | 2.98 | 3.84 | 4.62 | 5.49 | 7.89 |
| BH02 | 2.98 | 3.84 | 4.62 | 5.49 | 7.89 |
| BH03 | 2.98 | 3.84 | 4.62 | 5.49 | 7.89 |
| BH04 | 2.98 | 3.84 | 4.62 | 5.49 | 7.89 |
| BH04A | 2.69 | 3.48 | 4.19 | 5.01 | 7.30 |
| BH05 | 2.69 | 3.48 | 4.19 | 5.01 | 7.30 |
| BH06 | 2.69 | 3.48 | 4.19 | 5.01 | 7.30 |
| BH07 | 2.69 | 3.48 | 4.19 | 5.01 | 7.30 |
| BH08 | 2.69 | 3.48 | 4.19 | 5.01 | 7.30 |
| BH09 | 2.69 | 3.48 | 4.19 | 5.01 | 7.30 |
| BH10 | 2.69 | 3.48 | 4.19 | 5.01 | 7.30 |
| BH11 | 2.69 | 3.48 | 4.19 | 5.01 | 7.30 |
| BH12 | 2.25 | 2.88 | 3.47 | 4.15 | 6.11 |
| BH13 | 2.25 | 2.88 | 3.47 | 4.15 | 6.11 |
| BH14 | 2.69 | 3.48 | 4.19 | 5.01 | 7.30 |
| BH15 | 2.98 | 3.84 | 4.62 | 5.49 | 7.89 |
| BH16 | 2.69 | 3.48 | 4.19 | 5.01 | 7.30 |
| BT01 | 2.98 | 3.84 | 4.62 | 5.49 | 7.89 |
| BT01A | 2.98 | 3.84 | 4.62 | 5.49 | 7.89 |
| BT02 | 2.69 | 3.48 | 4.19 | 5.01 | 7.30 |
| BT03 | 2.69 | 3.48 | 4.19 | 5.01 | 7.30 |
| BT03A | 2.25 | 2.88 | 3.47 | 4.15 | 6.11 |
| BT03B | 2.25 | 2.88 | 3.47 | 4.15 | 6.11 |
| BT05 | 2.25 | 2.88 | 3.47 | 4.15 | 6.11 |
| BT06 | 2.25 | 2.88 | 3.47 | 4.15 | 6.11 |
| BT07 | 2.25 | 2.88 | 3.47 | 4.15 | 6.11 |
| BT09 | 2.25 | 2.88 | 3.47 | 4.15 | 6.11 |
| BT10 | 2.25 | 2.88 | 3.47 | 4.15 | 6.11 |
| BT12 | 2.25 | 2.88 | 3.47 | 4.15 | 6.11 |
| BT13 | 2.25 | 2.88 | 3.47 | 4.15 | 6.11 |
| BT14 | 2.77 | 3.50 | 4.15 | 4.91 | 7.03 |
| BT15 | 2.25 | 2.88 | 3.47 | 4.15 | 6.11 |
| BT16 | 2.25 | 2.88 | 3.47 | 4.15 | 6.11 |
| BT17 | 2.25 | 2.88 | 3.47 | 4.15 | 6.11 |
| BT18 | 2.25 | 2.88 | 3.47 | 4.15 | 6.11 |
| BT19 | 2.25 | 2.88 | 3.47 | 4.15 | 6.11 |
| BT20 | 2.25 | 2.88 | 3.47 | 4.15 | 6.11 |
| BT21 | 2.25 | 2.88 | 3.47 | 4.15 | 6.11 |
| BT22 | 2.25 | 2.88 | 3.47 | 4.15 | 6.11 |
| BT23 | 2.25 | 2.88 | 3.47 | 4.15 | 6.11 |
| BT24 | 2.69 | 3.48 | 4.19 | 5.01 | 7.30 |
| BT24A | 2.25 | 2.88 | 3.47 | 4.15 | 6.11 |
| BT25 | 2.25 | 2.88 | 3.47 | 4.15 | 6.11 |
| BT26 | 2.25 | 2.88 | 3.47 | 4.15 | 6.11 |
| BT27 | 2.25 | 2.88 | 3.47 | 4.15 | 6.11 |
| BT28 | 2.25 | 2.88 | 3.47 | 4.15 | 6.11 |
| BT30 | 2.25 | 2.88 | 3.47 | 4.15 | 6.11 |
| BT31 | 2.25 | 2.88 | 3.47 | 4.15 | 6.11 |
| BT32 | 2.25 | 2.88 | 3.47 | 4.15 | 6.11 |
| BT33 | 2.69 | 3.48 | 4.19 | 5.01 | 7.30 |

**Big Thompson River** Appendix C.6 (continued)

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

| **Basin** | **10-yr** | **25-yr** | **50-yr** | **100-yr** | **500-yr** |
|---|---|---|---|---|---|
| BH01 | 2.92 | 3.76 | 4.53 | 5.37 | 7.72 |
| BH02 | 2.92 | 3.76 | 4.53 | 5.37 | 7.72 |
| BH03 | 2.92 | 3.76 | 4.53 | 5.37 | 7.72 |
| BH04 | 2.92 | 3.76 | 4.53 | 5.37 | 7.72 |
| BH04A | 2.63 | 3.40 | 4.10 | 4.90 | 7.15 |
| BH05 | 2.63 | 3.40 | 4.10 | 4.90 | 7.15 |
| BH06 | 2.63 | 3.40 | 4.10 | 4.90 | 7.15 |
| BH07 | 2.63 | 3.40 | 4.10 | 4.90 | 7.15 |
| BH08 | 2.63 | 3.40 | 4.10 | 4.90 | 7.15 |
| BH09 | 2.63 | 3.40 | 4.10 | 4.90 | 7.15 |
| BH10 | 2.63 | 3.40 | 4.10 | 4.90 | 7.15 |
| BH11 | 2.63 | 3.40 | 4.10 | 4.90 | 7.15 |
| BH12 | 2.20 | 2.82 | 3.39 | 4.07 | 5.98 |
| BH13 | 2.20 | 2.82 | 3.39 | 4.07 | 5.98 |
| BH14 | 2.63 | 3.40 | 4.10 | 4.90 | 7.15 |
| BH15 | 2.92 | 3.76 | 4.53 | 5.37 | 7.72 |
| BH16 | 2.63 | 3.40 | 4.10 | 4.90 | 7.15 |
| BT01 | 2.92 | 3.76 | 4.53 | 5.37 | 7.72 |
| BT01A | 2.92 | 3.76 | 4.53 | 5.37 | 7.72 |
| BT02 | 2.63 | 3.40 | 4.10 | 4.90 | 7.15 |
| BT03 | 2.63 | 3.40 | 4.10 | 4.90 | 7.15 |
| BT03A | 2.20 | 2.82 | 3.39 | 4.07 | 5.98 |
| BT03B | 2.20 | 2.82 | 3.39 | 4.07 | 5.98 |
| BT05 | 2.20 | 2.82 | 3.39 | 4.07 | 5.98 |
| BT06 | 2.20 | 2.82 | 3.39 | 4.07 | 5.98 |
| BT07 | 2.20 | 2.82 | 3.39 | 4.07 | 5.98 |
| BT09 | 2.20 | 2.82 | 3.39 | 4.07 | 5.98 |
| BT10 | 2.20 | 2.82 | 3.39 | 4.07 | 5.98 |
| BT12 | 2.20 | 2.82 | 3.39 | 4.07 | 5.98 |
| BT13 | 2.20 | 2.82 | 3.39 | 4.07 | 5.98 |
| BT14 | 2.71 | 3.42 | 4.07 | 4.80 | 6.88 |
| BT15 | 2.20 | 2.82 | 3.39 | 4.07 | 5.98 |
| BT16 | 2.20 | 2.82 | 3.39 | 4.07 | 5.98 |
| BT17 | 2.20 | 2.82 | 3.39 | 4.07 | 5.98 |
| BT18 | 2.20 | 2.82 | 3.39 | 4.07 | 5.98 |
| BT19 | 2.20 | 2.82 | 3.39 | 4.07 | 5.98 |
| BT20 | 2.20 | 2.82 | 3.39 | 4.07 | 5.98 |
| BT21 | 2.20 | 2.82 | 3.39 | 4.07 | 5.98 |
| BT22 | 2.20 | 2.82 | 3.39 | 4.07 | 5.98 |
| BT23 | 2.20 | 2.82 | 3.39 | 4.07 | 5.98 |
| BT24 | 2.63 | 3.40 | 4.10 | 4.90 | 7.15 |
| BT24A | 2.20 | 2.82 | 3.39 | 4.07 | 5.98 |
| BT25 | 2.20 | 2.82 | 3.39 | 4.07 | 5.98 |
| BT26 | 2.20 | 2.82 | 3.39 | 4.07 | 5.98 |
| BT27 | 2.20 | 2.82 | 3.39 | 4.07 | 5.98 |
| BT28 | 2.20 | 2.82 | 3.39 | 4.07 | 5.98 |
| BT30 | 2.20 | 2.82 | 3.39 | 4.07 | 5.98 |
| BT31 | 2.20 | 2.82 | 3.39 | 4.07 | 5.98 |
| BT32 | 2.20 | 2.82 | 3.39 | 4.07 | 5.98 |
| BT33 | 2.63 | 3.40 | 4.10 | 4.90 | 7.15 |

**Big Thompson River** Appendix C.6 (continued)

NOAA Aerial Reduction (90% - Greater than 400 sq.mi.)

| Basin | 10-yr | 25-yr | 50-yr | 100-yr | 500-yr |
|---|---|---|---|---|---|
| BH01 | 2.92 | 3.76 | 4.53 | 5.37 | 7.72 |
| BH02 | 2.92 | 3.76 | 4.53 | 5.37 | 7.72 |
| BH03 | 2.92 | 3.76 | 4.53 | 5.37 | 7.72 |
| BH04 | 2.92 | 3.76 | 4.53 | 5.37 | 7.72 |
| BH04A | 2.63 | 3.40 | 4.10 | 4.90 | 7.15 |
| BH05 | 2.63 | 3.40 | 4.10 | 4.90 | 7.15 |
| BH06 | 2.63 | 3.40 | 4.10 | 4.90 | 7.15 |
| BH07 | 2.63 | 3.40 | 4.10 | 4.90 | 7.15 |
| BH08 | 2.63 | 3.40 | 4.10 | 4.90 | 7.15 |
| BH09 | 2.63 | 3.40 | 4.10 | 4.90 | 7.15 |
| BH10 | 2.63 | 3.40 | 4.10 | 4.90 | 7.15 |
| BH11 | 2.63 | 3.40 | 4.10 | 4.90 | 7.15 |
| BH12 | 2.20 | 2.82 | 3.39 | 4.07 | 5.98 |
| BH13 | 2.20 | 2.82 | 3.39 | 4.07 | 5.98 |
| BH14 | 2.63 | 3.40 | 4.10 | 4.90 | 7.15 |
| BH15 | 2.92 | 3.76 | 4.53 | 5.37 | 7.72 |
| BH16 | 2.63 | 3.40 | 4.10 | 4.90 | 7.15 |
| BT01 | 2.92 | 3.76 | 4.53 | 5.37 | 7.72 |
| BT01A | 2.92 | 3.76 | 4.53 | 5.37 | 7.72 |
| BT02 | 2.63 | 3.40 | 4.10 | 4.90 | 7.15 |
| BT03 | 2.63 | 3.40 | 4.10 | 4.90 | 7.15 |
| BT03A | 2.20 | 2.82 | 3.39 | 4.07 | 5.98 |
| BT03B | 2.20 | 2.82 | 3.39 | 4.07 | 5.98 |
| BT05 | 2.20 | 2.82 | 3.39 | 4.07 | 5.98 |
| BT06 | 2.20 | 2.82 | 3.39 | 4.07 | 5.98 |
| BT07 | 2.20 | 2.82 | 3.39 | 4.07 | 5.98 |
| BT09 | 2.20 | 2.82 | 3.39 | 4.07 | 5.98 |
| BT10 | 2.20 | 2.82 | 3.39 | 4.07 | 5.98 |
| BT12 | 2.20 | 2.82 | 3.39 | 4.07 | 5.98 |
| BT13 | 2.20 | 2.82 | 3.39 | 4.07 | 5.98 |
| BT14 | 2.71 | 3.42 | 4.07 | 4.80 | 6.88 |
| BT15 | 2.20 | 2.82 | 3.39 | 4.07 | 5.98 |
| BT16 | 2.20 | 2.82 | 3.39 | 4.07 | 5.98 |
| BT17 | 2.20 | 2.82 | 3.39 | 4.07 | 5.98 |
| BT18 | 2.20 | 2.82 | 3.39 | 4.07 | 5.98 |
| BT19 | 2.20 | 2.82 | 3.39 | 4.07 | 5.98 |
| BT20 | 2.20 | 2.82 | 3.39 | 4.07 | 5.98 |
| BT21 | 2.20 | 2.82 | 3.39 | 4.07 | 5.98 |
| BT22 | 2.20 | 2.82 | 3.39 | 4.07 | 5.98 |
| BT23 | 2.20 | 2.82 | 3.39 | 4.07 | 5.98 |
| BT24 | 2.63 | 3.40 | 4.10 | 4.90 | 7.15 |
| BT24A | 2.20 | 2.82 | 3.39 | 4.07 | 5.98 |
| BT25 | 2.20 | 2.82 | 3.39 | 4.07 | 5.98 |
| BT26 | 2.20 | 2.82 | 3.39 | 4.07 | 5.98 |
| BT27 | 2.20 | 2.82 | 3.39 | 4.07 | 5.98 |
| BT28 | 2.20 | 2.82 | 3.39 | 4.07 | 5.98 |
| BT30 | 2.20 | 2.82 | 3.39 | 4.07 | 5.98 |
| BT31 | 2.20 | 2.82 | 3.39 | 4.07 | 5.98 |
| BT32 | 2.20 | 2.82 | 3.39 | 4.07 | 5.98 |
| BT33 | 2.63 | 3.40 | 4.10 | 4.90 | 7.15 |

# Appendix C.6 (cont)

**Big Thompson River**

| HEC-HMS Design Point | Location Description | Area (sq. mi.) | Rainfall Depth-Area Reduction % |
|---|---|---|---|
| BT18 | Big Thompson River Headwaters Area | 29.56 | 98% |
| BT17 | Fern Creek Trib to BT in RMNP | 2.95 | 100% |
| J4026 | BT at confluence with Fern Creek in RMNP | 32.51 | 96% |
| R400 | BT below confluence with Fern Creek in RMNP | 32.51 | 96% |
| BT16 | BT area above and through Moraine Park | 7.55 | 100% |
| BT15 | Mill Creek Trib to BT in RMNP | 5.42 | 100% |
| BT14 | Glacier Creek Trib to BT in RMNP | 18.73 | 98% |
| J4032 | Confluence of Glacier Creek and Mill Creek in RMNP | 24.15 | 98% |
| R410 | Glacier Creek Trib to BT at Moraine Park | 24.15 | 98% |
| BT13 | BT area near confluence with Glacier Creek | 0.59 | 100% |
| J4040 | BT at Confluence of Glacier Creek | 64.79 | 94% |
| R380 | BT above confluence with Wind River | 64.79 | 94% |
| BT12 | Wind River Trib to BT | 10.25 | 100% |
| J4037 | BT at confluence with Wind River upstream of Estes Park | 75.04 | 94% |
| R390 | BT below confluence with Wind River | 75.04 | 94% |
| BT10 | BT area upstream of confluence with Beaver Brook | 1.26 | 100% |
| BT19 | Beaver Brook Trib to BT | 7.50 | 100% |
| J4047 | BT at confluence with Beaver Brook | 83.81 | 94% |
| R360 | BT upstream of confluence with Fall River | 83.81 | 94% |
| BT09 | BT area upstream of confluence with Fall River | 2.67 | 100% |
| BT21 | Fall River Headwaters | 12.86 | 98% |
| BT22 | Roaring River Trib to Fall River | 12.26 | 98% |
| J4070 | Fall River confluence with Roaring River | 25.12 | 98% |
| R310 | Fall River Trib to BT | 25.12 | 98% |
| BT20 | Lower Fall River Trib Area | 14.51 | 98% |
| **J4050** | **Fall River Trib to BT (NRCS Peak Estimation Point)** | **39.63** | 98% |
| J4052 | BT at confluence with Fall River | 126.10 | 92% |
| R300 | BT below confluence with Fall River | 126.10 | 92% |
| BT23 | Black Canyon Creek Trib to BT | 10.17 | 100% |
| J4061 | BT at confluence with Black Canyon Creek | 136.27 | 92% |
| R330 | BT upstream of Lake Estes | 136.27 | 92% |
| **BT05** | **Fish Creek Trib to Lake Estes** | **16.72** | 100% |
| BT06 | Trib area on North side of Lake Estes | 1.12 | 100% |
| J4055 | BT inflow to Lake Estes | 154.12 | 92% |
| **Lake Estes** | **Lake Estes (Olympus Dam)** | **154.12** | 92% |
| R340 | BT below Lake Estes | 154.12 | 92% |
| BT07 | Dry Gulch Trib to BT below Lake Estes | 6.30 | 100% |
| J4058 | BT at confluence with Dry Gulch below Lake Estes | 160.42 | 92% |
| R358 | BT below confluence with Dry Gulch | 160.42 | 92% |
| BT03B | BT upstream of Loveland Heights | 3.91 | 100% |
| **ICC_62** | **BT at Loveland Heightes (Peak Discharge Point #62)** | **164.32** | 92% |
| R355 | BT below Loveland Heights | 164.32 | 92% |
| BT03A | BT area at Mountain Shadows Lane upstream of Drake | 23.27 | 98% |
| **ICC_65** | **BT at Mountain Shadows Lane above Drake** | **187.59** | 92% |
| R350 | BT above Drake | 187.59 | 92% |
| BT03 | BT area above Drake | 2.08 | 100% |
| BT27 | Cow Creek Trib to NFBT | 9.78 | 100% |
| BT28 | West Creek Trib to NFBT | 12.24 | 100% |
| **J4093** | **West Creek upstream of Devils Gulch in NFBT** | **22.02** | 98% |
| R160 | West Creek above Glen Haven in NFBT | 22.02 | 98% |
| BT26 | Devils Gulch Trib to NFBT | 2.82 | 100% |
| **BT30** | **Fox Creek Trib to NFBT** | **7.23** | 100% |
| **BT31** | **Headwaters of North Fork Big Thompson River** | **18.80** | 98% |
| J4103 | NFBT upstream of Glen Haven | 26.03 | 98% |
| R130 | NFBT upstream of Glen Haven | 26.03 | 98% |
| J4098 | NFBT at Glen Haven | 50.87 | 94% |
| R140 | NFBT below Glen Haven | 50.87 | 94% |
| BT25 | NFBT area below Glen Haven | 4.19 | 100% |
| BT32 | Miller Fork Trib to NFBT | 14.18 | 98% |
| J4106 | NFBT at confluence with Miller Fork | 69.24 | 94% |
| R185 | NFBT below confluence with Miller Fork | 69.24 | 94% |
| BT24A | Trib area to NFBT at NRCS peak estimation point | 0.38 | 100% |
| **ICC_78** | **NFBT above Drake (NRCS Peak Estimation Point)** | **69.62** | 94% |
| R180 | NFBT above confluence with BT | 69.62 | 94% |
| BT24 | NFBT area above confluence with BT | 16.22 | 98% |
| **J4080b** | **NFBT at Drake upstream of Confluence with BT** | **85.84** | 94% |
| **J4080** | **Confluence of BT and NFBT at Drake** | **275.51** | 92% |
| R240 | BT below Drake | 275.51 | 92% |
| BT02 | BT area below Drake | 5.92 | 100% |
| BT33 | Cedar Creek Trib to BT | 18.97 | 98% |
| J4083 | BT at confluence with Cedar Creek | 300.40 | 92% |
| R265 | BT below confluence with Cedar Creek | 300.40 | 92% |
| BT01A | BT area at Mouth of Canyon | 13.63 | 98% |
| **ICC_66** | **BT at Mouth of Canyon (Jarrett Estimation point #66)** | **314.03** | 92% |
| R260 | BT upstream of Buckhorn Gulch confluence | 314.03 | 92% |
| BT01 | BT area near confluence with Buckhorn | 2.39 | 100% |
| BH12 | Buckhorn Creek Headwaters | 26.77 | 98% |
| BH13 | Twin Cabin Gulch Trib to Buckhorn Creek | 3.88 | 100% |
| J4029 | Buckorn Creek at confluence with Twin Cabin Gulch | 30.65 | 98% |
| R20 | Buckhorn Creek Headwaters | 30.65 | 98% |
| BH11 | Buckhorn Creek area above Sheep Creek confluence | 4.32 | 100% |
| BH10 | Sheep Creek Trib to Buckhorn Creek | 7.66 | 100% |
| J4130 | Buckhorn at confluence with Sheep Creek | 42.64 | 96% |
| R30 | Buckhorn Creek upstream of Stove Prarie Creek confluence | 42.64 | 96% |
| BH09 | Buckhorn Area above confluence with Stove Prarie Creek | 0.75 | 100% |
| BH14 | Stove Prarie Creek Trib to Buckhorn Gulch | 6.55 | 100% |
| **J4133** | **Buckhorn Creek at Confl. w/ Stove Prarie Creek (Jarrett #106)** | **49.94** | 96% |
| R40 | Buckhorn Creek upstream of confluence with Fish Creek | 49.94 | 96% |
| BH08 | Buckhorn area upstream of confluence with Fish Creek | 4.67 | 100% |
| BH07 | Upper North Fork Fish Creek Trib to Buckhorn | 8.85 | 100% |
| BH06 | Fish Creek Trib to Buckhorn | 6.25 | 100% |
| J4122 | Confluence of North Fork Fish Creek and Fish Creek (Buckhorn Tribs) | 15.10 | 98% |
| R50 | Fish Creek Trib to Buckhorn | 15.10 | 98% |
| BH05 | Buckhorn area near Fish Creek confluence | 0.58 | 100% |
| J4125 | Buckhorn at Fish Creek confluence | 70.27 | 94% |
| R95 | Buckhorn Creek above NRCS Estimation Point | 70.27 | 94% |
| BH04A | Buckhorn area upstream of NRCS Estimation Point | 17.75 | 98% |
| **ICC_79** | **Buckhorn 3.5 miles above Masonville (NRCS estimation point)** | **88.02** | 94% |
| R90 | Buckhorn Creek upstream of Redstone Creek | 88.02 | 94% |
| BH04 | Buckhorn Area upstream of confluence with Redstone Creek | 8.49 | 100% |
| **J4119b** | **Buckhorn at Masonville upstream of Redstone Creek (Jarrett #108)** | **96.51** | 94% |
| **BH16** | **Redstone Creek Headwaters (NRCS Estimation Point)** | **17.46** | 98% |
| J4121 | Redstone Creek NRCS Peak Estimate Location | 17.46 | 98% |
| R100 | Redstone Creek upstream of confluence with Buckhorn | 17.46 | 98% |
| BH15 | Redstone Creek area near confluence with Buckhorn | 13.60 | 98% |
| **J4120** | **Redstone Creek U/S of Confl. w/ Buckhorn (Jarrett #109)** | **31.06** | 98% |
| J4119 | Buckhorn at confluence with Redstone Creek | 127.57 | 92% |
| R190 | Buckhorn downstream of Confluence with Redstone Creek | 127.57 | 92% |
| BH02 | Buckhorn area below confluence with Redstone Creek | 8.34 | 100% |
| **BH03** | **Indian Creek Tributary to Buckhorn (Jarrett #110)** | **7.93** | 100% |
| **J4088** | **Buckhorn at County Road 24H (CDWR Gage, Jarrett #111)** | **143.84** | 92% |
| R230 | Buckhorn Creek upstream of confluence with BT | 143.84 | 92% |
| BH01 | Buckhorn area at BT | 0.88 | 100% |
| J4077 | BT confluence with Buckhorn | 461.14 | 90% [a] |
| R220 | BT downstream of confluence with Buckhorn | 461.14 | 90% [a] |
| **Outlet_BT-BH** | **BT downstream study limit** | **461.14** | 90% [a] |

[a] Rainfall depth-area reduction factor at confluence of Big Thompson and Buckhorn is provisional and subject to change.

| 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 Big Thompson watershed, several model scenarios were run using different rainfall depths. The six different scenarios included the unadjusted NOAA rainfall depth and five levels of reduced NOAA rainfall depths (98%, 96%, 94%, 92%, and 90%). 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 "BT Max24hr Predictive Model".
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 *BT Raingage Zone.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 *BT Raingage Zone.xls* spreadsheet. This process must be repeated up to thirty times to develop peak discharges for all five design storms and all six 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.