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MEMORANDUM

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Subject: Technology Development (DSO Research) Report: Colorado Front Range Streamflow, Geomorphological Hazard and Rainfall Relationship. Storm and Flood of September 11-13, 2013. Technical Memorandum No. 85-833000-2016-15. (DSO-2017-03).

Attached for your use is the Research Project Report focusing on the Colorado Front Range Streamflow, Geomorphological Hazard and Rainfall Relationship caused by the Storm and Flood of September 11-13, 2013. This report has been prepared by the Technical Service Center at the request of the DSO Research Office.

Key findings of this research project are summarized in the Executive summary section.

This transmittal concludes this Research Project. If you have any questions, please contact me at 303-445-3027, or via email: gdewolfe@usbr.gov.

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RECLAMATION

Managing Water in the West

Colorado Front Range Streamflow, Geomorphological Hazard and Rainfall Relationship. Storm and Flood of September 11-13, 2013.

Technical Memorandum No. 85-833000-2016-15 (DSO-2017-03)



U.S. Department of the Interior
Bureau of Reclamation

August 2017

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Cover Figure: Water from the Big Thompson River washes through a wide landscape south of County Road 20E in Johnstown on Friday, September 13, 2013. (From Jenny Sparks, Loveland Reporter-Herald)

Colorado Front Range Streamflow, Geomorphological Hazard and Rainfall Relationship. Storm and Flood of September 11-13, 2013.

Technical Memorandum No. 85-833000-2016-15

by

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**U.S. Department of the Interior
Bureau of Reclamation
Technical Service Center
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Denver, Colorado**

August 2017

PEER REVIEW CERTIFICATION

This report documenting the result of a research project conducted at selected sites along the Colorado Front Range impacted by the September 11-13, 2013 flood was prepared by Georgia F. deWolfe of the Seismology, Geomorphology and Geophysics Group (86-68330), David Keeney and Lee Mauney, of the Flood Hydrology and Meteorology Group (86-8250) and Christopher Shupe, of the Hydraulic Investigations & Laboratory Services (86-8560). Peer review was provided by Lucille Piety of the Geomorphology and Geophysics Group (86-8330) and Joseph Wright of the Flood Hydrology and Meteorology Group (86-8250). Questions concerning this report should be addressed to Georgia deWolfe, principal investigator, at (303) 445-3027. This research effort was sponsored during 2014 and 2015 fiscal years by the Bureau of Reclamation Dam Safety Office.

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Executive Summary

A unique opportunity arose on September 11-13, 2013 for Reclamation scientists and engineers when the Northern Front Range of Colorado was impacted by one of the largest rainstorms in recorded history. Initial estimates of the total rainfall far exceed previous recorded values and the widespread flooding that resulted from the rainfall affected most of the major drainages heading in the foothills east of the continental divide and west of the major population centers in the Denver-Boulder-Fort Collins corridor.

The September 2013 storm is of particular interest to Reclamation scientists and engineers for several reasons, but first and foremost, because of its extreme magnitude and location near the Denver metro area. Because it was local, the 2013 flood offered the opportunity to scientists and engineers involved in flood hazard studies to examine the results of the storm and flood first-hand, and to fully document the magnitude of this event.

Secondly, the storm and resultant flooding occurred in a physiographic setting very similar to that of many Reclamation dams in the western U.S. Studying the dynamics of this storm and the resultant flooding evidences not only provided a unique opportunity to improve our understanding of flood and geomorphological hazard in general, but in particular the link between an extreme precipitation event and the flooding process.

Some of the most difficult aspects associated to modeling and estimating flood hazard in any drainage basin relate to the assumptions about the flooding processes, such as rainfall, basin response and runoff, the links between these parameters, and how we currently apply this information in hazard studies, which can affect the failure probability estimate of a structure.

This inter-disciplinary research project documents the findings of a field investigation focused on estimating and documenting the peak discharges associated with the September 11-13, 2013 flood. This report has been structured in three major components: 1) understanding the storm meteorology 2) computing the stream flow and flood frequency analysis of each site investigated and 3) interpreting the fluvial geomorphology and paleoflood history of the drainages investigated.

A total of seven drainages and nine sites were selected and analyzed as part of this study. Two sites were investigated along the North Saint Vrain Creek (sites NSV1 and NSV2) and along the South Saint Vrain Creek (sites SSV1 and SSV2). One site was analyzed respectively in each of the following drainages: Middle Saint Vrain Creek (site MSV1), Left Hand Creek (site LHC1), Coal Creek (site CC1), North Fork of the Big Thompson River near Drake (site NBT1), and along Fourmile Canyon Creek (site 4MC1-4MC2) north west of the town of Boulder, Colorado.

The Colorado Front Range Flood of September 2013 was an uncommon meteorological and hydrological event. The precipitation amounts, in locations like Boulder, were record breaking, even though Colorado has experienced similar flood response. The September 1938 and June 1965 extreme precipitation events featured similar spatial and temporal precipitation patterns with very large precipitation amounts. A unique feature of the September 2013 event was the occurrence of mesolows that aided in focusing intense precipitation over small spatial domains for several hours.

As part of the flood frequency analysis performed using expected moments algorithm (EMA),

flood frequency curves were developed based on USGS peak annual streamflow data. The method used to transpose the gage data follows the USGS method (Vaill, 2000) specific to the Mountain Region of Colorado. Peak discharge estimates for Annual Exceedance Probabilities (AEP) were determined by fitting a log Pearson III distribution to the peak annual streamflow data according to Bulletin 17B [USGS, 1981].

One of the intriguing aspects of the September 2013 extreme precipitation event was the lack of AEP (annual exceedance probability) neutrality. In many locations, the precipitation amounts were estimated to be equal to or above a 1 in 1000 year event. However, the flood frequency analysis performed on the drainages investigated revealed that the flooding response was not proportional to the rarity of the precipitation event. Based on flood frequency and peak discharge results, the 2013 flood can be associated to a return period as low as 25 and 50 years on the Middle Saint Vrain and Coal Creek drainages respectively. On the North Fork of the Big Thompson, the South St Vrain, and Left Hand drainages the return period varies respectively from 150 year, to 200 years and 200 to 350 years. Based on flood frequency analysis results, the highest return periods for the 2013 flood event were associated to the peak flows recorded on Fourmile Creek near Boulder Colorado (return period between 200-500 years) and on the North St. Vrain basin with return period greater than 500 years. Table 1 below summarizes the peak discharge values and the radiocarbon ages information collected at each site.

TABLE 1.1: SUMMARY OF PEAK DISCHARGES AND RADIOCARBON DATA FOR ALL SITES INVESTIGATED ALONG THE FRONT RANGE, CO.

Site	Drainage areas	Envelope Curve Peak Discharge (cfs)	Cross section discharge flood 2013 (cfs)	Flood Frequency Return Period (yrs.)	Radiocarbon age RCYBP	Calibrated age BP adjusted to 1950 datum
NSV1	101	18,000	7,300-9,950 (NEB) 470-570 (2013 flood)	NA	5720 +/- 30BP	6690-6505 (NEB)
NSV2	102	18,000	16,950-14,570 *	>500	1290 +/-30 BP	1355-1245
SSV1 near Lyons	84	16,000	8,300-11,000	>200	NA	NA
SSV2 near MSV	70	14,000	1,150-2,050	25-50	70 +/-30 BP	325-285
MSV1	30	7,500	1,500-1,680	25	MSV1-2, 37 cm, 1410 +/- 30BP MSV1-4, 53 cm, 1830 +/- 30 BP	1415-1355 1925-1765
LHC1	47	11,000	3,400-5,000	200-350	NA	NA
CC1	9	2,700	960-1,110	50	820 +/-30BP	850-750
NBT1	77	15,000	9,750	150	NBT-3, 63 cm, 1860+/-30BP NBT-6, 33 cm, 160+/-30BP	1940-1780 350-125
4MC1-4MC2	7	2,000	1,700-1,900	200-500**	8750 +/-40BP 3230 +/- 30 BP	9970-9625 3620-3450
* 9,000 to 11,000 cfs were discharged during the flood from the spillway which as a total capacity of 32,000 cfs						
** based on comparison with the Peak-Flow Statistics available from USGS StreamStats 4.0 tool for the site 100 yrs. =890 cfs and 200-500 yrs.=1600-1700 cfs						

At the sites where surfaces were found to have sustained little to no impact from the 2013 flood event, the stratigraphy and radiocarbon ages collected to corroborate the paleoflood site interpretation indicated that most surfaces have actually experience a period of stability greater than 1000 years. This will indicate that inmost basin the discharge associated with the 2013 flood appear had been exceeded by larger flood in the past.

Due to the impact along the Front Range from the flooding, numerous government and state agencies were involved in making similar estimates throughout the region. Peak discharges were published by the Natural Resources Conservation Service (NRCS) in 2013 (Yochum and Moore, 2013), and by the USGS in 2016 (Moody, 2016). A comparison among the peak discharges was made where sites of close location to the one analyzed by this research were found. The comparison indicated a general agreement on the peak discharge values computed when similar methods were used (Slope conveyance using Critical depth and Manning's equation methods). The estimate obtained for the site on the North Fork Big Thompson River was the only one substantially different, arguably due to the methodology used in making the estimate. The NRCS estimate, $18,400 \text{ ft}^3/\text{s}$, was made based on a critical depth calculation and it's a little less than twice the estimate determined in this study, $9,750 \text{ ft}^3/\text{s}$, based on a four-section HEC-RAS 1D model.

The causes for the discrepancy identified between the precipitation event AEP and the flooding event AEP are multiple and of different nature. With certainty, we can point to a group of factors related to the characteristics of the precipitation, as the duration, intensity, and spatial distribution over an entire basin. While the AEP associated to the precipitation event compares rainfall total for the 2013 event, it is important to remember that flood magnitudes are strongly influenced by high rainfall intensities over relatively short time periods and not by rainfall totals exclusively, therefore rainfall averages over upstream watershed sections are also important. Another possible explanation for these differences in AEP offered by the USGS analysis (Moody, 2016) was that the band of high-accumulation, high-intensity rainfall for the 2013 event was narrow (about 50 kilometers wide), oriented nearly perpendicular to the predominant drainage pattern of the mountains, resulting in entire drainage areas not to be subjected to the same range of extreme rainfall.

Field observation conducted as part of this research corroborated the observation that flood AEP were found lower that precipitation AEP, perhaps, because evidences of severe flooding were recorded in the lower section of several basins, while the flows caused by the 2013 precipitation event were in most cases contained within the riverbanks in the upstream section of the same watersheds. This is the case for example of the Big Thompson River and the St. Vrain River, where several tributaries located in high elevation mountain environments (upper section of the basin) were less impacted by the flood.

Aside from the characteristics of the precipitation, a key role in the AEP discrepancy between precipitation and flood events is also played by the geological making and morphology of each drainage. This second set of causes is perhaps harder to quantify numerically but influence directly the amount of run-off and sediment load that is transported by flows within a drainage. A detailed analysis conducted by the USGS in 2014 (Coe et al., 2014) in response to the widespread debris flows and sliding caused by the 2013 precipitation event indicates that over 1,138 slides were triggered from this event along the Colorado Front Range. Ninety-five percent of debris

flows were found to initiate in canyons and on hogbacks at elevations lower than a widespread erosion surface of low slope and relief (below 2,600 m or 8,500 feet). These debris flows were on steep ($>25^\circ$), predominantly south- and east-facing slopes, while, debris flows with the largest scars and longest travel distances occurred at elevations above 8,500 feet on steep slopes. Areal concentrations of debris flows revealed that colluvial soils formed on sedimentary rocks were more susceptible to flows than soils on crystalline rocks. A previous research on the debris flows frequency in Colorado (Coe et al., 2003) has also concluded that mean debris-flow recurrence intervals are consistently long on north-facing slopes (450 to 2,640 years) and wide ranging (7 to 2,900 years) on south-facing slopes.

During the reconnaissance site visits conducted immediately after the flood, several heavily damaged drainages were not selected as areas of interest for this study because the determination of peak discharges at these sites would have been flawed with large uncertainty. The large majority of these sites consisted of areas in and near the mountains that had experienced flash flood conditions aggravated by landslides and debris that temporarily dammed streams, then after weakening, freed enormous destructive surges of floodwater. An example of this specific mechanism was exemplified by a site along Jams Creek located upstream the town of Springdale, but similar situations were also observed along Fish Creek, near Estes Park, along James Creek upstream of Springdale and on the Fourmile Canyon Creek near Boulder, Colorado.

While there is little doubt that Colorado experienced an extremely rare precipitation event in September 2013, within the limits of the data collection effort and analysis conducted by this research it can be concluded that most drainages along the Front Range have experienced floods of greater magnitude in the past. Peak discharges computations as well as paleoflood interpretation and flood frequency analysis developed for the drainages of interest all support the conclusion that the annual exceedance probability estimated for the precipitation event, being described as a 1000-year event, is greater than the estimated return period associated to the flooding event in all drainages investigated. In the other hand the widespread amount of debris flows and landslide occurred in a short period, over a very large section of the Front Range is considered rare. A detailed analysis conducted by the USGS on the debris-flow hazard associated to the September 2013 event and field observation captured by this research effort have documented that the sediment load released by these slope failures into the stream, already at or above flood stage, has severely worsen the damages caused by the flood.

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Project Overview

A unique opportunity arose on September 11-13, 2013 for Reclamation scientists and engineers at the Technical Service Center (TSC) who work on flood hazards. The Northern Front Range of Colorado was impacted by one of the largest precipitation events in recorded history. Initial estimates of the total precipitation far exceed previous recorded values at some locations, and the widespread flooding that resulted from the precipitation impacted most of the major drainages in the foothills east of the Continental Divide and west of the major population centers in the Denver-Boulder-Fort Collins corridor. The regional flooding affected 24 counties in Colorado and approximately 15 percent of the total land area of the state. The primarily east-west highways that paralleled these drainages in the canyons connecting the foothills to these population centers were severely damaged or destroyed. Sadly, nine Colorado fatalities were caused by the rage of the flood. Property losses for the 2013 Colorado flood have reached a cost greater than \$2 billion. Preliminary estimates of precipitation probability (by NWS) range up to 1 in 1,000 (0.001 AEP), while the flood probability ranged from perhaps as little as 1 in 10 up to or greater than around 1 in 100 (0.1 to > 0.01 AEP).

The September 2013 storm is of particular interest to Reclamation scientists and engineers for several reasons. First, because of its extreme magnitude and location near the Denver metro area, the 2013 flood offers the opportunity for TSC staff involved in flood hazard studies to examine the results of the storm and flood first-hand, and to fully document the magnitude of this extraordinary event. Secondly, the storm and resultant flooding occurred in a physiographic setting very similar to that of many Reclamation dams in the western U.S. Studying the dynamics of this storm and the resultant flooding evidences not only provides a unique opportunity to improve understanding of flood and geomorphological hazard in general, but in particular the link between an extreme precipitation event and the flooding process. One of the fundamental problems in making estimates of the flood hazard for dam safety are the assumptions about the flooding processes such as rainfall, basin response and runoff, the links between these parameters, and how we currently apply this information in hazard studies which can impact failure probability estimates of a structure.

This research presented the staff involved in making flood hazard estimates the opportunity to better understand flood processes by developing and analyzing data that resulted from one of the largest floods to affect the area historically. This research study investigated the frequency of the rainfall, the runoff characteristics of the flood in particular basins, and the effect of the geology, topography, and canyon aspect may have had on flooding.

Quantifying the geomorphic impacts, rainfall magnitudes, and flood magnitudes for this event also provides data and insights for subsequent comparisons of design events and flood risk at specific facilities. This report focuses on the (Section 1) meteorological, (Section 2) streamflow components of the 2013 event, and (Section 3) interpreting the fluvial geomorphology and paleoflood history of the drainages impacted by the storm and flood event.

The sites selection for this project was bases on initial field reconnaissance trips, conducted during late fall of 2013, of several flood-impacted drainages along the Front Range. Limiting factors influencing the selection of the sites were the restricted road access in the months immediately following the flood due to road repairs and the degree of site disturbance both caused by the

flood debris as well as the heavy equipment utilized to mitigate the damages. Furthermore, all sites used to compute peak discharge estimates had well-preserved high water marks (HWMs), had a stable hydraulic setting needed to compute peak discharge estimates (e.g., relatively straight, narrow, constrained reaches) and were free of debris and large volumes of obviously transported sediment that might complicate flood flow computations. Every attempt was made to select sites that avoided or eliminated as many sources of uncertainty as possible based on our experience in making indirect measurements of peak discharge.

Based on all these criteria a total of 7 drainages and 9 sites were selected and analyzed as part of this study (Figure1):

- Sites NSV1 and NSV2 along the North Saint Vrain Creek,
- Sites SSV1 and SSV2 along the South Saint Vrain Creek,
- Site MSV1 on the Middle Saint Vrain Creek immediately upstream of the confluence with the South Saint Vrain,
- Site LHC1 on Left Hand Creek immediately downstream of the confluence with Six-Miles River,
- Site CC1 on Coal Creek less than a mile downstream of the intersection between Coal Creek Canyon road and Twin Spruce Gap road,
- Site NBT1 on the North Fork of the Big Thompson River approximately two miles upstream of the town of Drake
- And sites 4MC1-4MC2 along Fourmile Canyon Creek on the north-west of the town of Boulder, Colorado.

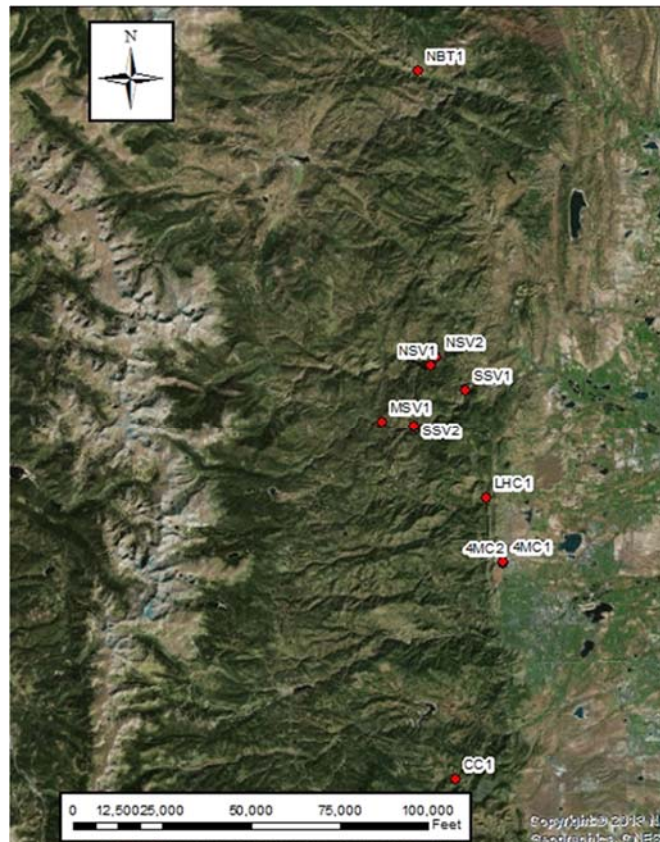


FIGURE 1: MAP SHOWING THE GENERAL LOCATION OF ALL SITES INVESTIGATED AS PART OF THIS STUDY.

1. Meteorological analysis of the 9-13 September 2013 event

Introduction

This section investigates the causes and partial results of the extreme precipitation event near Boulder and Estes Park along the Front Range of Northern Colorado on 9-13 September 2013. The project study area encompasses the geographic region of the Front Range and Plains of eastern Colorado from the Palmer Divide north to the Wyoming border and west of a line from Limon to Fort Morgan to the Continental Divide.

Background

Colorado typically experiences a maximum of heavy rain events from mid-April to mid-October (Petersen et al. 1999). There are two distinct statistical peaks during this time frame: from May to early June and again from late July to early September (Petersen et al. 1999). The period from late July to early September typically features the heaviest precipitation (Petersen et al. 1999). The spatial pattern for the heaviest rainfall occurs along or near the foothills on the eastern side of the Continental Divide (Petersen et al. 1999). The Colorado Front Range extreme precipitation event of 9-13 September 2013 fits into the late July to early September timeframe and the spatial pattern previously given. The 9-13 September 2013 flooding event is similar to the 31 August–3 September 1938 and 16-17 June 1965 events in size, duration, and intensity (Figure 11.1 compares 1965 and 2013 events). In all three storms, there was a slow moving upper-level low across the southwestern United States. This setup typically allows for large amounts of moisture to flow into Colorado from the Gulf of Mexico and occasionally from the Pacific Ocean. This arrangement also provides favorable lift over Colorado caused by the divergence of winds in the upper atmosphere. The 1938 event occurred in the same area as the 2013 event while in 1965 the heavy precipitation occurred south of the Denver metro area.

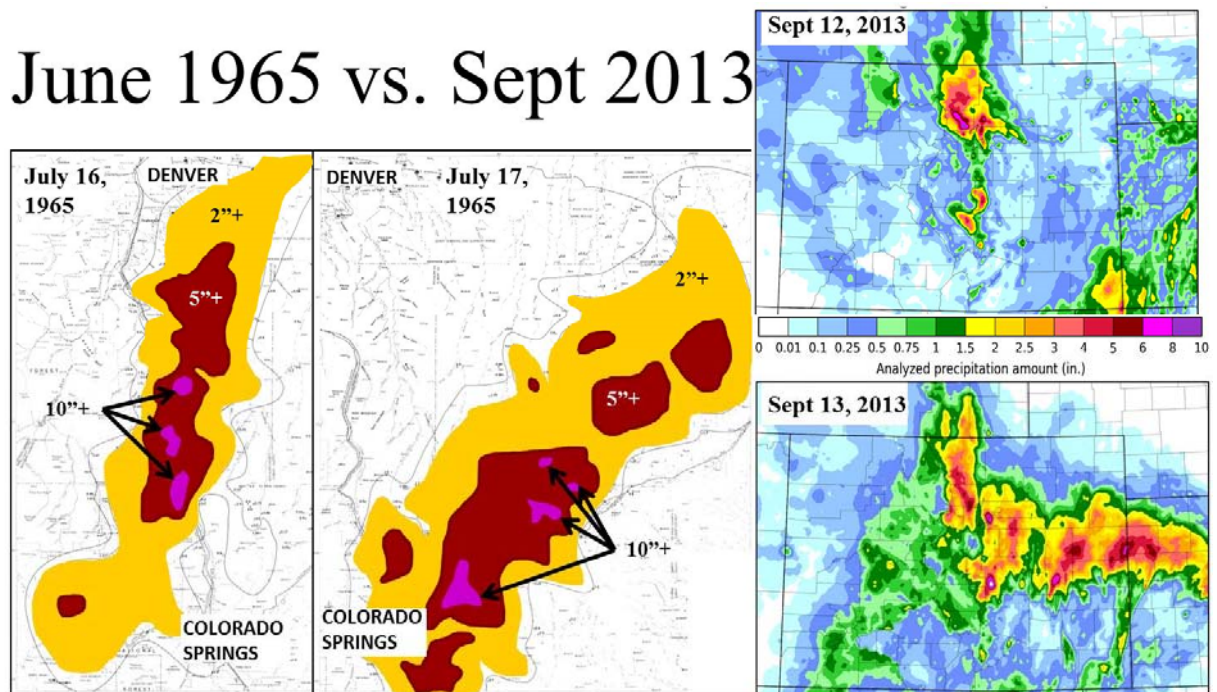


FIGURE 1.1: COMPARISON OF JUNE 1965 AND SEPTEMBER 2013 FLOODING EVENTS (MATTHAI 1969).

Meteorological Setup for 9-13 September 2013

A large slow moving upper-level low was setup across the western US during the event. This allowed moisture transport in the lower-levels of the atmosphere from the Gulf of Mexico and in the mid-levels from the Pacific Ocean to reach eastern Colorado (a back trajectory showing the path parcels of air at different levels took is located in Figure 1.2). For context, back trajectories for the September 1938 and June 1965 events are also shown (Figure 1.3 and Figure 1.4 respectively) (Barras and Simmonds 2009, Noone and Simmonds 1999). Both the 1965 and 2013 events had two moisture sources while the 1938 event appears to have received moisture only from the Gulf of Mexico. In addition to the upper-level low, the 2013 storm featured a cold front across the plains of northeast Colorado that focused low-level convergence and aided in uplift.

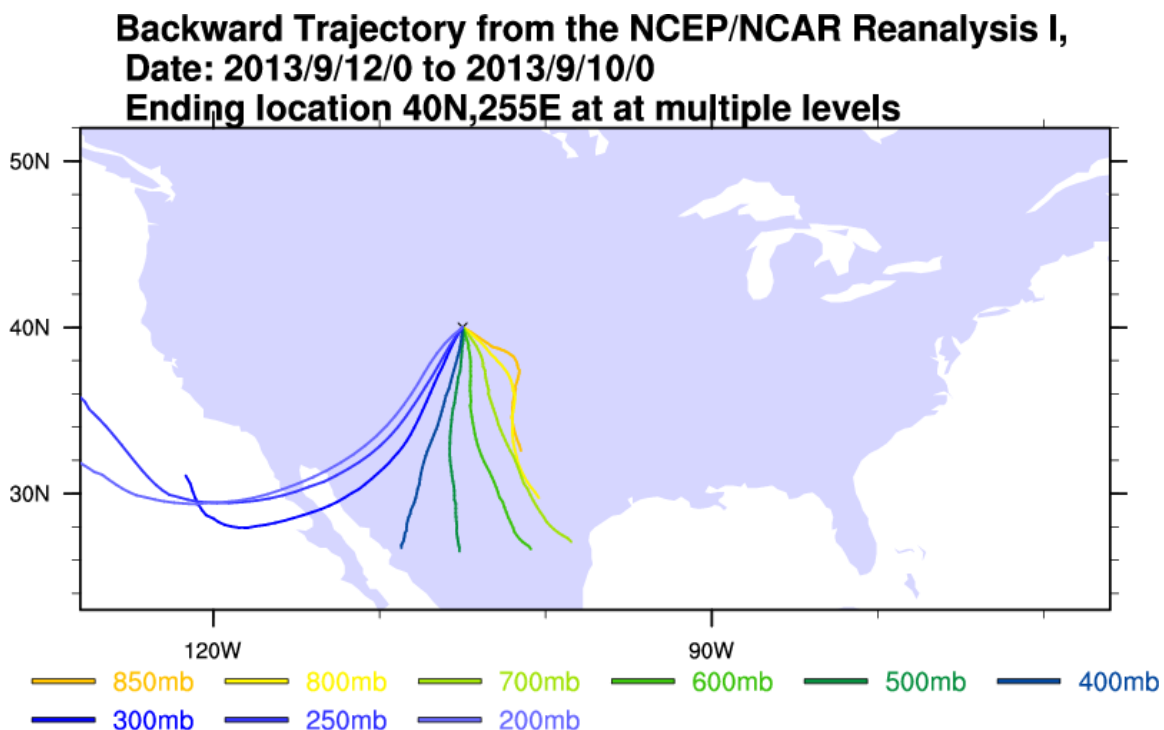


FIGURE 1.2: BACK TRAJECTORY SHOWING THE MOISTURE SOURCE FOR DIFFERENT LEVELS OF THE ATMOSPHERE FOR THE 9-13 SEPTEMBER 2013 EVENT. "X" DENOTES LOCATION OF DENVER.

With two distinct sources of moisture for the 2013 event, Precipitable Water (PW), which is the total atmospheric water vapor contained in a vertical column of a unit cross-sectional area extending between any two specified levels (AMS 2015a), reached record levels (1.39 inches) during the month of September over the Denver area (SPC 2015). This moisture allowed heavy rainfall to occur off-and-on from 9-13 September over the Denver metropolitan area especially in areas around Boulder (Figure 1.5). On 12 September 2013, Boulder received 9.08 inches of rain and during 9-13 September Boulder received 14.71 inches of rain (UCAR 2015). The five day total surpassed the record rainfall in Boulder for the period of a day (previous record was 4.8 inches), a month (previous record was 9.59 inches) and any previous September (previous record was 5.5 inches). The 14.71 inches also was more precipitation than Boulder had received during 2013 (12.96 inches) leading up to the event.

**78 hour air parcel trajectory on multiple pressure levels
Ending at 40N,255E on 1938/9/3/00
Dataset: 20th Century Reanalysis V2**

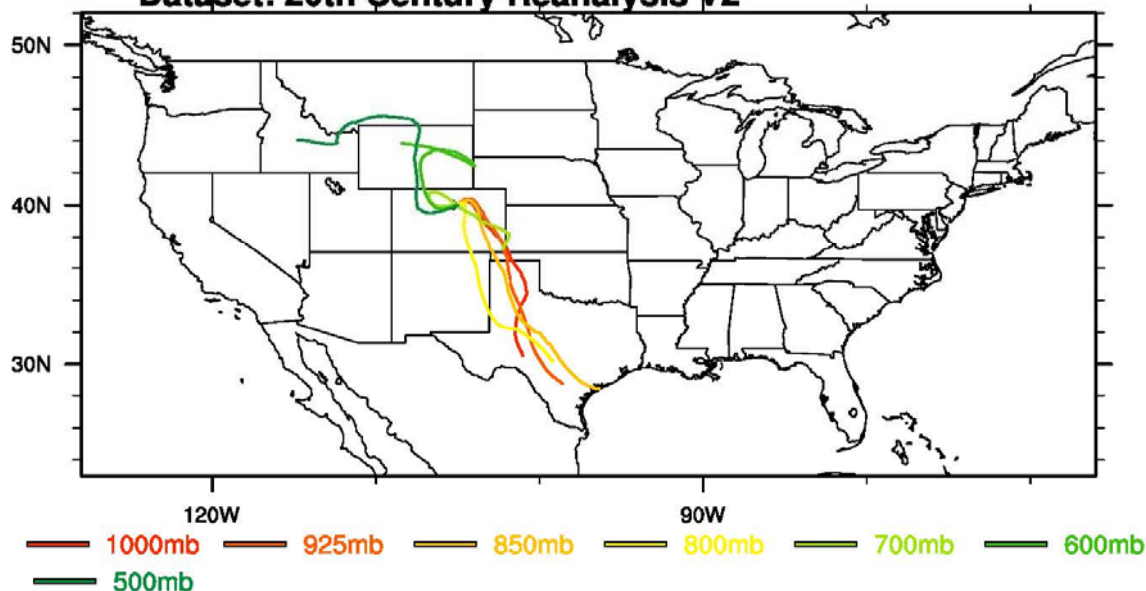


FIGURE 1.3: BACK TRAJECTORY SHOWING THE MOISTURE SOURCE FOR DIFFERENT LEVELS OF THE ATMOSPHERE FOR THE 31 AUGUST - 3 SEPTEMBER 1938 EVENT. "X" DENOTES LOCATION OF DENVER. IMAGE PROVIDED BY THE NOAA-ESRL PHYSICAL SCIENCES DIVISION, BOULDER COLORADO FROM THEIR WEB SITE AT [HTTP://WWW.ESRL.NOAA.GOV/PSD/](http://www.esrl.noaa.gov/psd/).

**78 hour air parcel trajectory on multiple pressure levels
Ending at 40N,255E on 1965/6/18/00
Dataset: NCEP/NCAR Reanalysis I**

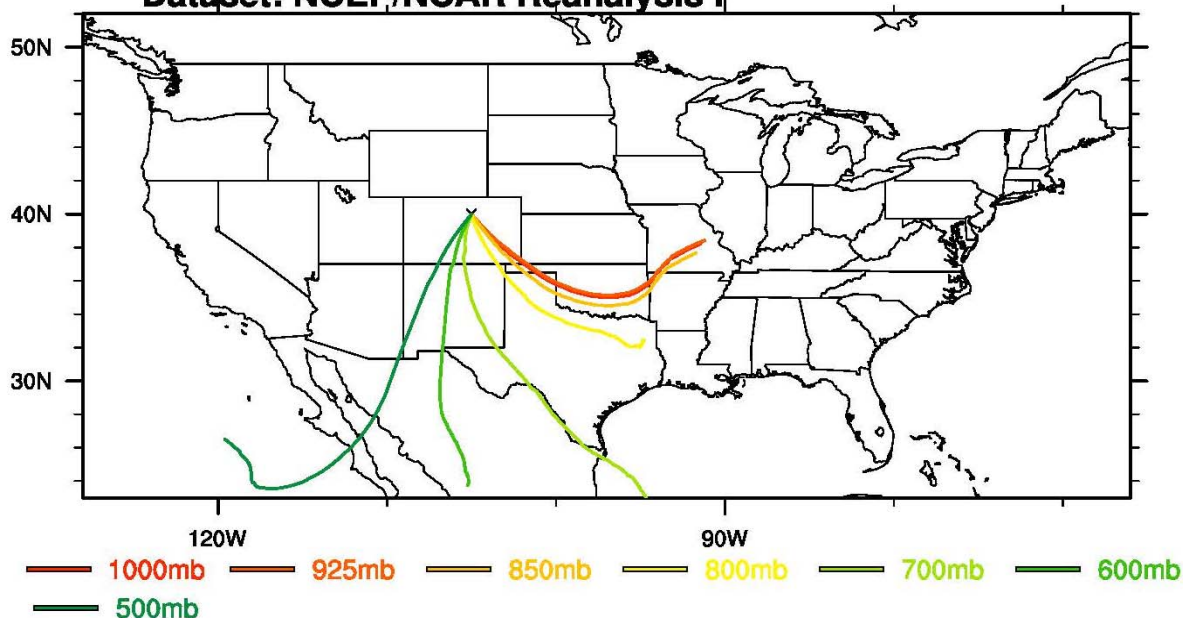


FIGURE 1.4: BACK TRAJECTORY SHOWING THE MOISTURE SOURCE FOR DIFFERENT LEVELS OF THE ATMOSPHERE FOR THE 16-17 JUNE 1965 EVENT. "X" DENOTES LOCATION OF DENVER. IMAGE PROVIDED BY THE NOAA-ESRL PHYSICAL SCIENCES DIVISION, BOULDER COLORADO FROM THEIR WEB SITE AT [HTTP://WWW.ESRL.NOAA.GOV/PSD/](http://www.esrl.noaa.gov/psd/).

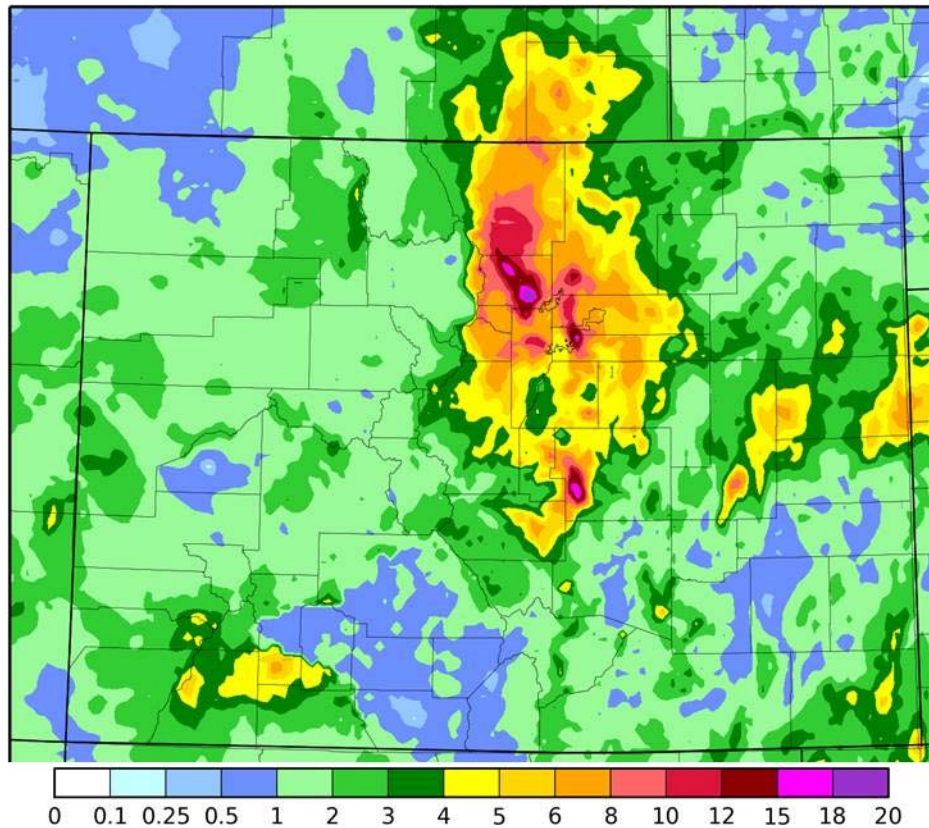


FIGURE 1.5: MAP SHOWING THE LOCATIONS AND AMOUNTS OF PRECIPITATION THAT OCCURRED OVER COLORADO FROM 9-16 SEPTEMBER 2013.

An interesting feature of the September 2013 heavy precipitation was the occurrence of mesolows. A mesolow is an area of low pressure on the mesoscale (scales ranging from a few to several hundred kilometers) (AMS 2015b). The mesolows aided in the organization of the storms by providing low-level convergence, which assisted in lifting of the moist air mass. This helped produce some of the most intense rainfall during the event and kept that heavy rainfall in the same location for hours.

Historical Significance

To put the rainfall totals in perspective, Figure 1.6 shows that many areas experienced greater than 1000-year rainfall totals for the seven-day period starting 9 September 2013 (HDSC 2013). This means there is a probability of 0.1% that this much rainfall will occur in any given year.

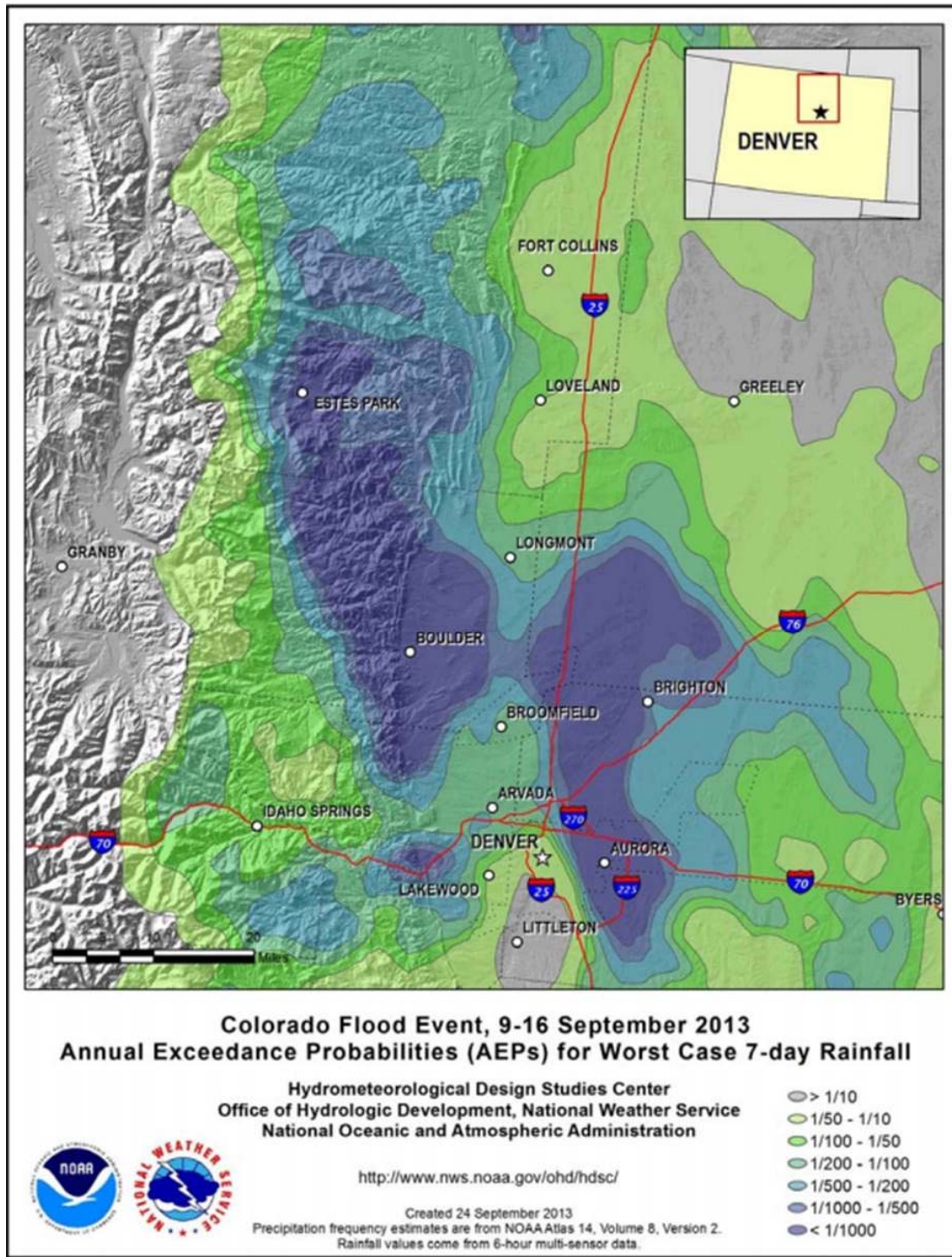


FIGURE 1.6: MAP SHOWING AEPs OF THE 9-16 SEPTEMBER 2013 PRECIPITATION TOTALS (HDSC 2013).

Seven day rainfall totals were estimated at each stratigraphic site (Figure 1.7) using the National Weather Service Boulder rainfall totals map from the event (NWS 2013) and then compared to the 1000-year 7-day median, 95%, and 5% confidence levels provided by NOAA Atlas 14 volume 8 (Perica 2013). Only the most northern site (NBT1) falls below the median threshold for a 1000-year 7-day rainfall total. The stratigraphic site at LHC1 was an estimated 5.3 inches above the median 1000-year 7-day value and 1.2 inches above the 95% confidence level for a 1000-year 7-day precipitation total. It should be noted that the NOAA Atlas 14 values are only point precipitation estimates and do not factor in the spatial extent of the heavy rainfall. In reality, some of the stratigraphic sites and the surrounding areas likely experienced point and spatial precipitation amounts in excess of a 1000-year 7-day precipitation total.

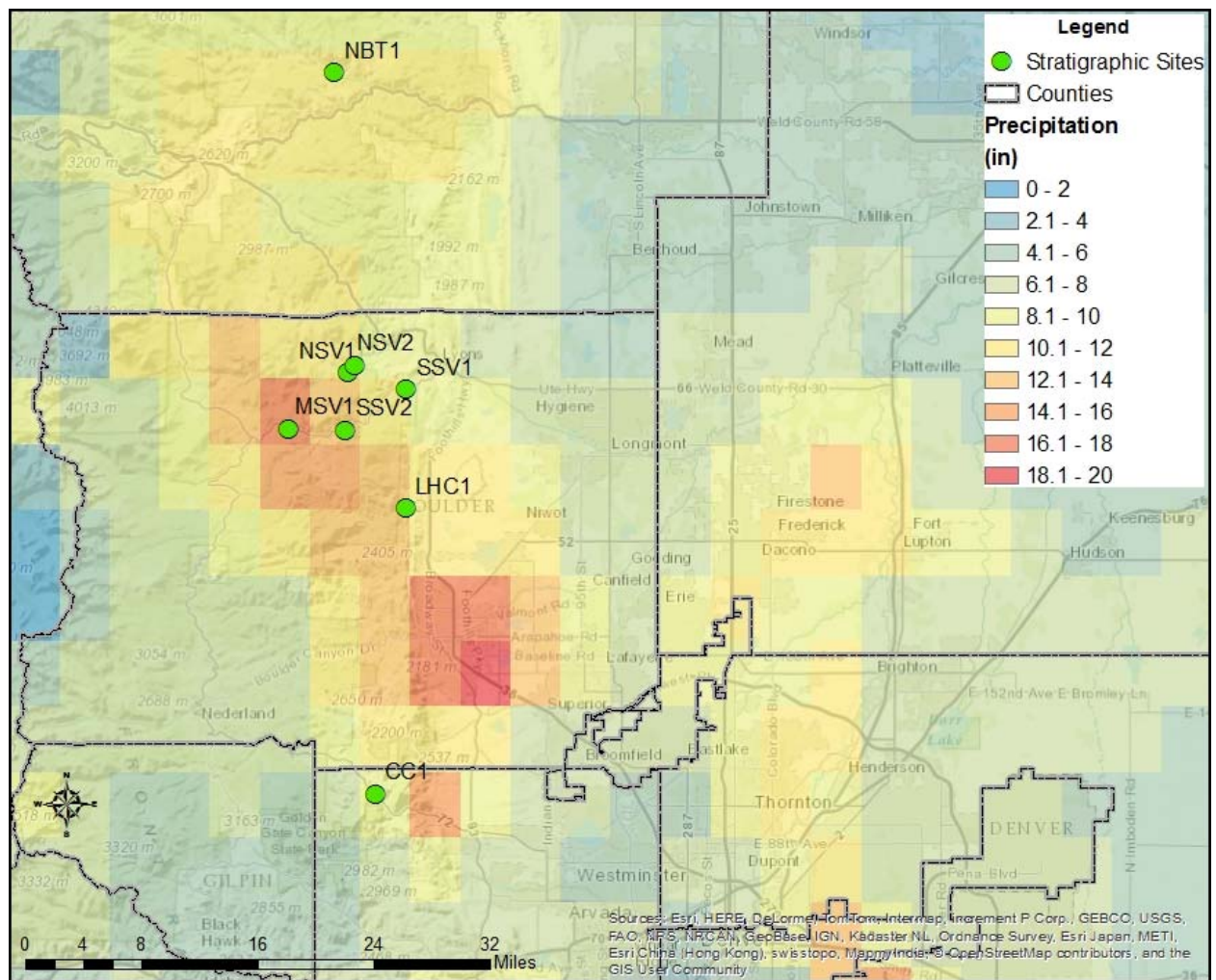


FIGURE 1.7: SEPTEMBER 9-16, 2013 RAINFALL TOTALS MAP SHOWING THE SPATIAL DISTRIBUTION OF THE HEAVIEST ESTIMATED PRECIPITATION AND THE LOCATION OF THE STRATIGRAPHIC SITES (NWS 2013).

TABLE 1.1: SEPTEMBER 9-16, 2013 ESTIMATED RAINFALL TOTALS AT STRATIGRAPHIC SITES WITH MEDIAN, 90% CONFIDENCE LEVEL, AND 10% CONFIDENCE LEVEL PRECIPITATION AMOUNTS FOR A 1000-YEAR 7-DAY RAINFALL EVENT (NWS 2013, PERICA 2013).

Site	9-16 Sept Est Precipitation (in)	1000-year 7-day Median AEP (in)	1000-year 7-day 95% level AEP (in)	1000-year 7-day 5% level AEP (in)
MSV1	15.5	10.8	15.3	7.4
NBT1	10.2	10.9	16.0	7.4
SSV1	12.4	10.3	14.5	7.1
SSV2	15.1	10.7	15.0	7.3
NSV1	14.2	10.6	15.1	7.2
NSV2	13.7	10.6	15.1	7.2
LHC1	16.0	10.7	14.8	7.3
CC1	12.0	11.6	16.4	7.9

2. Flood Frequency analysis of the September 2013 flood

Introduction

This section presents flood frequency estimates for the September 2013 Northern Colorado Front Range flood event using records obtained at the drainages of interest. Frequency estimates are compared to local historic peak flood events, including the 1976 Big Thompson Flood. Regional maximum historic peak flows are estimated for basins assumed hydrologically similar to the study area.

Background

The September 2013 flood event was unique with respect to duration, time of year, spatial extent, and the occurrence of isolated thunderstorms. Research shows that floods occur most frequently on the eastern slope of the Front Range both in the South Platte and in the Arkansas River Basins (Follansbee and Sawyer, 1948, p7). Spring and early summer flooding events often result from the combination of rainfall and melting snow. During the September 2013 precipitation event, the heaviest rainfall occurred in the South Platte River Basin between Colorado Springs and the Wyoming border, east of the Continental Divide, particularly in the Boulder and Estes Park area. Eight drainage points of interest were chosen for this study (Figure 2.1). The North Fork Big Thompson River (NBT1) point of interest is located approximately 2 miles northwest of Drake and US Highway 34. The North Saint Vrain Creek (NSV1 and NSV2) points are located within a mile east of Button Rock Reservoir and 5 miles west of Lyons. The South Saint Vrain Creek (SSV1) and South Saint Vrain Creek (SSV2) points of interest are located approximately 3 and 7 miles southwest of Lyons respectively. The Middle Saint Vrain Creek (MSV1) point of interest is located approximately 3 miles northeast of the intersection of Highway 72 and Highway 7. The drainage basin SSV1 is downstream of the SSV2 sub basin, which is downstream of the MSV2 sub basin. The MSV1 sub basin is within the SSV2 sub basin and both are contained within the SSV1 drainage basin. The Left Hand Creek (LHC1) point is located in Buckingham Park, approximately 4 miles east of Jamestown. The Coal Creek (CC1) point of interest is located about a mile north of Golden Gate Canyon State Park and just west of the Asel Open Space Park. A map showing the points of interest with the corresponding watershed drainage areas is included in Appendix D. Because of proximity between points, the North Saint Vrain Creek points NSV1 and NSV2 are grouped.



FIGURE2.1: MAP SHOWING THE LOCATIONS OF POINTS OF INTEREST FOR THIS STUDY

Regional Envelope Curve

A regional envelope curve is an analysis of nearby historical peak streamflow gage data that, when plotted with the corresponding drainage area for each gage, provides information relative to peak floods that have occurred in the hydrologic and meteorologically homogenous region. The envelope curve may be used to provide context for the flood frequency analysis. The envelope

curve representative of the 2013 Colorado floods points of interest is comprised of 123 gages. The gages were limited to the eastern portion of the hydrologic Mountain Region of Colorado, as delineated by the U. S. Geological Survey (USGS) (Capesius and Stephens 2009), from the Continental Divide on the west to the border of the Plains Region on the east and south and the Wyoming border on the north.

Figure 2.2 shows the peak annual streamflow regional envelope curve developed for the basins of interest, with corresponding point of interest site values listed in Table 2.1. The gages used to develop the regional peak annual discharge envelope curve are shown on the map in Figure 2.3 and tabulated in Appendix E. The envelope curve is controlled by floods on the Little Beaver Creek, Michigan River, and Sand Creek.

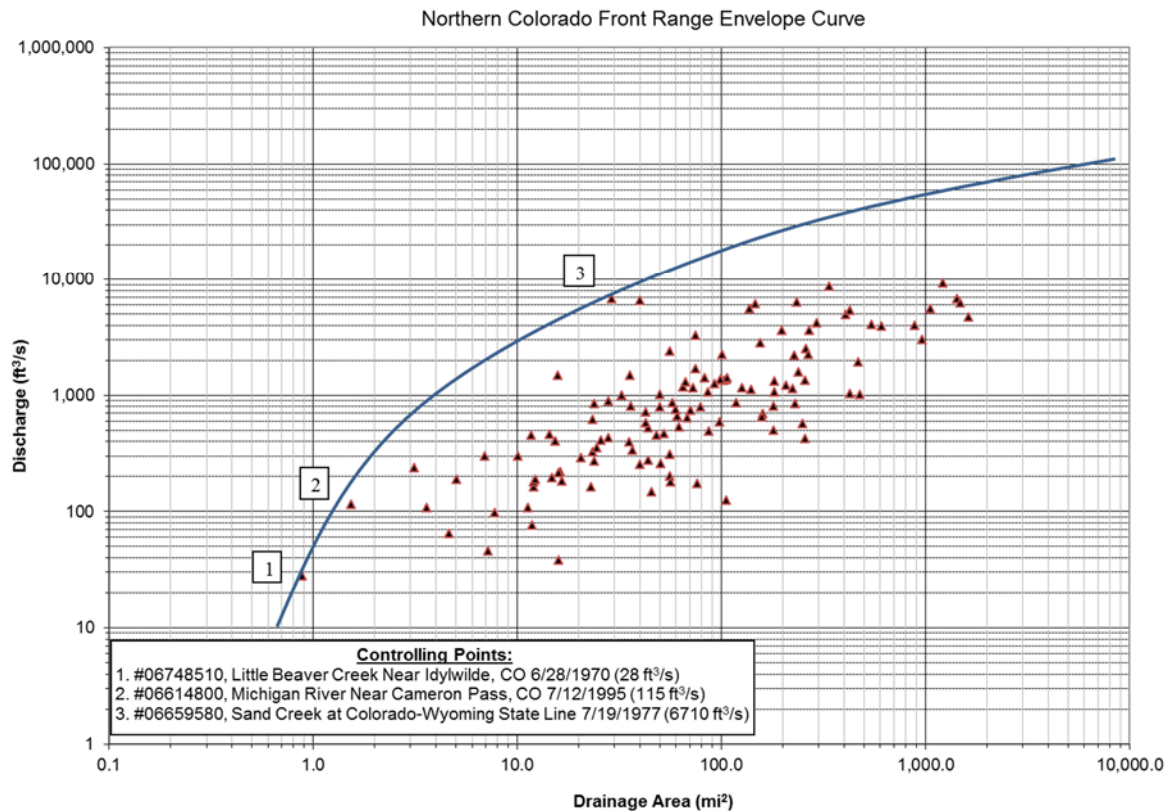


FIGURE 2.2: NORTHERN COLORADO FRONT RANGE ENVELOPE CURVE

TABLE 2.1: POINTS OF INTEREST WITH DRAINAGE BASIN AREAS AND ENVELOPE CURVE PEAK DISCHARGES

Point of Interest	Drainage Area (mi ²)	Peak Discharge (ft ³ /s)
NBT1	77	15,000
NVS1	102	18,000
NSV2	102	18,000
MSV1	30	7,500
SSV1	84	16,000
SSV2	70	14,500
LHC1	47	11,000
CC1	9	2,700

Appendix F compiles all the envelope curves developed for each point of interest listed in Table 2.1 extrapolating the peak discharges that would be associated to a specific drainage area.

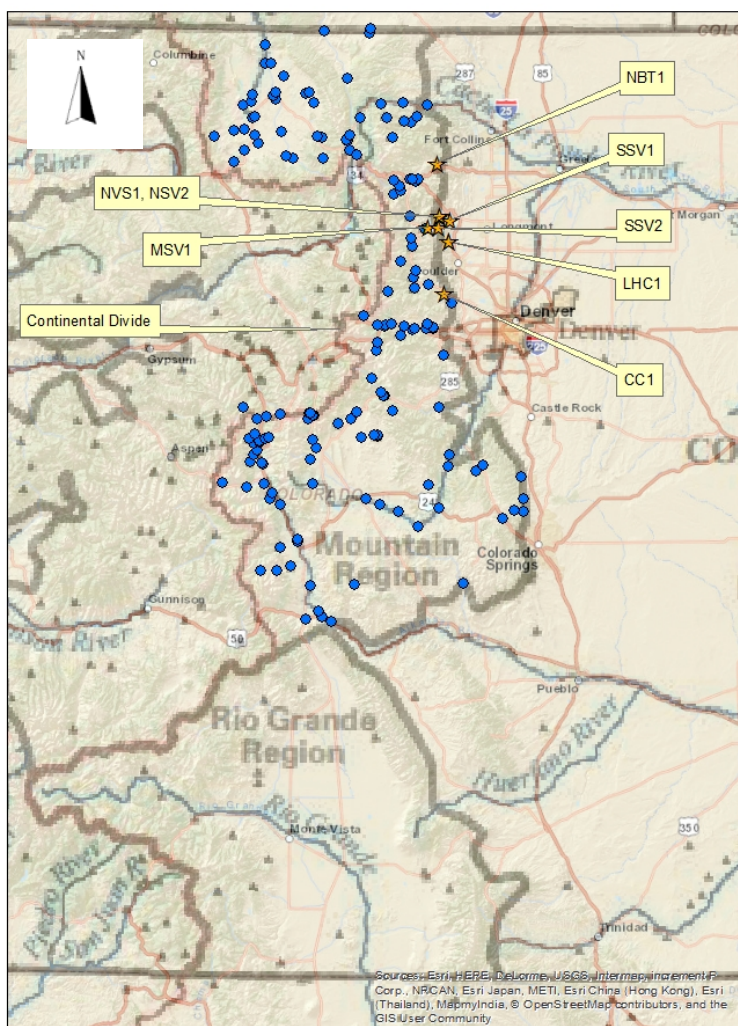


FIGURE 2.3: ENVELOPE CURVE STREAM GAGES USED NORTHERN COLORADO FRONT RANGE

Peak Annual Discharge Estimates

Flood frequency curves were developed for the sites of interest, based on USGS peak annual streamflow data. Gages were selected according to proximity to the ungaged point of interest, size of drainage area, and available period of record. The method used to transpose the gage data follows the USGS method (Vaill, 2000) specific to the Mountain Region of Colorado. USGS gage data used in the analyses and maps showing the points of interest and the USGS Gage used for analyses are provided in Appendix A.

Frequency analyses for the points of interest were performed using expected moments algorithm (EMA). Peak discharge estimates for Annual Exceedance Probabilities (AEP) were determined by fitting a log Pearson III distribution to the peak annual streamflow data according to procedures described in Bulletin 17B [USGS, 1981].

The streamflow gage records were adjusted to account for the difference in drainage area between the gaged and ungaged points of interest. A drainage area ratio method (Cudworth,

1992) was used to adjust the peak discharge estimates. The USGS National Streamflow Statistics (NSS) suggests an exponent equal to 0.69 be used to scale the peak discharge based on the ratio of the contributing areas (Vaill, 2000, p.10), for the Mountain hydrologic region in Colorado.

In order to compare the reasonableness of the shapes of the frequency curves that were developed, regression equations provided by USGS were applied to each of the sites for comparison. Estimates of the magnitude and frequency of peak discharges at ungaged stream sites in Colorado are provided by USGS [Vaill et al., 2000], and are available on the National Streamflow Statistics (NSS) website. Equations are provided for estimating the magnitude of peak discharges for recurrence intervals of 2-, 5-, 10-, 25-, 50-, 100-, 200-, and 500- years, and are based on USGS gage data as well as basin and climatic characteristics. The equations used were for the Mountain hydrologic region of Colorado.

NBT1 (North Fork Big Thompson River)

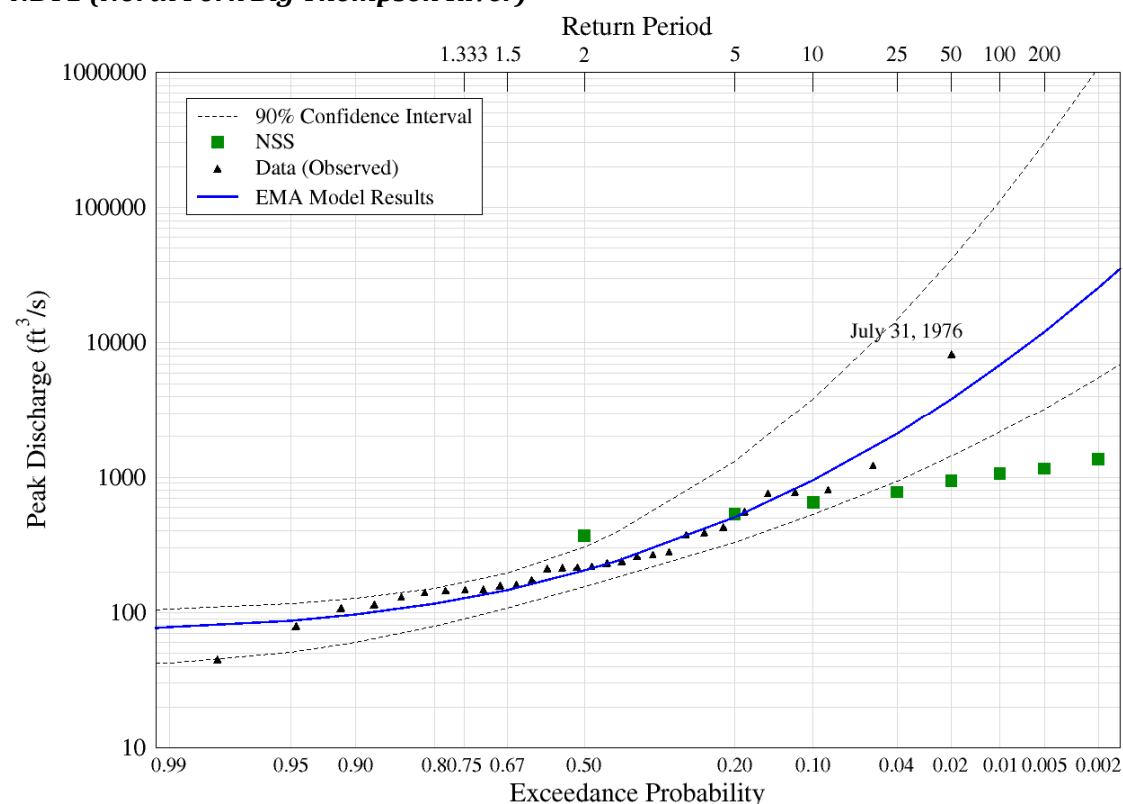


FIGURE 2.4: FLOOD FREQUENCY CURVE FOR THE NBT1 POINTS OF INTEREST

The flood frequency plot for NBT1 (Figure 2.4) was developed using the peak annual discharge data from the USGS stream gage ID 06736000, located approximately 2 miles downstream from the point of interest. The NBT1 and gage ID 06736000 drainage areas were 76.7 mi² and 85.1 mi² respectively.

Indirect measurements were made by Reclamation, in November of 2013, approximately 2 miles upstream of the confluence with the Big Thompson River and the town of Drake (Harden, deWolfe, Klinger, 2014). Results of the hydraulic modeling estimated the September 2013 peak discharge through the reach at 9,750 ft³/s. The indirect measurements were performed at approximately the same site represented by the flood frequency curve in Figure 2.4. Indirect peak flow measurements were also performed by USDA and the peak discharge flow was estimated to

be 18,400 ft³/s. “The discharge was measured at three adjacent sections on the N.F. Big Thompson River upstream of Drake.... The average peak flow of 18,400 ft³/s is approximately 2.5 times the 100-year flow, as indicted by a log-Pearson flow frequency analysis of peak flow data from the N.F. Big Thompson River at Drake stream gage (06736000), (Yochum 2013)”. The indirect peak flow measurement performed by USDA appears to be approximately twice the indirect peak flow measurement performed by Reclamation. For context, the peak discharge at this site during the 1976 Big Thompson flood was recorded at 8,107 ft³/s and the June 1965 flood yielded a discharge of 1,201 ft³/s.

NSV1 and NSV2 (North Saint Vrain Creek)

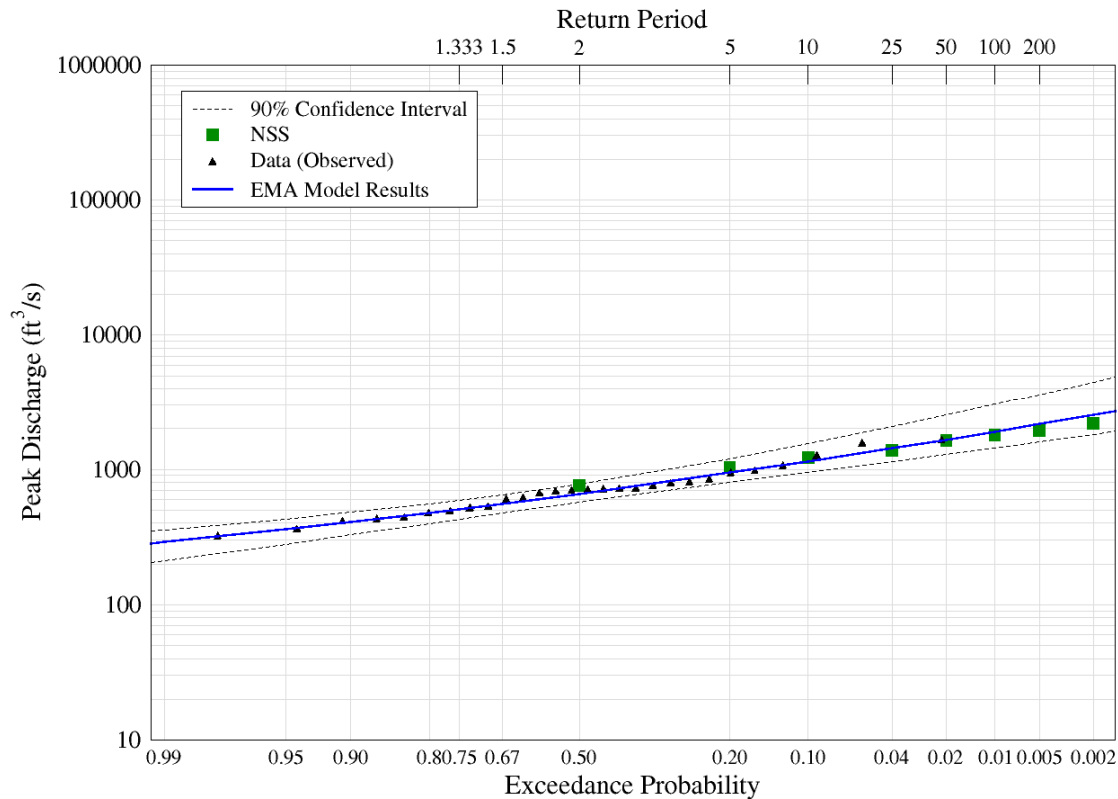


FIGURE 2.5: FLOOD FREQUENCY CURVE FOR THE NSV1 AND NSV2 POINTS OF INTEREST

The NSV1, NSV2 flood frequency curve (Figure 2.5) was developed with the peak annual discharge data from the USGS stream gage ID 06722000, approximately the same location as point NSV2. Peak flow records not found for the September 1894, June 1921, May 1955, June 1965, July 1976 flood events. The September 1938 flood produced peak flow of 972 ft³/s. The maximum peak flow on record was from June 1941 and was 1,630 ft³/s. This event was not considered an outstanding flood event. Stream gage peak flow data from the 2013 flood event was not available.

SSV1 (South Saint Vrain Creek)

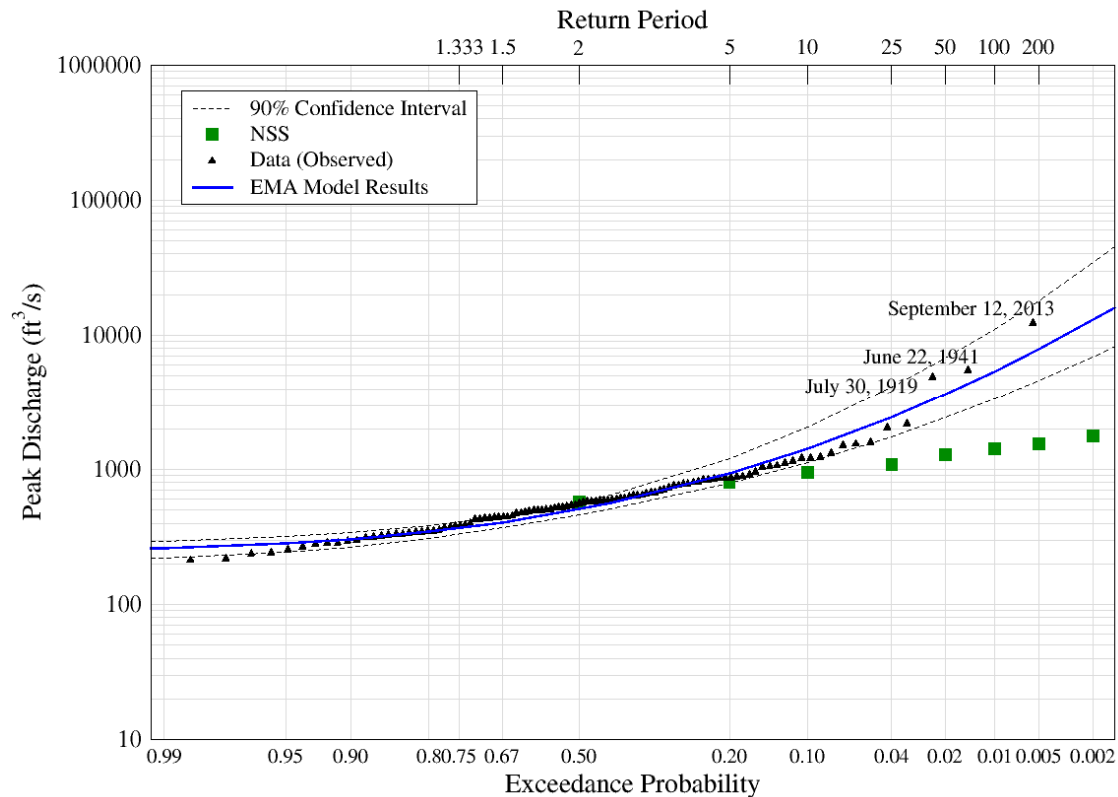


FIGURE 2.6: FLOOD FREQUENCY CURVE FOR THE SSV1 POINT OF INTEREST

The flood frequency plot for SSV1 (Figure 2.6) was constructed using data from USGS stream gage 06724000 located approximately three miles downstream. The gage watershed area was 216 mi² and the watershed area of SSV1 was 83.7 mi². The ratio of ungaged to gaged area is 0.39, which is outside the range, 0.5 to 1.5, that is considered reliable. This gage was chosen because it had greater than 10 years of recorded data, 109 years, including data from the June 1921, September 1938, June 1965, July 1976 and the September 2013 major flood events. The point of interest is located about three miles east of the Colorado mountains/plains region border. The drainage area was found to be primarily in the USGS Colorado mountain region and therefore the equation and exponent applicable to the USGS delineated mountains region were employed to develop the plot in Figure 2.7 (Vaill 2000). USGS stream gage 06724000 is located on the Saint Vrain Creek approximately half a mile downstream of the confluence of the North and South Saint Vrain Creeks. The transposed peak flow values for SSV1 are included for comparison purposes only. The transposed peak flow for the 2013 event was 12,373 ft³/s, which was more than twice the next largest recorded peak flow, that of June 22, 1941 of 5,459 ft³/s. The peak flows of the June 1921, September 1938, June 1965, and July 1976 were 1,066 ft³/s, 858 ft³/s, 957 ft³/s, 434 ft³/s, respectively.

SSV2 (South Saint Vrain Creek)

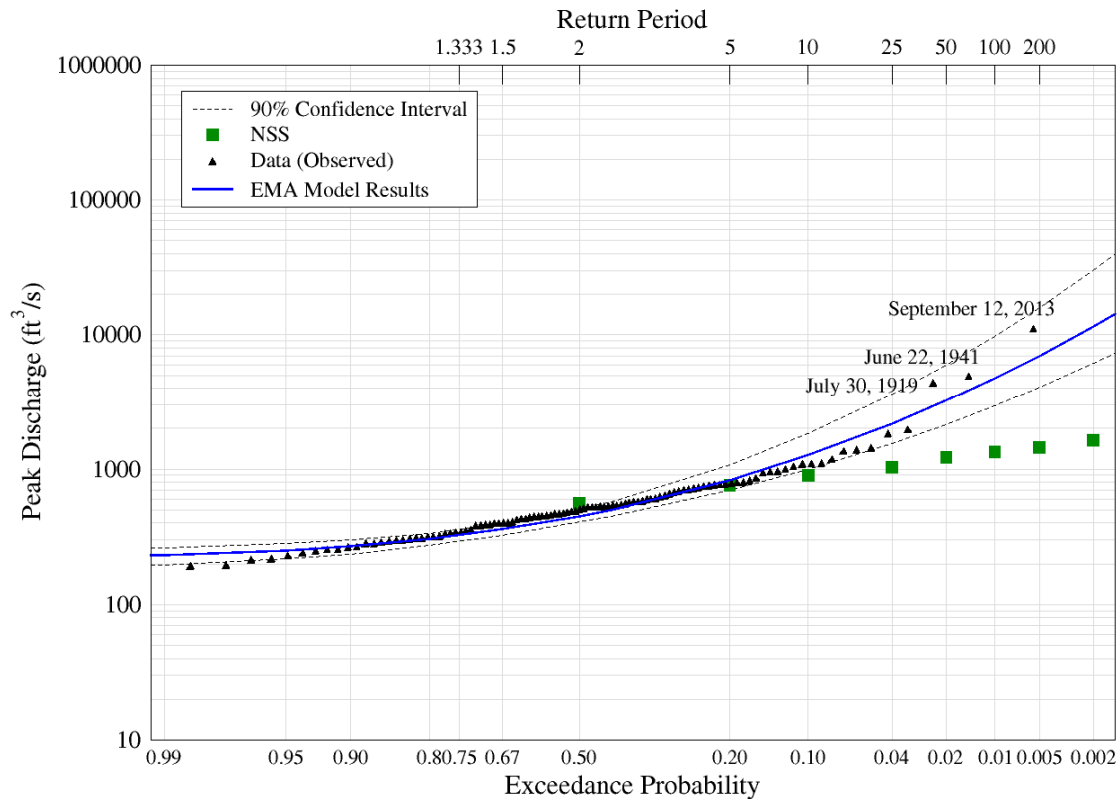


FIGURE 2.7: FLOOD FREQUENCY CURVE FOR THE SSV2 POINT OF INTEREST

The flood frequency plot for SSV2 (Figure 2.7) was constructed using data from USGS stream gage 06724000 located approximately eight miles downstream. The gage watershed area was 216 mi² and the watershed area of SSV2 was 70.1 mi². The ratio of ungaged to gaged area is 0.32, which is outside the range, 0.5 to 1.5, that is considered reliable. This gage was chosen because it had greater than 10 years of recorded data, 109 years, including data from the June 1921, September 1938, June 1965, July 1976 and the September 2013 major flood events. USGS stream gage 06724000 is located on the Saint Vrain Creek approximately half a mile downstream of the confluence of the North and South Saint Vrain Creeks. The transposed peak flow values for SSV1 are included for comparison purposes only.

The transposed peak flow for the 2013 event was 10,948 ft³/s, which was more than twice the next largest recorded peak flow, that of June 22, 1941 of 4,830 ft³/s. The peak flows of the June 1921, September 1938, June 1965, and July 1976 were 943 ft³/s, 759 ft³/s, 846 ft³/s, 384 ft³/s, respectively.

MSV1 (Middle Saint Vrain Creek)

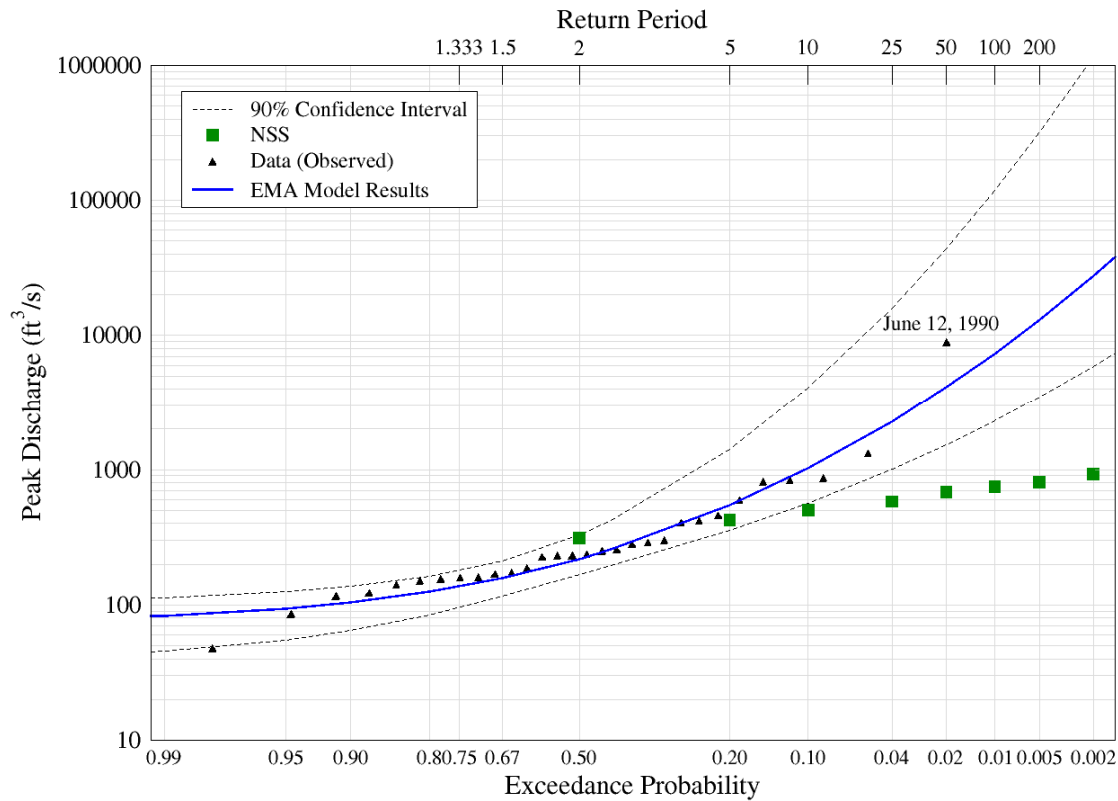


FIGURE 2.8: FLOOD FREQUENCY CURVE FOR THE MSV2 POINT OF INTEREST

The flood frequency plot for MSV2 (Figure 2.8) was constructed using data from USGS stream gage 06723000 located approximately 1.7 miles upstream. The gage watershed area was 28 mi² and the watershed area of MSV2 was 30.4 mi². The ratio of ungaged to gaged area is 0.92, which is within the range, 0.5 to 1.5, that is considered reliable. This gage was chosen because it had greater than 10 years of recorded data, 20 years, and was on the same watercourse. The largest transposed peak flow was 892 ft³/s from June 12, 1990. There was no recorded data from the September 2013 precipitation event, the 1976 Big Thompson flood event, the June 1965 flood event, or the September 1938 flood event.

LHC1 (Left Hand Creek)

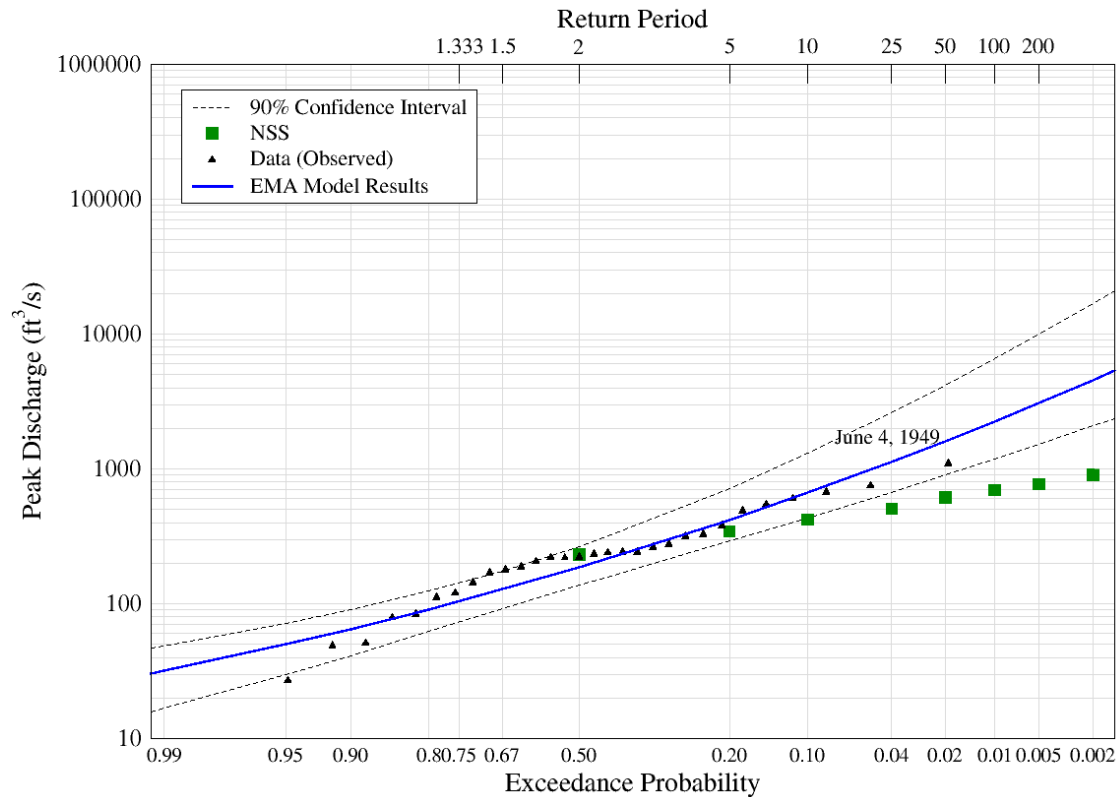


FIGURE 2.9: FLOOD FREQUENCY CURVE FOR THE LHC1 POINT OF INTEREST

The LHC1 flood frequency plot (Figure 2.9) was constructed using data from USGS stream gages ID 06724500 and 06725000, located approximately 1 and 13 miles downstream respectively. The point of interest is located within 3 miles east of the Colorado mountains/plains region border. The drainage area of LHC1 was primarily in the USGS Colorado mountain region. Gage 06725000 was included in the analysis because it was on the same watercourse, the drainage area was predominantly in the mountain region, and it nearly doubled the years of record available. The equation and exponent applicable to the USGS delineated mountains region were employed to develop the plot in Figure 2.7 (Vaill 2000). The stream gage data includes data from the September 1938 flood event, which was 529 ft³/s. There was not peak flow data for the May 1894, June 1921, June 1965, or July 1976 flood events. For comparison purposes, the peak discharge flow from USGS gage ID 06725450, located 18.5 miles downstream and with a drainage area of 423 mi², was transposed to the LHC1 point for the September 2013 flood and was 3,545 ft³/s.

CC1 (Coal Creek)

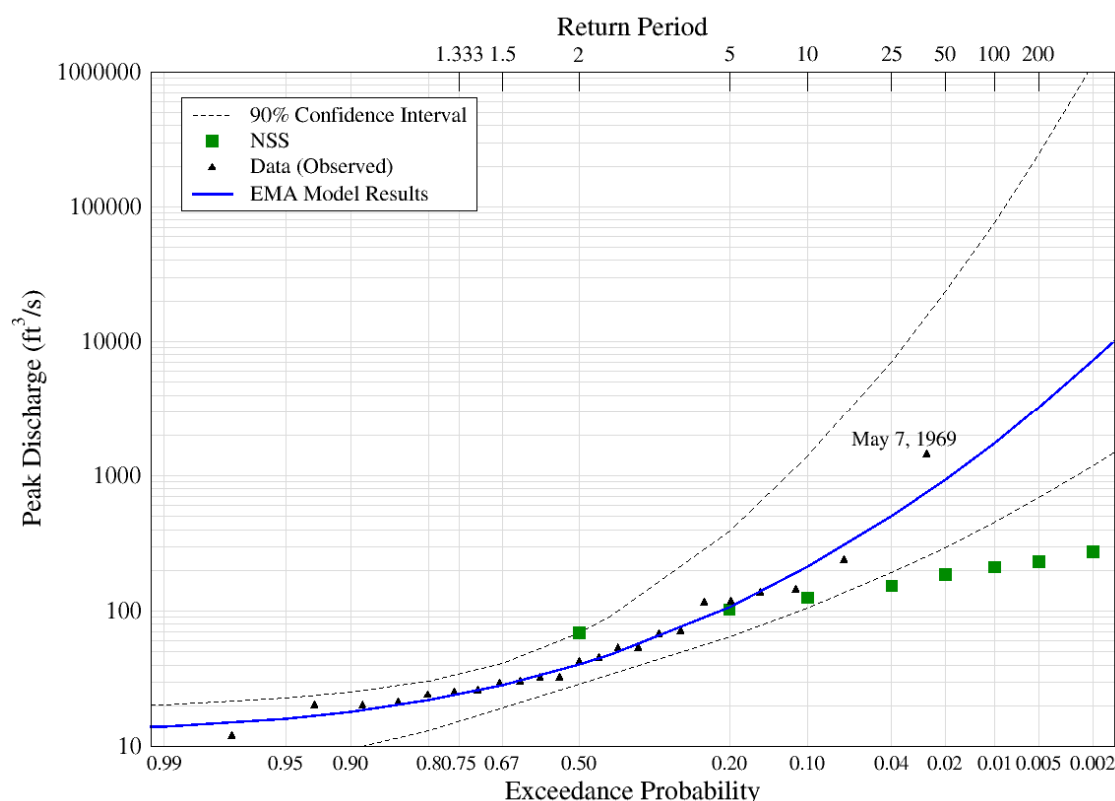


FIGURE 2.10: FLOOD FREQUENCY CURVE FOR THE CC1 POINT OF INTEREST

The CC1 flood frequency plot (Figure 2.10) was constructed using data from USGS stream gage 06730300, which is located approximately 3.3 miles downstream of the point of interest labeled CC1. The available peak flow data had been recorded from the year 1960 until the year 1982. The June 1965 flood event produced a peak flow of 78 ft³/s. The July 1976 Big Thompson flood event was not the largest flow measured for the year 1976, instead it was a rainfall event that occurred on May 25 that produced a peak flow of 22 ft³/s. Evidence that thunderstorms in the Rocky Mountain Front Range often are spatially concentrated and do not necessarily affect nearby watersheds. The maximum-recorded peak flow was from the May 1969 flood event, which produced a peak flow of 1,590 ft³/s.

3. Geomorphological interpretation of the September 2013 flood

Introduction

This section investigates and documents the impact of the September 2013 precipitation event at nine sites along seven drainages within the Front Range of Northern Colorado. Utilizing the physical (geologic and geomorphic) characteristics of the drainages investigated as well as the stratigraphic soil characteristic and age of the flood terraces analyzed, this study attempts to understand the main factors influencing the different response that each drainage had to the 2013 flood event. Furthermore, the current study documents the channel and floodplain characteristics, evaluate the channel morphology trends within a recent historical timeframe, and compute the peak discharge capacity of the channel relative to the September 2013 event.

Methods

Site Selection

The site selection for this project was based on initial field reconnaissance trips, conducted during late fall of 2013, of several flood-impacted drainages along the Front Range. Limiting factors influencing the selection of the sites were the restricted road access in the months immediately following the flood due to road repairs and the degree of site disturbance both caused by the flood debris as well as the heavy equipment utilized to mitigate the damages. Of the sites where access was available and that appeared less modified by the devastation of the flood, sections along the rivers were chosen where the discharge could be contained between geomorphological features such as a relatively straight, narrower section of the valley, or a rock outcrop, to obtain a more reliable discharge computation. Sites where high water marks, left by the current and past flood, were well preserved were also favored, as the availability of this field information can help to corroborate the indirect discharge computation and interpretation. Based on all these criteria a total of 7 drainages and 9 sites were selected and analyzed as part of this study.

Two sites were investigated along the North Saint Vrain Creek (sites NSV1 and NSV2) and along the South Saint Vrain Creek (sites SSV1 and SSV2). One site was analyzed respectively in each of the following drainages: on the Middle Saint Vrain Creek (site MSV1) immediately upstream of the confluence with the South Saint Vrain, on Left Hand Creek (site LHC1) immediately downstream of the confluence with Six Miles river, on Coal Creek (site CC1) less than a mile downstream of the intersection between Coal Creek Canyon road and Twin Spruce Gap road, on the North Fork of the Big Thompson River approximately two miles upstream of the town of Drake (site NBT1) and along Fourmile Canyon Creek (site 4MC1-4MC2) on the north west site of the town of Boulder, Colorado.

Although making stream flow indirect measurements of peak discharge of extreme floods is fraught with uncertainties (Benson, and Dalrymple, 1967; Pellitier, 1988) every attempt was made to select sites that avoided or eliminated as many sources of uncertainty as possible. All of the selected sites are easily accessible, had well-preserved high water marks (HWMs), had a stable hydraulic setting needed to compute peak discharge estimates and were free of debris and large volumes of obviously transported sediment that might complicate flood flow computations.

Topographic Data

Topographic survey cross sections were conducted during each field work section at all of the nine sites analyzed to facilitate the accurate reconstruction of flood peak discharges. As part of the topographic survey, data were collected on the channel geometry and elevation as well as the elevation of preserved HWMs. The data collected were used to reconstruct a 1D single cross section for each site. The survey field data were collected using a lightweight hand-held laser ranging instrument (Figure 3.1) that allows to measure distances, height and vertical angles. The maximum range of distance of the instrument is 1640 feet while the range resolution on each



FIGURE 3.1: LIGHT WEIGHT HAND-HELD LASER RANGING INSTRUMENT USED TO COLLECT SURVEY DATA FOR THE DETERMINATION OF A CHANNEL SINGLE CROSS SECTION AT EACH SITE.

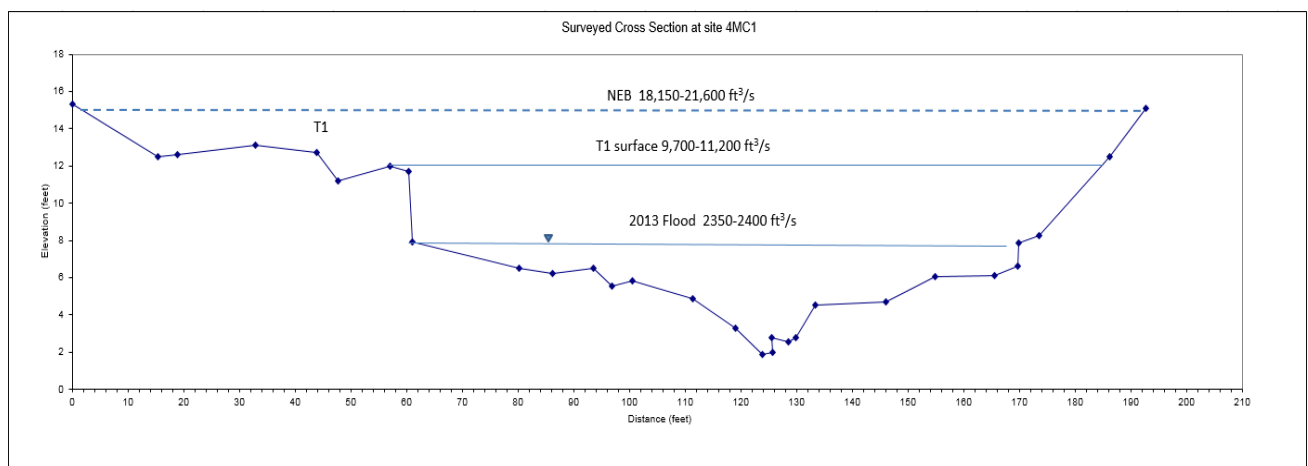


FIGURE 3.2: EXAMPLE OF SURVIED CROSS-SECTION ON FOURMILE CANYON CREEK AT SITE 4MC1.

Identification of High Water Marks (HWMs)

High water marks are physical indicators that provide evidence for the depth of water at peak stage of the flood at any particular site. HWMs can vary in elevation within the same flood due to many factors including surging or pulsing fluctuations in the flow or water surface, the type and volume of sediment or debris within the flow, and by temporary channel obstructions that might cause ponding or backwatering. Elevations of HWMs can also vary depending on what part of the hydrograph they were deposited (i.e., at the peak or on the declining or falling limb of the flood). Because of this variability in elevation, when more data is collected it allows for a comparison between elevations, which permits a more accurate peak discharge estimate to be calculated. HWMs observed and surveyed during field work included deposits of fine-grained sediment that had settled out in shallow water, mud and scour lines along the banks and channel margins, and flotsam (organic debris including leaves, grass, branches and sticks, even uprooted trees) that got caught on trees, bushes or in tall grass or on manmade objects at the peak of the flood (Figure 3.3 and 3.4). High water marks from the September 2013 flood were easily recognized and very well preserved within each of the study sites. The elevations of these indicators were measured during the cross section survey to provide information on the water surface for the peak flow and help constrain the stage of the flood.



FIGURE 3.3: SITE LCH1 ON LEFT HAND CREEK DOWNSTREAM OF THE CONFLUENCE WITH SIXMILE CREEK LOOKING DOWNSTREAM, EVIDENCE OF HWMS ON THE RIGHT BANK.



FIGURE 3.4: SITE SSV1 ON THE SOUTH SAINT VRAIN RIVER NEAR LYONS. LOOKING UPSTREAM, EVIDENCE OF HWMS ON THE LEFT BANK

Hydraulic computation

Using the topographic data collected in the field a peak discharge estimate of the 2013 flood event was calculated at each site using a single cross section conveyance method (Figure 3.5). This method compares the peak discharge estimate obtained using the Manning's equation and the Critical Depth method. For the Manning's equation, roughness values were assumed based on the site geomorphology and vegetation aspect while slope gradient was estimated from two elevation points upstream and downstream of the cross section analyzed. All water flow in the cross section is assumed to have the same (average) velocity and the same water surface elevation. In reality, there is significant variation across the cross section in velocity and water surface elevation. The one-dimensional step-backwater Hydraulic model HEC-RAS was used in conjunction with HEC-geoRAS (U.S. Army Corps of Engineers, 2010a, 2010b) to develop the hydraulic models and estimate stream discharge at site NBT1 (Harden, deWolfe and Klinger, 2014; Figure 3.6). The water surface elevation and corresponding peak discharge that closest represents the elevation of the surveyed HWMs, are derived from the model.

Work looking at the variability of discharge estimates using the different methodologies (Bauer and Klinger, 2010) suggests that discharge values derived from the critical depth and Manning's equation calculations may differ from 1D hydraulic model results by up to a factor of two or more.

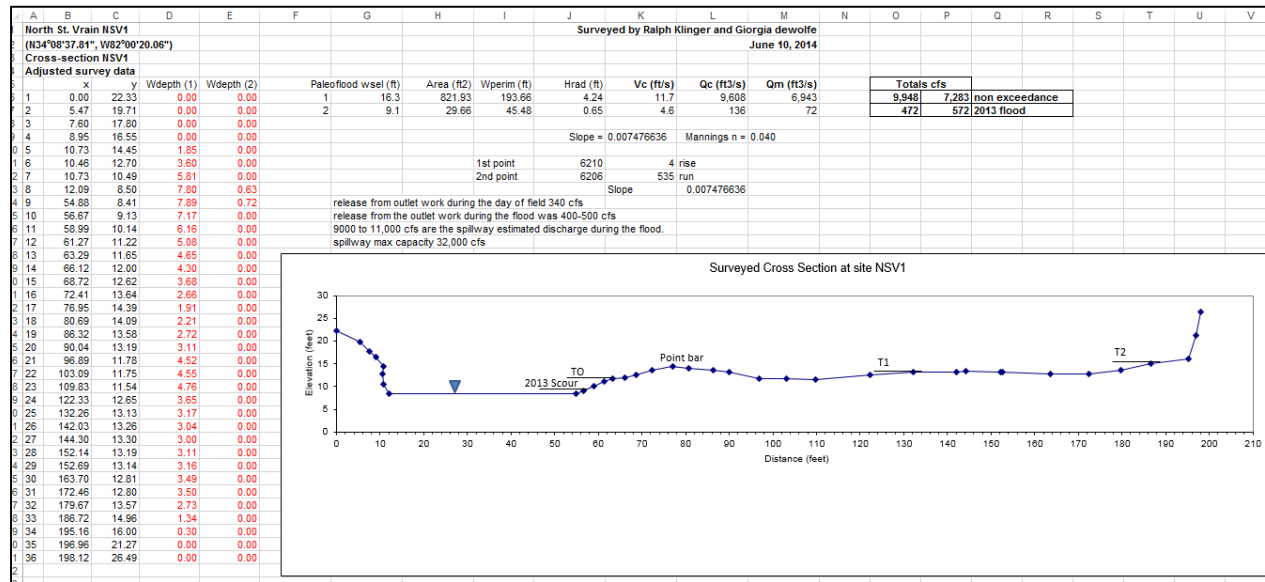


FIGURE 3.5: EXAMPLE CROSS SECTION FROM THE NORTH SAINT VRAIN RIVER AT SITE NSV1 AND COMPUTATION OF HYDRAULIC DISCHARGE USING A SINGLE CROSS SECTION CONVEYANCE METHOD.



FIGURE 3.6: CROSS SECTIONS SURVEYED AT SITE NBT1 ON THE NORTH FORK OF THE BIG THOMPSON RIVER NEAR DRAKE. THE CROSS-SECTION WHERE USED TO DEVELOP THE 1D HEC-RAS HYDRAULIC MODEL FOR THE SITE (HARDEN, DEWOLFE AND KLINGER, 2014).

Geomorphological mapping

During the field investigation, a geomorphological map was created for each site documenting the lateral and vertical changes to the river channel occurred in consequence of the 2013 flood. Geomorphological features, such as debris flow, landslides, terraces impacted by erosion or deposition, were mapped when present. The mapping effort was particularly important to understand the source of new sediment deposited during the flood, whether of fluvial or gravitation nature. For each site pre-2013 flood photos from Google Earth were used as a base map and possibly compared to post-2013 flood photos where available. While the initial mapping was entirely developed using Google Earth imagery, at a later time, Lidar topography with higher quality resolution was made available by FEMA allowing the digital rendering of the maps using ArcMap 10.2.2. An example of a completed mapping effort is shown below in Figure 3.7. Appendix B compiles the geomorphological map developed for all nine sites.

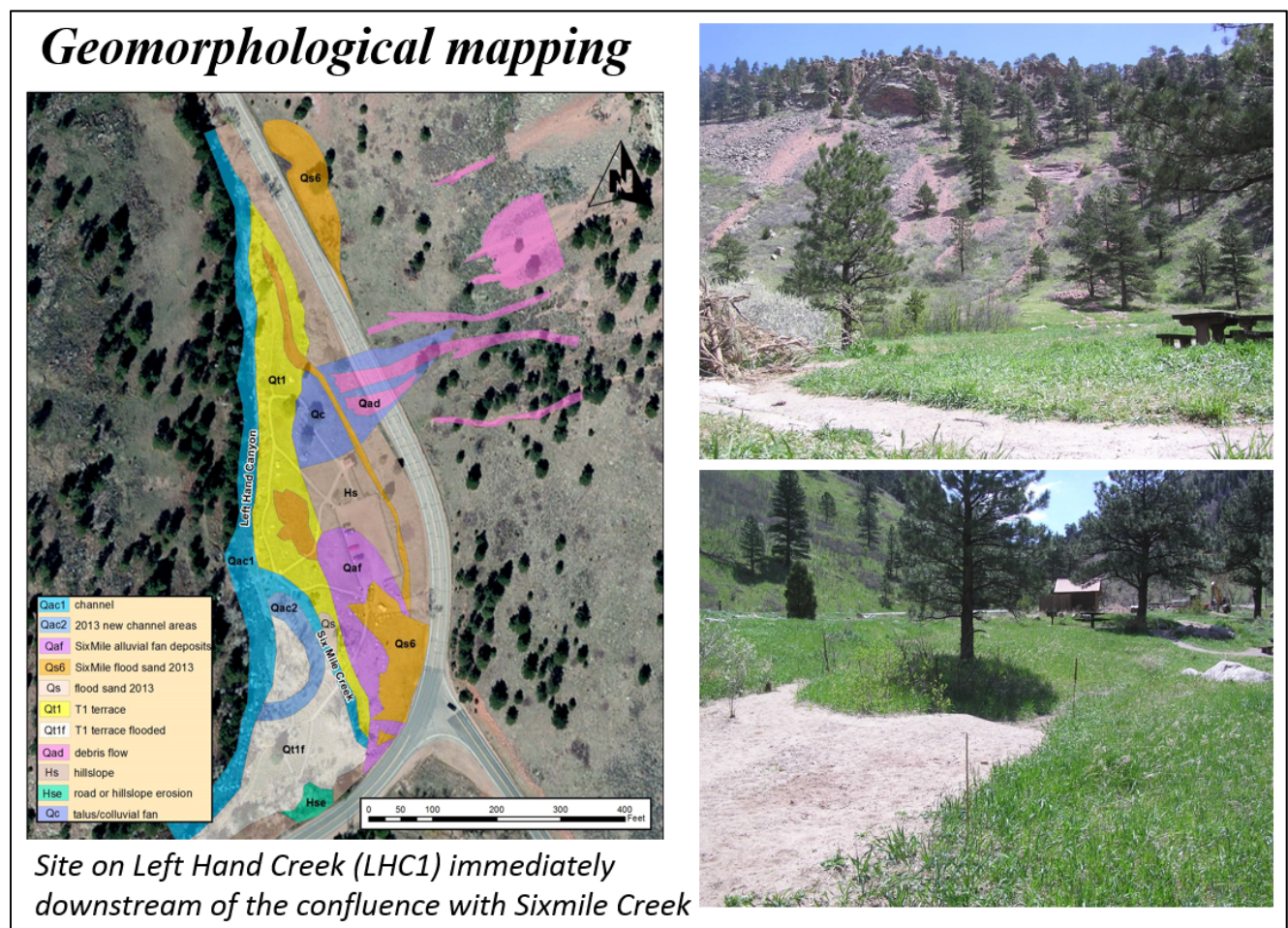


FIGURE 3.7: EXAMPLE OF DIGITIZED GEOMORPHOLOGICAL MAP REPRESENTING THE SITE ON LEFT HAND CREEK (LHC1).THE TWO PHOTOS ON THE RIGHT REPRESENT IMPORTANT GEOMORPHOLOGICAL FEATURES (DEBRIS FLOWS AND SEDIMENT DEPOSITION OCCURRED DURING THE FLOOD) PRESENT AT THE SITE.

Paleoflood analysis using radiocarbon data

In appropriate environments an effective means of reducing uncertainties regarding probabilities of flood recurrence is to augment observational and historical peak flow records by using paleohydrologic techniques (Costa, 1978; Hosking and Wallis, 1986; Stedinger and Baker, 1987; Frances et al., 1994; Webb et al., 2002) – typically using geologic, geomorphic and paleobotanical evidence to determine the ages and magnitudes of floods that occurred before the collection of observational records (paleofloods). One widely used technique in the study of paleofloods uses the fine-grained sedimentological record that accumulates in backwater areas (slackwater) to construct a detailed history of past floods (Patton and others, 1979; Kochel and Baker, 1988). This approach has been developed during the last several decades and is now a widely used method for quantifying unrecorded floods (Baker, 1987; Ely et al., 1993; O'Connor et al., 1994; Sheffer et al., 2008, Harden et al., 2011). This technique can be extremely useful in characterizing the frequency of large floods; however, slackwater sediments often times do not represent a complete and continuous record of floods at a particular site.

Another methodology uses the age of a terrace surface that lacks clear evidence of recent inundation, erosion and deposition, or alternatively displays evidence for long-term stability, to establish an upper limit to flooding. This non-inundation approach can be extremely useful in flood hazard assessment because geomorphic and stratigraphic information derived from the terrace surface can provide an upper limit or bound on the age and magnitude of extreme floods (Levish, 2002). Rather than constructing a detailed record of past floods, the non-inundation approach focuses on identifying a non-exceedance bound. Establishing a non-exceedance bound is accomplished by identifying terrace surfaces that serve as limits for the paleostage of large floods and estimating ages for those terraces (Figure 3.8). These bounds do not represent actual floods, but instead physical limits to peak flood stage over some measured time interval. Simply stated, a non-exceedance bound is a maximum stage that has not been exceeded in the time period since the terrace surface stabilized. The maximum stage can be used to estimate peak discharge given some knowledge of the channel characteristics. It is not necessary to develop evidence of specific paleofloods using this methodology. What is important is determining the discharge for a flood that has not been exceeded over the time interval represented by the preserved stable landscape.

Stable terrace surfaces are simply flood plains that have been abandoned due to either stream incision and/or channel migration. Once abandoned, the surface characteristics of the terrace begin to change recognizably with time. An abandoned terrace surface will tend to lose all evidence of having been inundated and become more planar and smooth with time. Once stabilized, soil will begin to form on the terrace deposits. Thus, stable terrace surfaces represent the field expression for the level of non-inundation or non-exceedance bounds and are a direct indication for the physical upper limit of floods along a stream through time. The geometric characteristics of the channel and terrace surfaces define the channel conveyance. The minimum overtopping depth required for the initiation of large-scale erosion of and/or deposition on the stable terrace surface is certainly dependent on sediment size and extent of induration, but can be evaluated formally in terms of shear stress or stream power (Parker, 1978; Andrews, 1984; Baker and Costa, 1987).

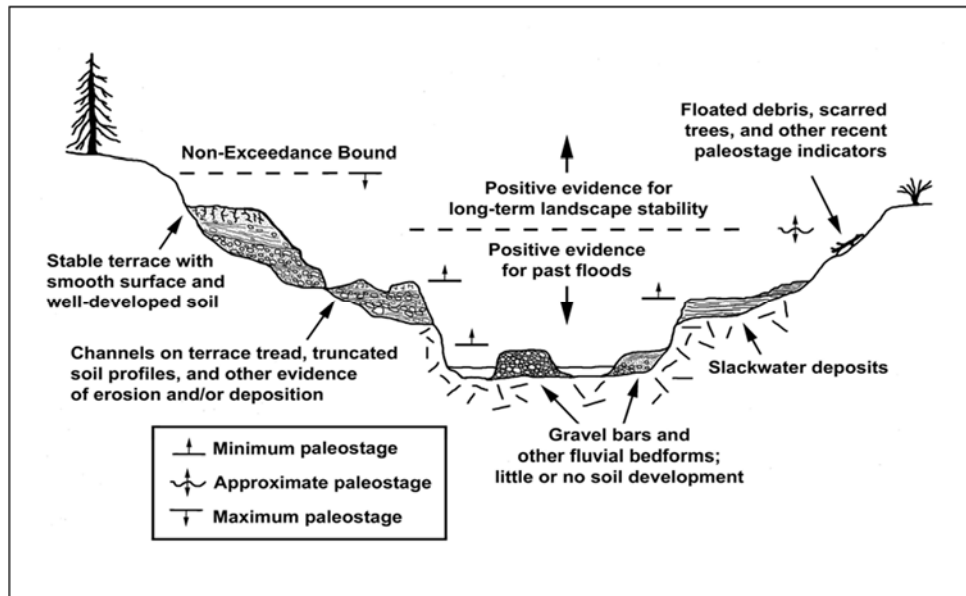


FIGURE 3.8: IDEALIZED CHANNEL CROSS-SECTION ILLUSTRATING THE CONCEPT OF A NON-EXCEEDANCE BOUND AND THE FLUVIAL LANDFORMS AND RELATED DEPOSITS IMPORTANT TO PALEOFLOOD STUDIES.

This information can also be derived directly from empirical data for historical floods. On high gradient streams, relatively shallow flow depths may produce higher values of stream power or shear stress. Ultimately, the depth of flow associated with a non-exceedance bound is that which is sufficient to cause modification of the overtopped terrace surface. Through step-backwater modeling or other one or two-dimensional techniques (Webb and Jarrett, 2002), a peak discharge for a non-exceedance bound can be easily derived from stage. In flood frequency analyses, a non-exceedance bound is set as the time interval (age of the terrace surface) during which the modeled peak discharge has not been exceeded.

The ages associated with the terrace surfaces that form the non-exceedance bounds should always be considered minimum ages because of the problems related to determining the precise time when a particular surface was abandoned, stabilized, and soil began forming. Determining the age of soils can be complicated because they contain a wide variety of organic components due to the relatively continual input of new material introduced into the profile by biotic processes (Johnson, 1990; Hsieh, 1992, 1993; Birkeland, 1999; Puseman and Cummings, 2004). Therefore, an estimate for the maximum discharge over the minimum time interval since the terrace surface stabilized makes the non-exceedance bound a conservative estimate for the flood hazard. These estimates are made even more conservative with time because channels may down cut and erode laterally resulting in apparently larger cross-sections and peak discharges than those that may have actually been present or occurred, so underestimation of a non-exceedance bound in most cases is typically not a problem. Estimating the peak discharge associated with a paleoflood deposit can be equally problematic. Assumptions must be made regarding the peak stage of the flood flow responsible for depositing the paleoflood deposit, particularly in respect to the channel geometry at the site and the grain size of the deposit.

As part of the stratigraphic description included in this study, soils horizon nomenclature as well as soil properties, such as color, boundaries, structure, consistence, texture and gravel content, were described following the Soil Survey Staff classification from 1960 to 1981 (Soil Survey Staff, 1960, 1975, 1981) outlined by Birkeland (Birkeland et al., 1991).

Radiocarbon samples submitted for AMS radiocarbon analysis as part of this study are initially floated, identified, and weighed prior to dating. Laboratory radiocarbon ages are reported in RCYBP (radiocarbon years at 1 standard deviation corrected for $\delta^{13}\text{C}$), and Cal BP (2-sigma calibrated) (Taylor and Bar-Yosef, 2014). The Cal BP radiocarbon age is subsequently adjusted by adding 65 years to the calibrated age to account for the 1950 datum in the radiocarbon calibration curve (Hua and Barbetti, 2004). Appendix H compiles the documentation obtained from the sample identification and AMS radiocarbon analysis performed on all charcoal samples collected at the sites.

Sites hydraulic and geomorphological characterization

North Saint Vrain Creek

Two sites were investigated on the North Saint Vrain immediately downstream of Button Rock Dam. The first site (NSV1) is located immediately downstream of the dam outlet work and is characterized by a flood plain and two terrace surfaces (a higher T1 surface and a lower T2 surface) preserved on the left bank of the river that appears to be isolated from historical flows. While the North Saint Vrain is historically been impacted by several floods, the terraces morphology at this site is particularly well preserved due to the presence of the dam and outlet work controlled flow releases. The center section of the lower terrace T2 is characterized by a gravel bar with large exposed boulders, while the back of the terrace presents evidence of an old back channel. While the terrace, approximately three feet above the floodplain, appears of a certain age, evidences of old flows are still present on the surface. The highest and older T1 surface (Figure 3.9), approximately two feet above the T2 surface has a smooth appearance with no evidence of flooding. A 55-inch deep test pit was excavated on this surface exposing what appears to be a continuous stratigraphic profile, which will be an indication of prolonged surface stability (Figure 3.10). The upper part of the profile (O/A/Bw1/Bw2 horizons) is characterized by fine sandy alluvium parent material, while the lower part (2Bw horizon) is composed by sandy gravelly alluvium.



FIGURE 3.9: HIGHER T1 TERRACE ON THE LEFT SIDE OF THE CHANNEL AT SITE NSV1 DOWNSTREAM OF BUTTON ROCK DAM.

A piece of charcoal collected in the 2Bw horizon yielded a radiocarbon age of 5720 ± 30 (RCYBP), 6690-6505 CAL years BP, (Appendix G) indicating that this is indeed a very old stable surface. A peak discharge in the range of 7,300 to 9,950 ft^3/s was estimated for the non-exceedance bound at this site on the basis of a slope conveyance calculation through a single cross-section using Manning's equation and a critical depth calculation (Appendix C). This discharge range represents a 3-foot flood depth over the surface of the terrace T1.

Based on high water marks identifiable on the riser between the flood plain and the T2 surface, using the same methodology indicated above, a potential peak discharge for the 2013 flood event was estimated in the range of 470 to 570 ft^3/s .

Based on the peak discharge and age information collected on the T1 surface it can be concluded that a discharge range of 7,300 to 9,950 ft^3/s appears not have been exceeded at site NSV1 approximately in the last 6,500 to 6,700 years.

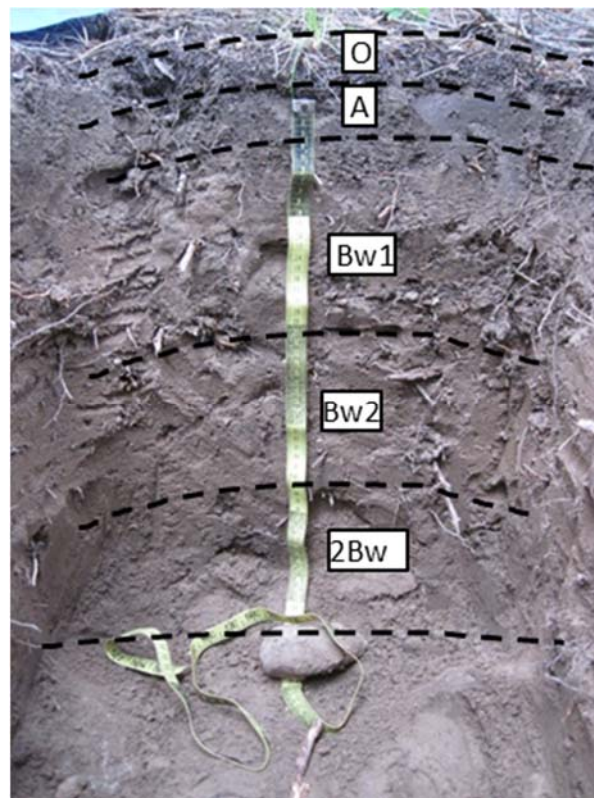


FIGURE 3.10: SOIL PROFILE AT SITE NSV1.

The second sites (NSV2) investigated along North Saint Vrain Creek is located immediately downstream of the confluence with the flows of Button Rock Dam emergency spillway.

During the September 2013 event, the combination of the two flow sources resulted in a noticeable impact along the road and the embankment fill slope above the terrace investigated due to surface erosion from run off flows, but did not largely effected the river geometry. It was estimated that during the flood 9,000 to 11, 000 ft^3/s were discharged in addition to the already elevated stage of the river. Based on the high water marks identified at the site (Figure 3.11), a peak discharge in the range of 16,950 to 14,570 ft^3/s was estimated based on a slope conveyance calculation through a single cross-section using Manning's equation and a critical depth

calculation (Appendix C). This value is consistent with the peak discharge estimate of 18,000 ft³/s, for a drainage area of approximately 100 mi² such as the drainage at site NSV2, obtained from the Envelope curve developed for Northern Colorado (see Figure 2.2). The flood frequency return period estimated for flows of this magnitude in the North Saint Vrain Creek basin is greater than 500 years.

The surface T1 stratigraphy was described in a soil exposure on the left riverbank (Figure 3.11). From the observation of numerous high water marks at the site, it was clear that the T1 surface had been lightly overtopped by flows in 2013 while run off flows along the road were responsible for the scour of the road embankment slope. The soil stratigraphy of surface T1 appears continuous and consistent with what already described at site NSV1 (A/Bw/2Bw). A piece of charcoal collected in the Bw horizon yielded a radiocarbon age of 1290 ±30 (RCYBP), 1355-1245 CAL years BP, (Appendix G). Because the T1 terrace remnant did not appear to be heavily overtopped or modified in its continuous stratigraphy by the 2013 flows, and because the computed flows cannot be considered a natural flow due to the large contribution from the emergency spillway discharge, it can be concluded that discharges in the range of 16,950 to 14,570 ft³/s have not been exceeded at this site approximately in the past 1250 to 1350 years.



FIGURE 3.11: T1 SURFACE SCoured BY THE 2013 FLOOD FLOWS ON THE LEFT SIDE OF THE CHANNEL AT SITE NSV2. THE ORANGE LINE IDENTIFIES THE HIGH WATER MARK ELEVATION ON THE SLOPE.

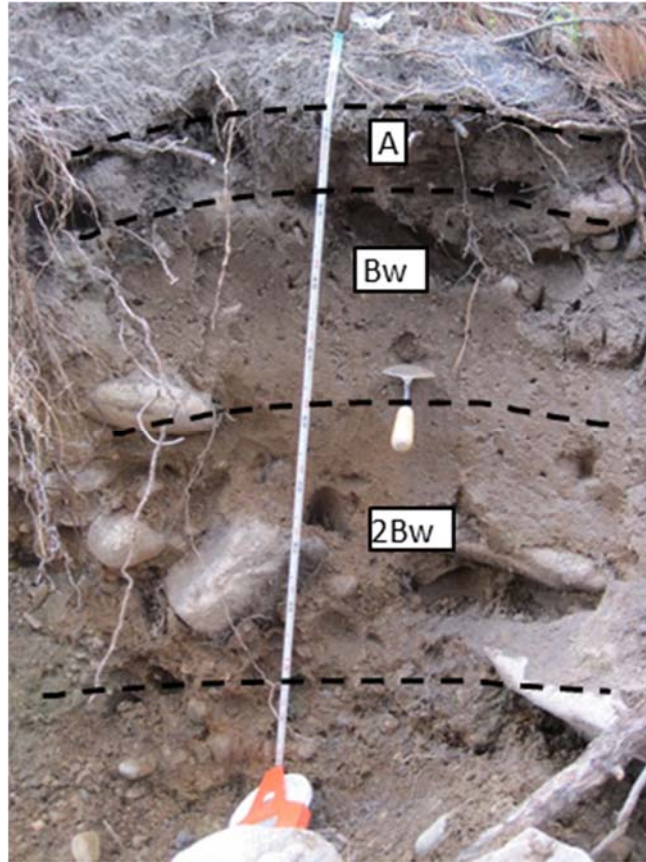


FIGURE 3.12: SOIL PROFILE AT SITE NSV2. THE TROWEL INDICATES THE LOCATION OF THE CHARCOAL COLLECTION.

South Saint Vrain Creek (SSV1)

Two sites were investigated on the South Saint Vrain River. The first site (SSV1) is located approximately two miles upstream of the South St. Vrain mouth in the proximity of Lyons quarry. This site is characterized by one terrace surface T1 on the right riverbank approximately 5 feet above the river channel (Figure 3.13). The surface appeared largely preserved and only marginally overtopped by the 2013 flood. At this site, the flows from the 2013 flood had widely enlarged the flood plain on the left riverbank. High water mark and flotsams were visible at the elevation of the T1 surface on both the right and left riverbanks.

A soil pit was excavated on the T1 surface exposing a discontinuous stratigraphy (C/Ab/C/C2/C3) where several floods were most likely recorded (Figure 3.14). The T1 terrace is characterized by fine gravelly alluvium and gravelly alluvium parent materials. The C-horizon on the surface was identified as 2013 well-sorted flood sand. The deposit appeared to be fining upward from pebbly sand to coarse sand. Pieces of the Ab horizon below were found to extend upward into the 2013 flood sand deposit as they would it been eradicated by the force of the flows and incorporated into subsequent deposition. Based on the high water marks identified at the site, a peak discharge in the range of 8,300 to 11,000 ft³/s was estimated based on a slope conveyance calculation through a single cross-section using Manning's equation and a critical depth calculation. The flood frequency return period estimated for flows of this magnitude in the South Saint Vrain basin is greater than 200 years. A charcoal sample was collected at a depth of 51 cm but the quantity was insufficient to undergo radiocarbon analysis.



FIGURE 3.13: T1 SURFACE AND FLOOD PLAIN WIDEN BY THE 2013 FLOWS ON THE LEFT RIVERBANK AT SITE SSV1.

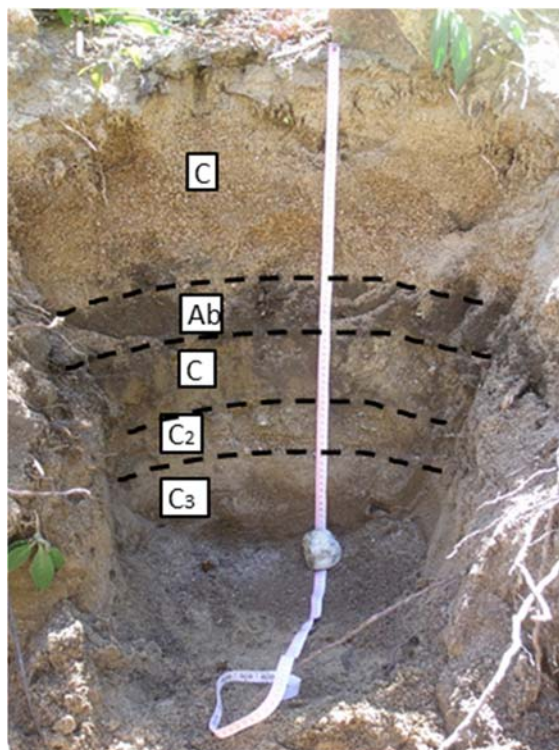


FIGURE 3.14: SOIL PROFILE AT SITE SSV1.

The second site (SSV2) is located along the South St. Vrain downstream and near the confluence with the Middle St Vrain. The site is characterized by a one single terrace, which appears partially overtopped by recent flows only on its margins near to the floodplain (Figure 3.15).



FIGURE 3.15: T1 SURFACE AND FLOOD PLAIN ON THE LEFT RIVERBANK AT SITE SSV2. NUMEROUS LARGE BOULDERS ARE PRESENT ON THE FLOOD PLAIN AND ON THE SURFACE OF THE T1 TERRACE.

The majority of the terrace surface appears in its natural state, irregular as punctuated by several large boulder in place, and highly vegetated. Several large boulders, which represent talus from the near hillslope, are present on the flood plain. Flotsam and flood sand from recent events, most likely the 2013 flood) are visible on the floodplain but not on the terrace surface analyzed. A test pit was excavated on the T1 terrace, which is composed by sandy and gravelly alluvium parent materials (Figure 3.16).

The stratigraphy, comprised of three horizons (A/C1/C2) is characteristic of a surface were one or more large floods depositional events have been recorded in the past and since a new soil had formed but not developed yet, due to the absence of a B horizon. The presence of angular large boulder in place within the A horizon suggests gravitational activity from the slope after the large flood depositional events.

Based on the high water marks identified at the site, a peak discharge in the range of 1,150 to 2,050 ft³/s was estimated based on a slope conveyance calculation through a single cross-section using Manning's equation and a critical depth calculation (Appendix C). The flood frequency return period estimated for flows of this magnitude in the South Saint Vrain basin is approximately between 25 and 50 years. Of the three charcoal samples collected in the C1 horizon at a depth between 20 and 50 cm, only one was suitable for radiocarbon analysis and returned an age of 70 ±30 (RCYBP), 325-285 CAL years BP, (Appendix G). Since the T1 surface appeared to be only marginally wetted and not majorly disturbed by the 2013 flood event, a non-exceedance flow was calculated for this site reflecting a two feet stage water increase over the T1 surface. The non-exceedance peak discharge computed for the site is in the range of 5,000 to 6,400 ft³/s. Based on the age and discharge information obtained from the T1 surface it can be concluded that discharges in the range of 5,000 to 6,400 ft³/s have not been exceeded at this site approximately in the past 325-285 years.

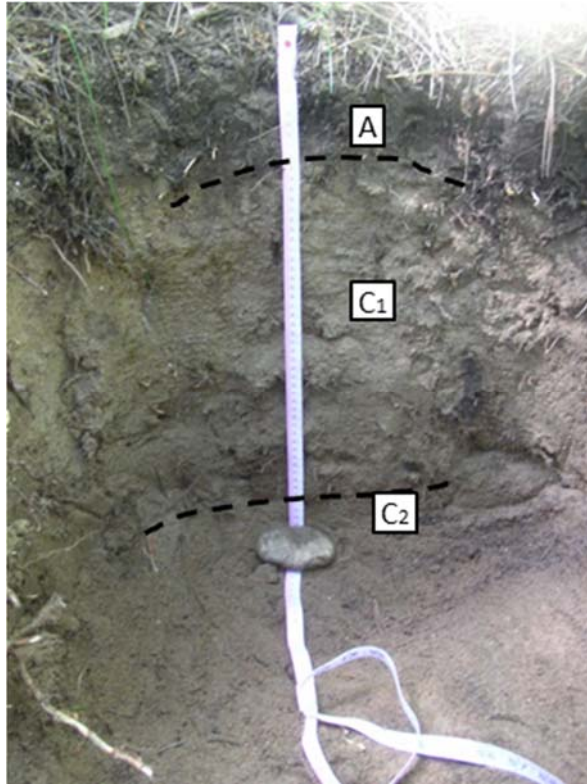


FIGURE 3.16: SOIL PROFILE AT SITE SSV2.

Middle Saint Vrain Creek

The single site investigated on the Middle Saint Vrain River (MSR1) is located immediately upstream of the confluence with the South St. Vrain River. The site is characterized by one terrace preserved on the right riverbank, of which only the upstream margin appeared to be marginally overtopped with signs of sand deposition during the 2013 flood event. While most the main terrace surface appears to be non-disturbed and smooth, the downstream end of the terrace is covered by slope failures debris. Both riverbanks are developed over unconsolidated materials. The channel relief in the right riverbank is approximately five feet while on the left riverbank is closer to 15 feet. Large non in-place boulders and rocks are present on the riverbed while bedrock is not exposed in the channel or the riverbanks (Figure 3.17). Flotsams were observed on the upstream side of the T1 terrace on the right riverbank, and on the rock slope of the left canyon wall. The T1 terrace stratigraphy, characterized by fine grain alluvium, was described on a soil exposure approximately five feet above the river channel (Figure 3.18). The stratigraphy reveals a medium developed soil formed above a 26- thick flood sand deposit fining downward. This sand deposit, that most likely represent multiple stages of a single event, appears to truncate a buried Ab soil horizon which, had developed over an older buried flood sand (Cb horizon).



FIGURE 3.17: T1 SURFACE ON THE RIGHT RIVERBANK AT SITE MSV1. FLOTSAMS FROM THE 2013 FLOOD EVENT ARE CONTAINED FOR THE MAJOR PART WITHIN THE RIVER CHANNEL. THE HIGH WATER MARKS ELEVATION IS IDENTIFIED WITH A RED LINE.

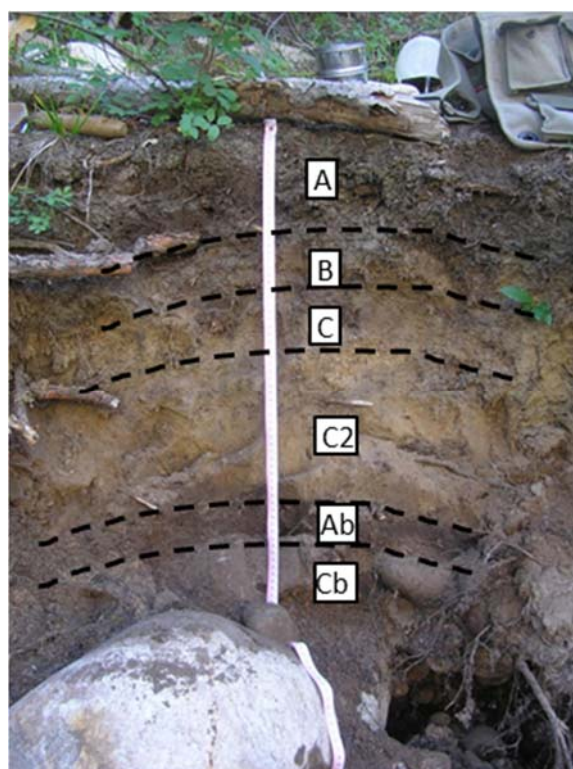


FIGURE 3.18: SOIL PROFILE AT SITE MSV1.

Based on the high water marks identified at the site, a peak discharge in the range of 1,500 to 1,680 ft³/s was estimated for the 2013 flood event based on a slope conveyance calculation through a single cross-section using Manning's equation and a critical depth calculation (Appendix C). The flood frequency return period estimated for flows of this magnitude in the Middle Saint Vrain basin is approximately 25 years. When comparing observation from the two site on the South St. Vrain River and the single site on the Middle St. Vrain River it can be noted that sites situated at higher elevation in the watershed (MSV1 and SSV2) seem to have experience lower return period flood associated with the 2013 precipitation event.

Two charcoal samples collected in the C2 horizon at a depth of 37 cm and on the Ab horizon at 53-cm depth, yielded respectively an age of 1410 ±30 (RCYBP), 1415-1355 CAL years BP, and 1830 ±30 (RCYBP), 1925-1765 CAL years BP (Appendix G). Since the T1 surface appeared to be only marginally wetted on its upstream end, a non-exceedance flow was calculated for this site reflecting a two feet stage water increase over the T1 surface. The non-exceedance peak discharge computed for the site is in the range of 4,650 to 5,000 ft³/s. Based on the age and discharge information obtained from the T1 surface it can be concluded that discharges in the range of 4,650 to 5,000 ft³/s have not been exceeded at this site approximately in the past 1355 to 1415 years.

Left Hand Creek

The site investigated on Left Hand Creek (LHC1) is located immediately downstream of the confluence with the Six Mile Creek in the proximity of a recreational area. The site is characterized by one large flat terrace on the right riverbank where the recreational area was developed. Almost the entire majority of the terrace was impacted by erosion and deposition of sand from the 2013 flood event. As shown in the geomorphologic map developed for the site (Appendix B), the flood sand deposited from Left Hand Creek appear to have covered the section of the T1 terrace closer to the river while the flood sand from Six Mile Creek is concentrated on the back section of the terrace and along the adjacent road. The location of Six Mile Creek flood sand is most likely due to the obstructing forces of the flows from Left Hand Creek. Furthermore, the two sand deposits are characterized by a distinct color difference. The section of the terrace closer to the confluence is particularly disturbed and covered by large wooden debris (Figure 3.19). Several recent debris flows are visible on the hillside behind the T1 terrace and could represent an additional source for sediments and larger angular boulders that are present on the T1 surface.

The downstream section of the T1 terrace further from the confluence appears overtopped but less disturbed (Figure 3.20). From his position and from the exposed stratigraphy this inset section of the terrace could be cut on alluvial fan material. The stratigraphy of the T1 terrace was described in this downstream section in a soil exposure characterized by medium to coarse grained, quartz-rich granitic sand parent material. The stratigraphy of the exposure shows a poorly developed soil (A/Ab/2Bw) incorporating medium to large rounded boulders in the lower section of the soil profile (Figure 3.21). Pockets of lighter sand (possibly from Six Mile Creek) are also incorporated in the upper portion of the A horizon, suggesting the potential presence of multiple wetting flows on this surface in recent years. In this section of the T1 terrace, flotsams were observed along the margins near to the right riverbank as well as on the left riverbank slope at similar elevation (Figure 3.20).

Based on the high water marks identified at the site, a peak discharge in the range of 3,400 to 5,000 ft³/s was estimated for the 2013 flood event based on a slope conveyance calculation through a single cross-section using Manning's equation and a critical depth calculation

(Appendix C). A peak discharge estimate of 11,000 ft³/s can be obtained from the Envelope curve developed for Northern Colorado (see Figure 2.2), for a drainages area of approximately 47 mi², such as the drainage at site LHC1. The flood frequency return period estimated for flows of this magnitude in the Left Hand Creek basin is approximately 200 to 350 years. Charcoal samples for radiocarbon analysis were not found at this site reducing the possibility of additional age comparisons between the 2013 flood and past paleoflood events.



FIGURE 3.19: T1 SURFACE NEAR THE CONFLUENCE WITH SIX MILE CREEK. FLOTSAMS AND LARGE WOODEN DEBRIS FROM THE 2013 FLOOD EVENT ARE DEPOSITED ON THE WIDEN AND ERODED RIVER CHANNEL.



FIGURE 3.20: T1 SURFACE ON THE LEFT RIVERBANK LOOKING UPSTREAM AT SITE LHC1. FLOTSAMS AND ELEVATION OF HIGH WATER MARKS FROM THE 2013 FLOOD EVENT ARE IDENTIFIED BY A RED LINE.

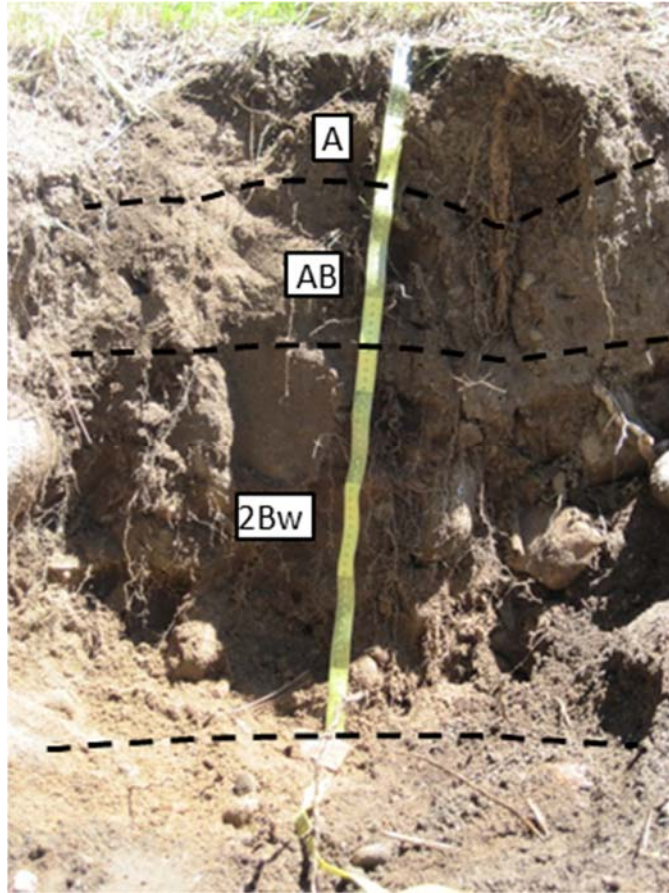


FIGURE 3.21: SOIL PROFILE AT SITE LHC1.

Coal Creek

A single site was investigated along Coal Creek (CC1) just upstream of the location known as Chapel of the Hill along highway 72. The site is characterized by two terrace surfaces, a higher T1 surface preserved on the right riverbank, approximately 6 to 7 feet above the river channel and a lower T2 surface on the left riverbank approximately two feet above the river channel (Figure 3.22). While the majority of the T1 terrace appears in a well-preserved natural state, the upstream section of the terrace shows sign of sand deposition from the 2013 flood event. In this section of the T1 terrace, the water appears to have flooded over the banks and inundated the surface pushed by debris flow materials that had slumped immediately upstream from the opposite hillside. The debris flow was large enough to dam the road and cause the failure of the road cover conveying flows from the hillside to the river.

The high water marks and flotsams present on the T1 surface offered an identifiable trail that allowed determining the location where the overbanked flows had re-entered the river. The section of the T1 terrace downstream of this location, where the stratigraphy was described, was therefore considered non-disturbed by flows for the 2013 event.



FIGURE 3.22: LOWER T2 SURFACE ON THE LEFT RIVERBANK AND HIGHER T1 SURFACE ON THE RIGHT RIVERBANK LOOKING DOWNSTREAM AT SITE CC1.

Based on the high water marks identified at the site, a peak discharge in the range of 960 to 1,110 ft^3/s was estimated for the 2013 flood event based on a slope conveyance calculation through a single cross-section using Manning's equation and a critical depth calculation (Appendix C). A peak discharge estimate of 2,700 ft^3/s can be obtained from the Envelope curve developed for Northern Colorado (see Figure 2.2), for a drainage area of approximately 9 mi^2 , such as the drainage at site CC1. The flood frequency return period estimated for flows of this magnitude in the Coal Creek basin is approximately 50 years.

The T1 terrace stratigraphy, characterized by sandy and gravelly alluvium, was described on a soil exposure approximately six feet above the river channel (Figure 3.23). The stratigraphy revealed a 37-cm-thick medium developed soil formed over a horizon characterized by fluvial gravelly sand. Below the C horizon, the C2 horizon is formed by fluvial coarse sand and interbedded organic-rich brown sand beds. The C3 horizon below is characterized by a thin upper portion formed by weak sand cross beds with charcoal-rich sand layer and a lower thicker section formed of gravelly sand with subangular to subrounded cobbles on clast-to-clast contact. Based on its content, this lower section could be of fluvial or debris flow origin.

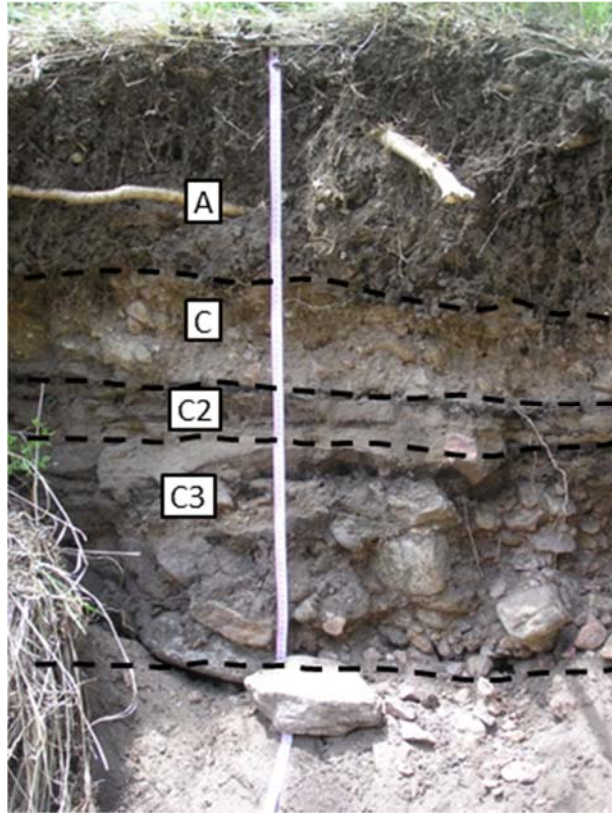


FIGURE 3.23: SOIL PROFILE AT SITE CC1.

A charcoal piece collected near the interface between the C2 and C3 horizons yielded a radiocarbon age of 820 ± 30 (RCYBP), 850-750 CAL years BP, (Appendix G) indicating that the coarse sand forming the C2 horizon should have been deposited at least 750 years ago. Since the T1 surface appeared to be overtopped on its upstream end from causes unrelated to the river flows, and the remaining of the surface is considered well preserved, a non-exceedance flow was calculated for this site reflecting a three feet stage water increase over the T1 surface. The non-exceedance peak discharge computed for the site is in the range of 5,600 to 6,700 ft³/s. Based on the age and discharge information obtained from the T1 surface it can be concluded that discharges in the range of 5,600 to 6,700 ft³/s have not been exceeded at this site approximately in the past 750 to 850 years.

North Fork Big Thompson River

The site along the North Fork Big Thompson River (NBT1) is located approximately 2 miles upstream of the confluence with the Big Thompson River and the town of Drake.

The river channel is composed of large cobbles and boulders with interstitial sand and silt. Bedrock outcrops are visible through the reach, primarily along the right bank and in the hillslope along the left valley wall. The site is characterized by a, fairly broad, lower surface T2 presents on both riverbanks about 5-6 feet above the active river channel and a higher surface T1 observed on the right riverbank approximately 7-8 feet above the river (Figure 3.24). From field observation, the T2 surface appeared extensively overtopped during the 2013 flood, with high water marks visible along the contact between the terrace and the hillslope and flood sand deposition on the margins of the terrace closest to the river channel. As shown on the site

geomorphological map (Appendix B) a small but continuous remnant of the T1 surface is preserved on the right riverbank between the T2 surface and the hillslope. Flood sand and flotsams from the 2013 flood were visible on this surface only along the bend in the upstream section of the reach, while the T1 surface on the center section of the reach did not show any sign of recent flows.



FIGURE 3.24: LOWER T2 SURFACE ON THE LEFT RIVERBANK AND HIGHER T1 SURFACE ON THE RIGHT RIVERBANK LOOKING DOWNSTREAM AT SITE NBT1.

The T2 terrace stratigraphy, characterized by a combination of overbank fine alluvium and coarse colluvium/alluvium sediments, was described on a soil exposure on the left riverbank approximately five feet above the river channel (Figure 3.25).

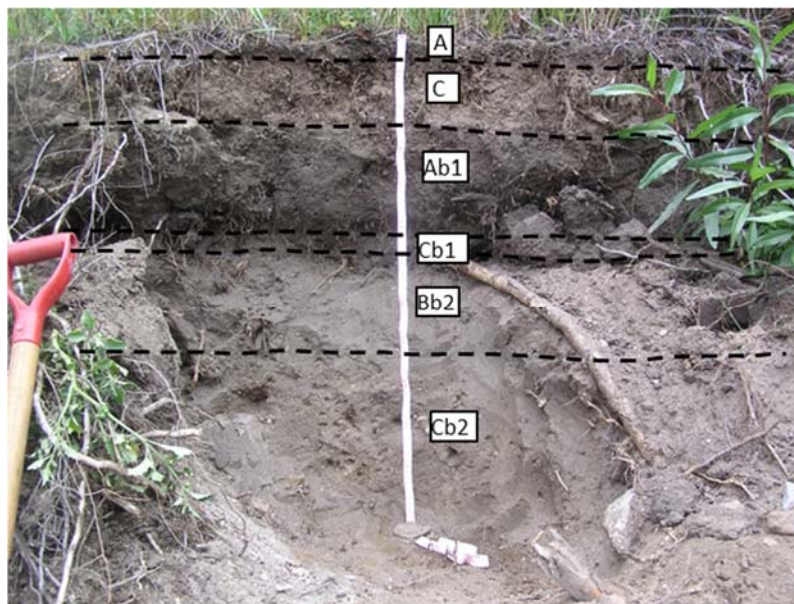


FIGURE 3.25: SOIL PROFILE AT SITE NBT1.

The exposures edge appeared eroded and partially collapsed in near sections of the terrace from the action of recent flows. Although not visible in the exposure, flood sand from the 2013 event is deposited extensively along the surface (Figure 3.26).



FIGURE 3.26: SITE NBT1, EVIDENCE OF 2013 FLOOD SAND OVER THE TERRACE A-HORIZON.

The stratigraphy shows a thin A-horizon forming over a flood sand C-horizon, most likely deposited during the 1976 Big Thompson flood. The 1976 flood sand is deposited over a 26-cm-thick, medium developed, buried Ab1 horizon. Below the Ab1 horizon, another flood sand is deposited over a holder buried Bb2-horizon of which the upper A-horizon may have been removed by flows erosion. The bottom of the exposure is characterized by another Cb2-horizon over which the buried Bb2-horizon had developed. This stratigraphy sequence suggests that at least three paleoflood events are recorded at the site.

Two charcoal samples collected in the Ab1 horizon at a depth of 33 cm and on the Bb2 horizon at 63-cm depth, yielded respectively an age of 160 ± 30 (RCYBP), 350-125 CAL years BP, and 1860 ± 30 (RCYBP), 1940-1780 CAL years BP (Appendix G). The age collected on the Ab1 horizon would infer that that paleo-surface was stable before the deposition of the C-horizon, most likely from the 1976 Big Thompson flood, for a period between 125 and 350 year. The age collected from the Bb2 horizon would suggest that the flood recorded in the Cb1-horizon happened sometime after a period of stability of approximately 1800 years and that the flood recorded in the Cb2 horizon is most likely significantly older.

As part of a study conducted by Reclamation in 2014 (Harden, deWolfe and Klinger, 2014) a HEC-RAS model of the same site was developed using four cross sections measured along a channel segment of about 280 feet (Figure 3.27).



FIGURE 3.27: SURVEYED CROSS SECTIONS AND HWMs ALONG THE NORTH FORK BIG THOMPSON RIVER AT SITE NBT1 (FROM HARDEN, DEWOLFE AND KLINGER, 2014)

The results of the hydraulic modeling indicate that the peak discharge through the reach was about 9,750 ft³/s. The flood frequency return period estimated for flows of this magnitude in the North Fork Big Thompson River basin is approximately 150 years. A peak discharge estimate of 15,000 ft³/s can be obtained from the Envelope curve developed for Northern Colorado (see Figure 2.2), for a drainage area of approximately 77 mi², such as the drainage at site NBT1. Based on the peak discharge of 8,710 ft³/s recorded at the town of Drake (USGS 06736000) during the 1976 flood, for a drainage area of 85mi², it can be concluded that the discharge produced by the 2013 event was comparable to the 1976 flood event and most likely slightly larger. Based on the comparable nature of the 2013 and 1976 flood at this site it could be suggested that both flood can be associated to a return period of approximately 150 years.

Fourmile Canyon Creek

Two sites were investigated along Fourmile Canyon Creek (4MC1 and 4MC2), but due to the proximity of their location, these were considered as a one single reach. The reach investigated along the river in the proximity of the city of Boulder, Colorado, encompasses a drainage area of 7.2 mi². The site analyzed is characterized by a well-defined flood plain, greatly widened by the 2013 flood event, and scoured remnants of a lower (T2) and higher (T1) surfaces (Figure 3.28-3.29, geomorphological map on Appendix B).

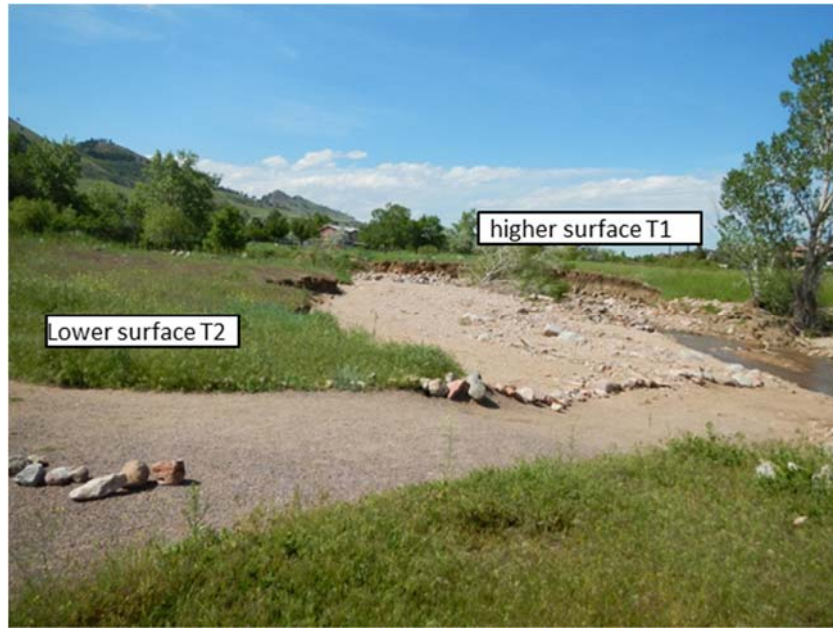


FIGURE 3.28: LOWER T2 SURFACE ON THE RIGHT RIVERBANK AND HIGHER T1 SURFACE ON THE LEFT RIVERBANK LOOKING DOWNSTREAM ALONG FOURMILE CANYON CREEK.

The T1 surface, which is the most preserved along the reach, is characterized by a combination of overbank fine-grained alluvium and coarse alluvium/colluvium sediment. A soil exposure was described on the left riverbank of Fourmile Creek (site 4MC1). While the terrace edge was clearly eroded during the 2013 flood event, the T1 terrace surface appears not to have been overtopped. The exposure (Figure 3.30) shows a well-developed soil with presence of carbonate at the bottom of the B-horizon overlaying a sequence of coarse C-horizons and older buried B-horizons.



FIGURE 3.29: FLOODPLAIN AND LOWER T2 SURFACE ON THE RIGHT RIVERBANK LOOKING DOWNSTREAM ALONG FOURMILE CANYON CREEK.

This stratigraphic sequence indicates that evidence of several floods have been preserved at this site. A charcoal sample collected from this exposure, at 30 to 45-cm depth, in the Bt1 horizon returned an age of 8750 ± 40 (RCYBP), 9,970- 9,625 CAL years BP and is considered late Holocene.

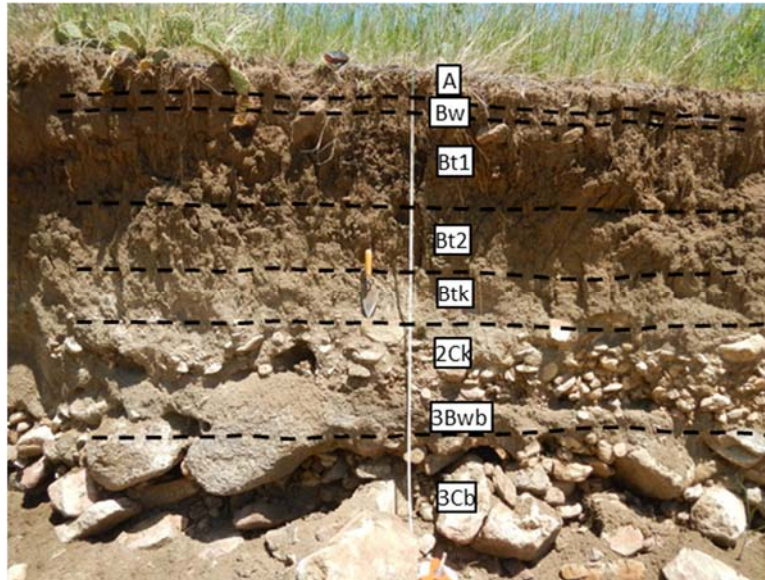


FIGURE 3.30: SOIL PROFILE AT SITE 4MC1.

A second exposure was described on the lower T2 surface (site 4MC2) approximately four feet above the river channel on the right riverbank (Figure 3.31).

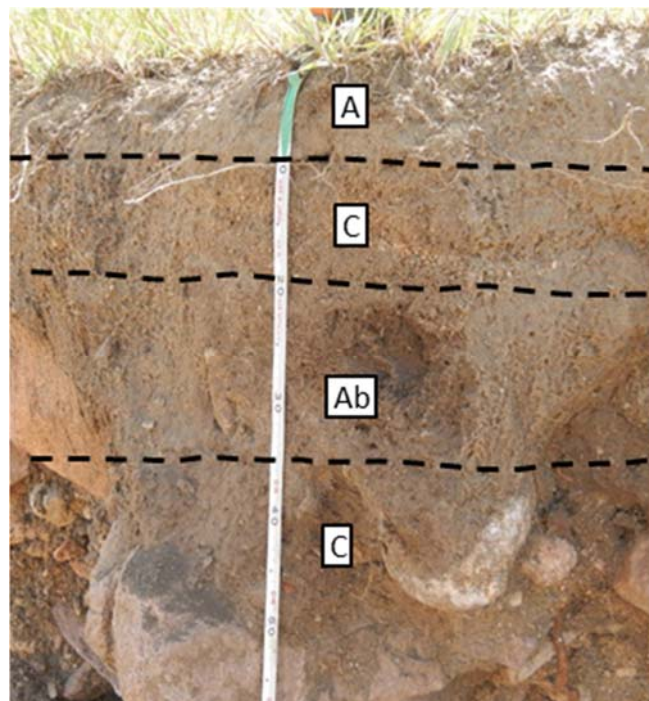


FIGURE 3.31: SOIL PROFILE AT SITE 4MC2.

The stratigraphy shows an A-horizon overlaying a coarse flood sand (C-horizon) deposited over a

buried soil (Ab- horizon) that was developed in an older flood sand (Cb-horizon). A charcoal sample collected from this exposure, at 20 to 30-cm depth, in the Ab horizon returned an age of 3230 ± 30 (RCYBP), 3,620- 3,450 CAL years BP and is considered early Holocene.

A single cross section was surveyed on Fourmile Creek to compute the peak discharge estimate for the 2013 flood (Appendix C). Based on the surveyed cross-section and visible high water marks on both sides of the river channel, a peak discharge between 2,350 and 2,400 ft³/s was estimated for the 2013 flood event. The wetting flow necessary to inundate the T1 higher surface was estimated to be in the range between 9,700 and 11,200 ft³/s. A peak discharge range between 18,150 and 21,600 ft³/s, associated with a non-exceedance bound reflecting a 3 feet stage increase over the T1 surface, was also computed at the site based on the observation that the T1 surface appeared not have been overtopped by recent flows. All the peak discharge ranges were computed based on slope conveyance calculation through a single cross-section using Manning's equation and a critical depth calculation. Based on the data collected it can be concluded that peak discharges between 18,150 and 21,600 ft³/s have not been exceeded at site 4MC1 approximately in the past 9,600 to 10,000 years.

While a flood frequency return period was not computed by Reclamation for this site, due to the lack of a sufficient gage records, a comparison with peak flow statistics, computed by the USGS Streamstats 4.0 tool for the site, indicated that flows of this magnitude in the Fourmile Creek basin can be associated to a return period between 200 and 500 years. A peak discharge estimate of approximately 2,000 ft³/s can be obtained from the Envelope curve developed for Northern Colorado (see Figure 2.2), for a drainages area of approximately 7 mi², such as the drainage encompassed by this reach.

4. Discussion and Conclusions

The Colorado Front Range Flood of September 2013 was an uncommon meteorological and hydrological event. The precipitation amounts, in locations like Boulder, were record breaking even though Colorado has experienced similar flood response. When comparing rainfall total from the 2013 precipitation event at all the drainages analyzed it can be observed that all drainages but one (site NBT1) fall above the median threshold for a 1000-year 7-day rainfall total. Comparing the information obtained from the meteorology and the flood frequency analysis has highlighted that the annual exceedance probability (AEP) associate with the September 2013 precipitation event was in most drainages much higher than the AEP associated with the flooding event in the same drainages.

Based on flood frequency and discharge results, the 2013 flood can be associated to a return period as low as 25 and 50 years on the Middle Saint Vrain and Coal Creek drainages respectively, while on the North Fork of the Big Thompson, the South St Vrain and Left Hand drainages the return period varies respectively from 150 year, to 200 years and 200 to 350 years. Based on flood frequency analysis results, the highest return periods for the 2013 flood event were associated to the peak flows recorded on Fourmile Creek near Boulder Colorado (return period between 200-500 years) and on the North St. Vrain basin with return period greater than 500 years. Table 4.1 summarizes the peak discharge values and the radiocarbon ages information collected at each site.

At the sites where surfaces were found to have sustained little to no impact from the 2013 flood event, the stratigraphy and radiocarbon ages collected to corroborate the paleoflood site interpretation indicated that most surfaces have actually experience a period of stability greater

than 1000 years. This will indicate that in most basins the discharge associated with the 2013 flood appear had been exceeded by larger flood in the past. The age of 160 ±30 (RCYBP), collected on the Ab1 horizon at site NBT1 on the North Fork of the Big Thompson River would infer that that paleo-surface was stable before the deposition of the C-horizon, most likely from the 1976 Big Thompson flood, for a period between 125 and 350 year. This age estimate is in accord with the flood frequency analysis conducted for this site which based on the comparable nature of the 2013 and 1976 flood discharges would conclude that both floods can be associated to a return period of approximately 150 years.

TABLE 4.1: SUMMARY OF PEAK DISCHARGES AND RADIOCARBON DATA FOR ALL SITES INVESTIGATED ALONG THE FRONT RANGE, CO.

Site	Drainage areas	Envelope Curve Peak Discharge (ft ³ /s)	Cross section discharge flood 2013 (ft ³ /s)	Flood Frequency Return Period (yrs.)	Radiocarbon age RCYBP	Calibrated age BP adjusted to 1950 datum
NSV1	101	18,000	7,300-9,950 (NEB) 470-570 (2013 flood)	NA	5720 +/- 30BP	6690-6505 (NEB)
NSV2	102	18,000	16,950-14,570 *	>500	1290 +/-30 BP	1355-1245
SSV1 near Lyons	84	16,000	8,300-11,000	>200	NA	NA
SSV2 near MSV	70	14,000	1,150-2,050	25-50	70 +/-30 BP	325-285
MSV1	30	7,500	1,500-1,680	25	MSV1-2, 37 cm, 1410 +/- 30BP MSV1-4, 53 cm, 1830 +/- 30 BP	1415-1355 1925-1765
LHC1	47	11,000	3,400-5,000	200-350	NA	NA
CC1	9	2,700	960-1,110	50	820 +/-30BP	850-750
NBT1	77	15,000	9,750	150	NBT-3, 63 cm, 1860 +/-30BP NBT-6, 33 cm, 160 +/-30BP	1940-1780 350-125
4MC1-4MC2	7	2,000	1,700-1,900	200-500**	8750 +/-40BP 3230 +/- 30 BP	9970-9625 3620-3450
* 9,000 to 11,000 cfs were discharged during the flood from the spillway which as a total capacity of 32,000 ft ³ /s.						
** based on comparison with the Peak-Flow Statistics available from USGS StreamStats 4.0 tool for the site 100 yrs. =890 ft ³ /s and 200-500 yrs.=1600-1700 ft ³ /s.						

The Natural Resources Conservation Service (NRCS) released a report in December 2013 (Yochum and Moore, 2013) that included a peak discharge estimate for three sites investigated by this research. The peak estimates present for the 2013 flood by the NRCS research tend to be higher at all three sites (Coal Creek, 3900 ft³/s, Fourmile Canyon Creek, 2300 ft³/s, and North Fork Big Thompson River, 18,400 ft³/s). While the discrepancy could in part be caused by the different location along the river where the estimates may have been computed for the sites along Coal Creek and Fourmile Canyon Creek, the estimate obtained for the North Fork Big Thompson River site is substantially different arguably due to the methodology used in making the estimate. The site investigated by NRCS is about 2.4 miles upstream of site NBT1 analyzed by this study. Their estimate, 18,400 ft³/s, was made

based on a critical depth calculation and it's a little less than twice the estimate determined in this study, 9,750 ft³/s, based on a four-section HEC-RAS 1D model (U.S Army Corps of Engineers, 2010a, 2010b). In 2016, additional peak discharges estimated for the 2013 flood were published by the USGS for 21 sites across the Front Range (Moody, 2016). The discharges obtained from this research were estimated as the ensemble average of the Cowan, Jarrett, Empirical, Critical flow, and Slope-area methods. Among the 21 sites analyzed, the location of three sites was such to allow a close comparison with the site investigated by this research. The peak discharges obtained for the three sites, respectively, on the South St. Vrain Creek above the confluence with Middle St. Vrain Creek (2120 ft³/s), on Left Hand Creek at Buckingham Park (6,000 ft³/s), and on Fourmile Canyon Creek at Wagonwheel Gap Rd (2,370 ft³/s) are comparable to the peak discharges obtained by this research for the sites SSV2, LHC1 and 4MC1/4MC2.

The causes for the discrepancy identified between the precipitation event AEP and the flooding event AEP are multiple and of different nature. With certainty, we can point to a group of factors related to the characteristics of the precipitation, as the duration, intensity, and spatial distribution over an entire basin. While the AEP associated to the precipitation event compares rainfall total for the 2013 event, it is important to remember that flood magnitudes are strongly influenced by high rainfall intensities over relatively short time periods and not by rainfall totals exclusively, therefore rainfall averages over upstream watershed sections are also important. Further details on the discrepancy between total rainfall AEP and short duration rainfall intensity AEP for the 2013 flood event are available in an analysis conducted in 2014 by the UDFCD (Harberg et al., 2014). A similar explanation is also supported by the conclusions offered by the USGS analysis of the 2013 storm (Moody, 2016). The USGS research summarizes that one possible explanation for these differences in AEP was that the band of high-accumulation, high-intensity rainfall for the 2013 event was narrow (about 50 kilometers wide), oriented nearly perpendicular to the predominant drainage pattern of the mountains, resulting in entire drainage areas not to be subjected to the same range of extreme rainfall.

Field observation conducted as part of this research corroborated the observation that flood AEP were found lower than precipitation AEP, perhaps, because evidences of severe flooding were recorded in the lower section of several basins, while the flows caused by the 2013 precipitation event were in most cases contained within the riverbanks in the upstream section of the same watersheds. This is the case for example of the Big Thompson River and the St. Vrain River, where several tributaries located in high elevation mountain environments (upper section of the basin) were less impacted by the flood. Figure 4.1 shows the river channel and banks along Glacier Creek, a tributary of the Big Thompson upstream of Estes Park, just few weeks after the 2013 flood event. The site appears preserved in its natural state with no sign of erosion or sediment deposition from the flood. A similar trend was observed along the South St. Vrain where site SVV1, near to the river mouth upstream of the city of Lyons, experienced severe flooding (AEP > 200 years) while the site upstream in the watershed (SSV2), near to the confluence with the Middle St. Vrain, experienced less impact from the flood (AEP of 25-50 years). During the reconnaissance investigation leading to the selection of the sites examined, the upstream section of the South St. Vrain drainage, from the recreational area of Brainard Lake to the confluence with the Middle St Vrain, showed little to no sign of impact from the 2013 flood event on its channel or riverbanks.



FIGURE 4.1: GLEICER CREEK ALONG BEAR CREEK ROAD, UPSTREAM OF ESTES PARK, CO.

Aside from the characteristics of the precipitation, a key role in the AEP discrepancy between precipitation and flood events is also played by the geological making and morphology of each drainage. This second set of causes is perhaps harder to quantify numerically but influence directly the amount of run-off and sediment load that is transported by flows within a drainage. In the early 1980, a study conducted on debris floods event associated with intense rainfall (Costa and Jarrett, 1981) had separated Colorado into two debris-flow environments. The study concluded that below 2300 m (7545 feet), frequent intense rainfall caused large water floods, while above this elevation the intense rainfall was less frequent and that both debris flows and water floods occurred in response to rainfall. Previous research on debris flows in Colorado (Coe et al., 2003) has also concluded that mean debris-flow recurrence intervals are consistently long on north-facing slopes (450 to 2640 years) and wide ranging (7 to 2,900 years) on south-facing slopes. A detailed analysis conducted by the USGS in 2014 (Coe et al. 2014) in response to the widespread debris flows and sliding caused by the 2013 precipitation event indicates that most debris flows were triggered in response to two intense rainfall periods, one 12.5-hour-long period on 11–12 September, and one 8-hour-long period on 12 September, 2013. It was estimated that at least 1,138 debris flows were triggered from this event along the Colorado Front Range. Ninety-five percent of debris flows were found to initiate in canyons and on hogbacks at elevations lower than a widespread erosion surface of low slope and relief (below 2,600 m or 8,500 feet). These debris flows were on steep ($>25^\circ$), predominantly south- and east-facing slopes, while, debris flows with the largest scars and longest travel distances occurred at elevations above 8500 feet on steep slopes. Areal concentrations of debris flows revealed that colluvial soils formed on sedimentary rocks were more susceptible to flows than soils on crystalline rocks.

As observed in another USGS publication completed in 2014 (Godt et al, 2014) the common link between nearly all debris flows observed during the 2013 event was that they began as discrete sliding masses that moved downslope as a fluidized mixture of sediment and water. Thicknesses of these initial slides ranged from about one foot to more than 16 feet. In general, debris flows

that entered drainages having flowing water had the longest travel distances and those that occurred on open grass-covered slopes had the shortest travel distances. Part of the reason for this difference in travel distances was that debris flows that entered drainages increased their size by eroding and incorporating additional material into the flow, whereas debris flows on open slopes were limited in size to the volume of the initial landslide.

During the reconnaissance site visits conducted immediately after the flood, several heavily damaged drainages were not selected as areas of interest for this study because the determination of peak discharges at these sites would have been flawed with large uncertainty. The large majority of these sites consisted of areas in and near the mountains that had experienced flash flood conditions aggravated by landslides and debris that temporarily dammed streams, then after weakening, freed enormous destructive surges of floodwater. An example of this specific mechanism was exemplified by a site along Jams Creek located upstream the town of Springdale. As shown in Figure 4.2.a the creek at this location was dammed by a large debris flow generated on the left slope. Immediately upstream of the location where the large debris load entered the creek the river channel could be observed in a preserved natural state, with no modifications of the riverbanks of the channel bed geometry (Figure 4.2.b). In the other hand, the section of the channel downstream of the debris sediments entry point shows a channel bed widen almost 10 times from its original dimensions and large boulders and wood debris been deposited along the eroded riverbanks (Figure 4.2.c).



FIGURE 4.2: JAMES CREEK UPSTREAM OF THE TOWN OF SPRINGDALE, CO. (A) DEBRIS FLOW ENTRY POINT, (B) UPSTREAM SECTION OF THE CREEK, (C) DOWNSTREAM SECTION OF THE CREEK.

Other sites where the channel banks have gave way destroying roadways, bridges, and culvert crossings were observed along Fish Creek, a tributary south of Estes Park (Figure4.3), along Left Hand Creek, approximately 1.5 miles upstream of the junction with Highway7 (Figure 4.4) and along Fourmile Canyon Creek near the entrance to the Anne U. White Trailhead (Figure 4.5). At this location, the floodwater had abandoned the original channel located on the left of the photo and had eroded a new channel near to the left slope within the backfill sediments that used to host the parking area for the trail.



FIGURE 4.3: FISH CREEK ALONG FISH CREEK ROAD, SOUTH OF ESTES PARK, CO.

While there is little doubt that Colorado experienced an extremely rare precipitation event in September 2013, within the limits of the data collection effort and analysis conducted by this research it can be concluded that most drainages along the Front Range have experienced floods of greater magnitude in the past. Peak discharges computations as well as paleoflood interpretation and flood frequency analysis developed for the drainages of interest all support the conclusion that the annual exceedance probability estimated for the precipitation event, being described as a 1000-year event, is greater than the estimated return period associated to the flooding event in all drainages investigated. In the other hand the widespread amount of debris flows and landslides occurred in a short period, over a very large section of the Front Range is considered rare. A detailed analysis conducted by the USGS on the debris-flow hazard associated to the September 2013 event and field observation captured by this research effort have documented that the sediment load released by these slope failures into the stream, already at or above flood stage, has severely worsened the damages caused by the flood.



FIGURE 4.4: LEFT HAND CREEK, APPROXIMATELY 1.5 MILES UPSTREAM OF HWY 7. A DEBRIS FLOW GENERATED ON THE LEFT HILLSLOPE CROSSED THE ROAD ENTERING THE RIVER CHANNEL LOCATED ON THE OPPOSITE SIDE OF THE VALLEY.



FIGURE 4.5: FOURMILE CANYON CREEK NEAR THE ENTRANCE TO THE ANNE U. WHITE TRAILHEAD NEAR BOULDER, CO. THE RED ARROW INDICATES THE PRE-FLOOD LOCATION OF THE RIVER CHANNEL.

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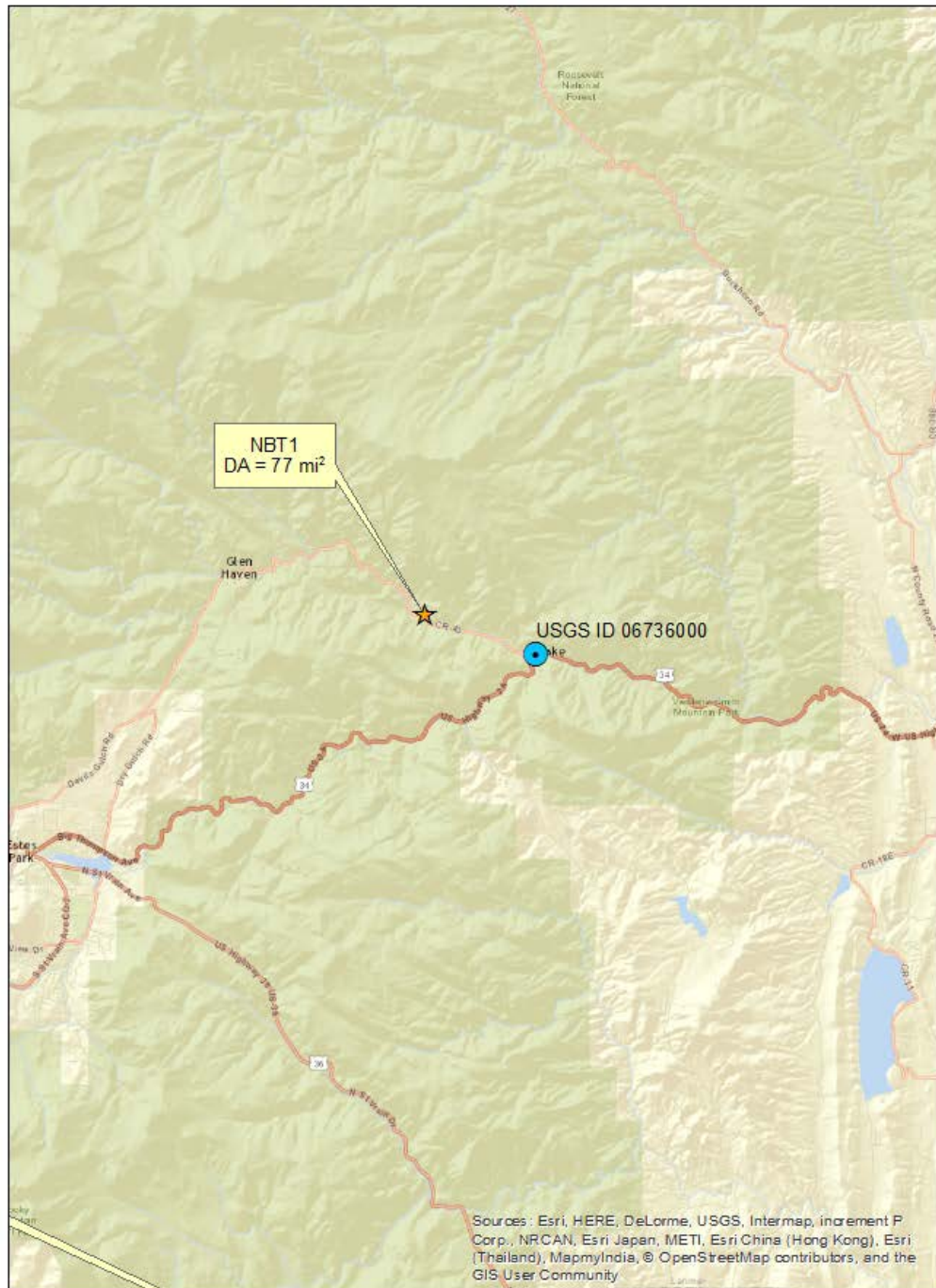
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APPENDICES

APPENDIX A-USGS STREAM GAGE RECORDS USED AT POINTS OF INTEREST

NBT1 (DA=77 mi²) GAGE DATA

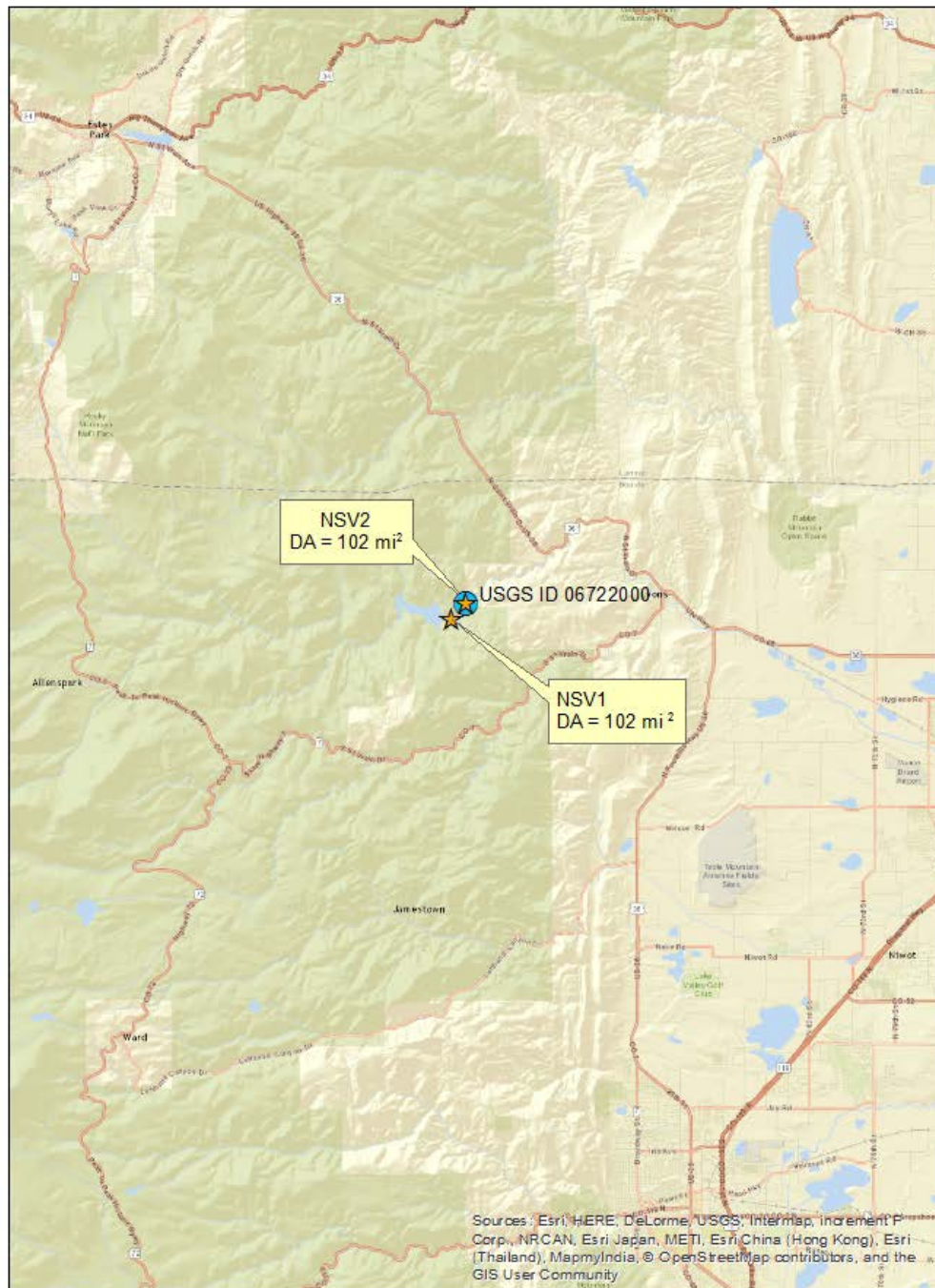
Date	Water Year	Flow, cfs		Transposed
		6736000 Gage (DA=85.1 mi ²)	Used for EMA	
6/21/1947	1947	410	382	*
6/11/1948	1948	166	155	*
6/4/1949	1949	820	763	*
7/10/1950	1950	450	419	*
6/19/1951	1951	232	216	*
6/5/1952	1952	283	263	*
6/13/1953	1953	223	208	*
6/27/1954	1954	47	44	*
8/14/1955	1955	114	106	*
5/21/1956	1956	228	212	*
7/29/1957	1957	850	791	*
5/24/1958	1958	295	275	*
6/20/1959	1959	153	142	*
6/18/1960	1960	120	112	*
6/3/1961	1961	275	256	*
7/12/1962	1962	138	128	*
6/16/1963	1963	157	146	*
6/8/1964	1964	84	78	*
6/16/1965	1965	1290	1201	*
7/20/1966	1966	584	544	*
6/21/1967	1967	148	138	*
8/12/1968	1968	156	145	*
5/7/1969	1969	800	745	*
6/24/1970	1970	251	234	*
6/19/1971	1971	227	211	*
6/4/1972	1972	170	158	*
6/11/1973	1973	398	370	*
6/17/1974	1974	184	171	*
6/18/1975	1975	245	228	*
7/31/1976	1976	8710	8107	*



MAP SHOWING NBT1 POINT OF INTEREST AND USGS GAGE ID 06736000

NSV1, NSV2 (DA=102 mi²) COMBINED GAGE DATA

Date	Water Year	Flow, cfs		Transposed
		06722000 Gage (DA=102 mi ²)	Used for EMA	
6/7/1926	1926	698	698	
6/29/1927	1927	426	426	
5/30/1928	1928	783	783	
6/9/1929	1929	1050	1050	
8/15/1930	1930	486	486	
6/5/1931	1931	835	835	
6/28/1932	1932	435	435	
6/20/1933	1933	744	744	
5/31/1934	1934	410	410	
9/6/1935	1935	930	930	
6/1/1936	1936	598	598	
6/26/1937	1937	713	713	
9/2/1938	1938	972	972	
6/6/1939	1939	356	356	
6/21/1940	1940	319	319	
6/22/1941	1941	1630	1630	
6/12/1942	1942	690	690	
6/2/1943	1943	681	681	
5/15/1944	1944	514	514	
6/24/1945	1945	713	713	
6/18/1946	1946	470	470	
6/17/1947	1947	1250	1250	
6/10/1948	1948	613	613	
6/4/1949	1949	1540	1540	
6/18/1950	1950	526	526	
6/18/1951	1951	800	800	
6/7/1952	1952	705	705	
6/13/1953	1953	662	662	



MAP SHOWING NSV1 AND NSV2 POINTS OF INTEREST AND USGS GAGE ID 06722000

SSV1 (DA=84 mi²) COMBINED GAGE DATA

Date	Water Year	Flow, cfs		Transposed
		6724000 Gage (DA=216 mi ²)	Used for EMA	
6/19/1888	1888	535	278	*
5/28/1889	1889	548	285	*
6/2/1890	1890	675	351	*
5/27/1891	1891	1400	728	*
6/16/1895	1895	1130	587	*
8/18/1896	1896	1500	780	*
5/18/1897	1897	1020	530	*
6/17/1898	1898	603	313	*
6/20/1899	1899	1180	613	*
4/29/1900	1900	918	477	*
6/23/1901	1901	857	446	*
6/9/1902	1902	514	267	*
6/23/1903	1903	1710	889	*
6/20/1904	1904	850	442	*
6/9/1905	1905	1660	863	*
6/13/1906	1906	1170	608	*
7/2/1907	1907	1120	582	*
7/30/1908	1908	650	338	*
7/4/1909	1909	1150	598	*
6/3/1910	1910	465	242	*
6/9/1911	1911	660	343	*
6/25/1912	1912	1150	598	*
6/11/1913	1913	490	255	*
6/2/1914	1914	1540	801	*
6/20/1915	1915	955	496	*
6/20/1916	1916	620	322	*
6/23/1917	1917	1240	645	*
6/22/1918	1918	1700	884	*
7/30/1919	1919	9400	4887	*
5/26/1920	1920	733	381	*
6/7/1921	1921	2050	1066	*
6/14/1922	1922	574	298	*
6/9/1923	1923	1670	868	*
6/14/1924	1924	2230	1159	*
6/2/1925	1925	410	213	*

Date	Water Year	Flow, cfs		Transposed
		6724000 Gage (DA=216 mi ²)	Used for EMA	
6/9/1926	1926	1100	572	*
6/29/1927	1927	604	314	*
5/31/1928	1928	1010	525	*
7/3/1929	1929	765	398	*
8/10/1930	1930	2040	1061	*
7/17/1931	1931	1450	754	*
6/18/1932	1932	854	444	*
6/20/1933	1933	1130	587	*
5/10/1934	1934	628	326	*
5/27/1935	1935	2340	1217	*
6/17/1936	1936	832	433	*
6/26/1937	1937	1230	639	*
9/3/1938	1938	1650	858	*
8/30/1939	1939	978	508	*
5/27/1940	1940	675	351	*
6/22/1941	1941	10500	5459	*
8/2/1942	1942	1510	785	*
5/29/1943	1943	1230	639	*
5/18/1944	1944	962	500	*
6/25/1945	1945	1000	520	*
7/18/1946	1946	2140	1113	*
6/17/1947	1947	2360	1227	*
6/11/1948	1948	820	426	*
6/4/1949	1949	2970	1544	*
6/13/1950	1950	712	370	*
8/3/1951	1951	3920	2038	*
6/8/1952	1952	1610	837	*
6/13/1953	1953	970	504	*
5/21/1954	1954	285	148	*
7/24/1955	1955	680	354	*
6/3/1956	1956	749	389	*
5/9/1957	1957	3060	1591	*
5/8/1958	1958	1290	671	*
6/15/1959	1959	857	446	*
6/18/1960	1960	717	373	*
6/3/1961	1961	2540	1321	*

Date	Water Year	Flow, cfs		Transposed
		6724000 Gage (DA=216 mi ²)	Used for EMA	
6/30/1962	1962	1140	593	*
6/16/1963	1963	1300	676	*
5/27/1964	1964	458	238	*
6/17/1965	1965	1840	957	*
7/20/1966	1966	1210	629	*
8/30/1967	1967	2010	1045	*
6/21/1968	1968	636	331	*
5/7/1969	1969	2900	1508	*
6/29/1970	1970	958	498	*
4/25/1971	1971	1760	915	*
6/4/1972	1972	940	489	*
6/11/1973	1973	1360	707	*
6/18/1974	1974	641	333	*
6/9/1975	1975	922	479	*
8/1/1976	1976	835	434	*
7/24/1977	1977	732	381	*
5/17/1978	1978	1560	811	*
6/15/1979	1979	1050	546	*
4/30/1980	1980	2330	1211	*
6/4/1981	1981	418	217	*
7/27/1982	1982	1600	832	*
6/19/1983	1983	1470	764	*
8/1/1984	1984	1340	697	*
6/9/1985	1985	1040	541	*
6/19/1986	1986	1120	582	*
6/9/1987	1987	1080	561	*
6/12/1988	1988	568	295	*
6/3/1989	1989	998	519	*
6/12/1990	1990	908	472	*
6/21/1991	1991	1280	665	*
6/12/1992	1992	548	285	*
6/17/1993	1993	818	425	*
8/10/1994	1994	874	454	*
5/29/1995	1995	4200	2184	*
5/26/1996	1996	1120	582	*
6/7/1997	1997	1640	853	*

Date	Water Year	Flow, cfs		Transposed
		6724000 Gage (DA=216 mi ²)	Used for EMA	
6/4/1998	1998	662	344	*
9/12/2013	2013	23800	12373	*



MAP SHOWING SSV1 POINT OF INTEREST AND USGS GAGE ID 06724000

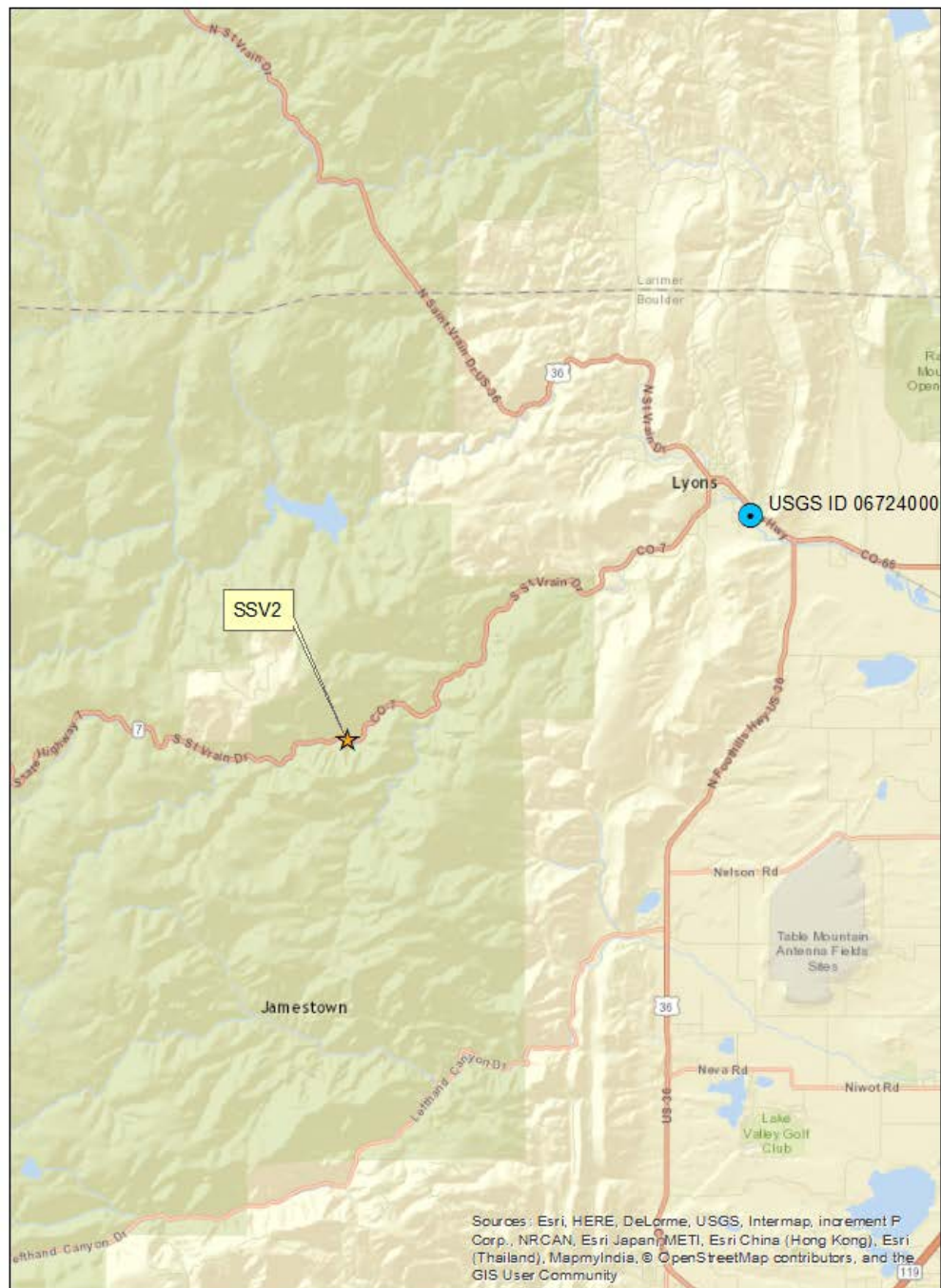
SSV2 (DA=70 mi²) COMBINED GAGE DATA

Date	Water Year	Flow, cfs		Transposed
		6724000 Gage (DA=216 mi ²)	Used for EMA	
6/19/1888	1888	535	246	*
5/28/1889	1889	548	252	*
6/2/1890	1890	675	311	*
5/27/1891	1891	1400	644	*
6/16/1895	1895	1130	520	*
8/18/1896	1896	1500	690	*
5/18/1897	1897	1020	469	*
6/17/1898	1898	603	277	*
6/20/1899	1899	1180	543	*
4/29/1900	1900	918	422	*
6/23/1901	1901	857	394	*
6/9/1902	1902	514	236	*
6/23/1903	1903	1710	787	*
6/20/1904	1904	850	391	*
6/9/1905	1905	1660	764	*
6/13/1906	1906	1170	538	*
7/2/1907	1907	1120	515	*
7/30/1908	1908	650	299	*
7/4/1909	1909	1150	529	*
6/3/1910	1910	465	214	*
6/9/1911	1911	660	304	*
6/25/1912	1912	1150	529	*
6/11/1913	1913	490	225	*
6/2/1914	1914	1540	708	*
6/20/1915	1915	955	439	*
6/20/1916	1916	620	285	*
6/23/1917	1917	1240	570	*
6/22/1918	1918	1700	782	*
7/30/1919	1919	9400	4324	*
5/26/1920	1920	733	337	*
6/7/1921	1921	2050	943	*
6/14/1922	1922	574	264	*
6/9/1923	1923	1670	768	*
6/14/1924	1924	2230	1026	*
6/2/1925	1925	410	189	*

Date	Water Year	Flow, cfs		Transposed
		6724000 Gage (DA=216 mi ²)	Used for EMA	
6/9/1926	1926	1100	506	*
6/29/1927	1927	604	278	*
5/31/1928	1928	1010	465	*
7/3/1929	1929	765	352	*
8/10/1930	1930	2040	938	*
7/17/1931	1931	1450	667	*
6/18/1932	1932	854	393	*
6/20/1933	1933	1130	520	*
5/10/1934	1934	628	289	*
5/27/1935	1935	2340	1076	*
6/17/1936	1936	832	383	*
6/26/1937	1937	1230	566	*
9/3/1938	1938	1650	759	*
8/30/1939	1939	978	450	*
5/27/1940	1940	675	311	*
6/22/1941	1941	10500	4830	*
8/2/1942	1942	1510	695	*
5/29/1943	1943	1230	566	*
5/18/1944	1944	962	443	*
6/25/1945	1945	1000	460	*
7/18/1946	1946	2140	984	*
6/17/1947	1947	2360	1086	*
6/11/1948	1948	820	377	*
6/4/1949	1949	2970	1366	*
6/13/1950	1950	712	328	*
8/3/1951	1951	3920	1803	*
6/8/1952	1952	1610	741	*
6/13/1953	1953	970	446	*
5/21/1954	1954	285	131	*
7/24/1955	1955	680	313	*
6/3/1956	1956	749	345	*
5/9/1957	1957	3060	1408	*
5/8/1958	1958	1290	593	*
6/15/1959	1959	857	394	*
6/18/1960	1960	717	330	*
6/3/1961	1961	2540	1168	*

Date	Water Year	Flow, cfs		Transposed
		6724000 Gage (DA=216 mi ²)	Used for EMA	
6/30/1962	1962	1140	524	*
6/16/1963	1963	1300	598	*
5/27/1964	1964	458	211	*
6/17/1965	1965	1840	846	*
7/20/1966	1966	1210	557	*
8/30/1967	1967	2010	925	*
6/21/1968	1968	636	293	*
5/7/1969	1969	2900	1334	*
6/29/1970	1970	958	441	*
4/25/1971	1971	1760	810	*
6/4/1972	1972	940	432	*
6/11/1973	1973	1360	626	*
6/18/1974	1974	641	295	*
6/9/1975	1975	922	424	*
8/1/1976	1976	835	384	*
7/24/1977	1977	732	337	*
5/17/1978	1978	1560	718	*
6/15/1979	1979	1050	483	*
4/30/1980	1980	2330	1072	*
6/4/1981	1981	418	192	*
7/27/1982	1982	1600	736	*
6/19/1983	1983	1470	676	*
8/1/1984	1984	1340	616	*
6/9/1985	1985	1040	478	*
6/19/1986	1986	1120	515	*
6/9/1987	1987	1080	497	*
6/12/1988	1988	568	261	*
6/3/1989	1989	998	459	*
6/12/1990	1990	908	418	*
6/21/1991	1991	1280	589	*
6/12/1992	1992	548	252	*
6/17/1993	1993	818	376	*
8/10/1994	1994	874	402	*
5/29/1995	1995	4200	1932	*
5/26/1996	1996	1120	515	*
6/7/1997	1997	1640	754	*

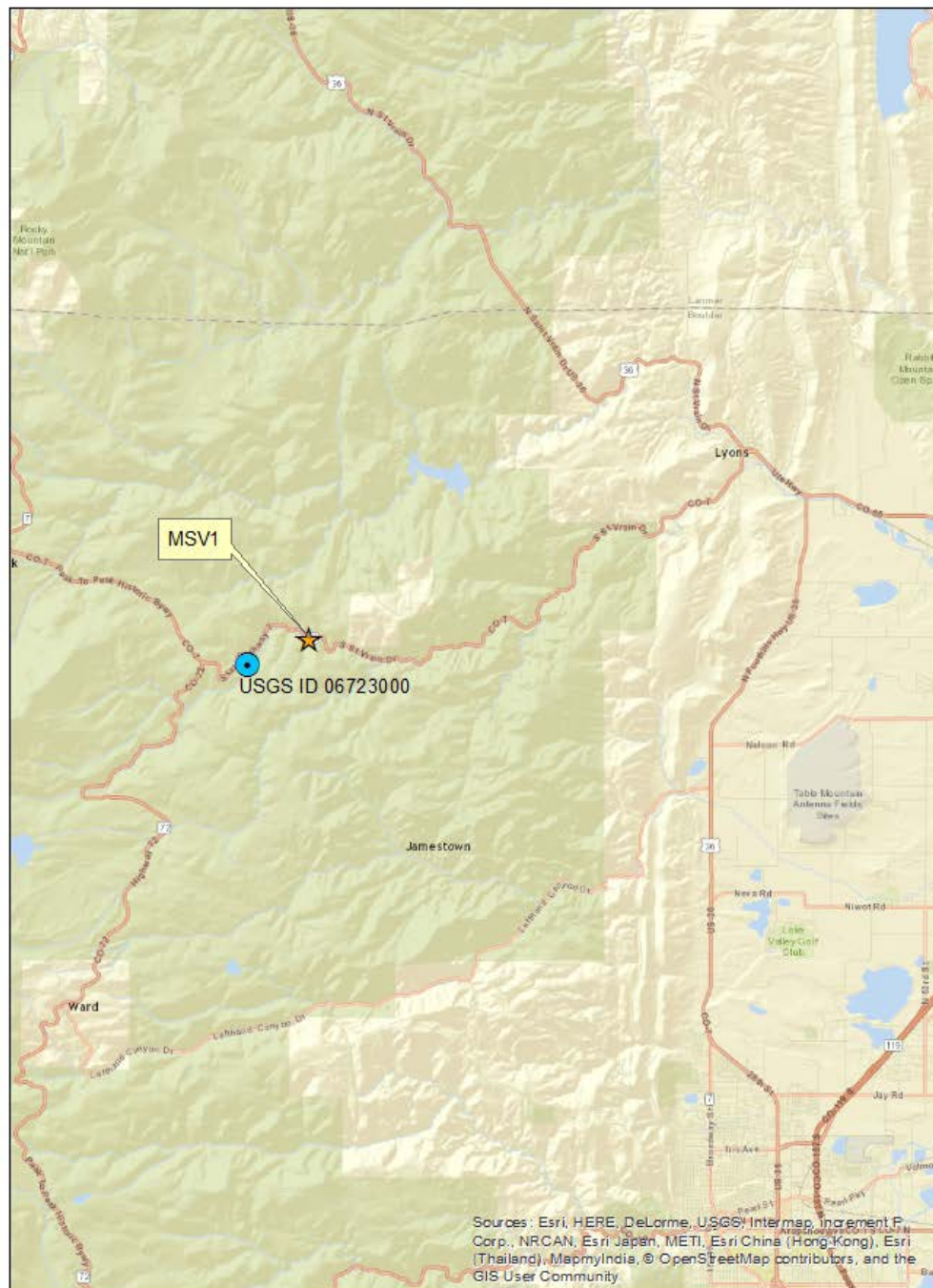
Date	Water Year	Flow, cfs		Transposed
		6724000 Gage (DA=216 mi ²)	Used for EMA	
6/4/1998	1998	662	305	*
9/12/2013	2013	23800	10948	*



MAP SHOWING SSV2 POINT OF INTEREST AND USGS GAGE ID 06724000

MSV1 (DA= 30 mi²) COMBINED GAGE DATA

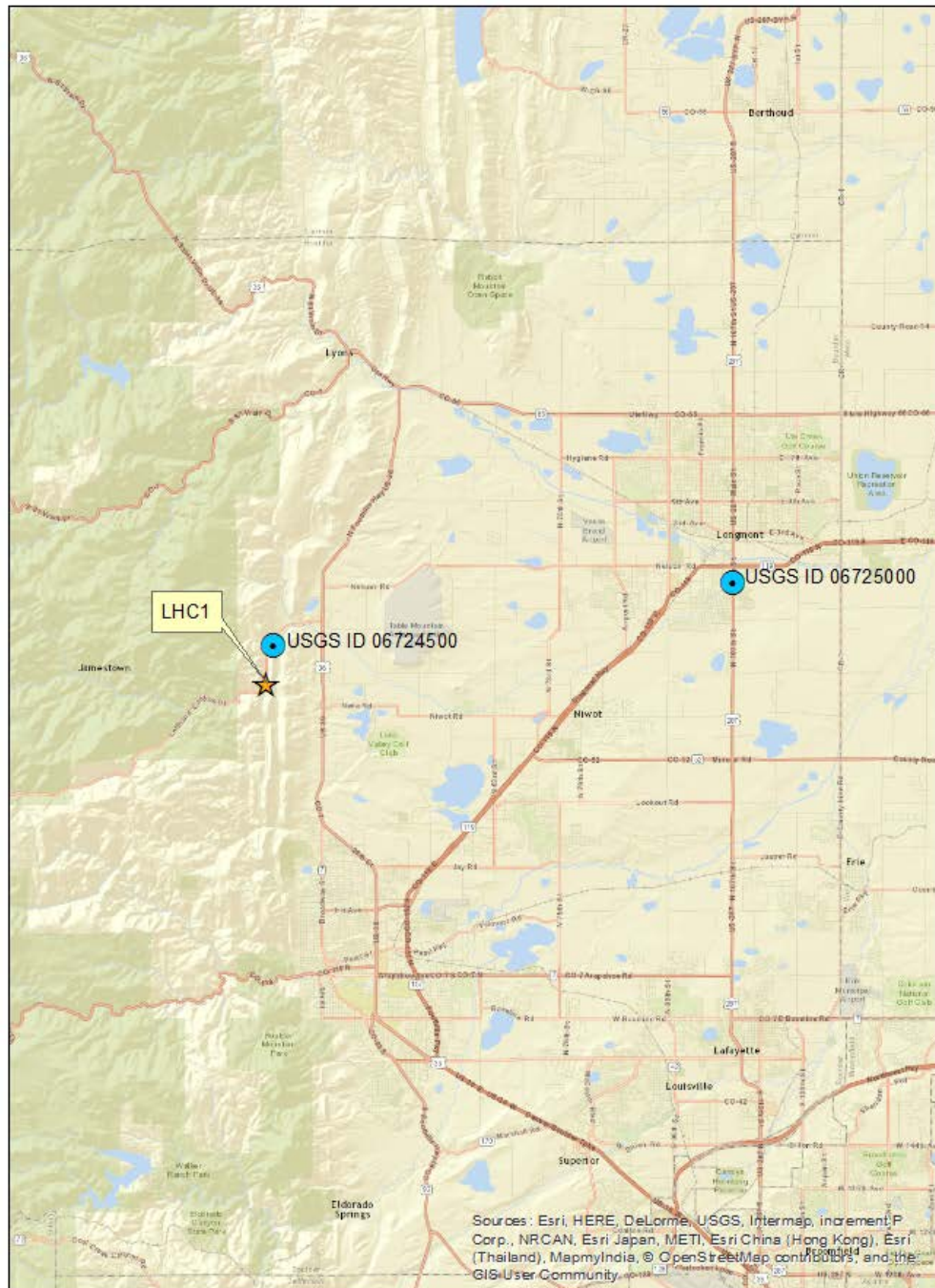
Date	Water Year	Flow, cfs		Transposed
		6723000 Gage (DA=28 mi ²)	Used for EMA	
6/6/1926	1926	387	410	*
6/28/1927	1927	194	205	*
5/27/1928	1928	290	307	*
6/8/1929	1929	240	254	*
8/14/1930	1930	211	223	*
1979	1979	440	466	*
1980	1980	675	714	*
1981	1981	235	249	*
1982	1982	320	339	*
1983	1983	490	519	*
1984	1984	690	730	*
1985	1985	470	497	*
1986	1986	520	550	*
1987	1987	178	188	*
7/30/1989	1989	489	518	*
6/12/1990	1990	892	944	*
6/1/1991	1991	717	759	*
5/9/1992	1992	717	759	*
6/18/1993	1993	424	449	*
5/13/1994	1994	185	196	*



MAP SHOWING MSV1 POINT OF INTEREST AND USGS GAGE ID 06723000

LHC1 (DA=47 mi²) COMBINED GAGE DATA

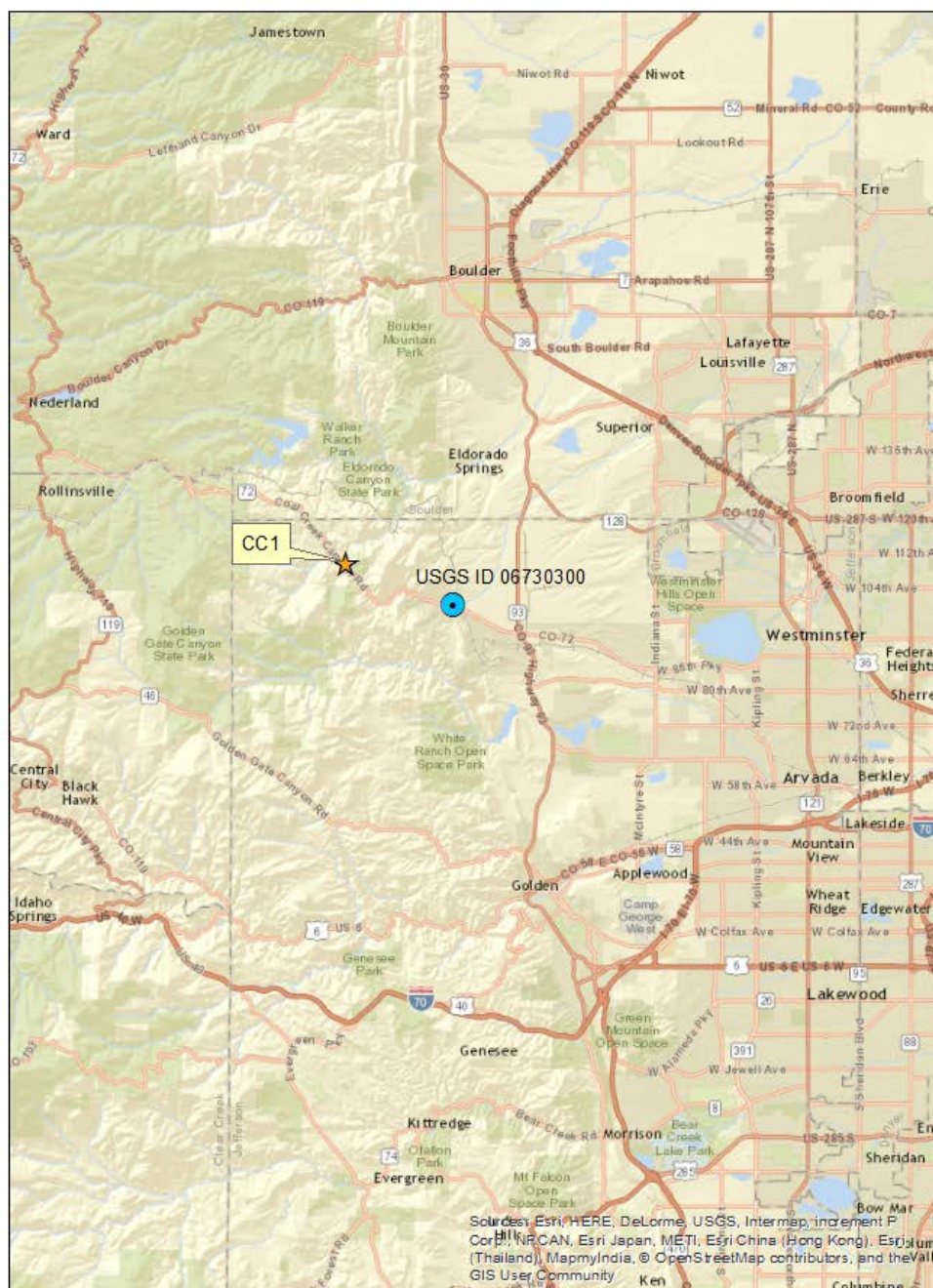
Date	Water Year	Flow, cfs			Transposed
		6724500 Gage (DA=50.6 mi ²)	6725000 Gage (DA=72.6 mi ²)	Used for EMA (6724500 and 6725000 Transposed)	
7/28/1927	1927		113	84	*
5/10/1928	1928		252	188	*
7/17/1929	1929	216		206	*
8/26/1930	1930	340		325	*
8/2/1931	1931	396		378	*
6/18/1932	1932		69	51	*
5/19/1933	1933		355	264	*
5/5/1934	1934		106	79	*
5/18/1935	1935		228	170	*
6/10/1936	1936		161	120	*
6/3/1937	1937		192	143	*
9/2/1938	1938		812	604	*
5/1/1939	1939		66	49	*
9/28/1940	1940		36	27	*
6/22/1941	1941		321	239	*
4/19/1942	1942		369	275	*
6/22/1947	1947	254		242	*
6/7/1948	1948	510		487	*
6/4/1949	1949	1140		1088	*
6/16/1950	1950	234		223	*
8/3/1951	1951	785		749	*
6/15/1952	1952	252		241	*
6/13/1953	1953	245		234	*
7/14/1954	1954		15	11	*
8/19/1955	1955		150	112	*
5/22/1956	1956	230		220	*
5/9/1957	1957	707		675	*
6/6/1977	1977	230		220	*
6/15/1978	1978	331		316	*
6/9/1979	1979	187		178	*
4/30/1980	1980	571		545	*



MAP SHOWING LHC1 POINT OF INTEREST AND USGS GAGES ID 06724500 AND ID 06725000

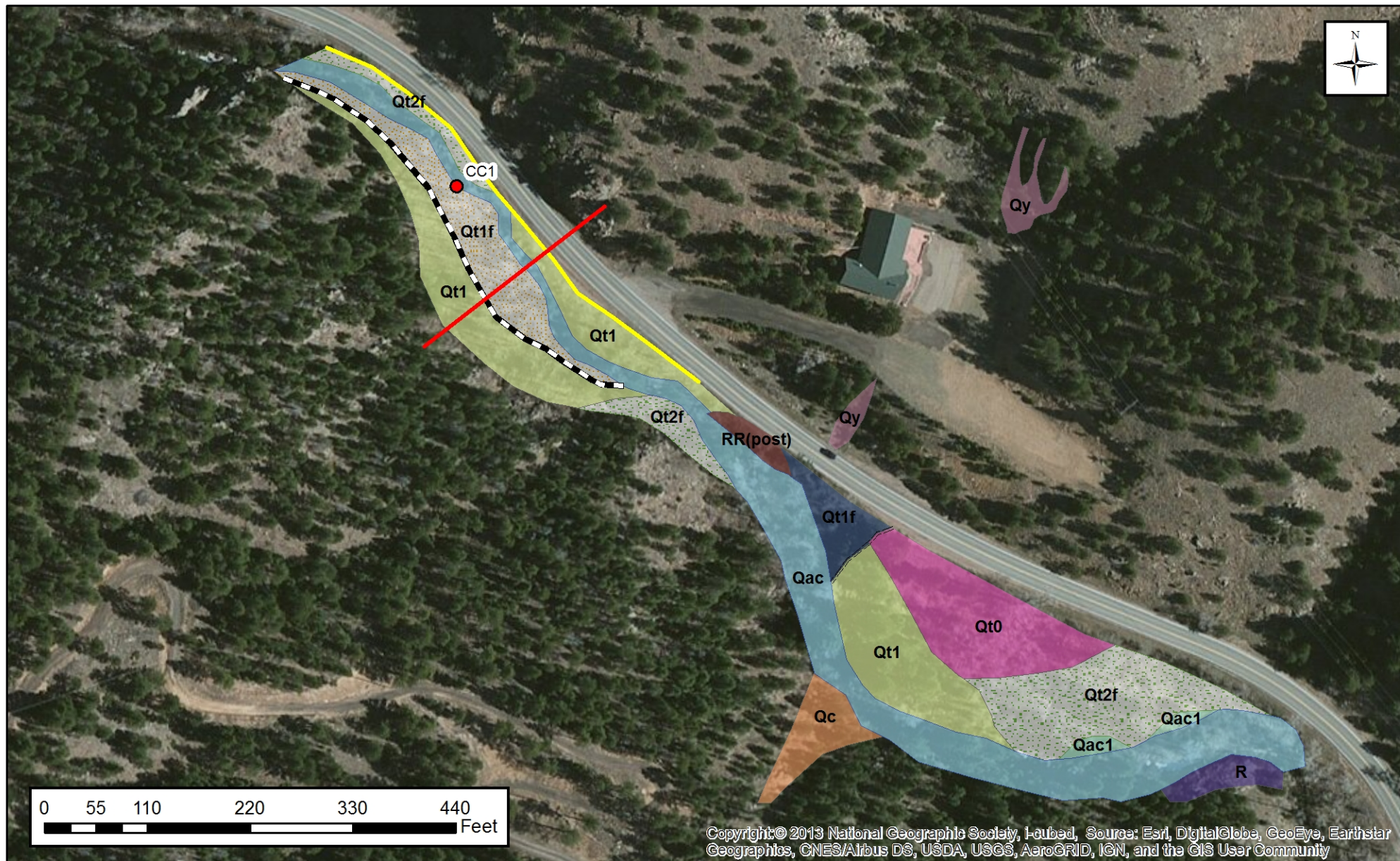
CC1 (DA = 9 mi²) COMBINED GAGE DATA

Date	Water Year	Flow, cfs		Transposed
		6730300 Gage (DA=15.2 mi ²)	Used for EMA (6730300 Transposed)	
5/7/1960	1960	164	115	*
5/17/1961	1961	60	42	*
4/19/1962	1962	34	24	*
6/16/1963	1963	195	136	*
3/14/1964	1964	17	12	*
7/24/1965	1965	101	71	*
3/4/1966	1966	36	25	*
6/21/1967	1967	46	32	*
5/24/1968	1968	37	26	*
5/7/1969	1969	2060	1441	*
6/11/1970	1970	76	53	*
4/25/1971	1971	167	117	*
5/6/1972	1972	30	21	*
5/6/1973	1973	338	237	*
5/4/1974	1974	28	20	*
6/3/1975	1975	76	53	*
5/25/1976	1976	28	20	*
7/24/1977	1977	41	29	*
5/10/1978	1978	46	32	*
6/9/1979	1979	96	67	*
4/30/1980	1980	205	143	*
5/30/1981	1981	64	45	*
5/20/1982	1982	43	30	*

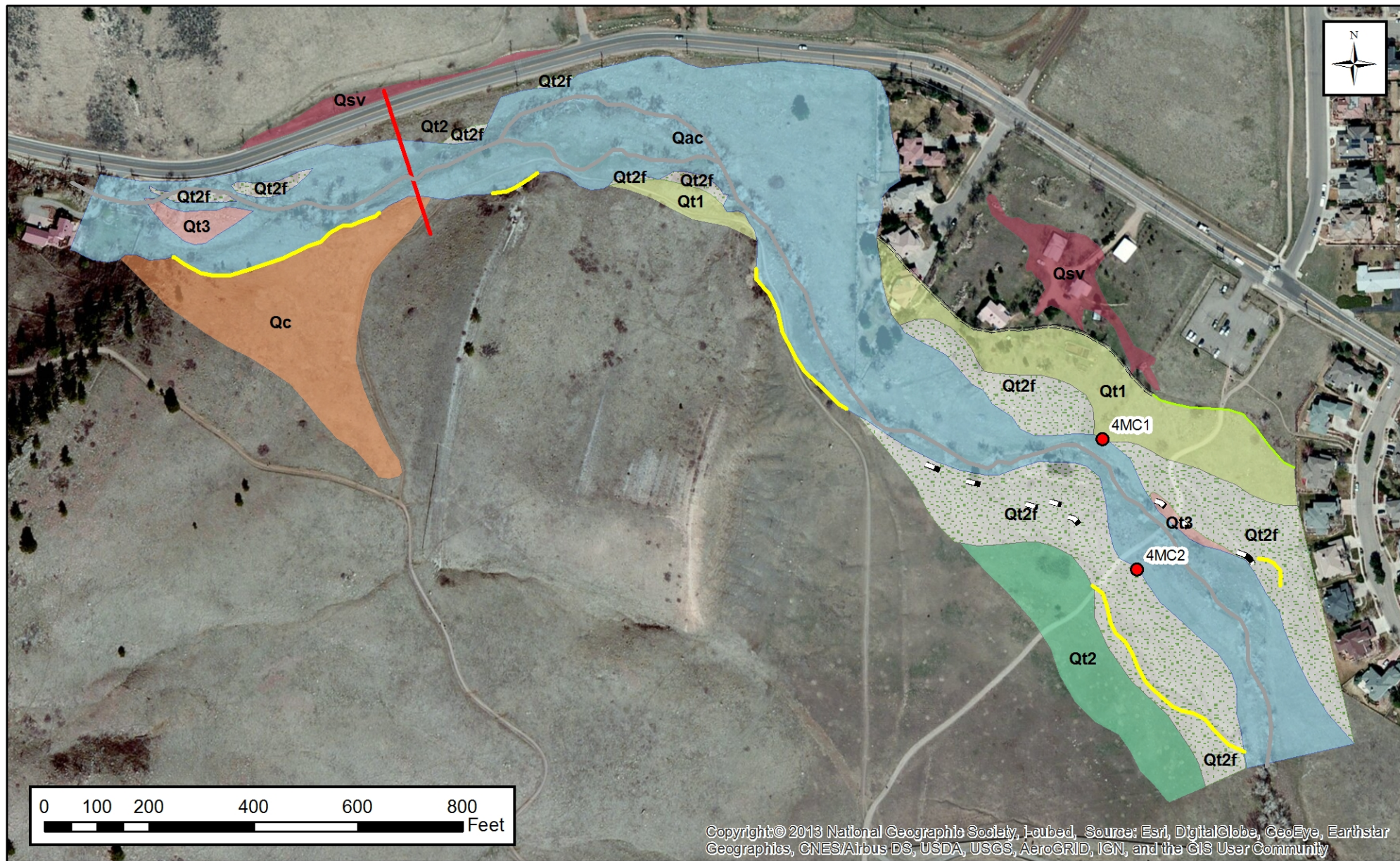


MAP SHOWING CC1 POINT OF INTEREST AND USGS GAGE ID 06730300

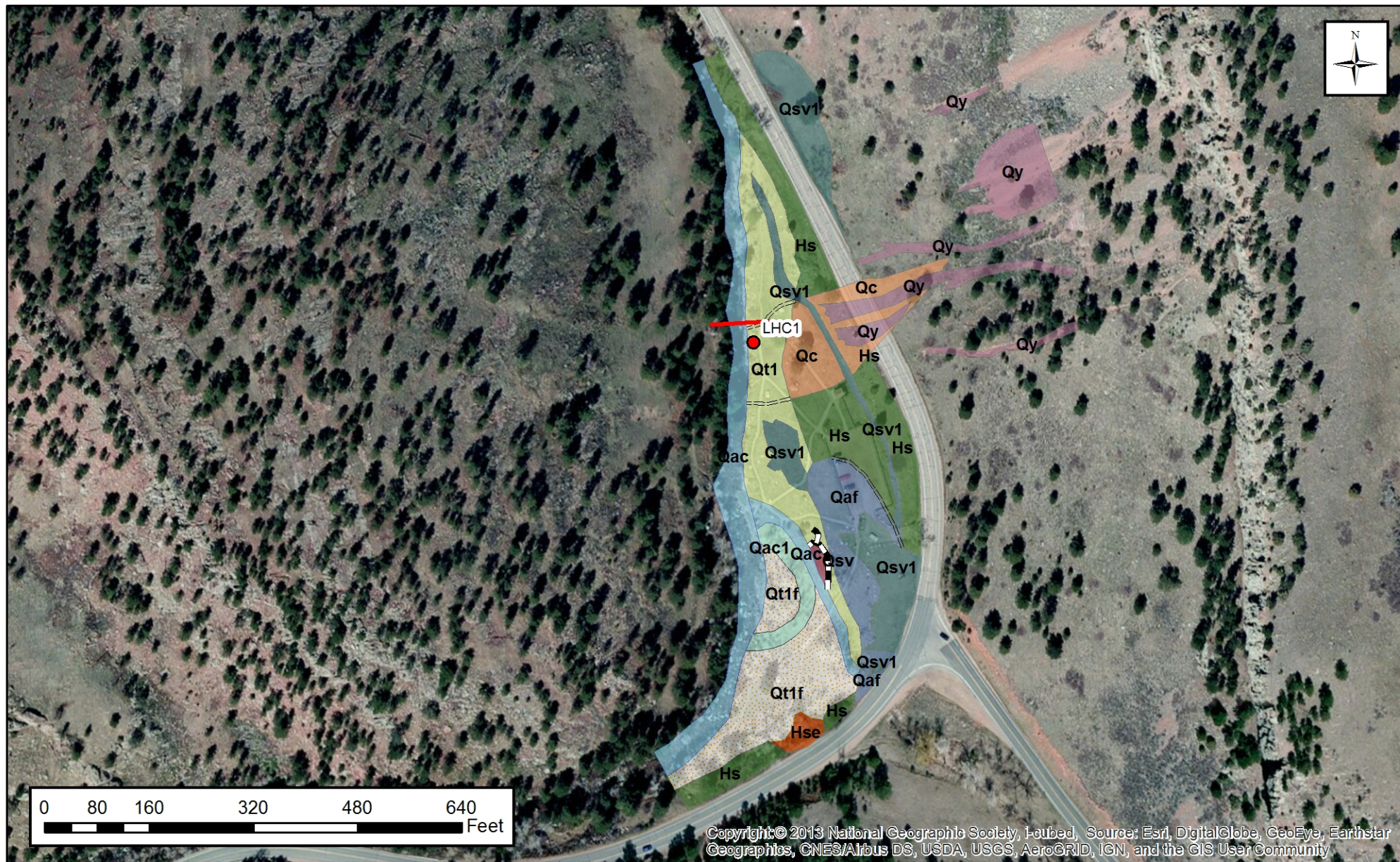
APPENDIX B- GEOLOGICAL MAPS



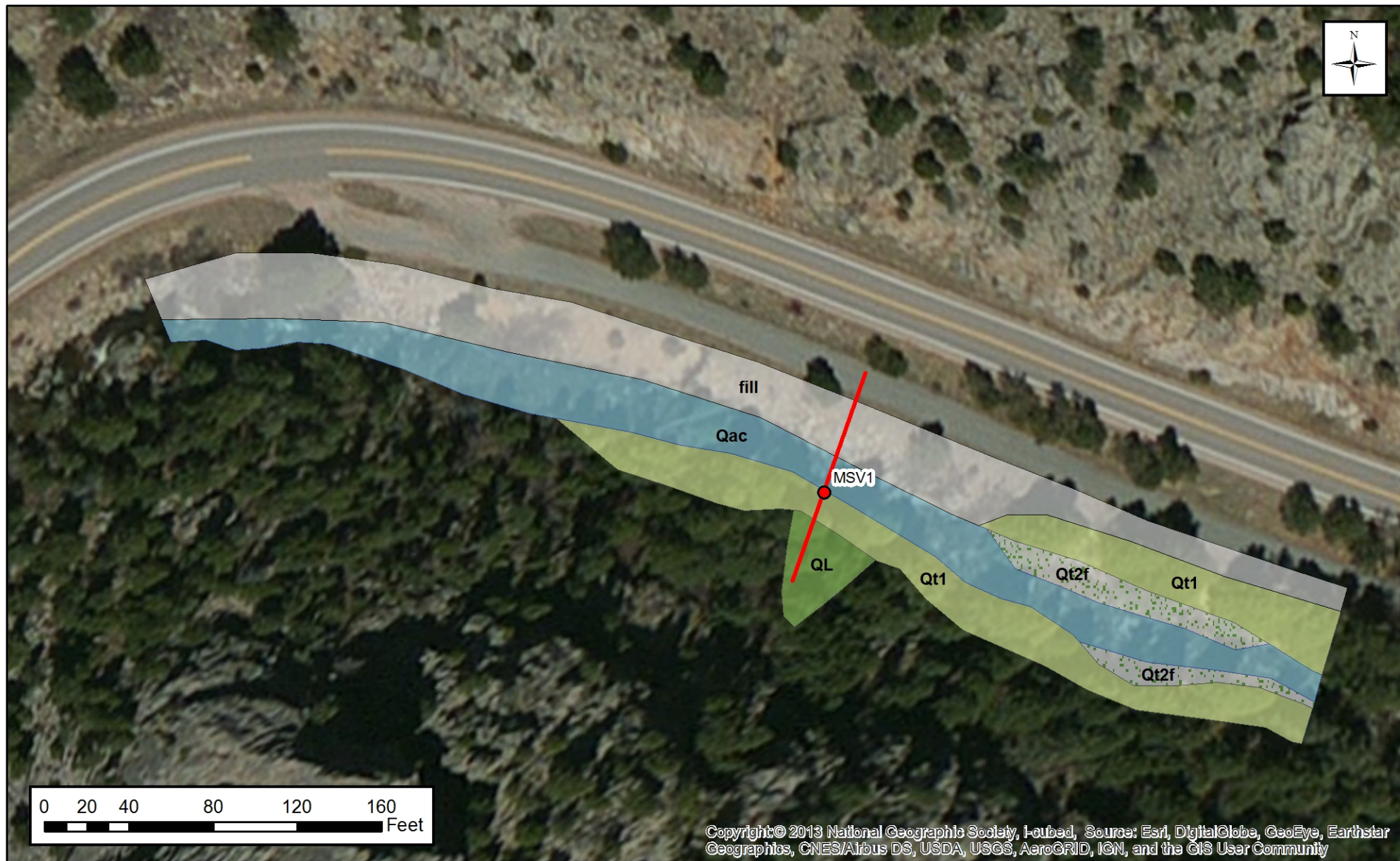
● Soil_desc	==== approximate contact	Labels, Unit Description	Qac, channel	Qt0, T0 terrace	Qt3, T3 (floodplain)
— Cross_section	— buried contact	Hs, hillslope	Qac1, 2013 new channel areas	Qt1, T1 terrace	Qy, debris flow
contacts	— erosion scarp	Hse, road or hillslope erosion	Qaf, SixMile alluvial fan deposits	Qt1f, T1 terrace flooded	R, bedrock face
Type	— paleochannel	QL, landslide	Qc, talus/colluvial fan	Qt1f, T1 terrace flooded by debris flow	RR(post), rip rap (post 2013 flood)
— high water mark		Qab, bar	Qsv, flood sand 2013	Qt2, T2 terrace	RR(pre), rip rap (pre 2013 flood)
		Qab, point bar	Qsv1, SixMile flood sand 2013	Qt2f, T2 terrace flooded	fill, road berm/fill



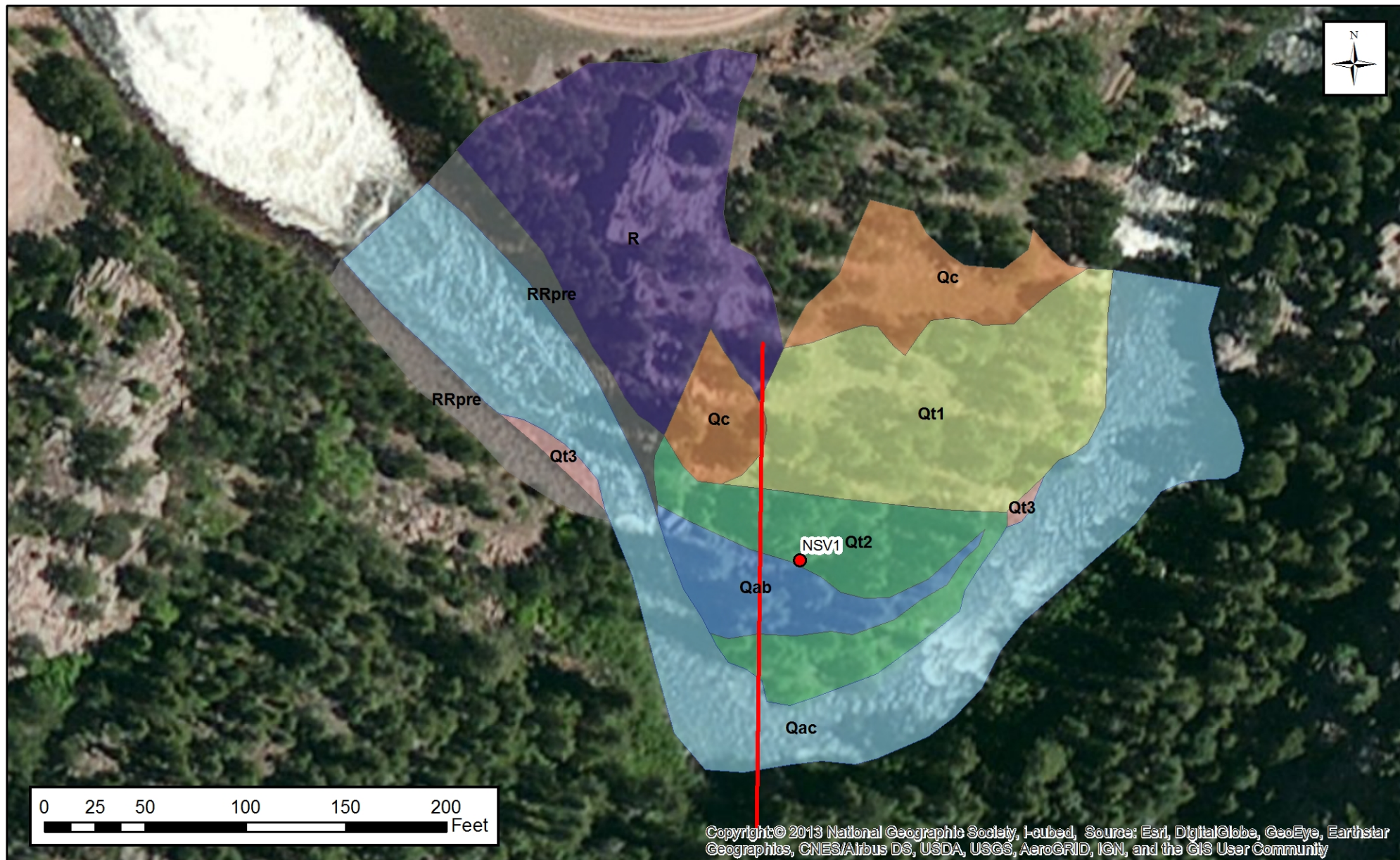
● Soil_desc	===== approximate contact	Labels, Unit Description	Qac, channel	Qt0, T0 terrace	Qt3, T3 (floodplain)
— Cross_section	— buried contact	Hs, hillslope	Qac1, 2013 new channel areas	Qt1, T1 terrace	Qy, debris flow
contacts	— erosion scarp	Hse, road or hillslope erosion	Qaf, SixMile alluvial fan deposits	Qt1f, T1 terrace flooded	R, bedrock face
Type	— paleochannel	QL, landslide	Qc, talus/colluvial fan	Qt1f, T1 terrace flooded by debris flow	RR(post), rip rap (post 2013 flood)
— high water mark		Qab, bar	Qsv, flood sand 2013	Qt2, T2 terrace	RR(pre), rip rap (pre 2013 flood)
		Qab, point bar	Qsv1, SixMile flood sand 2013	Qt2f, T2 terrace flooded	fill, road berm/fill



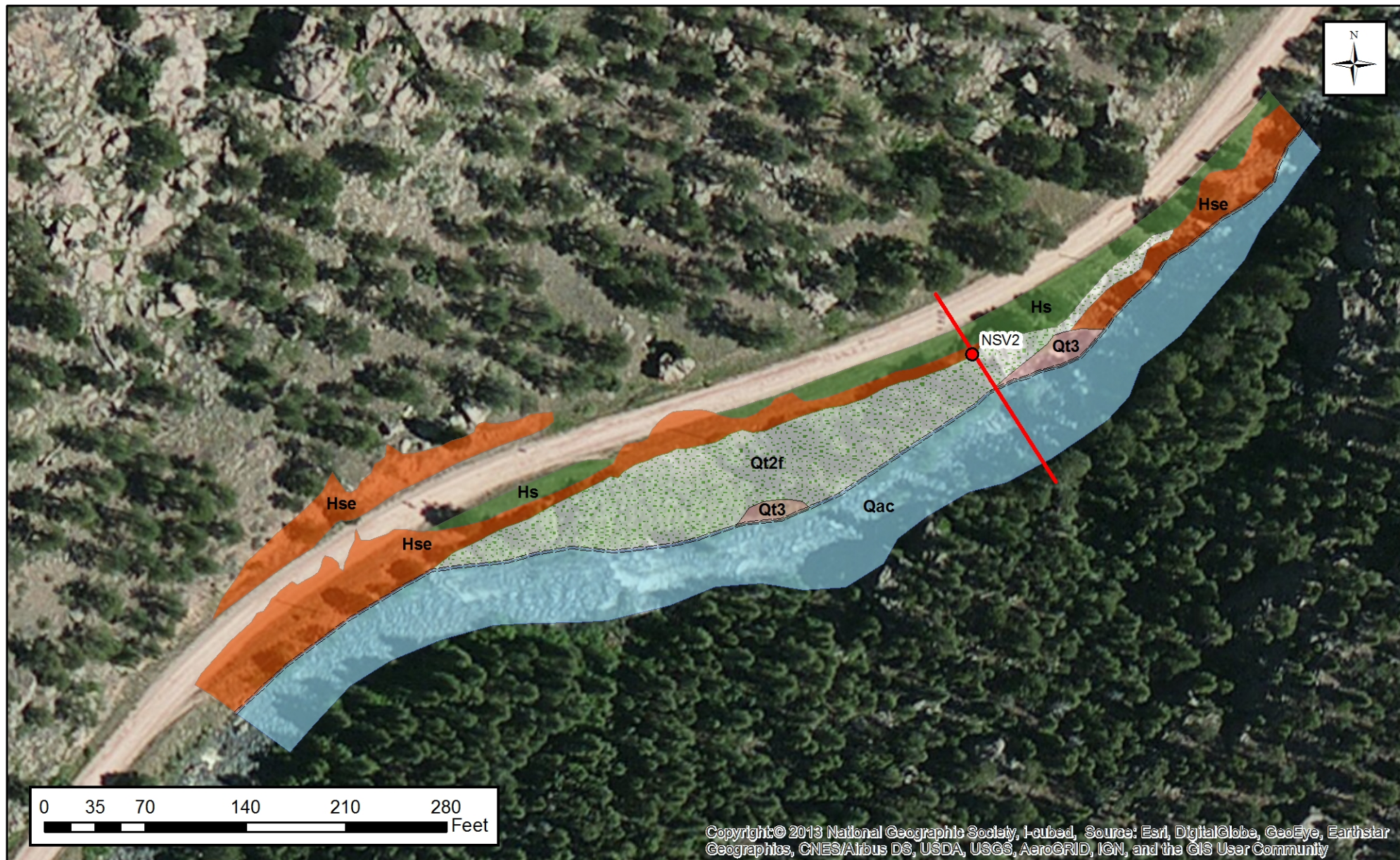
● Soil_desc	==== approximate contact	Labels, Unit Description	Qac, channel	Qt0, T0 terrace	Qt3, T3 (floodplain)
— Cross_section	— buried contact	Hs, hillslope	Qac1, 2013 new channel areas	Qt1, T1 terrace	Qy, debris flow
contacts	— erosion scarp	Hse, road or hillslope erosion	Qaf, SixMile alluvial fan deposits	Qt1f, T1 terrace flooded	R, bedrock face
Type	— paleochannel	QL, landslide	Qc, talus/colluvial fan	Qt1f, T1 terrace flooded by debris flow	RR(post), rip rap (post 2013 flood)
— high water mark		Qab, bar	Qsv, flood sand 2013	Qt2, T2 terrace	RR(pre), rip rap (pre 2013 flood)
		Qab, point bar	Qsv1, SixMile flood sand 2013	Qt2f, T2 terrace flooded	fill, road berm/fill



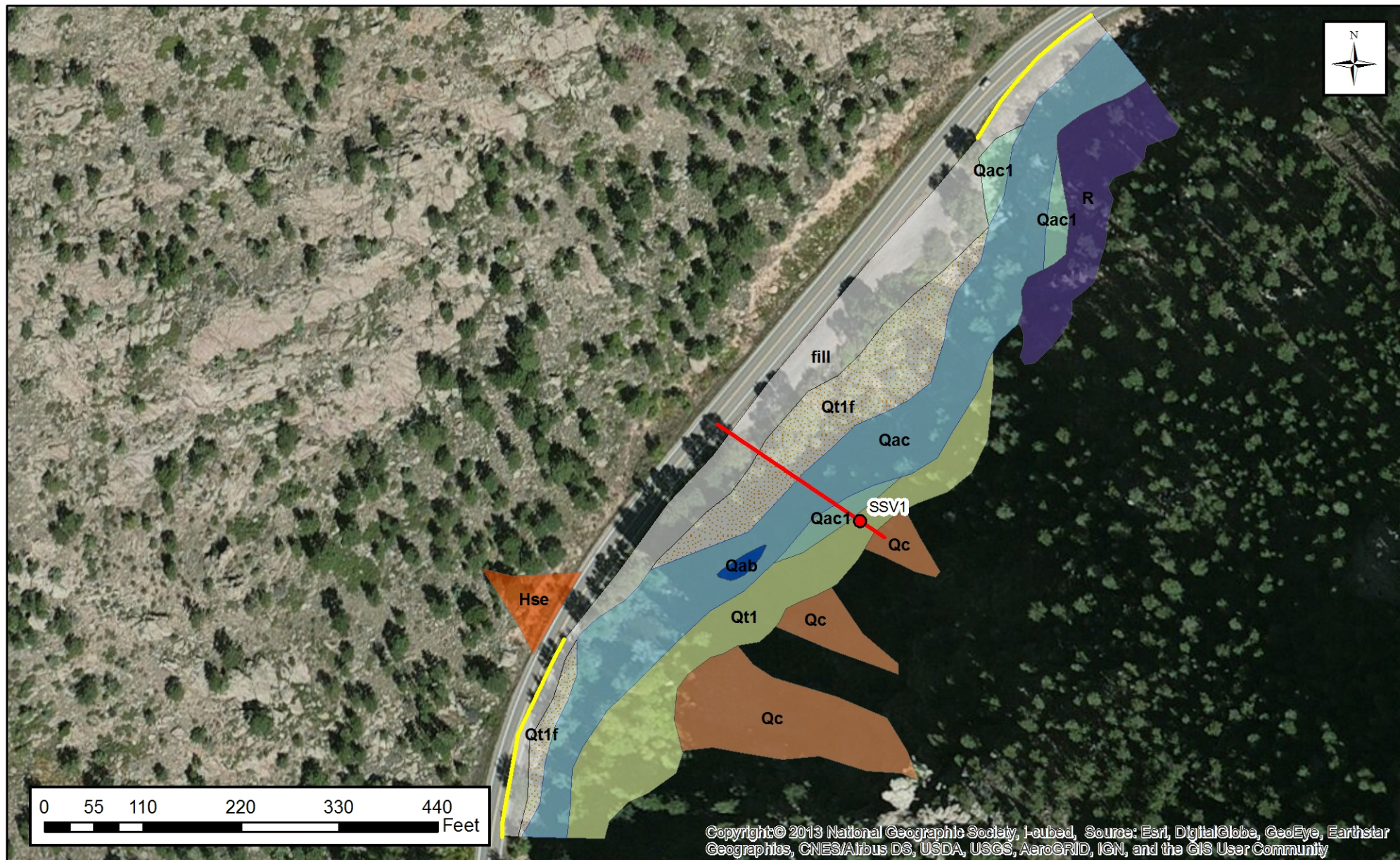
● Soil_desc	===== approximate contact	Labels, Unit Description	Qac, channel	Qt0, T0 terrace	Qt3, T3 (floodplain)
— Cross_section	— buried contact	Hs, hillslope	Qac1, 2013 new channel areas	Qt1, T1 terrace	Qy, debris flow
contacts	— erosion scarp	Hse, road or hillslope erosion	Qaf, SixMile alluvial fan deposits	Qt1f, T1 terrace flooded	R, bedrock face
Type	— paleochannel	QL, landslide	Qc, talus/colluvial fan	Qt1f, T1 terrace flooded by debris flow	RR(post), rip rap (post 2013 flood)
— high water mark		Qab, bar	Qsv, flood sand 2013	Qt2, T2 terrace	RR(pre), rip rap (pre 2013 flood)
		Qab, point bar	Qsv1, SixMile flood sand 2013	Qt2f, T2 terrace flooded	fill, road berm/fill



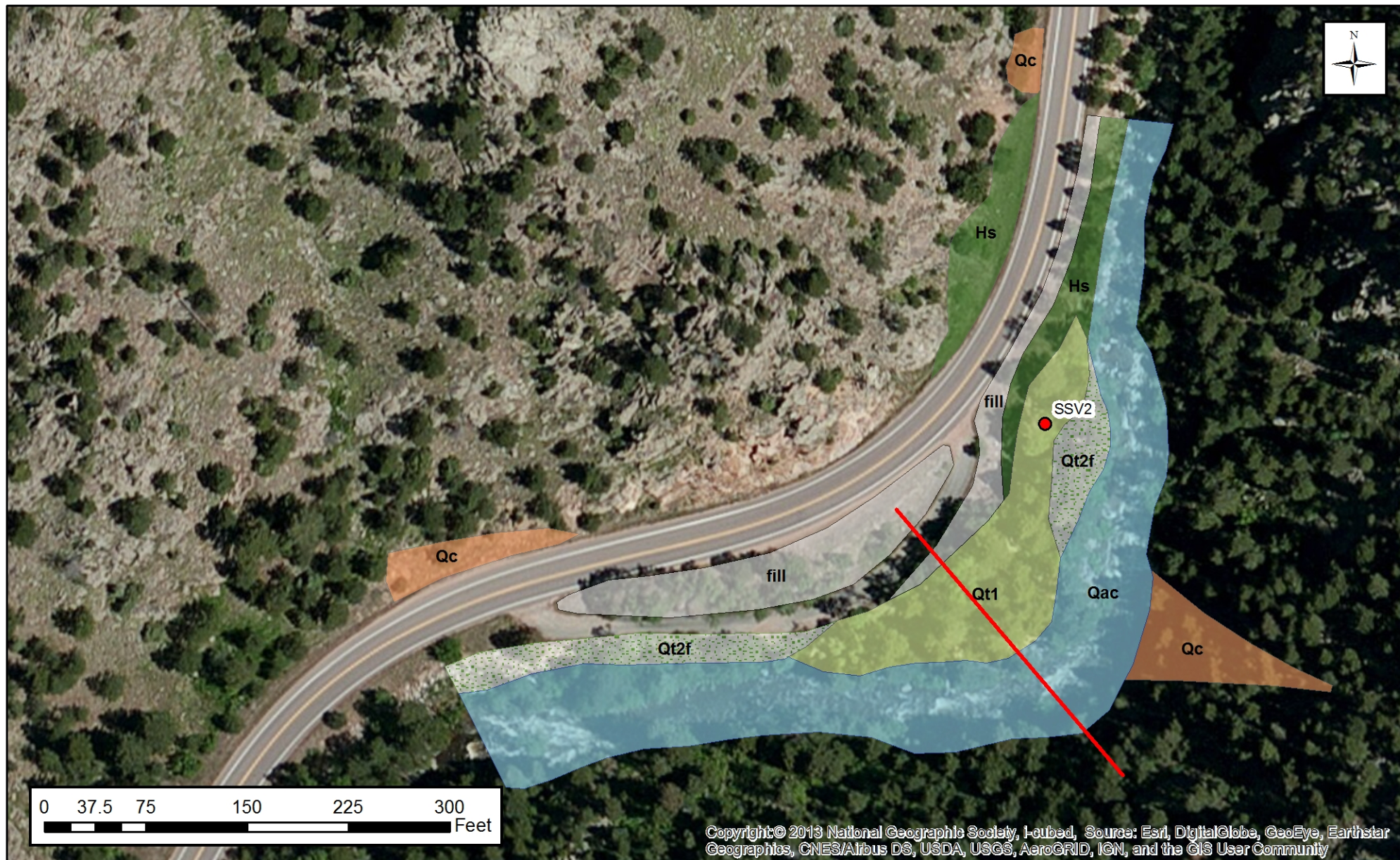
● Soil_desc	==== approximate contact	Labels, Unit Description	Qac, channel	Qt0, T0 terrace	Qt3, T3 (floodplain)
— Cross_section	— buried contact	Hs, hillslope	Qac1, 2013 new channel areas	Qt1, T1 terrace	Qy, debris flow
contacts	— erosion scarp	Hse, road or hillslope erosion	Qaf, Six Mile alluvial fan deposits	Qt1f, T1 terrace flooded	R, bedrock face
Type	— paleochannel	QL, landslide	Qc, talus/colluvial fan	Qt1f1, T1 terrace flooded by debris flow	RR(post), rip rap (post 2013 flood)
— high water mark		Qab, bar	Qsv, flood sand 2013	Qt2, T2 terrace	RR(pre), rip rap (pre 2013 flood)
		Qab, point bar	Qsv1, Six Mile flood sand 2013	Qt2f, T2 terrace flooded	fill, road berm/fill



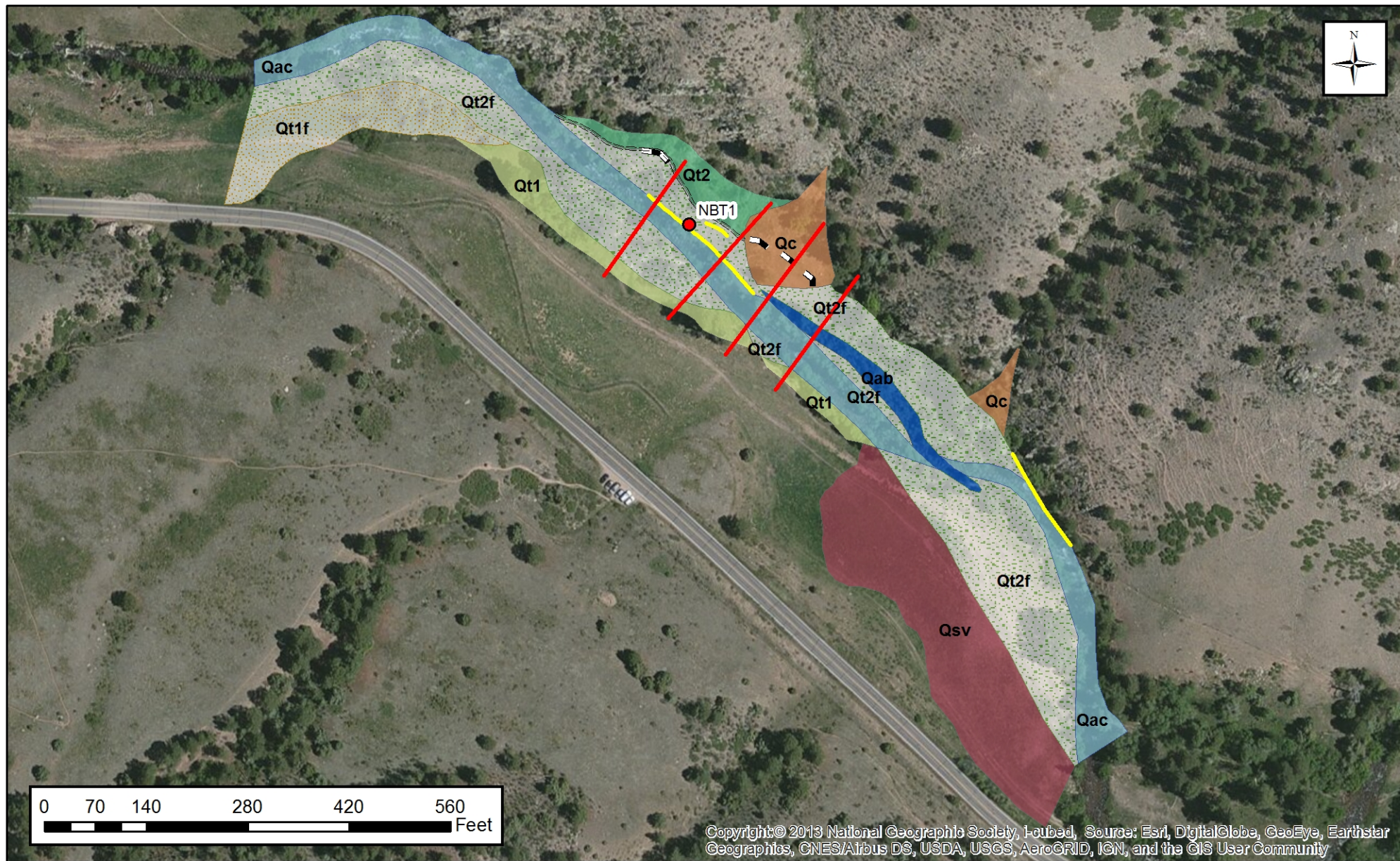
● Soil_desc	==== approximate contact	Labels, Unit Description	Qac, channel	Qt0, T0 terrace	Qt3, T3 (floodplain)
— Cross_section	— buried contact	Hs, hillslope	Qac1, 2013 new channel areas	Qt1, T1 terrace	Qy, debris flow
contacts	— erosion scarp	Hse, road or hillslope erosion	Qaf, SixMile alluvial fan deposits	Qt1f, T1 terrace flooded	R, bedrock face
Type	— paleochannel	QL, landslide	Qc, talus/colluvial fan	Qt1f, T1 terrace flooded by debris flow	RR(post), rip rap (post 2013 flood)
— high water mark		Qab, bar	Qsv, flood sand 2013	Qt2, T2 terrace	RR(pre), rip rap (pre 2013 flood)
		Qab, point bar	Qsv1, SixMile flood sand 2013	Qt2f, T2 terrace flooded	fill, road berm/fill



● Soil_desc	==== approximate contact	Labels, Unit Description	Qac, channel	Qt0, T0 terrace	Qt3, T3 (floodplain)
— Cross_section	— buried contact	Hs, hillslope	Qac1, 2013 new channel areas	Qt1, T1 terrace	Qy, debris flow
contacts	— erosion scarp	Hse, road or hillslope erosion	Qaf, SixMile alluvial fan deposits	Qt1f, T1 terrace flooded	R, bedrock face
Type	— paleochannel	QL, landslide	Qc, talus/colluvial fan	Qt1f, T1 terrace flooded by debris flow	RR(post), rip rap (post 2013 flood)
— high water mark		Qab, bar	Qsv, flood sand 2013	Qt2, T2 terrace	RR(pre), rip rap (pre 2013 flood)
		Qab, point bar	Qsv1, SixMile flood sand 2013	Qt2f, T2 terrace flooded	fill, road berm/fill



● Soil_desc	==== approximate contact	Labels, Unit Description	Qac, channel	Qt0, T0 terrace	Qt3, T3 (floodplain)
— Cross_section	— buried contact	Hs, hillslope	Qac1, 2013 new channel areas	Qt1, T1 terrace	Qy, debris flow
contacts	— erosion scarp	Hse, road or hillslope erosion	Qaf, SixMile alluvial fan deposits	Qt1f, T1 terrace flooded	R, bedrock face
Type	— paleochannel	QL, landslide	Qc, talus/colluvial fan	Qt1f, T1 terrace flooded by debris flow	RR(post), rip rap (post 2013 flood)
— high water mark		Qab, bar	Qsv, flood sand 2013	Qt2, T2 terrace	RR(pre), rip rap (pre 2013 flood)
		Qab, point bar	Qsv1, SixMile flood sand 2013	Qt2f, T2 terrace flooded	fill, road berm/fill



● Soil_desc	===== approximate contact	Labels, Unit Description	Qac, channel	Qt0, T0 terrace	Qt3, T3 (floodplain)
— Cross_section	— buried contact	Hs, hillslope	Qac1, 2013 new channel areas	Qt1, T1 terrace	Qy, debris flow
contacts	— erosion scarp	Hse, road or hillslope erosion	Qaf, SixMile alluvial fan deposits	Qt1f, T1 terrace flooded	R, bedrock face
Type	— paleochannel	QL, landslide	Qc, talus/colluvial fan	Qt1f, T1 terrace flooded by debris flow	RR(post), rip rap (post 2013 flood)
— high water mark		Qab, bar	Qsv, flood sand 2013	Qt2, T2 terrace	RR(pre), rip rap (pre 2013 flood)
		Qab, point bar	Qsv1, SixMile flood sand 2013	Qt2f, T2 terrace flooded	fill, road berm/fill

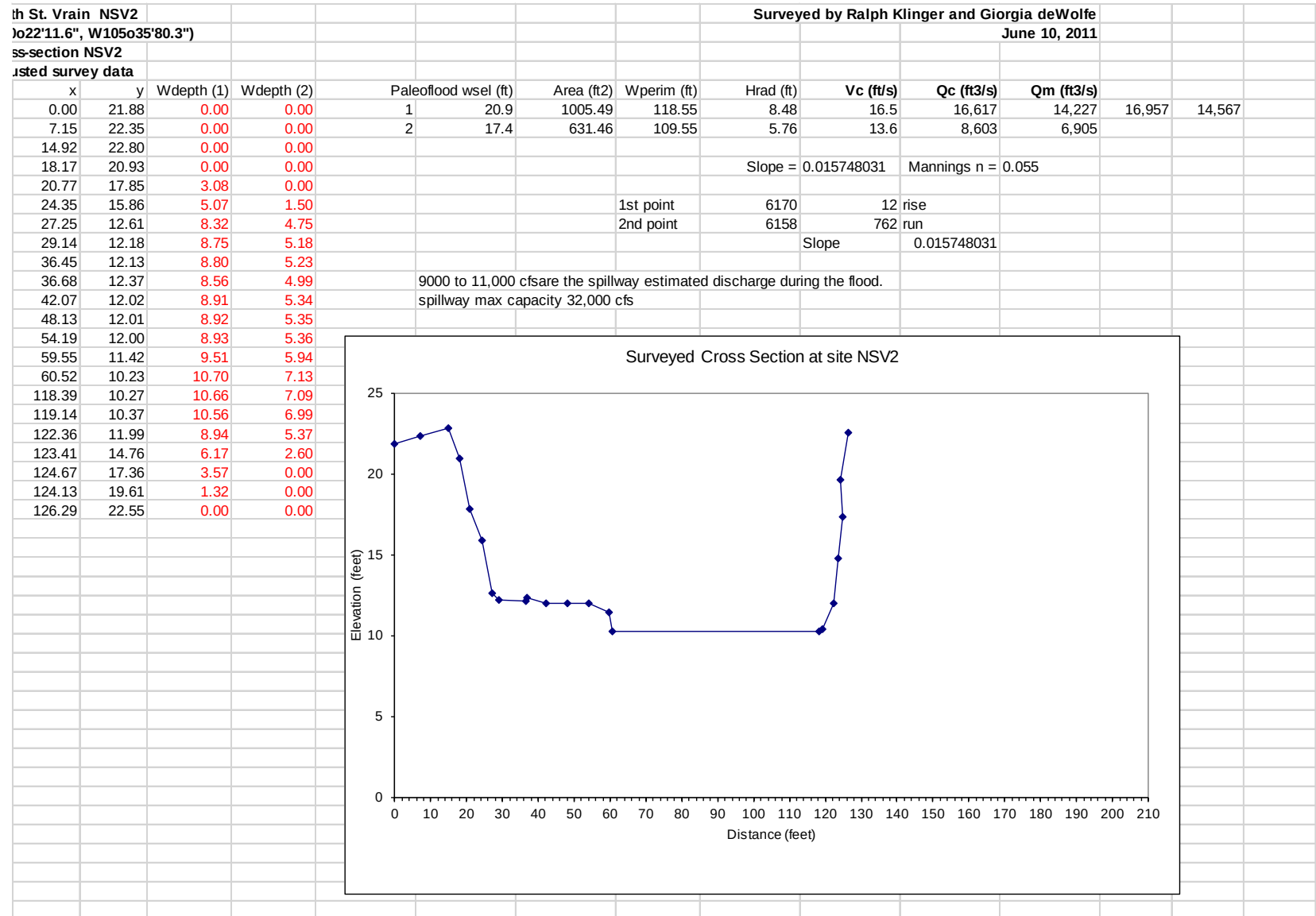
APPENDIX C- SLOPE CONVEYANCE ANALYSIS CALCULATIONS

North St. Vrain Creek (NSV1)

North St. Vrain NSV1			Surveyed by Ralph Klinger and Georgia dewolfe		
(N40°21'52.9", W105°36'39.6")			June 10, 2014		
Cross-section NSV1					
Raw survey data			Adjusted survey data		
	x	y	Notes	x	y
1	66.12	10.33	top of rock left bank slope	0.00	22.33
2	60.65	7.71	left bank rock	5.47	19.71
3	58.52	5.8	"	7.60	17.80
4	57.17	4.55	"	8.95	16.55
5	55.39	2.45	"	10.73	14.45
6	55.66	0.7	"	10.46	12.70
7	55.39	-1.51	"	10.73	10.49
8	54.03	-3.5	water surface right bank	12.09	8.50
9	11.24	-3.59	water surface left bank	54.88	8.41
10	9.45	-2.87	scour line	56.67	9.13
11	7.13	-1.86	mid riser	58.99	10.14
12	4.85	-0.78	edge of T1	61.27	11.22
13	2.83	-0.35	T1	63.29	11.65
14	0	0	instrument	66.12	12.00
15	2.6	0.62	riser to point bar	68.72	12.62
16	6.29	1.64	"	72.41	13.64
17	10.83	2.39	top of point bar	76.95	14.39
18	14.57	2.09		80.69	14.09
19	20.2	1.58		86.32	13.58
20	23.92	1.19	bottom of point bar	90.04	13.19
21	30.77	-0.22		96.89	11.78
22	36.97	-0.25	contact with the riser	103.09	11.75
23	43.71	-0.46		109.83	11.54
24	56.21	0.65		122.33	12.65
25	66.14	1.13		132.26	13.13
26	75.91	1.26		142.03	13.26
27	78.18	1.30		144.30	13.30
28	86.02	1.19	back of T2	152.14	13.19
29	86.57	1.14	alluvial fan	152.69	13.14
30	97.58	0.81	"	163.70	12.81
31	106.34	0.80	"	172.46	12.80
32	113.55	1.57	"	179.67	13.57
33	120.60	2.96	"	186.72	14.96
34	129.04	4.00	base of rock exposure	195.16	16.00
35	130.84	9.27	rock exposure	196.96	21.27
36	132.00	14.49	"	198.12	26.49

North St. Vrain Creek (NSV2)

North St. Vrain NSV2 (N40o22'11.6", W105o35'80.3")			Surveyed by Ralph Klinger and Giorgia deWolfe June 10, 2011		
Cross-section NSV2					
Raw survey data			Adjusted survey data		
	x	y	Notes	x	y
1	57.1	9.88	center of the road	0.00	21.88
2	49.95	10.35	"	7.15	22.35
3	42.18	10.8	edge of the road	14.92	22.80
4	38.93	8.93	HWM	18.17	20.93
5	36.33	5.85		20.77	17.85
6	32.75	3.86		24.35	15.86
7	29.85	3.05	Top of a remenant terrace T2	27.25	12.61
8	27.96	0.61	edge of floodplain	29.14	12.18
9	20.65	0.18	boulder point bar	36.45	12.13
10	20.42	0.13	"	36.68	12.37
11	15.03	0.37	"	42.07	12.02
12	8.97	0.02	"	48.13	12.01
13	2.91	0.01	"	54.19	12.00
14	0	0	instrument	59.55	11.42
15	2.45	-0.58	edge of point bar	60.52	10.23
16	3.42	-1.77	edge of water left bank	118.39	10.27
17	61.29	-1.73	water surface right bank	119.14	10.37
18	62.04	-1.63	rock	122.36	11.99
19	65.26	-0.01	"	123.41	14.76
20	66.31	2.76	"	124.67	17.36
21	67.57	5.36	"	124.13	19.61
22	67.03	7.61	"	126.29	22.55
23	69.19	10.55			
24					
25					



South St. Vrain Creek (SSV1)

South St. Vrain SSV1			Surveyed by Jeanne Godaire and Georgia dewolfe		
(N40°44'33.6", W105°37'8.00")			September 18, 2014		
Cross-section SSV1					
Raw survey data			Adjusted survey data		
	x	y	Notes	x	y
1	69.25	9.53	Slope	0.00	22.53
2	65.62	7.45	slope	3.63	20.45
3	63.5	7.19	floatsome on slope	5.75	20.19
4	61.29	5.42		7.96	18.42
5	57.68	4.81	sand surface	11.57	17.81
6	52.48	3.8	"	16.77	16.80
7	48.61	3.52	edge of eroded terrace	20.64	16.52
8	45.21	-2.62	flood channel	24.04	10.38
9	39.33	-3.7	edge of water	29.92	9.30
10	37.76	-4.29	channel	31.49	8.71
11	34.85	-3.85	"	34.40	9.15
12	31.2	-3.73	"	38.05	9.27
13	27.7	-4.27	"	41.55	8.73
14	24.9	-4.74	"	44.35	8.26
15	20.03	-4.93	"	49.22	8.07
16	16.62	-5.04	Tailweg	52.63	7.96
17	12.81	-4.91	channel	56.44	8.09
18	7.88	-3.46	edge of water	61.37	9.54
19	2.57	-0.38	top of bank	66.68	12.62
20	0	0	Instrument	69.25	13.00
21	11.38	-0.16		80.63	12.84
22	26.00	-0.62		95.25	12.38
23	36.89	-0.34	edge of riprap on the bank	106.14	12.66
24	45.45	1.45	higher terrace surface	114.70	14.45
25	62.77	2.59	breack of slope	132.02	15.59
26	63.19	2.75	edge of sand	132.44	15.75
27	70.62	5.88	height of floatsome	139.87	18.88
28	77.20	9.43	rock slope (riprap)	146.45	22.43
29	92.30	12.12	edge of road	161.55	25.12
30					
31					
32					

South St. Vrain SSV1
(N40o44'33.6", W105o37'8.00")

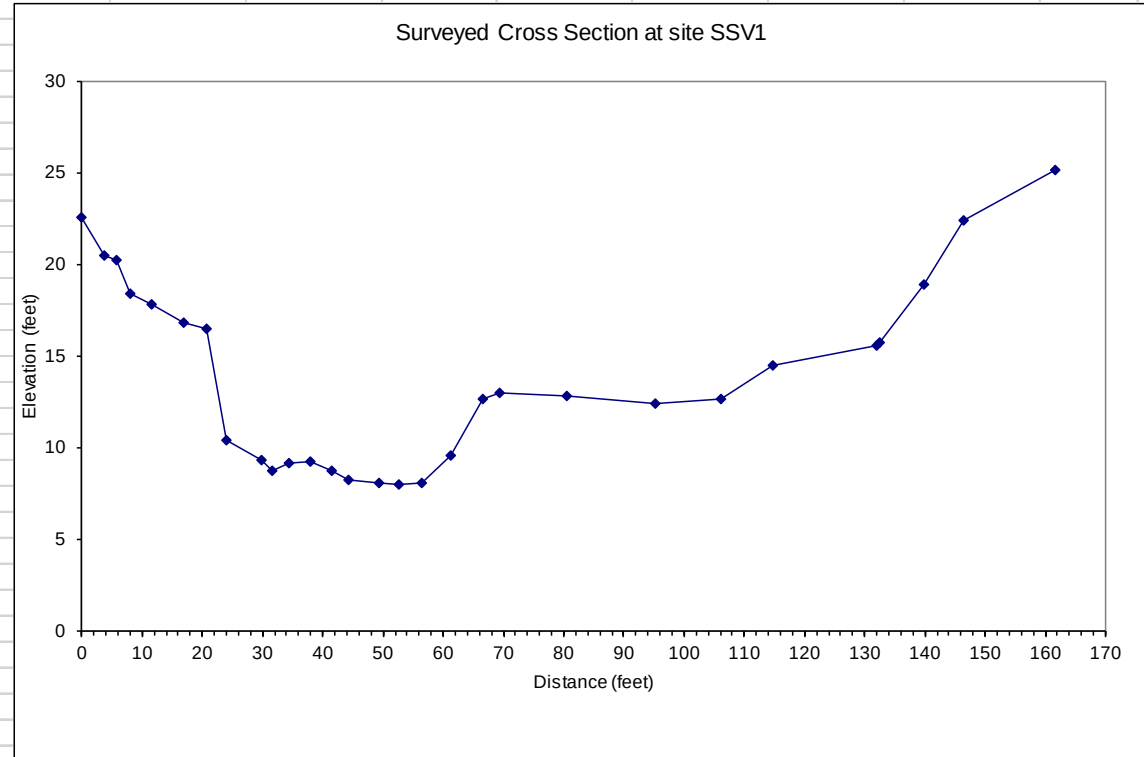
Surveyed by Jeanne Godaire and Giorgia dewolfe
September 18, 2014

Cross-section SSV1

Adjusted survey data

	x	y	Wdepth (1)	Wdepth (2)	Paleoflood wsel (ft)	Area (ft2)	Wperim (ft)	Hrad (ft)	Vc (ft/s)	Qc (ft3/s)	Qm (ft3/s)	
1	0.00	22.53	0.00	0.00	1	20.2	1002.31	143.57	6.98	15.0	15,028	16,999
2	3.63	20.45	0.00	0.00	2	18.9	826.10	138.71	5.96	13.8	11,440	12,601
3	5.75	20.19	0.00	0.00								
4	7.96	18.42	1.77	0.46				Slope = 0.029333333		Mannings n = 0.055		
5	11.57	17.81	2.38	1.07								
6	16.77	16.80	3.39	2.08			1st point	5710	11	rise		
7	20.64	16.52	3.67	2.36			2nd point	5699	375	run		
8	24.04	10.38	9.81	8.50				Slope		0.029333333		
9	29.92	9.30	10.89	9.58	On the NSV							
10	31.49	8.71	11.48	10.17	release from the outlet work during the flood was 400-500 cfs							
11	34.40	9.15	11.04	9.73	9000 to 11,000 cfs are the spillway estimated discharge during the flood.							
12	38.05	9.27	10.92	9.61	spillway max capacity 32,000 cfs							
13	41.55	8.73	11.46	10.15								
14	44.35	8.26	11.93	10.62								
15	49.22	8.07	12.12	10.81								
16	52.63	7.96	12.23	10.92								
17	56.44	8.09	12.10	10.79								
18	61.37	9.54	10.65	9.34								
19	66.68	12.62	7.57	6.26								
20	69.25	13.00	7.19	5.88								
21	80.63	12.84	7.35	6.04								
22	95.25	12.38	7.81	6.50								
23	106.14	12.66	7.53	6.22								
24	114.70	14.45	5.74	4.43								
25	132.02	15.59	4.60	3.29								
26	132.44	15.75	4.44	3.13								
27	139.87	18.88	1.31	0.00								
28	146.45	22.43	0.00	0.00								
29	161.55	25.12	0.00	0.00								

Surveyed Cross Section at site SSV1



South St. Vrain Creek (SSV2)

South St. Vrain SSV2			Surveyed by Jeanne Godaire and Giorgia dewolfe		
(N40°10'04.8", W105°22'53.4")			June 13, 2014		
Cross-section SSV2					
Raw survey data			Adjusted survey data		
	x	y	Notes	x	y
1	69.29	3.44	rock outcrop	0.00	15.44
2	65.11	-1.19	"	4.18	10.81
3	64.17	-4.2	water flood level	5.12	7.80
4	61.96	-6.54		7.33	5.46
5	57.41	-9.94		11.88	2.06
6	53.2	-11.92	current water level	16.09	0.08
7	19.13	-6.03	water level on the left bank	50.16	5.97
8	13.63	-4.2		55.66	7.80
9	6.68	-1.76		62.61	10.24
10	1.9	-0.54	floodplain with overtopped hill slope debris	67.39	11.46
11	0	0	instrument	69.29	12.00
12	10.07	0.32	marginally overtopped high point	79.36	12.32
13	16.79	-1.73		86.08	10.27
14	25.83	-3.86	low point of point bar/talus pile	95.12	8.14
15	33.76	-4.09		103.05	7.91
16	41.9	-5		111.19	7.00
17	46.62	-5.24	middle of the back channel	115.91	6.76
18	54.87	-5.95	start of the riser to T1	124.16	6.05
19	63.34	-4.68	T1 surface	132.63	7.32
20	72.38	-5.56	"	141.67	6.44
21	80.21	-6.05	"	149.50	5.95
22	91.46	-7.19	back of T1 surface	160.75	4.81
23	98.86	-5.32	flood water level on the left bank	168.15	6.68
24	102.96	-1.93	hill slope	172.25	10.07
25	111.20	1.82	edge of road	180.49	13.82
26					

Middle St. Vrain Creek (MSV1)

Middle St Vrain u/s confluence of South St. Vrain			Surveyed by Giorgia dewolfe and Jeanne Godaire	
N 10°16.1' W 105°24'37.7")			September 18, 2014	
Cross-section MSV1				
Raw survey data			Adjusted survey data	
x	y	Notes	x	y
91.68	-5.56	Slope	0.00	12.44
91.23	-10.62	back of the terrace	0.45	7.38
78.32	-10.7	terrace surface	13.36	7.30
70.35	-10.89	"	21.33	7.11
63.48	-11.38	"	28.20	6.62
62.33	-10.16	floatsome	29.35	7.84
59.1	-12.27	terrace surface	32.58	5.73
54.57	-12.89	edge of the terrace eroded	37.11	5.11
53.3	-16.29	edge of water	38.38	1.71
48.77	-16.75	channel	42.91	1.25
43.72	-17.07	"	47.96	0.93
37.8	-17.11	tailweg	53.88	0.89
33.66	-16.4	channel	58.02	1.60
30.65	-16	channel	61.03	2.00
24.57	-15.78	Edge of water	67.11	2.22
21.55	-15.73	"	70.13	2.27
18.17	-12.12	rock slope	73.51	5.88
16.02	-10.41	floatsome (estimated from several location)	75.66	7.59
9.31	-5.72	rock slope	82.37	12.28
0	0	instrument of the service road edge	91.68	18.00

Middle St Vrain u/s confluence of South St. Vrain
(N40°10'16.1" W105°24'37.7")

Cross-section MSV1

Adjusted survey data

	x	y	Wdepth (1)	Wdepth (2)	Paleoflood wsel (ft)	Area (ft2)	Wperim (ft)	Hrad (ft)	Vc (ft/s)	Qc (ft3/s)	Qm (ft3/s)
1	0.00	12.44	0.00	0.00	1	9.8	409.47	87.47	4.68	12.3	4,630
2	0.45	7.38	2.46	0.21	2	7.6	236.43	80.48	2.94	9.7	1,959
3	13.36	7.30	2.54	0.29							
4	21.33	7.11	2.73	0.48				Slope =	0.02222222	Mannings n =	0.055
5	28.20	6.62	3.22	0.97							
6	29.35	7.84	2.00	0.00			1st point	7280	10 rise		
7	32.58	5.73	4.11	1.86			2nd point	7270	450 run		
8	37.11	5.11	4.73	2.48				Slope	0.02222222		
9	38.38	1.71	8.13	5.88							
10	42.91	1.25	8.59	6.34							
11	47.96	0.93	8.91	6.66							
12	53.88	0.89	8.95	6.70							
13	58.02	1.60	8.24	5.99							
14	61.03	2.00	7.84	5.59							
15	67.11	2.22	7.62	5.37							
16	70.13	2.27	7.57	5.32							
17	73.51	5.88	3.96	1.71							
18	75.66	7.59	2.25	0.00							
19	82.37	12.28	0.00	0.00							
20	91.68	18.00	0.00	0.00							

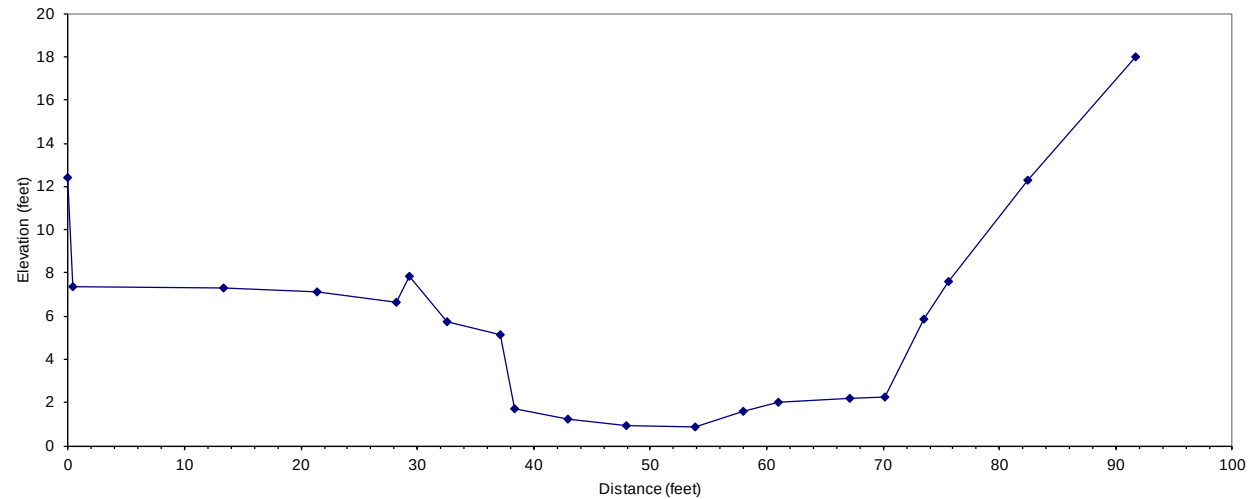
Surveyed by Georgia dewolfe and Jeanne Godaire

September 18, 2014

Slope = 0.022222222 Mannings n = 0.055

1st point 7280 10 rise
2nd point 7270 450 run
Slope 0.022222222

Surveyed Cross Section at site MSV1



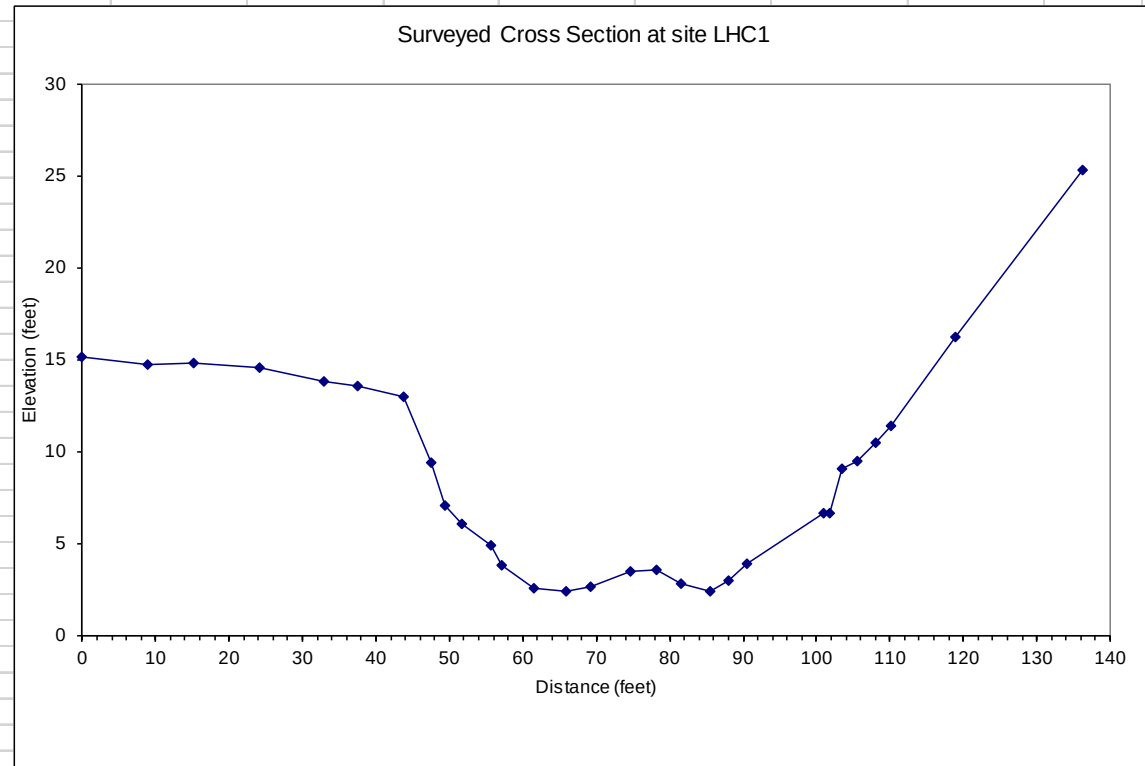
Left Hand Creek (LHC1)

Left Hand downstream confluence with six miles				Surveyed by Giorgia dewolfe and Jeanne Godaire	
				September 12, 2014	
Cross-section LH1					
Raw survey data				Adjusted survey data	
	x	y	Notes	x	y
1	43.67	2.11	right bank surface	0.00	15.11
2	34.72	1.75	"	8.95	14.75
3	28.45	1.85	"	15.22	14.85
4	19.48	1.59	"	24.19	14.59
5	10.74	0.81	"	32.93	13.81
6	6.17	0.57	floatsome	37.50	13.57
7	0	0	Instrument	43.67	13.00
8	3.9	-3.62	base of bank exposed bedrock	47.57	9.38
9	5.81	-5.96	exposed bedrock	49.48	7.04
10	8.12	-6.92	"	51.79	6.08
11	12.09	-8.09	"	55.76	4.91
12	13.41	-9.18	Edge of water	57.08	3.82
13	17.77	-10.41	channel	61.44	2.59
14	22.28	-10.59	channel thalweg	65.95	2.41
15	25.57	-10.38	channel	69.24	2.62
16	30.92	-9.51	point bar	74.59	3.49
17	34.59	-9.44	point bar	78.26	3.56
18	37.85	-10.18	channel	81.52	2.82
19	41.74	-10.59	"	85.41	2.41
20	44.34	-9.97	"	88.01	3.03
21	46.92	-9.11	Edge of water left bank	90.59	3.89
22	57.20	-6.31	top of sand bed	100.87	6.69
23	58.20	-6.31	back edge of sand bed	101.87	6.69
24	59.72	-3.91	edge of terrace	103.39	9.09
25	61.85	-3.54	back edge of terrace	105.52	9.46
26	64.34	-2.50	Slope break	108.01	10.50
27	66.46	-1.58	floatsome	110.13	11.42
28	75.27	3.24	slope	118.94	16.24
29	92.47	12.35	slope left bank	136.14	25.35
30					

Cross-section LHC1

Adjusted survey data

	x	y	Wdepth (1)	Wdepth (2)	Paleoflood wsel (ft)	Area (ft2)	Wperim (ft)	Hrad (ft)	Vc (ft/s)	Qc (ft3/s)	Qm (ft3/s)
1	0.00	15.11	0.00	0.00	1	565.51	83.11	6.80	14.8	8,371	7,708
2	8.95	14.75	0.00	0.00	2	416.69	70.04	5.95	13.8	5,767	5,193
3	15.22	14.85	0.00	0.00							
4	24.19	14.59	0.00	0.00				Slope = 0.019607843	Mannings n = 0.055		
5	32.93	13.81	0.00	0.00							
6	37.50	13.57	0.00	0.00			1st point	5885	6 rise		
7	43.67	13.00	0.57	0.00			2nd point	5879	306 run		
8	47.57	9.38	4.19	2.02				Slope	0.019607843		
9	49.48	7.04	6.53	4.36							
10	51.79	6.08	7.49	5.32							
11	55.76	4.91	8.66	6.49							
12	57.08	3.82	9.75	7.58							
13	61.44	2.59	10.98	8.81							
14	65.95	2.41	11.16	8.99							
15	69.24	2.62	10.95	8.78							
16	74.59	3.49	10.08	7.91							
17	78.26	3.56	10.01	7.84							
18	81.52	2.82	10.75	8.58							
19	85.41	2.41	11.16	8.99							
20	88.01	3.03	10.54	8.37							
21	90.59	3.89	9.68	7.51							
22	100.87	6.69	6.88	4.71							
23	101.87	6.69	6.88	4.71							
24	103.39	9.09	4.48	2.31							
25	105.52	9.46	4.11	1.94							
26	108.01	10.50	3.07	0.90							
27	110.13	11.42	2.15	0.00							
28	118.94	16.24	0.00	0.00							
29	136.14	25.35	0.00	0.00							



Coal Creek (CC1)

Coal Creek near Chappel of the Hills			Surveyed by Jeanne Godaire and Giorgia deWolfe		
(N39°04'05.0", W105°03'68.5")			June 3, 2014		
Cross-section CC1					
Raw survey data			Adjusted survey data		
	x	y	Notes	x	y
1	50.12	1.28	rock slope	0.00	14.28
2	43.66	-1.26		6.46	11.74
3	13.1	0	road	37.02	13.00
4	0	0	instrument	50.12	13.00
5	3.23	-0.25	top of bank	53.35	12.75
6	7.28	-2.5	Slope	57.40	10.50
7	11.13	-5.26	bottom of slope	61.25	7.74
8	18.24	-6.31	floodplain top of bank	68.36	6.69
9	22.45	-8.2	edge of water, left bank	72.57	4.80
10	24.27	-8.92	channel	74.39	4.08
11	26.58	-9.6	"	76.70	3.40
12	28.65	-9.31	"	78.77	3.69
13	31.64	-9.08	"	81.76	3.92
14	35.11	-8.81	"	85.23	4.19
15	36.7	-8.91	"	86.82	4.09
16	37.34	-8.39	Edge of water, right bank	87.46	4.61
17	38.89	-3.73	top of terrace	89.01	9.27
18	47.29	-4.12	terrace	97.41	8.88
19	53.89	-4.38	"	104.01	8.62
20	61.61	-4.92	"	111.73	8.08
21	72.6	-5.28	"	122.72	7.72
22	85.42	-5.67	"	135.54	7.33
23	95.90	-5.72	Edge of Terrace	146.02	7.28
24	104.43	-3.23	Slope	154.55	9.77
25	108.29	-0.87	Slope	158.41	12.13
26					

Coal Creek near Chappel of the Hills

(N39°84'05.0", W105°33'68.5")

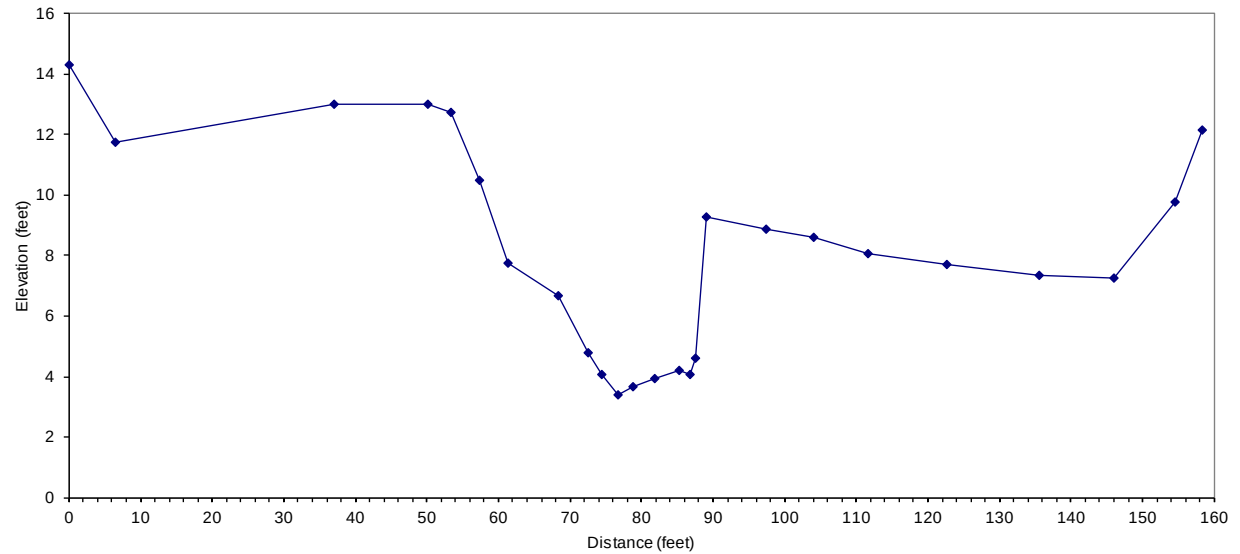
Cross-section CC1

Adjusted survey data

	x	y	Wdepth (1)	Wdepth (2)	Paleoflood wsel (ft)	Area (ft2)	Wperim (ft)	Hrad (ft)	Vc (ft/s)	Qc (ft3/s)	Qm (ft3/s)	
1	0.00	14.28	0.00	0.00	1	12.3	496.04	126.10	3.93	11.3	5,583	6,674
2	6.46	11.74	0.56	0.00	2	9.5	212.51	100.06	2.12	8.3	1,757	1,895
3	37.02	13.00	0.00	0.00								
4	50.12	13.00	0.00	0.00				Slope =	0.03968254	Mannings n =	0.055	
5	53.35	12.75	0.00	0.00								
6	57.40	10.50	1.80	0.00			1st point	7567	20 rise			
7	61.25	7.74	4.56	1.76			2nd point	7547	504 run			
8	68.36	6.69	5.61	2.81					Slope	0.03968254		
9	72.57	4.80	7.50	4.70								
10	74.39	4.08	8.22	5.42								
11	76.70	3.40	8.90	6.10								
12	78.77	3.69	8.61	5.81								
13	81.76	3.92	8.38	5.58								
14	85.23	4.19	8.11	5.31								
15	86.82	4.09	8.21	5.41								
16	87.46	4.61	7.69	4.89								
17	89.01	9.27	3.03	0.23								
18	97.41	8.88	3.42	0.62								
19	104.01	8.62	3.68	0.88								
20	111.73	8.08	4.22	1.42								
21	122.72	7.72	4.58	1.78								
22	135.54	7.33	4.97	2.17								
23	146.02	7.28	5.02	2.22								
24	154.55	9.77	2.53	0.00								
25	158.41	12.13	0.17	0.00								

Surveyed Cross Section at site CC1

Surveyed Cross Section at site CC1



Fourmile Canyon Creek (4MC1)

Fourmile Canyon near Boulder			Surveyed by Tess Harden and Giorgia deWolfe		
(N40°03'49.2", W115°17'40.3")			June 2, 2014		
Cross-section 4MC1					
Raw survey data			Adjusted survey data		
	x	y	Notes	x	y
1	57.13	3.3	road edge	0.00	15.30
2	41.7	0.51	channel	15.43	12.51
3	38.29	0.64	channel	18.84	12.64
4	24.29	1.14	terrace	32.84	13.14
5	13.29	0.71	channel	43.84	12.71
6	9.36	-0.82	terrace	47.77	11.18
7	0	0	"	57.13	12.00
8	3.25	-0.29	"	60.38	11.71
9	3.9	-4.09	edge of floodplain eroded	61.03	7.91
10	23.14	-5.5	edge of flood plain channel	80.27	6.50
11	29.09	-5.75	water edge	86.22	6.25
12	36.42	-5.51	Flood plain	93.55	6.49
13	39.84	-6.43	flood plain channel	96.97	5.57
14	43.45	-6.15	floodplain	100.58	5.85
15	54.27	-7.15	edge of channel	111.40	4.85
16	61.95	-8.71	water edge	119.08	3.29
17	66.68	-10.13	channel	123.81	1.87
18	68.58	-9.99	theilweg	125.71	2.01
19	68.47	-9.24	channel	125.60	2.76
20	71.44	-9.42	"	128.57	2.58
21	72.74	-9.23	Edge of water	129.87	2.77
22	76.34	-7.47	floodplain/midslope	133.47	4.53
23	88.92	-7.27	"	146.05	4.73
24	97.83	-5.95	water edge	154.96	6.05
25	108.45	-5.88	floodplain/midslope	165.58	6.12
26	112.63	-5.40	flood plain	169.76	6.60
27	112.73	-4.12	terrace edge	169.86	7.88
28	116.43	-3.76	slope	173.56	8.24
29	129.05	0.51	slope	186.18	12.51
30	135.53	3.12	slope	192.66	15.12

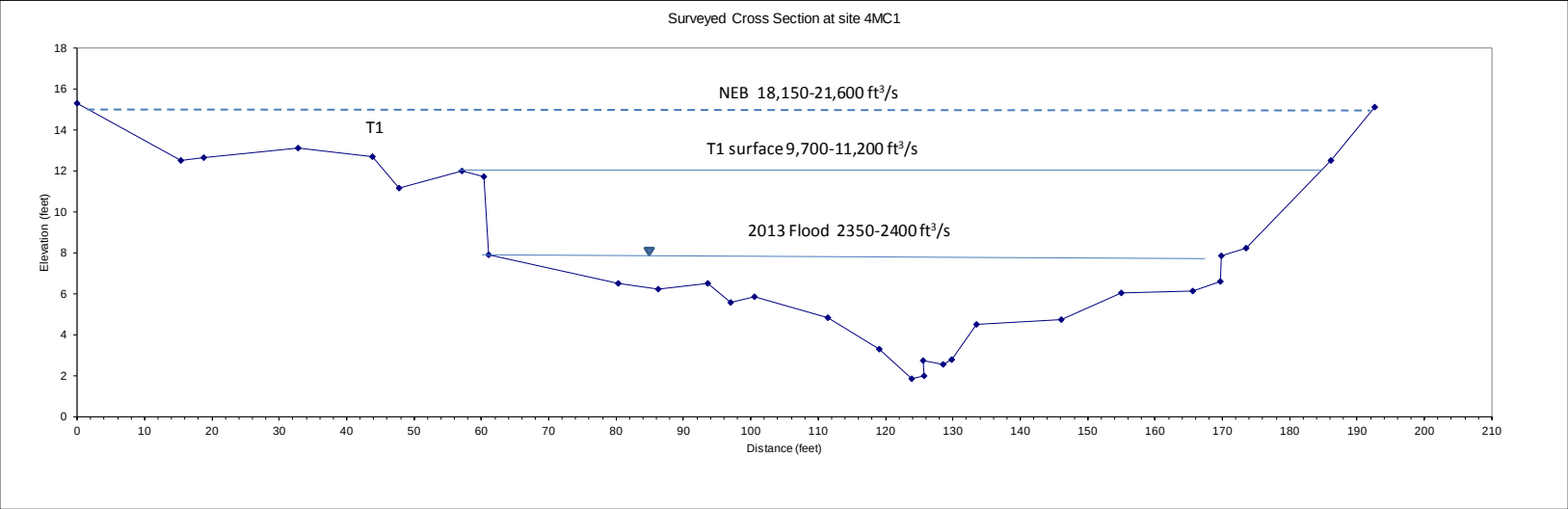
Fourmile Canyon near Boulder
(N34°08'37.81", W82°00'20.06")

Cross-section 4MC1
Adjusted survey data

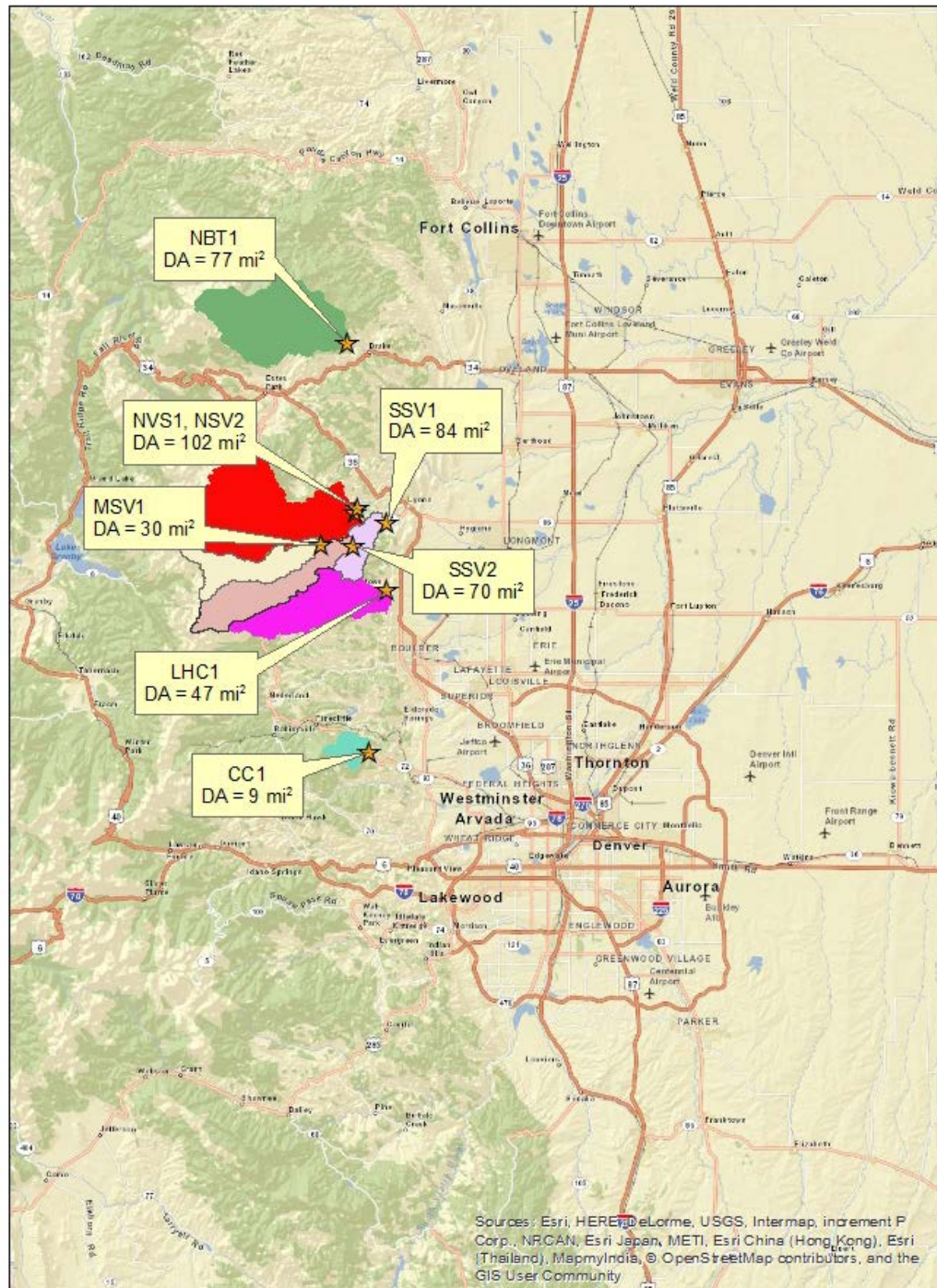
	x	y	Wdepth (1)	Wdepth (2)
1	0.00	15.30	0.00	0.00
2	15.43	12.51	2.49	0.00
3	18.84	12.64	2.36	0.00
4	32.84	13.14	1.86	0.00
5	43.84	12.71	2.29	0.00
6	47.77	11.18	3.82	0.82
7	57.13	12.00	3.00	0.00
8	60.38	11.71	3.29	0.29
9	61.03	7.91	7.09	4.09
10	80.27	6.50	8.50	5.50
11	86.22	6.25	8.75	5.75
12	93.55	6.49	8.51	5.51
13	96.97	5.57	9.43	6.43
14	100.58	5.85	9.15	6.15
15	111.40	4.85	10.15	7.15
16	119.08	3.29	11.71	8.71
17	123.81	1.87	13.13	10.13
18	125.71	2.01	12.99	9.99
19	125.60	2.76	12.24	9.24
20	128.57	2.58	12.42	9.42
21	129.87	2.77	12.23	9.23
22	133.47	4.53	10.47	7.47
23	146.05	4.73	10.27	7.27
24	154.96	6.05	8.95	5.95
25	165.58	6.12	8.88	5.88
26	169.76	6.60	8.40	5.40
27	169.86	7.88	7.12	4.12
28	173.56	8.24	6.76	3.76
29	186.18	12.51	2.49	0.00
30	192.66	15.12	0.00	0.00

Surveyed by Tess Harden and Giorgia deWolfe
June 2, 2014

Paleoflood wsel (ft)	Area (ft ²)	Wperim (ft)	Hrad (ft)	Vc (ft/s)	Qc (ft ³ /s)	Qm (ft ³ /s)
1 15.0	1267.49	198.90	6.37	14.3	18,156	21,587
2 12.0	756.02	146.27	5.17	12.9	9,753	11,198
3 7.91	268.85	112.35	2.39	8.8	2,360	2,382
Slope = 0.027613412 Mannings n = 0.050						
1st point			5687	14 rise		
2nd point			5673	507 run		
Slope				0.027613412		



APPENDIX D- POINTS OF INTEREST WATERSHED MAP



The drainage basin SSV1 is downstream of the SSV2 sub basin, which is downstream of the MSV2 sub basin. The MSV1 sub basin is within the SSV2 sub basin and both are contained within the SSV1 drainage basin.

APPENDIX E- ENVELOPE CURVE GAGES

USGS Station ID	Station Name	Lat	Long	USGS Peaks DA (mi ²)	Start Year	End Year	Max Peaks Date	Max Peaks (ft ³ /s)
06611000	COLORADO CREEK NEAR SPICER, CO.	40.44	- 106.50	26	1951	1955	5/4/52	408
06615000	SOUTH FORK MICHIGAN RIVER NEAR GOULD, CO	40.46	- 106.01	12	1951	1958	6/29/57	450
06617500	ILLINOIS RIVER NEAR RAND, CO.	40.46	- 106.18	71	1932	1940	5/23/32	745
06618000	WILLOW CREEK NEAR RAND, CO.	40.47	- 106.22	56	1932	1940	6/7/33	200
06611100	GRIZZLY CREEK NEAR SPICER, CO.	40.49	- 106.45	118	1977	1979	5/19/79	864
6614800	MICHIGAN RIVER NEAR CAMERON PASS, CO	40.50	- 105.86	2	1974	2014	7/12/95	115
06611200	BUFFALO CREEK NEAR HEBRON, CO.	40.52	- 106.37	56	1977	1980	4/21/80	180
06616000	NORTH FORK MICHIGAN RIVER NEAR GOULD, CO.	40.55	- 106.02	21	1951	1982	5/25/61	290
06611700	LITTLE GRIZZLY CREEK NEAR COALMONT, CO.	40.55	- 106.62	10	1968	1973	6/9/72	300
06615500	MICHIGAN RIVER NEAR LINDLAND, CO.	40.55	- 106.04	61	1932	1941	6/11/33	663
06611300	GRIZZLY CREEK NEAR HEBRON, CO.	40.56	- 106.39	223	1977	1980	5/9/80	1130
06611800	LITTLE GRIZZLY CREEK ABOVE COALMONT, CO.	40.57	- 106.51	35	1977	1979	5/28/79	394
06618300	ILLINOIS RIVER BLW ISH BALDWIN DITCH NR WALDEN, CO	40.58	- 106.24	181	2002	2004	6/2/03	500
06611900	LITTLE GRIZZLY CREEK ABOVE HEBRON, CO.	40.58	- 106.45	52	1977	1980	5/8/80	469

USGS Station ID	Station Name	Lat	Long	USGS Peaks DA (mi ²)	Start Year	End Year	Max Peaks Date	Max Peaks (ft ³ /s)
06612000	LITTLE GRIZZLY CREEK NEAR HEBRON, CO.	40.63	- 106.40	99	1905	1945	6/11/05	592
06611500	GRIZZLY CREEK NEAR WALDEN, CO	40.64	- 106.40	258	1904	1947	6/10/23	1340
06612500	ROARING FORK NEAR WALDEN, CO.	40.68	- 106.46	79	1904	1947	6/15/24	790
06619400	CANADIAN RIVER NEAR LINDLAND, CO.	40.70	- 106.07	44	1978	1983	7/21/83	527
06613000	NORTH PLATTE RIVER NEAR WALDEN, CO.	40.70	- 106.41	469	1904	1947	4/19/38	1940
06618480	ILLINOIS RIVER BLW POTTER CREEK NR WALDEN, CO	40.71	- 106.28	257	2002	2004	6/3/03	423
06618500	ILLINOIS CREEK AT WALDEN, CO.	40.73	- 106.29	259	1923	1947	5/28/26	2520
06614000	NORTH FORK NORTH PLATTE RIVER NEAR WALDEN, CO.	40.73	- 106.41	160	1924	1945	4/19/26	694
06617100	MICHIGAN RIVER AT WALDEN, CO.	40.74	- 106.28	182	1923	1947	6/10/23	1070
06619450	CANADIAN RIVER NEAR BROWNLEE, CO.	40.81	- 106.24	158	1978	1983	6/28/83	644
06619000	MICHIGAN RIVER NEAR COWDREY, CO.	40.86	- 106.34	478	1937	1947	4/21/45	1010
06619500	CANADIAN RIVER AT COWDREY, CO.	40.86	- 106.31	181	1929	1947	4/14/31	802
06620000	NORTH PLATTE RIVER NEAR NORTHGATE, CO	40.94	- 106.34	1431	1904	2014	6/11/23	6720
06657500	LARAMIE RIVER NEAR GLENDEVEY, CO	40.80	- 105.88	101	1905	1982	6/9/23	2240
6659580	SAND CREEK AT COLORADO-WYOMING STATE LINE	40.99	- 105.76	29	1969	2014	7/19/77	6710

USGS Station ID	Station Name	Lat	Long	USGS Peaks DA (mi ²)	Start Year	End Year	Max Peaks Date	Max Peaks (ft ³ /s)
06658500	LARAMIE RIVER NEAR JELM, WYO.	41.00	- 106.01	294	1905	1971	6/9/23	4200
06659600	SAND CREEK NEAR TIE SIDING, WY	41.01	- 105.76	40	1957	1968	6/8/57	253
06696000	SOUTH PLATTE RIVER NEAR LAKE GEORGE, CO.	38.91	- 105.47	963	1930	1998	4/28/70	3000
06695000	S PLATTE RIV AB 11-MILE CANYON RES, NR HARTSEL, CO	38.97	- 105.58	884	1939	1995	4/27/70	3970
06694100	MIDDLE FORK SOUTH PLATTE RIVER NR HARTSEL, CO.	39.02	- 105.76	250	1978	1980	6/13/80	570
06699500	TARRYALL CREEK NEAR LAKE GEORGE, CO.	39.08	- 105.42	429	1925	1955	4/21/48	1030
06694400	SOUTH FORK SOUTH PLATTE RIVER AB FAIRPLAY, CO.	39.08	- 106.05	50	1978	1980	6/11/80	258
06694700	FOURMILE CREEK NEAR FAIRPLAY, CO.	39.18	- 106.06	12	1978	1980	6/9/80	163
06693980	MIDDLE FORK SOUTH PLATTE RIVER AB FAIRPLAY, CO.	39.24	- 106.03	62	1978	1980	6/11/80	530
06693800	MOSQUITO CREEK NEAR ALMA, CO	39.27	- 106.05	16	1999	2004	6/23/99	217
06697100	TARRYALL CREEK BLW PARK GULCH NR COMO, CO	39.28	- 105.79	76	1997	2001	6/9/97	173
06699005	TARRYALL CRK BELOW ROCK CREEK NEAR JEFFERSON, CO	39.29	- 105.70	230	1983	1997	6/30/95	850
06699000	ROCK CREEK NEAR JEFFERSON, CO	39.29	- 105.70	46	1987	1990	6/9/87	147
06698500	TARRYALL CREEK NEAR JEFFERSON, CO.	39.30	- 105.72	182	1912	1981	7/9/17	1320
06696980	TARRYALL CREEK AT UPPER STATION NEAR COMO, CO	39.34	- 105.91	24	1978	2014	5/30/14	270

USGS Station ID	Station Name	Lat	Long	USGS Peaks DA (mi ²)	Start Year	End Year	Max Peaks Date	Max Peaks (ft ³ /s)
06697450	MICHIGAN CREEK ABOVE JEFFERSON, CO.	39.36	- 105.84	23	1979	1986	6/27/83	163
06698000	JEFFERSON CREEK NEAR JEFFERSON, CO.	39.39	- 105.81	12	1978	1986	7/25/84	76
06701700	WEST CR. ABV SHREWSBURY GULCH NR WESTCREEK CO	39.14	- 105.16	56	2003	2014	7/7/06	2380
06700000	SOUTH PLATTE RIVER ABOVE CHEESMAN LAKE, CO.	39.16	- 105.31	1627	1925	2014	7/28/03	4690
06701620	TROUT CREEK BLW FERN CR NR WESTCREEK, CO.	39.17	- 105.12	106	2003	2014	5/1/07	124
06700500	GOOSE CREEK ABOVE CHEESMAN LAKE, CO.	39.21	- 105.30	87	1925	1982	6/9/57	487
06697200	FRENCH CREEK NEAR JEFFERSON,COLORADO	39.41	- 105.89	5	1986	1990	6/28/88	64
06706000	NF SOUTH PLATTE R BELOW GENEVA C, AT GRANT, CO.	39.46	- 105.66	127	1909	1998	6/18/95	1160
06705500	GENEVA CREEK AT GRANT, CO.	39.47	- 105.68	75	1909	1997	6/1/14	1700
06704500	DUCK CREEK NEAR GRANT COLORADO	39.53	- 105.73	8	1995	1997	6/19/95	97
06710385	BEAR CREEK ABOVE EVERGREEN, CO	39.63	- 105.34	103	1984	2014	9/13/13	1350
06714400	S CLEAR CR ABV LOWER CABIN CR RES NR GEORGETWN,CO	39.65	- 105.71	11	1995	2014	6/18/95	107
06714600	S CLEAR CRK ABV LEAVENWORTH CRK NR GEORGETWN, CO	39.69	- 105.70	16	1995	1997	6/23/95	215
06714800	LEAVENWORTH CREEK AT MOUTH NEAR GEORGETOWN, CO	39.69	- 105.70	12	1995	2014	6/3/14	179
06717400	CHICAGO CREEK BLW DEVILS CANYON NR IDAHO SPRGS, CO	39.72	- 105.57	44	1995	2009	6/19/95	275

USGS Station ID	Station Name	Lat	Long	USGS Peaks DA (mi ²)	Start Year	End Year	Max Peaks Date	Max Peaks (ft ³ /s)
06719000	CLEAR CREEK AT FORKS CREEK, CO.	39.75	- 105.40	339	1888	1912	#####	8700
06718300	CLEAR CREEK ABV JOHNSON GULCH NR IDAHO SPRINGS, CO	39.75	- 105.44	267	1995	2005	6/21/95	2250
06718550	NORTH CLEAR CREEK ABOVE MOUTH NR BLACK HAWK, CO	39.75	- 105.40	60	1995	2014	6/2/95	759
06715000	CLEAR CREEK ABV WEST FORK CLEAR CREEK NR EMPIRE CO	39.75	- 105.66	86	1995	2014	7/8/11	1060
06717000	FALL RIVER NEAR IDAHO SPRINGS, CO.	39.76	- 105.56	24	1930	1938	6/29/38	325
06716100	WEST FORK CLEAR CREEK ABV MOUTH NR EMPIRE, CO	39.76	- 105.66	57	1995	2014	5/31/03	855
06716500	CLEAR CREEK NEAR LAWSON, CO	39.77	- 105.63	147	1946	2014	6/4/56	6130
06719725	RALSTON CREEK NEAR PLAINVIEW, CO.	39.85	- 105.30	37	1983	1983	5/26/83	334
06729000	SOUTH BOULDER CREEK NEAR ROLLINSVILLE, CO.	39.91	- 105.50	43	1911	1949	6/12/49	718
06729300	SOUTH BOULDER CREEK AT PINECLIFFE, CO	39.93	- 105.42	73	1979	1980	6/7/79	1150
06725500	MIDDLE BOULDER CREEK AT NEDERLAND, CO.	39.96	- 105.50	36	1908	1995	6/2/14	811
06722500	SOUTH ST. VRAIN CREEK NEAR WARD, CO.	40.09	- 105.51	14	1926	1973	6/29/57	462
06723000	MIDDLE ST. VRAIN CREEK NEAR ALLENS PARK, CO.	40.17	- 105.44	28	1926	1994	6/12/90	892
06721500	NORTH ST. VRAIN CREEK NEAR ALLENS PARK, CO.	40.22	- 105.53	33	1926	1997	6/9/29	1000
06732000	GLACIER CREEK NEAR ESTES PARK, CO.	40.35	- 105.58	25	1942	1970	6/29/57	352

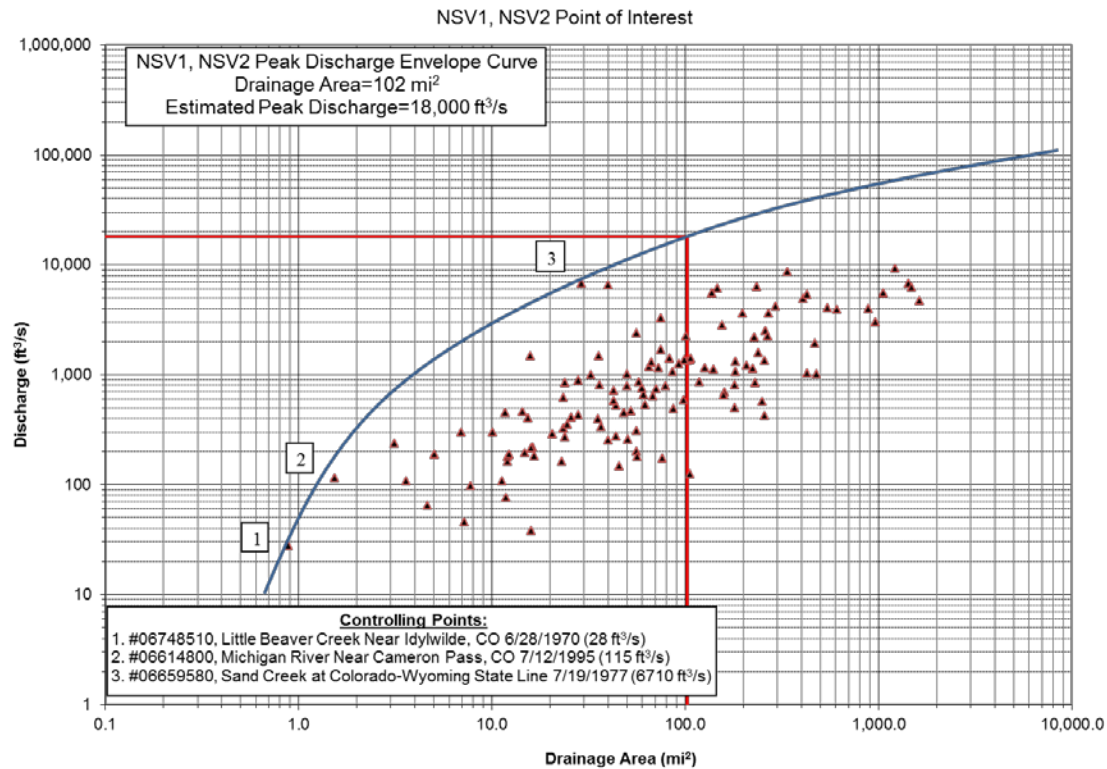
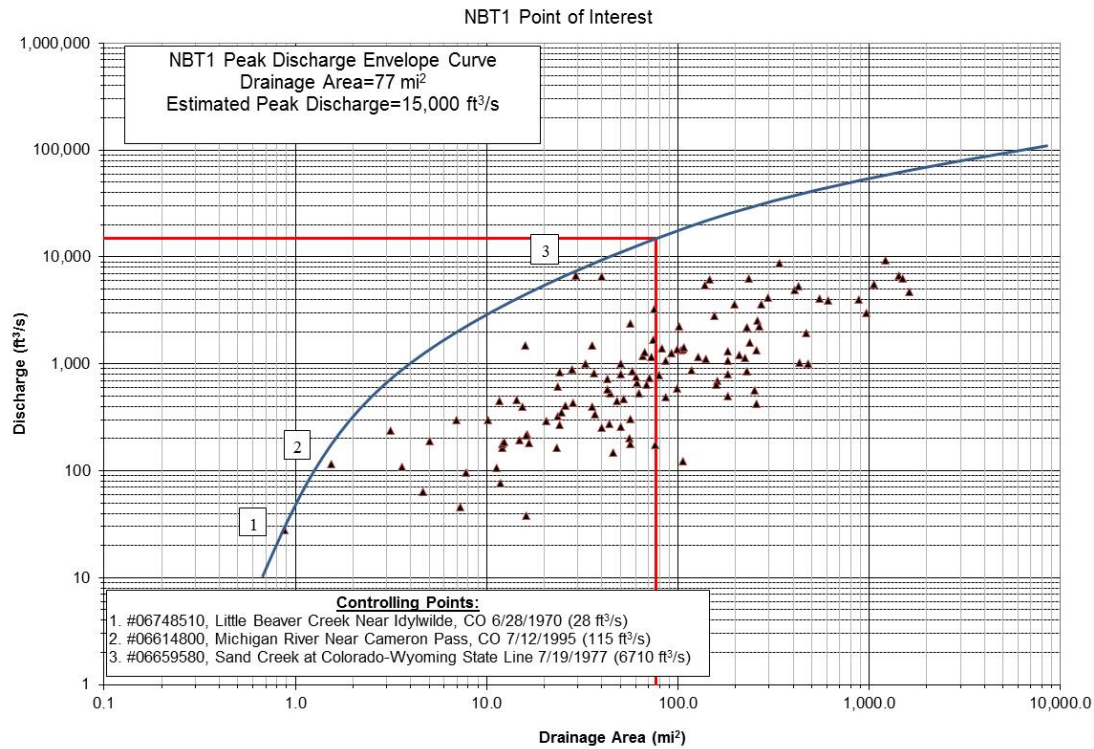
USGS Station ID	Station Name	Lat	Long	USGS Peaks DA (mi ²)	Start Year	End Year	Max Peaks Date	Max Peaks (ft ³ /s)
06734500	FISH CREEK NEAR ESTES PARK, CO.	40.37	- 105.49	16	1947	1979	5/25/51	1480
06735500	BIG THOMPSON RIVER NEAR ESTES PARK, CO.	40.38	- 105.49	155	1930	1995	6/20/33	2800
06732500	FALL RIVER AT ESTES PARK, CO.	40.38	- 105.53	40	1945	1994	7/15/82	6550
06733000	BIG THOMPSON RIVER AT ESTES PARK, CO.	40.38	- 105.51	138	1947	1998	7/15/82	5500
06746100	JOE WRIGHT CREEK NEAR CAMERON PASS, CO	40.55	- 105.88	5	1974	1977	6/8/77	190
06746095	JOE WRIGHT CREEK ABOVE JOE WRIGHT RESERVOIR, CO	40.54	- 105.88	3	1979	2014	7/7/83	238
06748200	FALL CREEK NEAR RUSTIC, CO.	40.55	- 105.63	4	1961	1973	6/16/65	108
06746110	JOE WRIGHT CREEK BELOW JOE WRIGHT RESERVOIR, CO	40.56	- 105.86	7	1978	2014	6/30/11	301
06748530	LITTLE BEAVER CREEK NEAR RUSTIC, CO	40.62	- 105.56	12	1961	1973	6/17/65	187
6748510	LITTLE BEAVER CREEK NEAR IDYLVILDE, CO	40.64	- 105.66	1	1961	1973	6/28/70	28
06748600	SOUTH FORK CACHE LA Poudre RIVER NR RUSTIC, CO.	40.65	- 105.49	92	1957	1979	6/17/65	1260
06749000	CACHE LA Poudre RIVER BELOW ELKHORN CREEK, CO.	40.69	- 105.43	409	1946	1959	6/30/57	4900
06747500	CACHE LA Poudre RIVER NEAR RUSTIC, CO.	40.70	- 105.69	198	1957	1968	6/29/57	3610
06748000	CACHE LA Poudre RIVER NEAR LOG CABIN, CO.	40.70	- 105.57	234	1909	1931	6/19/09	6310
07093700	ARKANSAS RIVER NEAR WELLSVILLE, CO.	38.50	- 105.94	1485	1961	2007	6/12/80	6240

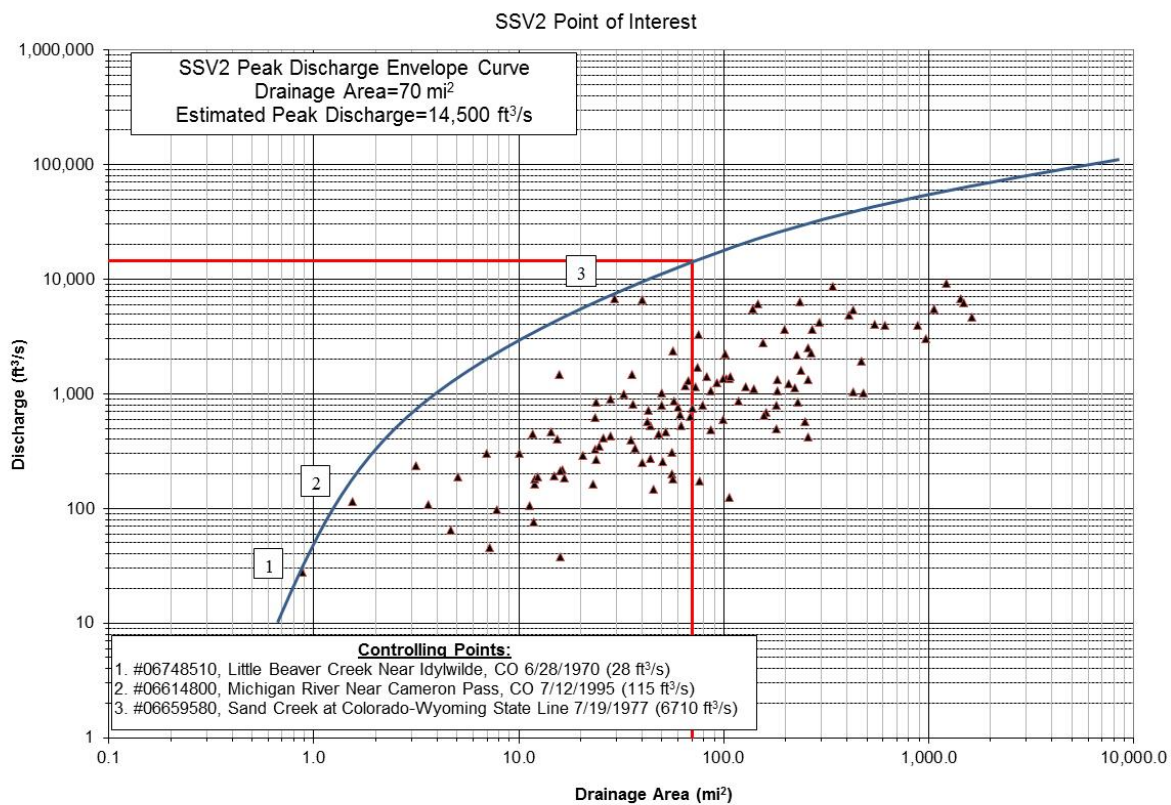
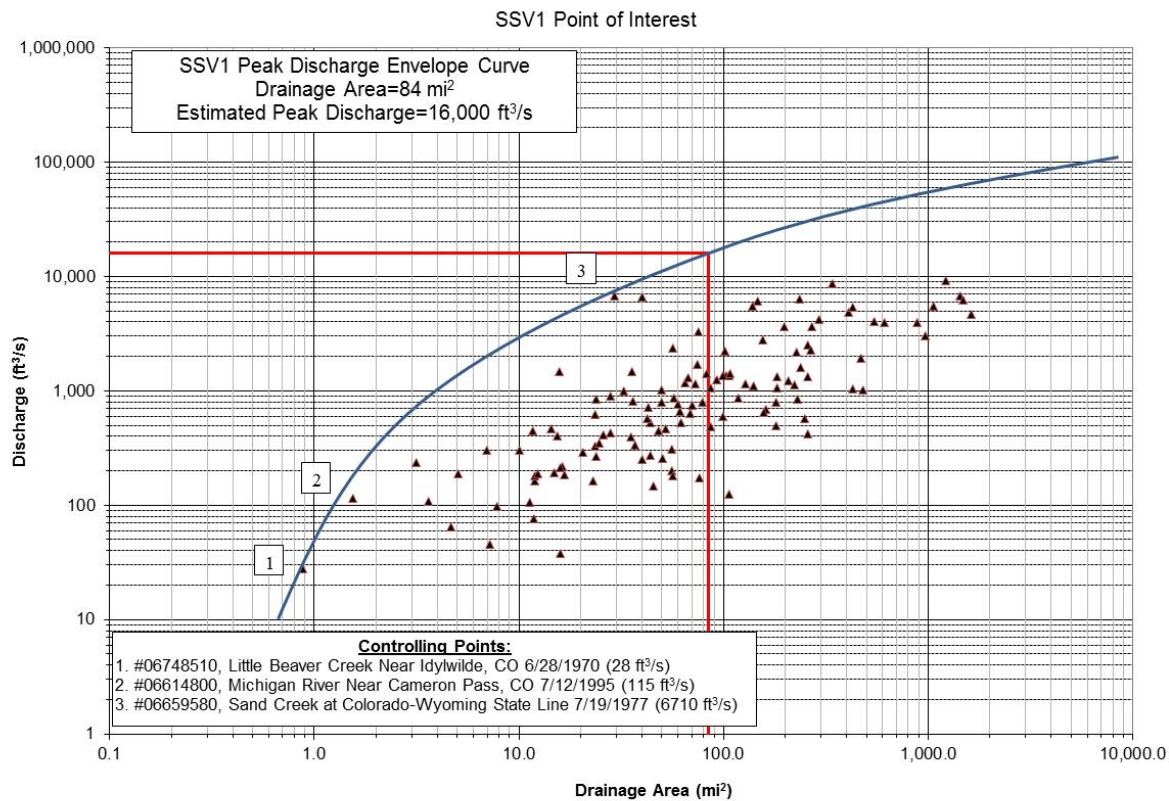
USGS Station ID	Station Name	Lat	Long	USGS Peaks DA (mi ²)	Start Year	End Year	Max Peaks Date	Max Peaks (ft ³ /s)
07093000	PONCHA CREEK AT PONCHA, CO.	38.51	- 106.08	56	1912	1917	5/27/12	307
07092000	SOUTH FORK ARKANSAS RIVER AT PONCHA, CO.	38.51	- 106.08	140	1911	1917	7/5/11	1110
07093500	SOUTH ARKANSAS RIVER NEAR SALIDA, CO.	38.52	- 105.99	208	1922	1940	6/17/23	1220
07091500	ARKANSAS RIVER AT SALIDA, CO.	38.55	- 106.01	1218	1895	1980	6/29/57	9220
07091200	ARKANSAS RIVER NEAR NATHROP, CO	38.65	- 106.05	1055	1965	2014	7/14/95	5540
07093740	BADGER CREEK, UPPER STATION, NEAR HOWARD, CO	38.66	- 105.81	106	1981	2003	8/14/83	1360
07090000	CHALK CREEK (UPPER STATION) NEAR ST. ELMO, CO	38.71	- 106.32	43	1914	1919	6/10/18	575
07090500	CHALK CREEK NEAR ST. ELMO, CO	38.71	- 106.23	68	1911	1915	6/6/12	635
07091000	CHALK CREEK NEAR NATHROP, CO	38.73	- 106.16	83	1949	1993	11/30/85	1400
07089000	COTTONWOOD C BL HOT SPRINGS, NR BUENA VISTA, CO.	38.81	- 106.22	65	1912	1986	7/1/57	1180
07087200	ARKANSAS RIVER AT BUENA VISTA, CO.	38.85	- 106.12	611	1965	1993	6/11/80	3950
07087050	ARKANSAS RIVER BELOW GRANITE, CO	39.00	- 106.22	546	1999	2014	6/8/10	4070
07086500	CLEAR CREEK ABOVE CLEAR CREEK RESERVOIR, CO.	39.02	- 106.28	67	1946	1995	6/29/57	1300
07086000	ARKANSAS RIVER AT GRANITE, CO.	39.04	- 106.27	427	1897	2007	6/28/57	5360
07084500	LAKE CREEK ABOVE TWIN LAKES RESERVOIR, CO.	39.06	- 106.41	75	1946	1998	6/15/78	3270

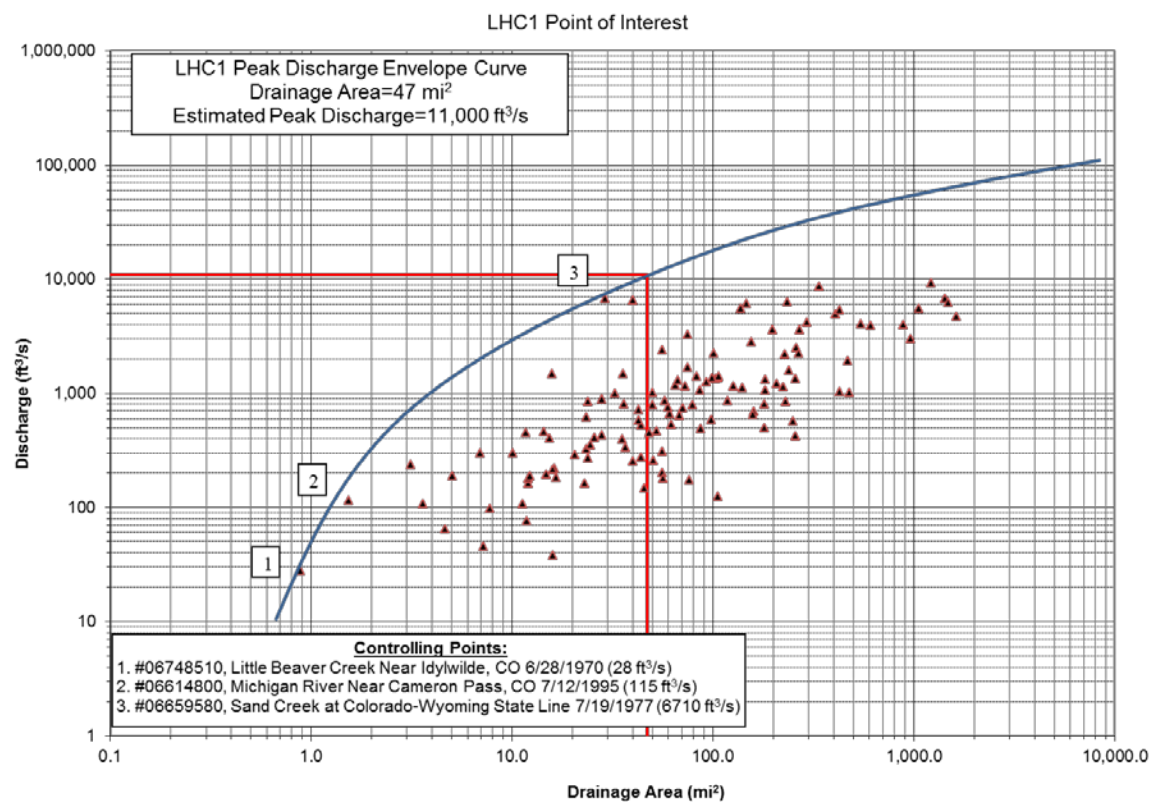
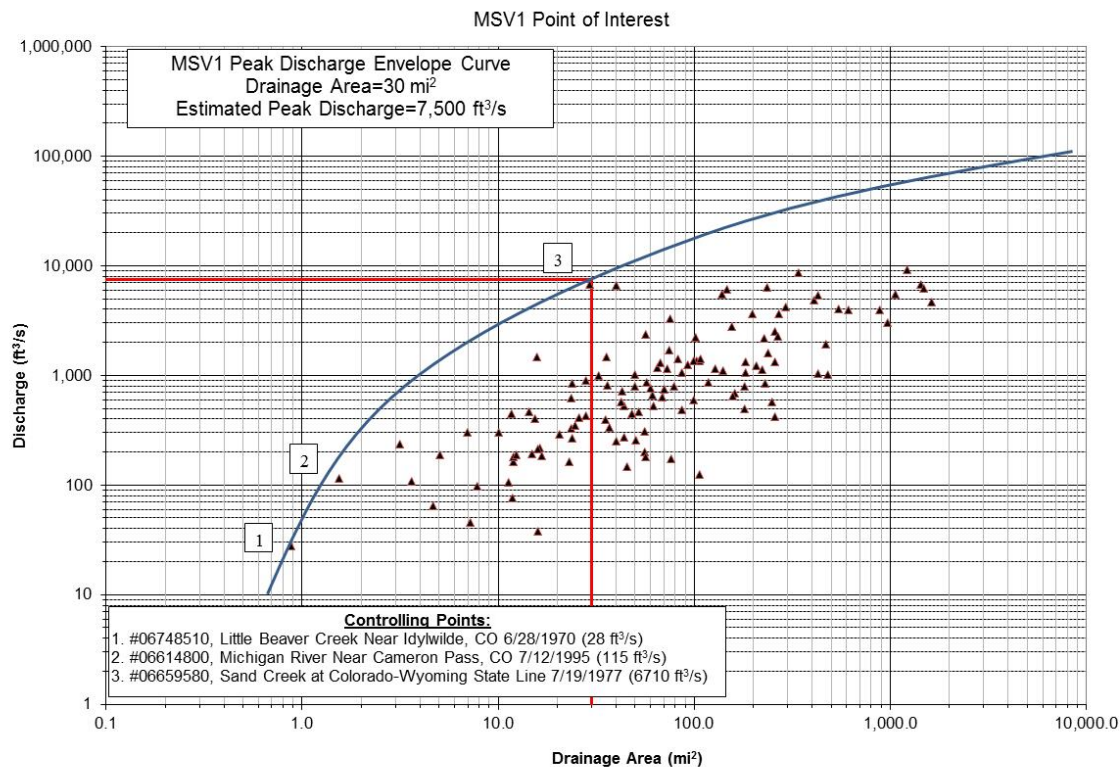
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07085500	LAKE CREEK BELOW TWIN LAKES RESERVOIR, CO.	39.08	- 106.31	107	1946	1953	6/22/47	1420
07083710	ARKANSAS RIVER BELOW EMPIRE GULCH NEAR MALTA, CO	39.16	- 106.32	238	1990	2014	6/17/11	1590
07083700	ARKANSAS RIVER NEAR MALTA, CO.	39.17	- 106.32	228	1965	1984	6/12/80	2200
07083000	HALFMOON CREEK NEAR MALTA, CO	39.17	- 106.39	24	1947	2014	6/30/84	615
07082500	LAKE FORK BELOW SUGAR LOAF RESERVOIR, CO.	39.25	- 106.37	28	1890	1952	#####	428
07081200	ARKANSAS RIVER NEAR LEADVILLE, CO	39.25	- 106.35	99	1968	2014	6/9/97	1360
07079500	EAST FORK ARKANSAS RIVER NEAR LEADVILLE, CO.	39.26	- 106.34	50	1890	1924	6/15/21	794
07081000	TENNESSEE CREEK NEAR LEADVILLE, CO.	39.26	- 106.34	48	1890	1924	6/14/18	450
07082000	LAKE FORK ABOVE SUGAR LOAF RESERVOIR, CO.	39.27	- 106.39	24	1946	1967	6/28/57	841
07079300	EF ARKANSAS R AT US HIGHWAY 24, NR LEADVILLE, CO.	39.27	- 106.31	50	1990	2014	6/8/97	1010
07096250	FOURMILE CREEK BELOW CRIPPLE CREEK NEAR VICTOR, CO	38.66	- 105.23	271	1993	2014	8/2/10	3620
07099990	FOUNTAIN CREEK AT GREEN MOUNTAIN FALLS, CO	38.94	- 105.02	17	2001	2005	7/13/01	183
07103800	WEST MONUMENT CREEK AT U.S. AIR FORCE ACADEMY, CO	38.97	- 104.90	15	1970	2014	7/30/12	194
07103900	WEST MONUMENT CREEK NEAR PIKEVIEW, CO.	38.97	- 104.90	15	1958	1969	6/17/65	400
07103797	WEST MONUMENT CREEK BELOW RAMPART RESERVOIR, CO	38.98	- 104.95	7	1994	2014	6/6/97	46

USGS Station ID	Station Name	Lat	Long	USGS Peaks DA (mi ²)	Start Year	End Year	Max Peaks Date	Max Peaks (ft ³ /s)
07103785	DEADMANS CR ABV DEADMANS LAKE AT USAF ACADMY, CO	39.02	- 104.90	2	2000	2003	4/9/00	2
07103740	N MONUMENT CRK AT SPRING ST AT PALMER LAKE, CO	39.12	- 104.91	16	2003	2004	4/28/03	38
09064000	HOMESTAKE CREEK AT GOLD PARK, CO.	39.41	- 106.43	36	1948	2014	6/5/10	1480

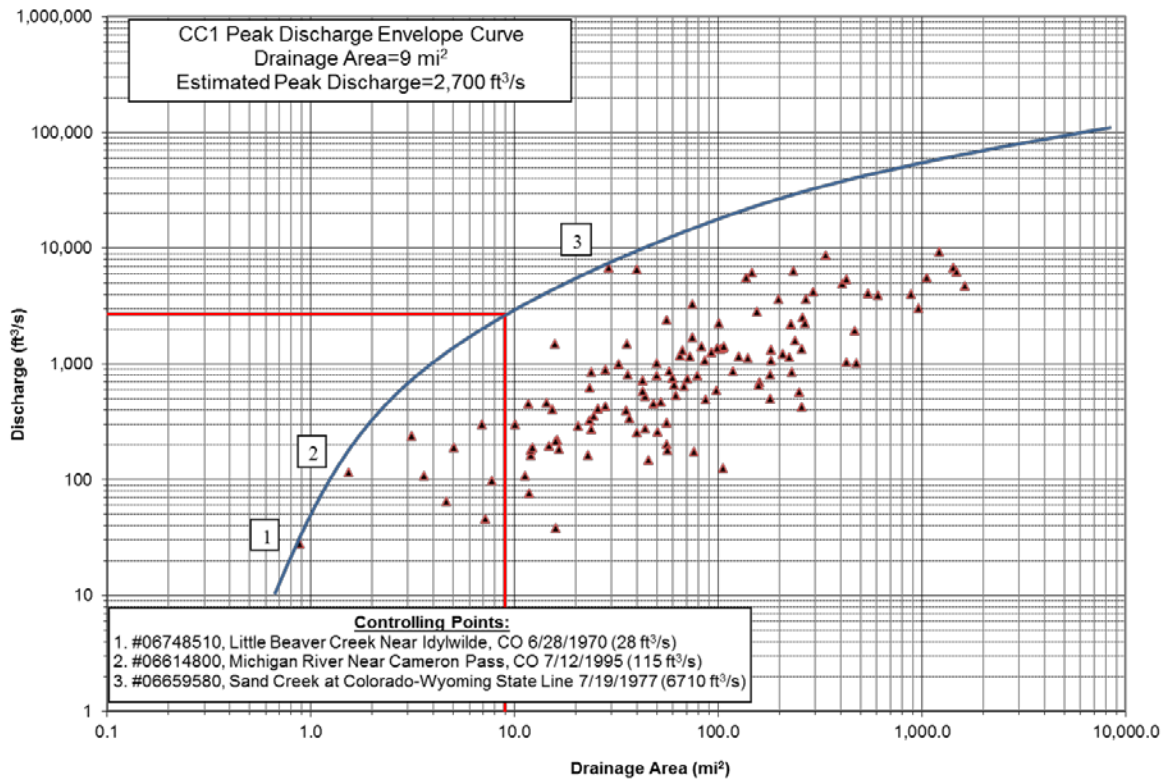
APPENDIX F-REGIONAL ENVELOPE CURVE WITH POINTS OF INTEREST PLOTS







CC1 Point of Interest



APPENDIX G- SOIL STRATIGRAPHY DATA

SOIL STRATIGRAPHIC FIELD DESCRIPTIONS

Site No.: SSV2

Described by: Giorgia deWolfe/Jeanne Godarie

Date: 6/13/2014

Map Unit: Stream Terrace deposit T1

Parent Material: sandy and gravelly alluvium

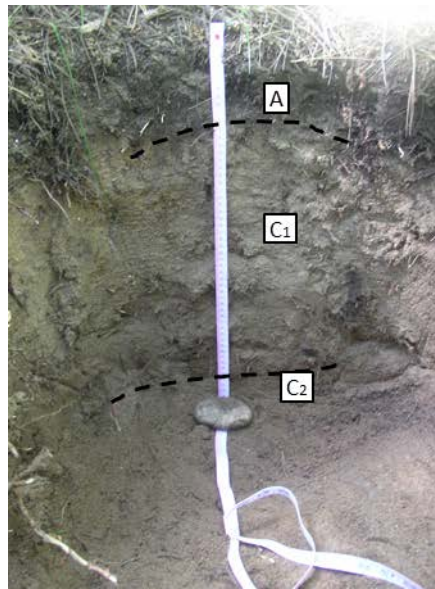
Quadrangle: Raymond, CO (USGS 7.5')

Longitude/Latitude coordinates N40° 10' 5.66" W 105° 22' 51.67"

Elevation: 6806 ft

Location: Margin of floodplain terrace on the left side of the river channel. Site near a pullout along Colorado Hwy 7 near and downstream of the confluence with the Middle Fork of the St. Vrain River.

Horizon	Depth (cm)	Boundaries	Structure	Clay Films	Consistence			Texture	Gravel %	CaCO3 Morphology	Color (moist)	Color (dry)
					Stickiness	Plasticity	Dry					
A	0-13	as	1cgr-sg	none	so	po	so-lo	mSL	0	none	10YR2/1	10YR3/2
C1	13-52	cw	sg	none	so	po	lo	vcSL	10	none	10YR3/4	10YR5/4
C2	52-57	aw to i	sg	none	so	po	lo	vcLS	25	none	10YR3/3	10YR5/3
Large rock at the base cover the bottom of soil pit 57+												10YR6/3.5



SOIL STRATIGRAPHIC FIELD DESCRIPTIONS

Site No.: SSV1 **Described by:** Giorgia deWolfe/Jeanne Godarie **Date:** 9/18/2014
Map Unit: Stream terrace deposit T1 **Parent Material:** fine grain alluvium and gravelly alluvium
Quadrangle: Lyons, CO (USGS 7.5') **Longitude/Latitude coordinates:** N40° 11' 48.0" W 105° 19' 40.8" **Elevation:** 5708
Location: Exposure on the right river bank approximately 5 feet above the river channel. Surface preserved and marginally overtopped by the 2013 flood. Site located approximately 2 mile upstream of the South St Vrain mouth near Lyons Quarry.

Horizon	Depth (cm)	Boundaries	Structure	Clay Films	Consistence			Texture	Gravel %	CaCO3 Morphology	Color (moist)
					Stickiness	Plasticity	Dry				
C	0-35	ai	sg	none	so	po	lo	cS	10 top to 50-75 base	none	10YR4/3
Ab	35-44	aw	1fsbk	none	ss	po	so	mSL	<10	none	10YR3/2
C	44-53	aw	sg	none	so	po	lo	cLS	<10	none	10YR4/3
C2	53-61	aw	sg	none	so	po	lo	cS	50-75	none	10YR4/3
C3	61-74+	-	sg	none	so	po	lo	cS	25	none	10YR4/4



SOIL STRATIGRAPHIC FIELD DESCRIPTIONS

Site No.: MSV1

Described by: Giorgia deWolfe/Jeanne Godarie

Date: 9/18/2014

Map Unit: Stream Terrace deposit T1

Parent Material: fine grained alluvium

Quadrangle: Raymond, CO (USGS 7.5')

Longitude/Latitude coordinates N40°10'18.62" W105°24'45.14"

Elevation: 7276 ft

Location: Margin of floodplain terrace on the right side of the river channel. Site near a pullout along Colorado Hwy 7. The site is located upstream of the confluence with the South St. Vrain River.

Horizon	Depth (cm)	Boundaries	Structure	Clay Films	Consistence			Texture	Gravel %	CaCO3 Morphology	Color (dry)	Color (moist)
					Stickiness	Plasticity	Dry					
A	0-18	as	2mgr	none	so	po	sh	fSL	<10	none	10YR3/2	10YR2/2
B	18-26	cs	1msbk	none	so	po	so	c-mLS	<10	none	10YR4/3	10YR3/3
C	26-36	aw	sg	none	so	po	lo	mS	25	none	10YR4/4	10YR4/4
C2	36-52	aw	m	none	so	po	lo	cS	<10	none	10YR4/4	10YR4/4
Ab	52-59	ai	1msbk	none	-	-	so	c-mLS	0	none	10YR3/3	10YR3/2
Cb	59-66+	-	sg	none	-	-	lo	cS	25	none	10YR5/3-4/3	10YR4/3



SOIL STRATIGRAPHIC FIELD DESCRIPTIONS

Site No.: NSV1

Described by: Giorgia deWolfe/Ralph Klinger

Date: 6/10/2014

Map Unit: Stream terrace deposit T1

Aspect: S

Parent Material: Combination of fine sand (flood deposits) and perhaps distal fine- grained sandy gravelly alluvium and find sandy alluvium

Quadrangle: Raymond, CO (USGS 7.5')

Longitude/Latitude coordinates: N40° 12' 55.04" W 105° 21' 50.25"

Elevation: 6208 ft

Location: Oldest preserved terrace in a protected site (left side of the river channel) downstream of the dam outlet works but upstream of the dam spillway.

Horizon	Depth (cm)	Boundaries	Structure	Clay Films	Consistence			Texture	Gravel %	CaCO3 Morphology	Color (dry)	Color (moist)
					Stickiness	Plasticity	Dry					
O	4-0	as	-	none	-	-	-	-	0	none	10YR3/2	-
A	0-5	aw	1cgr	none	so	po	lo	fLS	0	none	10YR4/2	10YR3/2
Bw1	5-20	cw	1cgr-1fsbk	none	so	po	lo	fLS	0-<10	none	10YR5/3	10YR4/3
Bw2	20-42	cw	1csbk	none	so	po	lo	fSL	0-<10	none	10YR5/3	10YR4/3.5
2Bw	42-55	-	1cgr-1fsbk	none	so	ps	so	mL	50	none	10YR5/3	10YR4/3



SOIL STRATIGRAPHIC FIELD DESCRIPTIONS

Site No.: NSV2

Described by: Giorgia deWolfe/Ralph Klinger

Date: 6/10/2014

Map Unit: Stream terrace deposit T1
grained alluvium from hill slope.

Aspect: S

Parent Material: combination of fine sand (flood deposit) and distal fine

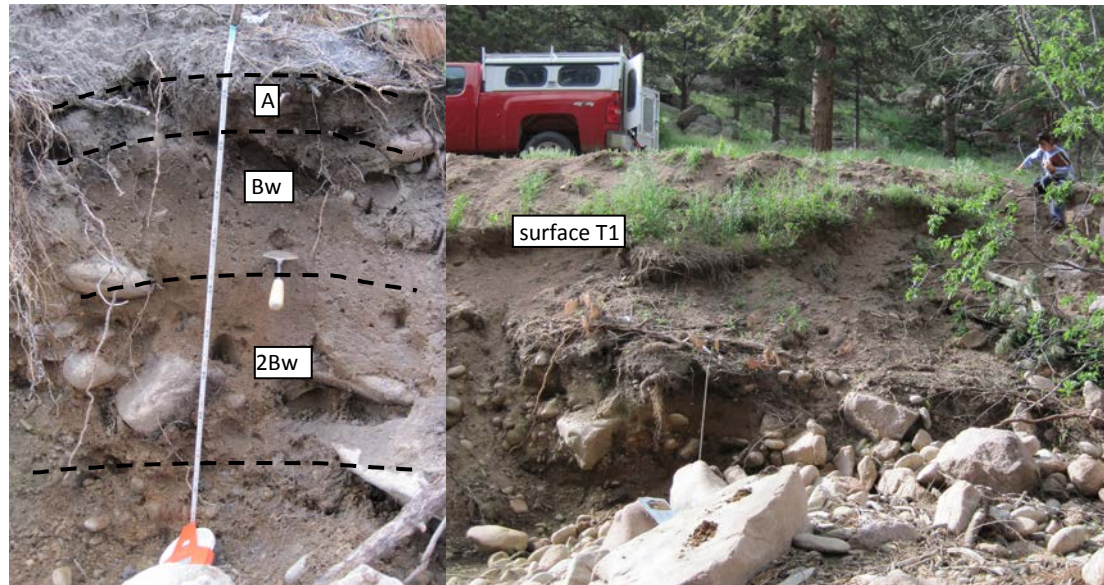
Quadrangle: Raymond, CO (USGS 7.5')

Longitude/Latitude coordinates: N 40° 13' 16.17" W 105° 21' 28.9"

Elevation: 6168 ft

Location: Higher terrace and channel geometry largely unaffected by rebuilding activity since the 2013 flood. High water marks and remnant of a T1 surface are preserved on the left side of the river bank.

Horizon	Depth (cm)	Boundaries	Structure	Clay Films	Consistence			Texture	Gravel %	CaCO3 Morphology	Color (dry)	Color (moist)
					Stickiness	Plasticity	Dry					
A	0-25	cw	2vcgr-2fsbk	none	so	ps	so	fL	0	none	10YR3/2	10YR2/2
Bw	25-55	aw	1fsbk	none	so	p	sh	mL	<10	none	-	10YR4/4
2Bw	55-120+	-	sg-1msbk	none	so	p	sh	vc-g L	50-75	none	-	10YR4/6



SOIL STRATIGRAPHIC FIELD DESCRIPTIONS

Site No.: LHC1

Described by: Giorgia deWolfe/Ralph Klinger

Date: 6/9/2014

Map Unit: Stream terrace deposit T1

Parent Material: medium to coarse grained, quartz-rich granitic sand. 10% >2 mm pebbles,

max diameter 0.5 cm, rounded to subrounded.

Quadrangle: Boulder, CO (USGS 7.5')

Longitude/Latitude coordinates: N 40° 6' 42.65" W 105° 18' 25.05"

Elevation: 5882 ft

Location: Immediately downstream of the confluence between Left Hand Creek and Six miles creek, the site is encompassed in a recreational area. The soil stratigraphy was described on a high surface on the right bank exposure mostly preserved and marginally flooded by the 2013 Front Range flood. Flotsams are preserved on the edge of the right riverbank and sand deposit on the left riverbank.

Horizon	Depth (cm)	Boundaries	Structure	Clay Films	Consistence			Texture	Gravel %	CaCO3 Morphology	Color (dry)	Color (moist)
					Stickiness	Plasticity	Dry					
A	0-20	cw	2cgr	none	ss	po-ps	so	f-m L	10	none	10YR4/2	10YR3/3
AB	20-35	aw	1mbk	none	so	po	so	fSL	<10	none	10YR4/2	10YR3/2
2Bw	35-77	-	1msbk	none	so	po	so	m-c LS	<50	none	10YR4/4	10YR3/4



SOIL STRATIGRAPHIC FIELD DESCRIPTIONS

Site No.: CC1

Described by Georgia deWolfe/Jeanne Godaire

Date: 6/3/2014

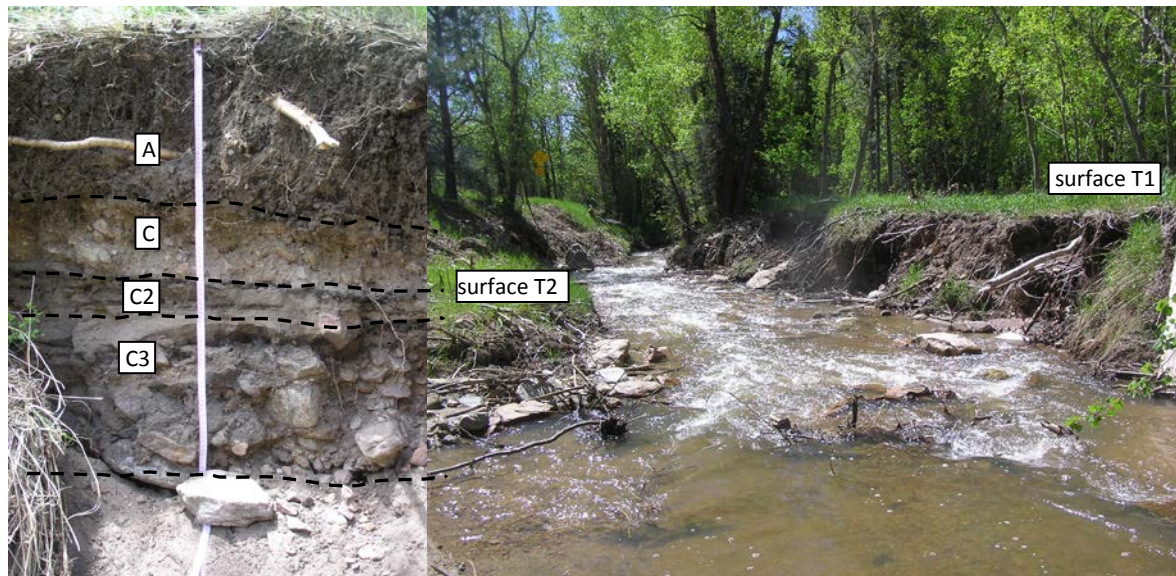
Map Unit: Stream terrace deposit T1

Parent Material: sandy and gravelly alluvium

Quadrangle: Ralston Buttes, CO (USGS 7.5") **Longitude/Latitude coordinates:** N 39° 53' 38.58" W 105° 20' 12.65" **Elevation:** 7557 ft

Location: Soil description of the right bank terrace exposure of Coal Creek just upstream of Chapel of the Hills. Flotsams are observed mostly along the edges on the upstream section of the terrace which was marginally overtopped in 2013. The downstream section of the terrace appears to be fully preserved and not recently overtopped.

Horizon	Depth (cm)	Boundaries	Structure	Clay Films	Consistence			Texture	Gravel %	CaCO3 Morphology	Color (dry)	Color (moist)
					Stickiness	Plasticity	Dry					
A	0-37	aw	2mgr	none	so	po	so	cSL	<10	none	10YR3/2	10YR2/2
C	37-53	as	sg	none	so	po	lo	c-vc S	50	none	7.5YR5/3	7.5YR4/3
C2	53-62	as	sg	none	so	po	lo	mSL	<10	none	7.5YR4/3	7.5YR3/2
C3	62-100	-	1fsbk- 2msbk	none	so	po	so	vcLS	50-75	none	7.5YR4/3	7.5YR3/3



SOIL STRATIGRAPHIC FIELD DESCRIPTIONS

Site No.: 4MC1

Described by: Giorgia deWolfe/Tessa Harden

Date: 6/2/2014

Map Unit: Alluvium terrace deposit T1
colluvium/ alluvium sediments.

Parent Material: combination of overbank fine alluvium and coarse

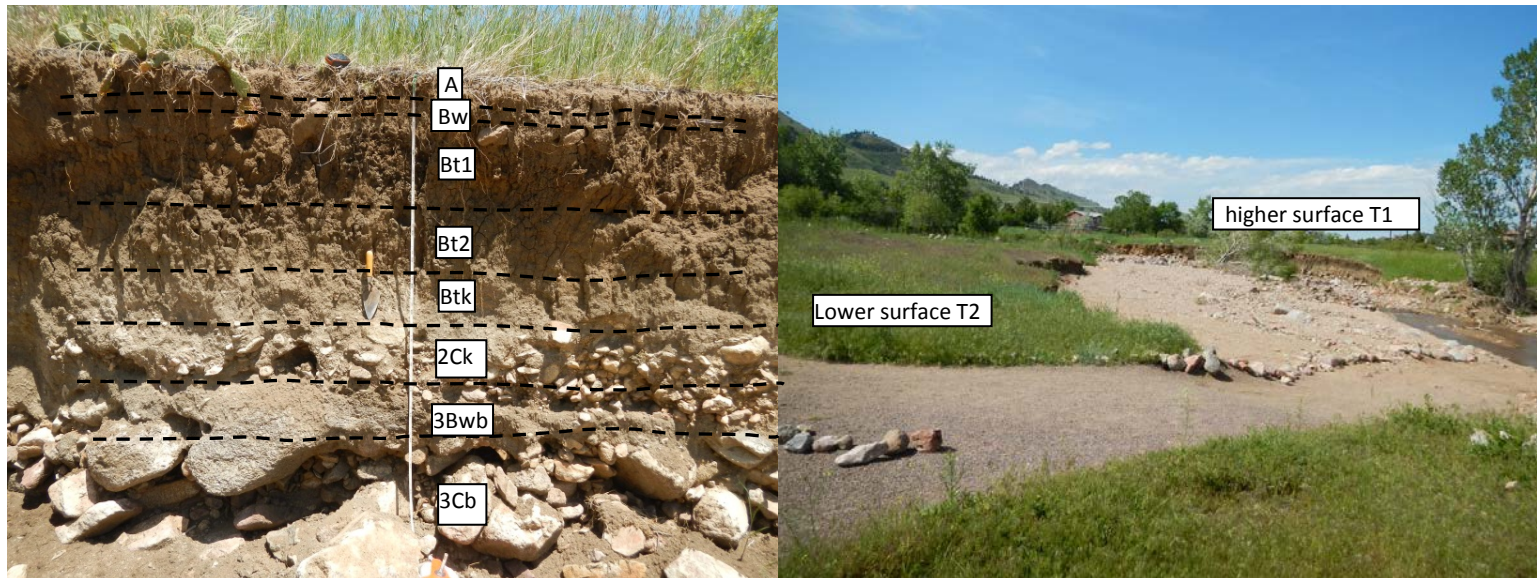
Quadrangle: Boulder, CO (USGS 7.5')

Longitude/Latitude coordinates: N40° 03' 42.8" W 105° 17' 22.3

Elevation: 5673ft

Location: High terrace exposure on the left riverbank of four Miles Creek near the entrance and parking lot of a trail recreational area. The exposure edge was cut off during the 2013 flood on Fourmile Canyon Creek but the terrace at this location appears not overtopped.

Horizon	Depth (cm)	Boundaries	Structure	Clay Films	Consistence			Texture	Gravel %	CaCO3 Morphology	Color (dry)	Color (moist)
					Stickiness	Plasticity	Dry					
A	0-10	gw	1fgr	none	ss	ps	so	fL	<10	none	10YR4/3	10YR3/2
Bw	10-23	cw	1fsbk-1mgr	none	ss	ps	so	fL	<10	none	10YR4/2	10YR3/2
Bt1	23-51	cw	3cabk	none	s	p	so-sh	CL	trace	none	10YR3/2	10YR3/2
Bt2	51-79	as	3cabk	none	s	p	h	CL	trace	none	10YR4/2	10YR3/2
Btk	79-94	as	2fsbk-2msbk	none	s	p	h	SiCL	<10	e-	10YR5/2	10YR4/2
2Ck	94-119	as	gr	none	s	p	sh-h	CL	50-75	e-	10YR5/2	10YR4/2
3Bwb	119-135	as	2fsbk	none	s	p	sh-h	CL	<10	e-	10YR5/1	10YR4/2
3Cb	135-177	-	sg	none	so	po	lo	c-cv S	>75	none	10YR4/3	10YR3/3



SOIL STRATIGRAPHIC FIELD DESCRIPTIONS

Site No.: 4MC2

Described by: Giorgia deWolfe/Tessa Harden

Date: 6/2/2014

Map Unit: Alluvium terrace deposit T1
sediments.

Parent Material: combination of overbank fine alluvium and coarse colluvium/ alluvium

Quadrangle: Boulder, CO (USGS 7.5')

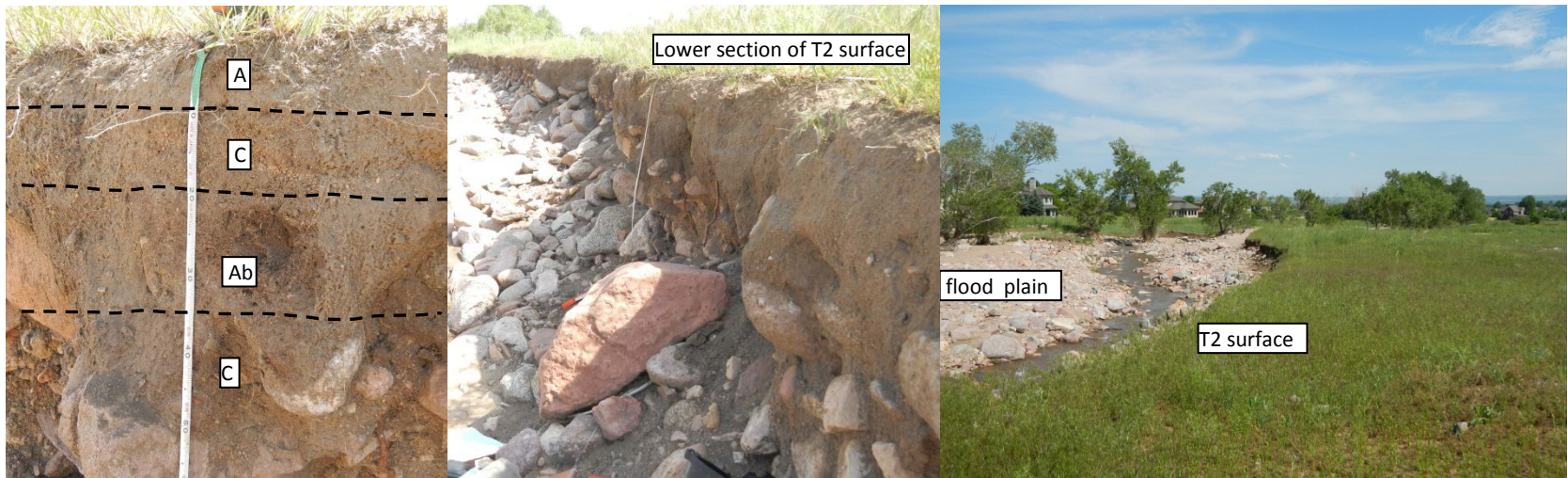
Longitude/Latitude coordinates: N40°3'41.1"; W105°17'22.5"

Elevation: 5672 ft

Location: terrace exposure on a lower section of surface T1 on the right river bank of four Miles Creek, between the active channel and the overflow channel. The exposure edge was created during the 2013 flood on Four Miles creek. Flotsam were observed over this portion of terrace T1 which appeared been overtopped during the 2013 floods at this location.

Horizon	Depth (cm)	Boundaries	Structure	Clay Films	Consistence			Texture	Gravel %	CaCO3 Morphology	Color (dry)*
					Stickiness	Plasticity	Dry				
A	0-10	as	sg-1fsbk	none	so	po	lo	L	<10	none	Dark brown
C	10-20	as	sg	none	so	po	lo	vcS	<10	none	Brown with tan very coarse quartz sand
Ab	20-35	aw	1f gr-sbk	none	so	po	so	L	<10	none	Dark brown
C	35-120+	-	sg	none	so	po	lo	S	>75	none	- (too many large boulder)

*Field Color Book was not used to describe the soil property at this exposure due to the high soil variability in material and size.



SOIL STRATIGRAPHIC FIELD DESCRIPTIONS

Site No.: NBT

Described by: Giorgia deWolfe/Jeanne Godaire

Date: 9/12/2014

Map Unit: Alluvium terrace deposit T2
colluvium/ alluvium sediments.

Parent Material: combination of overbank fine alluvium and coarse

Quadrangle: Glen Haven, CO (USGS 7.5')

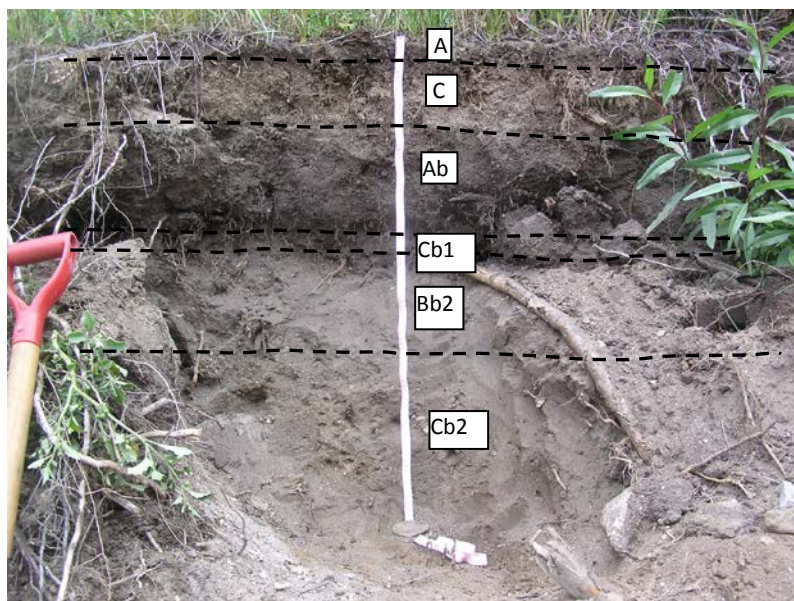
Longitude/Latitude coordinates: N40° 26' 36.02" W 105° 22' 40.83"

Elevation: 5897ft

Location: Terrace exposure on the left river bank of the North Fork of the Big Thompson River just upstream of a small alluvial fan. The exposure edge was cut off during the 2013 flood and the terrace at this location appears overtopped.

Horizon	Depth (cm)	Boundaries	Structure	Clay Films	Consistence			Texture	Gravel %	CaCO3 Morphology	Color (dry)	Color (moist)
					Stickiness	Plasticity	Dry					
A	0-7	aw	sg-1fgr	none	so	po	lo-so	cSL	10	none	10YR3/3	10YR2/2
C	7-20	as	sg-1fsbk	none	so	po	lo-so	c-vcSL	25	none	10YR4/3	10YR3/3
Ab*	20-46	as	2msbk-1mgr	none	so	po	sh	mSL	10-25	none	10YR3/2	10YR2/2
Cb1	46-50	aw	sg	none	so	po	lo	cLS	10-25	e(l)	10YR4/3	10YR3/2.5
Bb2*	50-70	cs	1msbk	none	so	po	so-sh	mSL	10-25	e-	10YR4/2	10YR3/2
Cb2	70-95+	-	sg-1fsbk	none	so	po	lo-so	c-SL	25	e (l)	10YR4/3	10YR3/2.5

*Radiocarbon ages were obtained from this horizon



APPENDIX H- SAMPLE IDENTIFICATION AND RADIOCARBON DATING ANALYSIS

**Examination of Bulk Soil Samples for Charred Botanic Remains and
Identification of Detrital Charcoal from Sites in the
Front Range 2013 Flood Research Study, Colorado**

by

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Technical report 14025 prepared for
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INTRODUCTION

A total of 6 bulk soil samples and 26 detrital charcoal samples were examined as part of the Front Range 2013 Flood Research study in Colorado. These samples were collected from stream deposits at eight testing sites along the North Fork of the Big Thompson, North St. Vrain, Middle St. Vrain, South St. Vrain, Coal Creek Canyon, and Four Mile Creek to identify charcoal or other charred botanic remains for radiocarbon analysis. Botanic remains were identified, and charred remains were separated and placed into labeled microcentrifuge tubes.

METHODS

The six bulk soil samples were floated using a bucket system. Prior to flotation, 200 ml of sediment from each of the two larger samples (SSV2-2 and SSV2-3) was retained for possible microcharcoal and/or humate extraction. The remaining sediment was measured and added to a bucket filled with water. The sample was swirled, and then the floating material (light fraction) was poured through a 150-micron-mesh sieve. This process was repeated with additional water until all floating material was recovered. For the four smaller samples from Four Mile Creek, all sediment that passed through the screen was retained and dried for possible microcharcoal and/or humate extraction. After the heavy fraction remaining in the bottom of the bucket was poured through a 0.5-mm-mesh screen, the floated light and heavy fractions were dried.

After the light fractions were weighed, they were screened using a series of graduated screens (US Standard Sieves with 4-mm, 2-mm, 1-mm, 0.5-mm, and 0.25-mm openings). The contents of each screen then were examined. Charcoal fragments were examined under a Bausch and Lomb Stereozoom microscope at a magnification of 70x and a Nikon Optiphot 66 microscope at magnifications of 100-600x. Whenever possible, both counts and weights were recorded. Weights were taken using a top-loading Tree[®] high resolution electronic balance with an accuracy level to 0.001 g.

Organic material remaining in the 4-mm, 2-mm, 1-mm, 0.5-mm, and 0.25-mm screens was examined under a Bausch and Lomb Stereozoom microscope at magnifications of 10-70x. The light fraction material measuring smaller than 0.25 mm in size was not examined. Macrofloral remains were recorded as charred and/or uncharred, whole and/or fragments using counts, weights, and/or frequencies.

A total of 24 detrital charcoal samples were examined without any additional processing. The charcoal fragments were examined under a Bausch and Lomb Stereozoom microscope at a magnification of 70x and a Nikon Optiphot 66 microscope at magnifications of 100-600x. Both counts and weights were recorded. Two of the detrital charcoal samples

contained larger amounts of sediment (NSV1-1 and NSV1-2); therefore, they were water-screened through a 150-micron-mesh sieve and dried prior to identification.

Macrofloral remains and charcoal fragments were identified using standard identification manuals (Carlquist 1988; Core et al. 1976; Davis 1993; Delorit 1970; Hoadley 1990; Martin and Barkley 2000; Panshin and deZeeuw 1980), internet web sites (InsideWood 2004) and a modern comparative collection. Clean laboratory methods were used so that charcoal and/or other charred botanic remains could be submitted for AMS radiocarbon analysis. Samples were protected from contact with modern carbon, and all instruments were washed prior to analysis and between samples.

RESULTS

Samples were derived from various stream deposits at eight study sites. Local vegetation in these areas varies with elevation and ranges from grasses (Poaceae) and brushes at the lower elevations (Four Mile Creek and North Fork of the Big Thompson) to pines (*Pinus* spp.), aspen (*Populus tremuloides*), juniper (*Juniperus* spp.), sagebrush (*Artemisia* spp.), other unidentified shrubs, and grasses at higher elevations (Coal Creek Canyon and St. Vrain Basin).

Middle St. Vrain

A total of six detrital charcoal samples were collected from the Middle St. Vrain (Table 1). Sample MSV1-1 was taken from a depth of 43 cm and yielded three fragments of *Pinus* charcoal weighing 0.011 g, reflecting local pines that burned (Tables 2 and 3). The largest charcoal fragment weighed 0.009 g and can be submitted for AMS radiocarbon analysis. The average life spans for pine trees are variable, depending on species, from 100-500+ years.

Table 1. Provenience Data for Samples from Sites in the Front Range 2013 Flood Research.

Site Location	Sample Number	Depth (cm)	Description	Analysis
MSV1 Middle St. Vrain	MSV1-1	43	Detrital charcoal	Charcoal ID
	MSV1-2	37	Detrital charcoal	Charcoal ID
	MSV1-3	55	Detrital charcoal	Charcoal ID
	MSV1-4	53-54	Detrital charcoal	Charcoal ID
	MSV1-5	27	Detrital charcoal	Charcoal ID
	MSV1-6	36	Detrital charcoal	Charcoal ID
NBT North Fork of the Big Thompson	NBT-1	51	Detrital charcoal	Charcoal ID
	NBT-2	62	Detrital charcoal	Charcoal ID
	NBT-3	63	Detrital charcoal	Charcoal ID
	NBT-4	34	Detrital charcoal	Charcoal ID
	NBT-5	28	Detrital charcoal	Charcoal ID

Site Location	Sample Number	Depth (cm)	Description	Analysis
NBT	NBT-6	33	Detrital charcoal	Charcoal ID
North Fork of the Big Thompson	NBT-7	72	Detrital charcoal	Charcoal ID
SSV1 – South St. Vrain (mouth)	SSV1-1	51	Detrital charcoal	Charcoal ID
SSV2 – South St. Vrain (d/s of confluence with Middle St. Vrain)	SSV2-1	32	Detrital charcoal	Charcoal ID
	SSV2-2	40-50	Bulk sediment	Float/Charcoal ID
	SSV2-3	20-30	Bulk sediment	Float/Charcoal ID
NSV1 – North St. Vrain (near outlet work)	NSV1-1	50	Detrital charcoal	Charcoal ID
	NSV1-2	55	Detrital charcoal	Charcoal ID
	NSV1-3	16	Detrital charcoal	Charcoal ID
NSV2 – North St. Vrain (downstream of spillway confluence)	NSV2-1	50	Detrital charcoal	Charcoal ID
	NSV2-2	10-20	Detrital charcoal	Charcoal ID
CC1	CC1-1	52	Detrital charcoal	Charcoal ID
Coal Creek Canyon (near Chapel in the Hills)	CC1-2	73	Detrital charcoal	Charcoal ID
	CC1-3	66	Detrital charcoal	Charcoal ID
	CC1-4	53-54	Detrital charcoal	Charcoal ID
	CC1-5	51	Detrital charcoal	Charcoal ID
	CC1-6	50	Detrital charcoal	Charcoal ID
4MC	4MC1-1	30-45	Bulk sediment	Float/Charcoal ID
Four Mile Creek (near the mouth in Boulder City)	4MC1-2	52-71	Bulk sediment	Float/Charcoal ID
	4MC2-1	20-30	Bulk sediment	Float/Charcoal ID
	4MC2-2	12-19	Bulk sediment	Float/Charcoal ID

Table 2. Macrofloral Remains in Samples from Sites in the Front Range 2013 Flood Research Study.

Sample Number	Identification	Part	<u>Charred</u>		<u>Uncharred</u>		Weights/ Comments
			W	F	W	F	
MSV1-1							
43 cm	<i>Pinus</i> (LSP = 0.009 g)	Charcoal		3			0.011 g
MSV1-2							
37 cm	Salicaceae	Charcoal		1			0.010 g
MSV1-3							
55 cm	Unidentifiable – small	Charcoal		18			0.002 g
MSV1-4	<i>Pseudotsuga menziesii</i>	Needle		1			<0.001 g
53-54 cm	Periderm			23			0.008 g
MSV1-5							
27 cm	<i>Pinus</i> - rounded edges	Charcoal		1			0.022 g
MSV1-6	Conifer	Charcoal		15			0.004 g
36 cm				2			<0.001 g

Sample Number	Identification	Part	Charred		Uncharred		Weights/ Comments
			W	F	W	F	
NBT-1							
51 cm	<i>Pinus</i> (LSP = 0.012 g)	Charcoal		27			0.019 g
NBT-2							
62 cm	<i>Pinus</i>	Charcoal		9			0.008 g
NBT-3							
63 cm	<i>Pinus</i>	Charcoal		1			0.024 g
NBT-4							
34 cm	Periderm			1			0.002 g
NBT-5							
28 cm	<i>Pinus</i>	Charcoal		1			0.017 g
NBT-6							
33 cm	<i>Pinus</i>	Charcoal		1			0.019 g
NBT-7							
72 cm	<i>Pinus</i>	Charcoal		31			0.001 g
SSV1-1	Conifer	Charcoal		6			<0.001 g
51 cm	<i>Pseudotsuga menziesii</i>	Charcoal		1			<0.001 g
	Unidentified hardwood	Charcoal		12			<0.001 g
SSV2-1	<u>Floral Remains:</u>						
32 cm	Periderm			2			0.018 g
	Rootlets					X	
	<u>Charcoal:</u>						
	<i>Alnus</i> twig – vitrified	Charcoal		2			0.236 g
	<i>Pinus</i> - vitrified	Charcoal		6			0.286 g
	<i>Pinus</i>	Charcoal		1pc			0.008 g
	<i>Pseudotsuga menziesii</i>	Charcoal		2			0.012 g
	Unidentified	Charcoal		X			
	<u>Non-Floral Remains:</u>						
	Muscovite					X	
	Sand					X	
SSV2-2	Volume Floated						700 mL
40-50 cm	Light Fraction Weight						3.338 g
	<u>Floral Remains:</u>						
	Periderm			1			0.002 g
	<i>Pinus</i>	Needle				1	<0.001 g
	<i>Pseudotsuga menziesii</i>	Needle				1	<0.001 g
	<i>Rubus</i>	Seed			1		
	Rootlets					X	Few
	Sclerotia				X		Moderate
	<u>Charcoal:</u>						
	<i>Pinus</i>	Charcoal		23			0.065 g
	<i>Pinus</i> – vitrified	Charcoal		5			0.018 g
	<i>Pseudotsuga menziesii</i>	Charcoal		2			0.007 g
	Salicaceae	Charcoal		5			0.008 g

Sample Number	Identification	Part	Charred		Uncharred		Weights/ Comments
			W	F	W	F	
SSV2-2 40-50 cm	<u>Non-Floral Remains:</u> Insect Mica Muscovite Rock/Gravel Sand	Chitin				4 X X X X	
SSV2-3 20-30 cm	Volume Floated Light Fraction Weight <u>Floral Remains:</u> Parenchymous tissue <i>Chenopodium</i> <i>Pinus</i> <i>Pseudotsuga menziesii</i> Rootlets Sclerotia <u>Charcoal:</u> <i>Pinus</i> <u>Non-Floral Remains:</u> Insect Mica Muscovite Rock/Gravel Sand	Seed Needle Needle Charcoal Puparium	1 18			1 2 1 X 1 X X X X	450 mL 2.311 g <0.001 g 0.002 g 0.003 g Few Few 0.044 g
NSV1-1 50 cm	<i>Pinus</i> (LSP = 0.172 g)	Charcoal		10			0.546 g
NSV1-2 55 cm	Conifer <i>Pinus</i>	Charcoal		6 3			0.092 g 0.109 g
NSV1-3 16 cm	<i>Pinus</i> <i>Pinus</i> - slightly vitrified	Charcoal		4ic 5			0.620 g 0.111 g
NSV2-1 50 cm	<i>Pinus</i>	Charcoal		2			0.092 g
NSV2-2 10-20 cm	<i>Pinus</i> (LSP = 0.092 g)	Charcoal		3			0.182 g
CC1-1 52 cm	Salicaceae twig	Charcoal		1			0.015 g
CC1-2 73 cm	<i>Pinus</i>	Charcoal		1			0.061 g
CC1-3 66 cm	<i>Pinus</i> (LSP = 0.363 g)	Charcoal		6			0.855 g
CC1-4 53-54 cm	Salicaceae twig	Charcoal		1			0.062 g
CC1-5 51 cm	<i>Pinus</i>	Charcoal		1			0.056 g
CC1-6 50 cm	<i>Pinus</i> – rounded edges Salicaceae	Charcoal		1 1			0.008 g 0.014 g

Sample Number	Identification	Part	<u>Charred</u>		<u>Uncharred</u>		Weights/ Comments
			W	F	W	F	
4MC1-1	Volume Floated						400 mL
30-45 cm	Light Fraction Weight						2.643 g
	<u>Floral Remains:</u>						
	Vitrified tissue			2			<0.001 g
	Roots					X	Few
	Rootlets					X	
	<u>Charcoal:</u>						
	<i>Pinus</i>	Charcoal		7			0.006 g
	<u>Non-Floral Remains:</u>						
	Insect	Chitin				4	
	Mica					X	
	Muscovite					X	
	Rock/Gravel					X	
	Sand					X	
4MC1-2	Volume Floated						400 mL
52-71 cm	Light Fraction Weight						4.327 g
	<u>Floral Remains:</u>						
	Periderm			12			0.004 g
	Rootlets					X	Few
	<u>Charcoal:</u>						
	Conifer	Charcoal		6			0.002 g
	<u>Non-Floral Remains:</u>						
	Mica					X	
	Muscovite					X	
	Rock/Gravel					X	
	Sand					X	
4MC2-1	Volume Floated						700 mL
20-30 cm	Light Fraction Weight						3.338 g
	<u>Floral Remains:</u>						
	Periderm			4			<0.001 g
	Parenchymous tissue			4			0.002 g
	Unidentified	Seed		3			<0.001 g
	Vitrified tissue			9			0.002 g
	<i>Opuntia</i>	Seed				2	
	Rootlets					X	Few
	Sclerotia				X		Moderate
	<u>Charcoal:</u>						
	<i>Pinus</i> (LSP = 0.016 g)	Charcoal		24			0.045 g
	<u>Non-Floral Remains:</u>						
	Mica					X	
	Muscovite					X	
	Rock/Gravel					X	
	Sand					X	

Sample Number	Identification	Part	Charred		Uncharred		Weights/ Comments
			W	F	W	F	
4MC2-2	Volume Floated						100 mL
12-19 cm	Light Fraction Weight						3.338 g
	Volume Water-Screened						150 mL
	Water-Screened Sample Weight						172.047 g
	<u>Floral Remains:</u>						
	Parenchymous tissue			1			0.001 g
	<i>Picea</i>	Needle		1			<0.001 g
	<i>Pinus</i>	Needle		1			<0.001 g
	<i>Carex</i>	Seed			1		
	<i>Chenopodium</i>	Seed			1		
	Rootlets					X	Few
	<u>Charcoal:</u>						
	Conifer	Charcoal		28			0.005 g
	<i>Pseudotsuga menziesii</i>	Charcoal		1			0.001 g
	Salicaceae	Charcoal		2			<0.001 g
	<i>Pseudotsuga menziesii</i>	Wood				3	0.022 g
	<u>Non-Floral Remains:</u>						
	Insect	Chitin				8	
	Insect	Puparium				1	
	Mica					X	
	Muscovite					X	
	Rock/Gravel					X	
	Sand					X	

W = Whole

F = Fragment

g = grams

X = Presence noted in sample

ic = incompletely charred

pc = partially charred

LSP = Largest Single Piece

Table 3. Index of Macrofloral Remains in Samples from Sites in the Front Range 2013 Flood Research Study.

Scientific Name	Common Name
FLORAL REMAINS:	
<i>Carex</i>	Sedge
<i>Chenopodium</i>	Goosefoot
<i>Opuntia</i>	Prickly pear cactus, Cholla
Periderm	Technical term for bark; Consists of the cork (phellum) which is produced by the cork cambium, as well as any epidermis, cortex, and primary or secondary phloem exterior to the cork cambium
<i>Picea</i>	Spruce

Scientific Name	Common Name
<i>Pinus</i>	Pine
<i>Pseudotsuga menziesii</i>	Douglas-fir
<i>Rubus</i>	Raspberry, Blackberry, etc.
Parenchymous tissue	Relatively undifferentiated tissue composed of many similar cells with thin primary walls. occurs in different plant organs in varying amounts, especially large fleshy organs such as roots and stems, but also fruits, seeds, cones, periderm (bark), leaves, needles, etc.
Vitrified tissue	Charred material with a shiny, glassy appearance due to fusion by heat
Sclerotia	Resting structures of mycorrhizae fungi
CHARCOAL/WOOD:	
<i>Alnus</i>	Alder
Conifer	Cone-bearing, gymnospermous trees and shrubs, mostly evergreens, including the pine, spruce, fir, juniper, cedar, yew, hemlock, redwood, and cypress
<i>Pinus</i>	Pine
<i>Pseudotsuga menziesii</i>	Douglas-fir
Salicaceae	Willow family
Unidentified hardwood	Wood from a broad-leaved flowering tree or shrub
Unidentifiable - small	Charcoal fragments too small for further identification
NON-FLORAL REMAINS:	
Insect puparium	A rigid outer shell made from tough material that includes chitin (a natural polymer found in insect exoskeleton and crab shells) and hardens from a larva's skin to protect the pupa as it develops into an adult insect
Muscovite	The most common mica, found in granites, pegmatites, gneisses and schists, with a layered structure of aluminum silicate sheets weakly bonded together by layers of potassium ions

Sample MSV1-2 was recovered at a depth of 37 cm. The sample yielded a single piece of Salicaceae charcoal weighing 0.010 g that can be submitted for AMS radiocarbon analysis. This charcoal reflects a woody member of the willow family such as aspen, cottonwood, or willow. Members of the Salicaceae have shorter average life spans of 30-200 years.

Sample MSV1-3, collected at a depth of 55 cm, contained several fragments of charcoal too small for identification. The combined weight of these fragments is 0.002 g, which can be enough for AMS radiocarbon analysis if little mass is lost during chemical pre-treatment.

One charred *Pseudotsuga menziesii* needle fragment weighing less than 0.001 g was present in sample MSV1-4, taken from a depth of 53-54 cm. This needle fragment reflects Douglas-fir trees that burned. Several fragments of charred periderm (bark) weighing 0.008 g were also present and can be sent for AMS radiocarbon analysis.

Sample MSV1-5 was removed from a depth of 27 cm. A single piece of *Pinus* charcoal weighing 0.022 g and exhibiting rounded edges was noted in this sample. The rounded edges reflect transport of the charcoal from upstream.

Sample MSV1-6 was collected at a depth of 36 cm and yielded several fragments of conifer charcoal too small for further identification. These combined charcoal fragments weighed a total of 0.004 g. Two small pieces of charred periderm weighed less than 0.001 g.

North Fork of the Big Thompson

Seven detrital charcoal samples were recovered from deposits along the North Fork of the Big Thompson. One piece of charred periderm weighing 0.002 g was present in sample NBT-4, taken at a depth of 34 cm. The remaining six samples contained varying fragments of *Pinus* charcoal that are present in sufficient quantities for AMS radiocarbon analysis. One exception might be sample NBT-7, where the fragments of *Pinus* charcoal were very small (31 total fragments weigh 0.001 g). A starting weight of 0.001 g might not be sufficient for AMS radiocarbon analysis if too much mass is lost during chemical pre-treatment. This area appears to have had pine trees that burned.

South St. Vrain

Two detrital charcoal samples and two bulk soil samples represent two study sites along the South St. Vrain. Charcoal sample SSV1-1 was taken at the mouth of the South St. Vrain from a depth of 51 cm. This sample contained six fragments of conifer charcoal weighing less than 0.001 g, a piece of *Pseudotsuga menziesii* charcoal weighing less than 0.001 g, and twelve fragments of hardwood charcoal too small for identification and weighing less than 0.001 g. Although each charcoal type alone does not have enough weight for AMS radiocarbon analysis, the combined charcoal might yield an adequate weight, although the small starting weight might not be sufficient if too much mass is lost during chemical pre-treatment.

Charcoal sample SSV2-1 and two bulk soil samples were collected from downstream of the confluence with the Middle St. Vrain. Sample SSV2-1, recovered at a depth of 32 cm, yielded several charcoal types. Two fragments of vitrified *Alnus* twig charcoal weighed 0.236 g. Vitrified charcoal has a shiny, glassy appearance that can range from still recognizable in structure "to a dense mass, completely 'molten' and non-determinable" (Marguerie and Hunot 2007; McParland et al. 2010:2679). Recent experiments by McParland et al. (2010) have demonstrated that it is currently not clear exactly what conditions produce vitrified charcoal. It

likely is a combination of factors such as burning at high temperature and/or burning green wood. The average life spans for alders are variable, depending on species, from 40-150 years. Other charred remains include six pieces of vitrified *Pinus* charcoal weighing 0.286 g, a partially charred *Pinus* wood fragment weighing 0.008 g, two pieces of *Pseudotsuga menziesii* charcoal weighing 0.012 g, and two charred periderm fragments weighing 0.018 g. The sample also contained smaller fragments of unidentified charcoal, rootlets from modern plants, and sand.

Bulk soil sample SSV2-2 was taken from a depth of 40-50 cm. This sample yielded a charred periderm fragment weighing 0.002 g, several fragments of *Pinus* charcoal weighing 0.065 g, five pieces of vitrified *Pinus* charcoal weighing 0.018 g, two fragments of *Pseudotsuga menziesii* charcoal weighing 0.007 g, and five Salicaceae charcoal fragments weighing 0.008 g. All of these charred remains are present in sufficient quantities for AMS radiocarbon analysis. Uncharred *Pinus* and *Pseudotsuga menziesii* needle fragments, an uncharred *Rubus* (raspberry/blackberry) seed, and a few rootlets represent modern plants. The sample also contained a few insect chitin fragments and a moderate amount of sclerotia. Sclerotia are round, black, smooth, and range in size from 0.5 to 4+ mm in diameter (Trappe 1969). They are the resting structures of the reproductive organs of fungi such as *Cenococcum*, a mycorrhizal fungus, and were originally identified by Dr. Kristiina Vogt, a professor of Ecology in the school of Forestry and Environmental Studies at Yale University (McWeeney 1989:228). These fungi produce a symbiotic relationship between themselves and the roots of vascular plants, resulting in increased nutrient uptake, expansion of water absorption capabilities, and protection against pathogenic fungi (Harley and Smith 1983). Sclerotia can survive at great depths in the soil and in a variety of soil types, from poor to rich, dry woods to bogs, and often are found in areas of deep surface organic accumulation (Mikola 1948:70). *Cenococcum* fungi and their associated sclerotia are found with conifers such as fir (*Abies* spp.), spruce (*Picea* spp.), pine (*Pinus* spp.), and Douglas-fir (*Pseudotsuga menziesii*), as well as deciduous trees including alder (*Alnus* spp.), birch (*Betula* spp.), hazelnut (*Corylus* spp.), cottonwood/aspen (*Populus* spp.), oak (*Quercus* spp.), willow (*Salix* spp.), and mountain ash (*Sorbus* spp.) (Trappe 1962). It is one of the most common and globally abundant genera of ectomycorrhizal fungi, often the dominant mycorrhizal fungus on the roots of trees in arctic, temperate, and subtropical forests (The Regents of the University of California 1997-2014). Experimentation by Trappe (1969) has shown that dead sclerotia will float, resulting in their recovery in archaeobotanic flotation samples.

Several fragments of *Pinus* charcoal weighing 0.044 g were present in bulk soil sample SSV2-3 from a depth of 20-30 cm. This charcoal is sufficient for AMS radiocarbon analysis. One piece of charred parenchymous tissue weighed less than 0.001 g. Parenchyma cells exhibit a thin primary wall and no secondary wall, as well as great diversity in size, shape, metabolism, and functional roles. Parenchyma occurs in many different plant tissues in varying amounts, especially large fleshy organs such as roots and stems, but also in fruits, seeds, cones, periderm (bark), leaves, needles, etc. (Hather 2000:1; Mauseth 1988:43-51). In addition, the sample contained an uncharred *Chenopodium* (goosefoot) seed fragment, small uncharred *Pinus* and *Pseudotsuga menziesii* needle fragments, a few uncharred rootlets, a few sclerotia, and an insect puparium fragment.

North St. Vrain

Detrital charcoal samples were taken from near outlet work (NSV1) and from downstream of the spillway confluence (NSV2) along the North St. Vrain. Larger fragments of *Pinus* charcoal weighing 0.546 g were present in sample NSV1-1 from a depth of 50 cm. The largest single piece weighed 0.172 g. *Pinus* charcoal was also present in sample NSV1-3 from a depth of 16 cm. Five fragments of *Pinus* charcoal were slightly vitrified (0.111 g), while four pieces of charcoal were incompletely charred (0.620 g).

Sample NSV1-2 was recovered from a depth of 55 cm. This sample contained three pieces of *Pinus* charcoal weighing 0.109 g and six fragments of conifer charcoal weighing 0.092 g.

Sample NSV2-1 (50 cm) contained two fragments of *Pinus* charcoal weighing 0.092 g, and sample NSV2-2 (10-20 cm) yielded three pieces of *Pinus* charcoal weighing 0.182 g. The North St. Vrain study sites appear to support an area of pine trees that have burned, resulting in sufficient charcoal for AMS radiocarbon analysis.

Coal Creek Canyon

A total of six detrital charcoal samples were collected from along Coal Creek Canyon near Chapel in the Hills. One piece of Salicaceae twig charcoal weighing 0.015 g was present in sample CC1-1 from a depth of 52 cm. A charred Salicaceae twig fragment weighing 0.062 g was also present in sample CC1-4 from a depth of 53-54 cm. These charcoal fragments are present in sufficient quantities for AMS radiocarbon analysis. Aspen, cottonwood, and willow can all be found in Coal Creek Canyon.

Sample CC1-6 was recovered from a depth of 50 cm. This sample contained one piece of Salicaceae charcoal weighing 0.014 g that can be submitted for AMS radiocarbon analysis. One piece of *Pinus* charcoal weighing 0.008 g exhibited rounded edges, reflecting transport.

Pieces of *Pinus* charcoal were also present in sample CC1-2 from a depth of 73 cm (0.061 g), sample CC1-3 from a depth of 66 cm (0.855 g), and CC1-5 from a depth of 51 cm (0.056 g). These *Pinus* charcoal fragments note pine trees that burned, and all are sufficient for AMS radiocarbon analysis.

Four Mile Creek

Four bulk soil samples were taken from near the mouth of Four Mile Creek in Boulder. Sample 4MC1-1 was collected from a depth of 30-45 cm. This sample yielded seven pieces of *Pinus* charcoal weighing 0.006 g that can be submitted for AMS radiocarbon analysis. Two small fragments of charred, vitrified tissue weighed less than 0.001 g and might represent charcoal or

other charred plant tissue that is too vitrified for identification. The sample yielded a few uncharred roots and rootlets, as well as a few insect chitin fragments.

Several small, charred periderm fragments weighing 0.004 g were present in sample 4MC1-2 from a depth of 52-71 cm. Six pieces of conifer charcoal weighing 0.002 g were too small for further identification. The charred periderm and the conifer charcoal are present in sufficient quantities for AMS radiocarbon analysis.

Sample 4MC2-1 was collected from a depth of 20-30 cm. Several fragments of *Pinus* charcoal weighing 0.045 g reflect local pine trees that burned. The sample also contained four pieces of charred parenchymous tissue weighing 0.002 g, four charred periderm fragments weighing less than 0.001 g, three charred unidentified seed fragments weighing less than 0.001 g, and small pieces of charred, vitrified tissue weighing 0.002 g. Two uncharred *Opuntia* seed fragments represent modern prickly pear cactus. A few uncharred rootlets and sclerotia were also noted.

Several charred remains were noted in sample 4MC2-2, reflecting local fires in the area. Several fragments of conifer charcoal weighing 0.005 g were too small for further identification. One piece of *Pseudotsuga menziesii* charcoal weighing 0.001 g reflects Douglas-fir that burned, while two small pieces of Salicaceae charcoal weighing less than 0.001 g represent a member of the willow family. Uncharred *Pseudotsuga menziesii* wood fragments (0.022 g) were also recovered. In addition, the sample contained a charred parenchymous tissue fragment weighing 0.001 g, a charred *Picea* (spruce) needle fragment weighing less than 0.001 g, and a charred *Pinus* needle weighing less than 0.001 g. An uncharred *Carex* (sedge) seed, an uncharred *Chenopodium* seed, and a few rootlets represent modern plants. A few insect chitin fragments and an insect puparium fragment note limited insect activity in this area.

SUMMARY AND CONCLUSIONS

Examination of detrital charcoal and bulk soil samples from stream deposits at eight study sites for the Colorado Front Range 2013 Flood Research study resulted in recovery of charcoal and other charred botanic remains in sufficient quantities for radiocarbon analysis. Charcoal types recovered from these areas reflect members of the willow family, alder, pine, Douglas fir, and possibly other types of conifers and hardwoods. Pine was the most abundant charcoal type, noted in 21 samples, while a charred pine needle fragment was also recovered in sample 4MC2-2. Douglas-fir charcoal fragments were present in three samples from along the South St. Vrain (SSV1-1, SSV2-1, and SSV2-2) and also in sample 4MC2-2. A charred Douglas-fir needle fragment was noted in sample MSV1-4 from along the Middle St. Vrain. Although no spruce charcoal was identified in these samples, a charred spruce needle fragment was found in sample 4MC2-2. Conifer charcoal not identified to genus occurred in single samples from along the Middle St. Vrain (MSV1-6), South St. Vrain (SSV1-1), and North St. Vrain (NSV1-2), as well as in two samples from along Four Mile Creek (4MC1-2 and 4MC2-2). Salicaceae charcoal

fragments from aspen, cottonwood, and/or willow were noted in three samples from along Coal Creek Canyon (CC1-1, CC1-4, and CC1-6) and in single samples from along the Middle St. Vrain (MSV1-2), South St. Vrain (SSV2-3), and Four Mile Creek (4MC2-2). Sample SSV2-1 from along the South St. Vrain yielded the only alder charcoal for this project. Charred periderm (bark) can also be submitted for radiocarbon analysis. Charred periderm fragments were noted in samples from along the Middle St. Vrain (MSV1-4 and MSV1-6), the North Fork of the Big Thompson (NBT-4), the South St. Vrain (SSV2-1 and SSV2-3), and Four Mile Creek (4MC1-2).

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January 7, 2015

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U.S. Bureau of Reclamation
Seismotectonic and Geophysics division
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United States

RE: Radiocarbon Dating Results For Samples 4MC1-1 Pinus, 4MC2-1 Pinus, CC1-3 Pinus, MSV1-2 Salicaceae, MSV1-4 Bark, NBT-3 Pinus, NBT-6 Pinus, NSV1-1 Pinus, NSV2-1 Pinus, SSV2-1 Alnus

Dear Dr. deWolfe:

Enclosed are the radiocarbon dating results for ten samples recently sent to us. As usual, the method of analysis is listed on the report with the results and calibration data is provided where applicable. The Conventional Radiocarbon Ages have all been corrected for total fractionation effects and where applicable, calibration was performed using 2013 calibration databases (cited on the graph pages).

The web directory containing the table of results and PDF download also contains pictures, a cvs spreadsheet download option and a quality assurance report containing expected vs. measured values for 3-5 working standards analyzed simultaneously with your samples.

Reported results are accredited to ISO/IEC 17025:2005 Testing Accreditation PJLA #59423 standards and all chemistry was performed here in our laboratories and counted in our own accelerators here in Miami. Since Beta is not a teaching laboratory, only graduates trained to strict protocols of the ISO/IEC 17025:2005 Testing Accreditation PJLA #59423 program participated in the analyses.

As always Conventional Radiocarbon Ages and sigmas are rounded to the nearest 10 years per the conventions of the 1977 International Radiocarbon Conference. When counting statistics produce sigmas lower than +/- 30 years, a conservative +/- 30 BP is cited for the result.

The cost of the analysis was charged to the MASTERCARD card provided. Thank you. As always, if you have any questions or would like to discuss the results, don't hesitate to contact me.

Sincerely,


Digital signature on file



REPORT OF RADIOCARBON DATING ANALYSES

Dr. Giorgia deWolfe

Report Date: 1/7/2015

U.S. Bureau of Reclamation

Material Received: 12/15/2014

Sample Data	Measured Radiocarbon Age	13C/12C Ratio	Conventional Radiocarbon Age(*)
Beta - 399441 SAMPLE : 4MC1-1 Pinus ANALYSIS : AMS-Standard delivery MATERIAL/PRETREATMENT : (charred material): acid/alkali/acid 2 SIGMA CALIBRATION : Cal BC 7955 to 7610 (Cal BP 9905 to 9560)	8710 +/- 40 BP	-22.6 o/oo	8750 +/- 40 BP
Beta - 399442 SAMPLE : 4MC2-1 Pinus ANALYSIS : AMS-Standard delivery MATERIAL/PRETREATMENT : (charred material): acid/alkali/acid 2 SIGMA CALIBRATION : Cal BC 1605 to 1585 (Cal BP 3555 to 3535) and Cal BC 1545 to 1435 (Cal BP 3495 to 3385)	3210 +/- 30 BP	-23.8 o/oo	3230 +/- 30 BP
Beta - 399443 SAMPLE : CC1-3 Pinus ANALYSIS : AMS-Standard delivery MATERIAL/PRETREATMENT : (charred material): acid/alkali/acid 2 SIGMA CALIBRATION : Cal AD 1165 to 1265 (Cal BP 785 to 685)	780 +/- 30 BP	-22.6 o/oo	820 +/- 30 BP
Beta - 399444 SAMPLE : MSV1-2 Salicaceae ANALYSIS : AMS-Standard delivery MATERIAL/PRETREATMENT : (charred material): acid/alkali/acid 2 SIGMA CALIBRATION : Cal AD 600 to 660 (Cal BP 1350 to 1290)	1420 +/- 30 BP	-25.7 o/oo	1410 +/- 30 BP

Dates are reported as RCYBP (radiocarbon years before present, "present" = AD 1950). By international convention, the modern reference standard was 95% the 14C activity of the National Institute of Standards and Technology (NIST) Oxalic Acid (SRM 4990C) and calculated using the Libby 14C half-life (5568 years). Quoted errors represent 1 relative standard deviation statistics (68% probability) counting errors based on the combined measurements of the sample, background, and modern reference standards. Measured 13C/12C ratios (delta 13C) were calculated relative to the PDB-1 standard.

The Conventional Radiocarbon Age represents the Measured Radiocarbon Age corrected for isotopic fractionation, calculated using the delta 13C. On rare occasion where the Conventional Radiocarbon Age was calculated using an assumed delta 13C, the ratio and the Conventional Radiocarbon Age will be followed by "**". The Conventional Radiocarbon Age is not calendar calibrated. When available, the Calendar Calibrated result is calculated from the Conventional Radiocarbon Age and is listed as the "Two Sigma Calibrated Result" for each sample.



REPORT OF RADIOCARBON DATING ANALYSES

Dr. Giorgia deWolfe

Report Date: 1/7/2015

Sample Data	Measured Radiocarbon Age	13C/12C Ratio	Conventional Radiocarbon Age(*)
Beta - 399445 SAMPLE : MSV1-4 Bark ANALYSIS : AMS-Standard delivery MATERIAL/PRETREATMENT : (charred material): acid/alkali/acid 2 SIGMA CALIBRATION : Cal AD 90 to 100 (Cal BP 1860 to 1850) and Cal AD 125 to 250 (Cal BP 1825 to 1700)	1830 +/- 30 BP	-24.8 o/oo	1830 +/- 30 BP
Beta - 399446 SAMPLE : NBT-3 Pinus ANALYSIS : AMS-Standard delivery MATERIAL/PRETREATMENT : (charred material): acid/alkali/acid 2 SIGMA CALIBRATION : Cal AD 75 to 235 (Cal BP 1875 to 1715)	1840 +/- 30 BP	-24.0 o/oo	1860 +/- 30 BP
Beta - 399447 SAMPLE : NBT-6 Pinus ANALYSIS : AMS-Standard delivery MATERIAL/PRETREATMENT : (charred material): acid/alkali/acid 2 SIGMA CALIBRATION : Cal AD 1665 to 1710 (Cal BP 285 to 240) and Cal AD 1720 to 1890 (Cal BP 230 to 60) and Cal AD 1910 to Post 1950 (Cal BP 40 to Post 0)	120 +/- 30 BP	-22.7 o/oo	160 +/- 30 BP
Beta - 399448 SAMPLE : NSV1-1 Pinus ANALYSIS : AMS-Standard delivery MATERIAL/PRETREATMENT : (charred material): acid/alkali/acid 2 SIGMA CALIBRATION : Cal BC 4675 to 4635 (Cal BP 6625 to 6585) and Cal BC 4615 to 4490 (Cal BP 6565 to 6440)	5730 +/- 30 BP	-25.6 o/oo	5720 +/- 30 BP

Dates are reported as RCYBP (radiocarbon years before present, "present" = AD 1950). By international convention, the modern reference standard was 95% the 14C activity of the National Institute of Standards and Technology (NIST) Oxalic Acid (SRM 4990C) and calculated using the Libby 14C half-life (5568 years). Quoted errors represent 1 relative standard deviation statistics (68% probability) counting errors based on the combined measurements of the sample, background, and modern reference standards. Measured 13C/12C ratios (delta 13C) were calculated relative to the PDB-1 standard.

The Conventional Radiocarbon Age represents the Measured Radiocarbon Age corrected for isotopic fractionation, calculated using the delta 13C. On rare occasion where the Conventional Radiocarbon Age was calculated using an assumed delta 13C, the ratio and the Conventional Radiocarbon Age will be followed by "**". The Conventional Radiocarbon Age is not calendar calibrated. When available, the Calendar Calibrated result is calculated from the Conventional Radiocarbon Age and is listed as the "Two Sigma Calibrated Result" for each sample.



REPORT OF RADIOCARBON DATING ANALYSES

Dr. Giorgia deWolfe

Report Date: 1/7/2015

Sample Data	Measured Radiocarbon Age	$^{13}\text{C}/^{12}\text{C}$ Ratio	Conventional Radiocarbon Age(*)
Beta - 399449 SAMPLE : NSV2-1 Pinus ANALYSIS : AMS-Standard delivery MATERIAL/PRETREATMENT : (charred material): acid/alkali/acid 2 SIGMA CALIBRATION : Cal AD 660 to 770 (Cal BP 1290 to 1180)	1270 +/- 30 BP	-23.6 o/oo	1290 +/- 30 BP
Beta - 399450 SAMPLE : SSV2-1 Alnus ANALYSIS : AMS-Standard delivery MATERIAL/PRETREATMENT : (charred material): acid/alkali/acid 2 SIGMA CALIBRATION : Cal AD 1690 to 1730 (Cal BP 260 to 220) and Cal AD 1810 to 1920 (Cal BP 140 to 30) and Post AD 1950 (Post BP 0)	110 +/- 30 BP	-27.7 o/oo	70 +/- 30 BP

Dates are reported as RCYBP (radiocarbon years before present, "present" = AD 1950). By international convention, the modern reference standard was 95% the ^{14}C activity of the National Institute of Standards and Technology (NIST) Oxalic Acid (SRM 4990C) and calculated using the Libby ^{14}C half-life (5568 years). Quoted errors represent 1 relative standard deviation statistics (68% probability) counting errors based on the combined measurements of the sample, background, and modern reference standards. Measured $^{13}\text{C}/^{12}\text{C}$ ratios (delta ^{13}C) were calculated relative to the PDB-1 standard.

The Conventional Radiocarbon Age represents the Measured Radiocarbon Age corrected for isotopic fractionation, calculated using the delta ^{13}C . On rare occasion where the Conventional Radiocarbon Age was calculated using an assumed delta ^{13}C , the ratio and the Conventional Radiocarbon Age will be followed by "**". The Conventional Radiocarbon Age is not calendar calibrated. When available, the Calendar Calibrated result is calculated from the Conventional Radiocarbon Age and is listed as the "Two Sigma Calibrated Result" for each sample.

CALIBRATION OF RADIOCARBON AGE TO CALENDAR YEARS

(Variables: C13/C12 = -23.6 o/oo : lab. mult = 1)

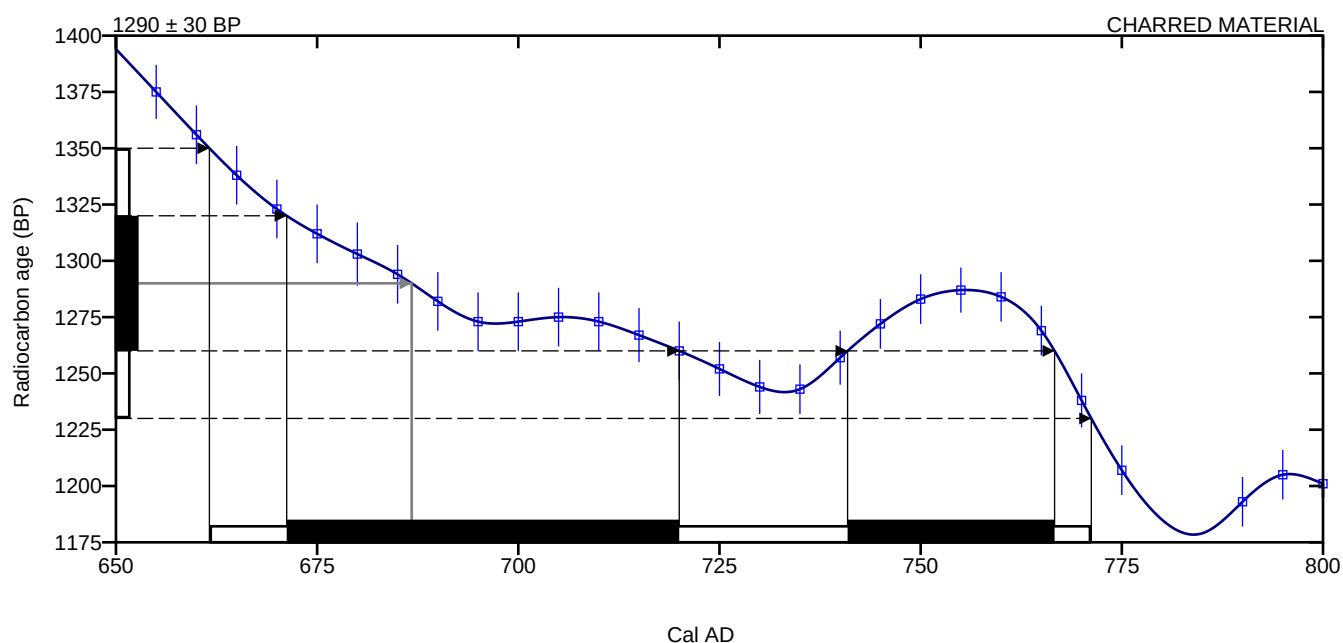
Laboratory number **Beta-399449**

Conventional radiocarbon age **1290 ± 30 BP**

2 Sigma calibrated result **Cal AD 660 to 770 (Cal BP 1290 to 1180)**
95% probability

Intercept of radiocarbon age with calibration curve Cal AD 685 (Cal BP 1265)

1 Sigma calibrated results **Cal AD 670 to 720 (Cal BP 1280 to 1230)**
68% probability **Cal AD 740 to 765 (Cal BP 1210 to 1185)**



Database used
INTCAL13

References

Mathematics used for calibration scenario

A Simplified Approach to Calibrating C14 Dates, Talma, A. S., Vogel, J. C., 1993, Radiocarbon 35(2):317-322

References to INTCAL13 database

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CALIBRATION OF RADIOCARBON AGE TO CALENDAR YEARS

(Variables: C13/C12 = -27.7 o/oo : lab. mult = 1)

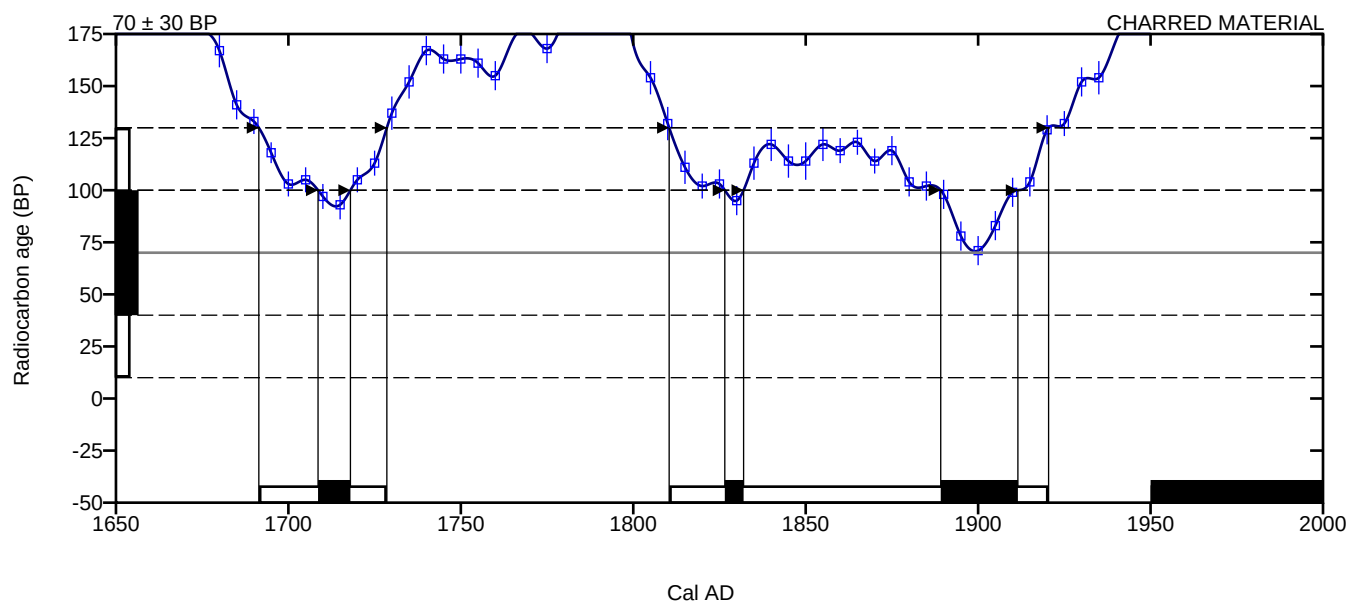
Laboratory number **Beta-399450**

Conventional radiocarbon age **70 ± 30 BP**

2 Sigma calibrated result **Cal AD 1690 to 1730 (Cal BP 260 to 220)**
95% probability **Cal AD 1810 to 1920 (Cal BP 140 to 30)**
 Post AD 1950 (Post BP 0)

Intercept of radiocarbon age with calibration curve Post AD 1950 (Post BP 0)

1 Sigma calibrated results **Cal AD 1710 to 1720 (Cal BP 240 to 230)**
68% probability **Cal AD 1825 to 1830 (Cal BP 125 to 120)**
 Cal AD 1890 to 1910 (Cal BP 60 to 40)
 Post AD 1950 (Post BP 0)



Database used
INTCAL13

References

Mathematics used for calibration scenario

A Simplified Approach to Calibrating C14 Dates, Talma, A. S., Vogel, J. C., 1993, Radiocarbon 35(2):317-322

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CALIBRATION OF RADIOCARBON AGE TO CALENDAR YEARS

(Variables: C13/C12 = -22.6 o/oo : lab. mult = 1)

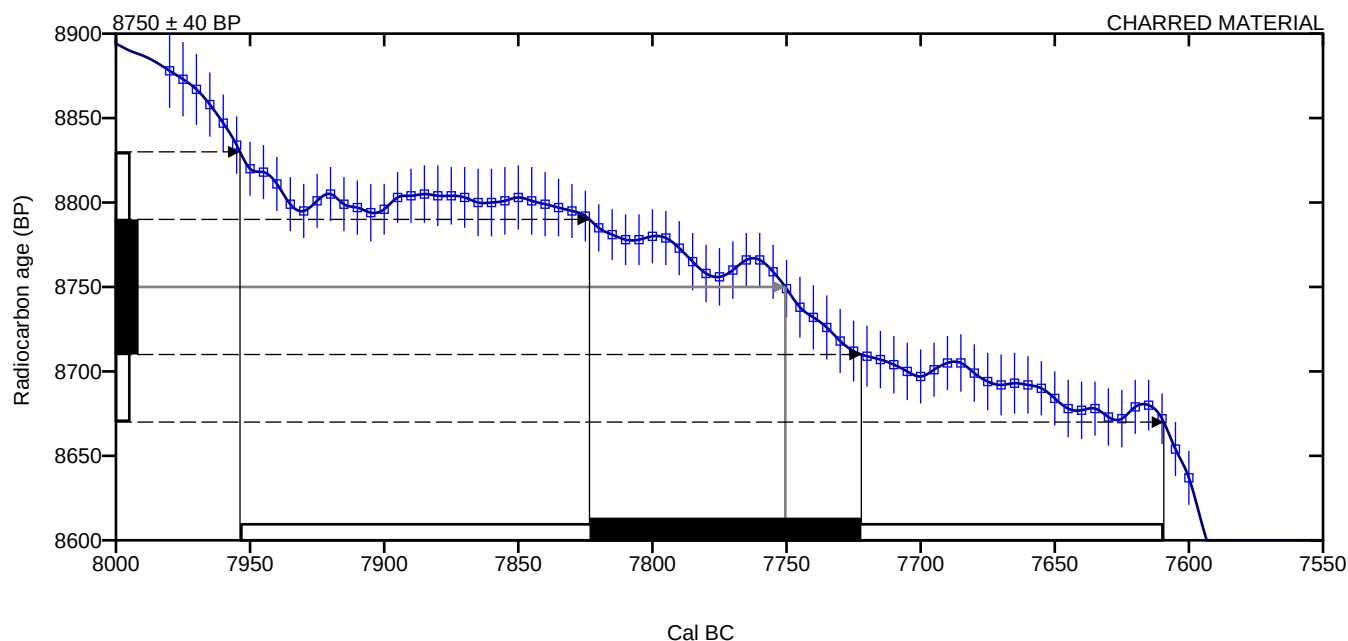
Laboratory number **Beta-399441**

Conventional radiocarbon age **8750 ± 40 BP**

2 Sigma calibrated result **Cal BC 7955 to 7610 (Cal BP 9905 to 9560)**
95% probability

Intercept of radiocarbon age with calibration curve **Cal BC 7750 (Cal BP 9700)**

1 Sigma calibrated results **Cal BC 7825 to 7720 (Cal BP 9775 to 9670)**
68% probability



Database used
INTCAL13

References

Mathematics used for calibration scenario

A Simplified Approach to Calibrating C14 Dates, Talma, A. S., Vogel, J. C., 1993, Radiocarbon 35(2):317-322

References to INTCAL13 database

Reimer PJ et al. IntCal13 and Marine13 radiocarbon age calibration curves 0–50,000 years cal BP. Radiocarbon 55(4):1869–1887., 2013.

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CALIBRATION OF RADIOCARBON AGE TO CALENDAR YEARS

(Variables: C13/C12 = -23.8 o/oo : lab. mult = 1)

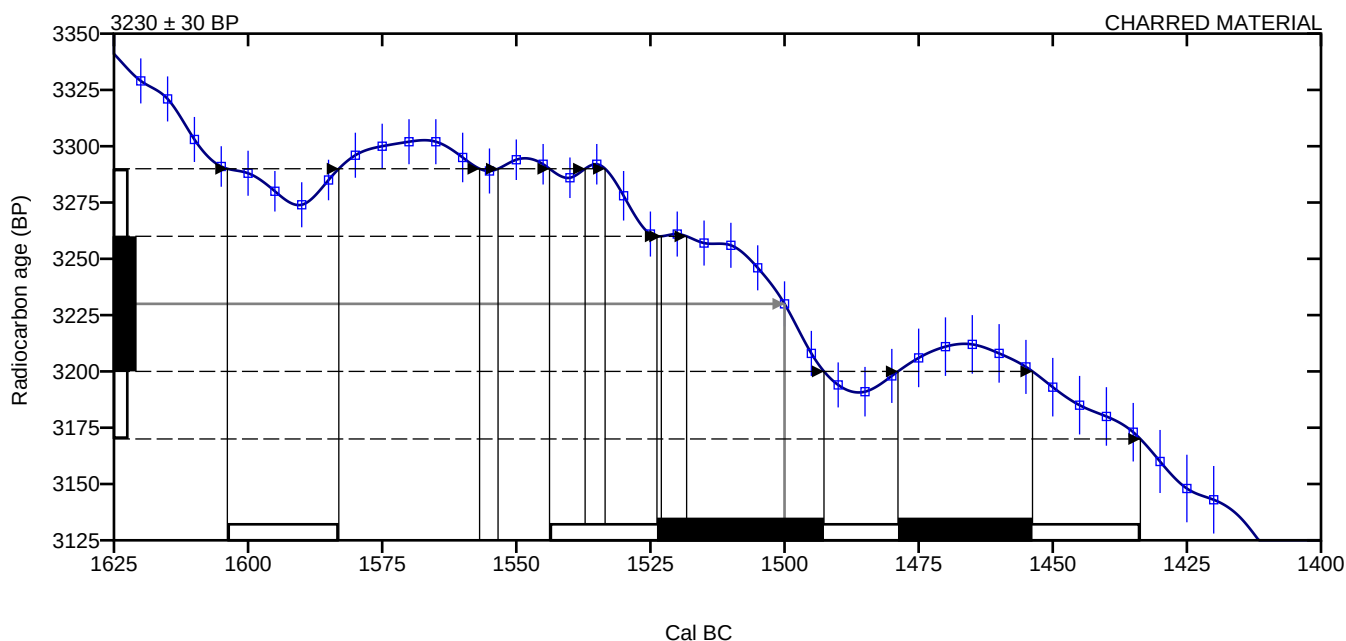
Laboratory number Beta-399442

Conventional radiocarbon age 3230 ± 30 BP

2 Sigma calibrated result Cal BC 1605 to 1585 (Cal BP 3555 to 3535)
95% probability Cal BC 1545 to 1435 (Cal BP 3495 to 3385)

Intercept of radiocarbon age with calibration curve Cal BC 1500 (Cal BP 3450)

1 Sigma calibrated results Cal BC 1525 to 1495 (Cal BP 3475 to 3445)
68% probability Cal BC 1480 to 1455 (Cal BP 3430 to 3405)



Database used
INTCAL13

References

Mathematics used for calibration scenario

A Simplified Approach to Calibrating C14 Dates, Talma, A. S., Vogel, J. C., 1993, Radiocarbon 35(2):317-322

References to INTCAL13 database

Reimer PJ et al. IntCal13 and Marine13 radiocarbon age calibration curves 0–50,000 years cal BP. Radiocarbon 55(4):1869–1887., 2013.

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CALIBRATION OF RADIOCARBON AGE TO CALENDAR YEARS

(Variables: C13/C12 = -22.6 o/oo : lab. mult = 1)

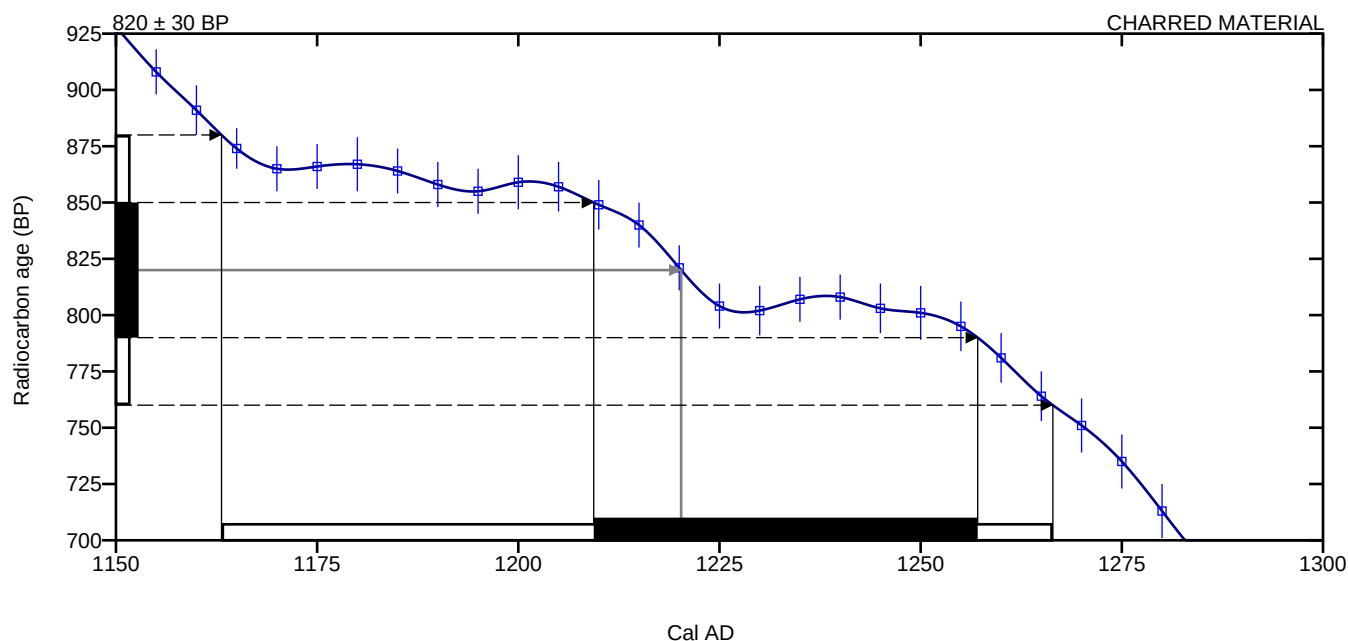
Laboratory number **Beta-399443**

Conventional radiocarbon age **820 ± 30 BP**

2 Sigma calibrated result **Cal AD 1165 to 1265 (Cal BP 785 to 685)**
95% probability

Intercept of radiocarbon age with calibration curve Cal AD 1220 (Cal BP 730)

1 Sigma calibrated results **Cal AD 1210 to 1255 (Cal BP 740 to 695)**
68% probability



Database used
INTCAL13

References

Mathematics used for calibration scenario

A Simplified Approach to Calibrating C14 Dates, Talma, A. S., Vogel, J. C., 1993, Radiocarbon 35(2):317-322

References to INTCAL13 database

Reimer PJ et al. IntCal13 and Marine13 radiocarbon age calibration curves 0–50,000 years cal BP. Radiocarbon 55(4):1869–1887., 2013.

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CALIBRATION OF RADIOCARBON AGE TO CALENDAR YEARS

(Variables: C13/C12 = -25.7 o/oo : lab. mult = 1)

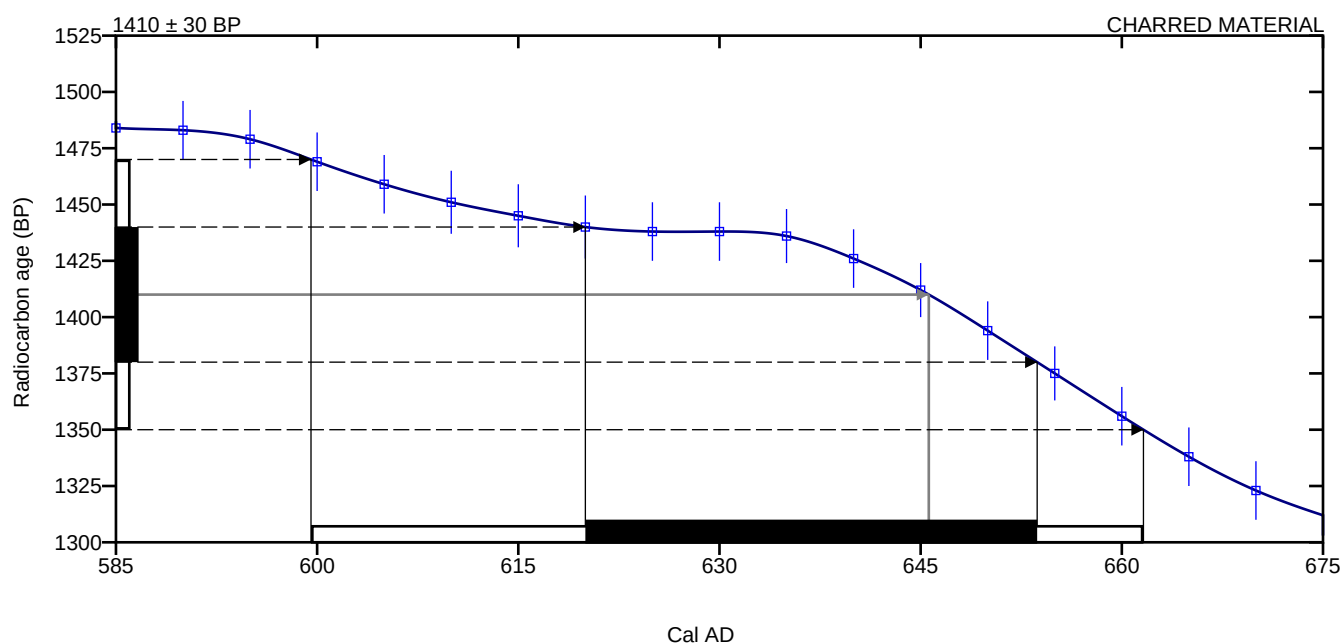
Laboratory number **Beta-399444**

Conventional radiocarbon age **1410 ± 30 BP**

2 Sigma calibrated result **Cal AD 600 to 660 (Cal BP 1350 to 1290)**
95% probability

Intercept of radiocarbon age with calibration curve Cal AD 645 (Cal BP 1305)

1 Sigma calibrated results **Cal AD 620 to 655 (Cal BP 1330 to 1295)**
68% probability



Database used
INTCAL13

References

Mathematics used for calibration scenario

A Simplified Approach to Calibrating C14 Dates, Talma, A. S., Vogel, J. C., 1993, Radiocarbon 35(2):317-322

References to INTCAL13 database

Reimer PJ et al. IntCal13 and Marine13 radiocarbon age calibration curves 0–50,000 years cal BP. Radiocarbon 55(4):1869–1887., 2013.

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CALIBRATION OF RADIOCARBON AGE TO CALENDAR YEARS

(Variables: C13/C12 = -24.8 o/oo : lab. mult = 1)

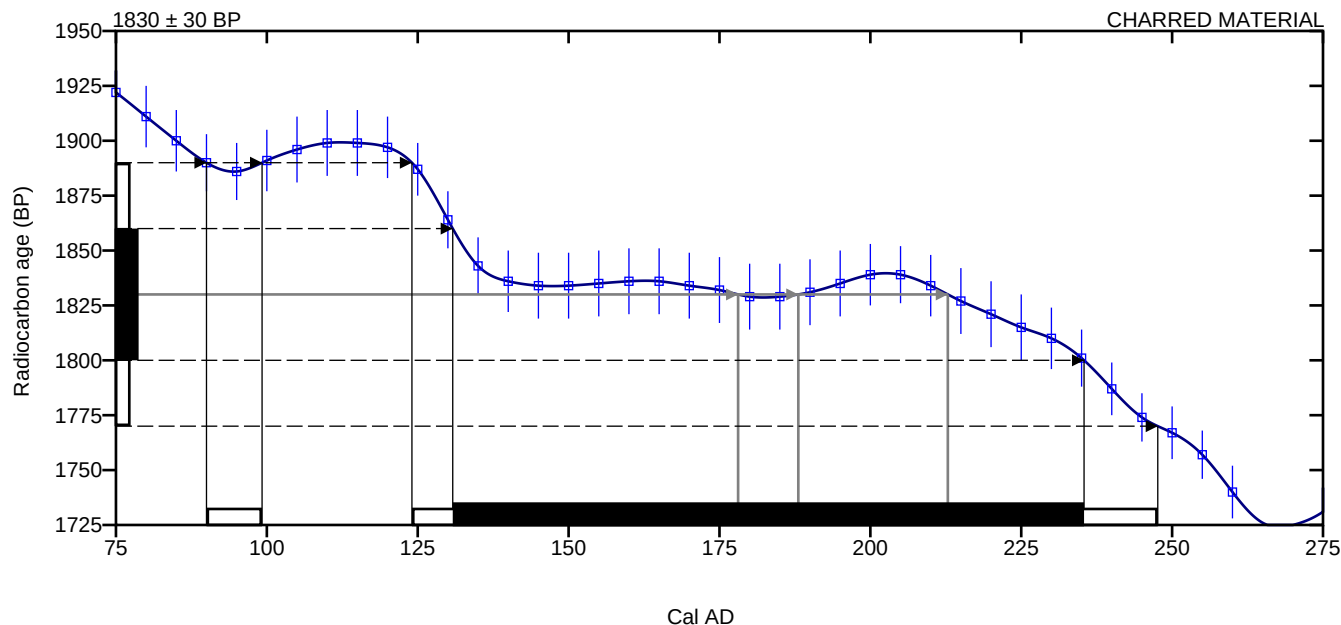
Laboratory number **Beta-399445**

Conventional radiocarbon age **1830 ± 30 BP**

2 Sigma calibrated result **Cal AD 90 to 100 (Cal BP 1860 to 1850)**
95% probability **Cal AD 125 to 250 (Cal BP 1825 to 1700)**

Intercept of radiocarbon age with calibration
curve Cal AD 180 (Cal BP 1770)
 Cal AD 190 (Cal BP 1760)
 Cal AD 215 (Cal BP 1735)

1 Sigma calibrated results **Cal AD 130 to 235 (Cal BP 1820 to 1715)**
68% probability



Database used
INTCAL13

References

Mathematics used for calibration scenario

A Simplified Approach to Calibrating C14 Dates, Talma, A. S., Vogel, J. C., 1993, Radiocarbon 35(2):317-322

References to INTCAL13 database

Reimer PJ et al. IntCal13 and Marine13 radiocarbon age calibration curves 0–50,000 years cal BP. Radiocarbon 55(4):1869–1887., 2013.

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CALIBRATION OF RADIOCARBON AGE TO CALENDAR YEARS

(Variables: C13/C12 = -24 o/oo : lab. mult = 1)

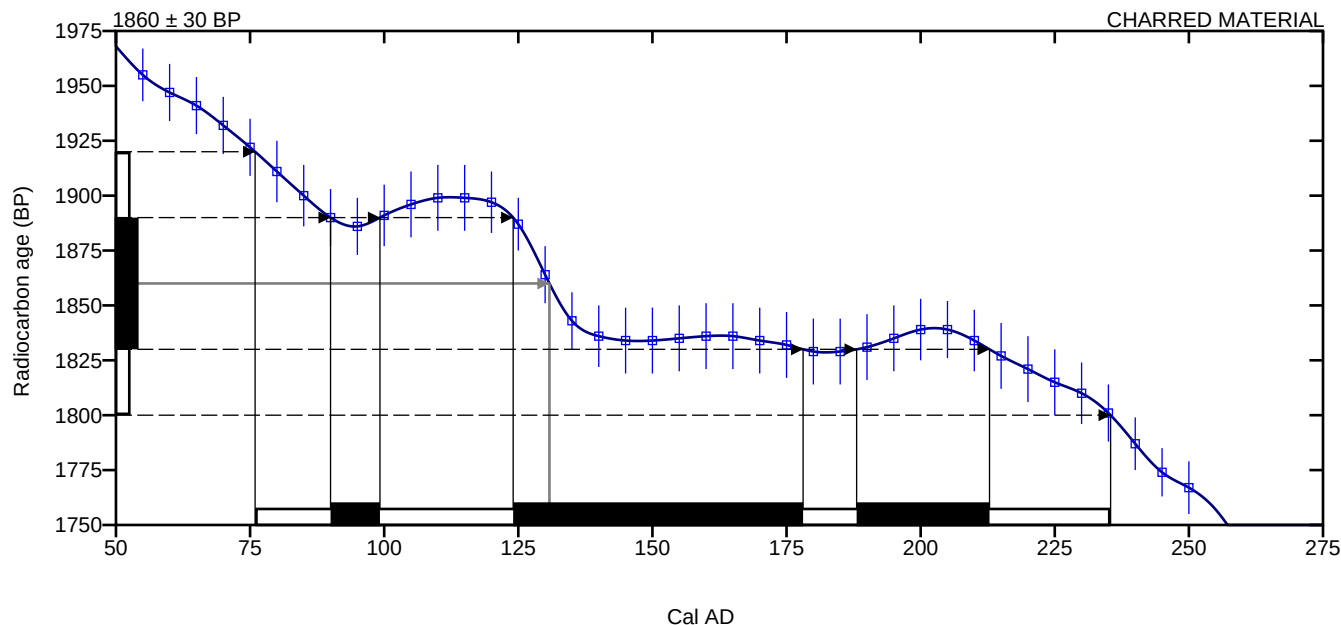
Laboratory number **Beta-399446**

Conventional radiocarbon age **1860 ± 30 BP**

2 Sigma calibrated result **Cal AD 75 to 235 (Cal BP 1875 to 1715)**
95% probability

Intercept of radiocarbon age with calibration curve Cal AD 130 (Cal BP 1820)

1 Sigma calibrated results Cal AD 90 to 100 (Cal BP 1860 to 1850)
68% probability Cal AD 125 to 180 (Cal BP 1825 to 1770)
Cal AD 190 to 215 (Cal BP 1760 to 1735)



Database used
INTCAL13

References

Mathematics used for calibration scenario

A Simplified Approach to Calibrating C14 Dates, Talma, A. S., Vogel, J. C., 1993, Radiocarbon 35(2):317-322

References to INTCAL13 database

Reimer PJ et al. IntCal13 and Marine13 radiocarbon age calibration curves 0–50,000 years cal BP. Radiocarbon 55(4):1869–1887., 2013.

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CALIBRATION OF RADIOCARBON AGE TO CALENDAR YEARS

(Variables: C13/C12 = -22.7 o/oo : lab. mult = 1)

Laboratory number **Beta-399447**

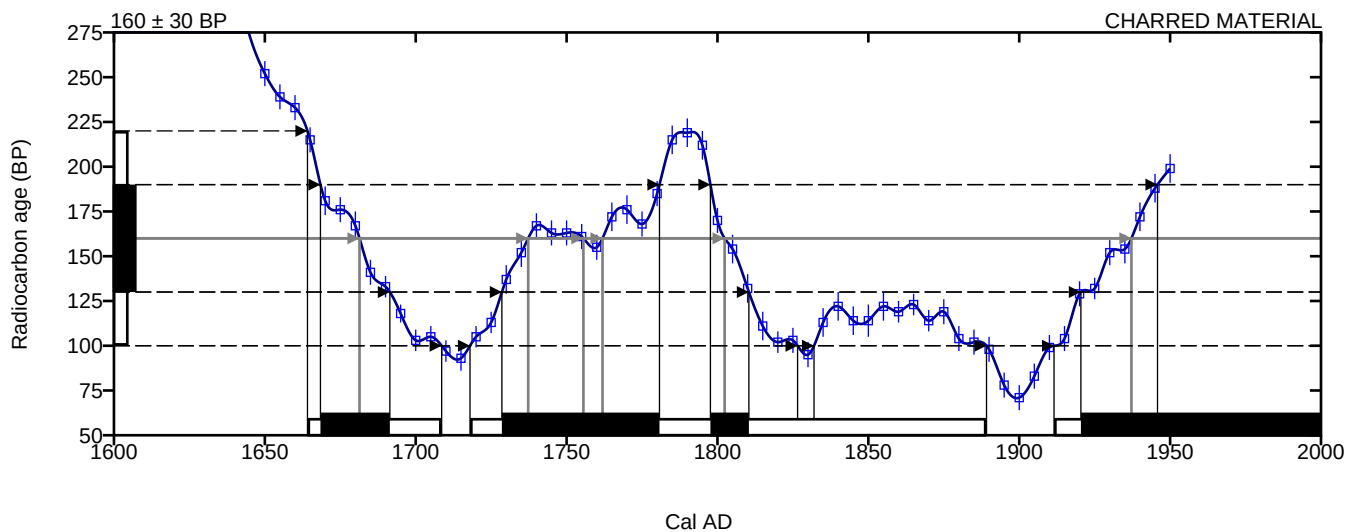
Conventional radiocarbon age **160 ± 30 BP**

2 Sigma calibrated result **Cal AD 1665 to 1710 (Cal BP 285 to 240)**
95% probability **Cal AD 1720 to 1890 (Cal BP 230 to 60)**
 Cal AD 1910 to Post 1950 (Cal BP 40 to Post 0)

Intercept of radiocarbon age with calibration
curve

Cal AD 1680 (Cal BP 270)
Cal AD 1735 (Cal BP 215)
Cal AD 1755 (Cal BP 195)
Cal AD 1760 (Cal BP 190)
Cal AD 1800 (Cal BP 150)
Cal AD 1935 (Cal BP 15)
Post AD 1950 (Post BP 0)

1 Sigma calibrated results **Cal AD 1670 to 1690 (Cal BP 280 to 260)**
68% probability **Cal AD 1730 to 1780 (Cal BP 220 to 170)**
 Cal AD 1800 to 1810 (Cal BP 150 to 140)
 Cal AD 1920 to Post 1950 (Cal BP 30 to Post 0)



Database used
INTCAL13

References

Mathematics used for calibration scenario

A Simplified Approach to Calibrating C14 Dates, Talma, A. S., Vogel, J. C., 1993, Radiocarbon 35(2):317-322

References to INTCAL13 database

Reimer PJ et al. IntCal13 and Marine13 radiocarbon age calibration curves 0–50,000 years cal BP. Radiocarbon 55(4):1869–1887., 2013.

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CALIBRATION OF RADIOCARBON AGE TO CALENDAR YEARS

(Variables: C13/C12 = -25.6 o/oo : lab. mult = 1)

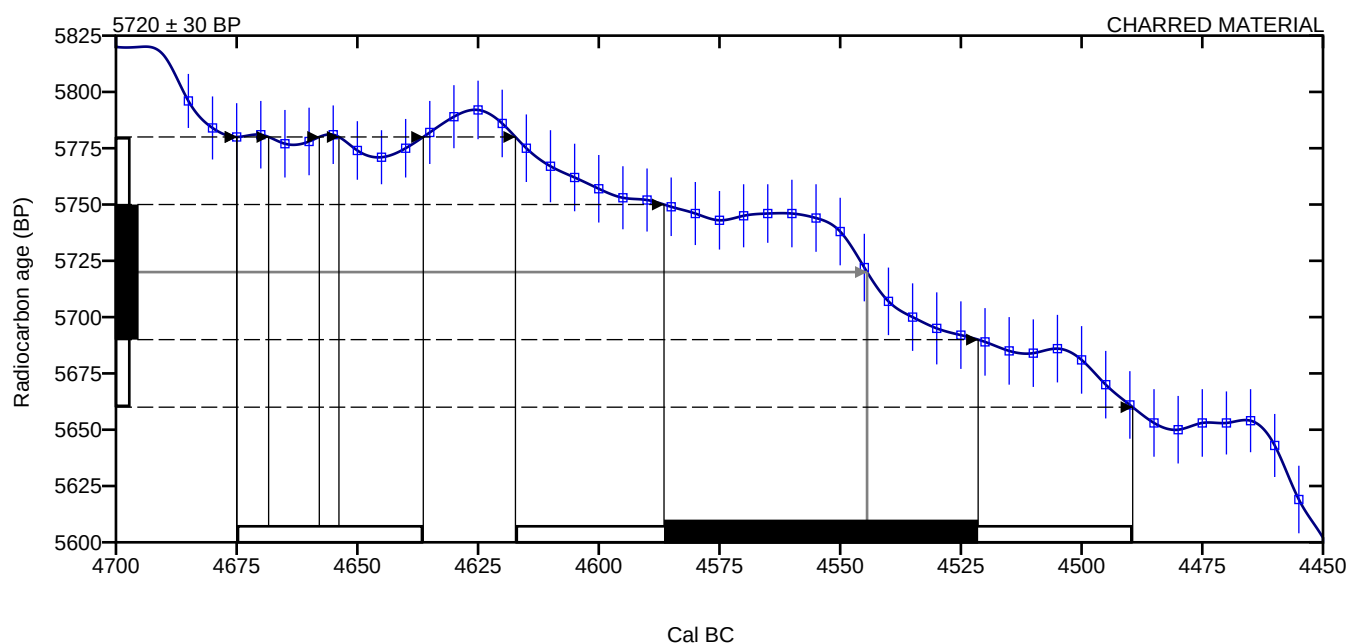
Laboratory number **Beta-399448**

Conventional radiocarbon age **5720 ± 30 BP**

2 Sigma calibrated result **Cal BC 4675 to 4635 (Cal BP 6625 to 6585)**
95% probability **Cal BC 4615 to 4490 (Cal BP 6565 to 6440)**

Intercept of radiocarbon age with calibration curve **Cal BC 4545 (Cal BP 6495)**

1 Sigma calibrated results **Cal BC 4585 to 4520 (Cal BP 6535 to 6470)**
68% probability



Database used
INTCAL13

References

Mathematics used for calibration scenario

A Simplified Approach to Calibrating C14 Dates, Talma, A. S., Vogel, J. C., 1993, Radiocarbon 35(2):317-322

References to INTCAL13 database

Reimer PJ et al. IntCal13 and Marine13 radiocarbon age calibration curves 0–50,000 years cal BP. Radiocarbon 55(4):1869–1887., 2013.

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