# Geomorphic Impacts of the 2013 Colorado Front Range Flood on Black Canyon Creek and North Fork Big Thompson River

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# Executive Summary

In September 2013, the Colorado Front Range experienced a five-day storm that brought record-breaking precipitation to the region. As a consequence, many Front Range streams experienced flooding, leading to erosion, debris flows, bank failures and channel incision. I compare the effects that debris flows and flooding have on the channel bar frequency, frequency and location of wood accumulation, and on the shape and size of the channel along two flood impacted reaches located near Estes Park and Glen Haven, Colorado within the RMNP and the ARNF: Black Canyon Creek (BCC) and North Fork Big Thompson River (NFBT). The primary difference between the two study areas is that BCC was inundated by multiple debris flows, whereas NFBT only experienced flooding. Fieldwork consisted of recording location and size of large wood and channel bars and surveying reaches to produce cross-sections. Additional observations were made on bank failures in NFBT and the presence of boulders in channel bars in BCC to determine sediment source. The debris flow acted to scour and incise BCC causing long-term alteration. The post-flood channel cross-sectional area is as much as 7 to 23 times larger than the pre-flood channel, caused by the erosion of the channel bed to bedrock and the elimination of riparian vegetation. Large wood was forced out of the stream channel and deposited outside of the bankfull channel. Flooding in NFBT caused bank erosion and widening that contributed sediment to channel bars, but accomplished little stream-bed scour. As a result, there was relatively little damage to mid-channel and riparian vegetation, and most large wood remained within the wetted channel.

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# Statement of the Problem

In September 2013, the Colorado Front Range experienced a five day storm event that dropped a record-breaking cumulative rainfall of 20-45 centimeters (Anderson et al., 2015). September is usually much drier, with average total precipitation of about 4 centimeters (Scott, 2013). The storm lasted from September 9$^{th}$ through September 15$^{th}$, falling most intensely between September 11$^{th}$ and September 13$^{th}$. This storm caused landslides, debris flows, bank failures, and channel incision (Gartner et al., 2015). Gorchis et al. (2015) noted property damage and infrastructure along the length of the Front Range, including areas within the Rocky Mountain National Park (RMNP) and the Arapaho-Roosevelt National Forest (ARNF).

I compare the effects that debris flows and flooding have on the channel bar frequency, frequency and location of wood accumulation, and on the shape and size of the channel along two flood impacted reaches located near Estes Park and Glen Haven, Colorado within the RMNP and the ARNF: Black Canyon Creek (BCC) and North Fork Big Thompson River (NFBT) (Figure 1). The primary difference between the two study areas is that BCC was inundated by multiple debris flows, whereas NFBT only experienced flooding.

In the past 60 years, fifteen other rain events have occurred that exceeded the total annual precipitation for the region (NCAR, 2007). The most deadly flood occurred in the summer of 1976, just downstream of Estes Park, Colorado. In 4 ½ hours, 12 inches of rain fell in Big Thompson Canyon, a seventy square mile area. The rain entered the Big Thompson River and was channelized by the canyon, creating a flash flood that claimed 144 lives (National Park Service, 2014).

Colorado's flood history calls to the importance in understanding the in-stream impacts of flooding and debris flows and the potential dangers these impacts pose for us. Thus, improved understanding of landscape response to increased precipitation, and subsequent landslides and debris flows, is essential for the improvement of future resiliency of flood prone areas.

## Study Area

Both field sites are within the boundaries of RMNP and ARNP with rivers flowing southwest from the Mummy Range. The areas studied in BCC and NFBT are both largely free of infrastructure with a few exceptions including a children's summer campground along NFBT, a water treatment plant in BCC, and a few cabins and various hiking trails within both study areas. Vulnerable infrastructure, including private residences, a ranch, and roads, are located downstream of both reaches. The town of Estes Park lies in the lower part of BCC's watershed and the town of Glen Haven lies below the NFBT watershed.

### *Black Canyon Creek (BCC) setting*

The 22.5 $km^2$ BCC basin originates from Mummy Ridge, between Mummy Mountain and Hagues Peak. BCC flows into Fall River and drains into Big Thompson River in Estes Park, Colorado. The study reach is 2.2 river kilometers long and the elevation ranges from 2511 meters at the most upstream reach, Reach 1, to 2398 meters at the most downstream reach, Reach 5 (Figure 2). The study reaches range from 78 to 177 meters long. Slope values vary throughout the study area from shallower, more uniform segments, to sharp slope breaks seen at small bedrock cliff waterfalls. The slope at Reach 1, just downstream of where the debris flow enters BCC, is 0.02 (Table 1). The average slope increases to 0.04 and then 0.06 moving downstream, as bedrock and waterfalls are expressed. Reach 5 has the shallowest slope of 0.01 (Figure 2). The study area makes up about 10% of the entire stream which is 20.2 river kilometers long.

Before the flood, and subsequent debris flow, BCC had a diverse riparian zone of grasses, shrubs, aspen (*Populus tremuloides)*, ponderosa pine (*Pinus ponderosa)* and lodgepole pine

(*Pinus contorta)* (Figure 3). The upper portion (the first 11.5 kilometers) shows little flood impact, lacking evidence of bank failures and lateral erosion on 2001 Google Earth imagery. The middle portion of the watershed was inundated in 2013 by a total of three debris flows (Ryan, 2015) (Figure 2). The longest and more destructive debris flow, Debris Flow 1, appears to originate from a colluvium hollow failure along MacGregor Mountain and travelled 1.8 kilometers before reaching the main stem of BCC from the right bank. Deposition at the confluence of the debris flow and BCC includes a mixture of wood debris and boulders, as well as adjacent scour (Figure 4). The channel portion just below the debris flow appears to be scoured up to 10 meters (Ryan, 2015). Scour and deposition continues throughout the entire study area (Figure 5).

### *North Fork Big Thompson (NFBT) setting*

NFBT basin is about 46 $km^2$ (above Glen Haven, Colorado) (Soule, 1976). It originates between Rowe Peak and Hagues Peak and flows in a general southeast direction (Clausen, 2012). The study area is composed of 5.4 river kilometers and has an elevation change from 2475 meters at the most upstream segment, to 2312 meters at the most downstream segment (Figure 2). The study reaches range from 55 to 251 meters long. The slope at Reach 1 is 0.01 (Table 2). Most of the study area has a similar slope throughout, but at Reach 5 the slope increases to 0.04 due to valley narrowing caused by adjacent bedrock hillslopes (Figure 2). Overall, the study area in BCC has a steeper slope than the NFBT study area. The study area makes up about 8% of the entire stream which is 38 river kilometers long.

Channel widening and re-working of floodplains is not readily apparent in the headwaters of the NFBT on 2011 Google Earth imagery until about two-thirds of the way downbasin, and about two kilometers upstream of the study area (Ryan, 2015). The more readily-apparent disturbance begins at approximately the lower end of the glacial drift area, suggesting a geologic control on channel response here (Ryan, 2015). Landsliding is not prevalent on the 2011 Google Earth imagery along this reach, but there are noticeable bank failures from channel widening and loss of riparian forest along the lower portion (Figure 6).

### *Peak flow estimates for BCC and NFBT*

Using peak flow data obtained from the U.S. Geological Survey (USGS) and the Natural Resources Conservation Service (NRCS), Yochum and Moore (2013) estimated peak flow discharges for over a dozen rivers impacted by the 2013 Front Range Flood. They applied the critical depth method using a single cross-section, implementing high water marks at each location and replicating flow estimates for several adjacent cross-sections to confirm consistency in the estimations. High-intensity rain events in mountainous topography, commonly occur at elevations below 2300 meters in the Colorado Front Range. However, high discharges were computed at some locations with higher elevations, like Estes Park and Glen Haven areas, both within my study areas (Yochum and Moore, 2013).

Yochum and Moore (2013) did not estimate peak flow discharge for BCC, but they did estimate peak flow discharge for Fox Creek, which is located three kilometers north of BCC and has a similar catchment area of 18.6 kilometers squared. Flow data were taken at three adjacent locations in Fox Creek with an average peak flow of 99 cubic meters per second (cms) (Yochum and Moore, 2013). Using Fox Creek as a reference for discharge, the estimated minimum peak discharge in BCC was 119 cms, an estimated 38 times the bankfull discharge. Ryan (2015) estimated pre-flood bankfull discharge to be 2.5 cms.

The NFBT basin received about ten times its monthly precipitation during the 2013 storm. Average September precipitation for Glen Haven, Colorado is 4 centimeters, but 43 centimeters fell in September 2013 (WeatherDB, 2015). Yochum and Moore (2013) measured discharges at three adjacent section on the NFBT (upstream of Glen Haven, Colorado), with an average peak flow of 48 cms, an estimated 11 times greater than bankfull discharge. Ryan (2015) estimated pre-flood bankfull discharge to be 4.5 cms.

## Study Background

### *Previous studies of the 2013 Colorado Front Range Flood*

The landscape response to the 2013 flood was so unique in that, in an otherwise inactive landscape, over 1,100 landslides and debris flows occurred along the Front Range (Anderson et al., 2015). Anderson et al. (2015) concluded debris flows dominate sediment transport and channel erosion for canyons along the Front Range and that the total amount of sediment removed by these landslides and debris flows is equivalent to hundreds to thousands of years of sediment accumulation.

Another study characterizing debris flows after the 2013 storm was by Coe et al. (2014). The debris flows initiated in response to high precipitation and all recorded slides began as colluvial soil failures that liquefied and moved rapidly downslope (Coe et al., 2014). Their inventory reveals that seventy-eight percent of the failures initiated on south-facing slopes, thirty-eight percent of the headscarps occurred within Proterozoic Granite, and ninety-seven percent of the failures occurred in open slopes and swales. Similar conditions are seen along the failure location of Debris Flow 1 in BCC.

### *Debris flow and flood effects on river channels, wood, and sediment*

Debris flows are infrequent compared to other natural disasters, such as flooding, but cause significant long-term effects on stream channel morphology (Eaton et al., 2003). In forested mountain drainage basins, debris flows scour steep headwater channels (Montgomery et al., 2003) as the BCC study area. The erosive force of a debris flow scours sediment and wood out of stream channels, and mobilizes and deposits large clasts within the channels, promoting a cycle between channel degradation and channel aggradation (Benda, 1990). Channel degradation results in mixed bedrock and boulder bed morphology, and channel aggradation, resulting in a gravel bed morphology (Benda, 1990). Debris flow deposition has also been characterized by the deposition of isolated boulder and tree levees (Cenderelli and Kite, 1998). In addition to tree levees, wood also accumulates as log jams (Montgomery et al., 2003). Abbe (2000) found that no debris flow formed jams were found in channels with log jam frequencies of greater than 20 jams per kilometer. This indicates that debris flow formed log jams are less frequent within a stream channel than log jams formed by other processes.

Flooding acts to widen stream channels and promotes bank erosion. Channel widening is the most common geomorphic response to floods (Magilligan et al., 2015). Channels widen in response to increases in channel conveyance (Magilligan et al., 2015). Banks that are saturated, and high flow velocities that are adjacent to banks, contribute to channel widening (Magilligan et al., 2015). Another reoccurring impact is the entrainment and transport of extremely coarse clasts, including the deposition of gravel bars. Floods in the Big Thompson River in Colorado, promote both deposition of coarse sediments in the stream channel, as well as coarse and fine sediment along the floodplain (Jarrett, 1990). Unlike debris flows, previous studies on flooding do not report substantial amounts of scour to stream channels. Sediment and debris are transported and deposited within the stream by accumulating along stream banks and in-stream vegetation (Jarrett, 1990).

## Scope of Work

In cooperation with Dr. Sandra Ryan, a research geomorphologist for the Rocky Mountain Research Station within the USFS, I surveyed current conditions of two flood-impacted streams, BCC and NFBT, and assisted in establishing reference areas for monitoring natural recovery following large-scale, widespread floods.

To ensure the field portion of this project was completed within the summer months, five reaches within each study area were chosen to map in more detail, rather than mapping each study area in its entirety. These reaches were chosen with the guidance of Dr. Ryan based on how well they characterized the overall flood impacts seen throughout the study area. Selected reaches were either characterized generally, which consisted of documenting channel bar extent and LW position and extent, or characterized in greater detail with the addition of multiple cross-section surveys. Five reaches along the BCC and NFBT are a combination of general and more detailed characterization (Figure 7, Figure 8). In addition to the five reaches in BCC, a cross section was taken along the river above the debris flow confluence and is referred to as the 'reference cross-section' in this study (Figure 7). After further reconnaissance upstream in the 'reference' reach, I concluded that the single cross-section surveyed is representative of the reach walked.

To compare the consequences from flooding and debris flows, I compared the spatial patterns of sediment and wood accumulation in the two streams. I also compared the erosional effects of flooding and debris flows by comparing the post-flood channel widths and areas in the two streams. Based on previous studies, I expect BCC to show evidence of channel bed scour and incision, boulder deposition, and wood debris accumulation along channel banks. In NFBT, I expect to see channel widening and the accumulation of wood and sediment deposition mostly instream.

## Methods

I combined field observations and field collected global positioning system (GPS) coordinates with GIS analyses to characterize and count the wood and sediment accumulation along both streams. Before going in the field, I used aerial photographs from Google Earth, dated October 2013 at a 0.6 meter resolution, and aerial LiDAR flown October 2013 at a resolution of 0.75 meters (USGS, 2015) of each stream to compare and locate erosional features such as bank failures and lateral widening scars. The areas identified in the desk review were verified through field visits to determine Reaches 1-5. Fieldwork consisted of characterizing the position and extent of LW, channel bars, and channel geometry using TerraSync on a Trimble GeoXH unit. Data points collected with the GPS unit were processed and corrected to improve the accuracy of the field data, georeferenced, and transferred into ArcMap.

### *Characterizing position and extent of large wood*

Adapting the work of Montgomery (2008) and Schuett-Hames et al. (1999) for surveying LW, I produced a field data sheet to characterize LW jams (Figure 9). For LW jams, estimates of jam dimensions (height, width, and length) were recorded by visual approximation or using a TerraSync on a Trimble GeoXH unit. Four zones were used to characterize LW jam deposition locations (Figure 10). The jam key piece, if present, size and position within the jam were noted. In addition, evidence of bank scour or imbedded sediment were also recorded. After fieldwork was complete, I used ArcGIS to digitize line segments connecting the points to trace LW jam boundaries and produce polygons. I compiled the data for depositional location and the number of LW jams in each of the five reaches along both streams.

Much of the deposited wood in BCC collected as one elongated mass of debris parallel to the stream, referred to here, as a debris line, and is seen throughout the upper half of the study area (Figure 11). Because I did not consider debris lines to be jams, I did not include them in my data collection.

### *Characterizing channel bar deposition*

To see the channel bar frequency per 100 meters, I counted the number of channel bars in each of the five reaches along both streams using GPS and ArcGIS. To highlight boulder deposition along BCC, a pebble count was conducted for channel bars within Reaches 1-5 using a gravelometer and measuring tape. A pebble count was performed along the upstream, middle, and downstream section of the bar. Grain size data was collected in NFBT using a digital grain size method. This method proved to be ineffective in measuring cobble to boulder size grains and is not presented in this study.

### *Describing channel geometry and slope data for BCC and NFBT*

I surveyed eleven cross-sections along BCC and seven cross-section along NFBT. From each cross-section, bankfull width and average depth are measured. Bankfull was identified as the point in which the gradually sloping floodplain changes to an abrupt bank edge. In some cases, this criteria was only visible along one bank due to the other bank being eroded. In these cases, bankfull estimations were made at the height where bare alluvium and vegetation met. Bankfull width and average depth were used to obtain width-to-depth ratios and cross-sectional areas, which were then normalized to the respective drainage area. Lastly, I used ArcGIS, to obtain the average river bed slope for each reach. In addition, I used a level and stadia rod to produce channel cross-sections along selected reaches. Locations were chosen by Dr. Ryan that characterized the spatial variation of the channel and flood deposits in that reach.

Drainage area was calculated using ArcGIS. I used a 10-meter DEM of Colorado to approximate the flow network based solely on topography. From this network I extracted points at each cross-section and stream line intersection. I then used these as pour points to derive estimated drainage area contributing to flow at each cross-section.

I calculated mean channel bed slope estimates for each reach using ArcGIS (Figure 2). The slope raster was made from the 10-meter Colorado DEM. Longitudinal profiles are produced based on the blue stream line in Figure 7 and Figure 8. The profile for BCC starts at the debris flow and stream confluence to the most southern extent of the watershed (a total of 3005 river meters). The profile for NFBT starts at Reach 1 and ends just downstream of Reach 5 (a total of 4500 river meters).

# Results

## *Large wood accumulation and deposition*

Large wood in BCC was predominantly deposited outside of the bankfull channel (Zone 4), whereas in NFBT, large wood accumulated within the wetted channel (Zone 1) (Figure 12). All LW jams in BCC are recorded outside of the bankfull channel, except one, located within the bankfull channel (Zone 2). Zone 4 jams accumulated behind alive and upright trees on the adjacent upland zones, terraces and eroded riparian zone (Figure 13). Half of the LW jams recorded in NFBT are located within the wetted channel (Zone 1). The remaining LW jams in NFBT are found within the bankfull channel (Zone 2), directly above (Zone 3) and outside the bankfull channel (Zone 4). In NFBT, wood located in the wetted channel accumulated behind stable, upright trees on mid-channel bars, or trail bridges (Figure 14). Some jams were comprised of a mixture of trail bridge infrastructure and transported wood.

Comparing the wood in each reach, BCC has more LW jams per 100 meters than NFBT. The frequency of LW jams per 100 meters in BCC ranged from 0.08 to 3.0 (Table 2). In NFBT the frequency ranged from 1.1 to 3.1. On average BCC has 1.3 times the amount of LW jams per 100 meters than NFBT. Results from both study areas show an increase in LW jam deposition moving downstream.

### *Large clasts accumulation and deposition*

Comparing the channel bars in each reach, NFBT has more channel bars per 100 meters than BCC (Table3). Average channel bar frequency for NFBT was 1.5 per 100 meters and 1.1 for BCC. The frequency of channel bars per 100 meters in NFBT ranged from 0.06 to 2.2 (Table 3). In BCC the frequency ranged from 0.05 to 2.4. Along NFBT, many channel bars accumulate along the opposite bank of bank failures.

Coarse grained sediment and boulder size clasts are recorded throughout the channel bars in BCC (Table 4). In Reach 1 the channel bar surface was mostly fine to medium gravel (5-11 millimeters). From Reaches 2, 4 and 5 the dominant sediment size observed was very coarse gravel (45-65 millimeters). Small cobbles (64-128 millimeters) are the dominant grain size in Reach 3. The largest clasts recorded are in Reach 5 with deposition of small to large boulders, one measured almost 2 meters in height.

### *Channel morphology*

BCC has a greater mean, and wider range in width-to depth ratio normalized by drainage area (Figure 15). The mean value is almost double in BCC than in NFBT, at 0.9 versus 0.5, and the data set for BCC ranges from 0.3 to 1.8 and from 0.3 to 0.9 in NFBT. These results are connected to the variance in channel cross-section widths, as cross-section depth were a similar value throughout the study area. In BCC, two cross-sectional widths in Reach 5 are much greater than the rest of the study area, at widths of 32 times greater than the corresponding depths (Table 5). The average cross-sectional width is only 12 times greater than the corresponding depth in BCC. Standard deviation for BCC is 0.5 and 0.3 for NFBT (two-sample t-test, p=0.04).

The normalized cross-sectional area mean and range in data is greater in BCC than NFBT (Figure 16). On average, the normalized cross-sectional area for BCC was 2.5 times greater than values for NFBT, at 0.5 versus 0.2, and the data set for BCC ranges from 0.2 to 1.5 and from 0.1 to 0.3 in NFBT. Most of the values for normalized cross-sectional area in BCC concentrate around 0.4, but is greatest at the debris flow and stream confluence with a value of 1.5 (Table 5). The cross-sectional area at the confluence was approximately three times greater than the areas at the other cross-sections. Standard deviation for BCC is 0.4 and 0.1 for NFBT (two-sample t-test, p=0.01).

Comparing the single reference cross-section in BCC surveyed upstream of the debris flow, to the cross-sections in the debris flow reach, suggests that the debris flow widened the downstream reach by 4 to 11 times the pre-debris flow condition. The reference cross-section was 1.3 meters wide by 0.9 meters deep, with a cross-sectional area of 1.1 square meters. The average width for the entire study area (from Reach 1 to Reach 5) was approximately 10.7 meters, the average depth was similar to the study area at 0.8 meters with cross-section areas averaging around seven square meters, but was as high as 23 square meters at the debris flow confluence (Table 5).

# Discussion

## *Debris flow and flood effects on wood and sediment accumulation*

Past research shows that debris flows scour sediment and debris from a channel. Results of this study are consistent with this expectation in that in BCC 1) all large wood jams that could accumulate, did so outside of bankfull channel and 2) by the overall lower frequency of channel bars per 100 meters compared to NFBT. Throughout the upstream half of the study area, wood accumulated as levees, or what I called, a debris line. As wood is recruited from the debris flow source and the riparian zone, it is pushed towards the front and sides of the flow (Johnson et al., 2012). The upstream portion can be summarized by a steeper slope, with wood levees lining the adjacent hillslope, and a low amount of LW jam deposition. This portion of the study area is inferred to be the transport driven portion of the debris flow, rather than the depositional zone of the debris flow. As the slope in BCC becomes shallower downstream, wood and large clasts are deposited and accumulate as jams and isolated boulders. Wood debris was eroded by the debris flow from the adjacent hillslopes and vegetated riparian zones. The wood debris was transported along BCC and contributes to the high frequency in LW jams per 100 meters.

The floodwaters of the NFBT were less erosive than the debris flow in BCC. Instead of sediment and wood being scoured from the channel, deposition happened along, and within, the stream channel. Observation at NFBT support this by 1) half of the LW jams accumulated within the wetted channel, 2) the higher frequency in channel bars per 100 meters, and 3) lower frequency of LW jams per 100 meters. I speculate that the lower average frequency of LW jams per 100 meters can be attributed to less scour and incision of the river bed and less erosion of the riparian zone. By NFBT not being entrenched, the flow had more opportunities to overtop banks and deposit wood. Similarly, by the preservation of some streamside vegetation, wood snag opportunities existed for wood accumulation within the bankfull channel.

### *Debris flow and flood effects on channel morphology*

Debris flow and flooding differently scoured and reshaped the two stream channels. With a larger watershed area, we expect, and observe, NFBT to have greater cross-section dimensions than BCC due to the accommodation of a greater influx of water, but normalized cross-section dimensions are larger in BCC than NFBT because of the effects the debris flow had on BCC. This is also the case for normalized width-to-depth ratios, again, due to the effects the debris flow had on BCC. For both the normalized width-to-depth ratio and the normalized cross-sectional area plots, BCC had a larger distribution and overall greater average than NFBT. This is due the scouring of the stream bed and lateral erosion of the stream banks by the debris flow in BCC.

Using photos and cross-sectional data from the reference cross-section for BCC as a proxy for pre-debris flow conditions, the extent to which the debris flow impacted the downstream reach is substantial. The debris flow acted to remove streamside vegetation and entrench the stream. If the data from the reference cross-section is similar to pre-debris flow cross-sections downstream, the debris flow did a considerable amount of incision and lateral erosion. The change is so great from pre to post-debris flow conditions that the channel impacts are likely to be more long-term.

### *Future studies*

The study of geomorphic impacts of BCC and NFBT could be furthered by conducting a complete inventory on large wood accumulation and grain size distribution from the headwaters to the floodplain. This inventory would provide a detailed report on the spatial distribution of degradation and aggradation produced during these two events. In addition, an interesting investigation would be to use the large clasts and levee positions to estimate height, velocity, and stream competency of the debris flow and flooding. This information could be used with flood reoccurrence intervals to predict when the recently deposited boulders might be reworked again. By doing studies such as these, a better understanding of the short and long-term effects to which these two channels have been altered can be obtained.

# Conclusion

This study compared the effects that debris flows and flooding have on the channel bar frequency, frequency and location of wood accumulation, and on the shape and size of the channel along BCC and NFBT. The channel entrenchment and widening has left BCC unrecognizable compared to pre-flood stream conditions. All wood has been pushed out of the channel and deposited as levees and jams outside of bankfull channel. The debris flow widened and incised BCC. Current channel conditions of BCC are up to 11 times the original width, with cross-sectional areas 7 to 23 times larger than pre-flood dimensions. Many portions of the stream are scoured to bedrock. Compared to NFBT, BCC is occupied by fewer channel bars made up of large clasts, and in-stream and streamside wood and vegetation have been ripped away. Flooding in NFBT caused bank erosion and widening that fed numerous channel bars, but did little scour the stream bed. This preserved mid-channel and riparian vegetation, allowing wood to accumulate within the stream.

# References

Anderson, S., Anderson, S., and Anderson, R., 2015, Exhumation by debris flows in the 2013 Colorado Front Range storm: Geology, v. 43, no. 5, p. 391-394, doi: 10.1130/G36507.1.

Andy, 2013, Hiking Rocky Mountain National Park: http://www.hikingrmnp.org/2013/01/macgregor-mountain-via-lumpy-ridge-th.html (accessed September 2015).

Benda, L., 1990, The influence of debris flows on channels and valley floors in the Oregon Coast Range, USA: Earth Surface Processes and Landforms, v.15, no. 5, p. 457-466.

Brummer CJ, Abbe TB, Sampson JR, Montgomery DR. 2006. Influence of vertical channel change associated with wood accumulations on delineating channel migration zones, Washington, USA. Geomorphology 80: 295-309.

Cenderelli, D.A. and Kite, J.S., 1998, Geomorphic effects of large debris flows on channel morphology at North Fork Mountain, eastern West Virginia, USA *in* Earth Surface Processes and Landforms, p. 1096-9837, doi: 10.1002/(SICI)1096-9837(199801)23:1<1::AID-ESP814>3.0.CO;2-3.

Clausen, E., 2012, Cache la Poudre River-Big Thompson River Drainage divide Area Landform Origins in the Colorado Mummy Ridge, USA: Geomorphology Research: http://geomorphologyresearch.com/2012/12/20/cache-la-poudre-river-big-thompson-river-drainage-divide-area-landform-origins-in-the-colorado-mummy-range-usa/ (accessed October 2015).

Coe, J.A., Kean, J.W., Godt, J.W., Baum, R.L., Jones, E.S., Gochis, D.J., and Anderson, G.S., 2014, New insights into debris-flow hazards from an extraordinary event in the Colorado Front Range: GSA Today, v. 24, no. 10, doi: 10.1130/GSATG214A.1.

Collins BD, Montgomery DR, Fetherston KL, Abbe TB. 2012. The floodplain large-wood cycle hypothesis: a mechanism for the physical and biotic structuring of temperate forested alluvial valleys in the North Pacific coastal ecoregion. Geomorphology 139-140: 460-470.

Dickinson, W.R., Klute, M.A., Hayes, M.J., Jancke, S.U., Lundin, M.A., McKittrick, M.A., and Olivares, M.D., 1988, Paleogeographic and paleotectonic setting of the Laramide sedimentary basins in the central Rocky Mountain region: Geoloical Society of America Bulletin, v. 100, p. 1023-1039, doi: 10.1130/0016-7606(1988)100<1023:PAPSOL>2.3.CO;2.

Eaton , L.S., Morgan, B.A., Kochel, R.C., Howards, A.D., 2003, Role of debris flow in long-term landscape denudation in the central Appalachians of Virginia, Geology, v. 31, p. 339-342 ,doi: 10.1130/0091-7613(2003)031<0339:RODFIL>2.0.CO;2.

Gochis, D., Schumacher, R., Friedrich, K., Doesken, N., Kelsh, M., Sun, J., Ikeda, K., Lindsey, D., Wood, A., Dolan, B., Matrosov, S., Newman, A., Mahoney, K., Rutledge, S., Johnson, R., Kucera, P., Kennedy, P., Sempere-Torres, D., Steiner, M., Roberts, R., Wilson, J., Yu, W., Chandrasekar, V., Rasmussen, R., Anderson, A., and Brown, B., 2015, The Great Colorado Flood of September 2013: Bulletin of American Meteorological Society, no. 96, p. 1461–1487, doi: http://dx.doi.org/10.1175/BAMS-D-13-00241.1.

Great Outdoors Colorado, 2015, Colorado Flood recovery: One Year Later: http://www.goco.org/blog/colorado-flood-recovery-one-year-later (accessed February 2016).

Griffin, K., 2012, Geology Teacher Guide to Rocky Mountain National Park: National Park Service: http://www.nps.gov/romo/learn/education/upload/Teacher_Guide_to_RMNP_Geology.pdf (accessed August 2015).

Hines, S., 2014, Science You Can Use Bulletin, US Forest Service Rocky Mountain Research Station, Issue 10: http://www.fs.fed.us/rm/science-application-integration/docs/science-you-can-use/2014-03.pdf (accessed May 2015).

Jarrett, R.D., 1990, Paleohydraulic techniques used to define the spatial occurrence of floods: geomorphology, v. 3, p. 181-195.

Johnson, C. G., Kokelaar, B. P., Iverson, R., Logan, M., LaHusen, R. G., & Gray, J. M. N. T., 2012, Grain-size segregation and levee formation in geophysical mass flows: Journal of Geophysical Research: Earth Surface, v.117, doi:10.1029/2011JF002185.

Klaar MJ, Hill DF, Maddock I, Milner AM. 2011. Interactions between instream wood and hydrogeomorphic development within recently degraded streams in Glacier Bay National Park, Alaska: Geomorphology, v. 130, p. 208-220.

Magilligan, F.J., Buraas, E.M., Renshaw, C.E., 2015, The efficacy of stream power and flow duration on geomporphic responses to catastrophic flooding: Geomorphology, v. 228, p.175-188: http://dx.doi.org/10.1016/j.geomorph.2014.08.016.

McCain, J.F., Hoxit, L.R., Maddox, R.A., Chappell, C.F., and Caracena, F., 1979, Storm and Flood of July 31-August 1, 1976, in the Big Thompson River and Cache la Poudre River Basins, Larimer and Weld Counties, Colorado: U.S. Geological Survey, National Oceanic and Atmospheric Administration Cooperating Organization: Colorado Geological Survey: United States Geological Survey Professional Paper 1115: http://pubs.usgs.gov/pp/1115a-b/report.pdf (accessed October 2015).

McCreary, J., 2004, Colorado Geology Overview: http://www.cliffshade.com/colorado/geo_overview.htm (accessed October 2015).

Montgomery, D.R., 2008, A Simple Alphanumeric Classification of Wood Debris Size and Shape: Stream Notes.

Montgomery, D.R., Abbe, T.B., Buffington, J.M., Peterson, N.P., Schmidt, K.M., and Stock, J.D., 1996, Distribution of bedrock and alluvial channels in forested mountain drainage basins: Letters to Nature, v. 38, p. 587-589.

Montgomery, D.R., Collins, B.D., Buffington, J.M., Abbe, T.B., 2003, Geomorphic Effects of Wood in Rivers: American Fisheries Society Symposium.

National Park Service, 2014, U.S. Department of Interior Rocky Mountain National Park, Front Range Floods Teacher Guide: http://www.nps.gov/romo/learn/education/upload/Floods-final.pdf (accessed September 2015).

NCAR, 2007, Colorado Flood Summaries by Location: http://www.assessment.ucar.edu/flood/fld_sum_loc.html (accessed September 2015).

Runnells, D. D., 1976, Boulder: A Sight to Behold: Guidebook: Self-Guided Tours of the Historic City, Geology and Scenery, University of Colorado: Estey Printing Co: http://bcn.boulder.co.us/basin/natural/geology/historic.html (accessed August 2015).

Ryan, S., 2015, The impacts of the 2013 Colorado Flood on portions of the Arapaho-Roosevelt National Forest and Rocky Mountain National Park: USFS, Rocky Mountain Research Station.

Schuett-Hames, D., Pleus, A.E., Ward, J., Fox, M., and Light, J., 1999, TFW Monitoring Program Method Manual for the Large Woody Debris Survey, Prepared for the Washington State Department of Natural Resources: TFW-AM9-99-004, DNR#106.

Soule, J.M, 1976, Damage Caused by Geologic Processes during Flood Producing Storms: United States Colorado Geological Survey: United States Geological Survey Professional Paper 1115: http://pubs.usgs.gov/pp/1115a-b/report.pdf (accessed October 2015).

United States Geologic Survey, 2015, USGS Lidar Point Cloud CO SoPlatteRiver-Lot2a 2013 13TDE457480 LAS 2015.

WeatherDB, 2015, Glen Haven, Colorado Average Rainfall: http://rainfall.weatherdb.com/l/10165/Glen-Haven-Colorado (accessed October 2015).

Western Regional Climate Center, 2001, Estes Park, Colorado Period of Record Monthly Climate Summary: http://www.wrcc.dri.edu/cgi-bin/cliMAIN.pl?coeste (accessed October 2015).

Wohl, E., Bestgen, K., Bledsoe, B., Fausch, K., Gooseff, M., and Kramer, N., 2015, Management of Large Wood in Streams of Colorado's Front Range: A Risk Analysis Based on Physical, Biological, and Social Factors: Colorado State University.

Yochum, S.E., and Moore, D.S., 2013, Colorado Front Range Flood of 2013: Peak Flow Estimates at Selected Mountain Stream Locations: United States Department of Agriculture: http://water.state.co.us/DWRIPub/Documents/PeakFlowEstimates_NRCS_12-16-2013[1]%20(1).pdf (accessed August 2015).

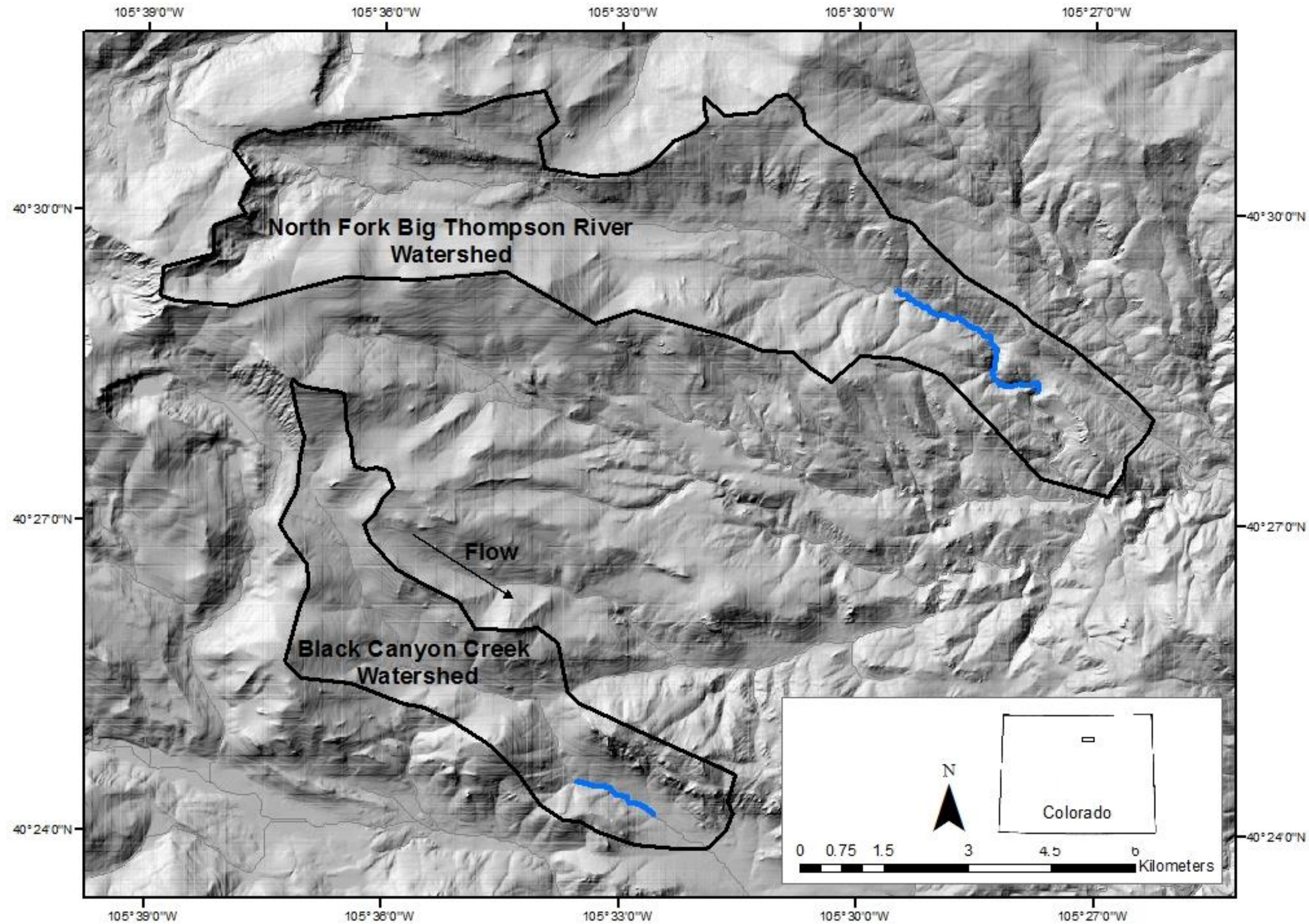

Figure 1. Location of the Black Canyon Creek and North Fork Big Thompson River watersheds. Study areas are outlined in blue.

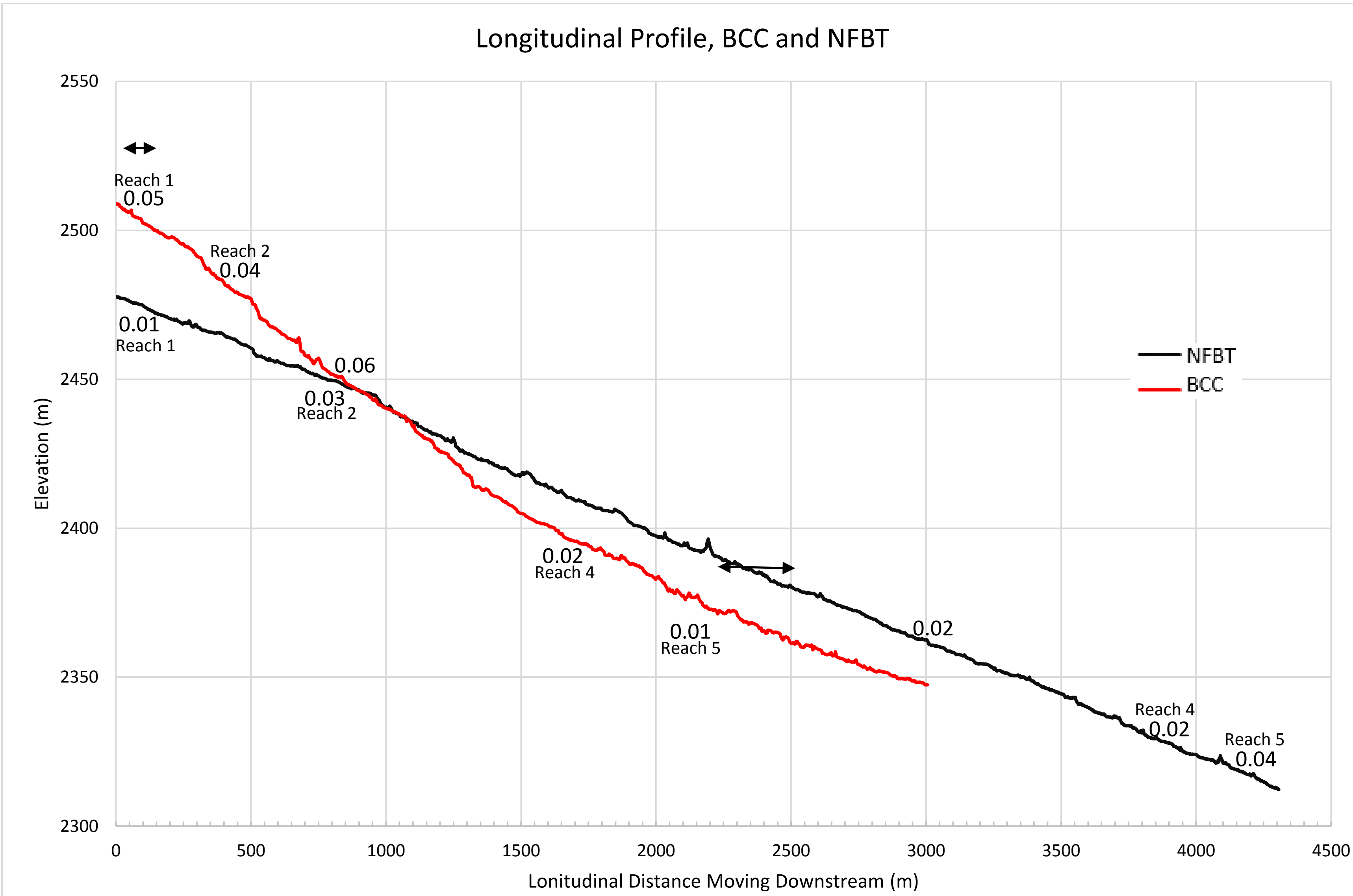


Figure 2. Longitudinal profile of BCC and NFBT study area highlights the location and mean slope of Reaches 1-5 in both streams.


Figure 3. Images of Black Canyon Creek. A) Black Canyon Creek in January 2013 before debris flow inundation (Andy, 2013). B) Black Canyon Creek above the debris flow confluence at the reference cross-section as of August 2015.

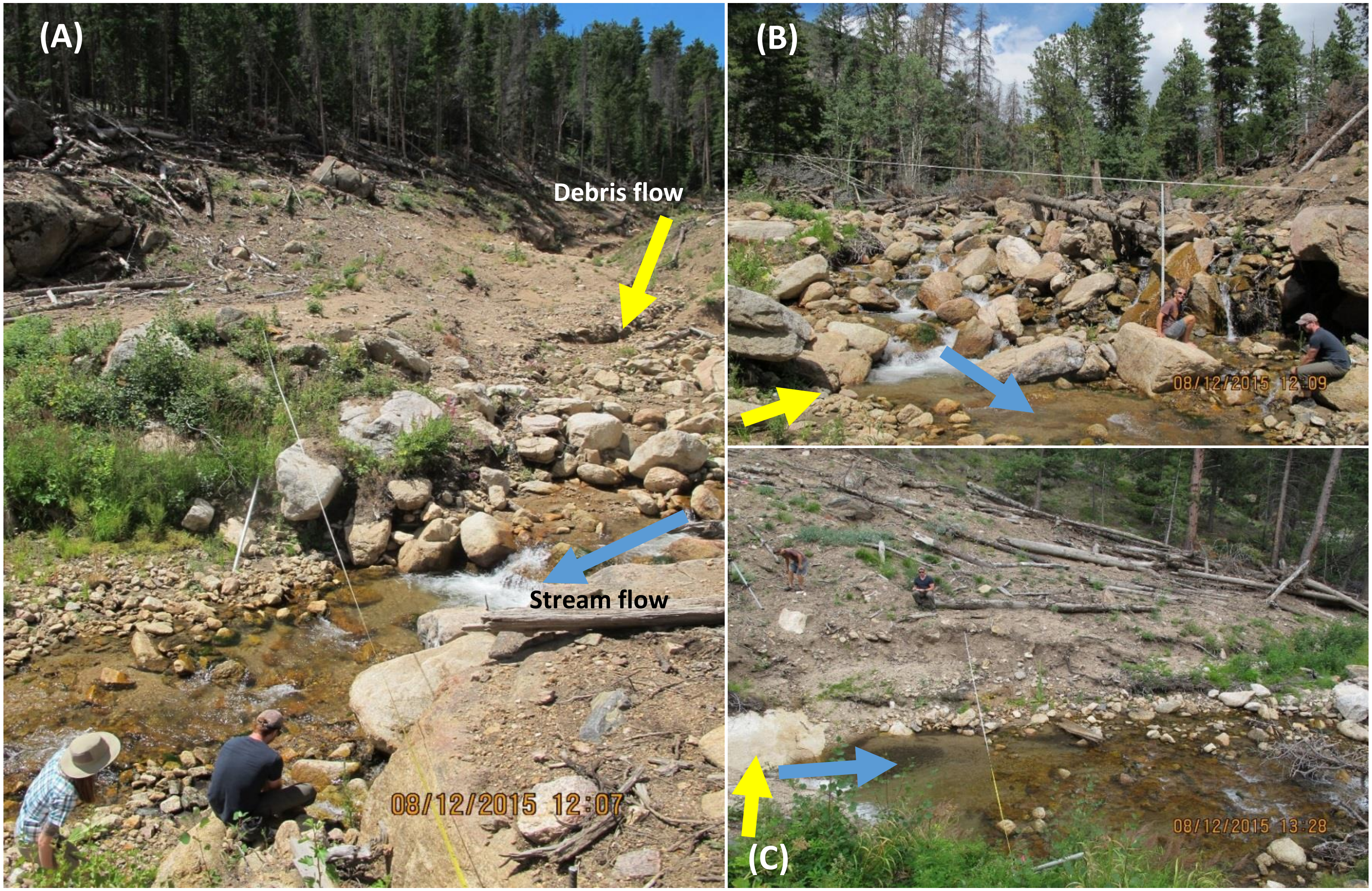


Figure 4. Debris flow and river confluence images for Black Canyon Creek taken August 2015. A) Taken from the left bank, looking across BCC towards the debris flow channel. B) Looking upstream at BCC at the large clasts and wood accumulation at the stream and debris flow confluence. C) Taken from the right bank of BCC at the stream and debris flow confluence facing towards the left bank.

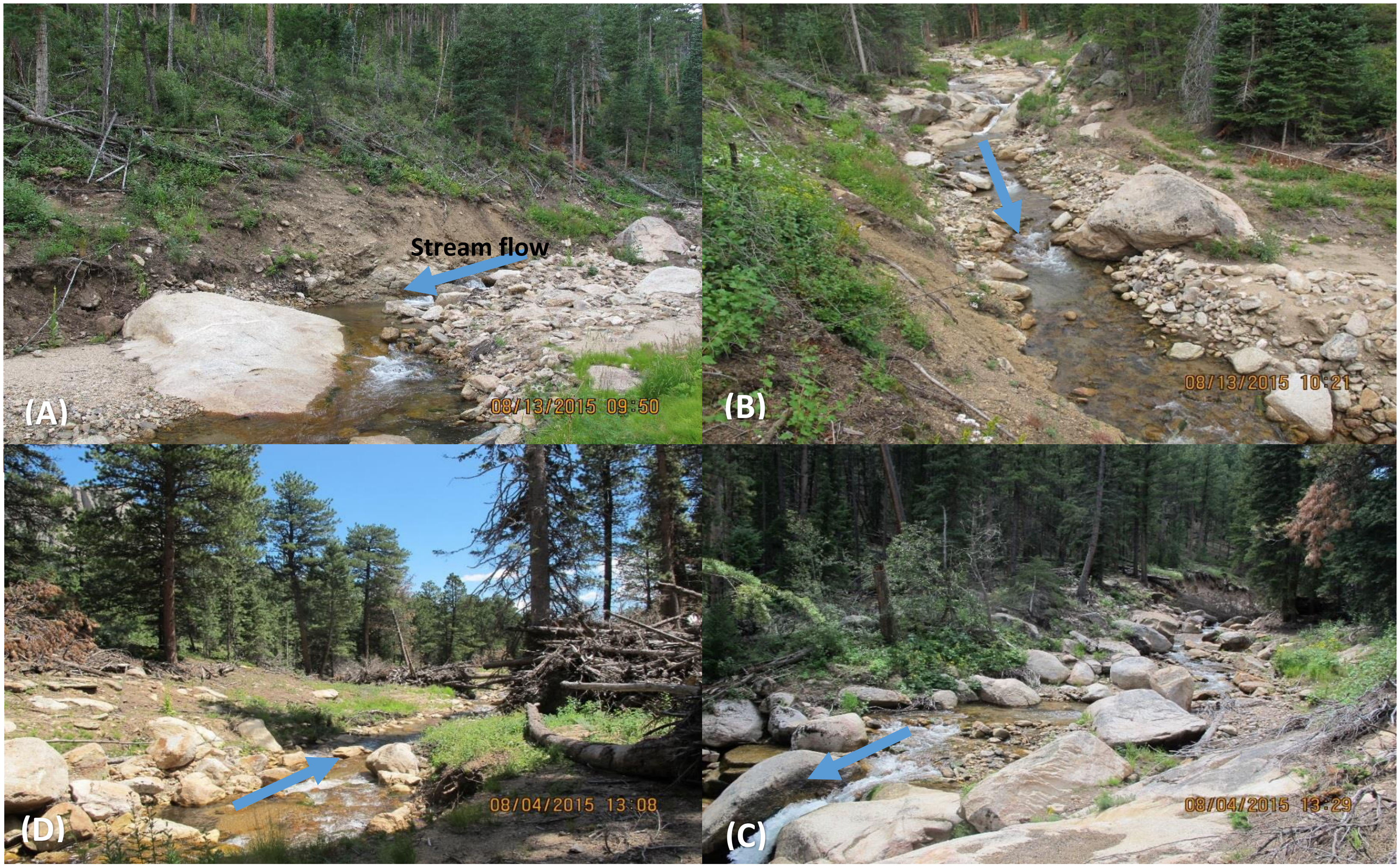

Figure 5. Scour images for Black Canyon Creek taken August 2015. Examples of the types of effects on BCC from the flood and debris flow. A) Bank erosion and boulder bar deposition 280 meters downstream of Reach 1. B) An example of incision to bedrock (above blue arrow) and bank erosion 280 meters downstream of Reach 1. C) Riparian vegetation removed by the flood on the left bank and accumulation of LW on the right bank between Reach 2 and Reach 3. D) Deposition of large boulders and channel widening in Reach 4.

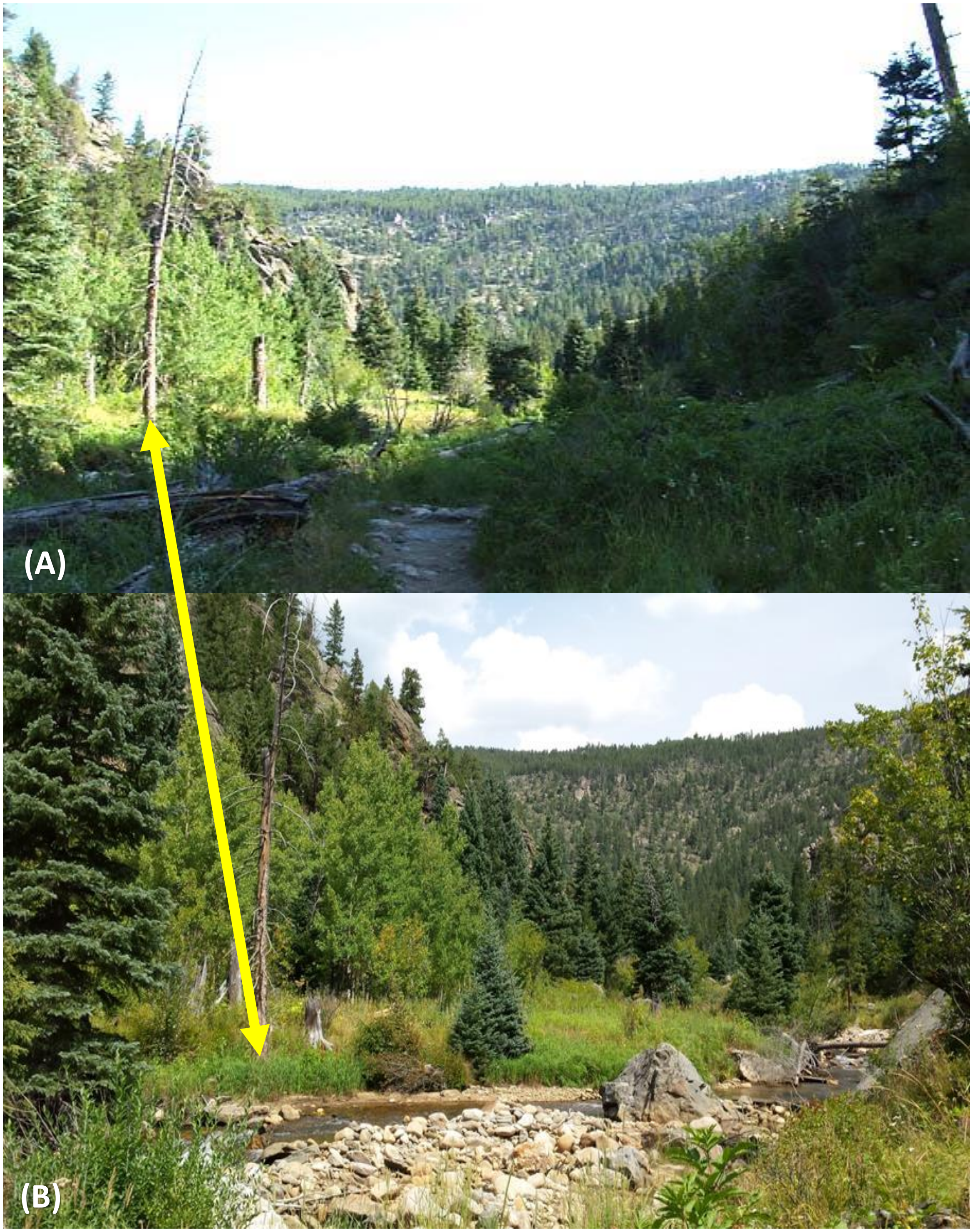

Figure 6. Before and after flood image at North Fork Big Thompson. An example along NFBT, between Reach 2 and 3, of channel widening and erosion of streamside vegetation. Yellow arrow highlighting the base of a tree used as a reference point. A) Before the flood in 2012 (http://hikingcoloradotrails.com/trails/north-fork-trail.php). B) Photo taken during my internship in August 2015.

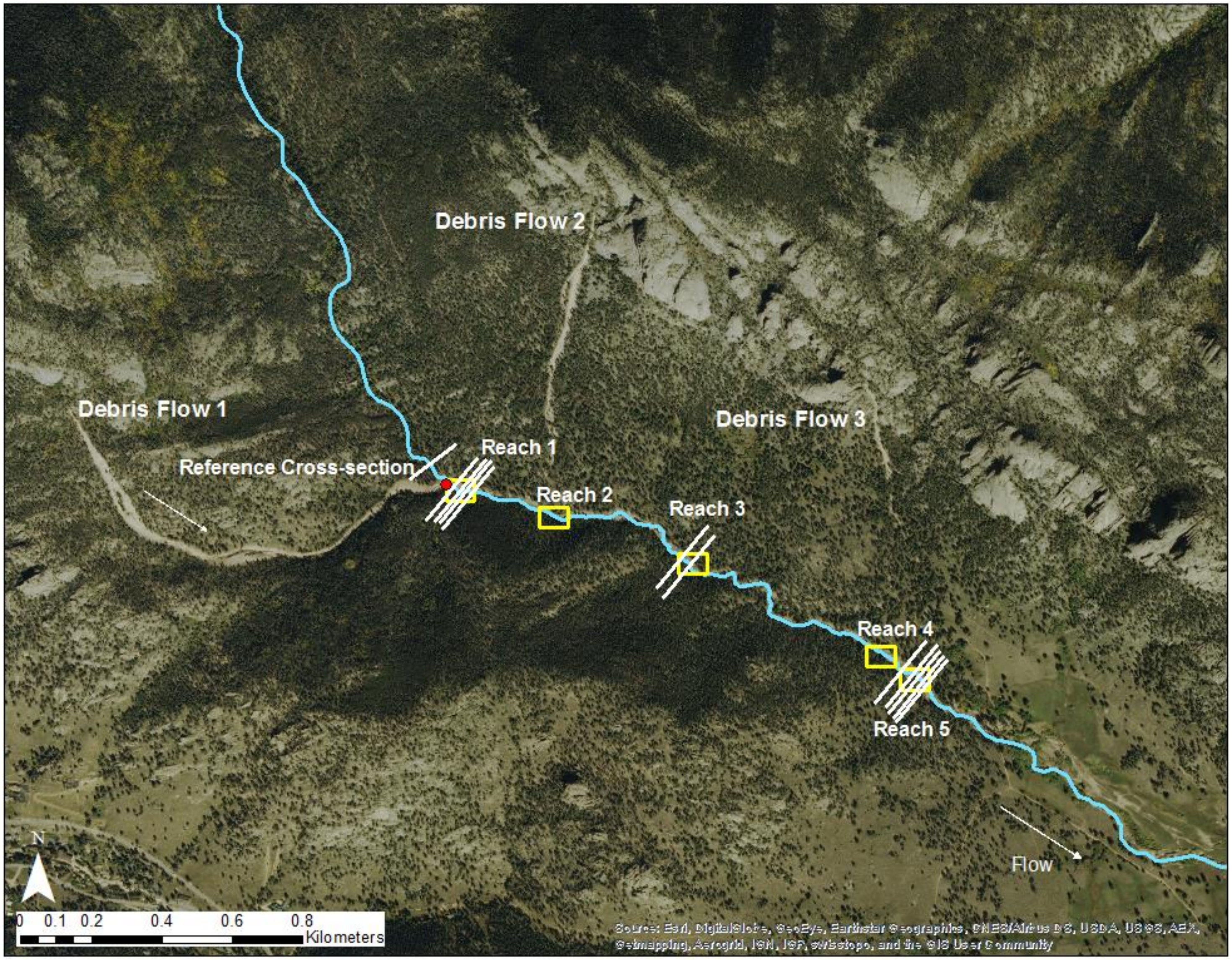


Figure 7. Black Canyon Creek Study Area.

Boxes show study reaches. White lines show cross-sections. Three debris flows occurred within BCC watershed. Debris flow 1 initiated during September 2013.

The confluence of the debris flow and creek noted with a red dot. The upstream section, above Reach 1, showed little evidence of flood impact and is the reference cross-section for pre-flood conditions

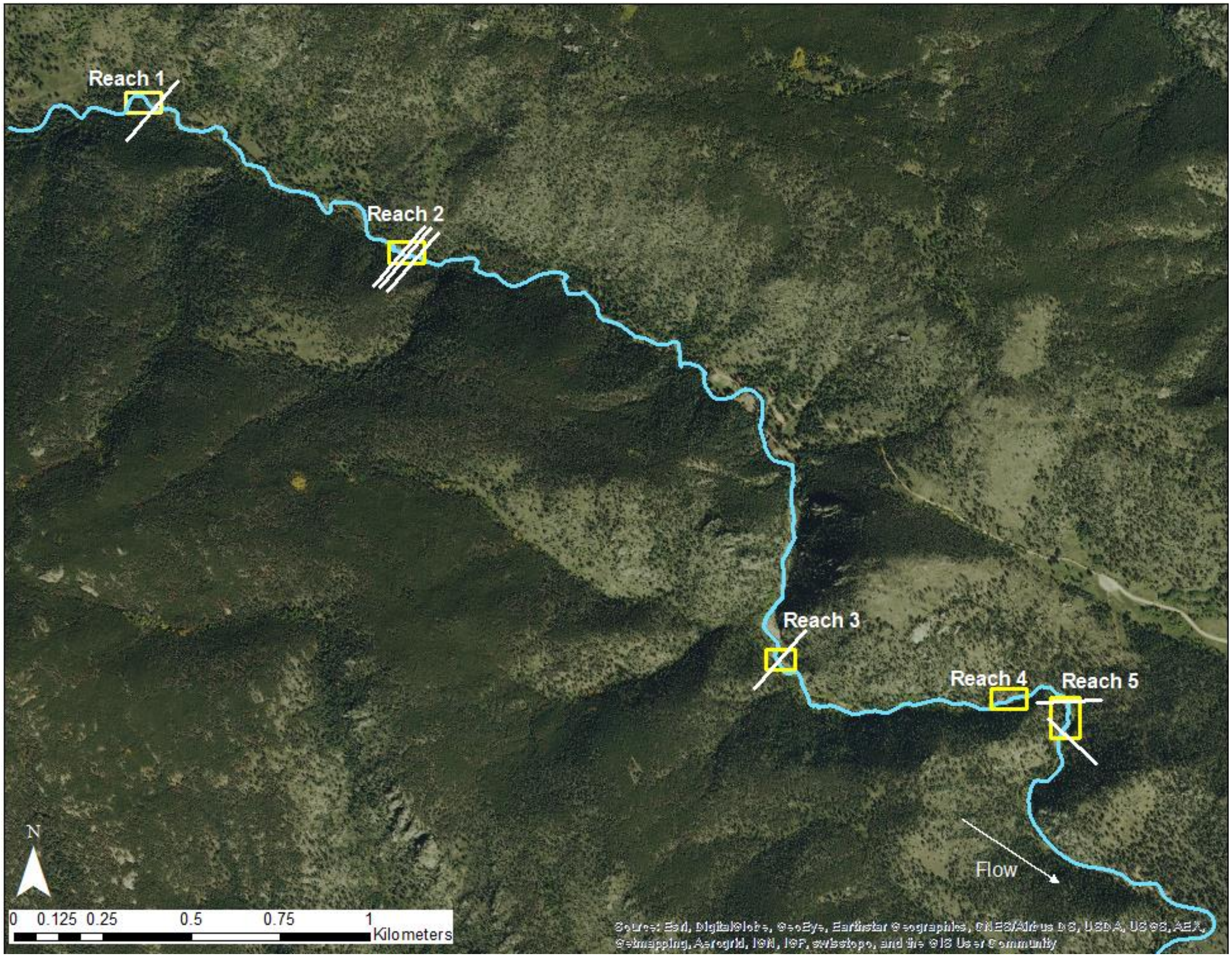

Figure 8. North Fork Big Thompson River Study Area. Boxes show study reaches. White lines show cross-sections.

**LWD Jam Data Sheet**

Stream Name:________________________________ Date:__________________________ Page __ of ________

Recorder:____________________________________________Crewmembers:_______________________________________

| GPS ID | Stability | Zone | Height above surface (m) | Length (m) | Width (m) | General composition | Broken or building | Comments |
|---|---|---|---|---|---|---|---|---|
| | | | | | | | | |
| | | | | | | | | |
| | | | | | | | | |
| | | | | | | | | |
| | | | | | | | | |
| | | | | | | | | |

| General Composition | |
|---|---|
| Wood Length letter code and classes (m) | Wood diameter numeric code and classes (m) |
| (A) 0-1 | (1) 0-0.1 |
| (B) 1-2 | (2) 0.1-0.2 |
| (C) 2-4 | (3) 0.2-0.4 |
| (D) 4-8 | (4) 0.4-0.8 |
| (E) 8-16 | (5) 0.8-1.6 |
| (F) 16-32 | (6) 1.6-3.2 |
| (G) >32 | (7) >3.2 |

| Stability | |
|---|---|
| R | Root system is attached to piece |
| B | Greater than 50% diameter buried at some point along length |
| P | Piece is pinned between vertical live or dead structures |
| U | Unstable |

| Zone system | |
|---|---|
| Zone 1 | Within wetted portion of channel |
| Zone 2 | From water surface to a line connecting the bankfull edges |
| Zone 3 | Directly above Zone 2 to infinity |
| Zone 4 | Outside of bankfull channel |

Created July 2015

Chelsey DeWitt

Additional Notes:

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______________________________________________________

______________________________________________________

Figure 9 Large Wood Jam Field Data Sheet. An example of the LW Jam Data Sheet used in the field to characterize individual LW jams. Adapted from Montgomery (2008) and Schuett-Hames et al. (1999).

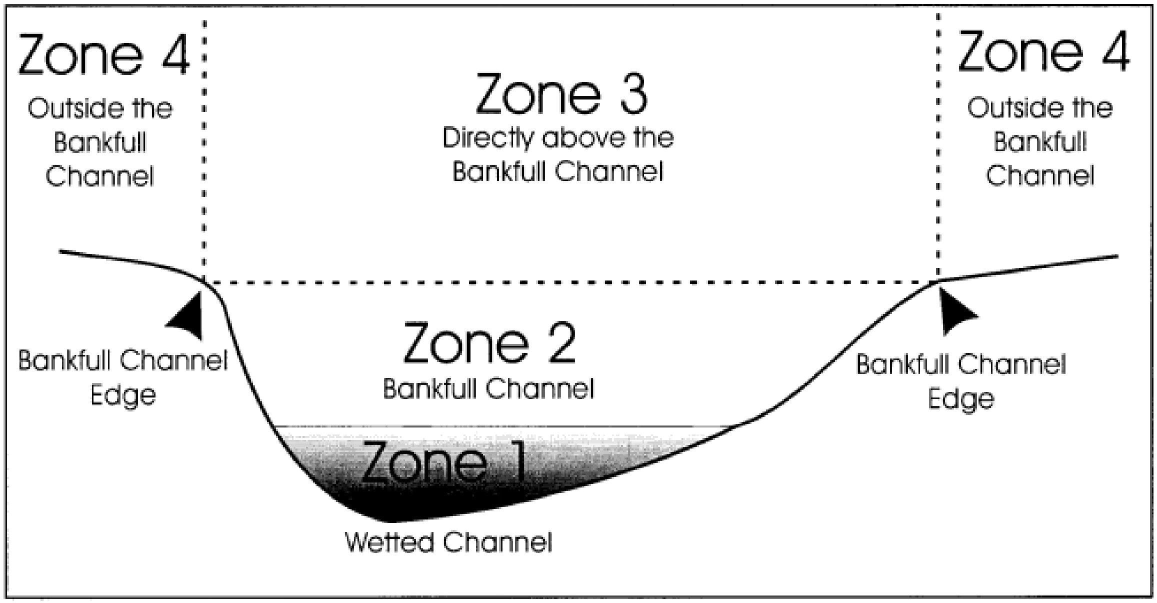



Figure 10. Criteria for channel zone identification of LW deposition. Zone 1 is defined as the portion of the bankfull channel that is wetted at the time of the survey. Zone 2 is defined as the area between the bankfull channel edges on both banks, above the wetted channel surface, and includes areas such as dry gravel bars. Zone 3 is defined as the area directly above Zone 2 and typically includes pieces that extend out over the bankfull channel that provide cover. Zone 4 is defined as the area outside of the bankfull channel and Zone 3, and typically includes the floodplain, terrace, and/or riparian areas (Schuett-Hames et al., 1999).


Figure 11. Debris line example in Black Canyon Creek along the right bank. Yellow arrow highlights elongated pattern of LW deposition that is parallel to the stream flow. Photo taken from left bank at Reach 1.

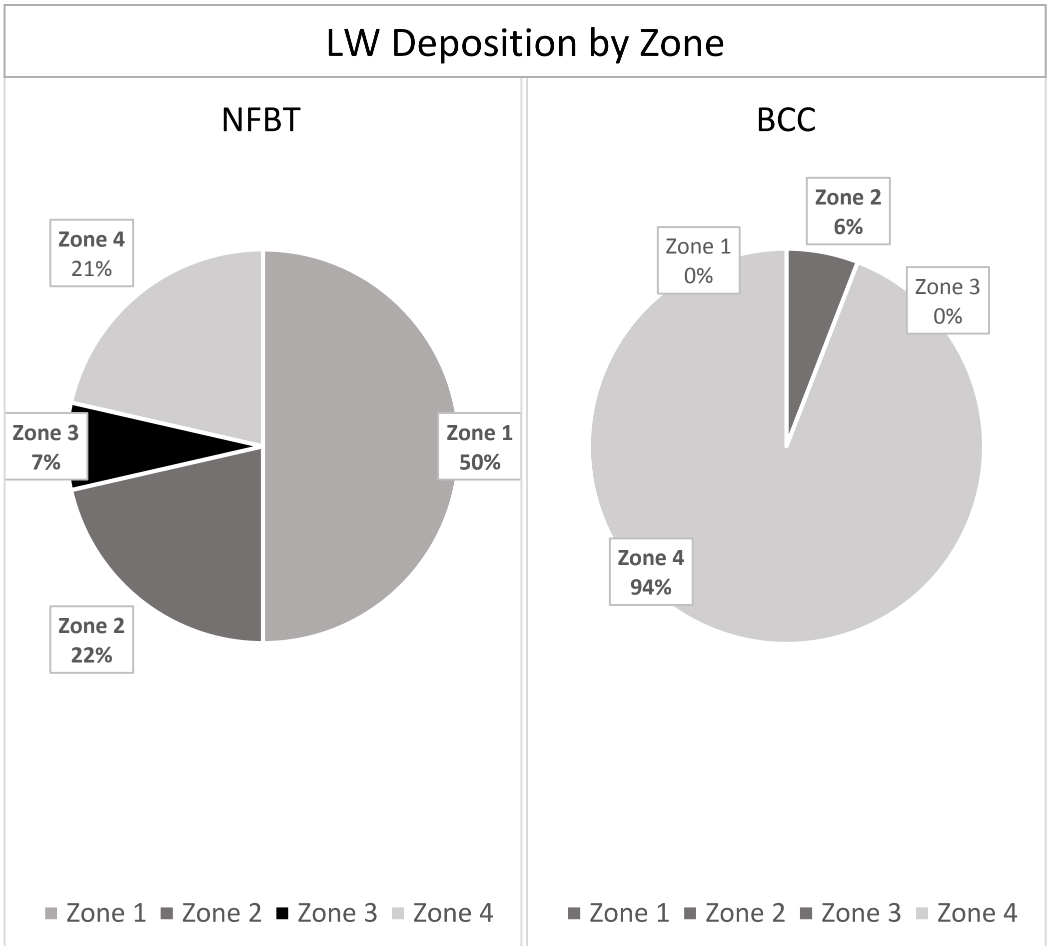



Figure 12. Large wood deposition by zone for BCC and NFBT. Zone criteria defined in Figure 11.


Figure 13. Large wood jams along Black Canyon Creek. Photos show a range of extent in the accumulation behind stable, upright trees. A) A LW jam in Reach 4. 5) A LW jam in Reach 5.

Figure 14. Large wood jams along North Fork Big Thompson. Photos show a range of extent in the accumulation behind stable, upright trees along and in the stream. A) A LW jam in upstream of Reach 4. 5) A LW jam in Reach 5.

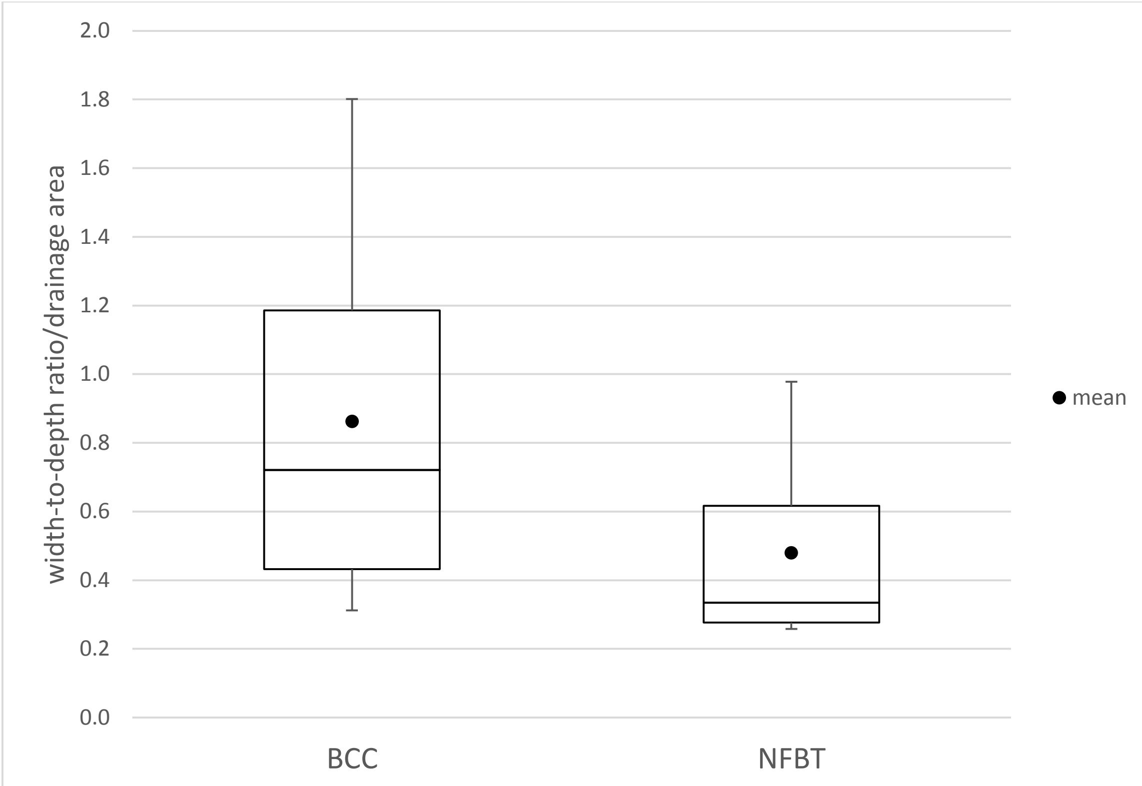



Figure 15. Width-to-depth ratio normalized by drainage area. Whiskers represent the range of data from maximum to minimum value. The box shows the interquartile range of the data. The upper box is 75th percentile and the lower box is the 25th percentile. The line within the box is the median.

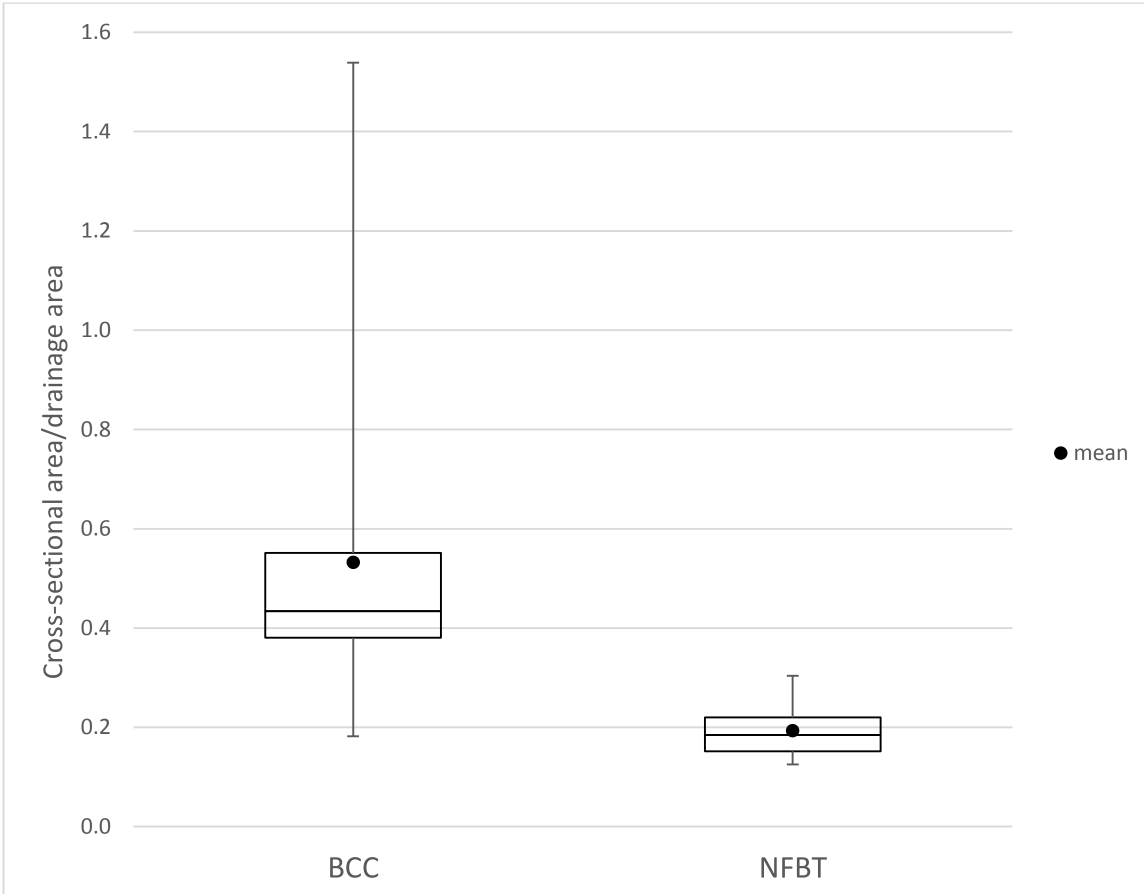



Figure 16. Cross-sectional area normalized by drainage area. Whiskers represent the range of data from maximum to minimum value. The box shows the interquartile range of the data. The upper box is 75$^{th}$ percentile and the lower box is the 25$^{th}$ percentile. The line within the box is the median.

Table 1. Reach lengths and number of cross-sections per reach in the BCC and NFBT.

| Study Area | Reach | Length (m) | Distance from Debris Flow Confluence (m) | Elevation Range (m) | Number of Cross-Sections in Reach |
|---|---|---|---|---|---|
| BCC | | | | | |
| | 1 | 129 | 10 | 2508-2511 | 4 |
| | 2 | 124.5 | 457 | 2479-2485 | 0 |
| | 3 | 78.7 | 891 | 2446-2451 | 2 |
| | 4 | 139.3 | 1601.8 | 2407-2411 | 0 |
| | 5 | 177.8 | 1950 | 2398-2400 | 5 |
| NFBT | | | | | |
| | 1 | 88 | n/a | 2475 | 1 |
| | 2 | 55 | n/a | 2442-2444 | 3 |
| | 3 | 168 | n/a | 2356-2359 | 1 |
| | 4 | 112.5 | n/a | 2322-2324 | 0 |
| | 5 | 251 | n/a | 2312-2323 | 2 |

Table 2. Frequency of LW per 100 meters in each reach in BCC and NFBT.

| Study Area | Reach | LW Frequency per 100 meters |
|---|---|---|
| BCC | | |
| | 1 | 0.8 |
| | 2 | 1.6 |
| | 3 | 3.8 |
| | 4 | 3.5 |
| | 5 | 3 |
| NFBT | | |
| | 1 | 1.1 |
| | 2 | 1.8 |
| | 3 | 1.7 |
| | 4 | n/a |
| | 5 | 3.1 |

Table 3. Frequency of channel bars per 100 meters in each reach in BCC and NFBT.

| Study Area | Reach | Channel Bar Frequency per 100 meters |
|---|---|---|
| BCC | | |
| | 1 | 0.8 |
| | 2 | 2.4 |
| | 3 | 1.3 |
| | 4 | 0.7 |
| | 5 | 0.5 |
| NFBT | | |
| | 1 | 2.2 |
| | 2 | 1.8 |
| | 3 | 0.6 |
| | 4 | 0.9 |
| | 5 | 1.9 |

Table 4. Pebblecount results for BCC.

| Grain size | Diameter (mm) | Reach 1 | Reach 2 | Reach 3 | Reach 4 | Reach 5 |
|---|---|---|---|---|---|---|
| Sand | <2 | | | | | |
| VF Gravel | 2 - 2.8 | | | | | |
| VF Gravel | 2.8 - 4 | | | | | |
| Fine Gravel | 4 - 5.6 | 15 | | | | |
| Fine Gravel | 5.6 - 8 | 8 | 11 | | 22 | 15 |
| Med. Gravel | 8 - 11.3 | 12 | 8 | 6 | 7 | 5 |
| Med. Gravel | 11.3 - 16 | 2 | 0 | 2 | 4 | 8 |
| Coarse Gravel | 16 - 22.6 | 5 | 0 | 1 | 14 | 7 |
| Coarse Gravel | 22.6 - 32 | 4 | 1 | 3 | 26 | 10 |
| VC Gravel | 32 - 45.3 | 2 | 4 | 4 | 11 | 17 |
| VC Gravel | 45.3 - 64 | 3 | 8 | 7 | 37 | 26 |
| Sm. Cobble | 64 - 90.5 | | 10 | 10 | 16 | 19 |
| Sm. Cobble | 90.5 - 128 | 2 | 4 | 10 | 11 | 23 |
| Lg. Cobble | 128 - 181 | | 7 | 7 | 5 | 9 |
| Lg. Cobble | 181 - 256 | | 1 | 6 | 2 | 8 |
| Sm. Boulder | 256 - 362 | 1 | 3 | | 9 | 4 |
| Sm. Boulder | 362 - 512 | | | | 4 | 3 |
| Med. Boulder | 512 - 1024 | | | | | 3 |
| Lg. Boulder | 1024 - 2048 | | | | | 1 |
| VL Boulder | 2048 - 4096 | | | | | |
| Bedrock | >4096 | | | | | |
| Sample total | | 54 | 57 | 56 | 168 | 158 |

Table 5. Drainage area and dimensions at each cross-section along BCC and NFBT.

| Cross-Sections by Reach | DA in km^2 | widths (m) | average depth (m) | Cross-section area ($m^2$) | w:d/ Drainage Area | Cross-sectional Area/ Drainage Area |
|---|---|---|---|---|---|---|
| BCC | | | | | | |
| Reference cross-section | 14.5 | 1.3 | 0.9 | 1.1 | 0.1 | 0.1 |
| 1.1 | 15.4 | 11.8 | 2.0 | 23.7 | 0.4 | 1.5 |
| 1.2 | 15.6 | 7.2 | 1.0 | 6.8 | 0.5 | 0.4 |
| 1.3 | 15.6 | 7.2 | 0.8 | 5.8 | 0.6 | 0.4 |
| 1.4 | 15.6 | 12.1 | 0.8 | 9.0 | 1.0 | 0.6 |
| 3.1 | 16.4 | 12.2 | 0.6 | 6.7 | 1.2 | 0.4 |
| 3.2 | 16.4 | 11.4 | 0.6 | 6.4 | 1.2 | 0.4 |
| 5.1 | 17.2 | 16.6 | 0.6 | 10.8 | 1.5 | 0.6 |
| 5.2 | 17.2 | 19.7 | 0.6 | 9.0 | 1.8 | 0.5 |
| 5.3 | 17.2 | 9.7 | 0.8 | 8.5 | 0.7 | 0.5 |
| 5.4 | 17.2 | 5.6 | 0.9 | 5.3 | 0.4 | 0.3 |
| 5.5 | 17.9 | 4.7 | 0.8 | 3.3 | 0.3 | 0.2 |
| Average | | 10.7 | 0.9 | | 0.9 | |
| NFBT | | | | | | |
| 1.1 | 39.5 | 10.4 | 0.5 | 5.5 | 0.6 | 0.1 |
| 2.1 | 41.2 | 9.0 | 0.8 | 8.0 | 0.3 | 0.2 |
| 2.2 | 41.2 | 10.7 | 0.9 | 10.1 | 0.3 | 0.2 |
| 2.3 | 41.4 | 9.5 | 0.7 | 6.8 | 0.3 | 0.2 |
| 3.1 | 44.6 | 8.1 | 0.7 | 5.6 | 0.3 | 0.1 |
| 5.1 | 45.2 | 19.4 | 0.4 | 8.3 | 1.0 | 0.2 |
| 5.2 | 45.2 | 21.7 | 0.7 | 13.7 | 0.7 | 0.3 |
| Average | | 12.7 | 0.7 | | 0.5 | |

# APPENDIX A: Survey data information

Table A 1. Dimension data for individual LW jam in each reach along BCC.

| Reach | Area ($m^2$) | Height (m) | Length (m) | Width (m) |
|---|---|---|---|---|
| 1 | 27.3 | 0.5 | 8 | 3 |
| 2 | 14.9 | 1 | 6 | 3 |
| | 9.0 | 1 | 5 | 3 |
| 3 | 12.2 | 1 | 5 | 3 |
| | 70.3 | 1.5 | 10 | 7.5 |
| | 37.0 | 1.1 | 11 | 4 |
| 4 | 125.1 | 1.8 | 23 | 7 |
| | 18.8 | 2 | 12 | 2.5 |
| | 70.9 | 3 | 14 | 4 |
| | 369.9 | 3 | 25 | 19 |
| | 161.0 | 3 | 23 | 8 |
| 5 | 65.1 | 1.5 | 13 | 6 |
| | 7.4 | 0.5 | 10 | 1.5 |
| | 15.1 | 2.5 | 4.5 | 3.5 |
| | 725.1 | 2 | 57 | 15 |
| | 138.3 | 1.5 | 24 | 7 |
| | 104.4 | 1 | 20 | 5 |

Table A 2. Dimension data for individual LW jam in each reach along NFBT. Reach 4 had no LW jams.

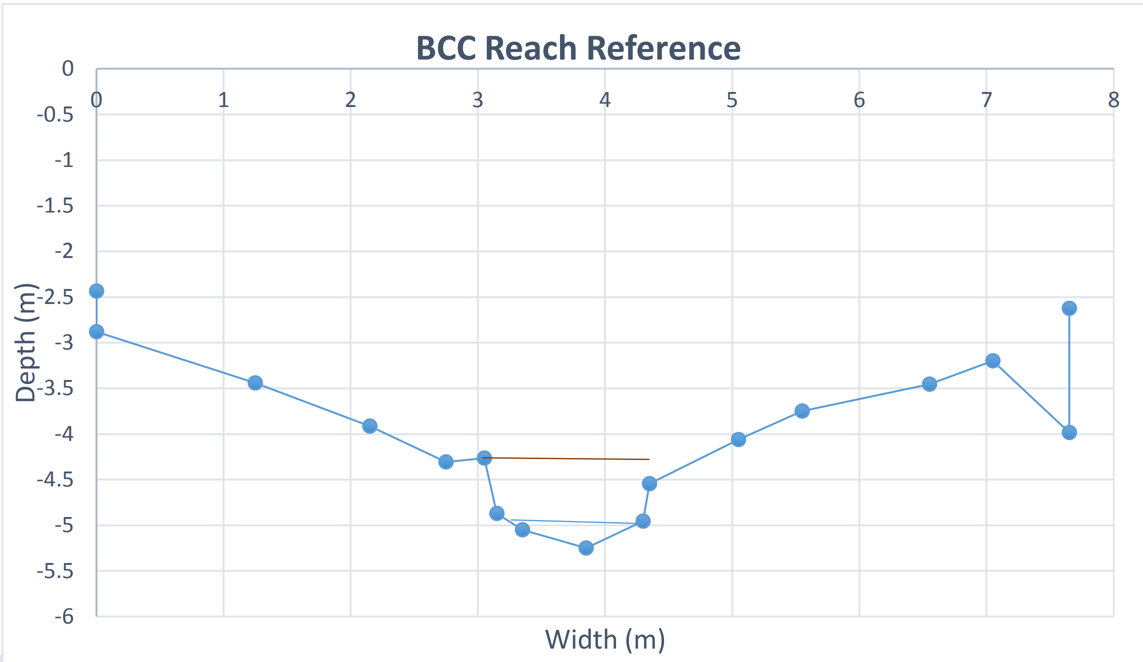
| Reach | Area ($m^2$) | Height (m) | Length (m) | Width (m) |
|---|---|---|---|---|
| 1 | 125.7 | 2.1 | 17.5 | 8.5 |
| 2 | 54.6 | 2 | 15 | 4 |
| 3 | 27.5 | 2 | 7 | 3 |
| | 16.0 | 1.3 | 12 | 1.5 |
| | 46.1 | 1 | 13 | 3 |
| 4 | n/a | n/a | n/a | n/a |
| 5 | 31.6 | 3.3 | 13.5 | 3 |
| | 6.1 | 1.75 | 4 | 3 |
| | 13.8 | 2 | 7.5 | 3 |
| | 2.9 | 2.5 | 3.5 | 1 |
| | 203.5 | 1.5 | 15 | 10 |
| | 128.4 | 1 | 21 | 1.8 |
| | 4.3 | 1 | 2.3 | 1.8 |
| | 92.3 | 1.5 | 16 | 5 |

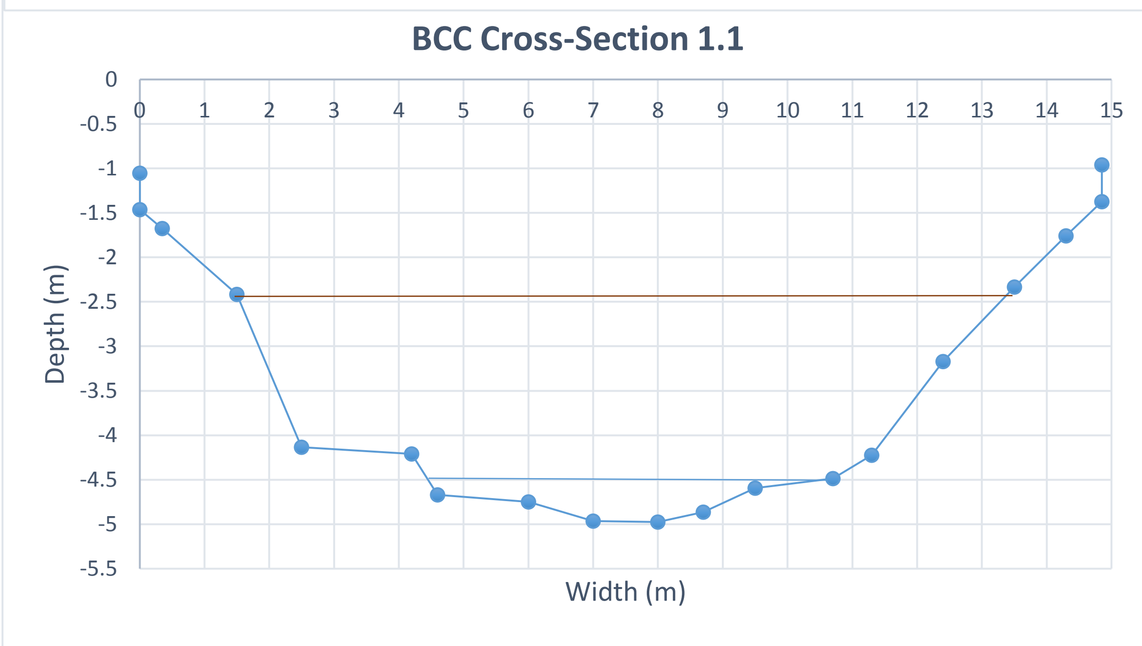
Table A 3.Channel bar areas for each reach along BCC and NFBT.

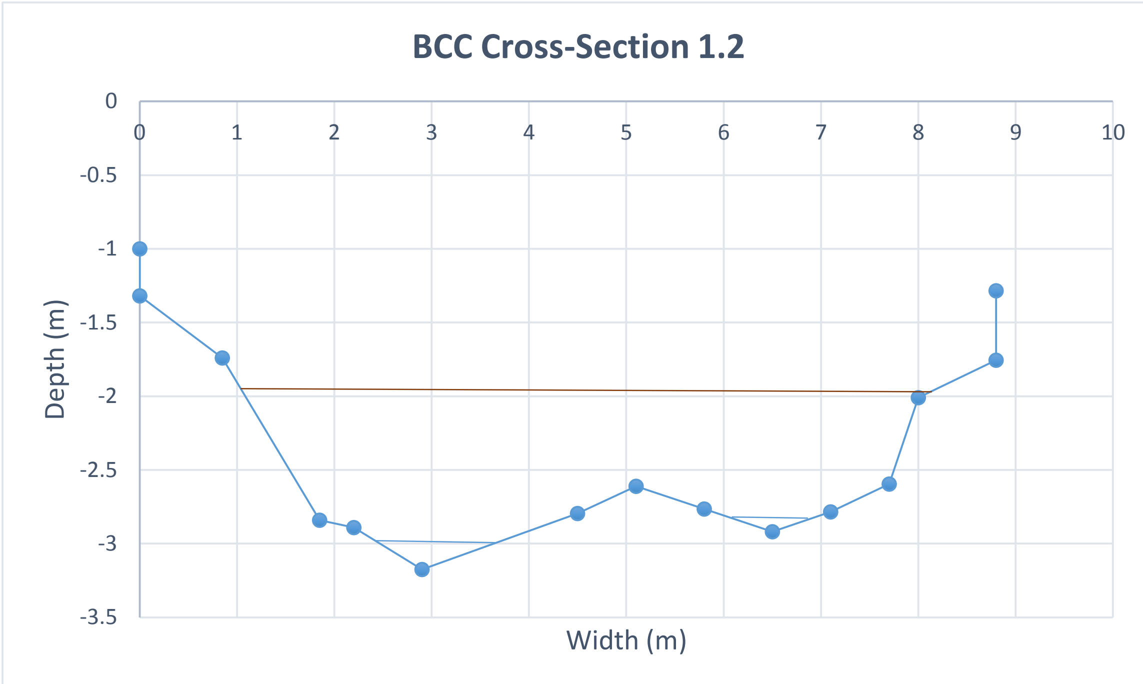
| Study Area | Reach | Area ($m^2$) |
|---|---|---|
| BCC | | |
| | 1 | 46.2 |
| | 2 | 185.5 |
| | | 196.8 |
| | | 243.4 |
| | 3 | 547.9 |
| | 4 | 855.1 |
| | 5 | 876.4 |
| NFBT | | |
| | 1 | 220.6 |
| | | 104.5 |
| | 2 | 211.9 |
| | 3 | 1742.9 |
| | 4 | 1437 |
| | 5 | 514.9 |
| | | 117.43 |
| | | 120.4 |
| | | 828.9 |
| | | 84.5 |

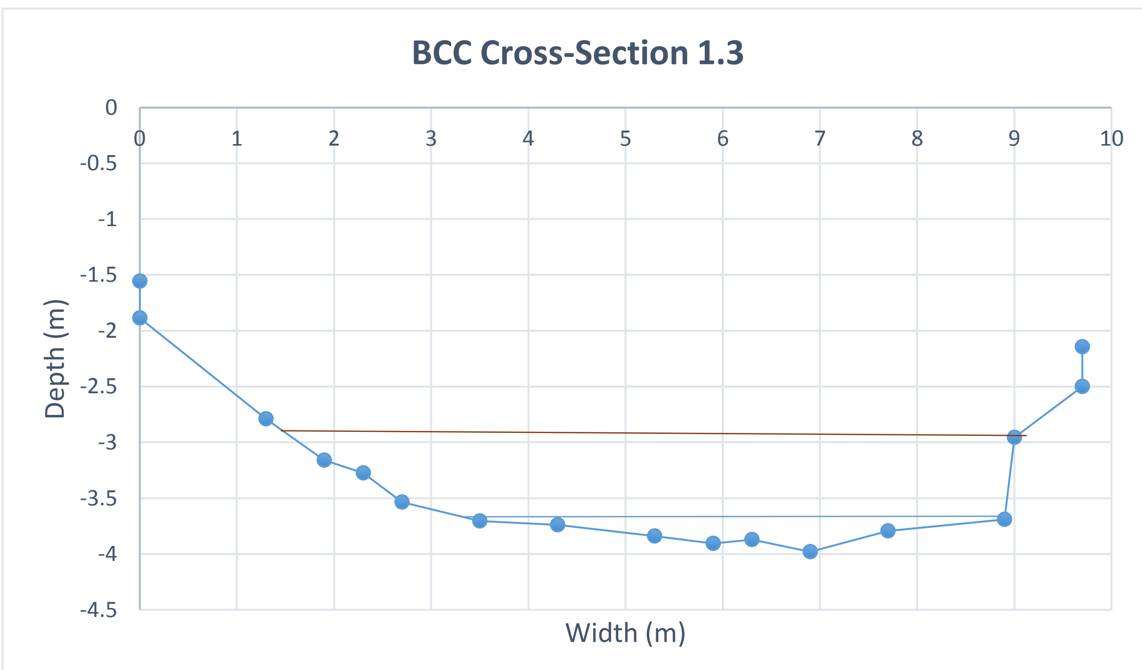
# APPENDIX B: Channel Cross-Sections

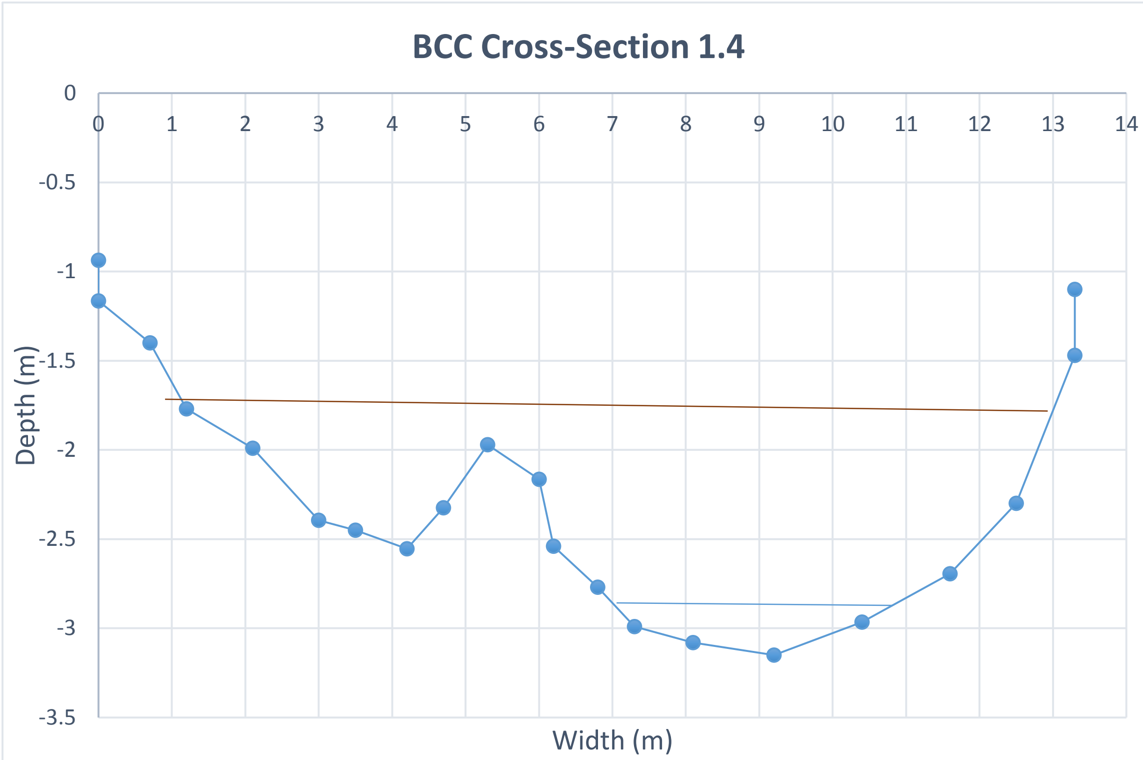
Figure B 1. Cross-sections along BCC. The brown line is estimated bankfull and the blue line is wetted width. Depth is relative to eye level of auto level.

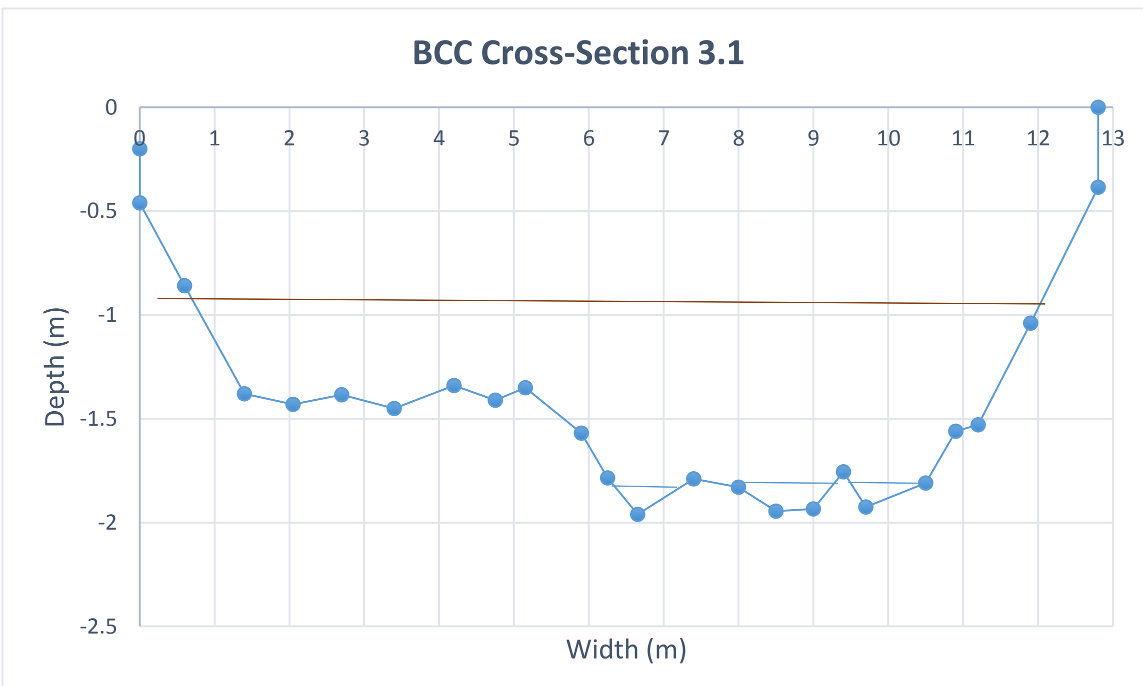


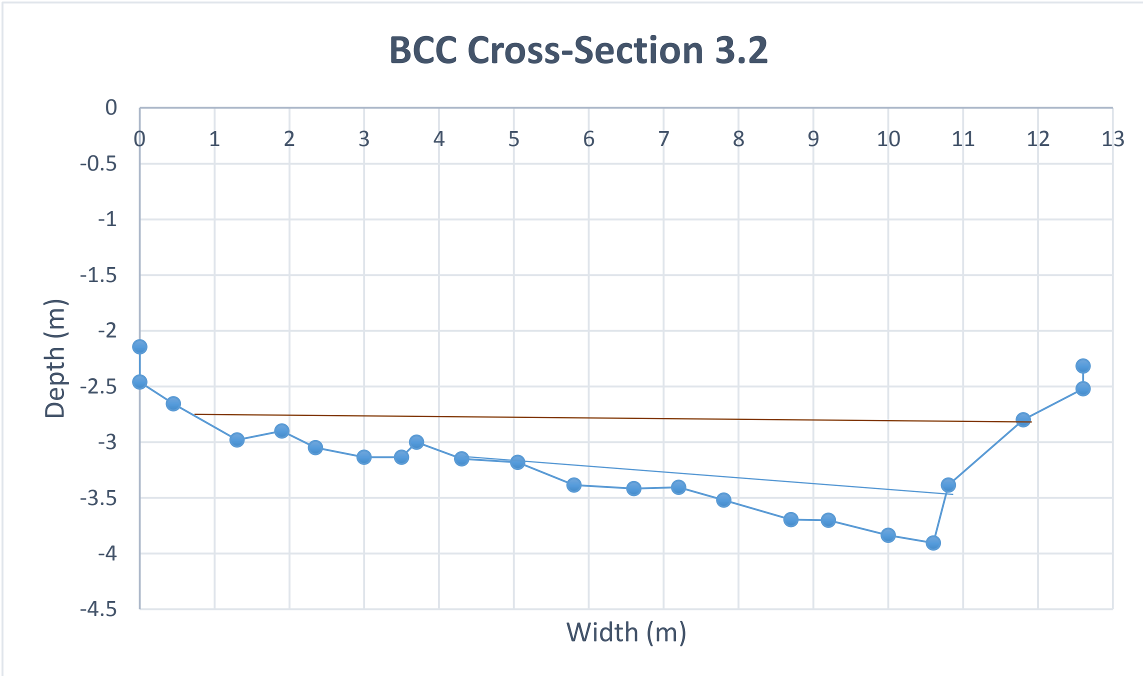



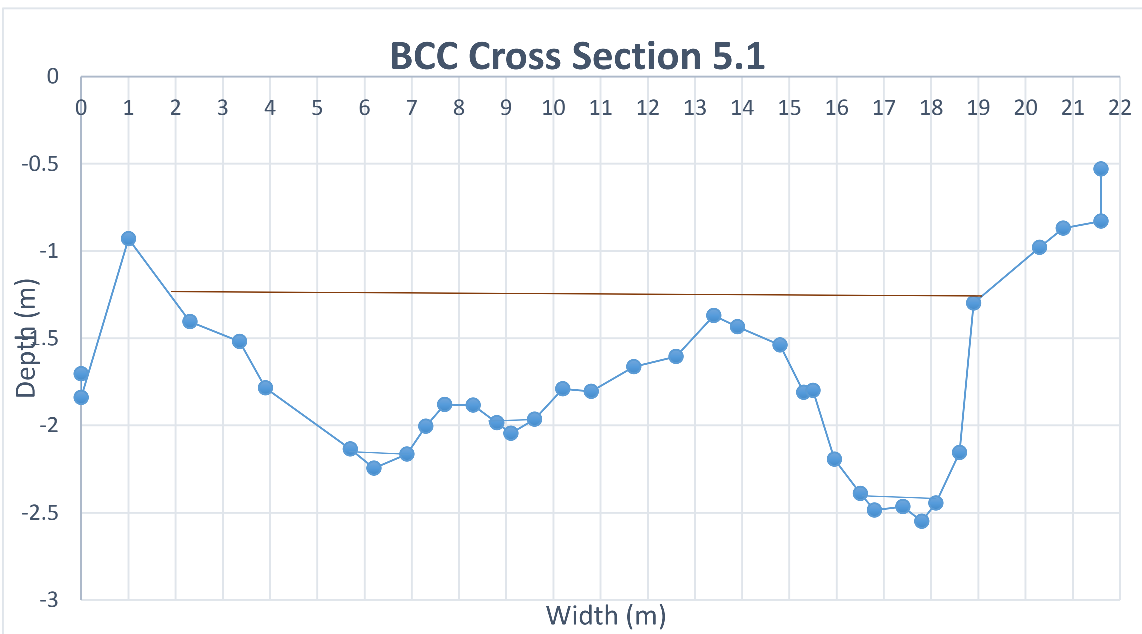

BCC Cross-Section 1.2
0
-0.5
-1
-1.5
-2
-2.5
-3
-3.5
0 1 2 3 4 5 6 7 8 9 10
Depth (m)
Width (m)

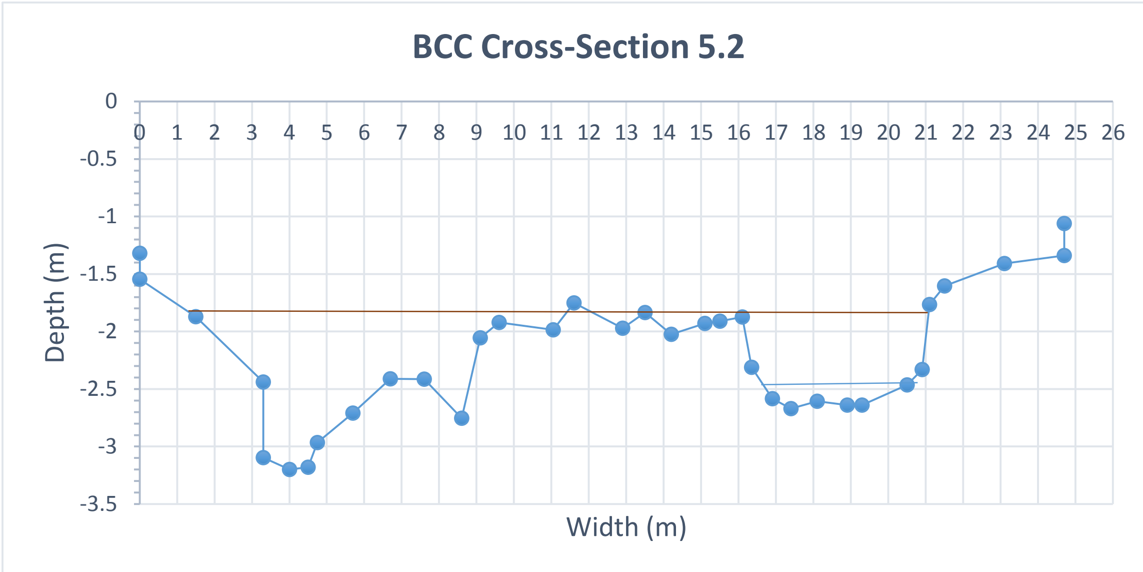

BCC Cross-Section 1.3
0
-0.5
-1
-1.5
-2
-2.5
-3
-3.5
-4
-4.5
0 1 2 3 4 5 6 7 8 9 10
Depth (m)
Width (m)

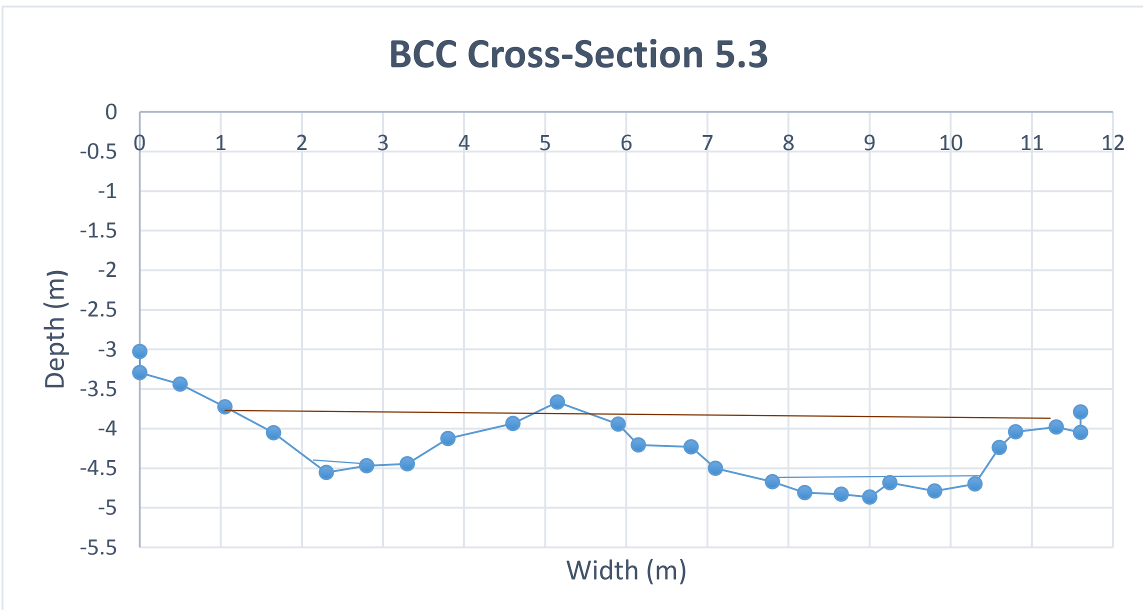

BCC Cross-Section 1.4
Depth (m)
Width (m)
0
-0.5
-1
-1.5
-2
-2.5
-3
-3.5
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14

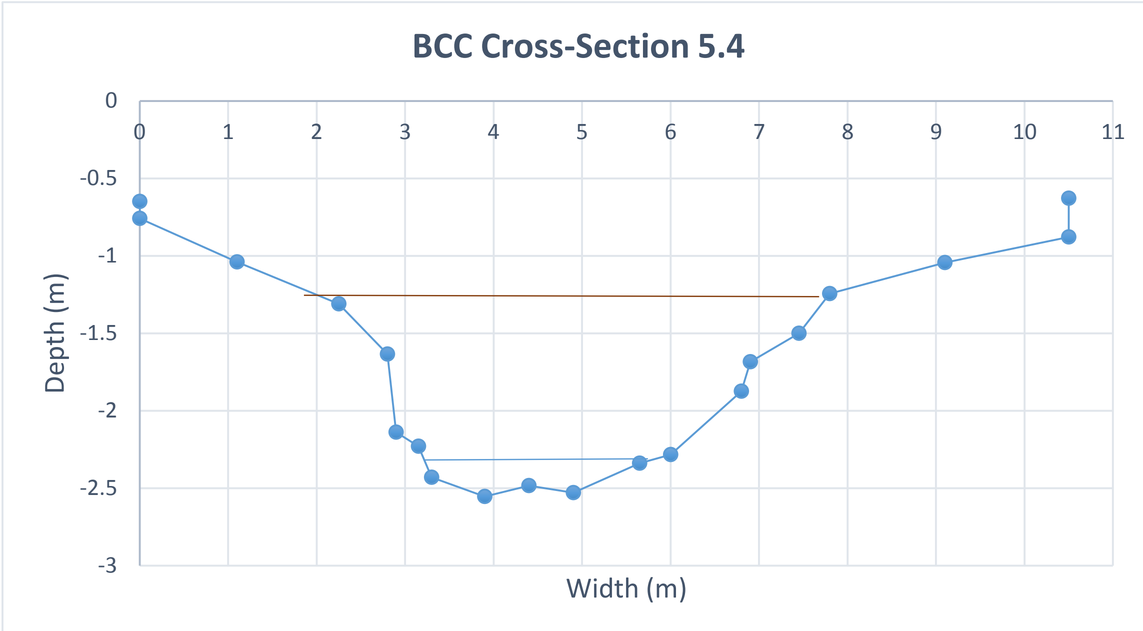

BCC Cross-Section 3.1
Depth (m)
Width (m)
0
-0.5
-1
-1.5
-2
-2.5
0 1 2 3 4 5 6 7 8 9 10 11 12 13


BCC Cross-Section 3.2
Depth (m)
Width (m)
0
-0.5
-1
-1.5
-2
-2.5
-3
-3.5
-4
-4.5
0 1 2 3 4 5 6 7 8 9 10 11 12 13


BCC Cross Section 5.1
Depth (m)
Width (m)
0
-0.5
-1
-1.5
-2
-2.5
-3
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22


BCC Cross-Section 5.2
Depth (m)
Width (m)
0
-0.5
-1
-1.5
-2
-2.5
-3
-3.5
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26


BCC Cross-Section 5.3
Depth (m)
Width (m)
0
-0.5
-1
-1.5
-2
-2.5
-3
-3.5
-4
-4.5
-5
-5.5
0 1 2 3 4 5 6 7 8 9 10 11 12


BCC Cross-Section 5.4
Depth (m)
Width (m)
0
-0.5
-1
-1.5
-2
-2.5
-3
0 1 2 3 4 5 6 7 8 9 10 11

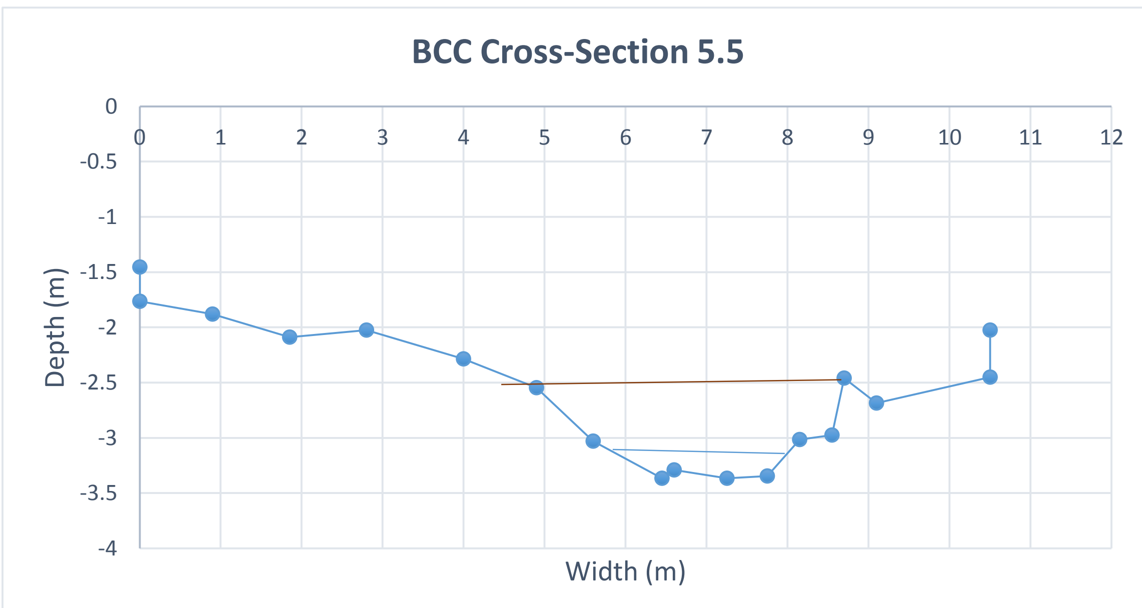
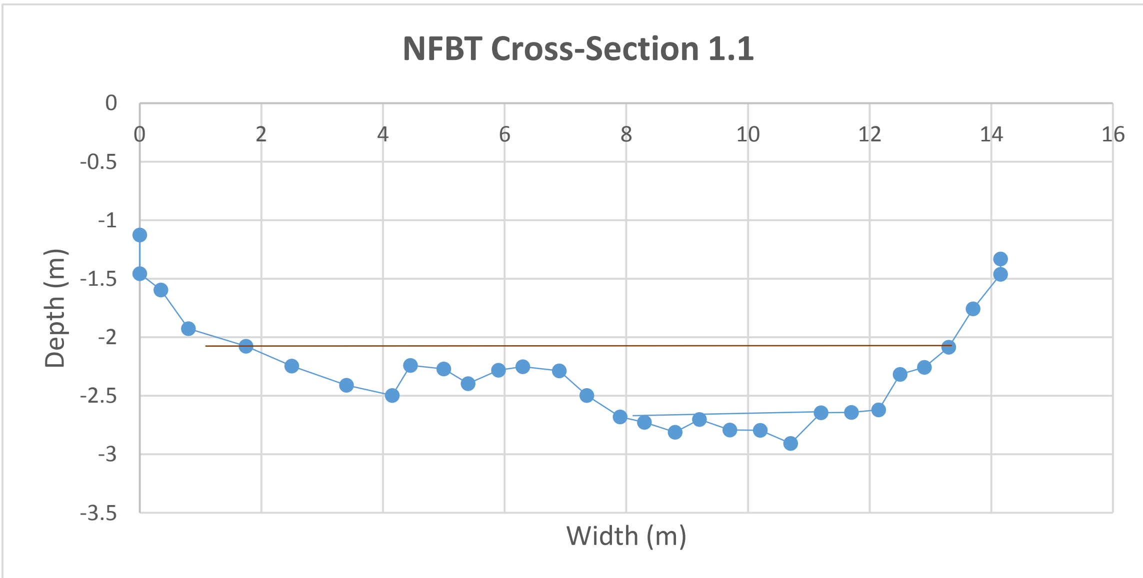
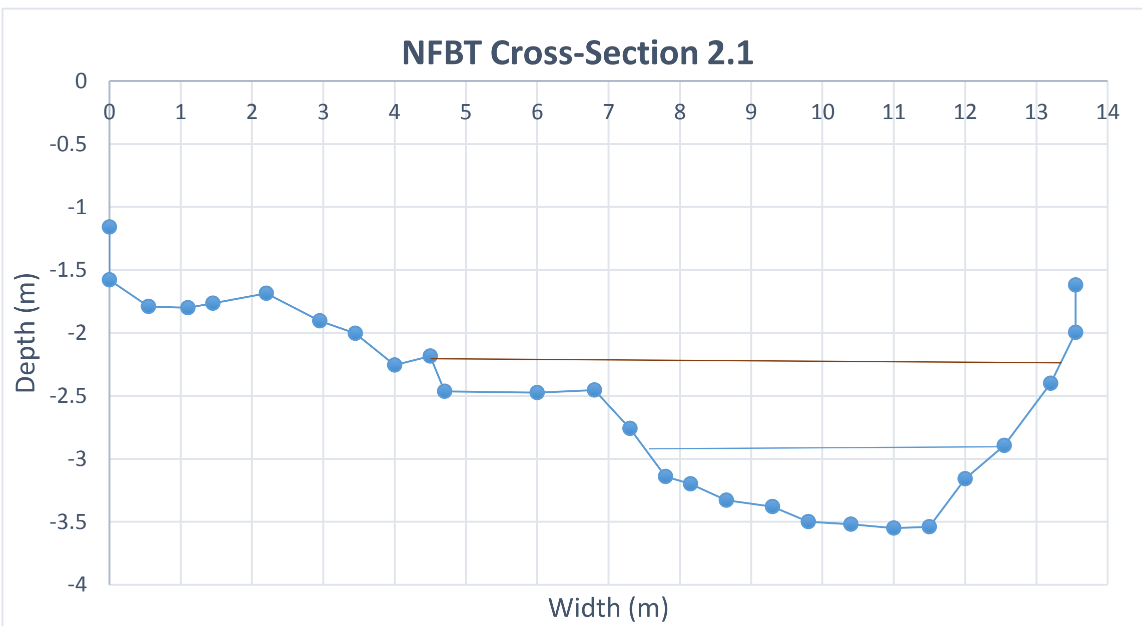
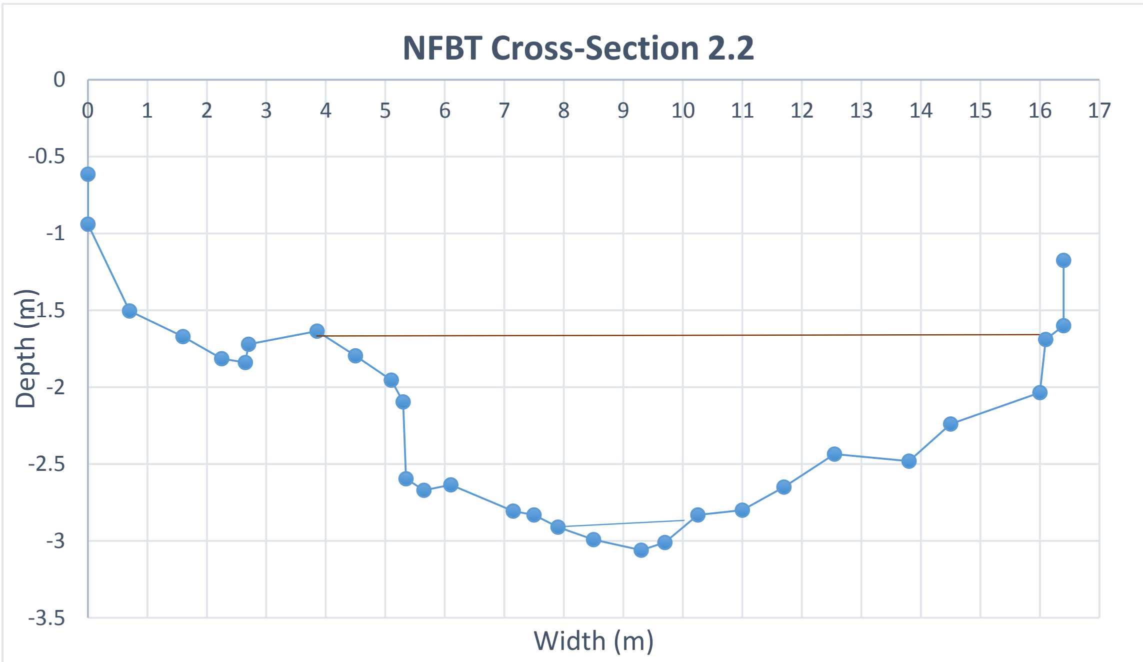

BCC Cross-Section 5.5
Depth (m)
Width (m)
0
-0.5
-1
-1.5
-2
-2.5
-3
-3.5
-4
0 1 2 3 4 5 6 7 8 9 10 11 12

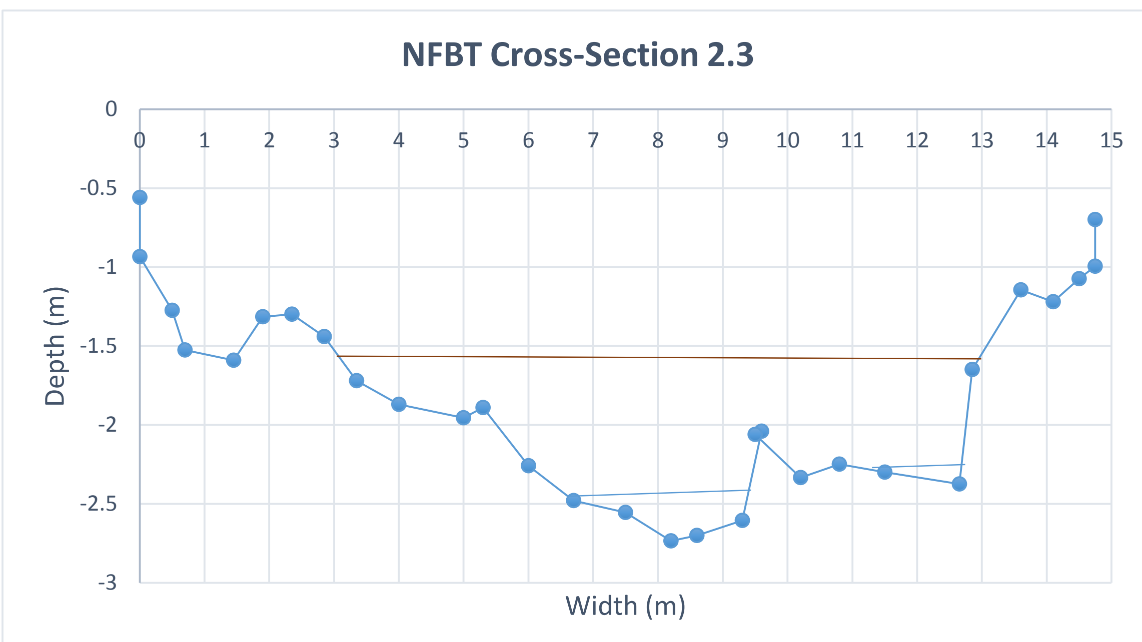
Figure B 2.Cross-sections along NFBT. The brown line is estimated bankfull and the blue line is

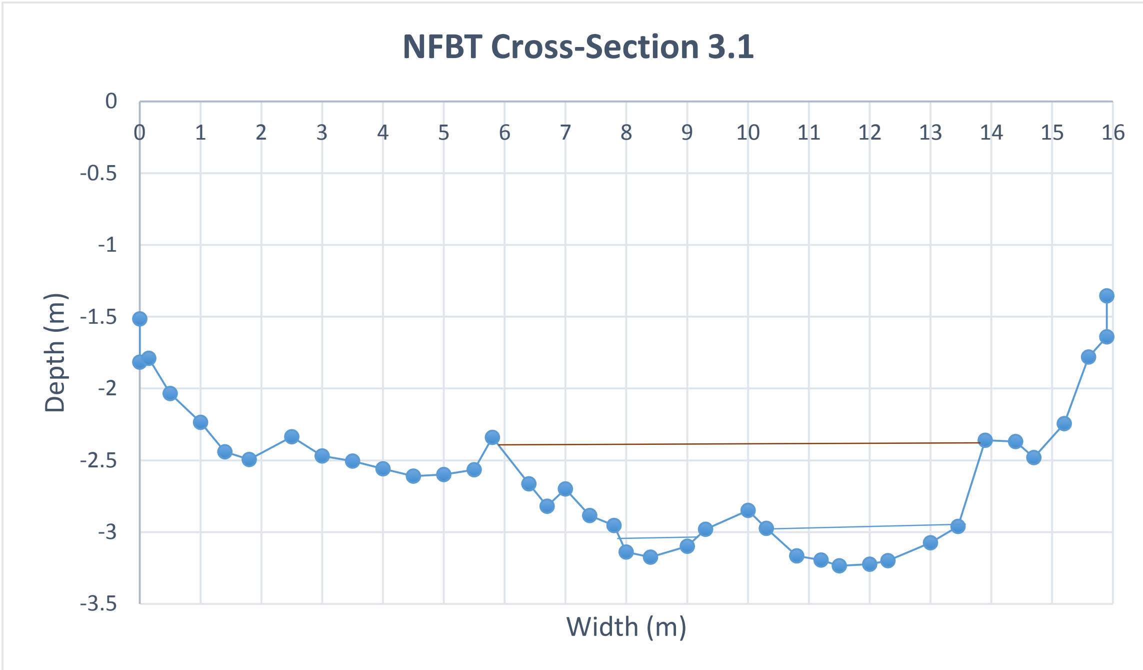


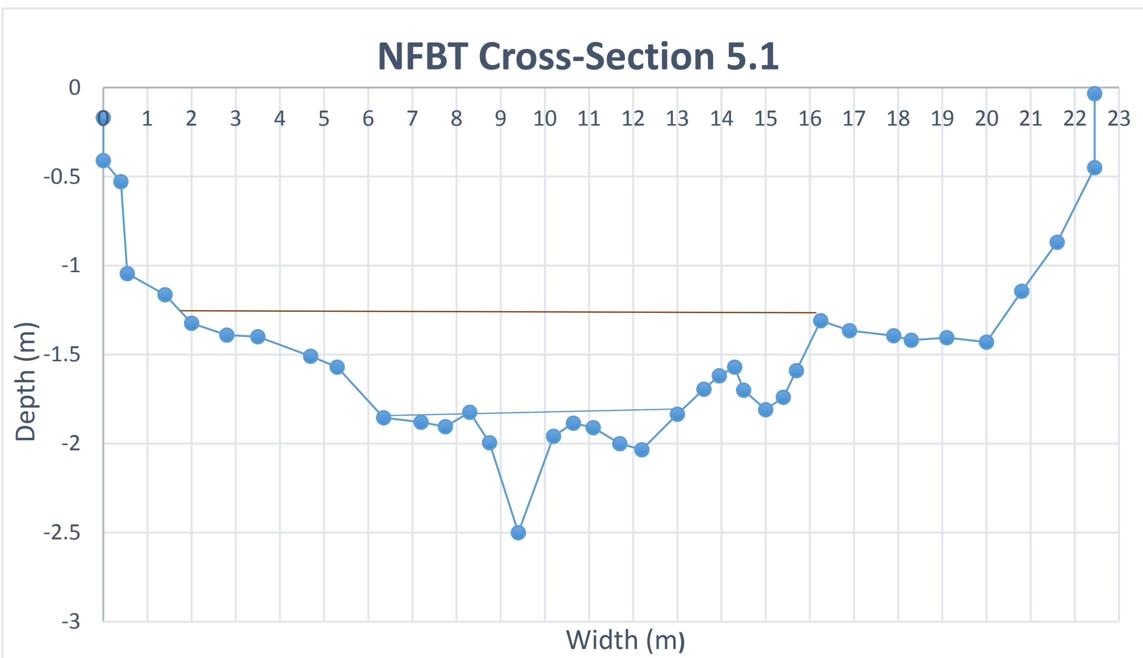



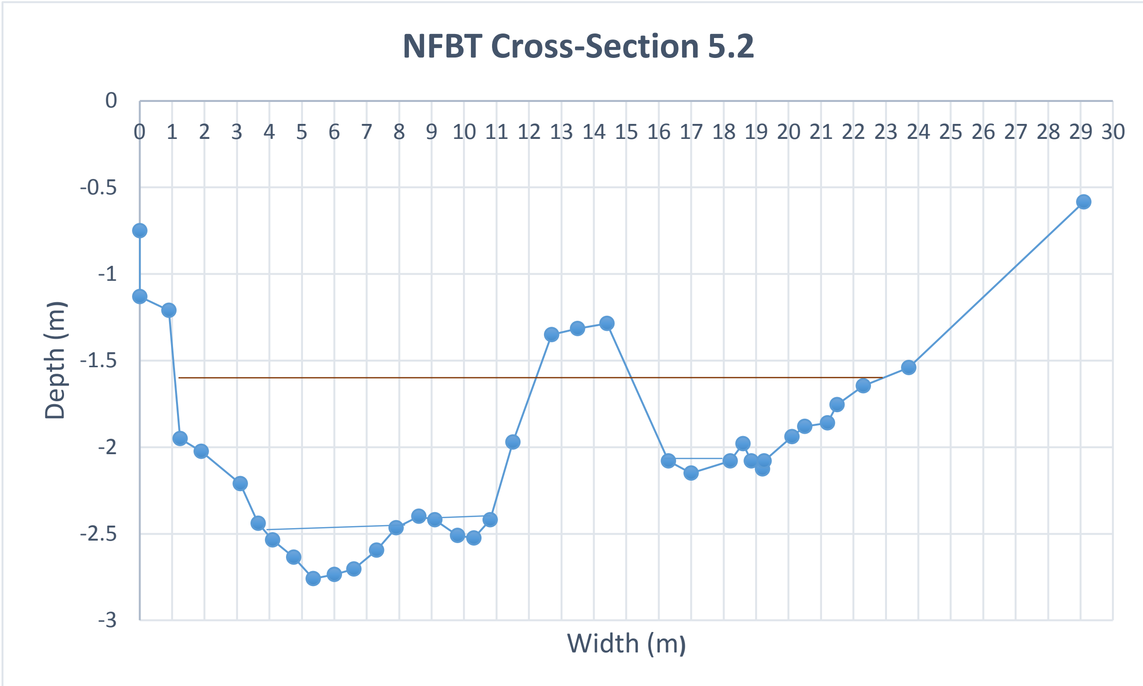

wetted width. Depth is relative to eye level of auto level.


NFBT Cross-Section 2.2
Depth (m)
Width (m)
0
-0.5
-1
-1.5
-2
-2.5
-3
-3.5
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17


NFBT Cross-Section 2.3
Depth (m)
Width (m)
0
-0.5
-1
-1.5
-2
-2.5
-3
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15


NFBT Cross-Section 3.1
Depth (m)
Width (m)
0
-0.5
-1
-1.5
-2
-2.5
-3
-3.5
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16


NFBT Cross-Section 5.1
Depth (m)
Width (m)
0
-0.5
-1
-1.5
-2
-2.5
-3
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23


NFBT Cross-Section 5.2
0
-0.5
-1
-1.5
-2
-2.5
-3
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30
Depth (m)
Width (m)