# THE ROLE OF LARGE WOODY DEBRIS AND RIPARIAN FOREST IN CHANNEL AVULSION IN THE CARBON RIVER, MOUNT RAINIER NATIONAL PARK, WA

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# Abstract

A specific type of natural log jam in the upper alluvial reach of the Carbon River was found to influence secondary channel avulsion, causing flooding hazards to the adjacent Carbon River Road in the northwest quadrant of Mount Rainier National Park, Washington. The fence-like natural log jam was characterized by large woody debris buttressed horizontally against standing riparian trees (i.e. "fence rails" and "fence post"). The objectives of this report are two-fold. First, physical characteristics and spatial distribution were documented to determine the geomorphic controls on the fence-like log jams. Second, the function and timing of the natural log jam in relation to channel avulsion was determined to provide insight into flooding hazards along the Carbon River Road. The fence-like log jams are most abundant in the upper reaches of the Carbon River between 3.0 and 5.5 kilometers from the Carbon Glacier terminus, where longitudinal gradient significantly decreases from about 0.06 to 0.03. Sediment impoundment can occur directly upstream of the fence-like log jam, creating vertical bed elevation difference as high as 1.32 meters, and can form during low magnitude, high frequency flood event (3.5-year recurrence interval). In some locations, headcuts and widening of secondary channel were observed directly to the side of the log jams, suggesting its role in facilitating secondary channel avulsions. Areas along the Carbon River Road more prone to damages from avulsion hazards were identified by coupling locations of the log jams and Relative Water Surface Elevation map created using the 1-meter 2012 Light Detection and Ranging Digital Elevation Map. Ultimately, the results of this report may provide insight to flooding hazards along the Carbon River Road from log jam-facilitated channel avulsion.

# Contents

# List of Figures

# List of Tables

# Introduction

The Carbon River, a rapidly aggrading proglacial river in the northwest quadrant of Mount Rainier National Park, has increasingly caused flooding hazards and significant damages to the adjacent Carbon River Road in the past decade (Figure 1). In the winter of 2006, the largest flood event on record washed away sections of the road near Falls Creek, Green Lake Trail, and the Ipsut Creek Campground vicinity (Figure 2). To this day, low magnitude, high frequency floods continue to damage road structure through channel avulsion and overbank flooding, rendering the road inaccessible to motor vehicle and even foot pedestrian further upstream (Figure 3). The National Park Service has observed that channel aggradation and a certain type of natural log jam may be acting in concert to facilitate channel avulsion and overbank flooding. The purpose of this study is to determine whether this specific type of log jam is promoting or preventing channel avulsion in an aggrading unconfined river system. In order to answer this question, I examined historical aerial photographs to determine main channel migration pattern, conducted field investigation to map locations and describe functionality of the log jams, and used remote sensing to identify areas more prone to potential log jam-facilitated avulsion.

## Carbon River Road and flood damage

On November 6th and 7th, 2006, a narrow strip of very wet air mass—the so-called "atmospheric river"—hit Mount Rainier National Park, dropping nearly 45 centimeters of rain over the course of 36 hours (Neiman et al., 2008). Peak precipitation intensity during the storm was measured at 2.0 centimeter/hour at the National Resource Conservation Service (NRCS) Paradise Snowpack Telemetry (SNOTEL) station (Legg et al., 2014). The Carbon River USGS gauging station near Fairfax, WA (USGS Gauge #12094000) measured a greater than 70-year recurrence interval discharge. Flood stage measurement rose from 4 meters at noon to 5 meters at about 18:00 on November 6th. Overbank flooding caused significant damage and led to 6 months of park closure—the single longest closure since the park was established in 1899. Several locations along the Carbon River Road were significantly damaged. Specifically, sections of the road near Falls Creek, Green Lake Trail, and the Ipsut Creek Campground vicinity were washed away. In the fall of 2015, a 3.5-year recurrence interval flood event additionally caused several bank failures and

tread damage between Falls Creek (river-kilometer 11.6) and Chenuis Falls (river-kilometer 8) (Figure 2, 3). Today, visitors are able to reach Ipsut Creek Campground on bike or foot, and only foot traffic is allowed above Ipsut Creek Campground. The condition of the road as of the time of this writing is hazardous, and any kind of access terminates at the "lower bridge crossing" at river-kilometer 3.0 (Figure 2).

The Carbon River Road corridor was first established in the 1920's for logging and mining access. Today, the corridor provides recreational access to unique habitat in the northwest quadrant of Mount Rainier National Park. The Carbon River Road corridor was established as a National Register of Historic Places, which is part of the Mount Rainier National Historic Landmark District (NHLD). In addition to its cultural significance, the Carbon River provides critical fish habitat to bull trout (Salvelinus confluentus), as well as other species that are federally listed resources under the Endangered Species Act of 1973 (Fish and Wildlife Services, 2011). Recent studies in Mount Rainier National Park have suggested interaction between instream woody debris and riparian old-growth stands can have significant impacts on local aggradation, secondary channel avulsion, and floodplain development (Entrix, 2010; Kennard et al., 2011). For the Carbon River, these effects can have managerial implications on the Carbon River Road, an easy access for the Mowich Lake hiking areas and the Carbon glacier in the northwest corner of Mount Rainier National Park (Figure 2).

## Geologic history and a melting glacier

The Carbon Glacier on Mount Rainier is a major source of sediment production for the Carbon River. Located in western Washington, Mount Rainier is a stratovolcano that rises to 4400 meters (14,410 feet) above sea level and contains the largest volume of glacial ice in the contiguous United States (Krimmel, 2002). Mount Rainier is situated along the Cascade Range volcanic arc, as a result of the subduction of the Juan de Fuca Plate under the North American Plate. Though volcanism in the Cascade Range has been active since the Oligocene (27 Ma), the modern edifice of Mount Rainier has only been assembled during the last half-million years from a series of andesitic and dacitic lava flows, pyroclastic flows, and lahars (Fiske, 1963).

The present day U-shaped valley of the Carbon River valley was formed through a series of alpine glaciation during the Pleistocene (Waitt and Thorson, 1983). The Puget Lobe of the continental Cordilleran Ice Sheet did not reach its maximum extent until 15 to 14 ka and stopped just north of Mount Rainier. Nevertheless, alpine glaciations, such as the Hayden Creek (170 to 130 ka) and the Evans Creek glaciations (22 to 15 ka), spread down valley onto the margins of the Puget Lowland and repeatedly scoured the landscapes. Several minor neoglacial advances occurred during the last 10,000 years as well, reaching its maximum between 2.8 and 2.6 ka (Crandell, 1969). As glaciers retreat, the valley experiences sedimentation of glaciofluvial drift such as till and outwash (Waitt and Thorson, 1983).

Evolution of the Carbon River valley following alpine glaciation occurred during the Holocene (Kennard, 2011). The Carbon River continuously incised into the valley bottom to form terraces that represent relic fluvial surfaces not inundated by high flow events. Over time, encroachment of maturing vegetation occupies the alluvial terraces to form old-growth forest stands along the margins of the valley bottom. Today, these old-growth riparian forests seen throughout the Carbon River are currently experiencing higher mortality from burial of sediments during the recent aggradational trends governed by glacial recession (Beason et al., 2014; Czuba et al., 2012).

Glacial recession affects sediment inputs into river valleys and can have significant implications to geologic hazards in Mount Rainier National Park (Beason et al., 2014). Mountain-wide glacier volume loss has been estimated at 14% from 1970 to 2008 (Sisson et al., 2011). Although no publication was found for the recession of the Carbon Glacier, Reidel et al. (2015) has been monitoring two of the major glaciers from 2003 to 2011—Emmons (11.6 square-kilometer) and Nisqually (6.9 square-kilometer). Cumulative net volume loss in the eight years is 89.4 million cubic-meter for Emmons Glacier and 58.1 million cubic-meter for Nisqually Glacier (Figure 4). Similar volume recession is expected for the Carbon Glacier.

## An aggrading river

Geologic hazards, such as flooding and channel avulsion, can be caused by channel aggradation when sediment production overwhelms the stream's ability to transport the sediment downstream. Recent studies have shown that glacial recession is increasing sediment inputs into rivers that radially drain Mount Rainier and limiting channel conveyance over the past 15 years (Beason et al., 2014; Czuba et al., 2012). The Carbon River is showing aggradation in certain segments of the study reach as well (Knoth, 2013; Entrix, 2008). In these aggradational areas, the valley cross sections show convexity, where the active channel is perched as high as 6 meters above adjacent floodplain (Kennard et al., 2011). The rivers are expected to respond by either changing its channel planform, its location in the valley bottom, or both; this has significant implications to many of the park infrastructures that are built along the adjacent floodplain. For example, the perched active channel above adjacent floodplain has been attributed to be the dominant factor in channel widening and avulsions during the 2006 storm event in the Carbon River, as well as in the White River and Tahoma Creek (Entrix, 2008; Entrix 2010; Beason et al., 2014).

Mount Rainier rivers have been experiencing aggradational trends for the past 15 years (Beason et al., 2014). In the Nisqually River and the White River, aggradational trends occurred in all of the surveyed cross sections between 1997 and 2012 with the exception of the 2007-2008 period. For example, at the Sunshine Point Reach in the Nisqually River, average aggradation rates range from 0.04±0.15 meter/year (2005-2006) to 0.36 ±0.15 meter/year (2006-2008  ). In the White River, aggradation rates of 0.04±0.15 meter/year and 0.05±0.15 meter/year occurred in periods 2005-2007 and 2008-2011, respectively.

Similar to the Nisqually River and the White River, the Carbon River is also showing aggradational trend in some sections of the river between 1994 and 2012 (Entrix, 2008; Knoth, 2013). Reference cross sections near the Ipsut Creek Campground showed elevation difference ranges from 0.5 to 1.5 meters with an uncertainty of 0.6 meters between 1994 and 2008 (Figure 5). This equates to an aggradation rate of 0.04 to 0.1 meters/year, suggesting a similar aggradation rate to certain sections on the Nisqually River and the White River. Entrix concluded that aggradational trends between 1994 and 2008 extend throughout the study reach and aggradation could occur even at low magnitude, high frequency flood (2-year

recurrence interval). In a similar study, Knoth observed aggradational trend in the Carbon River between the Carbon Glacier and Mother Mountain between 2008 and 2012 through LiDAR DEM differencing (Figure 6). Highest aggradation rate of 0.25 meters/year was seen between river-kilometer 2.5 and 3.0 (Figure 2, 6). Despite aggradation in the Carbon River close to the Carbon Glacier, Knoth (2013) observed no significant bed elevation change in the Ipsut Creek Campground vicinity, and even incisional trends close to the Park entrance (Figure 6).

Sediment input that is contributing to aggradation in the Carbon River is first initiated by rockfalls and debris avalanches in the surrounding hillslopes and glacier terminus (Czuba et al., 2012). Sediment is then transported downstream through debris flow and fluvial processes. Debris flows, consisting of both sediment and water, efficiently transport large sediment loads downstream. Czuba et al. (2012) observed debris flows in the Carbon River to have traveled as far as 2 kilometers downstream from the glacier terminus within the past 10 years. Debris flows in the upper reach of the Carbon River have become more active when compared to historical rate, increasing sediment inputs and exacerbating aggradation (Czuba et al., 2012; Legg et al., 2014). Throughout Mount Rainier, at least 12 separate debris flows initiated in six different drainages were recorded in 2001, 2003, 2005, and 2006; all of which occurred in recently deglaciated areas (Beason et al., 2014). Debris flows efficiently promote the overall delivery processes of sediment from the steeper section of the fluvial network near the glacier to the fluvial reaches at lower elevation, where flow competence and stream power is sufficient to mobilize larger particles into river sediment load.

## Role of natural log jams in channel avulsion

Natural log jams created by accumulation of wood and sediment play an important role in floodplain development and channel avulsion. Numerous studies have shown significant effects of natural log jams in the morphology of alluvial river valleys in the Pacific Northwest (Abbe and Montgomery, 2003; Collins et al., 2012). For example, lateral channel migration in the Queets River is strongly influenced by vertical channel adjustment due to some types of log jams such as those created by valley-spanning wood accumulation (Brummer et al., 2006). Up to 2 meters of vertical change in water surface and thalweg elevation was linked to the channel-spanning log jams. Sediment impoundment behind stable log jams initiates positive feedback when aggradation in the upstream channel bed reduces transport capacity, resulting in further sediment deposition and slope reduction. On the one hand, stable log jams have the potential to create hardpoints where channel bars and banks are protected against erosion to allow revegetation and floodplain development (Abbe and Montgomery, 2003; Collins et al., 2012). On the other hand, the processes of wood accumulation and sediment impoundment can end when the log jam is breached by overtopping or channel is forced to migrate laterally into surrounding floodplain.

In the White River, natural log jams can prevent migration of the main channel but the resulting aggradation in the main channel can promote secondary channel avulsion (Entrix, 2010; Kennard 2011). The specific type of log jam, created by instream wood horizontally buttressed against standing old-growth forest, effectively retain the main channel in place by creating stable surface for revegetation along the floodplain. As the White River remain in its historic channel, aggradation can result in an elevated bed surface. Entrix (2010) observed increasing lateral channel migration from 1957 to 2009 in some sections of the White River by mapping floodplain changes using historical orthoimageries. The two factors influencing secondary avulsions in the White River were the negative elevation of adjacent floodplain relative to main channel and the proximity of wetted channel to forest margins (Entrix, 2010; Kennard et al., 2011). Slope of valley cross sections from the main channel to the adjacent floodplain (7-20%) greatly exceed downstream gradient 0.01-1.3% (Entrix, 2010). Furthermore, secondary channel avulsion was found to be independent of flood magnitude; a small magnitude, high frequency flood (as little as 2-year recurrence interval) can cause secondary channel to laterally migrate into adjacent floodplain.

The specific type of natural log jam created by instream large woody debris and standing old-growth stands, as seen in the White River, may be unique to the proglacial alluvial rivers that radially drain Mount Rainier where old-growth riparian forest exist. Its distribution, functionality, and stability are not completely understood. Field investigation conducted in the spring of 2016 suggests that the log jam is a result of the interaction between instream woody debris and standing riparian forest, manifesting itself into a fence-like feature (i.e. fence post and fence rails). Therefore, this specific type of log jam will be mentioned as "fence jam" hereafter. In the Carbon River, aggradation and channel widening increases mortality of adjacent old-growth forests (Beyeler, 2013), providing an abundant input of large woody debris as "fence rails" to be buttressed against riparian trees that are still standing (fence posts).

The purpose of this study is to characterize fence jams in the Carbon River by evaluating its role in channel avulsion and floodplain development through literature review, remote sensing, and field mapping. This report will attempt to answer the following questions: (1) where in the Carbon River are fence jams located? (2) What are the physical characteristics of fence jams that render its uniqueness to the Carbon River? (3) Do fence jams facilitate or prevent channel avulsion? Ultimately, understanding the role of fence jams in the Carbon River may provide information on flooding hazards for the Carbon River Road.

In order to answer these questions the project was divided into three phases. First, I compiled geospatial information system (GIS) data to help constrain geomorphic characteristics of the Carbon River (Table 1). Bare-earth light detection and ranging (LiDAR) digital elevation maps (DEM) from 2012 was used to create hillshade base map, visualize longitudinal profile, and cross-sectional topography to determine the control of channel slopes on fence jam formation. In addition, I compared repeated years of U.S. Department of Agriculture's (USDA) National Agriculture Imagery Program (NAIP) orthoimagery to observe historical channel migration in the past decade. NAIP imageries from 2006, 2009, 2011, and 2015 were used to map main channel migration. This allowed me to determine changes in Carbon River main channel along the valley bottom in relation to the formation of fence jams.

Second, I conducted field mapping of log jams along the Carbon River and characterized the fence jams. Data collected in the field included number of individual woody debris and standing tree involved in the log jam, diameter at breast-height (DBH) of standing tree, diameter at midpoint of woody debris, standing tree spacing, spatial extent of log jam, flow geometry during formation, vertical height difference between stream bed and floodplain channel, and spatial distribution of log jams. This data serves as the basis to determine physical characteristics, log jam stability, and role of fence jams in channel avulsion.

The project concluded by determining the role of fence jams in potential avulsion hazards along the Carbon River-left. This is achieved by creating a Relative Water Surface Elevation (RWSE) map using the 2012 one-meter LiDAR DEM and comparing with the mapped locations of fence jams. RWSE maps help visualize areas that are more prone to flooding, and coupling with fence jam locations determines whether the fence jams are related to channel avulsion that pose flooding hazard to the adjacent Carbon River Road.

# Study Area

For the purpose of this study, I focused on the southern margin of the Carbon River on river-left, where the Carbon River Road is located (Figure 2). The study area spans throughout the 15-kilometer reach between the Carbon Glacier and park entrance. However, due to flood damages that occurred in the winter of 2015, I was only able to reach to river-kilometer 3.0 during field survey of the fence jams.

The study reach is characterized by a braided stream with a concave longitudinal profile (Figure 7) (Czuba et al., 2012). Slope in the headwaters decrease from 0.1 to 0.06 near the Carbon Glacier and gradually decreases from 0.02 near Mother Mountain to 0.015 at the park entrance; channel width typically ranges from 150 to 300 meters. One-quarter of the bed material within 3 kilometers of the glacier terminus consists of boulders. Grain size distribution generally decreases downstream, becoming predominantly cobbles with 10-20% of sand in the bed material. (Czuba et al., 2012).

The Carbon River is split into three sections—Upper Reach, Ipsut Creek Floodplain, and Lower Reach (Figure 2). First, the Upper Reach ranges from the Carbon Glacier terminus at river-kilometer 0 to river-kilometer 5.0. The Upper Reach is dominated by debris flow processes and shows steeper longitudinal profile (Czuba et al, 2012). During field reconnaissance, I observed mostly large boulders in poorly-sorted matrix in exposed cutbanks and midchannel bars upstream in the Upper Reach. Second, the middle section, Ipsut Creek Floodplain, is located at the Ipsut Creek Campground (river-kilometer 5 to 6). This section of the Carbon River shows transitional characteristics between debris flow-dominated to fluvial-dominated processes (J. Beyeler, personal communication, 2015). Third, the Lower Reach stretches from the downstream extent of Ipsut Creek Floodplain to park entrance (river-kilometer 6 to 15), where fluvial processes dominate suggesting a different longitudinal gradient, cross-sectional width, and different aggradational trends (Entrix 2008; Knoth, 2013).

# Methods

## Log jam survey

In order to determine spatial distribution of fence jam along the Carbon River, I conducted field investigation on 2/19/2016, 3/25/2016, 3/30/2016, and 4/07/2016. Geographic locations of these features were collected using the Trimble R10 global navigation satellite system (GNSS) unit paired with a TSC3 controller, and was collected in Universal Transverse Mercator (UTM) coordinate system Zone 10N. Using the Fast Static method, I recorded the GPS position of log jams by occupying the locations for approximately 7 minutes at each site.

To understand the characteristics of fence jams, field measurements were collected where they were identified. For each site, I catalogued the number and size of standing trees and woody debris involved in the log jam. Additional quantitative information includes the spacing of standing trees, spatial extent, and bed-surface elevation. Definition of data collected is summarized as the following:

Standing tree count: number of standing tree acting as "fence post" in riparian forest that is supporting accumulation of woody debris and resulting local aggradation on the upstream bed-surface.

Standing tree diameter: diameter of standing tree is measured at breast height (DBH) while standing on the downstream bed-surface. Circumference was measured in the field with a 50-feet measuring tape and was later converted to diameter. Diameter of standing trees helped determine if fence jams were limited to old-growth stands.

Standing tree spacing: showed the horizontal distant at breast height between two fence posts. Multiple post spacing were collected when more than two posts were identified. This determined whether there was a minimum requirement for tree spacing to create fence jams.

Woody debris count: number of horizontal large woody debris, acting as "fence rails," that is buttressed against the standing trees. In some cases where there were overabundances of small woody debris accumulation that may be buried, an estimated count was recorded. "Key member" was identified as the largest horizontal wood that was directly in contact with the fence post.

Woody debris key member diameter: diameter of the key member horizontal WD buttressed against the standing trees that was supporting aggradation on the upstream end. Key members were identified as the largest horizontal woody debris that was buttressed against standing tree and allowed accumulation of smaller woody debris and facilitate sediment impoundment in the upstream bed-surface. Woody debris diameter helped determine whether only old-growth debris was involved in the formation of fence jam.

Spatial extent: the fence-like log jam is recorded either "discrete" or "continuous." Discrete extent indicated that multiple log jams were not interconnected throughout the floodplain. Whereas continuous extent entailed multiple log jams that were interconnected throughout the floodplain. This provides information on the scale at which fence jams could occur.

Woody debris accumulation orientation: measurement to indicate orientation of log placement relative to flow. This is categorized into quadrants based on wood survey method by Bilby and Ward (1991). Figure 8 shows whether the log jam can be parallel (A), perpendicular (B), or askew (C and D) to the current flow direction of the main channel.

Bed-surface elevation change: measurement of the vertical drop from the locally aggraded bed-surface upstream to bed-surface downstream of the fence jam (Figure 9). A height difference was recorded at the point along the fence jam where bed-surface elevation change was at its maximum.

A total of 28 fence jams were identified along the 15 kilometer reach of Carbon River. Out of the 28 fence jams, I collected quantitative data (as described above) for 25 of the features, and measured geographic locations for 15 of the features. I collected additional descriptive information such as presence of alder (and size distribution), changes in sediment grain size from upstream of the fence jam to downstream bed-surface, and presence of headcut or evidence of avulsed channel associated with the fence jam.

## Relative cross-sectional profile at WF-13

I surveyed two cross-sectional profiles at fence jam location WF-13 to show relative elevation of floodplain below the wetted main channel. Fence jam at this specific location is particularly interesting because it was formed between field reconnaissance in the summer of 2015 and field mapping in the spring of 2016. Thus, this was a fairly new feature that may be linked to the 2015 winter storm. Measuring a relative elevation change from adjacent floodplain to the wetted channel provided information on channel avulsion facilitated by the fence jam. The elevation profiles were measured using a hand level, a stadia rod, and a 50-feet measuring tape. The horizontal distance extended from an arbitrary datum (control point), set at the valley wall, to the edge of the wetted main channel. Cross section 1 is located at the initial control point (46.967869, -121.819176). Cross section 2 is located 50 meters downstream from the control point.

## Historical aerial photograph

The Carbon River channel migration was analyzed using a series of historical aerial photographs. 2006, 2009, 2011, 2013, and 2015 orthophotos were obtained from the US Department of Agriculture (USDA) National Agriculture Imagery Program (NAIP) online database. Dates of publication of each NAIP imagery is shown in Table 1. Changes in main channel location along the valley bottom was associated with particular storm events that may have caused avulsions, channel widening, and timing of fence jam formation. NAIP imagery (.tiff files) was imported into ArcMap to digitize changes in thalweg position, identify channel avulsion, and potential widening of floodplain channel facilitated by fence jams.

## 2012 LiDAR DEM

The 2012 LiDAR one-meter DEM was obtained from Scott Beason, a Park Geologist in Mount Rainier National Park. The 2012 DEM was imported into ArcMap to create hillshade map, longitudinal gradient, cross-sectional profile, and a Relative Water Surface Elevation (RWSE) map. A hillshade map was created mainly to be used as basemap and visualize topographic relief in the alluvial valley. The longitudinal profile was plotted at 0.5-kilometer increments to show downstream variation in channel gradient. Meanwhile, cross-sectional profile was plotted at 10-meter interval at several locations on the Carbon River. RWSE map was used to determine locations that were well below the perched wetted channel and served as a flood hazard map to the Carbon River Road.

Methods of RWSE analysis was based on Model 2 developed by Jerry Franklin, of Washington State Department of Ecology, which was included in a compiled report by Patricia Olson (2012). First, cross-sectional cutlines were drawn at an evenly spaced interval along the thalweg using River Bathymetry Toolkit, developed by ESSA Technologies, Ltd. Second, elevation of surface water was defined at the intersection between cross-sectional cutlines and thalweg line. This elevation data was then added to each cross sections. Third, a triangulated irregular network (TIN) model was then created using the cross sections that contained elevation value. The TIN model could then be converted into a raster. Finally, a Relative Water Surface Elevation map was created by subtracting the raster TIN from the bare earth LiDAR.

## Hydrology

In order to understand magnitude and frequency of flood events that may be associated with fence jam formation or channel avulsion, I analyzed historical annual peakflow data using the Log Pearson (LPIII) statistical analysis. Peakflow data for the Carbon River was downloaded for the USGS gauge 12094000 near Fairfax, WA. The stream gauge is located outside of the study reach about 10 kilometers from the park entrance and at approximate river-kilometer 26 on the left bank; 2 kilometers from State highway 165 (Fairfax) bridge. Thus, peakflow statistics at this location used to determine flood patterns within the study reach would generate some degree of uncertainty due to factors such as difference drainage areas. Data was available from water years 1930 to 2014, with a data gap between 1978 and 1991. Log Pearson (LPIII) statistical analysis was used to analyze flow rates at various recurrence intervals. This was analyzed on a Microsoft Excel spreadsheet with written macros that was developed by the Natural Resource Conservation Service (http://go.usa.gov/KS6).

# Results and Discussion

## Characteristics of fence jam

A typical fence jam consists of fluvial-transported large woody debris as "fence rails" that are horizontally buttressed against standing trees or stump as "fence post" (Figure 10). Usually, a key rail member is identified to be the most stable that causes additional woody debris accumulation and sediment deposition, creating a steep vertical elevation drop from upstream channel bed to surrounding floodplain (Figure 11). Grain size generally ranges from cobbles to boulders upstream of the fence jam to coarse sand and cobbles downstream of the wood fence (Figure 12). The wood accumulation and subsequent sediment impoundment directly upstream of the fence jams effectively dissipate boundary shear stress by promoting spill resistance. Throughout the Carbon River, fence jams can occur at discrete locations where one or two standing trees can cause wood accumulation and sediment impoundment; it can also occur continuously where multiple fence jams are interconnected along the margins of the floodplain.

## Spatial distribution along the Carbon River

A total of 25 fence jam were surveyed throughout the 15 km reach of Carbon River (Figure 13, Appendix 1). Fence jams along the Carbon River are pervasive especially in the Upper Reach and Ipsut Creek Floodplain (river-kilometer 3.0 to 5.7). Although field investigation did not include the right side of the active channel, more fence jams are expected to be present on river-right between river-kilometer 3.0 and river-kilometer 5.0. At this location on the river-left, however, no fence jams were observed because the wetted channel borders bedrock outcrop where riparian forest does not exist. The high frequency zones of fence jams in the Upper Reach and Ipsut Creek Floodplain are associated with three factors— changes in longitudinal gradient (Figure 14), cross-sectional profiles (Figure 15-20), and lateral channel migration of the main channel between 2006 and 2015 (Figure 21).

In the longitudinal profile, there is a sudden decrease in slope at river-kilometer 4.0 (Figure 14). From river-kilometer 0.5 to 2.0, the slope decreased from 0.093 to 0.055. The Carbon River meanders almost 90° into the southern margin of the active channel at this location. Slope increased to 0.070 at river-kilometer 3.0, before decreasing again to about 0.058 at river-kilometer 4.0. At this location, gradient decreased significantly again, from 0.05 to 0.03. This break in slope is hypothesized to be the transition point between debris-flow-dominated processes and fluvial-dominated processes (J. Beyeler, personal communication, 2016). This is supported by field observations of cobbles- to boulder-sized material supported by poorly-sorted fine-grained matrix exposed in the cutbanks and mid channel bars in the Upper Reach, which suggest debris flow deposits.

Upstream of river-kilometer 4.0, the two concavities in longitudinal gradient (river-kilometer 2.0 and 3.5) coincide with changes in the cross-sectional profiles in this section of the river (Figure 15-20). At river-kilometer 1.6, the channel cross section is generally flat (neither convex nor concave). At river-kilometer 2.1, the cross-sectional profile begins to tilt to the river-right. This becomes more apparent as the point of lowest elevation deepens on the river-right at river-kilometer 2.5. At river-kilometer 3.2, the channel cross section returns to a flat bottom, with an apparent channel bank on river-left. At river-kilometer 4.0 and 4.3, the lowest point of elevation in the active channel evidently shifted river left. The higher elevations in the "seesaw" pattern of the cross-sectional profile between river-kilometer 1.6 and 4.3 likely indicates the transient alluvial storage mentioned by Czuba et al. (2012) and Beason et al. (2014).

High frequency of fence jams occurred in the vicinity where the largest lateral migration occurred in the main channel between 2006 and 2015 (Figure 21). The 2006 main channel (green in Figure 21) shows historical position of the Carbon River prior to the 2006 storm event. The Carbon River flowed along the river-right as it meanders around Mother Mountain. In 2009 and the subsequent years, the main channel of the Carbon River migrated dramatically into the river-left, inundating the former Carbon River Road (J. Beyeler, personal communication, 2016). The cause for the 2009 channel migration is linked to either the 2006, 2008 flood events, or both. According to the Log Pearson III flow statistics, the 2006 flood event have a recurrence interval of 67.5 years with an exceedance probability of 1.48%; and the 2008 flood

event have a recurrence interval of 26.4 years with an exceedance probability of 4.32% (Figure 22). In 2011 (gray in Figure 21), the main channel further migrated into the southern floodplain on river-left, possibly occupying secondary channels created during the 2006 flood event. The 2011 channel migration is linked to a relatively smaller flood event earlier in the same year that has a recurrence intervals of 4.8 years (Figure 22).

The changes in longitudinal gradient, cross-sectional profiles, and main channel migration discussed above likely show that fence jams in the Upper Reach and Ipsut Creek Floodplain are due to the combination of factors between increased aggradation and proximity of the wetted channel to riparian forests. First, higher gradient in the longitudinal gradient showing increased sediment deposition in river-kilometer 3.0 coincide with fence jams in the Upper Reach (shaded yellow in Figure 14). Meanwhile, fence jams in the Ipsut Creek Floodplain vicinity at river-kilometer 5.5 (shaded green) is at the same location of higher aggradation rate of about 0.1 meters/year between the years 1994 and 2008 (Figure 5) (Entrix, 2008). Second, active channel migration occurred between 2006 and 2015 due to flood events at various recurrence intervals, shifting the Carbon River closer to the southern floodplain on river-left (Figure 21). Thus, deposition of sediment onto adjacent floodplain during high flows results in buried riparian forests and creates the so-called "ghost forests" (Knoth, 2015). Increased tree mortality creates a positive feedback when large amount of instream wood is readily available to be transported downstream and deposited along channel margins. The large woody debris are then buttressed horizontally against old-growth trees that remain standing, creating fence-like log jams.

In the Lower Reach of the Carbon River, fence jams generally become relatively older when compared to those mapped upstream. I observed young alder stands, not observed in the upper reaches, approximately 1-3 years in age above developed floodplain caused by fence jam in the Lower Reach (dashed and shaded blue in Figure 14). The alders occupying armored bank surfaces have a maximum height of approximately 3 meters, and an average diameter of 3 centimeter. The relative stability of fence jams at the Lower Reach may be due to its distance from the main channel. The Lower Reach fence jam zones are approximately 250 to 500 meters from the wetted channel; whereas the zones in the Upper

Reach were in close proximity to the wetted channel (Figure 13). The absence of developed floodplain with revegetation from fence jam upstream suggests that these features are unstable compared to other types of natural log jams (Abbe and Montgomery, 2003). The oldest fence jams found in the Lower Reach where 1-3 year-old alders stands suggest the fence jams fail regularly and cannot support long-term revegetation of floodplain. However, I was unable to determine the mechanism of failure.

## Fence post and fence rails

Riparian forests in the Carbon River involved in providing fence posts mostly consist of a variety of conifers, including Douglas firs (Pseudotsuga menziesii), western hemlock (Tsuga heterophylla), western red-cedar (Tsuga heterophylla). I did not observe any alder (Alnus) that served as fence post. Forest age structure ranges from young stands (less than 100 years-old) to old-growth stands (1000 years-old or more) (NPS, 2011). There is not enough evidence to show that fence jam formation is dependent of riparian tree age even though the Upper Reach does include more old-growth tree stands (maximum diameter = 1.80 meters) when compared to Ipsut Creek Floodplain (Figure 23). The average post diameter is 0.53 meters and 0.58 meters for the Upper Reach and Ipsut Creek Floodplain, respectively. Furthermore, percentage of three size intervals shows majority of fence posts found in the Carbon River range between 0.20 m to 0.50 m; and only 15% in the Upper Reach and 5% in the Ipsut Creek Floodplain exceeds 1.0 m (Figure 24). Thus, fence jams found in the Carbon River does not require old-growth stands to act as fence post for accumulation of large woody debris and local aggradation.

Vertical bed elevation change due to sediment deposition from fence jams varies throughout the Carbon River. Distribution of vertical bed elevation ranges between 0.40 meters to 1.32 meters with a median of 0.75 meters (Figure 24). The ratio of key piece diameter to vertical bed elevation change is predominantly greater than 1:1 (Figure 24). Out of the 16 comparative ratios, 12 (75%) are plotted between the 1:1 and 3:1 range. This suggest the amount of the sediment impoundment is in direct relationship to the size of the log jam, and aggradation height is generally within 2- or 3-fold of the diameter of fence rail key member.   Furthermore, the plotted ratio resembles tree diameter to bed elevation change plot for valley-spanning jams in the Queets River, WA (Figure 25) (Brummer et al., 2006), even though vertical bed elevations found in fence jams are relatively smaller

## Role of fence jams in channel avulsion

For several mapped fence jams along the Carbon River, I observed active or relic secondary channel created by redirection of flow into adjacent floodplains (Table 2). At these locations, flow is directed by running parallel along the "fence rails," and spills around the corners of the log jams to create secondary channel avulsions (Figure 12). Through field mapping, I observed that fence jams can affect channel avulsion in a two-step process:

First, the redirection of flow effectively localized overbank flow to the side of the jam and incise into the secondary channel, while continuing to build up bed elevation of the main channel directly above the fence jam through wood accumulation and sediment impoundment. This resulted in the formation of headcuts at the downstream corner of the fence jams (Figure 11), creating a negative gradient from the main channel to the floodplain. This cross-sectional trend is seen at WF-13 (Figure 26), where the floodplain channel is incised behind and beyond the defined bank (approximately 100 meters from the wetted channel) at the headcut and continues to widen downstream. Width of the secondary channel widened from 10 meters to 60 meters within 50 meters of downstream distance (Figure 26). In other locations (WF-17, WF-28, WF-26, WF-28), where two discrete fence jams are adjacent to each other, orientation of the fence rails can cause flow to be concentrated in between (Figure 27). At these locations, headcuts can be much steeper, creating a more defined secondary channel that flows into the floodplain.

Second, channel avulsion occurs when the secondary channel around the fence jams described above continues to incise into the floodplain as flood events wanes, separating secondary flow from main channel flow. The resulting floodplain incision thus becomes an easier pathway for secondary channel to flow into the floodplain for future flood events. Theoretically, there is also a higher potential for main channel avulsion, though I did not observe evidence of main channel avulsion in the presence of fence jams. Overall, despite local armoring of floodplain directly upstream of the fence jams, redirection of flows suggests fence jams in the Carbon River promote secondary channel avulsions, which creates flooding hazards to the adjacent Carbon River Road.

## Implications of flooding hazards to the Carbon River Road

Flooding hazards in the Carbon River may be exacerbated by receding glaciers, increasing aggradation, and presence of fence jams at certain locations. With the current state of climate change, the Carbon River Road has the potential to experience higher frequency of flood damage. Between summer of 2015 and spring of 2016, I observed the newly-formed fence jam that is the direct result of the 2015 winter flood event at WF-13 (Figure 11). Timing of the fence jam at WF-13 suggests formation of these natural log jams only requires low magnitude, high frequency flood events (3.5-year recurrence interval) (Figure 22). This suggests avulsion of secondary channel facilitated by fence jam can occur more frequent, especially in the Upper Reach and Ipsut Creek Floodplain vicinity. The interaction between sediment, instream large woody debris, and standing riparian trees may be creating a positive feedback in these areas, where aggradation promotes tree mortality, providing woody debris that are readily available for creating fence jams. Sediment impoundments creates further increase bed elevation, reducing flood conveyance and creating more frequent and larger secondary channel avulsion. In the White River, Entrix (2011) and Kennard et al. (2011) observed floodplain channels can develop easily during low recurrence interval floods, while the mainstem stays relatively stable. I observed similar process in the Carbon River where secondary channels, initiated at an upstream fence jam (WF-28), are still actively conveying water at medium to low flow.

Throughout the study reach, many surrounding floodplains are well-below the main channel water surface, which pose significant flooding hazard to the Carbon River Road (Figure 28). Relative Water Surface Elevation (RWSE) map visualize valley bottom that is under the water surface as blue, and areas above water surface as yellow and green. Relative elevation in the valley bottom ranges between 7 meters below and more than 10 meters above the main channel water surface. Four major locations shows a negative elevation (height below water surface) of more than 6 meters. These areas pose potential flooding hazards to the Carbon River Road and surrounding floodplain on river-left.

At river-kilometer 3.2, the lower elevation on river-right coincide with the seesaw trend of cross-sectional profiles (Figure 15-20), as well as the significant decrease in longitudinal gradient. In addition, the 2009 and 2011 channel migration into the former Carbon River Road also occurred at this meander. The area immediate downstream of the low-lying area is a landform that is more than 10 meters above main channel surface (river-kilometer 4) (Figure 28). Historical images suggest this area was part of the active channel that was abandoned after 2003, resulting in floodplain development. Secondary channel avulsion facilitated by fence jam may not be considered a hazard because the main channel is already adjacent to bedrock outcrop on river-left.

At river-kilometer 5.5, RWSE shows secondary channel that avulsed into the Ipsut Creek during the 2006 flood event (Figure 28). This section of the Carbon River is extremely at risk for inundation during high flows, because the Carbon River Road and the Ipsut Creek Campground are located on the floodplain, at 5 to 6 meters below main channel water surface. I observed fence jams throughout the margin that facilitates small scale avulsion into the Ipsut Creek floodplain (Figure 29).

At river-kilometer 9.3, there is another low-lying floodplain (Figure 28). RWSE map shows several secondary channels that flows into Ranger Creek before returning back to the Carbon River main channel. This section of the river saw several proposed flood control measures by GEOMAX in 2008, including bank barbs, cross-valley dike, flood dike, and road humps. Due to the proximity of the main channel to the Carbon River Road and valley wall, erosional hazards have caused significant damages since 2006. In 2015, the Carbon River continues to erode the road away (Figure 3).

At river-kilometer 11.5, fence jam-facilitated channel avulsion can cause serious damage to the adjacent Carbon River Road (Figure 28). RWSE shows a tributary, sourcing from Falls Creek, runs parallel to the Carbon River in close proximity to the Carbon River Road. I observed evidence of numerous avulsed secondary channels, facilitated by fence jams that are directing flow into the tributary causing further incision (Figure 30). Some mitigation measures have taken place since 2006 as well, including road humps and drainage culverts (Entrix, 2008). However, with increasing aggradation and the potential for more frequent, low magnitude flood events, the section of the Carbon River Road may face more frequent flooding hazards from channel avulsion facilitated by fence jams.

## Classification of fence jam

Field observation shows that fence jam found in the Carbon River have different physical attribute than the 10 other archetypal natural log jams identified by Abbe and Montgomery (2003) because fence jams require live standing trees as "fence posts." Out of the 10 types of log jams described, these log jams found in the Carbon River most resembles bench jams.  Thus, I proposed to classify the fence jam as a "sub-type" of bench jam. Bench jam is classified as an allochthounous jam, where woody debris is transported downstream through fluvial processes and deposited along the margins of the active channel. Key members are wedged against irregularities in streams such as bedrock or outcrop to cause natural revetment. Orientation of key member can either be oblique or parallel to the flow. Accumulation of more woody debris and fine sediment creates floodplain-like feature upstream of the jam. Bench jams in the Queets River occurs mostly in the headwaters, where longitudinal gradient ranges between 0.06 and 0.20. Similarly, fence jams involves woody debris that are transported by fluvial processes and key members can be deposited at any orientation. Furthermore, it occurs only on the margins of active channel where riparian forest exists, and have the potential to create floodplain-like features where aggradation occur on the upstream bed-surface which armor parts of the floodplain.

Despite these similarities, several physical characteristics and functionality still differ from the described bench jam (Table 3). First, bench jams do not require standing riparian trees to act as "fence post." Key members in fence jam key members are buttressed against standing trees and pinned by subsequent deposition of sediment and woody debris. Second, although fence jams observed in the Carbon River show some armoring due to aggradation directly upstream, no long-term revegetation was observed. Fence jams that causes floodplain development did not stay in place for more than 2 or 3 years (with the exception of WF-24). This is supported by relatively young alders with a maximum height of approximately 3 meters, and an average diameter of 3 centimeter. Average growth rate of red alders in the Pacific Northwest is estimated at 1.8 meters/year (6 feet/year) for highly productive sites (Niemeic et al., 1995). Third, fence jams have the potential to redirect flow into adjacent floodplain. Thus, fence jam deserves its own definition that may be unique to aggrading unconfined forest rivers.

# Conclusion

Interaction between instream woody debris and standing old-growth riparian forests have shown significant effects on secondary channel migration in the aggrading Carbon River. These natural log jams manifest into fence-like features (i.e. fence post and fence rail) thus being named "fence jams." In the Carbon River, a fence jam is formed when one or more key members of woody debris, acting as "fence rails," is buttressed horizontally against one or more standing riparian trees, acting as "fence post" (Figure 12-14). This causes aggradation of coarse sediment and impoundment of additional woody debris directly upstream of the fence jams. Flows are then diverted around the natural log jam, causing headcuts and incisions into the adjacent floodplain. At numerous locations along the Carbon River, I observed avulsion pathway as wide as 60 meters facilitated by fence jams (WF-13). The spatial distribution of fence jams along the Carbon River is mainly associated with the significant changes in the longitudinal gradient and cross-sectional profile between river-kilometer 2.0 and 5.0. This section of the river is the most upstream meander of the Carbon River, where the main channel migrated dramatically to river-left after the 2006 flood event. Future flood events of low magnitude, high frequency peak flow is expected to create potential avulsion hazards to the Carbon River Road. Specifically, areas around river-kilometer 5.5 and 11.5 have the most potential to cause flood damage to the adjacent road due to fence jam-facilitated avulsions.

The product of this report serves as an initial findings of fence jams found in one Mount Rainier river. Future field investigation and constrains on geomorphic characteristics can further expand the understanding of this type of natural log jam throughout other proglacial rivers. Specifically, due to the relatively young floodplain development caused by fence jams, I hypothesized these unstable log jams may fail regularly. Further study on the understanding of the mechanisms and conditions required to breach the fence jams can provide valuable information on modes of channel avulsion in the Carbon River, providing further insight to flooding mitigation for the National Park Service.

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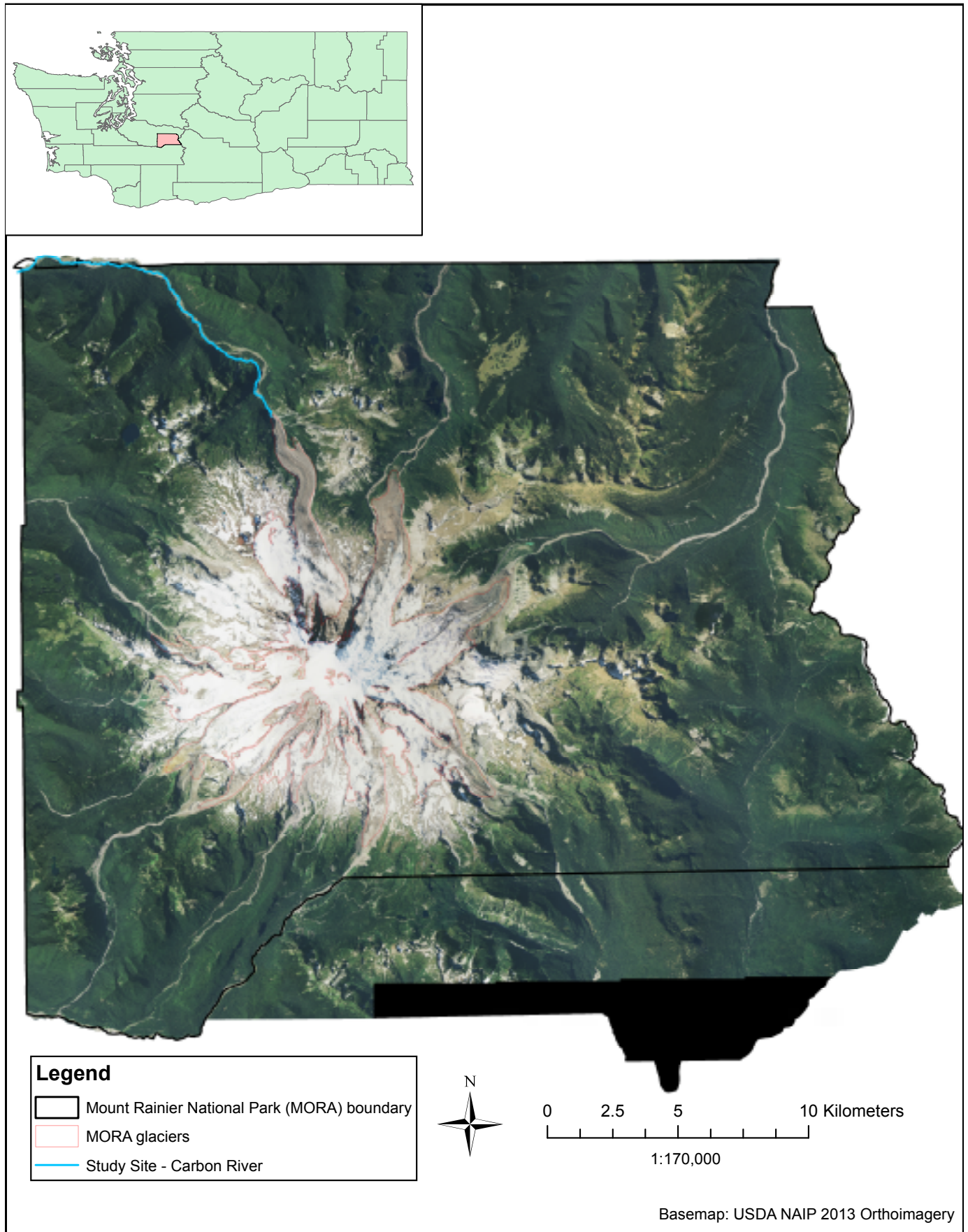
# Figures



Figure 1: Site location of study area in Mount Rainier National Park, Washington. The Carbon River is located on the northwest corner of the park boundary.
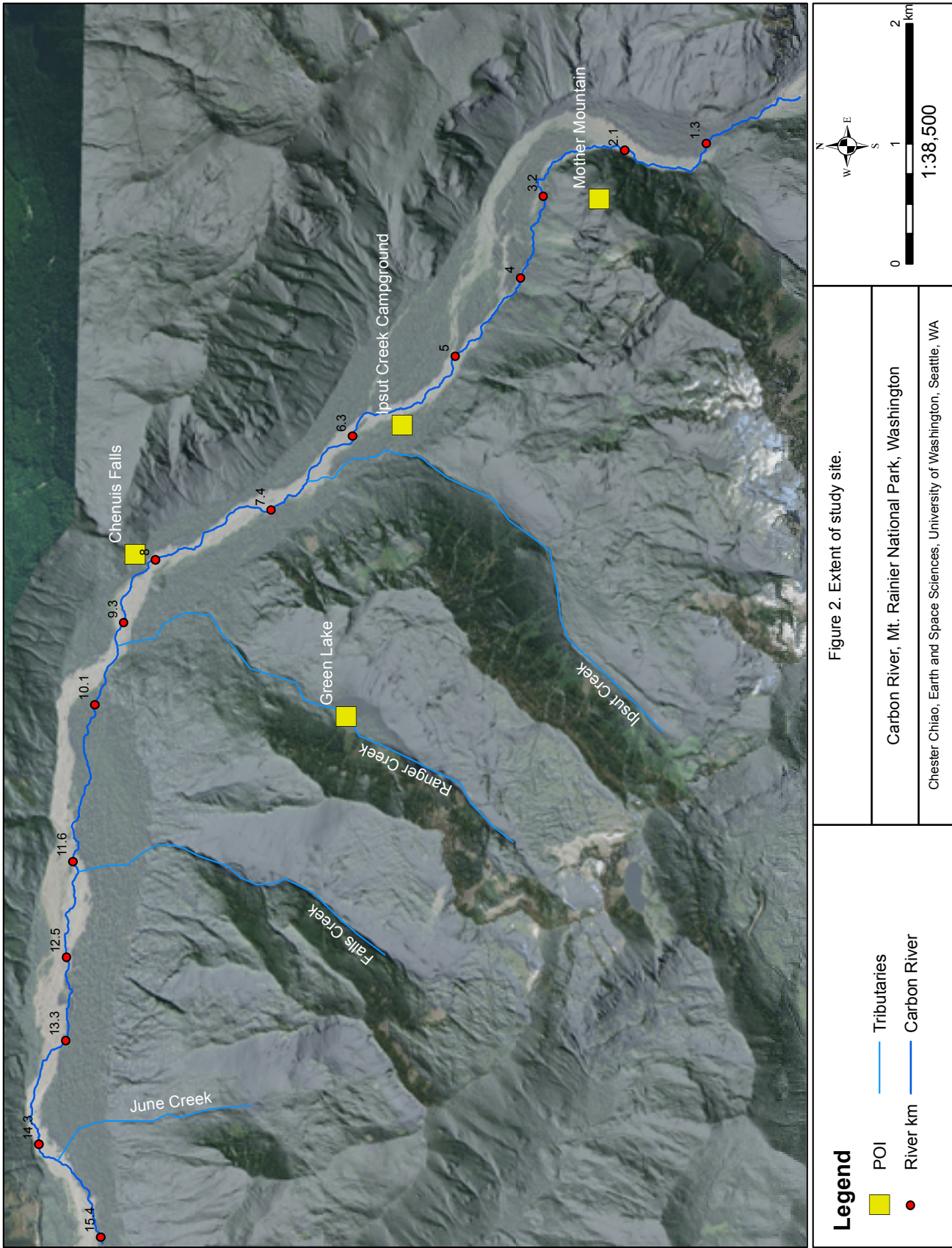
Figure 2. Extent of study site.

Carbon River, Mt. Rainier National Park, Washington

Chester Chiao, Earth and Space Sciences, University of Washington, Seattle, WA

Projection: NAD1983 UTM Zone 10N (meters)  Basemaps: 2012 1 meter LiDAR DEM hillshade, USDA NAIP 2011 orthophoto.

**Legend**

POI

River km — Tributaries

— Carbon River

1:38,500

Figure 2: Extent of study location with points of interest. Total length of study reach is 15.4 kilometers. River-kilometer is measured from the Carbon glacier. The Carbon River flows from the Carbon glacier (bottom right) to the park entrance (top left).

Figure 3: Flood damage from the 2015 winter storm event. This is located at 8.5 river-kilometer, which is just downstream of Chenuis Falls. Red arrow in the lower figures show same location before (bottom left) and after (bottom right) the flood event. Photographs obtained from Paul Kennard (2015).
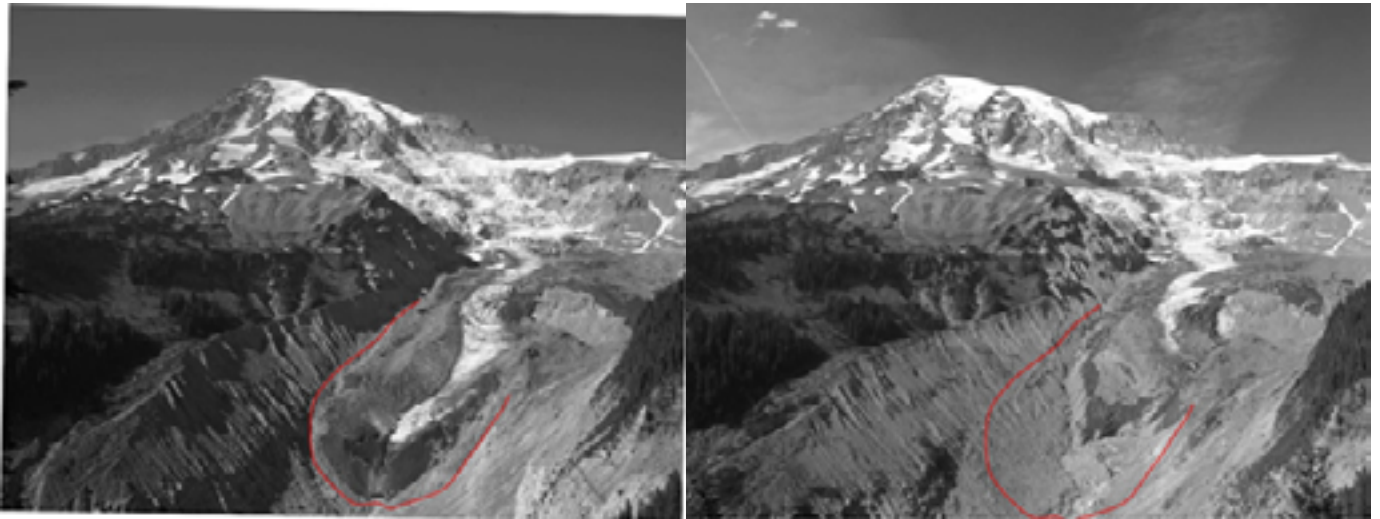
Figure 4: Nisqually glacial retreat from 1974 to 2004. Red line indicates same position of the 1974 extent of glacier. Photographs obtained from Paul Kennard.
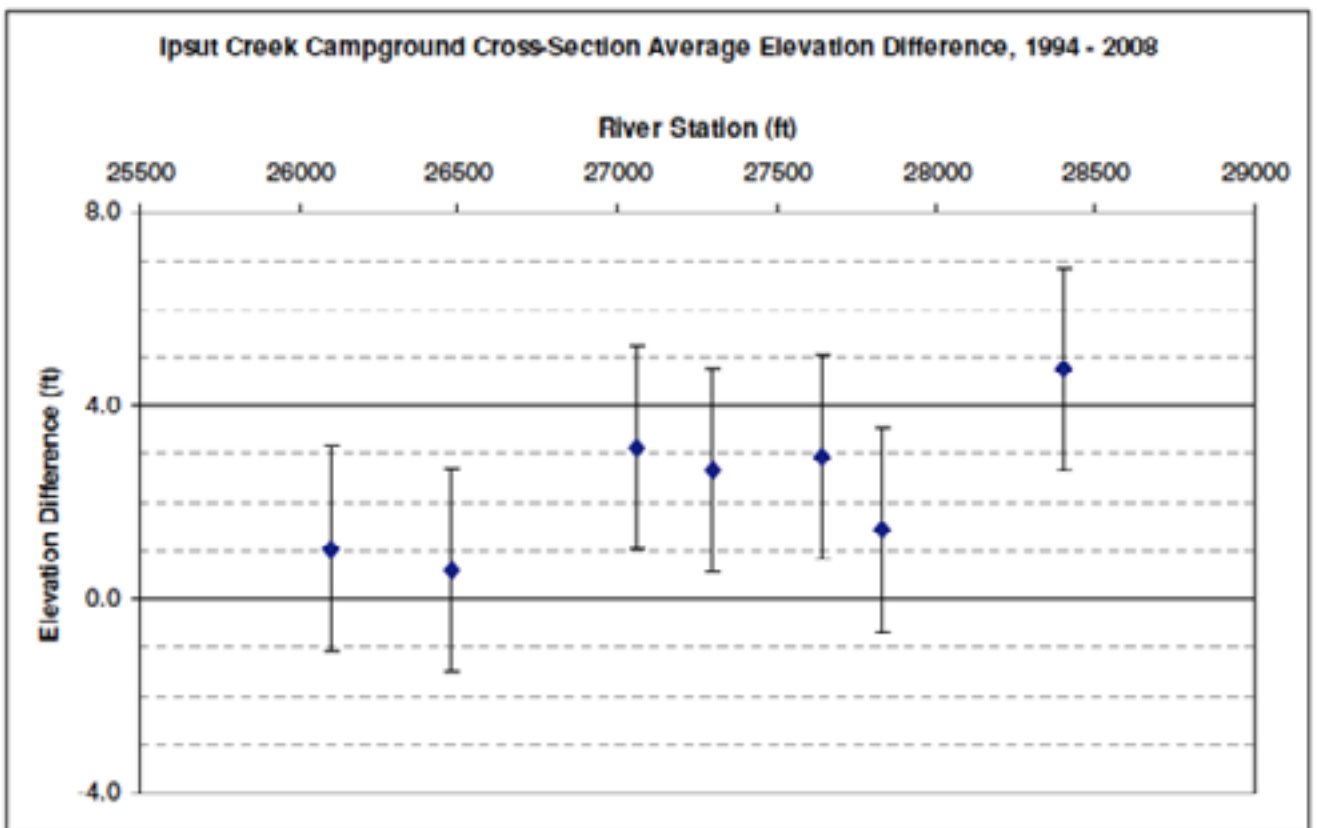


Figure 5: Estimated elevation difference between 1994 and 2008 at Ipsut Creek campground cross sections. The Carbon River flows from figure-right to figure-left (Entrix, 2008).
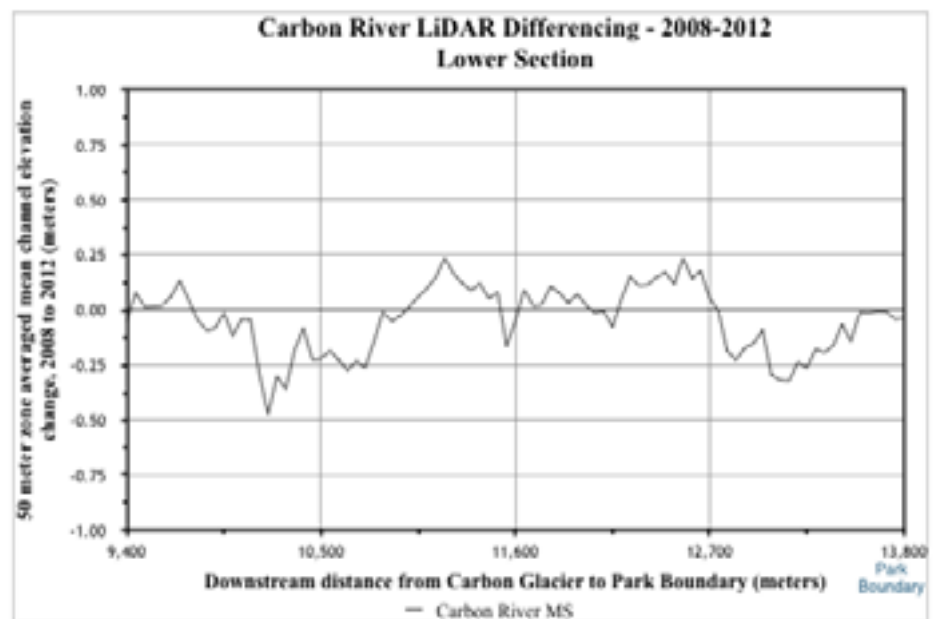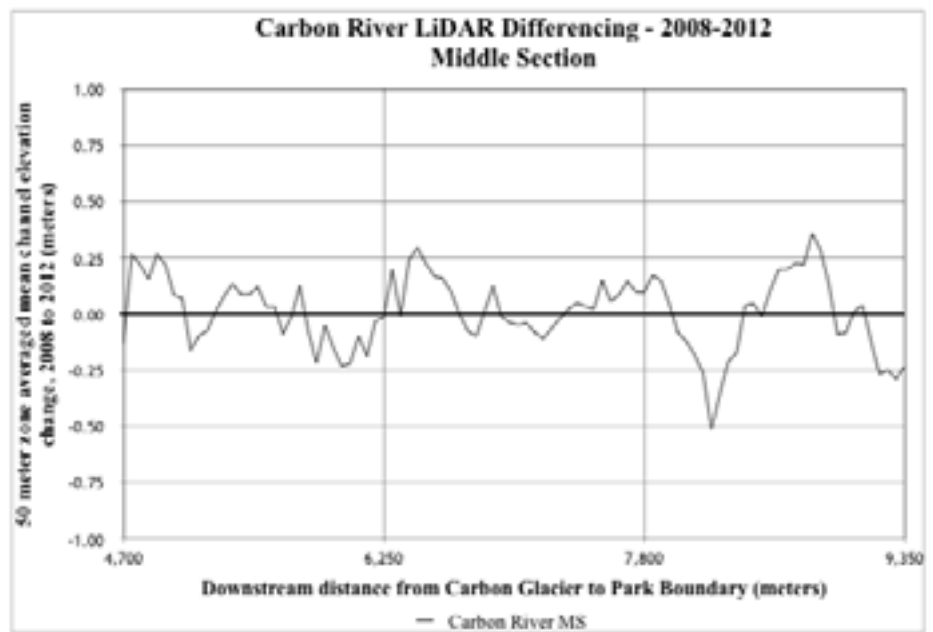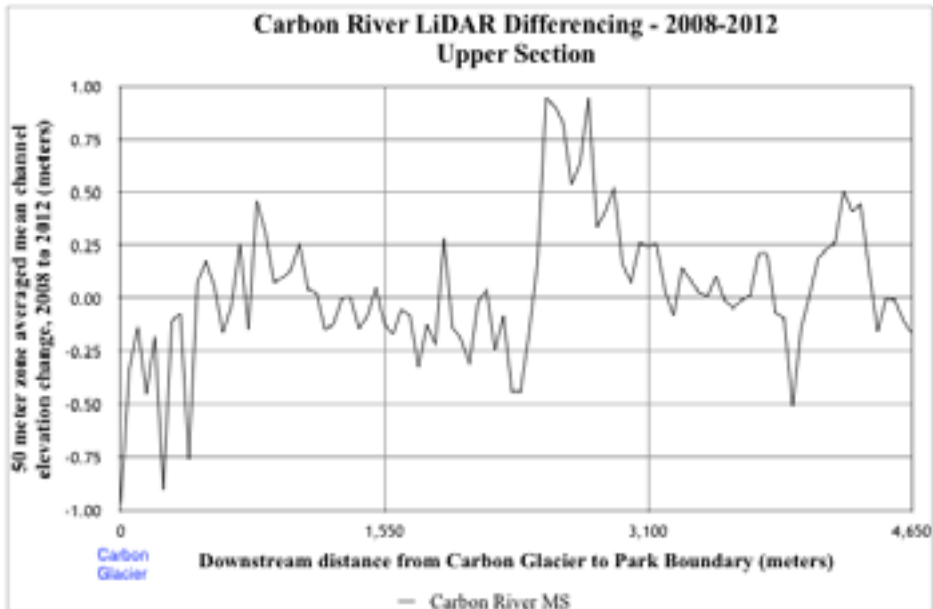
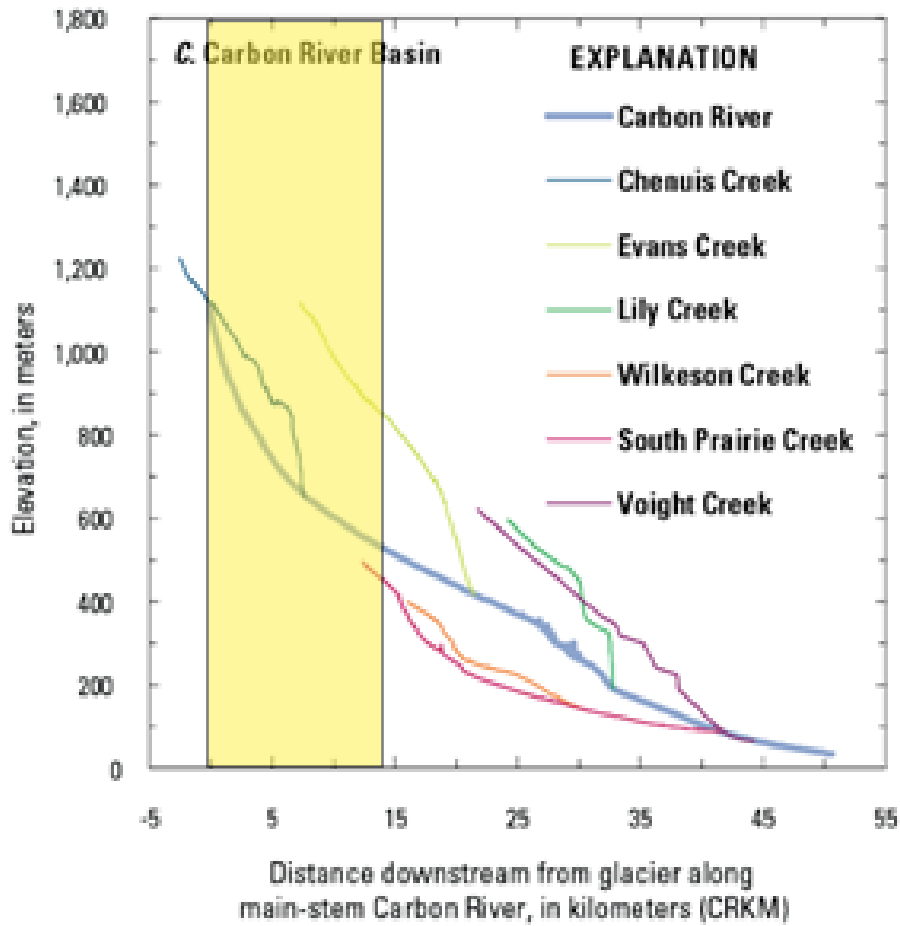Figure 6: Results from DEM differencing from 2012 and 2008 LiDAR for three sections of the Carbon River within the Park boundary (Knoth, 2013).

Figure 7: Longitudinal profile of various rivers that radially drains Mount Rainier. Yellow shaded area indicate studied reach (modified from Czuba et al, 2012).
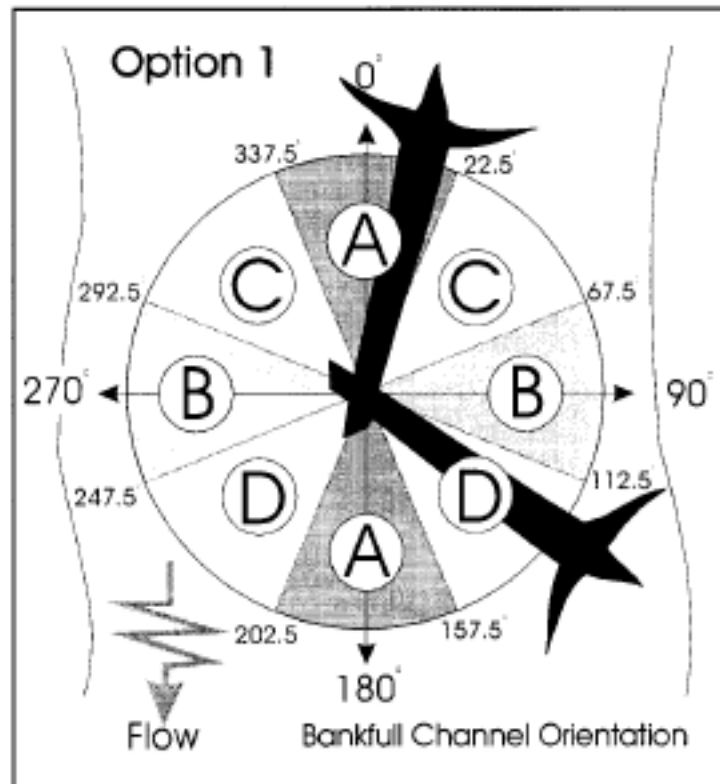


Figure 8: Orientation of log placement relative to flow (based on Bilby and Ward, 1991).

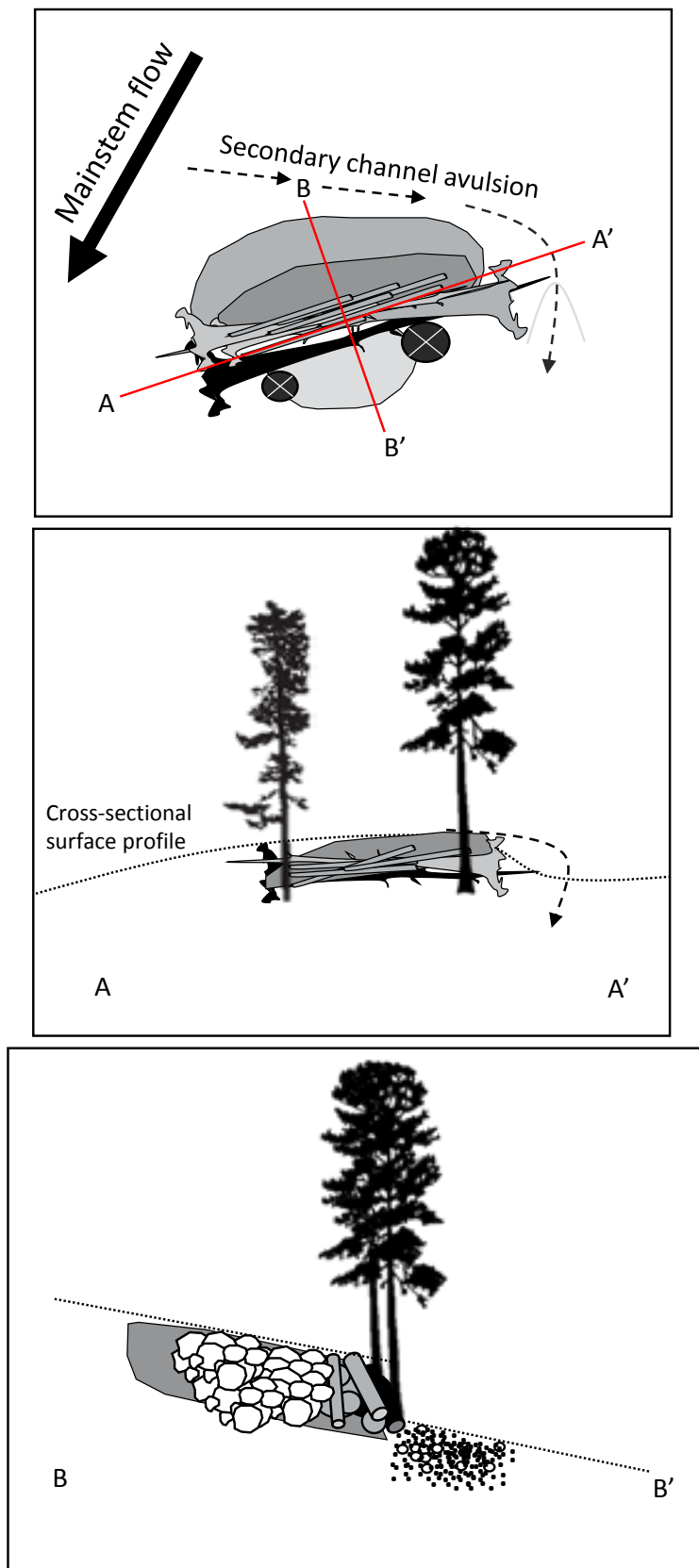Figure 9: Double arrow line show the bed-surface elevation change at a fence jam.

Figure 10: Schematic of an archetypal fence jam at various viewpoint: (a) Planview of fence jam showing standing riparian trees acting as "fence post" (black circle with x); keymember large WD acting as "fence rails" (black); additional stacked and loose WD (gray). Underlying shading shows coarse bed material (dark gray) to fine bed material (light gray). Arrow suggests avulsion pathways facilitated by the fence jam. Headcut is located directly to the right of the fence jam. (b) Upstream-view of a fence jam. (c) Cross-sectional view of a fence jam. Notice the bed-elevation change from upstream (figure-left) to downstream (figure-right).

Figure 11: Picture of fence jam at WF-13 where a large WD is buttressed against two variously-sized standing trees. Mainstem of the Carbon is located behind PhD student, Jonathan Beyeler. Notice that Jon Beyeler is standing on top of the aggraded bed upstream of the fence jam, which is significantly higher than elevation downstream. Headcut is formed directly to the left of fence jam (figure-right).



Figure 12: Picture of fence jam at WF-21 showing changes in bed material. Red dashed line shows avulsion pathway around the fence jam.
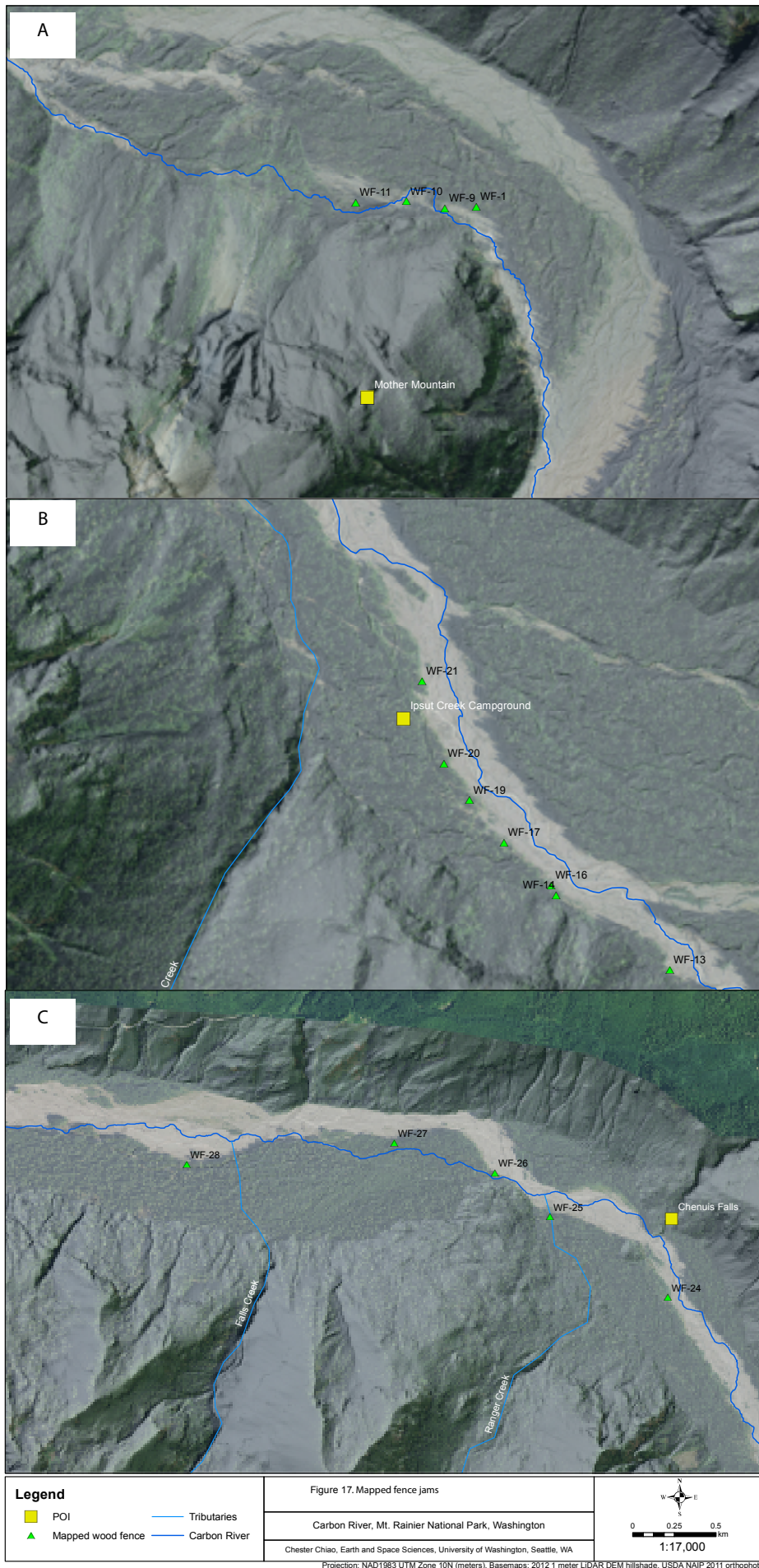
Figure 13: Locations of 25 fence jam for (A) the Upper Reach, (B) the Ipsut Creek floodplain, and (C) the Lower Reach.
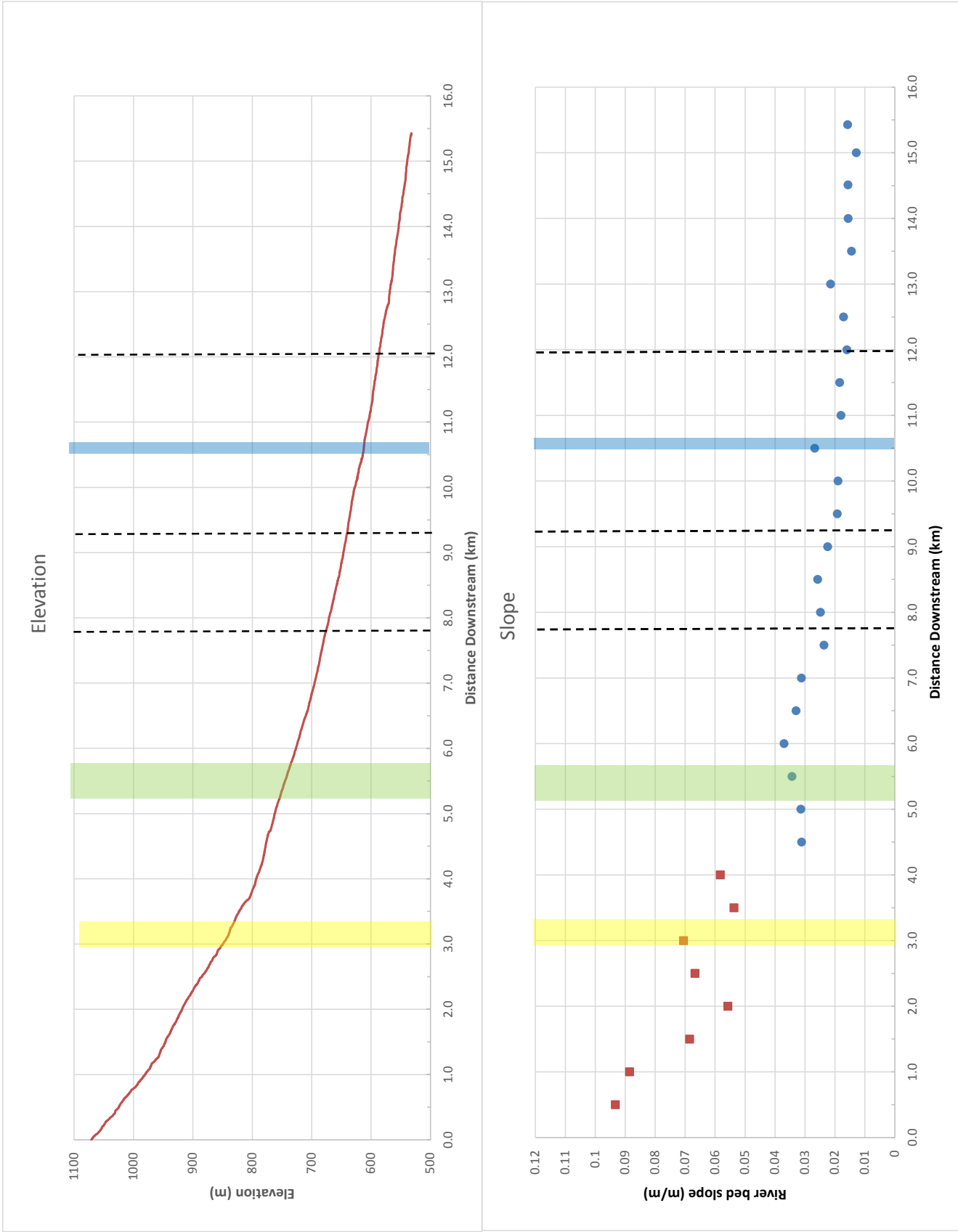
Figure 14: Longitudinal profile of the Carbon River from the Carbon glacier (figure-left) to the Park entrance (figure-right). Average slope is sampled at 500-meter intervals.
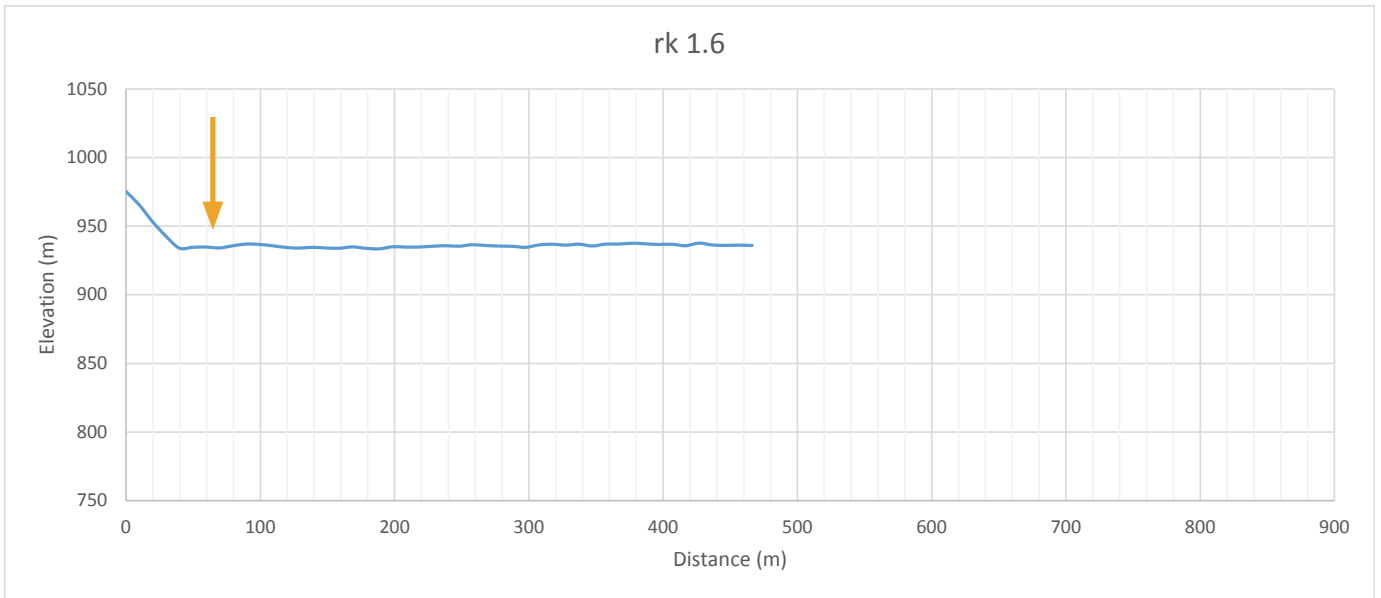
Figure 15: Cross-sectional profile sampled at river-kilometer 1.6. Orange arrow approximates position of thalweg.
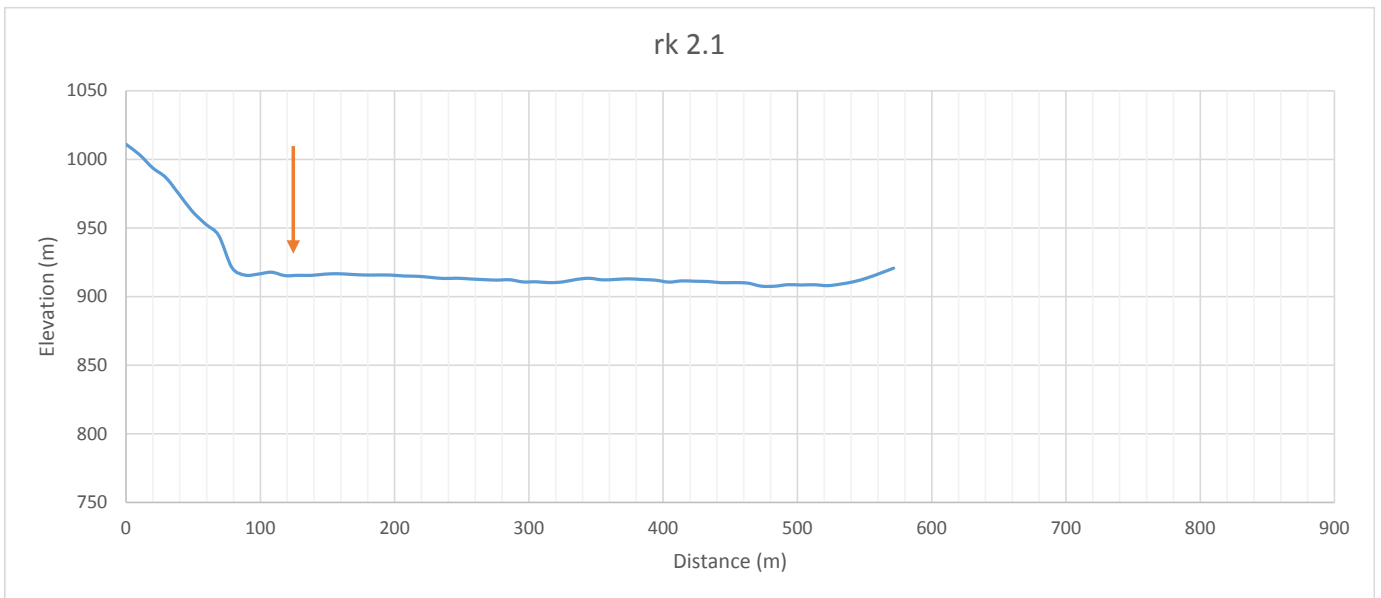

Figure 16: Cross-sectional profile sampled at river-kilometer 2.1. Orange arrow approximates position of thalweg.
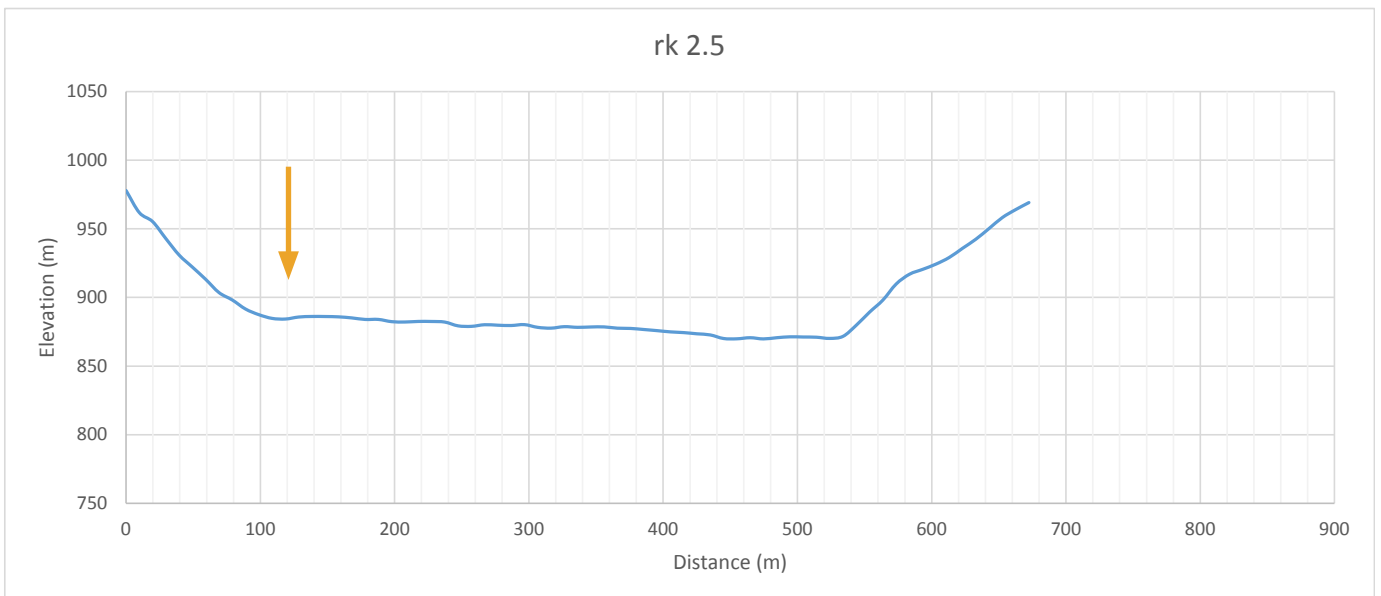

Figure 17: Cross-sectional profile sampled at river-kilometer 12.5. Orange arrow approximates position of thalweg.

Figure 18: Cross-sectional profile sampled at river-kilometer 3.2. Orange arrow approximates position of thalweg.



Figure 19: Cross-sectional profile sampled at river-kilometer 4.0. Orange arrow approximates position of thalweg.
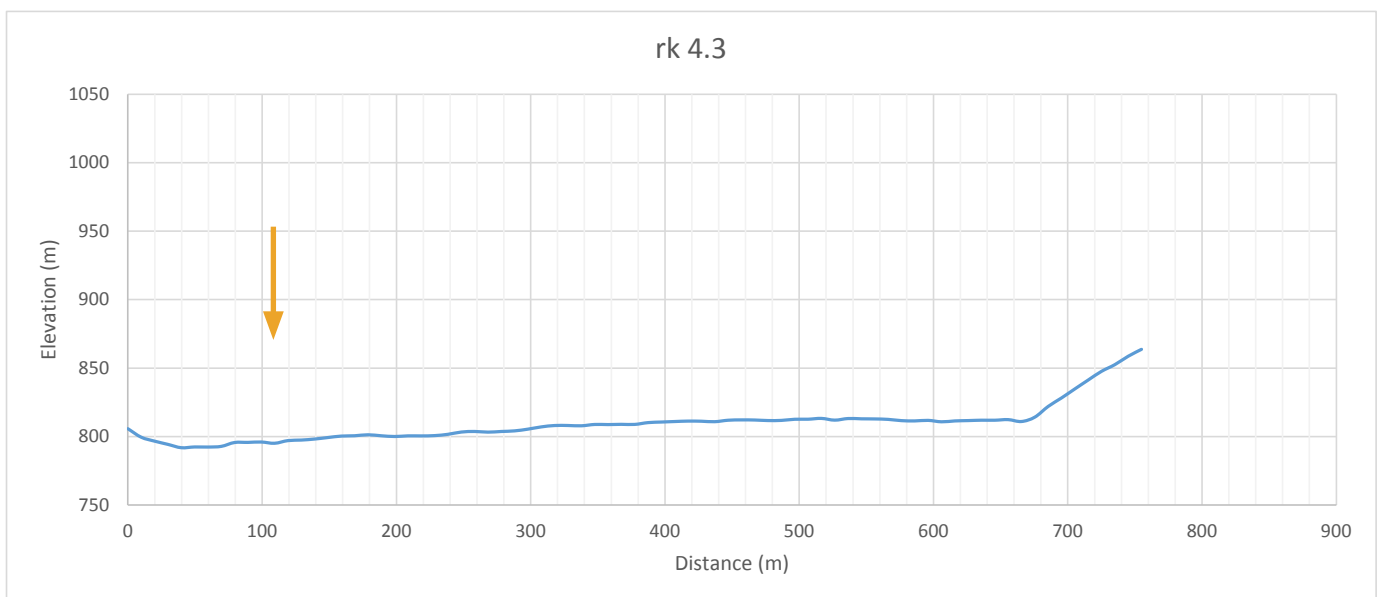


Figure 20: Cross-sectional profile sampled at river-kilometer 4.3. Orange arrow approximates position of thalweg.
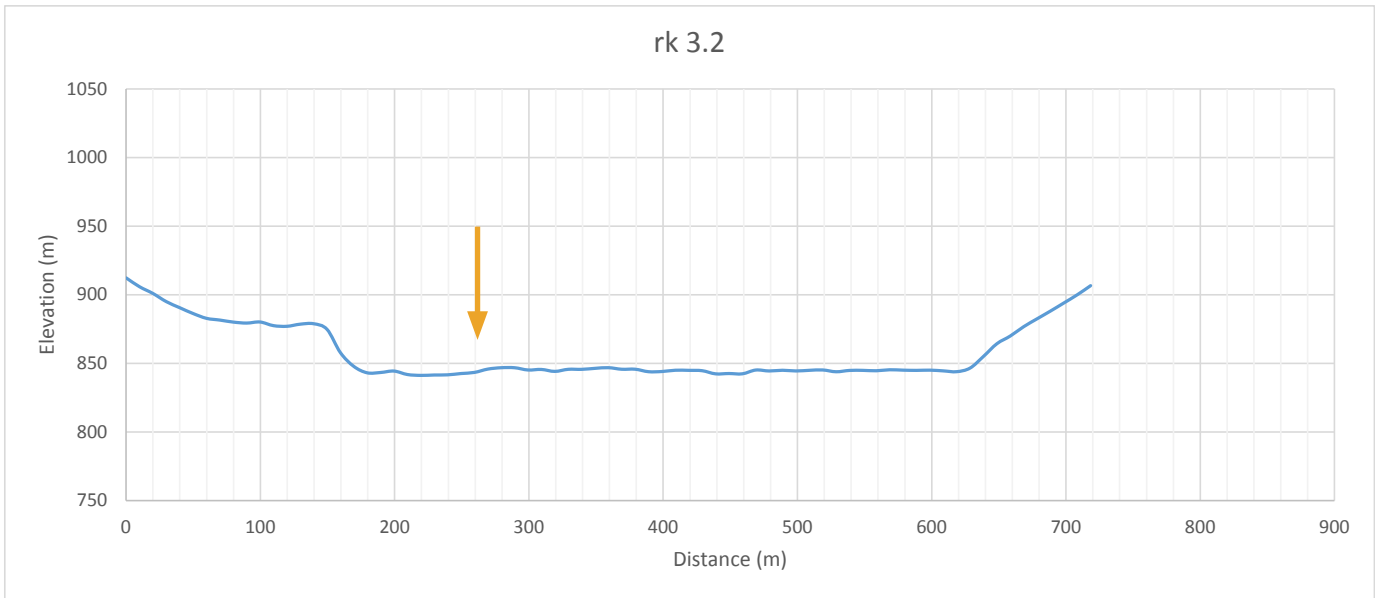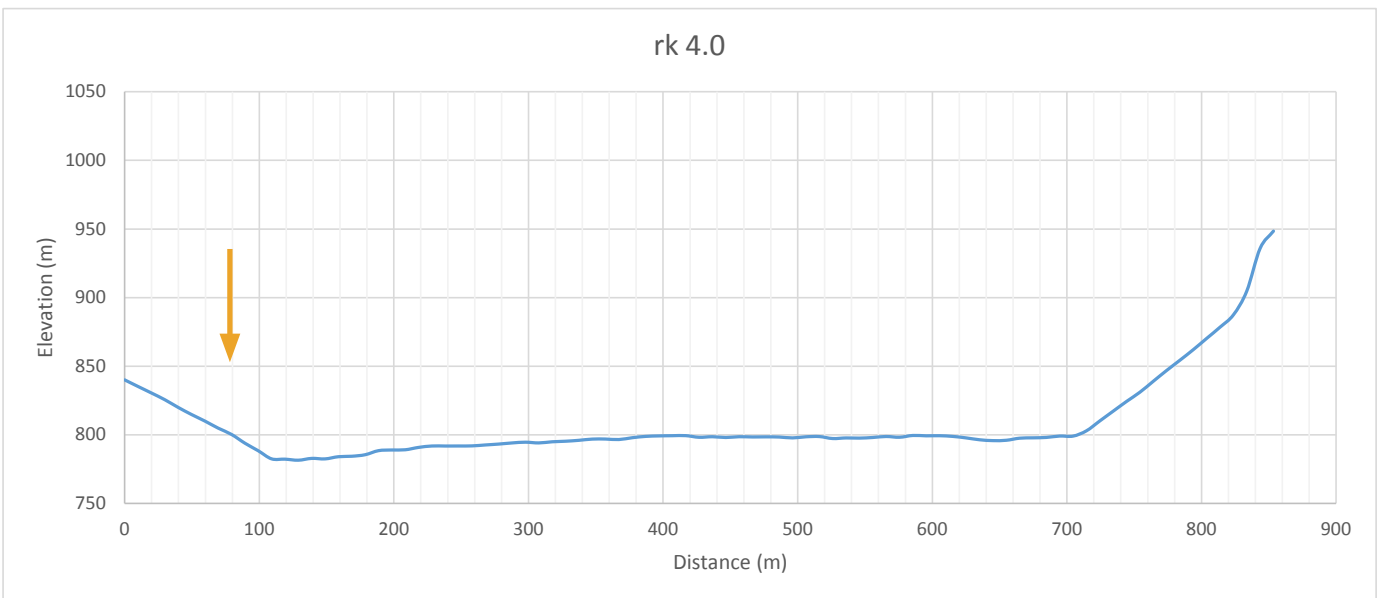
**Legend**

| | |
|---|---|
| ——— Tributaries | |
| ——— Carbon River Road | |
| ● River-kilometer | |
| ▨ Fence jam zone | |

**Historical Main Stems**

Year
- 2015
- 2013
- 2011
- 2009
- 2006

Figure 21. Historical migration of main channel and fence jam zones
in the Upper Reach and Ipsut Creek Floodplain

Carbon River, Mount Rainier National Park, WA

Chester Chiao, Earth and Space Sciences, University of Washington, Seattle, WA

1:17,000

Projection: NAD1983 UTM Zone 10N (meters). Basemaps: 2012 1 meter LiDAR DEM hillshade, USDA NAIP 2011 orthophoto.

Figure 21: Mainstem migration from 2006 to 2015. Map showing areas around river-kilometer 3, which is located
at the upstream meander of the Carbon River.
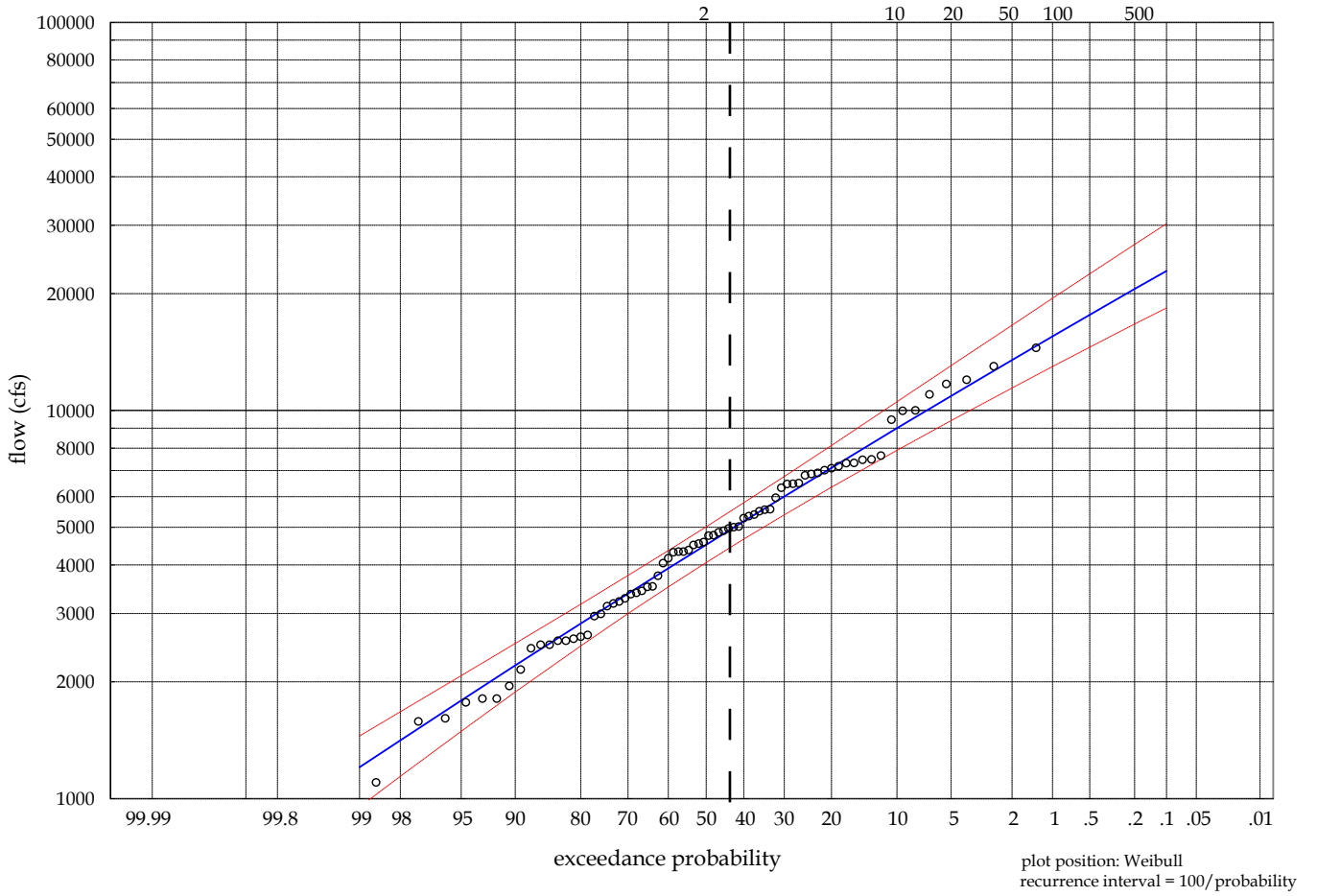
Figure 22: Annual maximum series determined using Log Pearson III distribution. Dashed line shows 2015 winter flood event that created the fence jam at WF-13.
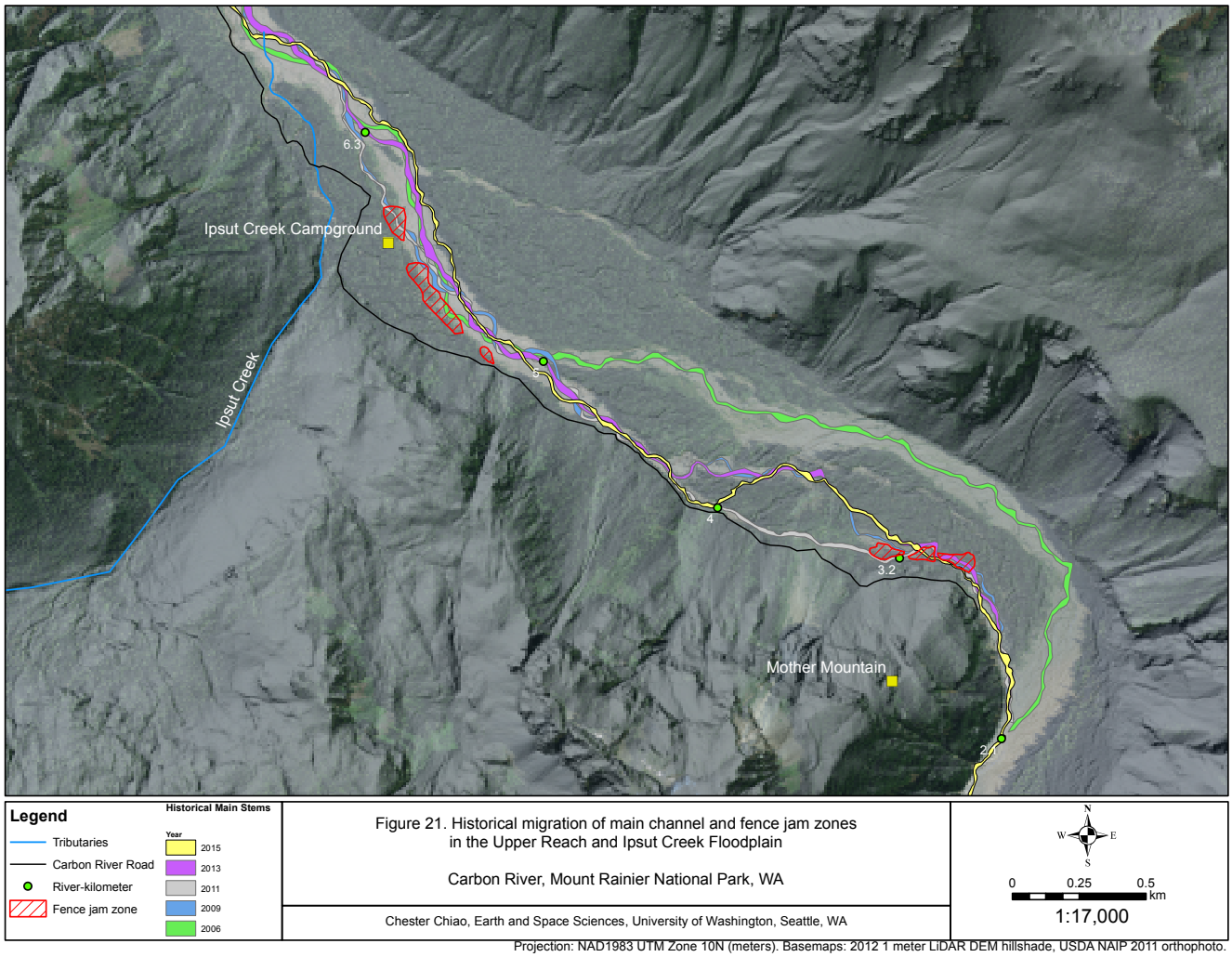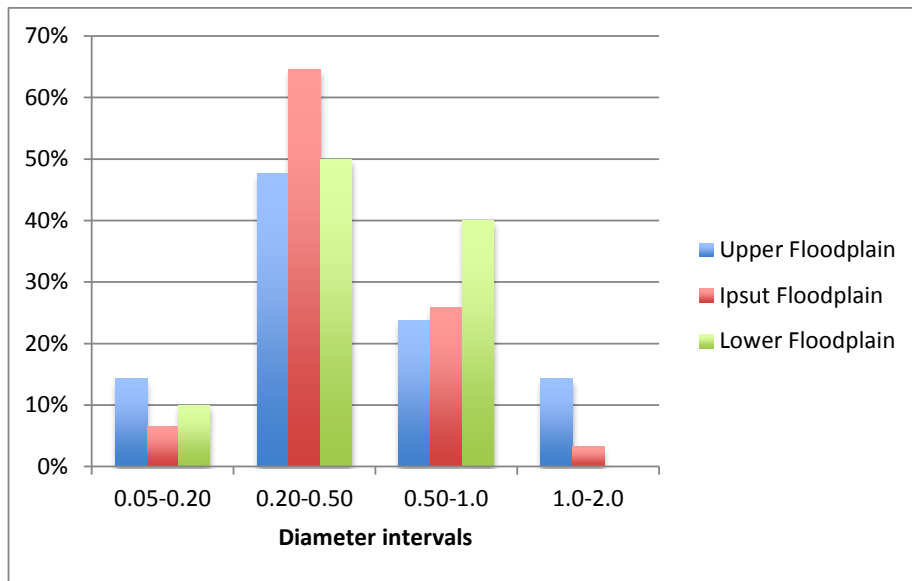
Figure 23: Normalized percentage of standing tree diameter at breast height (DBH) for the three sections of the River.
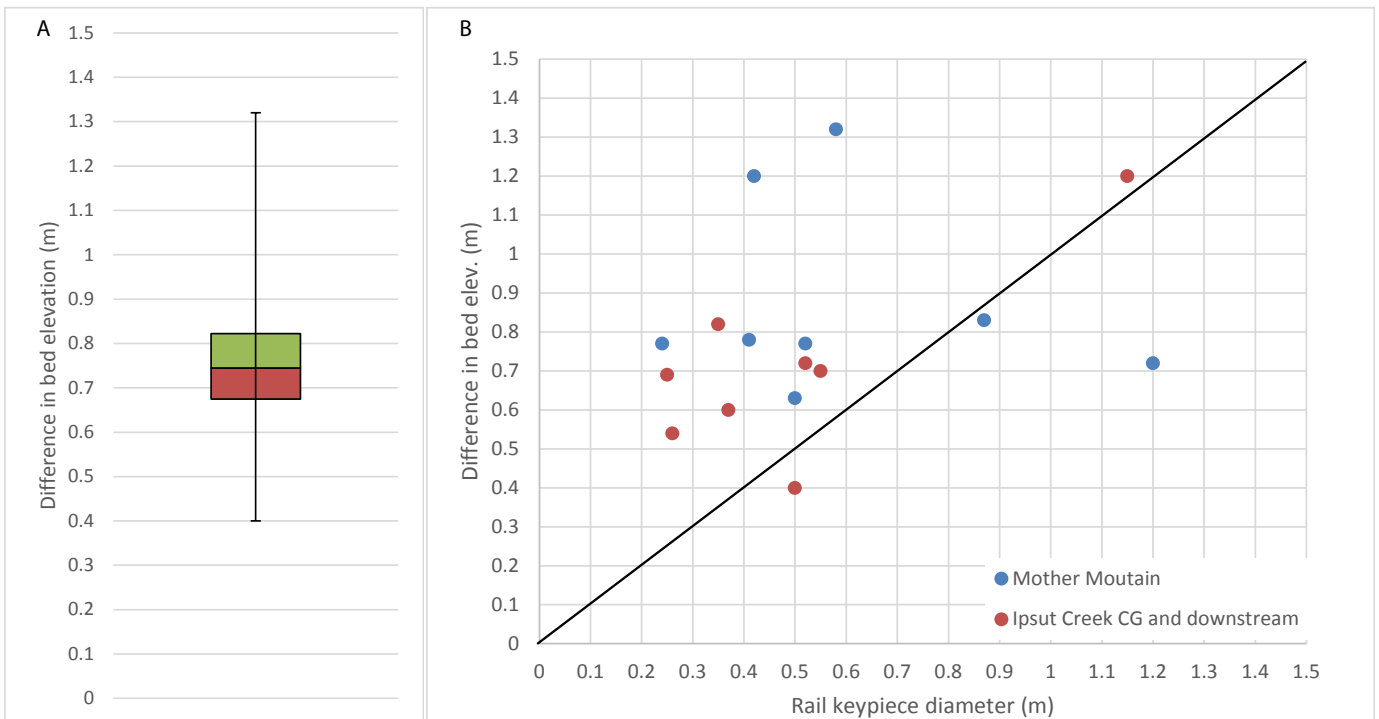


Figure 24: (a) Distribution of vertical bed-surface elevation change throughout all of the mapped fence jam. (b) Ratio of keymember WD (fence rail) diameter to the difference in bed elevation.

Figure 25: (A) Distribution of vertical bed-surface elevation change for valley-spanning log jams on the Queets River, Washington (Brummer et al., 2006). (B) Ratio of keymember WD (fence rail) diameter to the difference in bed elevation.
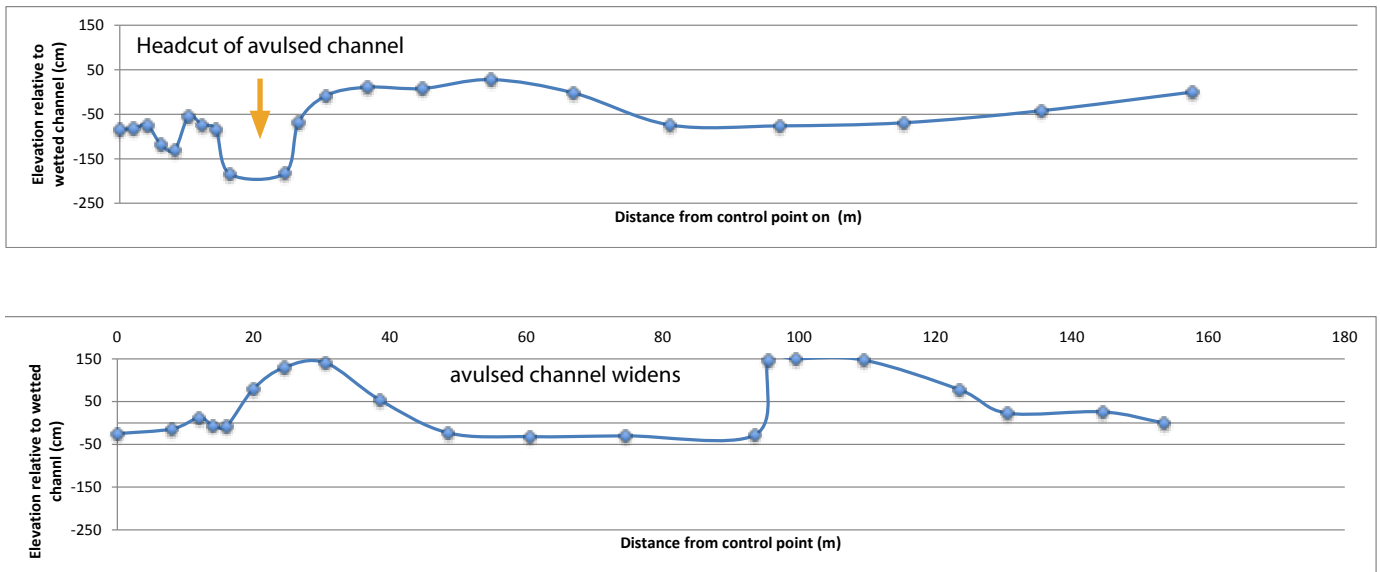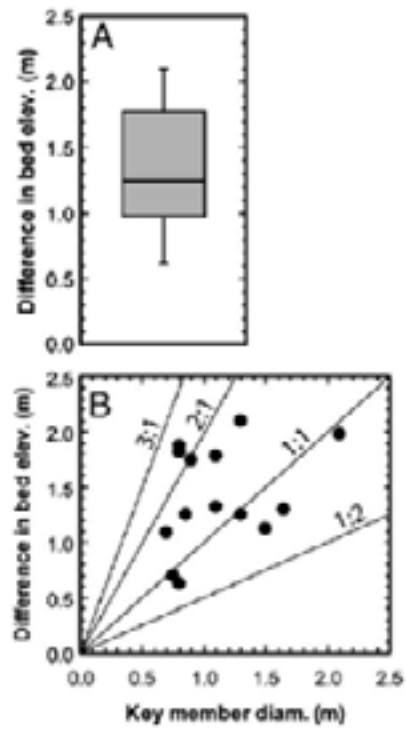




Figure 26: Cross sections measured at WF-13. (a) Cross section taken from valley wall (figure-left) to wetted channel (figure-right). (b) cross section taken 100 meter downstream from (a).

Figure 27: Two distinct fence jams (red and blue). Flow directed in between (yellow) at WF-20.
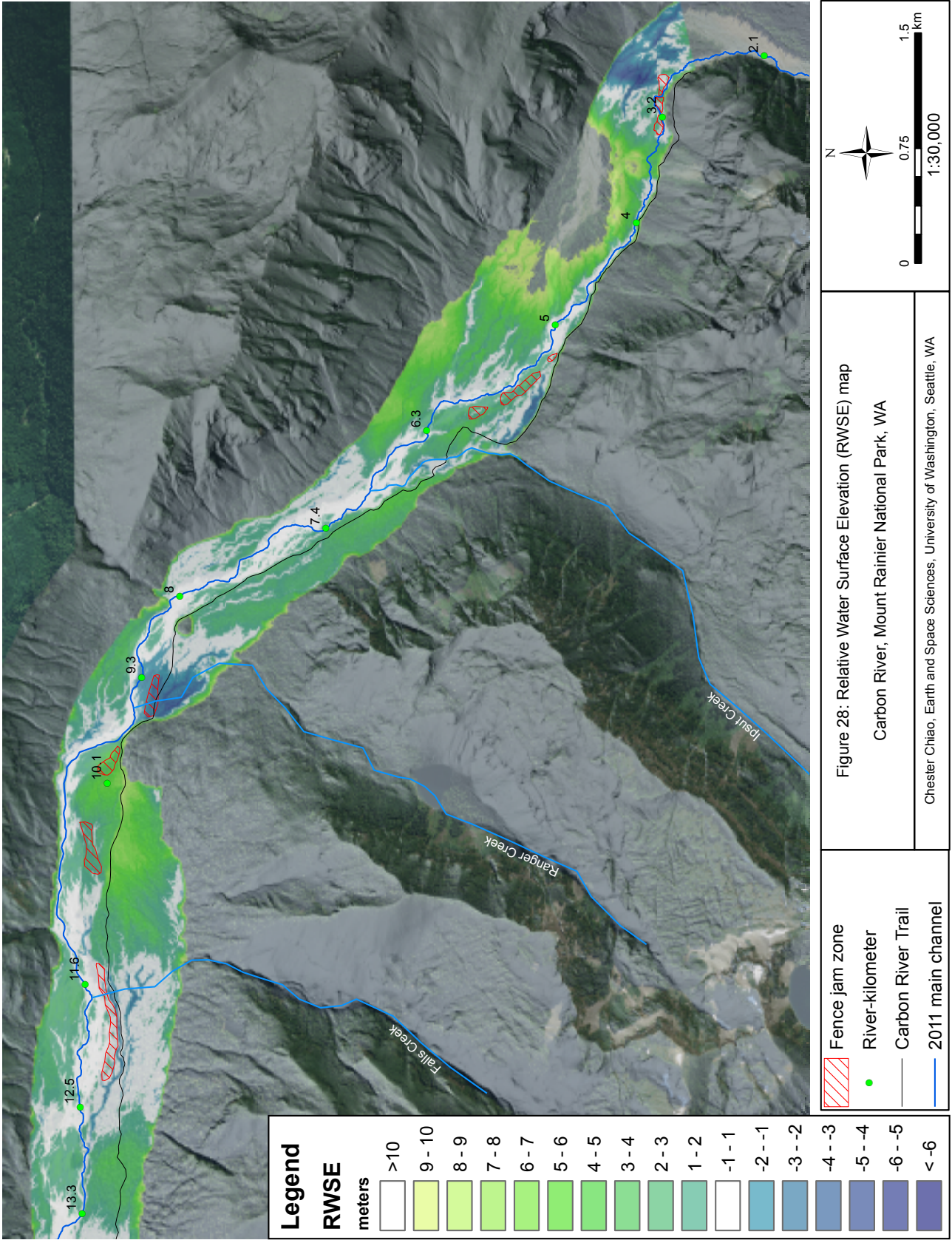
Figure 28: Relative height of water surface elevation map of the study reach.
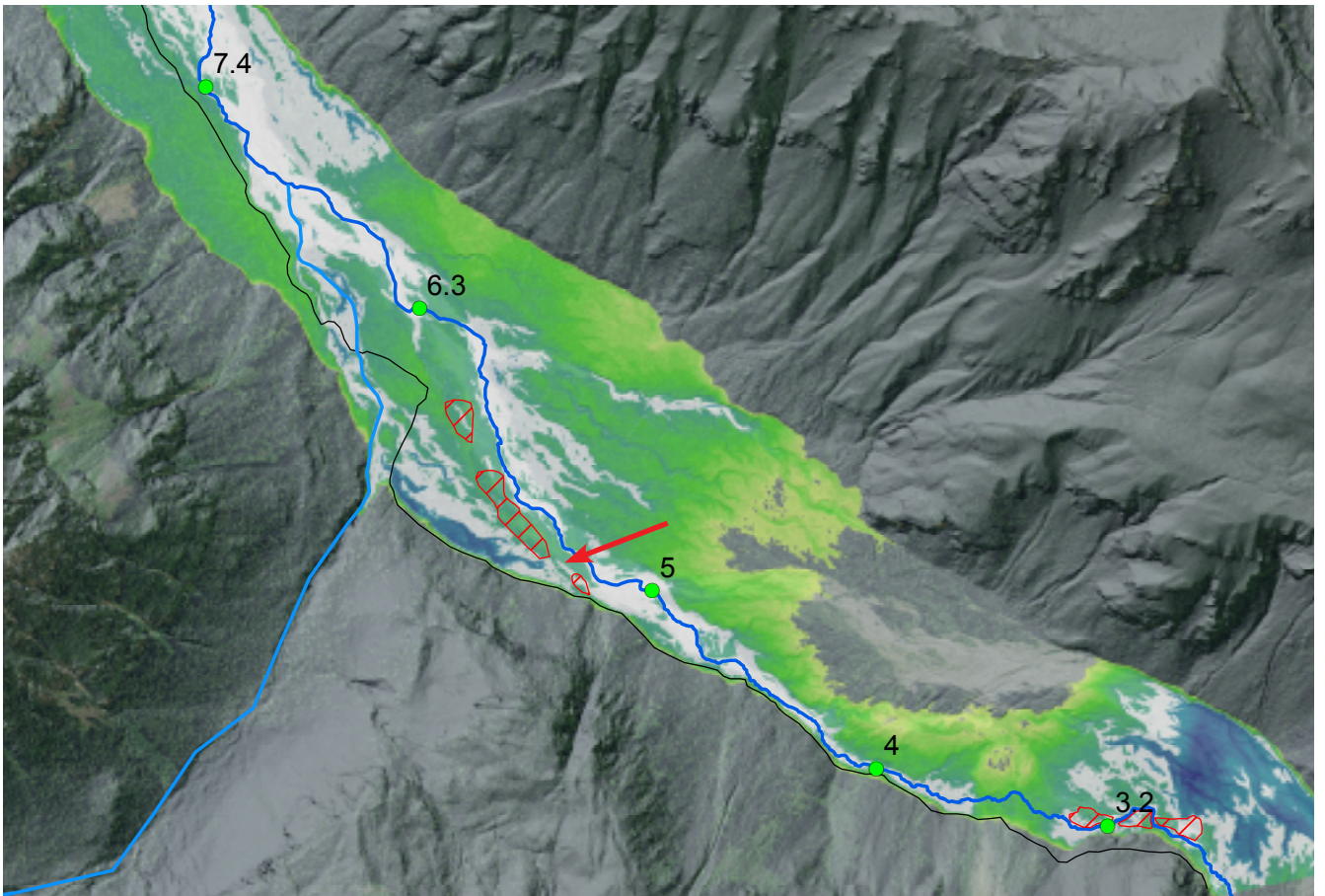
Figure 29: Potential avulsion pathway (red arrow) of secondary channel at Ipsute Creek Campground
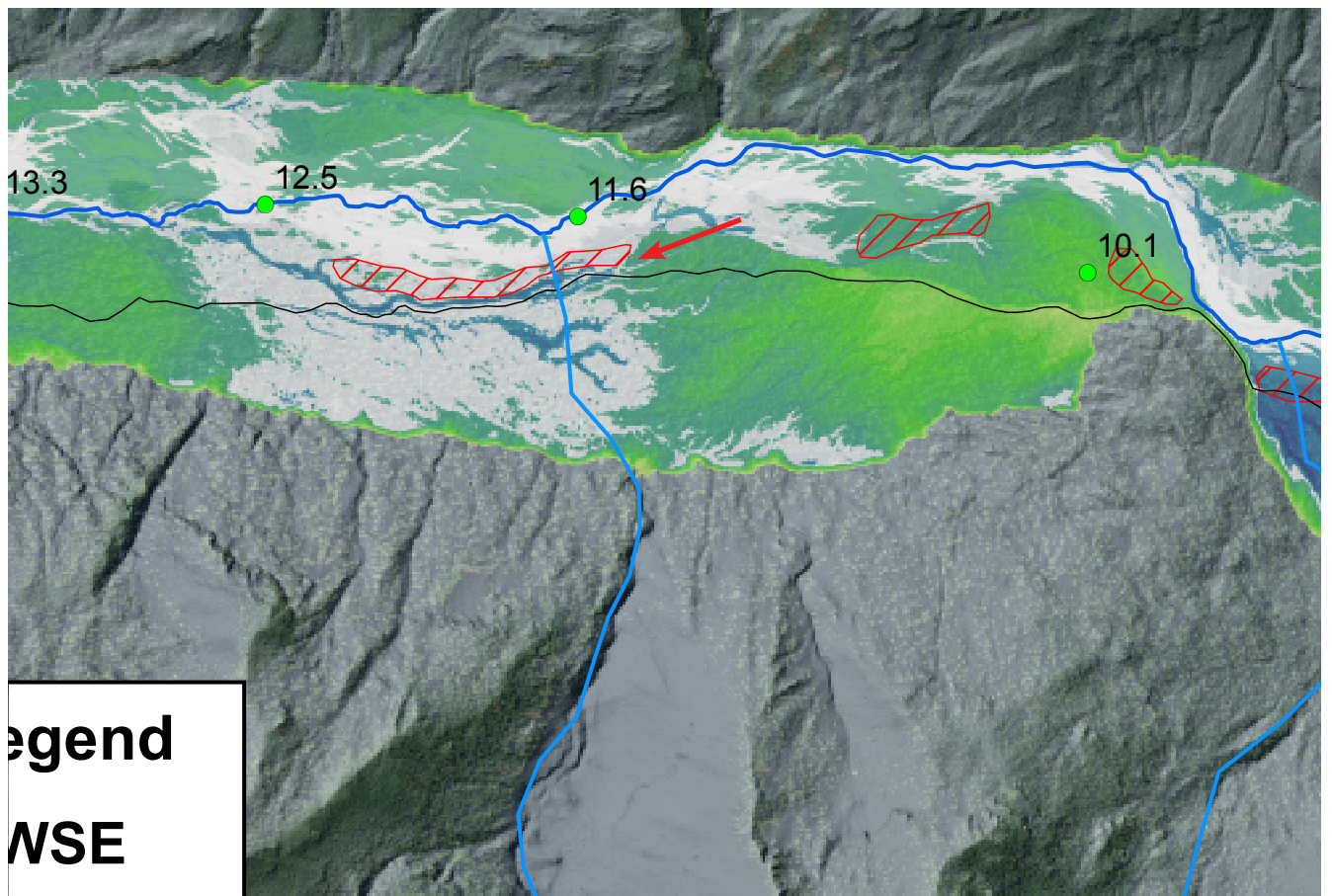


Figure 30: Potential avulsion pathway (red arrow) at Lower Reach

# Tables

Table 1: Summary of GIS data acquired for this project

| Data Type | Agency | Year | Publication Date | Resolution |
|---|---|---|---|---|
| LiDAR DEM | NPS | 2008 | n/a | 1-meter |
| LiDAR DEM | NPS | 2012 | n/a | 1-meter |
| NAIP Orthoimagery | USDA | 2006 | 10/15 | |
| NAIP Orthoimagery | USDA | 2009 | 10/15 | |
| NAIP Orthoimagery | USDA | 2011 | 10/5 | |
| NAIP Orthoimagery | USDA | 2015 | 11/11 | |

Table 2: List of fence jam with coordinate system that shows evidence of channel avulsion.

| ID | Latitude | Longitude | Flooding hazard to Carbon River Road |
|---|---|---|---|
| WF-9 | 46.962951 | -121.800385 | No |
| WF-11 | 46.963057 | -121.803256 | No |
| WF-13 | 46.967869 | -121.819176 | Yes |
| WF-17 | 46.970614 | -121.824550 | Yes |
| WF-20 | 46.972333 | -121.826522 | Yes |
| WF-21 | 46.974144 | -121.827252 | Yes |
| WF-26 | 46.995500 | -121.855917 | Yes |
| WF-28 | 46.995556 | -121.881944 | Yes |

Table 3: Comparison of bench jam observed in the Queets River (Abbe and Montgomery, 2003) and fence jam observed in the Carbon River.

| Types | Channel gradients | Distinguish characteristics | Source |
|---|---|---|---|
| Bench jam | 0.06-0.20 | Key members wedged along channel margin forms bench-like surface. Can support forested floodplain development. | Abbe and Montgomery (2003) |
| Fence jam | 0.02-0.1 | Key members buttressed against standing riparian trees to create bench-like surface. Relatively unstable. | This study |

# Appendices

# Appendix A: Data collected for fence jams surveys in the Carbon River.

| Zone | ID | Fence Post Count | Fence Post Circumference | Fence Post Diameter | Fence Rail Count | Fence Rail Diameter | Extent | Placement Orientation | Vertical bed-surface elevation change | Post Spacing | Notes |
|------|-----|------|------|-------|------|------|----------|-------|------|------|------|
| 1 | WF-1 | 1 | 4.0 | 1.3 | 2 | 0.34 | Discrete | B | 0.83 | | |
| | | | | | | **0.87** | | | | | |
| | WF-2 | 1 | 1.7 | 0.6 | 1 | 0.5 | Discrete | C | 0.63 | | |
| | WF-3 | 3 | 3.9 | 1.2 | 6 | 0.42 | Discrete | C | 1.2 | | |
| | | | 2.5 | 0.8 | | 0.12 | | | | | |
| | | | 1.5 | 0.5 | | 0.29 | | | | | |
| | | | | | | 0.28 | | | | | |
| | | | | | | **0.43** | | | | | |
| | WF-4 | 1 | 1.3 | 0.4 | 1 | **0.24** | Discrete | C | 0.77 | | |
| | WF-5 | 2 | 1.3 | 0.4 | 1 | **0.41** | Discrete | B | 0.78 | | |
| | | | 0.5 | 0.2 | | | | | | | |
| | WF-6 | 8 | 3.5 | 1.1 | 10 | | Continuous | C | 0.84 | | |
| | WF-7 (not sampled) | | | | | | | | | | |
| | WF-8 | 11 | | | 14 | | Continuous | A, B, C | | | |
| 2 | WF-9 | 5 | | | >20 | | Continuous | A | | | |
| | WF-10 | 2 | 1.4 | 0.4 | 3 | **0.52** | Discrete | A, C | 0.77 | | |
| | | | 2.7 | 0.9 | | | | | | | |
| | WF-11 | 3 | 0.8 | 0.3 | >20 | **1.2** | Discrete | B | 0.72 | | measurement taken for one main fence post |
| | | | 0.6 | 0.2 | | | | | | | Active! |
| | | | 2.0 | 0.6 | | | | | | | |
| 3 | WF-12 | >20 | | | >20 | | Continuous | B, C | | | lots of debris |
| | | | 0.76 | 0.242 | | | | | | | |
| | | | 0.73 | 0.232 | | | | | | | |
| | | | 0.42 | 0.134 | | | | | | | |
| | | | 0.86 | 0.274 | | | | | | | |
| 4 | WF-13 | 6 | 2.2 | 0.7 | >20 | 0.34 | Continuous | A | 1.32 | 3.15 | |
| | | | 5.6 | 1.8 | | **0.58** | | | | 1.15 | |
| | | | 1.4 | 0.4 | | 0.27 | | | | | |
| | | | 4.3 | 1.4 | | | | | | | |
| | | | 3.7 | 1.2 | | | | | | | |
| | | | 2.3 | 0.7 | | | | | | | |
| 5 | WF-14 | 2 | 3.5 | 1.1 | 1 | **0.5** | Continuous | B-1 | 0.4 | | |
| | | | 1.5 | 0.5 | | | | | | | |
| | WF-15 | 2 | 2.6 | 0.8 | 1 | **0.37** | Continuous | B-1 | 0.6 | 6.9 | |
| | | | 1.4 | 0.5 | | | | | | | |
| 6 | WF-16 | 3 | 1.21 | 0.39 | 3 | | Continuous | C | 0.78 | 3.4 | lots of debris |
| | | | 1.46 | 0.46 | | | | | | | |
| | | | 2.80 | 0.89 | | | | | | | |
| 7 | WF-17 | 6 | 0.82 | 0.26 | | | Continuous | C | 0.85 | 2.2 | unmeasurable degrated wood |
| | | | 0.99 | 0.32 | | | | | | 2.3 | |
| | | | 0.80 | 0.25 | | | | | | 3.2 | |
| | | | 0.85 | 0.27 | | | | | | | |
| | WF-18 | 4 | 0.65 | 0.21 | 3 | 0.3 | Discrete | C | 0.7 | 1.8 | lots of debris |
| | | | 1.00 | 0.32 | | **0.55** | | | | 1.2 | |
| | | | 0.80 | 0.25 | | | | | | 1 | |
| | WF-19 | 2 | 0.35 | 0.11 | 1 | **0.35** | Discrete | B-2 | 0.82 | 3.2 | lots of debris |
| | | | 1.20 | 0.38 | | | | | | | |
| | WF-20 | 4 | 1.17 | 0.37 | | | Continuous | C | 0.76 | 1.9 | no identifiable key member; lots of debris |
| | | | 1.15 | 0.37 | | | | | | 3.7 | |
| | | | 0.90 | 0.29 | | | | | | 7 | |
| | | | 1.50 | 0.48 | | | | | | | |
| | WF-21 | 3 | 1.65 | 0.53 | 2 | **1.15** | Continuous | A | 1.2 | 9.4 | |
| | | | 1.65 | 0.53 | | 1.2 | | | | 2.8 | |
| | | | 0.95 | 0.30 | | | | | | | |
| 8 | WF-22 | 2 | 1.15 | 0.37 | 2 | **0.25** | Continuous | C | 0.69 | 0.95 | |
| | | | 0.98 | 0.31 | | | | | | | |
| | WF-24 | 2 | 1.30 | 0.41 | 1 | **0.52** | Discrete | B2 | 0.72 | 3.55 | |
| | | | 2.28 | 0.73 | | | | | | | |
| | WF-25 | 2 | 1.75 | 0.56 | 1 | **0.26** | Discrete | B2 | 0.54 | 1.46 | |
| | | | 1.67 | 0.53 | | | | | | | |
| | WF-26 | 3 | 0.26 | 0.08 | | | Discrete | A | 1.5 | | |
| | | | 1.78 | 0.57 | | | | | | | |
| | | | 1.38 | 0.44 | | | | | | | |

Appendix B: Known GPS coordinates of fence jams.

| Name | Latitude | Longitude |
|------|----------|-----------|
| WF-1 | 46.963003 | -121.799378 |
| WF-9 | 46.962951 | -121.800385 |
| WF-10 | 46.963099 | -121.801624 |
| WF-11 | 46.963057 | -121.803256 |
| WF-13 | 46.967869 | -121.819176 |
| WF-14 | 46.969475 | -121.822861 |
| WF-16 | 46.969694 | -121.823018 |
| WF-17 | 46.970614 | -121.824550 |
| WF-19 | 46.971544 | -121.825680 |
| WF-20 | 46.972333 | -121.826522 |
| WF-21 | 46.974144 | -121.827252 |
| WF-26 | 46.995500 | -121.855917 |
| WF-24 | 46.988867 | -121.842567 |
| WF-27 | 46.997217 | -121.864383 |
| WF-28 | 46.995556 | -121.881944 |