SUMMARY MEMO:

ENCHANTED VALLEY CHALET
SITE FLOOD HAZARDS

Technical Assistance for **OLYM**.

To: Lee Taylor, Deputy Superintendent; and Christina Miller, Planning & Compliance Lead

From: Paul Kennard, Regional Fluvial Geomorphologist, Pacific West Region

Date: 4-26-18

This report consists of three principal parts: (1) summary memo; (2) figures; and (3) tables. Much of the field work and office analyses were done by Geological Society of America, GeoCorps Geologists-in-the-Park, April Kelly and Taylor Kenyon, under my direct supervision. I also relied significantly on work done by the Olympic National Park (OLYM) Cultural Resource Management Program and GIS Division. The report conclusions are mine. The report was reviewed by Jon Riedel, Geologist, North Cascades National Park.

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EXECUTIVE SUMMARY

Olympic National Park ("ONP") directed me to determine the flooding and erosion hazards within the Enchanted Valley ("the Valley") in the vicinity of the Enchanted Valley Chalet ("Chalet"). This research was requested in order to inform future decision-making in an Environmental Assessment (EA) regarding the final disposition of the Chalet. In this report, flood/erosion mitigations to protect the Chalet were not considered as those decisions will be guided by law and policy. Hazards were considered within the area 137 meters (450 feet) upstream and downstream of the Chalet's current location, along the river terrace landform upon which it resides (figure 1).

Three approaches were used to evaluate current and near-term hazards. The principal conclusion is that the remaining terrace area in the vicinity of the Chalet is at very high risk of erosion and flooding within the next 20 years. This means that moving the Chalet would be a short term solution at best. Large sediment accumulations are poised to enter the river in the vicinity of the Chalet from upstream, within 10 years. Additionally, large floods are increasing in both size and frequency. These factors could significantly hasten the erosion and flooding of the terrace in the Chalet area.

If the Chalet were to be moved again, the recommended location should be as close to the eastern valley-side terrace edge as practical, and intervening vegetation (particularly tree) damage minimized. (Please see Hazard Discussion for details on this and other factors considered here.). While moving the Chalet is not considered a long-term solution, relocation may buy time on the order of 10-20 years. Due to landscape responses to climate change, the area is experiencing historically unprecedented river conditions. This adds uncertainty to any hazard estimates.

For this report, the investigative team relied on field work (summer 2017), office analyses (winter 2018), and available, existing information. This memo describes how the problem was analyzed and provides conclusions based on that analysis. This report does not explain in detail the data or how it was used. Additional supporting information can be provided and analyses performed, as needed.

OVERVIEW

History

In general, the Quinault River ("the river") above Lake Quinault ("the lake") is sediment rich and aggrading, apparent given measured channel migration rates downstream of the Valley (from below the confluence of the North Fork Quinault River to the lake) of 12.7 +/- 3.3 meters per year (41.7 to 10.8 feet) between 1900 and 1994 (O'Conner and others 2003). The Enchanted Valley, in the area of the Chalet, was relatively stable until the river channel started moved rapidly towards it between 2002 and 2004 (figure 2). The river ultimately moved over 360 feet, threatening the Chalet for the first time. Park staff became concerned with the threat in 2004, and evaluated hazards and potential mitigations to the Chalet at that time (Kennard 2005). By 2006, the wetted channel had retreated from the bank near the Chalet, only to start migrating towards it again in 2011. The structure was eventually partially undermined in 2014. Park staff once again analyzed the hazards (Kennard 2014) in an emergency action EA, and the Chalet was temporarily relocated to its present location in September 2014. Significant bank erosion continues to this day.

Approach

In this report, short-term (current) and medium-term (decades) hazards are analyzed in the area of the Chalet, with the intent of generating information that can be used to assess management options regarding the Chalet's final disposition. Three methods were employed (detailed in the following Methods section and table 1):

(1) Traditional hazard analysis (e.g. Thomas and Kennard 2015), where bank erosion rates are considered in the context of river channel and terrace bank conditions;

(2) Radiocarbon dating to estimate the age of the Chalet area landform; and,

(3) Examination of the movement of large in-river sediment accumulations and other controls to both vertical and horizontal river bed and bank changes at and upstream of the Chalet to assess future, medium-term hazards.

Areas of Interest

Hazard Analysis Area

The specific region of interest (figure 1) is the area 137 meters (450 feet) up and downstream of the Chalet's current location on the alluvial terrace landform upon which the terrace is located. The average terrace width in this area is about 131 meters (430 feet). The terrace is mapped in Riedel and Dorsch (in prep.) and depicted in figure 3. A terrace is a relatively flat surface that grades gently downstream and represents the dissected remnants of a previous floodplain (Jarrett 1990).

Study Area

The entire upper watershed, from the Eel and Anderson glaciers down, was considered when analyzing flood and erosion hazards to the Chalet area. However, the principle study area, particularly for the on-site field work (2017) and office river channel widening investigation, consisted of the valley from the intersection of Anderson Creek and the Quinault River upstream of the Chalet, to the downstream Pleistocene Moraine (figure 3). Within this study area, the river was partitioned into three channel segments (figure 4) by channel gradient (Figures 5a, b) and valley confinement (ratio of valley to channel width), using the methods of Washington (State) Forest Practices Board (1995). Channel segments generally respond similarly to changes in the input factors (water, sediment, wood).

METHODS AND RESULTS

Changing climate triggers have prompted hydrologic, riverine, and landscape responses in the Quinault River Basin resulting in rapid river channel shifting (avulsions) and increased river bank erosion. To gain topographic and hydrologic insight into changing conditions, hazard levels were evaluated by three methods: (1) traditional hazard analysis; (2) radiocarbon dating; and (3) in-river sediment dynamics. Each method is discussed below.

Traditional Hazard Analysis

Hazard levels were evaluated by methods similar to those described in Thomas and Kennard (2015). Principle analyses components (summarized in table 1) include: (1) historic river bank erosion rates; (2) river flow regimes; and (3) river channel characteristics.

Bank erosion was calculated over several temporal and spatial scales using available time-series aerial photography (below). River flow characteristics examined included flooding history and changes in the magnitude and frequency of flooding over time. River channel characteristics assessed included lateral (or cross-channel) river gradients and vertical fluctuations in river channel bed elevations.

Channel bank Erosion

Channel bank erosion rates were calculated by quantifying river channel widening based on 1990, 2006, 2013, 2015, and 2016 aerial photography using Google Earth. The rates were calculated separately for the three channel segments (labeled Upper, Confined, and Lower; figure 4). Channel widening was calculated along a series of 24 cross sections drawn perpendicular to the main river flow (thalweg) as shown in figure 6. In the Upper, Confined, and Lower channel segments, there are 8, 7, and 9 cross sections, respectively.

Changes in average channel width along the slope/confinement classified reaches were identified by locating channel banks in successive photo years and the associated channel areas where vegetation was lost. These measurements included *total* stream channel widening, including losses to both the right and left stream banks. The results, by photo interval, channel segment, and individual cross section, are in table 2.

In addition to the slope/confinement classified reach results (above), bank erosion was calculated more locally: (1) at the Chalet's current location; and (2) in the area adjacent to the current location. For these measurements, only erosion of the river left bank (facing downstream, on the Chalet side of the river) was considered (and the vast majority of the erosion was to the left bank). For the Chalet's current location, a single cross section (labeled Chalet, figure 4) was used. For the surrounding area calculations, the six cross sections within 61 meters (200 feet) up and downstream of the Chalet's current location were used.

The segment totals for the Chalet cross section and Chalet area are in table 3. For the Chalet's current location, the average annual bank erosion (left bank) was 4.7 meters per year (15.3 feet) from 1990 to 2016. For the area surrounding the Chalet the average bank erosion was a similar 5.1 meters per year (16.68 feet) for the same time period.

River Flow Regimes

The U.S. Geological Survey (USGS) maintains a Quinault River gauge downstream of Lake Quinault that has been recording river flows since 1910. Station gauge information is in figure 7, and maximum annual peak flows (1910-2016) in table 4. River discharge information from the early part of the record was compared with the entire record to see if there was a change in the frequency and magnitude of flooding during the period of record. Specifically, we compared flood recurrence intervals from 1910-1998 with those from 1910-2017 (figure 8). (Flood recurrence intervals are the average number of years between floods of a certain size. For example, a flood with a 100-year recurrence interval occurs, on average, every 100 years with an annual probability of 1 in a 100 or 1%).

Figure 8 reveals that earlier characterized 100-year floods now occur about every 70 years and 10-year floods about every 9 years.

River Channel Characteristics

River channel characteristics considered include lateral (or cross-channel) river gradients, vertical fluctuations in river channel bed elevations, river bank heights, and the relative susceptibility of the river bank to erosion. The 2^{nd} factor, vertical fluctuations in river channel bed elevations, is covered in the River Sediment Dynamics section.

When lateral river channel gradients approach or exceed down-valley river gradients, erosive river energy is potentially directed to the river bank, increasing erosion hazards. In the field (2005 and 2017), we observed that this was the case in the river channel in the Chalet area.

A bank height and condition survey was conducted in the field (2017) in the Chalet area, along with 2 detailed stratigraphic columns. The bank survey was mainly done to assess terrace flooding potential (see Flood Flows section) but also included characterizing bank material composition. Twenty-two river-left bank height measurements were taken in the Lower channel segment (figure 4). Bank heights ranged from 0.49 to 2.83 meters (1.6 to 9.3 feet) with the higher bank heights near the Chalet. The average bank height was 1.35 meters (4.5 feet).

Factors controlling river bank erosion potential are bank materials and riparian vegetation (providing 'apparent cohesion' via root strength). A bank height and condition survey and stratigraphic columns both revealed that the river banks were mainly comprised of materials varying in size from small boulders to fine sands, with the majority being relatively easily erodible gravels. Most of the banks lacked significant riparian vegetation, and the lack of roots further contributed to the bank erodibility.

Radiocarbon Dating

Radiocarbon dating samples were taken to constrain the age of the terrace landform upon which the Chalet is located. This information was considered when determining the erosion hazards to the terrace in the Chalet area (Discussion section below). Radiocarbon dating (also known as carbon dating or carbon-14 dating) is a technique for determining the age of an object containing organic material by using the properties of a radioactive isotope of carbon, radiocarbon (^{14}C).

The strategy was to identify previously buried tree stumps or snags recently re-exhumed by river bank erosion (figure 9). The assumption is that the trees were originally entombed (smothered, but not toppled) by the paleo-river terrace emplacement and re-exposed (but again not toppled) by recent river bank and bed erosion. The tree may or may not have been dead when buried. In either case, the sampled ages would represent the maximum terrace age.

In the field, multiple potential sample trees were identified (figure 9), and we considered 11 sample locations to determine if the samples had not been moved by the river, and had been smothered by the terrace landform. For example, we excavated an area around the base of the stump to see if the roots were embedded in the stream bottom. Ultimately four samples were collected (figure 10) using standard field protocols. Of those, the park made the decision to analyze two samples (#189 and #203 in figures 11 and 12, respectively) which were sent for analysis to Beta Analytic. The specific two samples were chosen by us to represent both the near-Chalet area, and the upstream reach. The detailed dating reports are in figure 13 (a, b). The remaining two samples have been retained, and are available for future analyses.

Results

Despite our precautions, sample #189, taken from a stream-bed wood location, turned out to be a very recent tree. It was most likely a stump (figure 11) that floated in and was partially buried, appearing to be a recently exhumed tree. The sample date was not further considered. The 2nd sample analyzed, (#203), was from a stream bank stump that had been recently exhumed (winter 2016-2017) as seen in figure 12. We are much more confident that it was truly *in situ* based on the recent exposure.

The conventional radiocarbon age of sample #203 is 320+/- 30 before present (BP), which corresponds to the age range of 1482 AD to 1594 AD years old (calibrated dates, 95% probability), thus representing a maximum terrace age of about 1500 AD. Calibrated date is defined in the Glossary (Select Definitions).

River Sediment Dynamics

Due to climate change and glacier recession, Quinault River hydro-geomorphic conditions are in flux and we analyzed in-river sediment behavior to assess future, medium-term (0-20 years) hazards to complement the current hazards assessment. In particular, we investigated processes that controlled river channel-bed surface elevations, and thereby affected water-surface elevations and potential for lateral channel migration.

The dominant processes influencing river bed stability in the Upper Quinault River are: (1) wood-mediated fluctuations; and (2) transient zones of sediment accumulation. The initial river avulsion (2002-2004, discussed earlier) that threatened the Chalet was due to significant river bed aggradation (sediment deposition, raising the river bed). The aggradation followed a massive debris flow (Kennard 2005) in the upper basin (figure 14). Debris flow is defined in the Glossary (Select Definitions).

Wood-mediated Fluctuations

Large in-channel wood pieces and logjams initiate lateral channel migration by increasing bed or water-surface elevations above adjacent river banks. In the upper Enchanted Valley, there are ample sources of sufficiently large wood from the unmanaged riparian areas and valley walls. These processes include recruitment by treefall, bank erosion, landslides, and snow avalanches. Typical vertical bed changes in managed western Washington rivers are on the order of two meters (6.6 feet) (Brummer and others, 2006), though vertical changes of up to 10 meters (32.8 feet) have been observed in park rivers (Abbe 2000). The process is highly variable spatially and on shorter time scales, but it does not appear to fluctuate systematically over longer time periods.

Transient Zones of Sediment Accumulation

Field observations and the aerial photographic record reveal multiple channelized landslides (debris flows and landslide dam-break floods) have recently occurred in the Quinault River Basin, upstream of the Chalet. Landslide dam-break flood is defined in the Glossary (Select Definitions). These episodic events initially deposited large amounts of sediment in the area of the confluence of Anderson Creek and the small tributary of the Quinault River draining the Eel Glacier, at the up-stream end of our field study area (figure 5a), creating transient sediment fluxes that cause vertical changes in river bed elevations.

Since 1917 (Gilbert 1917), these transient zones of sediment accumulation in channels have been characterized as sediment waves. Despite their obvious importance on river form and behavior, there have been many inconsistent definitions and misconceptions about large sediment waves (reviewed in James 2010). This has frequently led to a fundamental misunderstanding of how massive, episodic sedimentation events behave and underestimation of their persistent effects. In this section, the focus is on a newly recognized type of channel bed form called sediment bulges (Mauch and Kennard 2016), distinct from traditionally defined sediment waves.

Sediment Bulges

Sediment bulges are a convex zone of sediment accumulation initiated by debris or hyperconcentrated flows that cause water to initially avulse around and subsequently incise (cut downward) through the local topographic high (Hinshaw and others, 2017). Hyperconcentrated flow is defined in the Glossary (Select Definitions). The initial upstream sediment bulge erodes in subsequent high water events and additional sediment bulges form downstream, resulting in a series of cascading sediment bulges that develop over time (Figure 15).

In 2017, multiple recent (since 2005) channelized landslides were observed in the upper watershed, including debris flows and landslide dam-break floods, distinguished by the sediment composition of their respective deposits. The tributary confluence area is complex, with multiple terraces of differing ages and landslide deposit levees (figure 16).

Multiple discrete, cascading sediment bulges were identified downstream of the tributary confluence area. They were field identified by characteristics in Hinshaw and others (2017): (1) the absence of stream banks; (2) translational and dispersional transport downstream; and (3) headward incision by headcuts and associated stepwise patterns. All three bulge types were present (defined in Mauch and Kennard 2016): 1st order (figures 15, 19) ─ debris flow or hyperconcentrated flow deposits; 2nd order (figures 15, 20) ─ fluvially reworked deposits from erosion of the 1st order bulge; and 3rd order ─ wood supported deposits (figure 21).

Spatially, sediment bulges extended through the Upper channel segment (figure 4) into the upper Confined channel segment. They have locally aggraded the river bed by several meters (tens of feet), and the stream has responded by migrating from the elevated surface to the now lower surrounding floodplain or terrace, sometimes getting pinned adjacent to the valley wall. (As a side note, recent trail damage on the valley walls by headward erosion, was associated with channel movements forced by sediment bulge emplacements, figure 18 a, b.)

The upstream (1st order) bulges are the oldest, and the stream has started to incise into them (figure 19). This tends to 'lock-in' the channel over time and if the stream is incised into the bulge, away from the valley wall, the avulsion and bank erosion potential is minimized until the next large input of sediment starts the process over again. The less mature, downstream bulges (2nd and 3rd order) have destabilized the stream, resulting in active stream bank, terrace, and valley wall erosion (figure 20). In these more recently formed bulges, the stream channel has not had time to re-equilibrate, and incise down to its former lower position. As a result, the newly formed, out-of-balance stream channel is relatively unconfined, with shallow stream banks, and more prone to migrate across the bulge and valley floor during relatively low stream flows.

The most downstream bulge (figure 21) is a large 3rd order feature. This bulge is likely interacting with substantial amounts of wood from an earlier climax snow avalanche that deposited copious amounts of uprooted old growth trees to the valley bottom. It is located in the upstream end of Confined channel segment (figure 4). Confined channel segments favor more rapid sediment transport than unconfined reaches, such as the Upper and Lower channel segments.

HAZARD DISCUSSION

Flooding and erosion hazards were determined for the river terrace landform in the vicinity of the current location of the Chalet (figure 1). A weight of the evidence approach was used and information from the three methods of hazard analysis (Methods and Results section and table 1) considered.

Bank Erosion Rates

Recent bank erosion rates, from the traditional hazard analysis, offers the most direct and compelling evidence of current hazards. River bank surveys (River Channel Characteristics section) confirmed river banks were easily erodible. Rates at the present Chalet location (summarized earlier, table 3) average 5 meters per year (16.3 feet) of bank erosion over the 26-year length of record. Values for the area near the Chalet (within 200 feet, or 61 meters, up and downstream of the current location) are similar at 4.7 meters per year (15.3 feet). Given the average width of the extant terrace at 430 feet, at the current erosion rates, the terrace would be removed in about 26 years (430 feet/16.3 feet per year) and 28 years (430/15.3), respectively. When several additional factors, discussed below, are considered we conclude terrace erosion will occur earlier.

Flood Flows

Future floods are predicted to be more frequent and of greater severity (Parzybok and others, 2009), as indicated by the local river gauge data which shows increases in flooding since 1998 (e.g. a previous 100-year recurrence interval flood now occurs every 70 years, see figure 8). It is expected that this trend of increasing flooding in both severity and frequency will continue into the foreseeable future.

Radiocarbon Date

The sampled tree predated the terrace deposition and could have been dead well before it was buried. The radiocarbon date (~1500 AD) is consistent with possible terrace emplacement following the Little Ice Age (approximately 1450-1890). At that time, glaciers were at a local maximum and the subsequent glacier retreat likely caused high sediment loads to rivers, including debris flows that led to terrace deposition.

A similar phenomena ─ rapid glacier retreat (Riedel and others, 2015) and attendant river sedimentation (e.g. Czuba and others, 2011; Anderson 2013) of the same order of magnitude is occurring regionally now on glacier sourced rivers.

Inundation

Numerous field observations revealed that the terrace in the Lower channel segment (figure 4) is flood prone, especially during aggradation events, such as 2002-2004. Measured river bank heights (River Channel Characteristics section) confirm this. The lower bank heights were upstream of the Chalet, where the river was more prone to avulse in the next large flood and/or aggradation event. Given anticipated future aggradation and flood magnitudes, much of the terrace is considered flood prone.

Sediment Bulges

Additionally, there are multiple cascading sediment accumulations moving downstream towards the site (River Dynamics section). It is inevitable that they will cause rapid streambed aggradation at the site, further increasing river avulsion and erosion potential significantly.

It is important to note that the most recent series of sediment bulges are still upstream of the Chalet area, and the furthest downstream bulge deposit is near the top of the Confined channel segment (figure 4), about 1,500 m. below the upstream landslide deposits, at the confluence of Anderson Creek and the Quinault River. In the initial geologic investigations (Kennard 2005) following the 2002-2004 river avulsion, it was recognized that the catastrophic channel shifting was caused by rapid aggradation of the river in the Chalet area, which additionally flooded parts of the terrace surface.

The initial triggering event, a large debris flow (figure 14), was also recognized. However, the specific sediment delivery system (sediment bulges) had not been recognized at that time. Based on field observations in summer 2017 and reexamination of my 2005 field photos, it is clear that sediment bulges were the linking mechanism. Additionally, the subsequent bank erosion in the Chalet area (post-2004 and continuing to this day) is associated with an incising river (Kennard 2014). When the recent series of sediment bulges reach the Chalet area we can expect stream bed aggradation and associated bank erosion or avulsions on the order of 100s of feet, as occurred in 2002-2004.

In the Quinault River, the recent bulges have migrated about 1,500 meters (4,921 feet) downstream in 11 years (2005 to 2017) averaging about 136 meters per year (446 feet). (The originating landslides, observed in the field in 2017, were not observed in the field in 2005.) The most downstream bulge is slightly over halfway to the Chalet area, and is in a Confined channel segment, where it is expected to travel significantly faster than in the Upper unconfined segment. Based on this, the effects of the upstream bulges are expected to arrive in the Chalet area within a decade. Additionally, the current bulges are expected to be significantly larger than those impacting the Chalet area 2002-2004 (mentioned earlier) when there were 100s of feet of lateral channel movements. This is based on field observations that the recent landslides' volumes, initiating the recent bulges, are larger than those observed in the field in 2005.

Terrace Hazard

Three approaches were used to evaluate current and near-term hazards. <u>The principal conclusion is that the remaining terrace area in the vicinity of the Chalet is at very high risk of erosion and flooding within the next 20 years</u>. This means that moving the Chalet would be a short term solution at best. Large sediment accumulations are poised to enter the river in the vicinity of the Chalet from upstream, within 10 years. Additionally, large floods are increasing in both size and frequency. These factors could significantly hasten the erosion and flooding of the terrace in the Chalet area.

If the Chalet were to be moved to another location on the surrounding terrace, the recommended location would be to move it as close to the eastern valley-side terrace edge as practical, and that intervening vegetation (particularly tree) damage minimized. This should apply to live and dead, and fallen and standing, trees.

Riparian and floodplain forest are the primary source of wood recruitment to stream channels, and provide river bed and bank stability (armoring of banks from root mats), coarse sediment storage (and increased bar stability), the development and maintenance of flood plain characteristics, and, particularly in the floodplain channels, hydraulic roughness. All these functions help reduce river energy during floods, decreasing river bank and floodplain erosion.

If the chalet is moved, care should be used to avoid hazards associated with the valley wall such as snow avalanche deposition areas and tributary stream fans.

This option exploits the remote possibility that the river will avulse away from the current location of the Chalet, towards the opposite (western) side of the valley. This is considered improbable, since channel movement has been almost exclusively towards the Chalet since 1990. There is also a small chance that if bank erosion continues towards the Chalet, some terrace remnants may survive longer than 20 years. These remnants, if any, would likely be small and it would be almost impossible to predict which areas may be spared.

GLOSSARY

Select Definitions

1) Radiocarbon dating measurements produce ages in "radiocarbon years", which must be converted to calendar ages by a calibration process, which includes corrections. The result is a **calibrated date** in calendar years.

2) A **debris flow** is a highly mobile slurry of soil, rock, vegetation and water that can travel many kilometers from its point of initiation and usually travels through steep (more than about 4 degrees) confined mountain channels. Erosion and entrainment of additional sediment and wood in steeper channels can increase the volume of the original landslide by 1000s of percent or more, enabling debris flows to become more destructive with distance traveled (Benda and Cundy 1990). In the study area, debris flows typically initiate as shallow-rapid landslides of unconsolidated glacial material recently exposed by glacier melt or from glacier outburst floods.

3) A **hyperconcentrated flow** is a two-phase flowing mixture of water and sediment in a channel which has properties intermediate between fluvial flow and debris flow.

4) Debris flows and other types of landslides can dam a narrow valley floor or canyon, or a tributary junction. If the landslide dam fails catastrophically, an extreme flood can form. These events are referred to as **landslide/dam-break floods**. The flood may entrain additional organic debris thereby causing the flood to increase in magnitude as the flood propagates downstream (Coho and Burges 1993).

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FIGURES

Figure 1. Area of Interest Map. Area on terrace used for Chalet hazard evaluation ─ 137 meters (450 feet) up and downstream of current Chalet location.

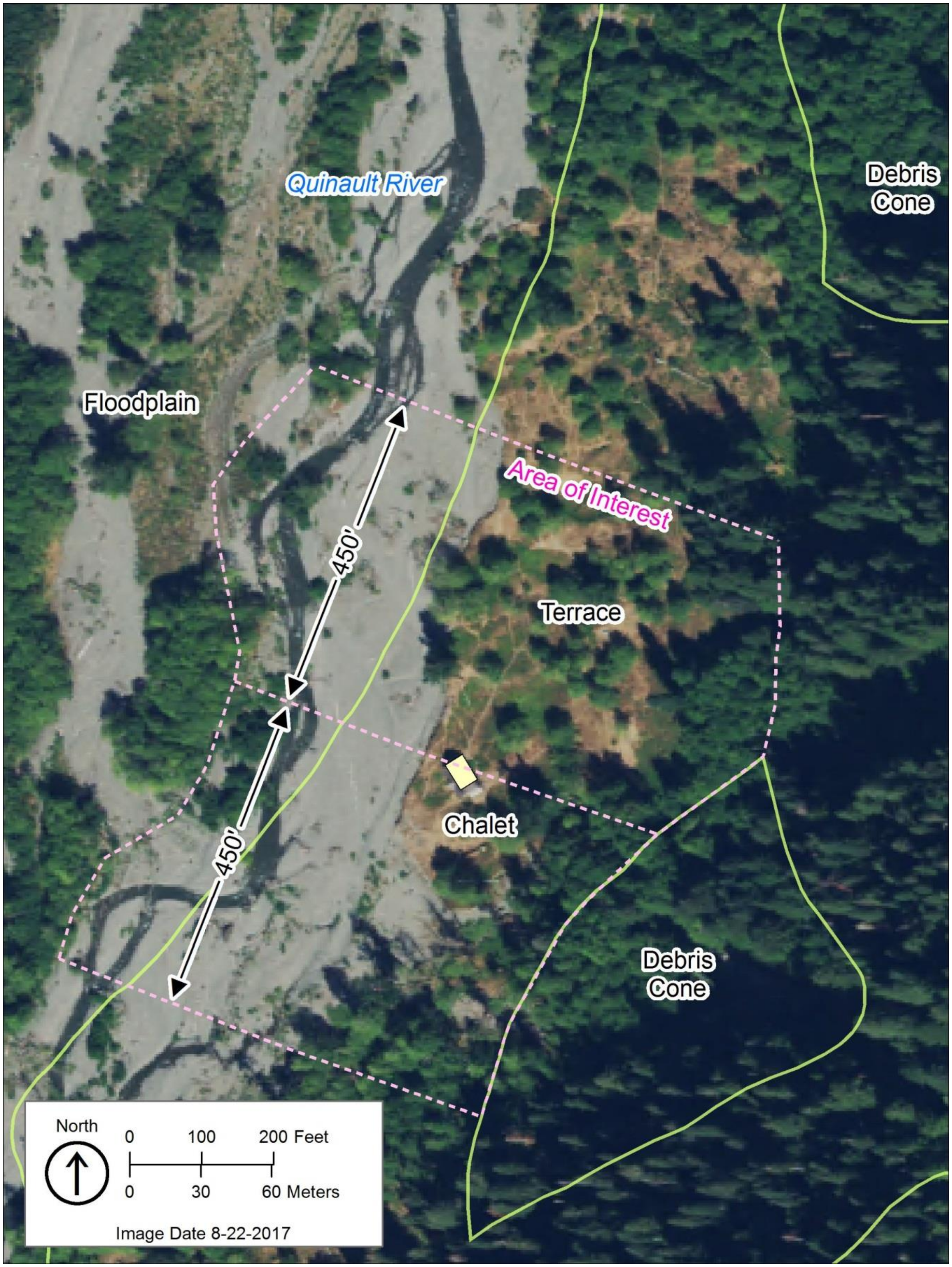


Figure 2. River avulsion 2002-2004 (2004 floodplain). Adapted from OLYM 2004.

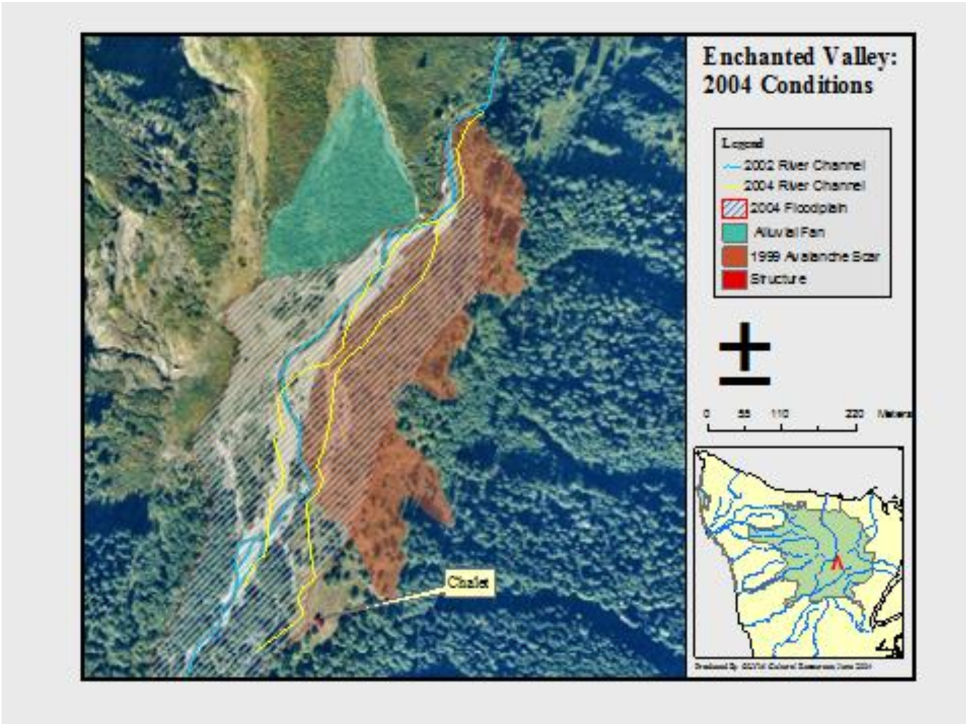


Figure 3. Landform map. Adapted from Riedel and Dorsch (in preparation).

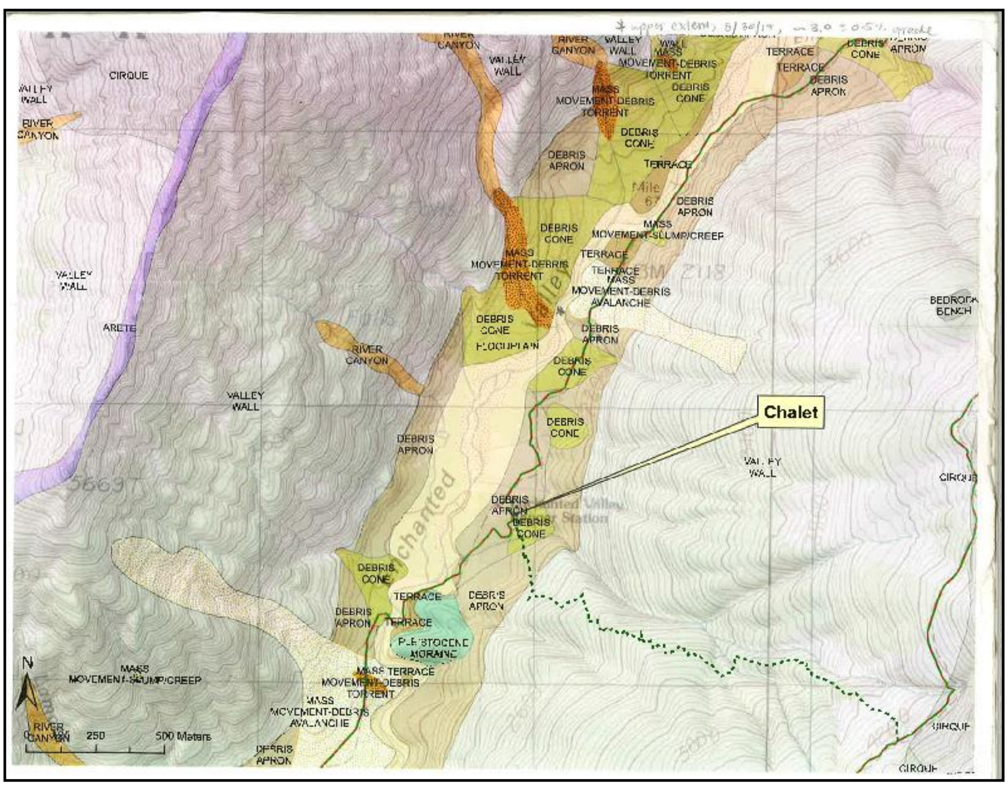


Figure 4. Stream channel segment map, based on gradient and confinement. The red cross sections indicate the segment boundaries.

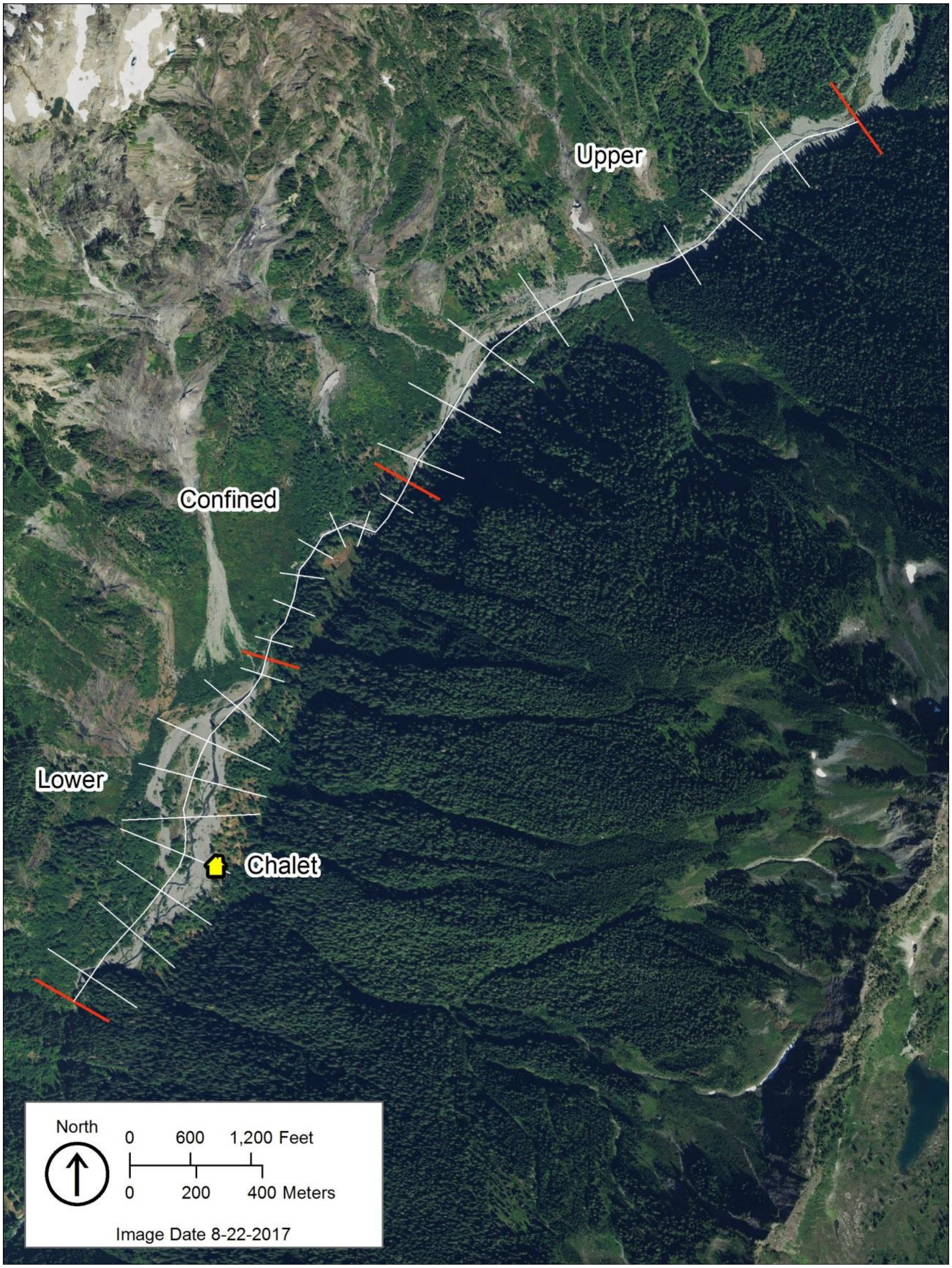
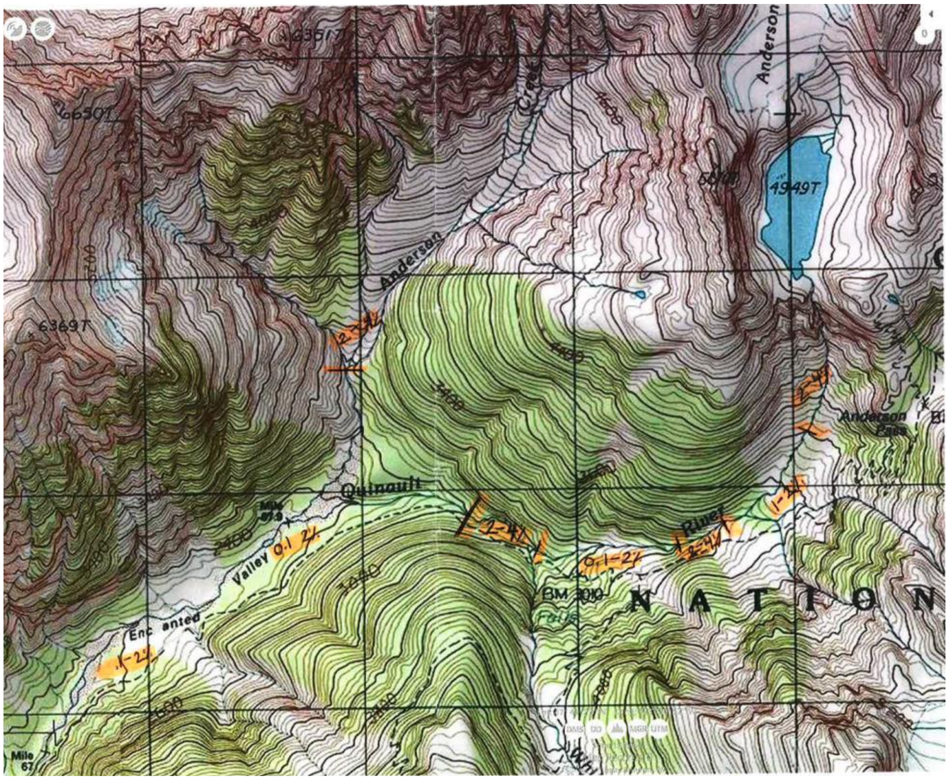


Figure 5. Stream gradients: (a) upper valley.



b) lower valley

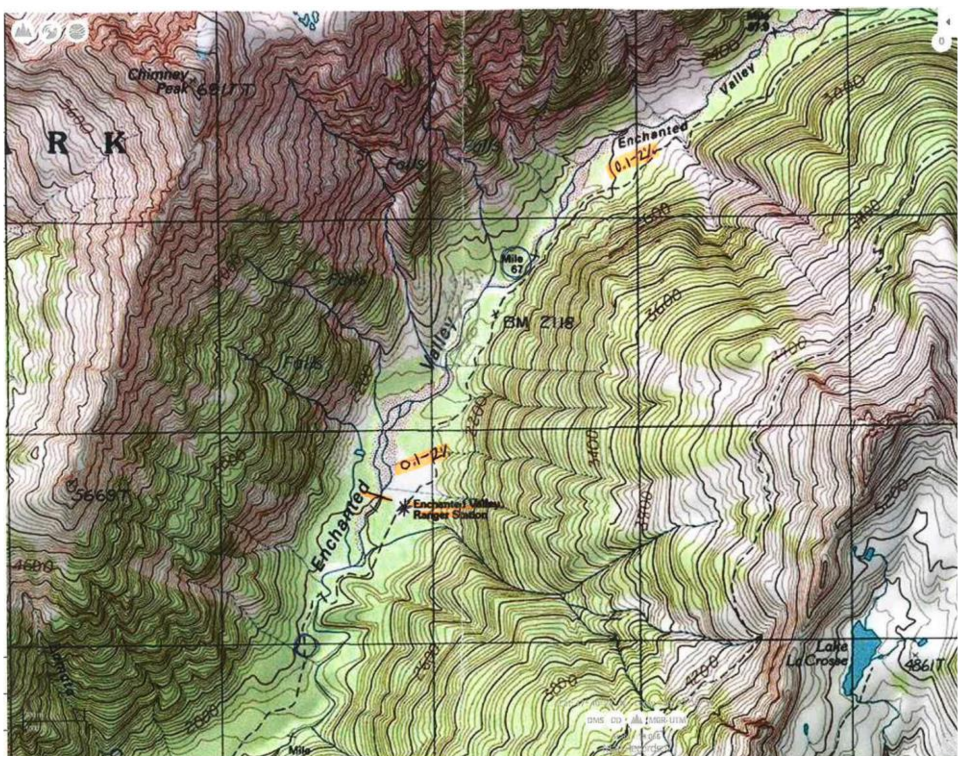


Figure 6. Cross sections used for bank erosion calculations. Red segments delineate channel segments (figure 4). Cross section labels correspond to those in table 2.

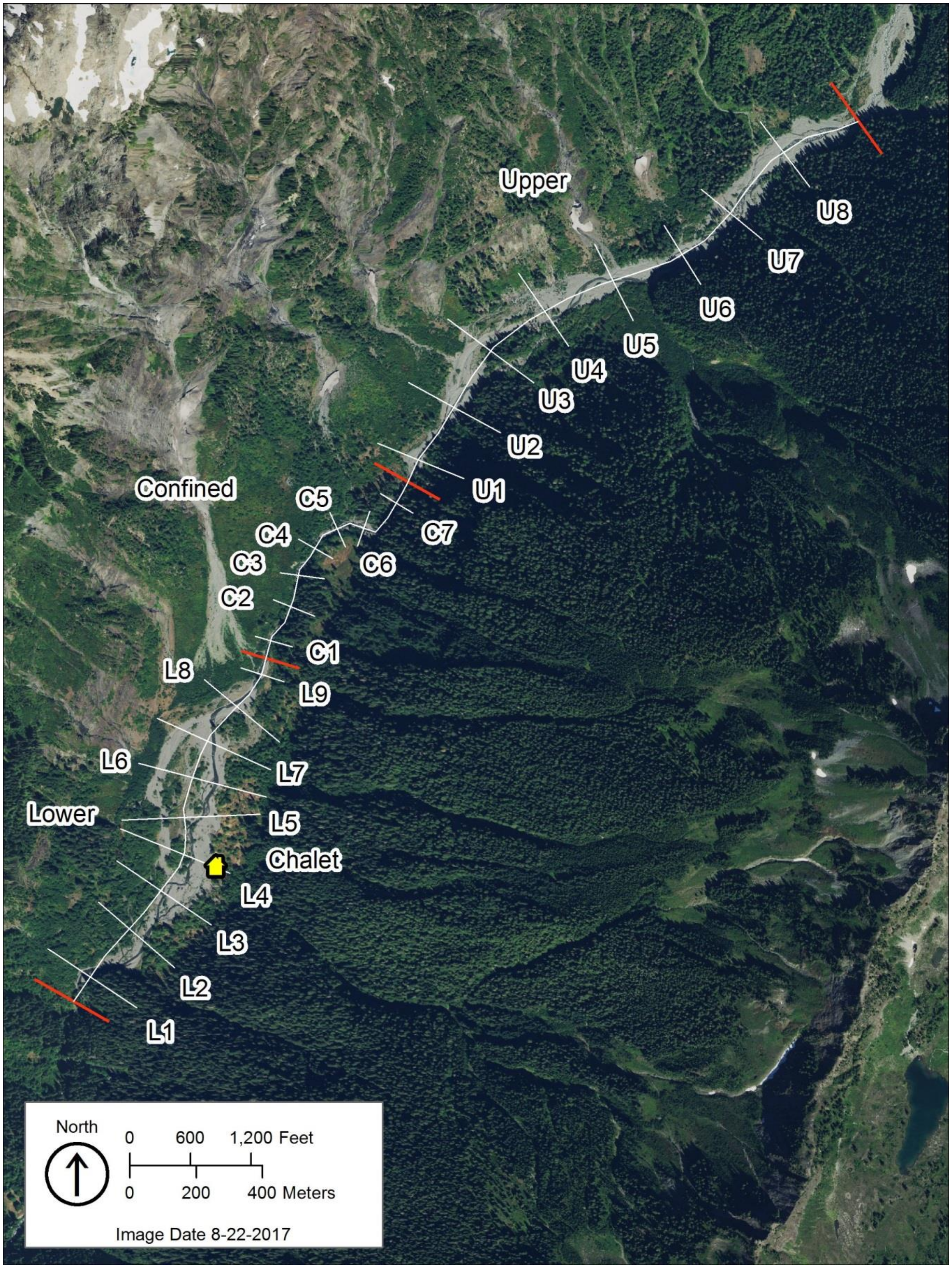


Figure 7. USGS stream gauge data for Quinault River at Quinault Lake.

12039500 QUINAULT RIVER AT QUINAULT LAKE, WA

LOCATION.--Lat 47°27'28", long 123°53'17", in SW1⁄4NE1⁄4, sec.25, T.23 N., R.10 W., Grays Harbor County, Hydrologic Unit 17100102, Quinault Indian Reservation, on left bank at outlet of Quinault Lake, 50 ft downstream from Olympic Highway bridge on U.S. Highway 101, 2.0 mi southwest of Quinault, and at mile 33.4.

DRAINAGE AREA.--264 mi2.

PERIOD OF RECORD.--October 1911 to current year. Monthly discharge for some months during the 1923-25, 1933 water years, published in WSP 1316.

REVISED RECORDS.--WSP 442: Drainage area. WSP 1286: 1915-16(M), 1934, 1936-39(M). WSP 1316: 1923, 1925, 1933. WSP 1635: 1917.

GAGE.--Water-stage recorder. Datum of gage is 178.44 ft above NGVD of 1929. Prior to Sept. 30, 1916, nonrecording gages at sites within 4 mi northeast of present site, at different datum. Oct. 1, 1916, to May 2, 1935, water-stage recorder at site 300 ft downstream from present site at datum 0.36 ft higher than present datum.

REMARKS.--Records good except estimated daily discharges, which are fair. Flow affected by natural storage in Quinault Lake. No diversions upstream from station. Chemical analyses July 1959 to June 1960, October 1962 to September 1970 (partial-record station), October 1971 to September 1974. U.S. Geological Survey satellite telemeter at station.

AVERAGE DISCHARGE.--93 years (water years 1912-2004), 2,865 ft3/s, 147.37 in/yr, 2,076,000 acre-ft/yr. Includes mean discharges for water years 1923-25, 1933, which were estimated for WSP 1316.

EXTREMES FOR PERIOD OF RECORD.--Maximum discharge, 50,200 ft3/s, Nov. 4, 1955, gage height, 20.51 ft; minimum daily discharge, 250 ft3/s, Oct. 29, 30, 1987.

EXTREMES OUTSIDE PERIOD OF RECORD.--Flood in November 1909 reached a stage of approximately 22 ft, present datum, discharge, 52,600 ft3/s.

Figure 8. Comparison of flood recurrence intervals (1910-1998 with 1910-2017).

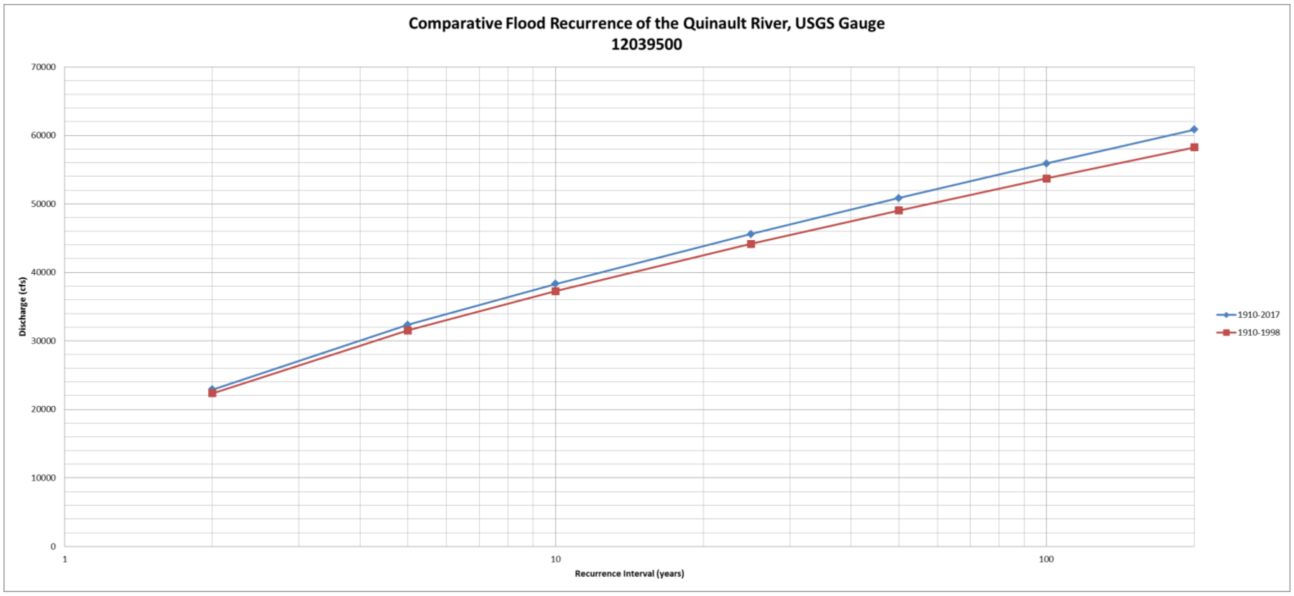


Figure 9. Paleo-tree stumps exhumed by bank erosion winter 2016-17. Photo Pat Crain, OLYM.

Figure 10. Location of Carbon 14 samples

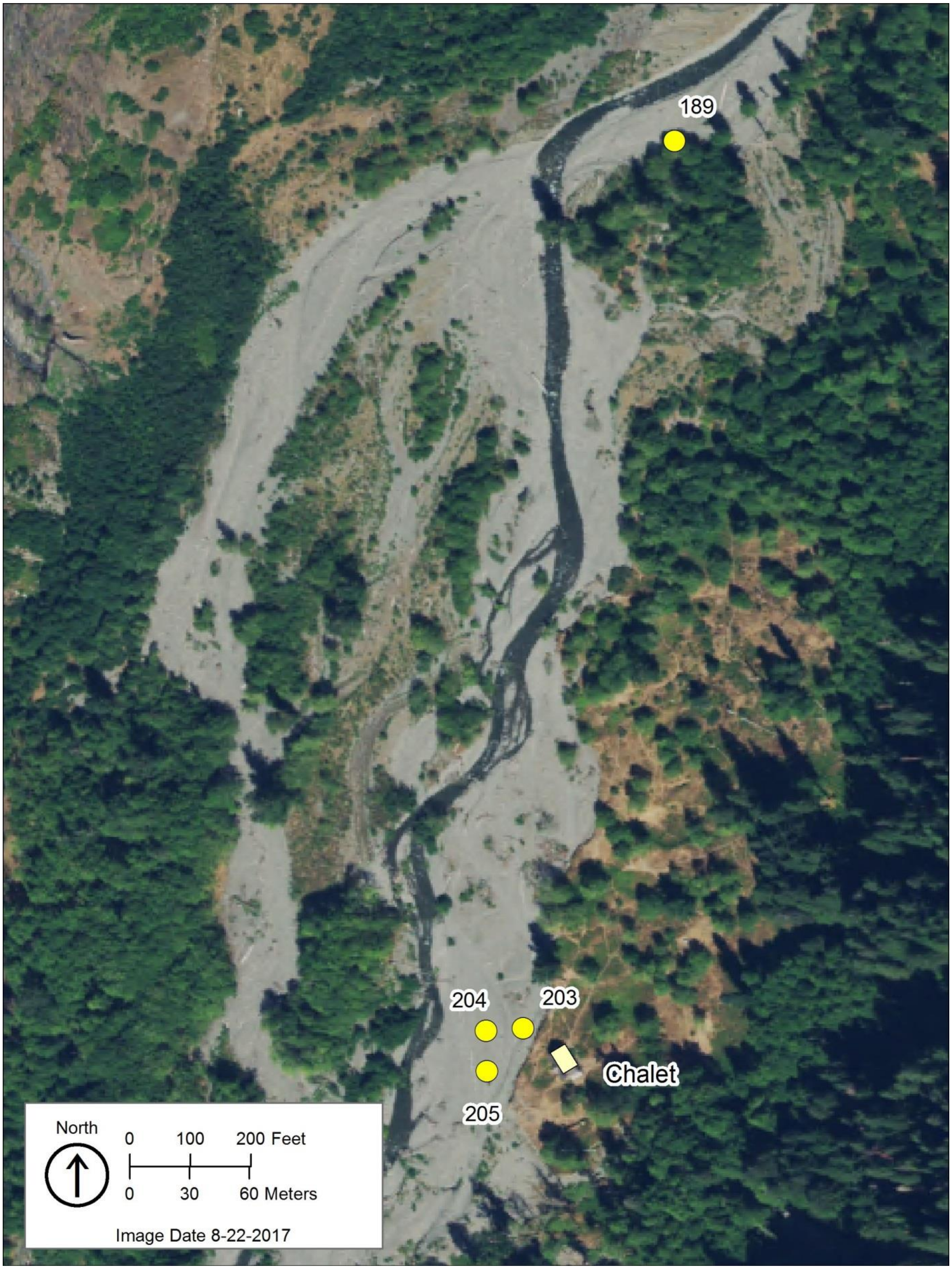


Figure 11. Sampling site #189. Taylor Kenyon pictured.

Figure 12. Sampling site #203. Stump recently exposed by erosion below Chalet (arrow).

Figure 13 (a). Sample #189 report.

BetaCal 3.9

Calibration of Radiocarbon Age to Calendar Years

(High Probability Density Range Method (HPD): INTCAL13 + NHZ1)

(Variables: d13C = -25.6 o/oo)

Laboratory number **Beta-483617**

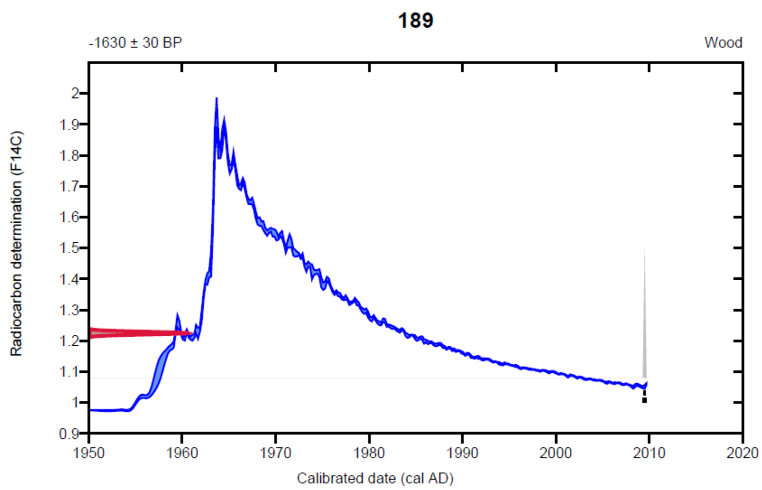
Percent modern carbon **122.50 +/- 0.46 pMC**

95.4% probability

(95.4%) 2009 cal AD (-60 cal BP)

68.2% probability

(68.2%) 2009 cal AD (-60 cal BP)



Database used
INTCAL13 + NHZ1

References
References to Probability Method
Bronk Ramsey, C. (2009). Bayesian analysis of radiocarbon dates. Radiocarbon, 51(1), 337-360.
References to Database INTCAL13 + NHZ1
Hua, et.al.,2013, Radiocarbon, 55(4). Reimer, et.al., 2013, Radiocarbon55(4).

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Figure 13 (b). Sample #209 report.

BetaCal 3.9

Calibration of Radiocarbon Age to Calendar Years

(High Probability Density Range Method (HPD): INTCAL13)

(Variables: d13C = -24.9 o/oo)

Laboratory number **Beta-483618**

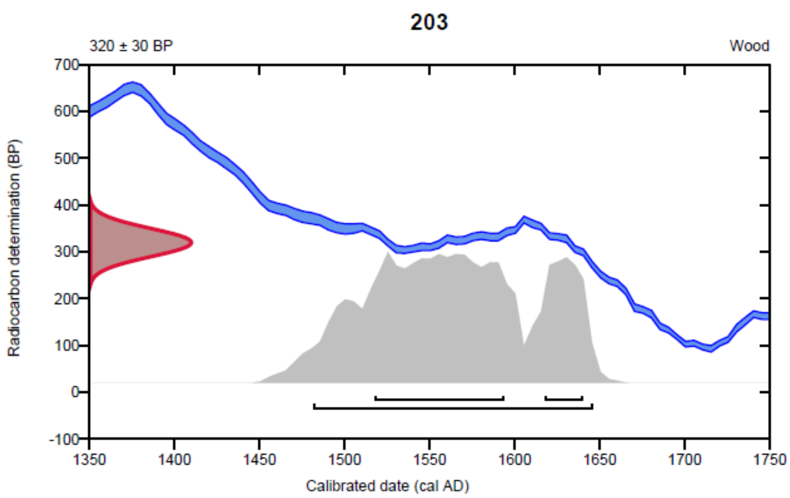
Conventional radiocarbon age **320 ± 30 BP**

95.4% probability

(95.4%)	1482 - 1646 cal AD	(468 - 304 cal BP)

68.2% probability

(53.5%)	1518 - 1594 cal AD	(432 - 356 cal BP)
(14.7%)	1618 - 1640 cal AD	(332 - 310 cal BP)



Database used
INTCAL13

References

References to Probability Method

Bronk Ramsey, C. (2009). Bayesian analysis of radiocarbon dates. Radiocarbon, 51(1), 337-360.

References to Database INTCAL13

Reimer, et.al., 2013, Radiocarbon55(4).

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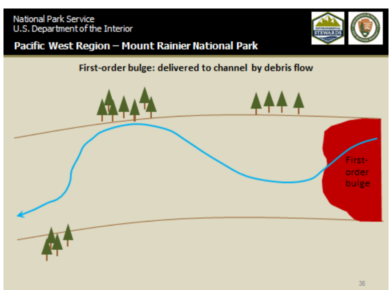
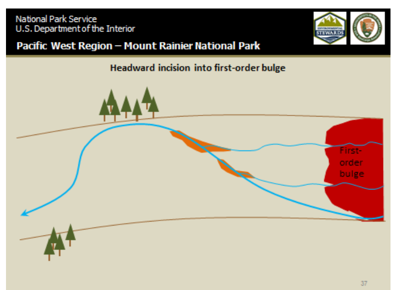
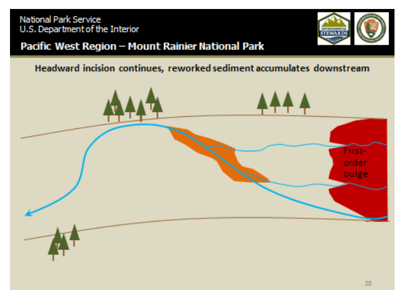
Figure 14. Sediment deposits up to 20 feet above channel, upper Enchanted Valley (2005).

Figure 15. Bulges: a conceptual understanding (six frames, from Mauch 2016)



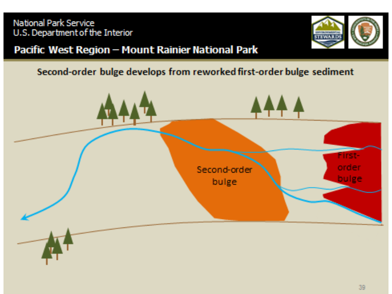


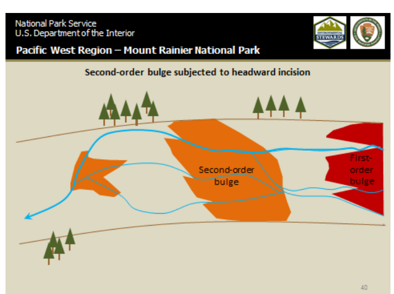


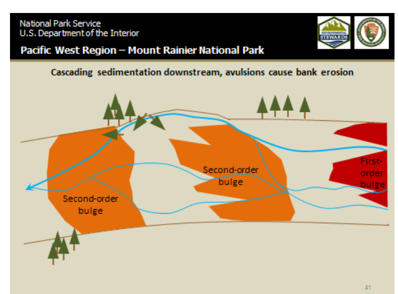
1)

2)

3)







4) 5) 6)

Figure 16. Landslide deposits upper valley (a, b, c)

a) Left bank composite terrace (1st order bulge remnant).

b) Multiple, superimposed terraces.

c) Legacy debris flow deposit (earliest identified).

Figure 17. Conceptual 3rd order (Mauch 2016). Pix of 3rd order bulge too?

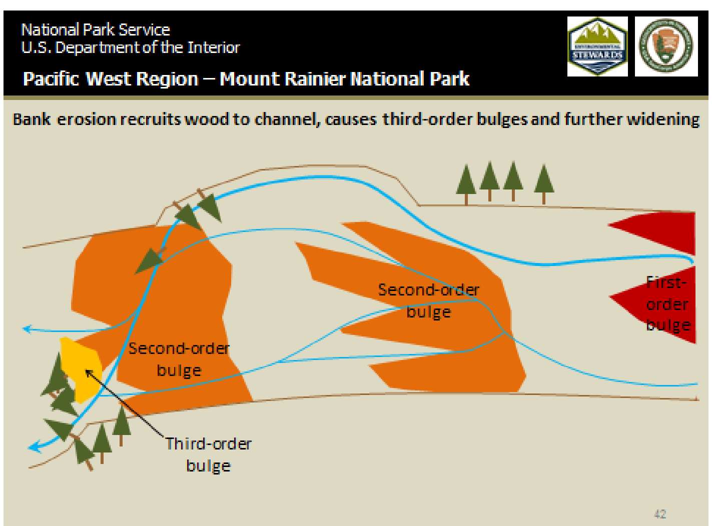


Figure 18. Bulge associated trail damage (a, b)

(a) Stream pushed valley left (looking downstream). Note valley wall erosion (arrow).

(b) Associated trail damage (higher up, valley left).

Figure 19. Mature (incised) 1st order bulge.

Figure 20. Active 2nd order bulge.

Figure 21. 3rd order bulge

TABLES

Table 1: Hazard components summary table.

ANALYSES TYPE	Sub-components	Parameters
Traditional Hazard Analysis	Channel migration rates	bank erosion avulsion
	River flow changes	flooding history changes of flood magnitudes changes of flood frequencies
	River channel characteristics	cross valley gradients river bed trends (vertical instability) inundation potential (bank height survey)
		stream bank erodibility
Radiocarbon Dating	Carbon-14 dating	In-channel wood
River Sediment Dynamics	Wood-mediated migration Sediment bulges	 field identification and classification

Table 2: Channel width changes through time.

Channel Width (ft)										
1990										
Upper	U1=	173	U2=	222.9	U3=	237.5	U4=	163	Average Width=	188.475
	U5=	174	U6=	159	U7=	116.2	U8=	262.2		
Confined	C1=	24.8	C2=	29.6	C3=	26.4	C4=	40.5	Average Width=	54.3
	C5=	104.8	C6=	132.2	C7=	21.8				
Lower	L1=	125	L2=	328.5	L3=	229.5	at Chalet=	147.3	Average Width=	267.4111
	L4=	282.5	L5=	422.4	L6=	443.5	L7=	188		
	L8=	240								
2006										
Upper	U1=	221.6	U2=	308.3	U3=	403	U4=	264.5	Average Width=	284.1175
	U5=	216.2	U6=	174.34	U7=	321.3	U8=	363.7		
Confined	C1=	85.9	C2=	39.5	C3=	41.8	C4=	55.6	Average Width=	80.52857
	C5=	151.5	C6=	164.1	C7=	25.3				
Lower	L1=	166.3	L2=	288.5	L3=	214.6	at Chalet=	357.9	Average Width=	397.4333
	L4=	421.7	L5=	685.9	L6=	669.7	L7=	513.8		
	L8=	258.5								
2013										
Upper	U1=	193.6	U2=	356.1	U3=	370	U4=	242	Average Width=	281.6
	U5=	201.5	U6=	189.6	U7=	324.4	U8=	375.6		
Confined	C1=	48.7	C2=	31.5	C3=	55.13	C4=	47.85	Average Width=	81.52571
	C5=	169.7	C6=	180.5	C7=	37.3				
Lower	L1=	140.6	L2=	169.7	L3=	411.6	at Chalet=	341.1	Average Width=	337.5444
	L4=	377.5	L5=	318.4	L6=	645.8	L7=	473.7		
Confined	C1=	51.1	C2=	41.6	C3=	37.3	C4=	42.6	Average Width=	62.77143
	C5=	88	C6=	128.8	C7=	50				
Lower	L1=	157.3	L2=	150.8	L3=	442.94	at Chalet=	401.5	Average Width=	301.0356
	L4=	411.98	L5=	366	L6=	457.5	L7=	239		
	L8=	82.3								
2016										
Upper	U1=	214.7	U2=	228.7	U3=	381.8	U4=	439.5	Average Width=	296.1875
	U5=	192.8	U6=	206.9	U7=	357.2	U8=	347.9		
Confined	C1=	40.9	C2=	32.3	C3=	36.8	C4=	38.2	Average Width=	67.25143
	C5=	110.4	C6=	156.66	C7=	55.5				
Lower	L1=	152.6	L2=	187.5	L3=	450.2	at Chalet=	411.4	Average Width=	329.8333
	L4=	448.1	L5=	441.2	L6=	543.8	L7=	253		
	L8=	80.7								

Table 3: Bank erosion rates (a) at Chalet; and (b) near Chalet.

(a) Chalet cross section:

Photo interval	Channel change (feet)	Annual rate (feet/year)
1990-2006	350.0	21.9
2006-2013	11.2	1.6
2013-2015	16.2	8.1
2015-2016	20.5	21.0

(b) area near Chalet:

Photo interval	Annual rate (feet/year)
1990-2006	21.8
2006-2013	3.8
2013-2015	18.4
2015-2016	21.4

Table 4. USGS Quinault Maximum Peak Flows (1910-2016)

Water Year	Date	Gage Height (feet)	Stream-flow (cfs)
1910	Nov. 1909	22	52,600
1912	Nov. 18, 1911	11.6	20,300
1913	Nov. 19, 1912	10.8	18,200
1914	Jan. 06, 1914	16.3	32,500
1915	Oct. 19, 1914	10	16,200
1916	Dec. 08, 1915	11.8	20,800
1917	Nov. 04, 1916	5.76	6,670
1918	Dec. 18, 1917	14.82	32,300
1919	Dec. 14, 1918	12.06	23,800
1920	Nov. 15, 1919	11.68	21,300
1921	Feb. 11, 1921	10.9	20,100
1922	Dec. 12, 1921	16.3	37,000
1926	Dec. 23, 1925	9.14	14,800
1927	Oct. 16, 1926	9.1	14,800
1928	Jan. 12, 1928	9.87	17,100
1929	Nov. 13, 1928	7.44	10,300
1930	Feb. 05, 1930	7.95	11,800
1931	Jan. 23, 1931	11.2	21,000
1932	Feb. 27, 1932	13.5	28,100
1933	Nov. 13, 1932	9.62	16,300
1934	Dec. 21, 1933	16	35,000
1935	Jan. 24, 1935	16	36,100
1936	Jan. 04, 1936	9.17	11,200
1937	Dec. 22, 1936	10.79	15,200
1938	Dec. 29, 1937	12.86	215,002
1939	Jan. 01, 1939	14.06	25,400
1940	Dec. 15, 1939	12.91	21,500
1941	Oct. 19, 1940	11.12	16,000
1942	Dec. 1941		15,500[B]
1943	Apr. 02, 1943	9.97	13,100
1944	Dec. 03, 1943	12.32	19,600
1945	Feb. 08, 1945	14.69	27,500
1946	Nov. 15, 1945	10.37	14,100
1947	Feb. 14, 1947	14.63	27,100
1948	Oct. 19, 1947	11.54	17,100
1949	Feb. 23, 1949	10.78	15,200
1950	Nov. 27, 1949	18.6	42,300
1951	Feb. 10, 1951	17.24	36,700
1952	Jan. 31, 1952	9.11	11,500
1953	Jan. 12, 1953	12.56	20,700
1954	Dec. 12, 1953	11.27	17,000
1955	Nov. 18, 1954	15.58	30,500
1956	Nov. 04, 1955	20.51	50,200
1957	Dec. 10, 1956	16.1	32,400
1958	Jan. 17, 1958	10.62	15,300
1959	Apr. 30, 1959	15.34	29,700
1960	Nov. 23, 1959	14.2	25,800
1961	Jan. 15, 1961	18.85	43,300
1962	Jan. 03, 1962	10.12	14,000
1963	Nov. 20, 1962	15.12	28,900
1964	Dec. 23, 1963	11.38	17,300
1965	Nov. 30, 1964	12.89	21,700
1966	Jan. 14, 1966	11.17	16,700
1967	Dec. 13, 1966	14.89	29,300
1968	Jan. 19, 1968	14.38	27,700
1969	Dec. 03, 1968	9.75	13,900
1970	Apr. 09, 1970	9.79	14,000
1971	Dec. 07, 1970	10.45	16,000
1972	Mar. 06, 1972	12.41	21,800
1973	Dec. 26, 1972	13.81	26,000
1974	Jan. 16, 1974	16.37	34,500
1975	Dec. 21, 1974	11.61	19,400
1976	Dec. 04, 1975	16.9	36,400
1977	Dec. 27, 1976	8.71	11,100
1978	Nov. 02, 1977	12.86	23,200
1979	Mar. 06, 1979	9.45	13,100
1980	Dec. 18, 1979	17.58	38,700
1981	Dec. 27, 1980	17	36,700
1982	Feb. 16, 1982	12.35	21,600
1983	Dec. 03, 1982	15.65	32,000
1984	Nov. 15, 1983	15.97	33,100
1985	Nov. 03, 1984	9.79	14,000
1986	Jan. 18, 1986	15.67	32,000
1987	Nov. 23, 1986	14.81	29,100
1988	Dec. 10, 1987	11.53	19,200
1989	Nov. 06, 1988	9.14	11,500
1990	Dec. 04, 1989	13.55	24,700
1991	Nov. 10, 1990	18.35	41,400
1992	Jan. 31, 1992	13.98	26,100
1993	Jan. 25, 1993	8.56	10,100
1994	Dec. 10, 1993	13.5	24,500
1995	Dec. 20, 1994	16.09	33,300
1997	Mar. 19, 1997	19.72	46,400
1998	Jan. 24, 1998	10.56	15,400
1999	Dec. 13, 1998	14.98	29,500
2000	Dec. 15, 1999	14.18	27,600
2001	Jan. 05, 2001	8.16	9,380
2002	Jan. 08, 2002	17.78	39,700
2003	Mar. 14, 2003	14.72	29,000
2004	Oct. 21, 2003	18.21	41,200
2005	Dec. 11, 2004	15.03	29,700
2006	Dec. 25, 2005	13.28	23,800
2007	Nov. 06, 2006	18.1	40,500
2008	Dec. 04, 2007	18.4	41,600
2009	Jan. 08, 2009	14.67	28,500
2010	Nov. 17, 2009	14.07	26,400
2011	Dec. 12, 2010	15.78	32,300
2012	Nov. 23, 2011	11.08	16,800
2013	Nov. 01, 2012	10.51	15,200
2014	Mar. 06, 2014	11.75	18,900
2015	Dec. 11, 2014	13.19	23,500
2016	Dec. 09, 2015	14.7	28,600