Channel Migration and Avulsion Hazards at Sunshine Point Campground, Mount Rainier National Park, Washington

Jesse Favia

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Project mentor:

Paul Kennard, National Park Service

Internship coordinator:

Brian Collins

Reading committee:

Brian Collins

Juliet Crider

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Executive Summary

In November 2006, the flood of record on the upper Nisqually River destroyed part of Sunshine Point Campground in Mount Rainier National Park, Washington. The Nisqually River migrated north and reoccupied five acres of its floodplain; Tahoma Creek partially avulsed into the west floodplain, topping banks of an undersized channel and flooding the campground. With help from Park geomorphologist, Paul Kennard, I assessed hazards to infrastructure at the old campground location, where the Park proposes to rebuild the remaining campground roads and sites. This assessment focuses on two major hazards: northward Nisqually River migration, which may reincorporate the floodplain into the river destroying infrastructure; and Tahoma Creek avulsions, which may flood the campground and deposit sediment burying campground infrastructure.

I quantify northward migration by: estimating migration rates and changes to channel width; evaluating river occupation of the pre- and post-2006 campground; and estimating scour depths at revetments protecting the campground. I digitized the Nisqually River channels and channel centerlines from maps and images between 1955 and 2013 into a GIS, which I used to estimate migration rate and river width changes. Centerline migration rates average 9 ft/yr along the length of the Nisqually River study reach; at Sunshine Point lateral migration rates average 11 ft/yr. Maximum migration along the study reach was 19 ft/yr between 2006 and 2009. Greater than average migration rates and channel widths correspond to river confluences and include the Tahoma Creek confluence at Sunshine Point. To determine historical channel locations and the frequency that the river occupied different parts of its floodplain, I digitized the river from maps and images between 1903 and 2013. The Nisqually River flows through Sunshine Point Campground in eight out of 15 historical images. I assess scour at revetments protecting infrastructure from the Nisqually River during a 100-year recurrence interval flood using measured cross-sections. During a 100-year flood, the Nisqually River may scour up to 10 feet below the bed elevation. These scour depths can

destabilize critical revetments leaving loose unconsolidated riverbanks exposed to Nisqually River flows.

To determine the causes, locations, and frequency of flood hazards from Tahoma Creek avulsions, I field map avulsion channels and compare the results with imagery and channel width changes between 1955 and 2013. Mapped avulsion channels occur with swaths of dead vegetation or nascent vegetation; both dead and recent vegetation are visibly distinct from surrounding vegetation in aerial images. Times of changes to these vegetation anomalies correspond to increases in Tahoma Creek channel width. Avulsions have occurred at least three times in the study period: pre-1955, between 1979 and 1984, and in 2006. The 1984 and 2006 avulsions both occur after increases in Tahoma Creek reach averaged width.

The NPS is considering two options to rebuild Sunshine Point Campground, both at the same location. The hazards posed by the Nisqually River and Tahoma Creek at Sunshine Point will affect both construction options equally. Migration hazards to the campground may be reduced by limiting the proposed campground infrastructure to an elevated ridge that has not been occupied by the Nisqually River since 1903. The hazards of damage from migration may be reduced by revetments, which were effective in preventing northward Nisqually River migration in 1959 and 1965. Tahoma Creek avulsions are related increased of Tahoma Creek reach averaged widths, which are near a 58-year maximum, and occurred during a 10-year flood in 1984. The campground may be as susceptible to flooding from avulsions during as little as a 10-year flood. A large avulsion may occur with the next significant Tahoma Creek width increase. Glacial retreat has been shown to increase debris flow activity and increase sediment delivery to Mount Rainier rivers. Increased sediment discharge has been correlated with aggradation, which will further encourage Tahoma Creek avulsions.

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Statement of the Problem

On November 6th and 7th, 2006, almost 18 inches of rain fell in 36 hours at Mount Rainier National Park (MORA). The resulting flooding caused significant damage within the Nisqually River Valley (Beason and Kennard, 2007). During this flood, the Nisqually River removed five acres of the Sunshine Point Campground, and Tahoma Creek partially avulsed from its course into the western floodplain flooding Sunshine Point Campground (Figure 1). MORA administrators closed the park for six months while workers fixed damage from the storm (NPS, 2014a). The National Park Service is considering re-building the campground at the same location. I evaluate hazards from the Nisqually River northward migration and Tahoma Creek avulsions, which may damage rebuilt infrastructure.

During an atmospheric-river-generated storm on November 6th 2006, the USGS National stream gage recorded the discharge of record (21,800 cfs). The Nisqually River threatened infrastructure at Longmire (Figure 1), scouring sediment from a levee and undercutting foundations to the Emergency Operations Center (Beason, 2007). The Nisqually River removed five acres of western Sunshine Point, including parts of the campground. Tahoma Creek avulsed its banks one mile upstream of the Nisqually confluence. Discharge in a small channel flowing between State Highway 706 and Sunshine Point Campground increased up to one-third of the total Tahoma Creek discharge (Paul Kennard, verbal communication 2014).

Scope of Work

The mission of the United States National Park Service (NPS) is to preserve natural and cultural resources and to provide access to those resources for the public (NPS, 2014b). Administrators at MORA are considering repairing and augmenting existing infrastructure at the Sunshine Point Campground. In cooperation with Paul Kennard, Park geomorphologist, I assess hazards to campground infrastructure and users at Sunshine Point in MORA (Figure 1). Using the results, I consider how documented glacial retreat may affect hazard potential.

Sunshine Point Campground comprises campsites, roads, and revetments remaining after the 2006 flood and could contain additional facilities, as proposed in the reconstruction options (Figure 2). Sunshine Point is used as an informal geographic name within the Park. For this report I refer to Sunshine Point as the debris fan bound by the confluence of Tahoma Creek with the Nisqually River to the southeast and between the Westside Road and the main Tahoma Creek channel south of 46°45’00” N.

Park administrators are considering three management options for Sunshine Point (Figure 2). The first option would leave the campground in its current inaccessible and unusable state. The second option would create a day-use area with minimal winter camping and reuse existing campsite locations from the pre-2006 campground. The third option would expand the current campground and create up to 20 permanent campsites and day use facilities. I evaluate how infrastructure and campgrounds users will be affected by Nisqually River migration and Tahoma Creek avulsions. The NPS can use the results from this investigation for risk assessment.

At its proposed location, the campground is exposed to bank and revetment scour during northward Nisqually River migration and flooding from Tahoma Creek partially avulsing west into its floodplain. I evaluate northward migration using images between 1903 and 2013 along 4.4 miles of the Nisqually River to measure migration rates and changes to river width. I use flow velocities and inundation depths from prior hydraulic modeling along with measured cross-section to estimate depths of bed scout at revetments protecting the Sunshine Point infrastructure from the Nisqually River. From field visits and a high-resolution 1-meter digital elevation model (DEM), I mapped incised channels in the Tahoma Creek west floodplain, which I compared with aerial photographs between 1955 and 2013. I compare anomalies from dead and recently re-established vegetation visible in aerial images between 1955 and 2013 with mapped incised channels to document when Tahoma Creek avulsions occur. I compare avulsion times with Tahoma Creek widths between 1955 and 2013 to determine the reasons for avulsions.

Prior workers have documented the hazards from catastrophic volcanic events such as large debris flows that will affect entire river drainages. Hazards at Sunshine Point Campground from volcanic hazards, such as an eruption, debris flow, or lahar, and risk mitigation plans for these events, can be found in Crandell (1971), Hoblitt et al. (1998), and Riedel (2007) are not evaluated in this report.

Sunshine Point Setting

The Nisqually River watershed drains about 68 square miles at Sunshine Point, with major inputs from Tahoma Creek, Kautz Creek, and Berry Creek (Figure 1; Beason et al. 2014). Rivers originating from Mount Rainier are fed by the Nisqually, Van Trump, Kautz, South Tahoma, and Tahoma Glaciers (Crandell, 1971). These glaciers in the Nisqually River watershed lost 27 percent of their surface area between 1913 and 1994 (Nylen, 2004). The glacially-fed Nisqually River flows south-southwest six miles from the Nisqually Glacier before turning west at approximately 80 degrees and flowing four miles to the MORA boundary. The watershed receives approximately 87" of rainfall annually, most between October 31st and May 1st (Beason et al., 2014; NPS, 2015). During these months, atmospheric rivers of concentrated warm water vapor raise freezing elevations and disproportionately affect areas with high topography bringing high concentrations of precipitation to relatively small geographic areas (Neiman et al., 2011; Beason et al. 2014).

The United States Geological Survey (USGS) has measured stream flow on the Nisqually River at two gages upstream of the Alder Dam between 1931 and the present. The Nisqually River near National, WA (National gage; USGS 12082500) sits 8 miles downstream of Sunshine Point (Figure 1) and has continually operated from June 1st 1942 to the present (Figure 3). The Nisqually River near Alder, WA (Alder gage; USGS 1208400) operated 20 miles downstream of Sunshine Point from September 1st 1931 to October 31st 1944 when construction of the Alder Dam inundated it (Figure 1).

The Sunshine Point Campground infrastructure remaining after the 2006 flood sit at the distal end of a debris fan at the mouth of the Tahoma Creek Valley (Riedel and Dorsch, in prep; Figure 4). The campground is on the Nisqually River northern floodplain between 8 and 12 feet above the Nisqually riverbed and 1500 feet downstream from the Tahoma Creek confluence. At the southwest side of the campground the Nisqually River flows 12 feet below the floodplain along a riverbank with a slope greater than 45 degrees for 300' directly along-side the campground. A 400' long riprap revetment defines the southeast side of the campground and ends sharply at the southwest extent where the 2006 flood scoured away the Nisqually River north bank. The northern sides of the Campground grade into the surrounding riparian floodplain where denser brush and a small stream define its edges.

The study reaches comprise portions of the gravel to cobble-bed, proglacial Nisqually River and Tahoma Creek (Nelson, 1987; Figure 4). Mid-stream and bank bars are dominantly coarse gravel and cobbles with red alder (*Alnus rubra*) and black cottonwood (*Populus trichocarpa*) establishing when allowed to seed and root. Both rivers are steep at Sunshine Point; the Nisqually River gradient is 80 feet per mile and the Tahoma Creek gradient is 150 feet per mile. The Nisqually Valley within the study reach is partially bedrock-confined on both sides by north-south trending ridges perpendicular to the valley. Between the ridges, Kautz Creek and Tahoma Creek flow into the Nisqually River from the north with debris fans 1 mile across at each confluence (Riedel and Dorsch, in prep; Figure 1). Less prominent bedrock spurs define the southern valley side; Berry Creek enters the Nisqually River valley from the south across from Kautz Creek with no prominent fan (Figure 1).

Study Reach Background

Site History

Sunshine Point Campground has been used intermittently since the Civilian Conservation Corps (CCC) established a camp on the site in 1938. Between 1938 and 1939, the CCC constructed several buildings to support year-round habitation, and at least part of a gabion dam revetment to protect the camp from side channels of the Nisqually River or Tahoma Creek. Other planned flood protection structures, such as a log-crib revetment, were never constructed. The United States Navy used the site and building through at least 1943 and made no further modifications (Burtchard et al., 2013). A large debris flow occurred in the Kautz Creek drainage in 1947. Though there is no evidence that the debris flow directly impacted Sunshine Point, the debris flow laterally restricted the Nisqually River in the study reach and introduced more sediment into the Nisqually River (Erdmann and Johnson, 1953)

The NPS used Sunshine Point as a campground between 1953 and 2006. Before 1990, the campground was partially developed, with no formal campsites or infrastructure. Records show little construction activity before 1990 and any modifications that may have been made for flood protection are no longer visible. In the early 1990's, the National Park Service constructed 18 formal campsites and a riprap revetment of angular basalt for flood protection from the Nisqually River. The revetment was built approximately 70 feet south of the existing CCC gabion dam (Burtchard et al., 2013). In this report I will refer to this structure as the 1990 riprap revetment.

Previous Studies of the Nisqually River and Tahoma Creek

Nelson (1987) assessed flood characteristics and flood hazards at Sunshine Point using the Hydrologic Engineering Center's (HEC) version 2 analysis software (HEC-2). At Sunshine Point, Nelson (1987) field surveyed 23 cross-sections across the Nisqually River and 10 cross-sections across Tahoma Creek below the Highway 706 Bridge to use in his assessments. The HEC-2 model results predict peak discharges, average velocities, and inundation zones during 25-, 50-, 100-, and 500-year recurrence interval (RI) floods. Modeled water levels during a 500-year flood would not inundate Sunshine Point, assuming the banks and levees present at the study time remained stable. Nelson (1987) warned average flow velocities as high as 10 feet per second (ft/s) during a 500-year, 4,300 cfs event could breach dikes and channel banks of Tahoma Creek. These dikes were composed of unstable, well-rounded streambed cobbles, and Tahoma Creek discharge through these dikes would flow downhill towards the Sunshine Point Campground. He also warned that aggradation in Tahoma Creek could cause high water and sediment discharge from a debris flow or outburst flood in the Tahoma drainage to enter the campground.

More recent work along the Nisqually River Valley has focused on aggradation and channel migration. Beason (2007) measured +0.13 feet per year (ft/yr) average aggradation between 2005 and 2006 using volumetric differences between field-surveyed cross-sections of the Nisqually River at Sunshine Point. He attributed the aggradation for the one-year interval to at least a century-long trend of increased sediment volumes from the retreating Nisqually Glacier. Beason et al. (2014) used the same method to measure aggradation between five additional cross-sections of the Nisqually River at Sunshine Point. They measure +0.24 ft/yr of aggradation between all measured sections over the study period and -0.55 ft/yr to +1.19 ft/yr of aggradation at individual cross-sections. The cross section with the highest average aggradation crosses the Nisqually River south of the 1990 riprap revetment.

Comparing three LiDAR-derived DEM's from 2002, 2008, and 2012, Anderson (2013) measured 0.33 feet of total incision along 8 miles of Tahoma Creek up stream of the Highway 706 Bridge from 2002 to 2012. Using aerial images to digitize the historical riverbanks, he measured an average channel width increase of 250 feet along the lower Tahoma Creek between 1951 and 2009. Between 1984 and 2009 channel width increases were more localized to an area below the Highway 706 Bridge, which widening more than the reach average. Localized aggradation also occurred below the bridge between 2008 and 2011 (Anderson, 2013). Anderson (2013) finds a correlation between decreasing glacial mass, increased debris flow activity, and increased downstream channel width. He concludes that despite increased river width and sediments input, the Tahoma Creek system has experienced normal and cyclical bed elevation fluctuations on the order of three feet from variations in sediment discharge from the Tahoma and South Tahoma Glaciers.

Two engineering firms have evaluated channel migration and erosion on the upper Nisqually River. GeoEngineers (2007) delineated Nisqually River Channel Migration Zones upstream of the Alder Dam for Pierce County as defined by the Washington State Department of Ecology (DOE) guidelines. From historical images and fieldwork near Sunshine Point, they cite alluvium and abandoned channels, which were lower than the 2007 channel elevation, as evidence that the Nisqually River has occupied the landward side of Pierce County levee before 2007 (Figure 4). From these observations, they conclude that the construction of the Pierce County levee has cut off an active part of the Nisqually River floodplain, which has caused aggradation and raised the streambed above the right floodplain. This creates a high risk of avulsion into the housing development east of the Nisqually River if it breaches the levee.

The NPS contracted Cardno Entrix in 2009 to evaluate erosion, inundation, and avulsion hazards to Highway 706 at Sunshine Point and at the Park headquarters at Longmire. Using a USGS 10-meter DEM based on 1971 USGS topography, Cardno Entrix defined geomorphic regions comprising Quaternary sediment and debris fans as erosion hazard zones. Cardno Entrix (2009) used the United States Geological Survey (USGS) Bulletin 17B log Pearson Type III methodology to calculate the flood recurrence-intervals at the National gage (Table 1). They also used the USGS web-based program Streamstats to estimate peak 2-, 10-, 25-, 50-, 100-, and 500-year flood magnitudes at Sunshine Point. Using measured cross-sections from Beason (2007) and Beason et al. (2014) they created a 1-D steady flow Hydrologic Engineering Center River Analysis System (HEC-RAS) model. The results predict Nisqually River flow velocities between 6 and 10 ft/s with water depths up to 9.5 feet during a 100-yr flood event. Modeled 100-year flood levels would inundate parts of the remaining (post-2006 flood) campground infrastructure. The Cardno Entrix (2009) report includes 21 more years of flood records than Nelson (1987), including the two largest floods at the National gage. The results conflict with Nelson's results that show no campground inundation at even a 500-year event. Cardno Entrix (2009) make note a trend of increasing discharge towards the present at the National gage (Figure 3), which they infer may be the result of increased glacial melting (Cardno Entrix, 2009).

The Pierce County Levee and riprap revetments along Highway 706 failed during the 2006 flood (Beason and Kennard, 2007). After the 2006 flood Cardno Entrix (2009) was contracted to evaluate the stability of structures protecting Highway 706. Using calculations based on the U.S. Army Corps of Engineers (USACOE) *Hydraulic Design of Flood Control Manual* (1994) they determined the average rock dimension necessary to withstand a 100-year flow is 3.2 feet (dimension not specified). Cardno Entrix engineers visually assessed the revetment rock size and predicted the riprap placed along Highway 706 (average size of 5 feet) should withstand a 100-year flow, but predict the Pierce County levee (average rock size 2-3 feet) might not. The Pierce County levee was constructed pre-2006 and partially failed during the 2006, 100-year event. The Highway 706 revetment was built after the 2006-flood to replace newly riverbanks exposed from northward Nisqually River migration.

Table 1. Estimated peak flood recurrence intervals at the National gage from Cardno Entrix (2009).

Recurrence Interval (annual probability)	*Estimated Discharge (cfs)*
2-Year (50%)	6,377
5-Year (20%)	9,771
10-Year (10%)	12,120
25-Year (4%)	15,158
50-Year (2%)	17,459
100-Year (1%)	19,782
200-Year (0.5%)	22,140

Investigation Methods

Within the study area, I use seventeen maps and aerial images from between 1903 and 2013 to digitize the Nisqually River boundaries and centerlines from each image into a GIS. Using the Washington State DOE Channel Migration Toolbox (Legg et al., 2014), I quantify channel migration and channel width changes between 1955 and 2013. Overlaying the digitized river in each image at Sunshine Point, I identify areas of the campground where the Nisqually River has historically flowed. I used equations from Maynord (1996), Ettema et al. (2010), and Racin et al. (2000) to determine scour depth at three revetments protecting infrastructure. During three field days, I mapped avulsion channels, perennial and intermittent streams, tree size and location, and sediment depths in at Sunshine Point to evaluate Tahoma Creek avulsion timing.

I defined a study reach along the Nisqually River to include Sunshine Point, the Kautz Creek confluence, the Tahoma Creek confluence, and the Piece County Levee. I include portions of the Nisqually River Valley upstream and downstream of Sunshine Point for comparison (Figure 1). I defined a study reach on Tahoma Creek comprising the entire Tahoma Creek fan west of the creek, which includes prior avulsion channels, the Highway 706 Bridge, and the confluence with the Nisqually River (Figure 1). I selected these boundaries because presence of incised channels extending from Tahoma Creek to Sunshine Point Campground is important to understanding the extent of past avulsions.

Nisqually River Migration and Occupation

Using maps, aerial photos, and orthophotos from between 1903 and 2013, I digitized channel banks and river centerlines. Paper copies of three maps and eight aerial photos from 1910 to 1990 were scanned at 600 dots per inch and georeferenced using parameters shown in Table. 2. An additional six orthophotos from the National Aerial Imagery Program (NAIP) had registration embedded in the images. Channel banks and river centerlines were digitized from each image into a GIS and used to define river boundary changes and quantify channel migration rates between 1955 and 2013. Channel boundaries were defined by prominent topographic line breaks in the 1910 map and by the drawn channel boundaries on the 1903 and 1924 maps. Resolution of aerial photos between 1955 and 1990 was insufficient to identify the low flow channel; I mapped the active channel, defined as the sum of the unvegetated banks and gravel bars of the channel (Osterkamp and Hedman, 1982). Channel centerlines were digitized halfway between the vegetated north and south banks by eye as a continuous line.

Typically, georeferencing error is quantified using fixed, known points to determine offset in each image (Hughs et al., 2006). Because of the lack of development within MORA near Sunshine Point, I estimated error in georeferenced position using the Highway 706 roadway. Highway 706 runs along the west side of the Tahoma Creek fan within 100 feet of Sunshine Point Campground, making a fixed reference point between images from 1924 to 2013. The road turns 60 degrees from northeast -rending to west-northwest-trending immediately west of the campground allowing me to estimate error in two dimensions. I digitized the road centerlines between 1955 and 2013, which I enclosed in a polygon. Offset existed between all digitized roads, including the NAIP images, so I divided the polygon enclosing the road centerlines between 1955 and 2013 by the total polygon length. The resulting polygon averages 50 feet wide along the 3.5 mile digitized length. The polygon is narrowest (40 feet wide) on the northeast trend, along Sunshine Point Campground and widest (120 feet) on the northwest-trend, west of the MORA boundary. The average error of any image between 1955 and 2013 is ± 25 feet (northwest to southeast direction) along Sunshine Point; the maximum error farther west of the campground is ± 60 feet (southwest to northeast direction). The Nisqually River at Sunshine Point varies between 400 feet and 1000 feet wide between 1955 and 2013; the maximum error nearest Sunshine Point is between 5 and 30 percent of the 2013 Nisqually river width. The 1924 road did not fit within the polygon and error calculated from the polygon (including the polygon width) is $\pm$ 140 feet. I could not quantify error in the 1903 or 1910 maps because they lacked any control points relatable to modern images; both were included in the occupation analysis because they extend the record an additional 21-years. The 1903 and 1910 river channels do not flow through the campground, so they did not create any false positives.

Channels may avulse back and forth across the valley between image years obscuring migration if vegetation re-establishes on riverbanks. Deciduous trees grow on exposed gravel banks after the river migrates away and no longer inundates the banks during high flows. Red alder (*Alnus rubra*) and black cottonwood (*Populus trichocarpa*) will grow large enough to incorporate banks that have not been inundated between aerial images into the floodplain (Anderson, 2013). Mean and median interval between the aerial photos and orthoimages used for migration analysis (1955 to 2013) is 5.3 and six years respectively. Red alder (*Alnus rubra*) can grow to 30 feet by five years old and black cottonwood (*Populus trichocarpa*) can grow to 20 feet in 4 years (USFS, 2004). I use the method outlined by O'Connor et al (2002) comparing reach averaged migration rate from the Channel Migration Toolbox with migration rate estimated for the average image interval (5.3 years) estimated from linear regression of migration rate versus image interval. This method measures lower migration rate bias in longer image intervals where vegetation growth has obscured evidence of migration.

Channel occupation is the area in any given image that that represents part of the river's active channel. The Nisqually River polygons were overlain on each other and the number of overlapping active channels at any point was given a percentage based on the number channels at any point. The results are an occupation map, which shows the percentage of the seventeen images occupied by the channel in an image at any one spot in the river through time. Since images are not equally spaced in time, the resulting occupation map approximates the percentage of time the river has flows at a particular point in the study reach. The images used between 1903 and 2013 are spaced on average seven-years apart with a 5.5-year median time interval.

Table 2. Summary of sources used to digitize channel banks and centerline and registration parameters.

Source	*Scale*	*Coverage*	*Date*	*Comments*
U.S. BLM General Land Office	1:31,680	W 1.6 miles of study reach	Surveyed between 1891 and 1903.	Georeferenced using section corners. Map not used in migration analysis.
Henshaw and Parker, 1913	1:31,680	Nisqually River only.	Surveyed in 1910.	Georeferenced using section corners. No error calculated. Map not used in migration analysis.
USGS[a]	1:125,000	Entire study reach	Map dated 1928, surveyed in 1924.	Georeferenced using latitude and longitude embedded in image. ± 140' error. Map not used in migration analysis.
Army Map Service[b]	1:66,000	E 4.2 miles of study reach.	Sep 18 1955	Georeferenced using 10 control points. ± 25' error.
USGS[b]	1:54,000	E 4.2 miles of study reach.	July 14 1959	Georeferenced using 10 control points. ± 25' error.
Pacific Aerial Survey[b]	1:60,000	Entire study reach	July 30 1965	Georeferenced using 10 control points. ± 25' error.
USDA[b]	1:70,000	Entire study reach	Aug 25 1972	Georeferenced using 10 control points. ± 25' error.
WADNR[b]	Flown at 1:24000; poor reproduction resolution.	W 3.5 miles of study reach.	Flown 1976	Orthophoto compiled from USGS imagery (Negative SW-H-76) and published by WADNR in 2 contiguous plates. Georeferenced using 6 control points. ± 25 ft error. Image not used for migration nor occupation analysis.
USDA[b]	1:80,000	Entire study reach	Jul 15 1979	Georeferenced using 10 control points. ± 25 ft error.
USDA[b]	1:58,000	W 4 miles of study reach	Aug 25 1984	False color infared image. Georeferenced using 10 control points. ± 25 ft error.
WADNR[b]	1:63,360	Entire study reach	1990	Georeferenced using 10 control points. ± 25 ft error.
USGS[c]	1:40,000	W 3.8 miles of study reach	1990-1996	Orthophoto compilation published by NAIP 2003. Georeferencing from NAIP. ± 25 ft error.
USDA[c]	1:12,000	Entire Study Reach	2005	Georeferencing from NAIP; not used for migration calc. ± 25 ft error.
USDA[c]	1:12,000	Entire Study Reach	2006	Georeferencing from NAIP. ± 25 ft error.
USDA[c]	1:12,000	Entire Study Reach	2009	Georeferencing from NAIP. ± 25 ft error.
USDA[c]	1:12,000	Entire Study Reach	2011	Georeferencing from NAIP. ± 25 ft error.
USDA	1:12,000	Entire Study Reach	2013	Georeferencing from NAIP. ± 25 ft error.

[a]USGS Earth Explorer
[b]UW Suzallo Library Maps Collection
[c]NAIP (2013)

I used the ArcGIS Channel Migration ToolBox from the Washington State DOE to quantify channel migration rates and channel width changes between 1955 and 2013 (Legg et al., 2014). Inputs are channel boundaries and channel centerlines digitized from aerial images. I restrict channel migration analysis to the images between 1955 and 2013 for consistency in defining channel boundaries and channel centerlines. Maps prior to 1955 do not specify the mapped channel displayed (low-flow channel or active channel). The Channel Migration Toolbox uses two methods to measure channel migration and one method to measure channel width changes between input years by:

I. Measuring reach-average channel migration using total channel centreline length, and calculating total area change between each centerline.
II. Measuring distance between channel centerlines at each of 40 evenly spaced transects orthogonal to the valley centerline. This method calculates lateral migration every 500 feet along the study reach.
III. Measuring number of channels and active channel width at each transect used in method II. Active channel widths are measured every 500 feet along study reach and along the entire reach, both between input years and over the entire time period (1955 to 2013).

Timing Tahoma Creek Avulsions

I visited Sunshine Point on December 12th, 2013 with Brian Collins and Paul Kennard and alone for two days on November 29th and 30th, 2014. I used the convention MORAXXX to designate field sites where I recorded information about incised channels, swaths of dead trees, overbank flood deposits, flowing streams, and remaining campground infrastructure (Figure 5). During field days I observed flow conditions along Nisqually River, Tahoma Creek, and small, unnamed creeks that flow through the Tahoma Creek west floodplain. At site MORA011, I used a stopwatch and floating debris to estimate velocity of flow in an unnamed stream in the west floodplain. Along with depth and width measurements, I made a rough discharge estimate on November 29th, 2015 (Leopold et al., 1964).

Tahoma Creek avulsions occur as short-lived events leaving oversized channels incised into the surrounding floodplain, overbank sediment deposits, and swaths of dead trees. Incised channels were field identified as linear topographic depressions containing alluvial deposits or running water. Overbank deposits were visible when they buried trees and campground infrastructure and were noted; mapping the extents and depth of overbank deposits was not possible in this study. I observed sediment deposition within Sunshine Point Campground only where burial of infrastructure made it obvious; subsurface coring or a systematic survey of floodplain trees is required to map the extent of these deposits. Swaths of dead trees observed in the field corresponded to elongate vegetation and color anomalies in aerial photographs (Figure 6). During my 2014 fieldwork, I visited these tree dies-offs and documented their lateral extents, presence of standing water, and spatial relation to incised channels.

I measured tree circumference at breast height and recorded my best estimate of tree species on the Tahoma Creek west floodplain. I calculated diameter at breast height (DBH), which I hoped to compare with DBH and age results from previous studies (Legg, 2013). I saw no correlation between DBH and age in the results from Legg (2013) and could not relate my DBH results to tree ages. I was not able to use the DBH measurements to date floodplains because of the lack of a relationship between DBH size and ages.

I compared incised channels, swaths of dead trees, and streams observed during field mapping with a 2009 LiDAR-derived 1-m Digital Elevation Model (DEM) and orthophotos from between 2009 and 2013 to create a 1:5000 scale geomorphic map of Sunshine Point (Figure 5). From each image I also digitized the Tahoma Creek active channel banks and used the Channel Migration Toolbox to measure channel width changes through time as I did with the Nisqually River.

Within the campground, I documented relict cutbanks, flood deposits, and remaining campground infrastructure. I could not find information on the construction of the 1990 riprap revetment south of Sunshine Point, so during my fieldwork I performed a clast size count for clast size distribution. I measured the intermediate axis of 37 randomly chosen clasts progressing from SW to NE along the length of the revetment and determined the median diameter (D_{50}) for the revetment rocks.

Scour

Scour at the toe of banks or revetments removes material, causing instability of riverbanks. The potential for the Nisqually River to scour and destabilize banks and migrate north into Sunshine Point Campground will change depending on flow velocity, depth, and the angle that the flow approached the banks. I calculated maximum scour depths for 25-, 50-, and 100-year flood recurrence intervals along a riprap revetment outside of a meander bend protecting Highway 706 from the Nisqually River at two locations using equations from Maynord (1996) and Ettema et al. (2010). I determined the stability of the 1990 riprap revetment using methods and equations from Racin et al. (2000

Equations for calculating scour outside of a bend from the U.S. Army Corps of Engineers overestimate scour depths, particularly for small streams, where width to depth aspect ratios are smaller than in larger streams (Maynord, 1996). Using multiple regression analysis, Maynord (1996) developed an equation for scour at the outside of a bend that more accurately predicted scour in 90 percent of test cases if a 1.08 factor of safety correction is applied. Following Maynord (1996), water depth after scour, d_{as} is

$$d_{as} = y\left[1.8 - 0.051\left(\frac{R_c}{W}\right) + 0.0084\left(\frac{W}{y}\right)\right] \, for \, 1.5 < \frac{R_c}{W} < 10 \, and \, 20 < \frac{W}{y} < 125, \qquad (1)$$

where R_c is bend radius of curvature at channel centerline, W is width of flow, and y_0 is approach flow depth; all variables are measured in feet.

The 1990 riprap revetment-caused constriction is best approximated as a bridge abutment for scour calculations because it sits on an elevated floodplain perpendicular to flow. Equation 2 estimates scour under non-uniform flow conditions and accounts for the proximity of the abutment to main channel flow (Ettema et al., 2010). When calculating scour of an abutment on a floodplain, other available equations require floodplain flow velocity, unavailable for this study, or were designed for sand-bed rivers (Froelich equation and HIRE equation in Arneson et al. 2012). Additionally, equation 2 does not require the abutment length exposed to flow; for the 1990 revetment this length is difficult to determine since the length of the riprap revetment exposed to flow will change depending on flood stage. I calculated scour at the tip of the 1990 revetment-caused constriction where the Nisqually River flows along the Sunshine Point Campground using method A from Ettema et al. (2010; NCHRP 24-20 Abutment Scour Approach-Live Bed). Since scour will occur in the active channel under flood conditions, the bed will be mobilized and the live-bed conditions are used. Final abutment scour depth is

$$y_s = y_{\max} - y_0, \tag{2}$$

maximum flow depth resulting from abutment scour is

$$y_{\max} = \alpha_A y_c, \tag{3}$$

and the total flow depth including live bed scour is

$$y_c - y_1 \left(\frac{q_{2c}}{q_1} \right)^{\frac{6}{7}}. \tag{4}$$

The variable y_0 is the flow depth prior to scour and y_1 is the approach flow depth, both measured in feet (ft). Additionally, α_A is an amplification factor for live-bed conditions determined from Ettema et al. (2010); q_1 is upstream unit discharge and q_{2c} is unit discharge in the constricted opening accounting for non-uniform flow distribution; both are measured in feet per second (ft/s).

Using methods outlined in California Department of Transportation report number FHWA-CA-TL-95-10, I calculate minimum rock D_{50} for the 1990 riprap revetment necessary to withstand a 100-year flood (Racin et al., 2000). Report FHWA-CA-TL-95-10 outlines methods for collecting and processing data and allows simple calculation for parallel and non-parallel flow; for these two reasons I found this the most accessible and appropriate method. I estimated stability for parallel and impinging flows of the revetment during 2008 conditions with a revetment comprising basalt rocks (the current constituents). The 50th percentile rock size necessary to withstand a 100-year flood with a velocity of 6.2 feet per second (ft/s) is

$$d_{50} = 1.5 d_{30}, \tag{5}$$

where the 30th percentile rock size (d_{30}) is

$$d_{30} = \left[6 \left(\frac{W}{\pi g_s} \right) \right]^{\frac{1}{3}}, \tag{6}$$

and

$$W = \left\lfloor \frac{\left(2.0x10^{-5}\right)\left(v^{6}\right)\left(sg\right)}{\left(sg-1\right)^{3} \sin^{3}\left(r-a\right)} \right\rfloor. \tag{7}$$

The variable W in pounds (lb) is theoretical minimum rock mass necessary to resist the force of v in feet per second (ft/s) and remain stable on the bank. Average velocity (v) is v x 0.67 for flow parallel to the revetment and v x 1.33 for impinged flow; sg is the specific gravity of basalt and g_s is the unit weight of stone in pound per cubic foot (lb/ft^3). The variable R is a constant 70 and a is the outside slope face from horizontal in degrees, 30 degrees at the 1990 riprap revetment (Racin et al., 2000). Though the calculation for "impinged flows" is designed for the outside of a meander bend, this method is appropriate for the 1990 riprap revetment because the angle of approaching flow directed at the revetment is similar to the flow directed at the outside of a meander bend.

I use the cross-sections from Beason (2007) and Beason et al. (2014) for depths and width parameters. I use velocity and flow depth estimates determined by Cardno Entrix (2009) from HEC-RAS modeling for all calculations. I use the cross-sections immediately upstream of each scour location for approach flow parameters (Cardno Entrix, 2009; Beason, 2014).

Results of Investigations

Channel Migration

Nisqually River centerline migration rates and width are greater at Sunshine Point than the study reach average. Lateral migration rates at transects across Sunshine Point Campground are in the 90th percentile of all transect migration rates along the study reach (Figures 7 and 8). The study reach centerline migrated on average nine (ft/yr) between 1955 and 2013. Along three transects at Sunshine Point Campground (31 to 33) average migration is 14 ft/yr during the same interval, with up to 16 ft/yr of migration at transect 32 directly south of the remaining infrastructure (Figure 8). At Sunshine Point maximum total migration between any images occurred at transect 32 from 2011 to 2013; the Nisqually River centerline migrated 207 feet south. This southward migration has increased the angle from parallel that the river approaches the north riverbank. Reach maximum migration of 376 feet occurred at transect 1 between images taken in 1990 and 1996. The cause of this anomalous migration, greater than 100 feet more than any other distance is unknown; the second largest flood at the National gage, during 1996, happened after this image was taken.

Channel centerline migration rates are greatest immediately downstream of river confluences along the study reach. Greater than average Nisqually River migration rates occur downstream of the Kautz Creek confluence and at the Berry Creek confluence (transects 16 to 22), and downstream of the Tahoma Creek confluence (transects 29 to 32) (Figures 7 and 8). Greater than average migration rates upstream of the Kautz Creek debris fan may result from reduced river gradient cause by sediment deposition upstream of the constriction from the 1947 Kautz Creek debris flow (transects 1 and 2).

Bankfull flows have been shown to most effectively change river morphology in rivers, typically in perennial, humid temperate rivers (Knighton, 1998). This discharge, referred to as effective discharge, on average, most changes the river morphology (Dunne and Leopold, 1978). Castro and Jackson

(2001) recommend using a 1.2-year recurrence interval for bankfull flow or effective discharge in western Washington rivers. Migration rates are expected to correlate with peak flows or bankfull flows (Knighton, 1998). For the study reach, a best-fit linear regression shows no significant correlation of migration rate and peak annual flow between images ($r^2=0.31$, $P>0.1$) or migration rate and total discharge over the 1.2-year recurrence interval (3780 cfs) ($r^2=0.04$ $p>0.5$).

The confluence of Tahoma Creek with the Nisqually River centerline has systematically migrated south by 400 feet between 1955 and 2013 (Figure 9). As the confluence migrated south, the angle that the Nisqually River approached Sunshine Point Campground changed from near parallel to greater than 30 degrees (Figure 9). This migration also lengthens Tahoma Creek, which decreases the local slope and promotes aggradation of the Tahoma Creek bed.

Channel width increases with distance downstream along the study reach (Figure 10). A best-fit linear regression shows channel width increases non-monotonically downstream along the study reach. The subset of channel widths that vary from the monotonic increase occur immediately downstream of river confluences. Three of the four widest sections of the study reach are downstream of the Kautz Creek confluence, at the Berry Creek confluence, and downstream of the Tahoma Creek confluence. Average channel width was 371 feet between 1955 and 2013. At Sunshine Point between transects 31 and 33 average channel width is 590 feet.

Similar to migration rate, channel width is expected to correlate to peak flows or effective discharge. A best-fit linear regression shows no significant correlation between channel width and peak annual flow between images ($r^2 = 0.07$, $p>0.2$) or channel width and total daily discharge greater 1.2-year recurrence interval between images ($r^2=0.15$, $p>0.2$). However, greatest active channels widths at Sunshine Point are seen in the 2011, 2009, and 2013 aerial images respectively (Figure 11). The 2006-flood of record occurred five years prior to significant increase in channel width. Though the river experienced a time lag in the width response to the flooding, it appears that the Nisqually River average width does increase with large discharges as expected. Other factors, like proximity to confluences, affect spatial changes to width.

Sources of Error

Due to back and forth migration between image years, estimated migration rates may be apparently less than true migration rates if vegetation re-growth masks riverbanks defining migration extents. Using the mean 5.3-year interval between aerial images, I calculate time-normalized centerline migration rate of 11 ft/yr (O'Connor et al., 2002) (Figure 12). This is greater than nine ft/yr reach averaged channel centerline migration rate. There is a bias towards lower migration rates at longer image-intervals.

Measurement of total centerline migration between images depends on the accuracy of image registration between image years. The total migration between image years ranges from 29 feet to 87 feet, within the larger margins of error for image registration. Annual migration rate correlates well with average channel width ($r^2=0.58$, $p<0.001$) (Figure 13). A positive correlation between migration rate and channel width is expected in rivers where migration into riverbanks is the dominant means of channel widening.

Nisqually River Channels Occupying Sunshine Point Campground

The Nisqually River has flowed within the pre-2006 campground in eight of seventeen images between 1904 and 2013. Before the 2006 flood, the Nisqually River flowed through the campground as recently as 1979 and channels in 1955, 1959, and 1965 were up to 120 feet north of the 2006-campground. The 1976, 1979, and 1984 channels were at least 80 feet north of the pre-2006 campground boundary. The river currently occupies the entire 300 feet of the western, pre-2006 campground (Figures 11 and 14). The Nisqually River has flowed through the proposed campground location in four of fifteen images. River channels in the 1959 and 1965 images flowed through the campground and parallel along the south side of the CCC gabion dam (Figure 14). Channels are not evident north of the CCC gabion dam in any image used for this study and this revetment appears to have effectively protected the campground from northward river migration between 1955 and 1965. The Nisqually River has flowed 80 feet northwest of the 1990 riprap revetment within the planned campground site (Figure 14).

Tahoma Creek Avulsion Channels

Incised channels in the western Tahoma Creek floodplain lead into a single channel that flows within five feet of Sunshine Point Campground. The west bank channels coalesce into a 100-foot wide depression between Highway 706 and Sunshine Point Campground (Figure 5). These channels extend one-mile north from the campground across the width of the floodplain (Figures 15 and 16). Flowing water or alluvial deposits were visible at all field sites where channels were observed (Figure 15) and many of these locations had some amount of discharge on November 29th and 30th 2014. A small stream flowed from Tahoma Creek avulsing on to the flood plain at field site MORA018 (Figure 15). This flow was less than six inches deep in an oversized 20-feet-wide by 10-feet-deep channel. This channel is intermittent and the flow on November 30th and 31st was from a minor avulsion resulting from flooding on November 26th, 2015 with 11,400 cfs discharge measured at the National gage (Paul Kennard, verbal communication 2015; USGS, 2015). The channels upstream of Highway 706 are too deep and wide to have been created by the discharge during my field visit. The National gage recorded greater than a two-year flood four days prior to the November 29th field visit; streams draining the ridge northwest of the Westside road did not create these channels. These channels were created from Tahoma Creek avulsions large enough to incise at least ten feet into the floodplain.

Channels downstream of the Highway 706 that I walked along are typically smaller than the upstream channels; they are between 5 to 15 feet wide and two to four feet deep at bankfull. At least five channels flow from the bedrock slope across and under Highway 706 and the Westside Road. The NPS recently built (post-2013) a large, about 10-foot diameter, culvert under Highway 706 at the Westside Road intersection to accommodate flow under the highway. The discharge from the Tahoma Creek avulsion at MORA018 was less than one percent of the total discharge measured at MORA011 on November 29th 2014 (Figures 5 and 15). At field site MORA011 an 8-inch deep and 8-foot wide wetted channel had 41 cfs discharge; the channel had near vertical banks and a 12-foot bankfull width.

Areas of tree die-offs inferred from vegetation anomalies on aerial photographs were verified as swaths of standing dead trees and between five and ten foot red alder (*Alnus rubra*) or black cottonwood (*Populus trichocarpa*) re-growth (Figure 6). Swaths of dead trees occur mainly on unchanneled floodplains with dense brush and wet hummocky ground. Laterally extensive flows were observed on the unchanneled flood plain and were flowing slower than in the active channel at MORA011. Floodplain areas with unchanneled flow were typically covered by flat-lying grasses directed downstream and fallen trees; the flows were fed by channels upstream and returned to channels downstream (Figure 5). I observed discharge in all incised channels associated with tree die-offs visited on November 29th and 30th.

Incised channels are spatially correlated with swaths of dead and young vegetation in aerial photographs between 1955 and 2013 (Figure 6). In these images individual avulsions cannot be seen, however areas of newly disturbed vegetation resulting from avulsions and are visible in the 1984 and 2009 images. In the 1984 image, a swath of disturbed vegetation connects Tahoma Creek to Sunshine Point Campground. The vegetation anomaly from the November 2006 flood, visible in the 2009 image, is the widest anomaly in the aerial images and was likely the largest avulsion between 1955 and

2013 (Figure 6). A vegetation anomaly is obvious in the 1955 image and an avulsion from Tahoma Creek likely occurred shortly before 1955. The persistent presence of disturbed vegetation between Tahoma Creek and Sunshine Point Campground between 1955 and 2013 strongly suggests that avulsions from Tahoma Creek have occurred at least three times.

Tahoma Creek channel width increased between 1959 and 2011. During this period an avulsion is suspected in 1984 and confirmed in 2006. Both avulsion times correspond to increases in channel width after periods of relatively stable channel width from 1972 to 1979 and 1990 to 2006. Though the 2006 avulsion was related to the flood of record on the Nisqually River, no flood greater than a 10-year recurrence interval occurred at the National gage between 1979 and 1984.

Areas where incised channels or tree die-offs intersected with the Tahoma Creek active channel I map as avulsion zones (Figure 15). These zones are typically associated with denuded banks or levee edges (natural or artificial) along the Tahoma Creek right bank. These avulsion zones were not observed on the left bank, though incised channel mapped from the DEM suggest Tahoma Creek has avulsed over the left bank.

One avulsion of the main Tahoma Creek flow is visible in the 2011 orthophoto (Figure 18). The Tahoma Creek wetted channel avulsed from its course 600 feet north of the Nisqually River confluence and flowed parallel to the Nisqually River just below the vegetation anomaly defined by larger floodplain vegetation to the north and smaller, channel bank vegetation to the south. This avulsion flowed along the south side of the 1990 revetment before joining the main Nisqually River flow near the Pierce County levee. During the time period of this avulsion, between the 2009 and 2011 images, Tahoma Creek reach average channel width and transect specific channel width decreased.

Sunshine Point Campground Conditions

The majority of the remaining Sunshine Point campsites and roads sit on a southwest-to-northeast trending ridge (central campground ridge). This ridge is approximately 2-3 feet high and between 100 and 200 feet wide and runs the length of the campground (Figure 16). Remaining campground infrastructure on the ridge includes roads, picnic tables, and garbage cans. The central ridge is flat and was dry during both visits, while the denuded land on either side was wetter and moderately hummocky. The northern edge is marked by a distributary of the Tahoma Creek avulsion channels approximately 100 feet wide and within five feet of the central Sunshine Point Campground road (Figure 19). The southern edge is marked by a relict cutbank with the largest trees observed in the campground one 42.4" diameter breast height (DBH) fir (*Abies*), one 48.4" DBH black cottonwood (*Populous trichocarpa*), and one 40.8" DBH western red cedar (*Thuja plicata*) sites MORA008, MORA007, and MORA005 respectively (Figure 5). South of the cutbank tree diameter decreases consistently across the floodplain. Four fir trees (*Abies*) and one black cottonwood (*Populous trichocarpa*), between 20.1" DBH and 17.4" DBH sit on a floodplain surface defined by meander scars to the north and south (Figure 5; sites MORA004a-MORA004d). The 1938 CCC gabion sits within this flat area and the 1990 riprap revetment defines the southern edge.

Approximately six to eight inches of fine-grained silt and sand covers the ground around the picnic tables in the northeast campground including the central campground ridge, near the northeast end of the CCC gabion dam (Figure 5). Floods are the only mechanism that could have deposited this sediment since the campground was abandoned; at least some of the sediment is likely from the 2006 flood. The CCC gabion dam was originally designed to be six to eight feet tall (Burtchard et al., 2014). Since 1938, enough sediment has deposited around the gabion dam that it is not immediately obvious and the top is nearly even with the present ground surface. Burtchard et al. (2014) note that park workers did not recognize the gabion dam until 2007. If the dam was built as designed, the campground surface has aggraded between three and six feet since 1938. The Nisqually River flowed along the gabion dam in the 1959 and 1965 images and Nisqually River overbank flooding or Tahoma Creek avulsions may have deposited the sediment.

Bank Scour at Sunshine Point Revetments

Scour at riprap revetments during a 100-year flood of the Nisqually River may incise up to 10 feet below the 2008 bed elevation along Highway 706 and 6.5 feet below the bed elevation at the southwest tip of the 1990 revetment (Tables 2 and 3). Total water depth due to scour along the revetment protecting Highway 706 could reach up to four feet and 13 feet respectively with a 1.08 safety factor correction (Figure 19, Table 2). Live-bed scour at the channel-ward side of the 1990 riprap revetment can increase total water depth during a 100-year flood to 14 feet when the Nisqually River width increases, inundates the floodplain, and flow is constricted by the revetment protruding into the channel (Figure 19; Table 2).

I use methods from Racin et al. (2000) to calculate the riprap size necessary to withstand a 100-year flood at the 1990 revetment with parallel flow and impinging flow. Predicted D_{50} of the basalt riprap necessary to withstand a 100-year flow parallel to the revetment is 0.17 feet. Predicted D_{50} of the basalt riprap necessary to withstand a 100-year flow directed at the revetment 30 degrees from parallel is 0.67 feet. From riprap measurements collected on November 30th 2014, I calculate the 1990 revetment is composed of angular basalt with an intermediate axis D_{50} of 2.75 feet. From these calculations and under the current site conditions, the 1990 revetment should withstand a 100-year flood on the Nisqually River.

Table 3. Results of scour outside of bend calculations using methods from Maynord et al. (1996).

Flow recurrence Interval (2008)	*25-year*	*50-year*	*100-year*
y (x-sec 7)	5.8	6.1	6.4
d or y (x-sec 6)	2.3	2.5	2.7
d (x-sec 5)	3.3	3.6	3.9
R_c	650	650	650
W (x-sec 6)	390	390	390
W (x-sec 5)	390	390	390
d_{as} (x-sec 6)	11	11	12
d_{as} (x-sec 5)	3.9	4	4
d_{as} (x-sec 6) x FS 1.08	12	12	13
d_{as} (x-sec 5) x FS 1.08	4	4	4
Depth below 2008 streambed (x-sec 6)	**10**	**9.5**	**10**
Depth below 2008 streambed (x-sec 5)	**0.7**	**0.4**	**0.1**

Table 4. Results of abutment restriction scour using methods from Ettema et al. (2010) (NCHRP 24-20 Abutment Scour Approach-Live Bed).

	Flow recurrence Interval (2008)		
	25-year	*50-year*	*100-year*
Q	8300	9820	11100
B1	560	560	560
B2	283	283	283
y_0 (from x sec8)	6.6	6.8	7.0
y_1 (from x sec7)	5.8	6.1	6.4
q_1	14.8	17.5	19.8
q_{2c}	29.3	34.7	39.2
α_A	1.175	1.175	1.175
y_c	10	11	12
y_{max}	12	13	14
y_s	**5.7**	**6.1**	**6.5**

Hazards to Sunshine Point Campground

The dynamic confluence of Tahoma Creek with the Nisqually River creates northward migration and avulsion hazards at the proposed Sunshine Point Campground location. Migration hazards exist for infrastructure and campground users from the Nisqually River scouring below and into existing banks and migrating north into Sunshine Point Campground. Flooding hazards exist from Tahoma Creek avulsing into existing incised channels by topping the banks of undersized channels and flooding the campground.

Nisqually River Occupation of Sunshine Point

Migration hazards at Sunshine Point Campground result from river instability due to increased sediment and stream discharge with accompanying aggradation at the southerly-migrating Tahoma Creek confluence. The 2006 flood that destroyed five acres of Sunshine Point Campground as the Nisqually River scoured into and under its banks and migrated 300 feet north to Highway 706 was not the only time that these hazardous conditions existed at Sunshine Point Campground. Between 1903 and 2013, the Nisqually River channel occupied the pre-2006 campground in 40 percent of images and the planned campground location in nearly 25 percent of images.

The largest Nisqually River total migration distance between image years at Sunshine Point occurred between 2011 and 2013, the most recent interval studied. The 207 foot southward migration significantly changed the river geometry increasing the sinuosity of a large meander directly south of the campground infrastructure and increasing the angle that the river approached its northern bank. The current angle of the approaching Nisqually River flow at Sunshine Point increases potential scour depths at revetments protecting the campground from channel migration. This angle has increased as the Tahoma confluence with the Nisqually River has migrated south, increasing the stress on the northern riverbanks. Over a long enough time period the Nisqually River will migrate into Sunshine Point Campground as channel banks fail from scour.

Presently, the Nisqually River flows directly against the southwestern campground boundary and every foot of northward migration is a foot of campground lost. As the Nisqually River migrates north, the 1990 revetment is most exposed to scour. Up to 6.5 feet of estimated scour below the riverbed may destabilize the revetment as its foundations are removed. The stability of the revetment protecting the Nisqually River from migration is a result of the scour depth and geotechnical stability of the revetment (Ettema et al., 2010). The riprap composing the 1990 revetment should withstand flows directed at it during a 100-year flood. However, the results from Table 3 show that the revetment would need to have a foundation extending 6.5 feet below the average channel depth to protect against geotechnical failure. Failure during the 2006 flood may have been the result of scour at the foot of the revetment creating instability. The 1938 CCC gabion dam effectively protected the campground during 1959 and 1965 northward migration. Revetments can effectively reduce the hazards associated with channel migration; the 1990 revetment effectively protected the campground during north and westward migration. However, it did not protect against the 2006, 100-year flood. The geotechnical design of the 1990 revetment was not available for this study and the stability under the calculated scour conditions were not evaluated.

Floods from Tahoma Creek Avulsions

It is difficult to determine when avulsions happen since they are short-lived events and active flows rarely appear in aerial images. However, aerial images show that at least three avulsions large enough to kill standing vegetation in images between 1955 and present. Large avulsions from Tahoma Creek correspond to years when Anderson (2013) documented aggradation from debris flows and large floods in the Tahoma Creek drainage. However, these avulsions are not always due to flows greater than 10-year recurrence interval and if the Tahoma Creek bed has recently aggraded, a 10-year recurrence interval flow may cause an avulsion towards Sunshine Point Campground.

Debris flows are an effective mechanism for increasing average channel widths after periods of relatively steady channels widths. My results show that as channel width increases from debris flows, an avulsion is more likely to occur than in other periods. Documenting an avulsion between 1959 and 1956, another period of increased channel width after stable average channel widths would help to strengthen this hypothesis. During the last six years, Tahoma Creek is the widest it has been in the last 58 years. A large debris flow, or series of debris flows in the Tahoma Creek drainage will increase sediment carried through the Tahoma Creek drainage and greatly increase the risk of an avulsion flooding the planned campground.

Mapped avulsion channels on the Tahoma Creek floodplain are associated with channel incision, perennial and intermittent flow, and vegetation death. During a flood, up to 30 percent of the total Tahoma Creek discharge can avulse into the west bank floodplain and travel towards the campground (Paul Kennard, verbal communication 2014). This amount of discharge will be channelized upstream of the Highway 706 Bridge, but top the undersized avulsion channels south of the highway and flood the campground. All channels incised into the right bank of Tahoma Creek join immediately north of the campground and directing flows within five feet of the northwest campground boundary.

Effects of Glacial Retreat

Mount Rainier glaciers are retreating more in the Nisqually watershed than elsewhere in MORA (Nylen, 2004). Beason et al. (2011) relate decreases in glacial mass to increased peak flood discharges and sediment discharge within MORA and the Nisqually River Valley. Anderson (2013) relates decreased glacial mass to increased debris flow activity and sediment delivery to Tahoma Creek. Both drainages in this study are displaying the effects of decreasing glacial mass, resulting in aggradation and increasing channels widths.

The potential effects of glacial retreat will likely increase at the confluence of Tahoma Creek with Nisqually River; results from this study show that migration rates and channel width are already magnified at confluences, increasing discharge should continue this trend. In the study reach previous large floods have caused bank scour and channel migration before inundating Sunshine Point Campground. Inundation hazards from the Nisqually River appear to have increased between work by Nelson (1987) and Cardno Entrix (2009). In addition in higher peak floods, aggradation may cause increased inundation hazards as the riverbed is raised closer to the floodplain top. The 100-year flood in 2006 did not inundate the campground. However, Cardno Entrix (2009) show that parts of the campground are already within the 100-year inundation zone.

Tahoma Creek channel widths have increased 250 percent since 1959. This increasing width has occurred in discrete events as periods of debris flows introduce more sediment into Tahoma Creek. Anderson (2013) and Beason (2007) have shown that debris flows occur more often as MORA glaciers retreat leaving unstable slopes exposed to erosion. Increased channel widths will further encourage avulsions and similar to inundation floods, the recurrence interval flood necessary from Tahoma Creek to avulse from its course into the floodplain will decrease as the streambed rises.

Management Implications and Recommendations

The two proposals for rebuilding the Sunshine Point Campground have the campground in the same location downstream of the Tahoma Creek confluence with the Nisqually River. The southern edges of both campgrounds are exposed to northward Nisqually River migration. The central campground ridge approximately 300 feet north of the present Nisqually River has not been part of the river since 1903 and is less exposed to northward migration hazards; however both proposed campgrounds extend south of this ridge. I recommend that the NPS consider this ridge within the proposed campground extent as the area least likely to be re-occupied by the Nisqually River.

Both campground options expose infrastructure to the same hazards, while option one exposes users to fewer hazards during the low-discharge summer season. Channel migration correlates poorly with peak flows or total daily discharge greater than a 1.2-year recurrence interval. The first campground option, for a seasonal campground with limited winter camping, would reduce the hazards to users by concentrating their presence in the campground during low-discharge months between May and October. The infrastructure in the two campground options will be exposed to the same migration hazards through the winter. Migration hazards to campground users may be limited by closing the campground during atmospheric river storms that typically cause large floods within the park, if these storms can be predicted in short enough time for evacuation.

Protection of the Nisqually River's north bank with revetments appears to be an effective means to reduce the hazards from migration. The 1938 gabion dam has been an effective barrier restricted migration in 1959 and 1965. Scour from channel migration destroyed part of the 1990 riprap revetment in a catastrophic manner and though the rocks comprising this revetment may have been designed to withstand a 100-year flood, the foundation likely does not extend deep enough to prevent geotechnical failure. The increased angle that the Nisqually River approaches the campground southern boundary increases normal forces from the river at revetments and increases scour potential. I recommend considering revetments that will withstand scour to depths greater than seven feet below the 2008 average riverbed for a 100-year event and the park may want to consider designing for scout depths during a 500-year. Additionally, I recommend considering increased approach flow angles greater than the present approximately 30 to 40 degrees when designing structures to restrict northward migration.

Tahoma Creek avulsions are a result of channel widening and bed aggradation due to periods of increased sediment input to the channel from debris flows. The plans for rebuilding Sunshine Point Campground account for northward migration with planned engineered structures along the north bank of the Nisqually River. The plans have no engineered structures to reduce flooding from Tahoma Creek avulsion channels. Incised channels in the western Tahoma Creek floodplain will direct avulsions into Sunshine Point Campground. Tahoma Creek avulsions have not been restricted to the most recent 2006 event; nor like the 1984 avulsion are they restricted to extremely high flows. Since any avulsions will pass within five feet of the campground, I recommend the NPS consider that any Tahoma Creek avulsion will top undersized banks and flood the campground.

Limitations

This report has been prepared at the request of Paul Kennard at the United States National Park Service (NPS). I, Jesse Favia, am not neither a Licensed Geologist or a Licensed Engineer. Any calculations within were performed for the purpose of this report and should not be used for future decisions requiring review by a Professional Engineer or Professional Geologist. I recommend users of this report consider that:

- Nisqually River migration rates, channel widths and occupation percentage were determined from registered aerial images with at least $\pm$ 20 feet of error. Images before 2003 were acquired at a low resolution and errors in digitizing bank extents may have occurred.
- Scour was calculated using velocity and water depth during flooding results from Cardno Entrix (2009) modeling of the 2008 river conditions. These scour results depend on the accuracy of the modeling and the 2008 measured cross-sections.

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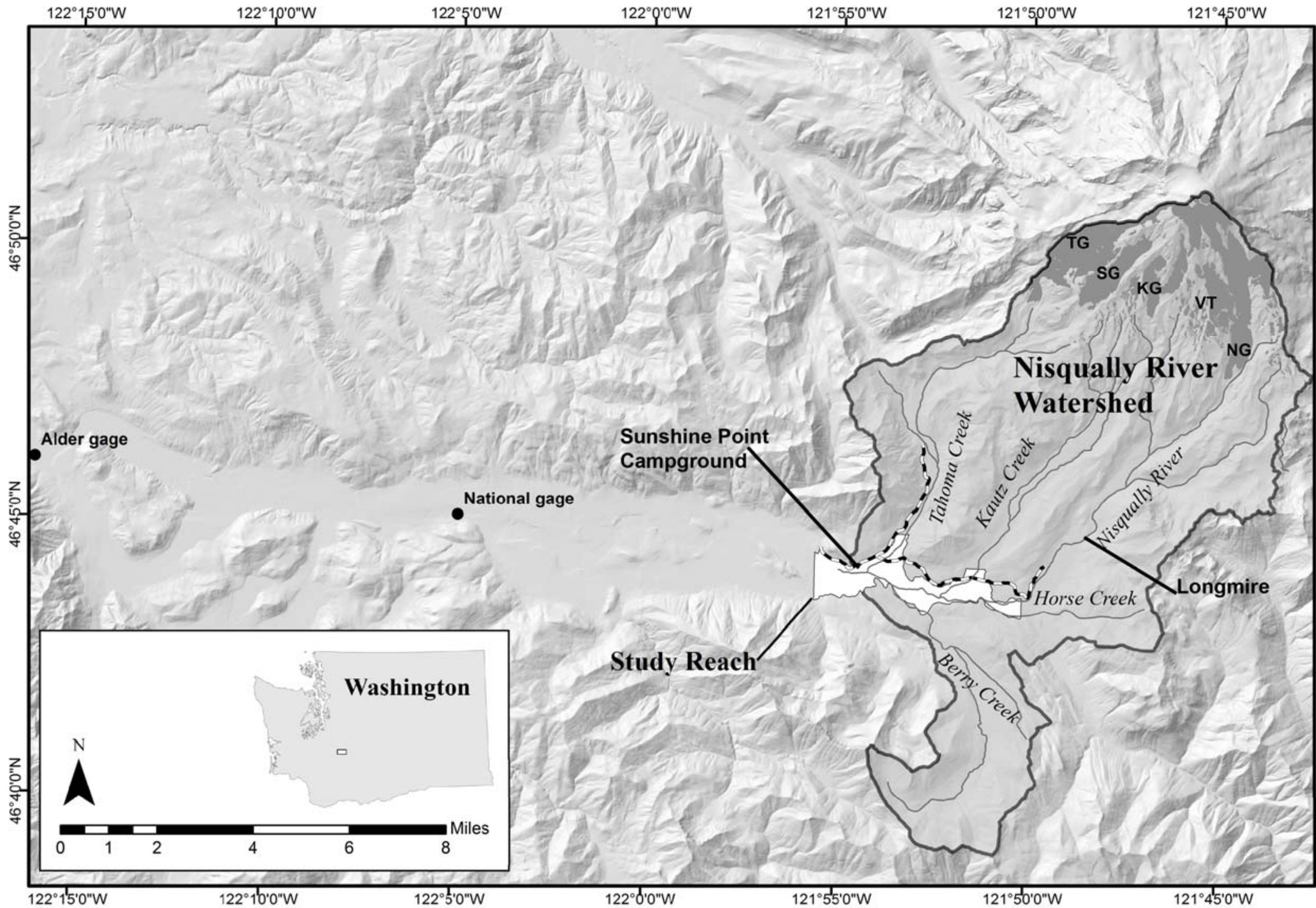

Figure 1. Map showing the study location, important drainages, and infrastructure within Mount Rainier National Park. Abbreviations of glaciers are: TG, Tahoma Glacier; SG, South Tahoma Glacier; KG Kautz Glacier; VT, Van Trump Glaciers; NG, Nisqually Glacier. Topographic basemap from a USGS 10-meter DEM.

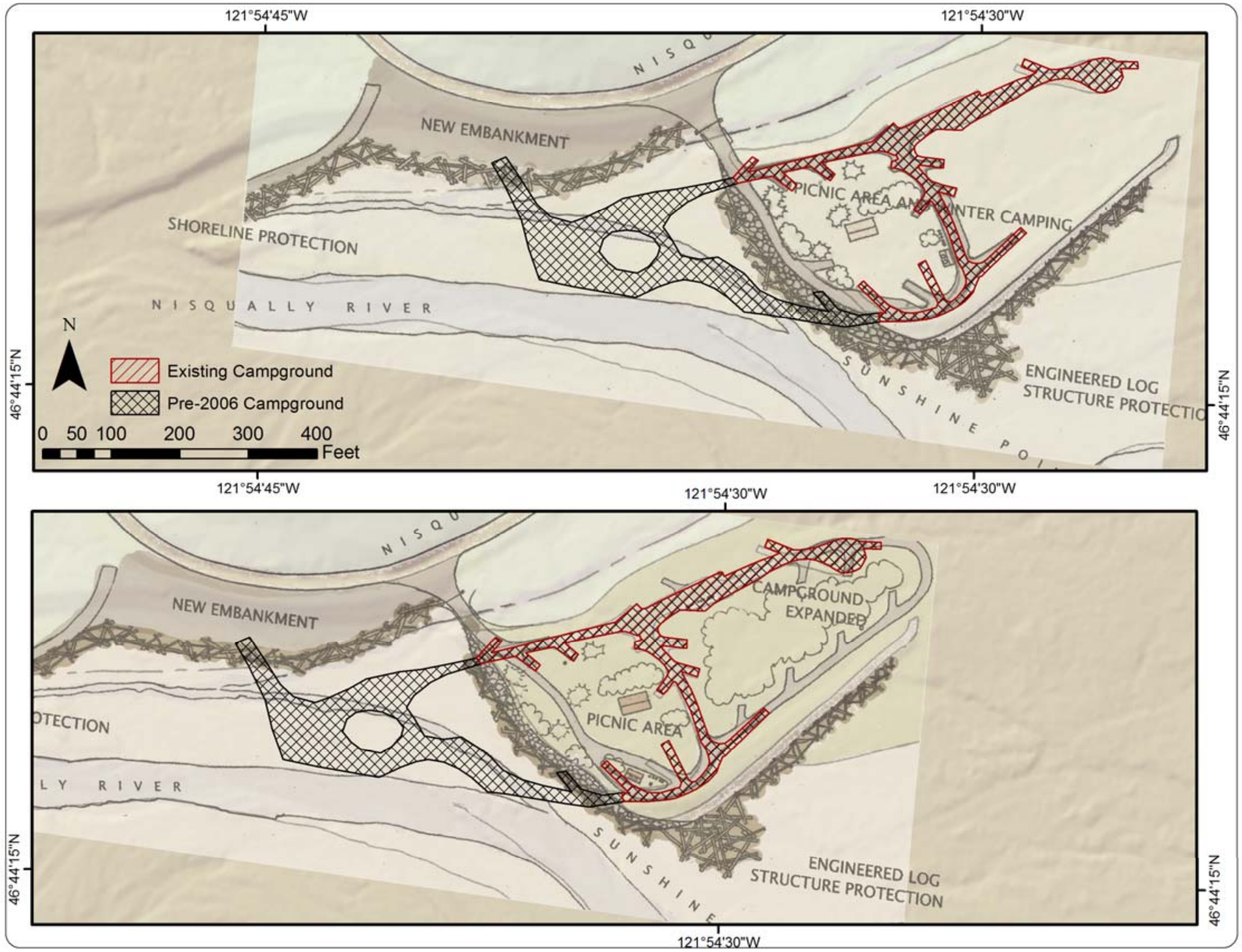

Figure 2. National Park Service proposed alternatives for rebuilding Sunshine Point Campground at its prior location. Alternative one, at top, would create a day-use area with minimal winter camping and occupying campsites from the pre-2006 campground. Alternative two, below, would expand the present campground footprint, creating up to 20 permanent campsites and day use facilities.

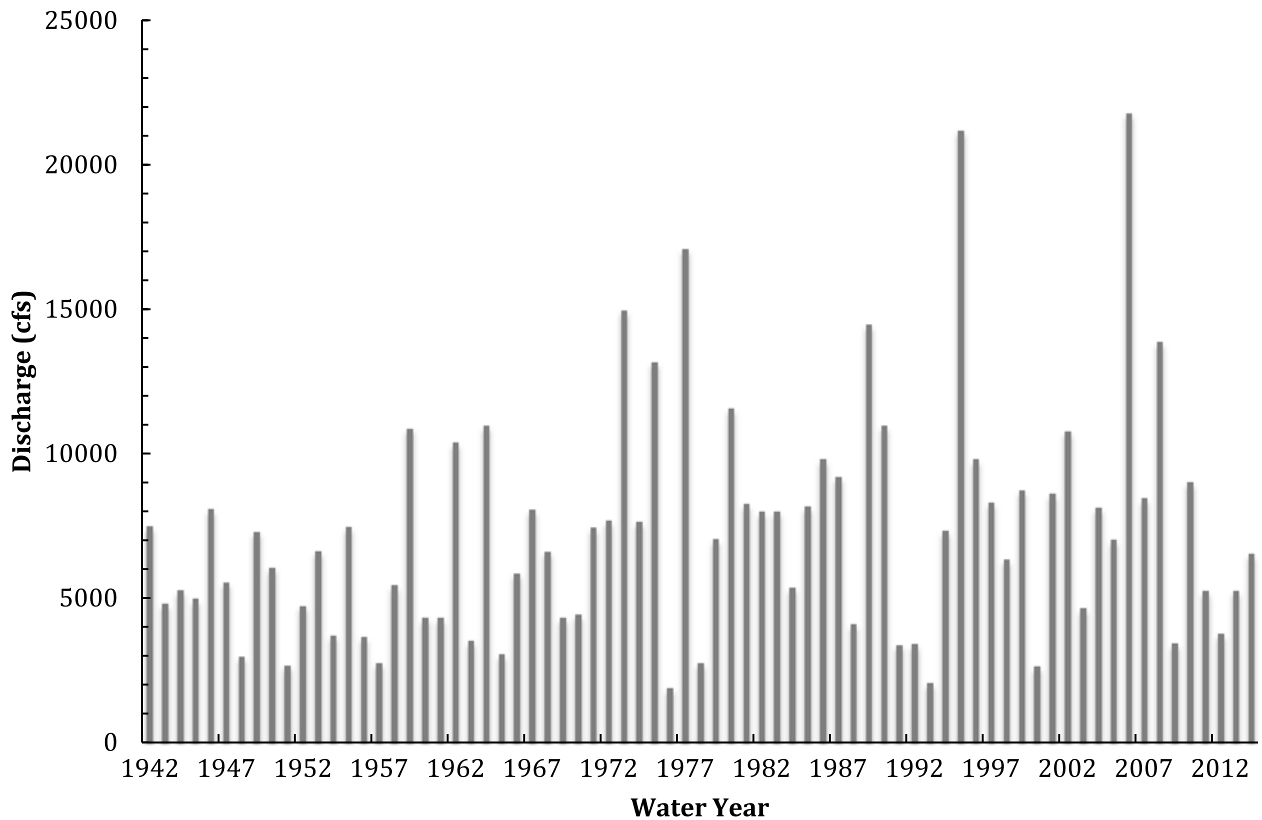

Figure 3. Peak flows for each water year measured at the Nisqually River near National, WA (USGS 12082500) stream gage. Annual peak discharge has increased since the beginning of the record in June 1942. The National gage is the closest continually monitored stream gage to Sunshine Point.

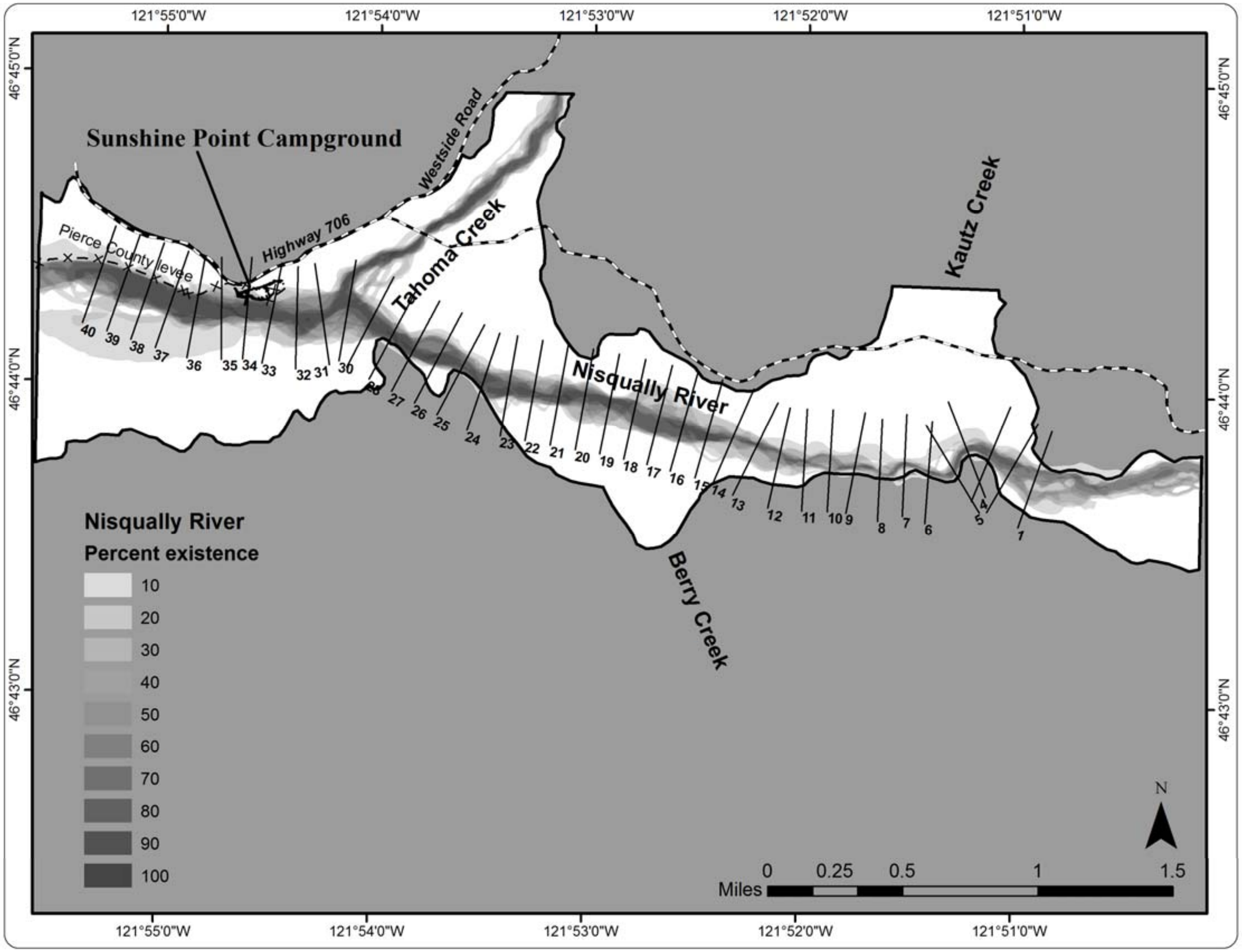

Figure 4. Study reach location map showing 500-foot river and floodplain transects orthogonal to valley centerline. The active channel digitized from each aerial photograph or map defines occupation polygons. Percent existence is defined as a percent of image polygons at any point of the total seventeen images.

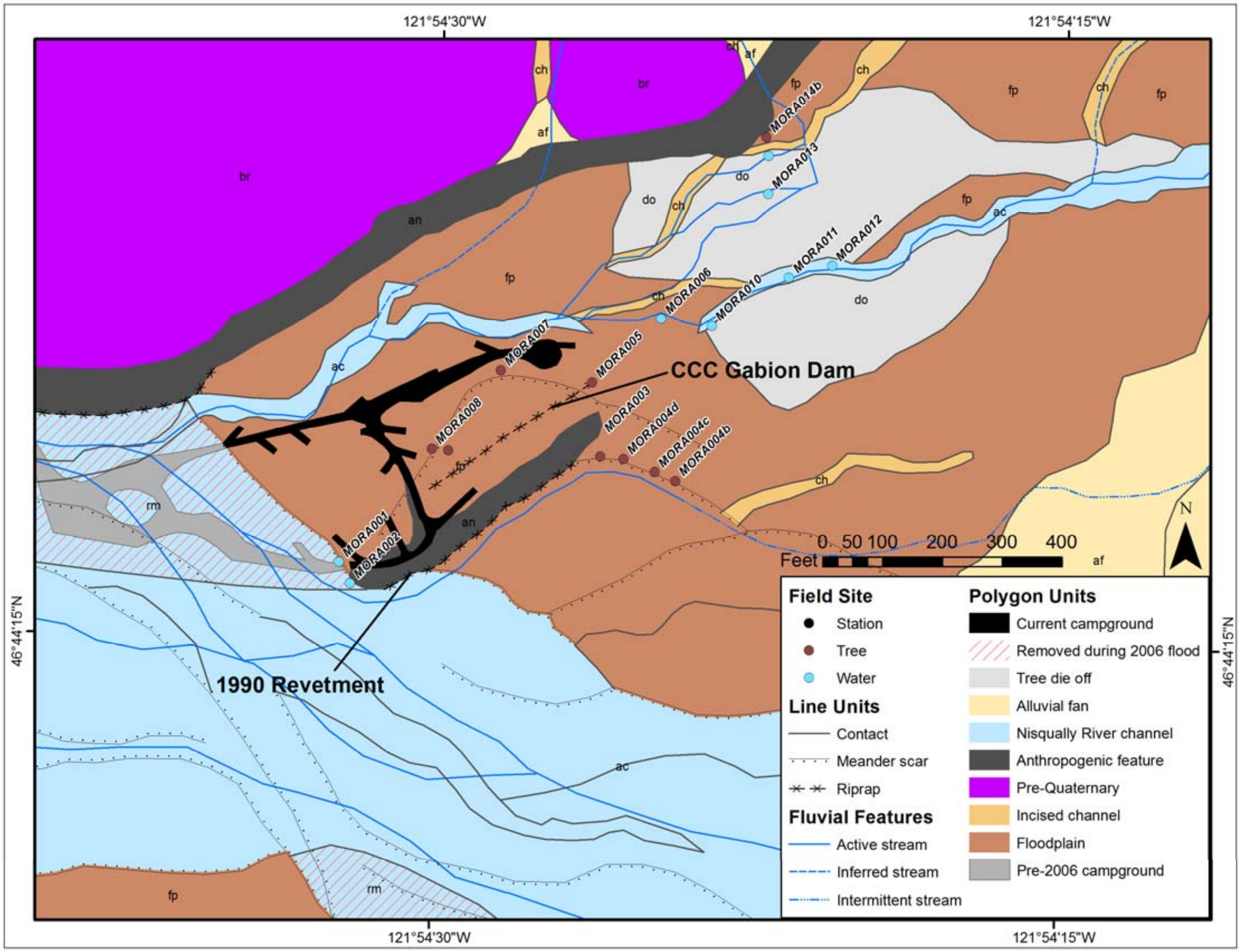

Figure 5. Geomorphic map of Sunshine Point compiled from fieldwork and 1-DEM analysis. Significant sites are labeled and colored. The gabion dam crosscuts a significant meander. The central campground ridge is north of this meander and runs parallel to the east trending campground road.

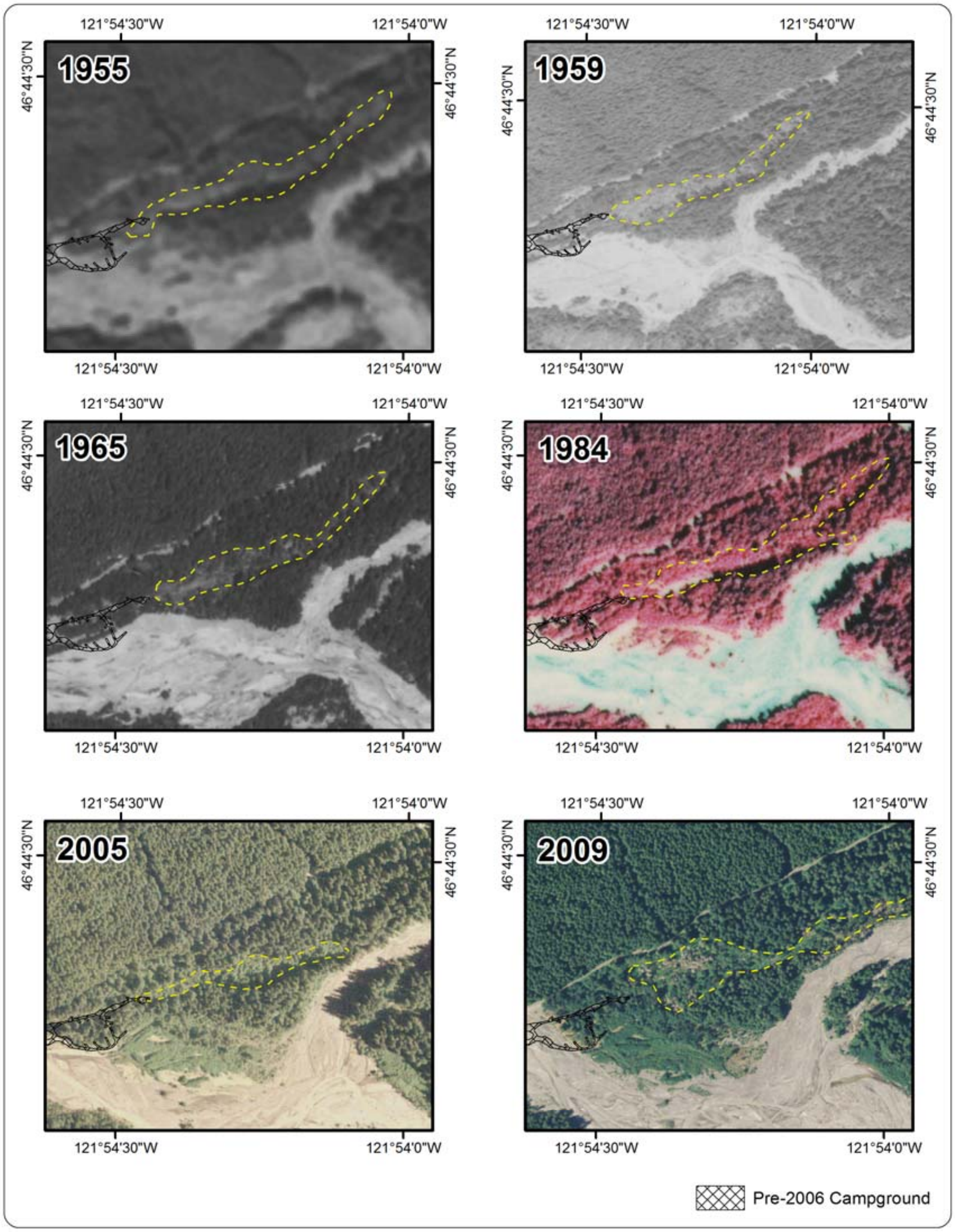

Figure 6. Aerial photographs and orthoimages from selected years. Avulsions west of the Tahoma Creek active channel (northeast-southwest channel) were identified by color and texture anomalies. Yellow dashed lines outline vegetation anomalies. The anomalies in the 1955 through 1965 images are similar in extent. In the 1984 and 2006 images, the anomalies change significantly from the previous images and connect lower Tahoma Creek to Sunshine Point. These anomalies are from new avulsions.

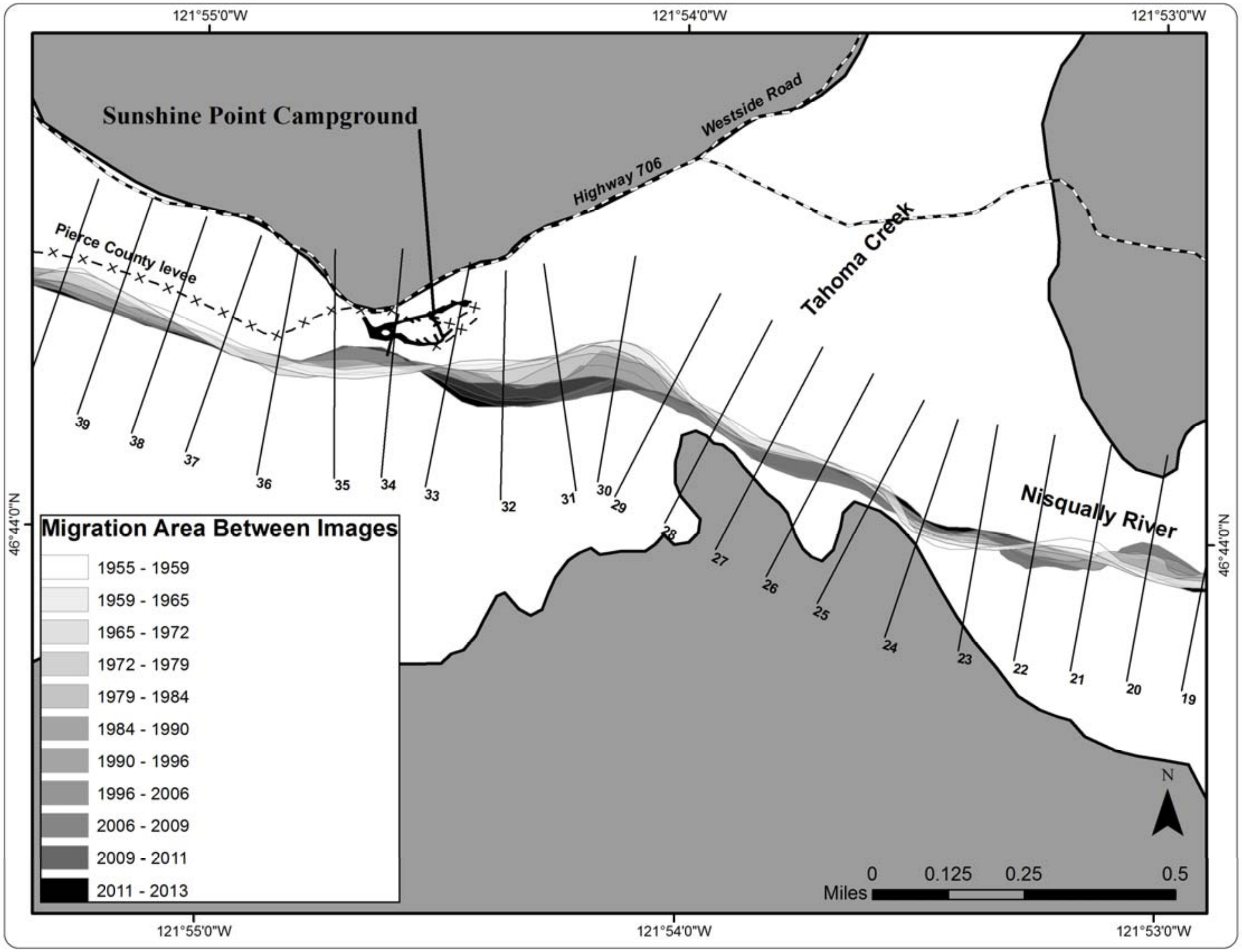

Figure 7. Map of centerline migration between images with shading representing the area across which the centerline has migrated in the specified interval. Transect numbers correspond to those plotted on Figure 8 and Figure 10. Sunshine Point Campground is shown between transects 33 and 35.

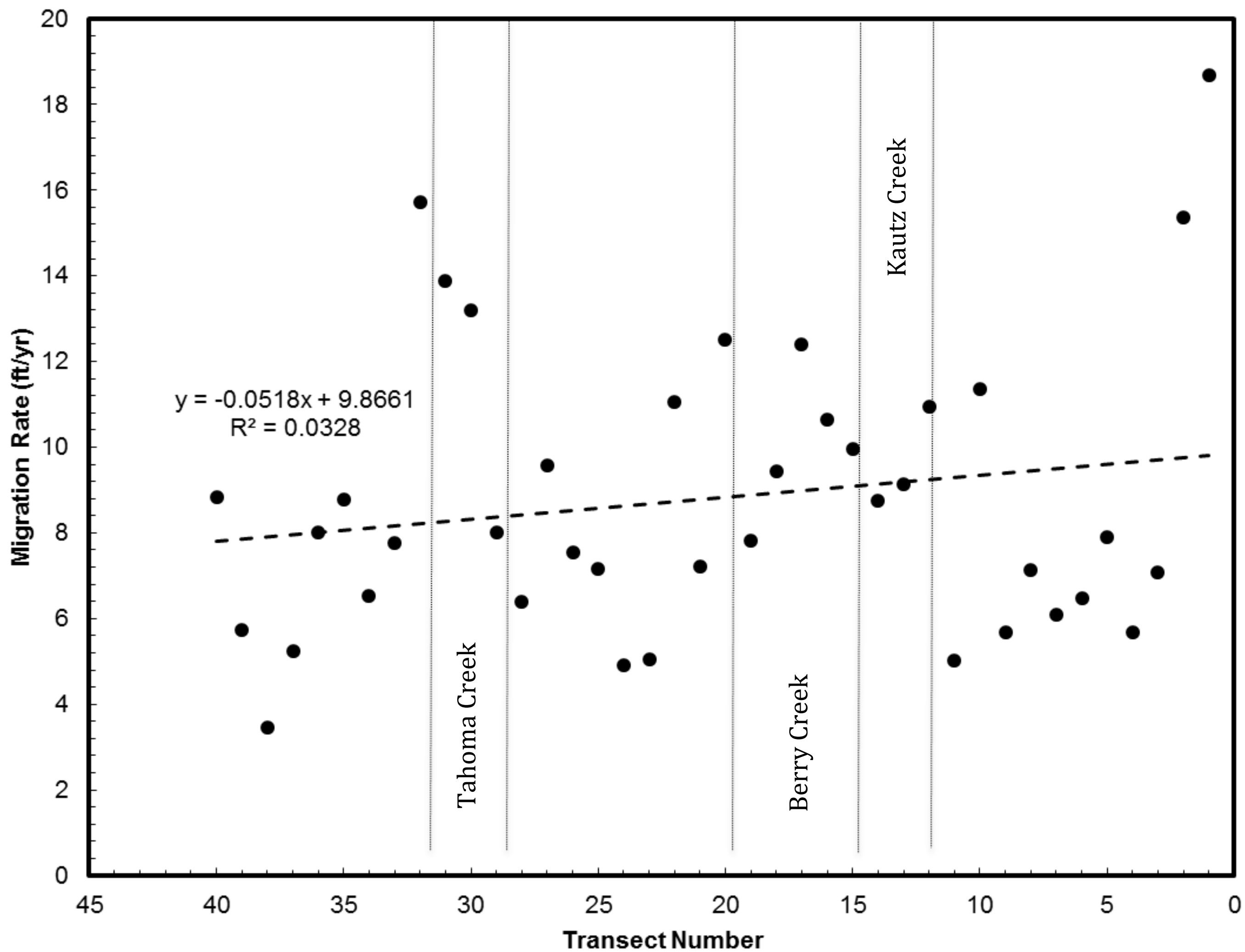

Figure 8. Migration rates along transects orthogonal to the valley centerline spaced every 500 feet along the study reach. Transects are numbered from east to west; transects 32 to 35 cross the Nisqually River at Sunshine Point. The best-fit linear regression shows a poor trend of increasing migration rates upstream, with poor R^2 correlation (0.03).

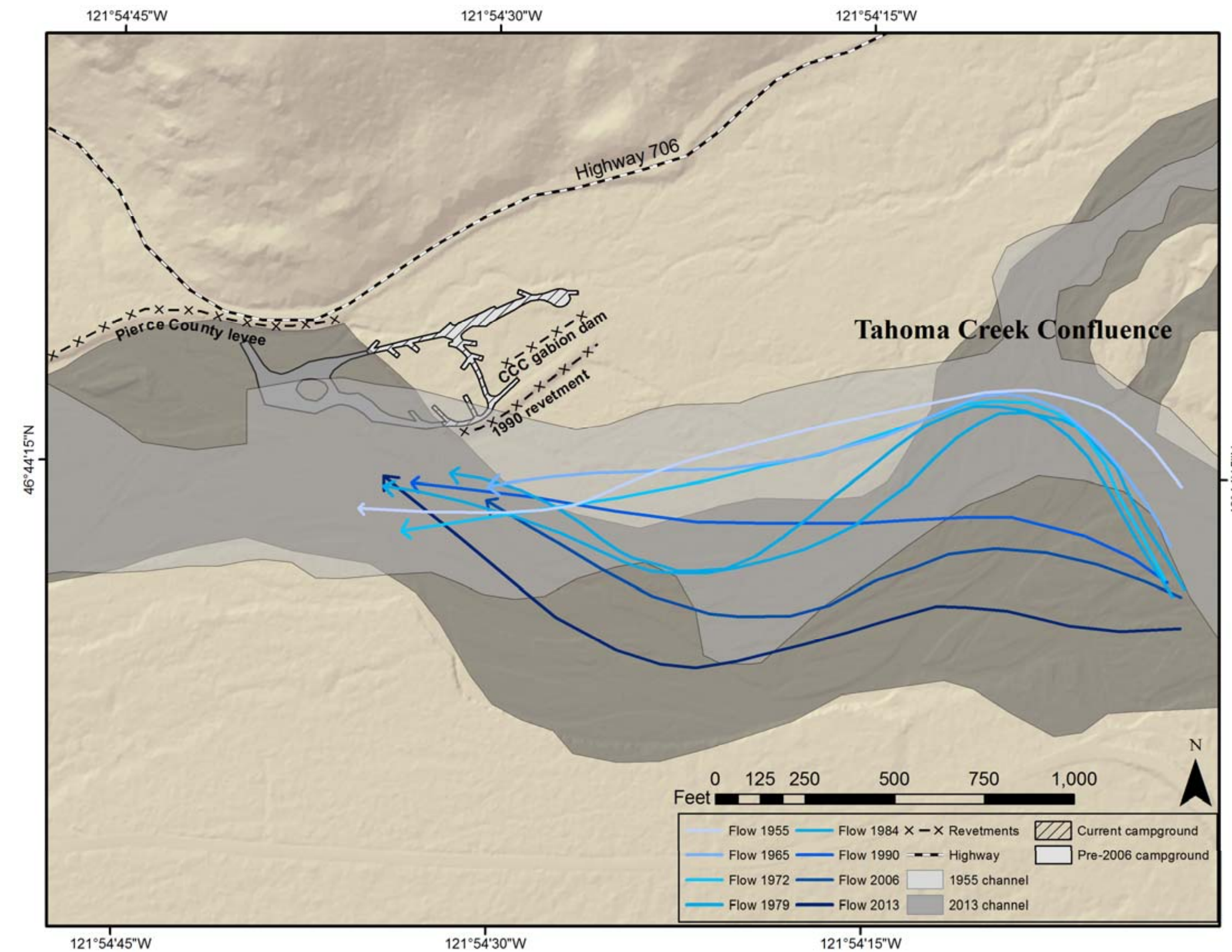

Figure 9. Topographic map of Sunshine Point with the river channel from the 1955 and 2013 aerial images. Blue lines represent flow direction during bankfull or greater flow conditions. Flow lines are roughly coincident with channel centerlines and show the direction of flow at the banks protecting Sunshine Point campground. The Tahoma Creek confluence with the Nisqually River moved approximately 400 feet south between 1955 and 2013 directing flow into Sunshine Point.

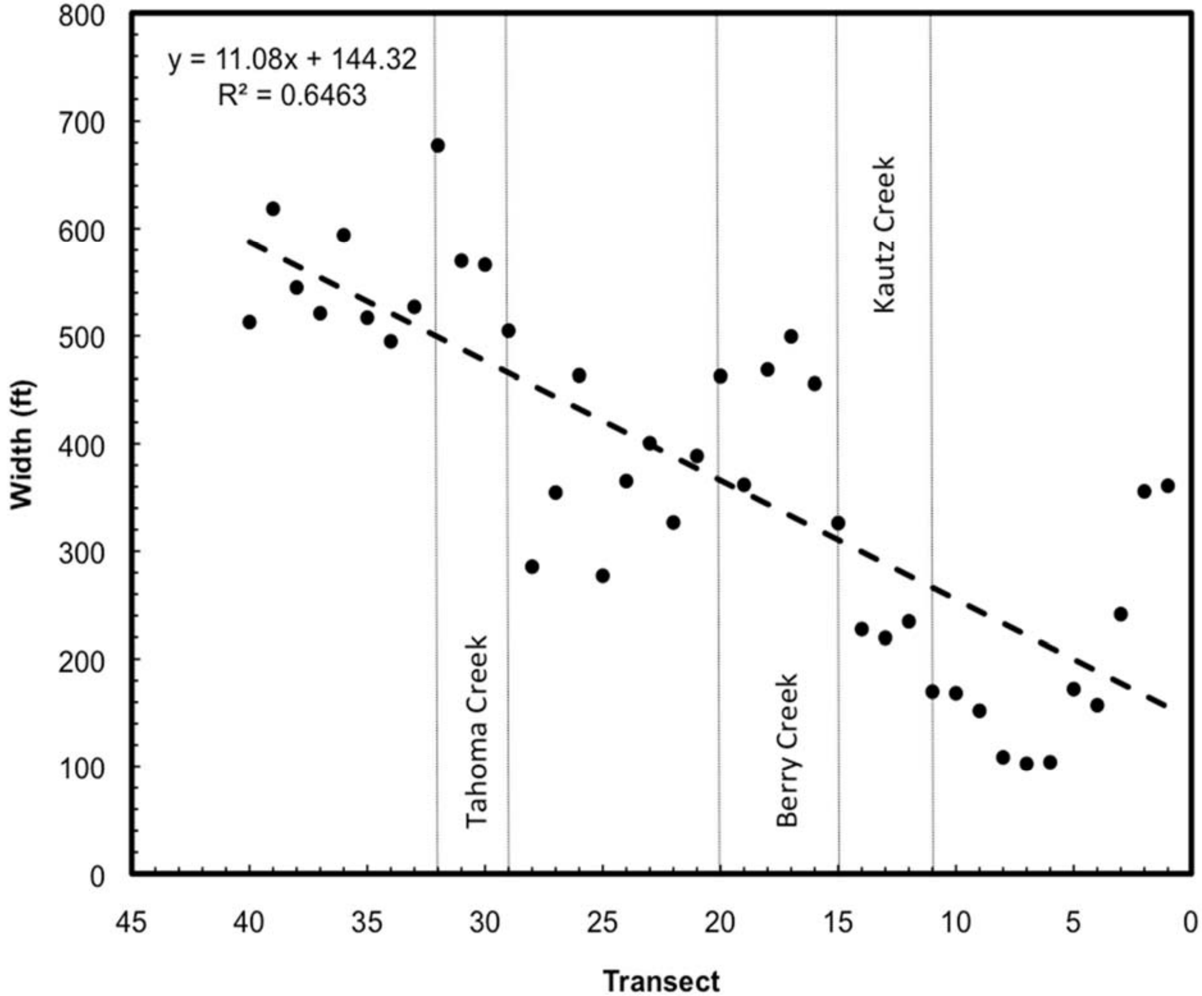

Figure 10. Average channel width between 1955 and 2013 at each transect orthogonal to the valley centerline and spaced every 500 feet along the study reach. Transects numbers increase from east to west along the study reach (downstream) with transects 32 to 35 crossing the Nisqually River at Sunshine Point. The linear regression shows a non-monotonic correlation with some greater than average widths correlated with river confluences. The below average widths at Kautz Creek may be the results of channel restriction from the 1947 debris flow.

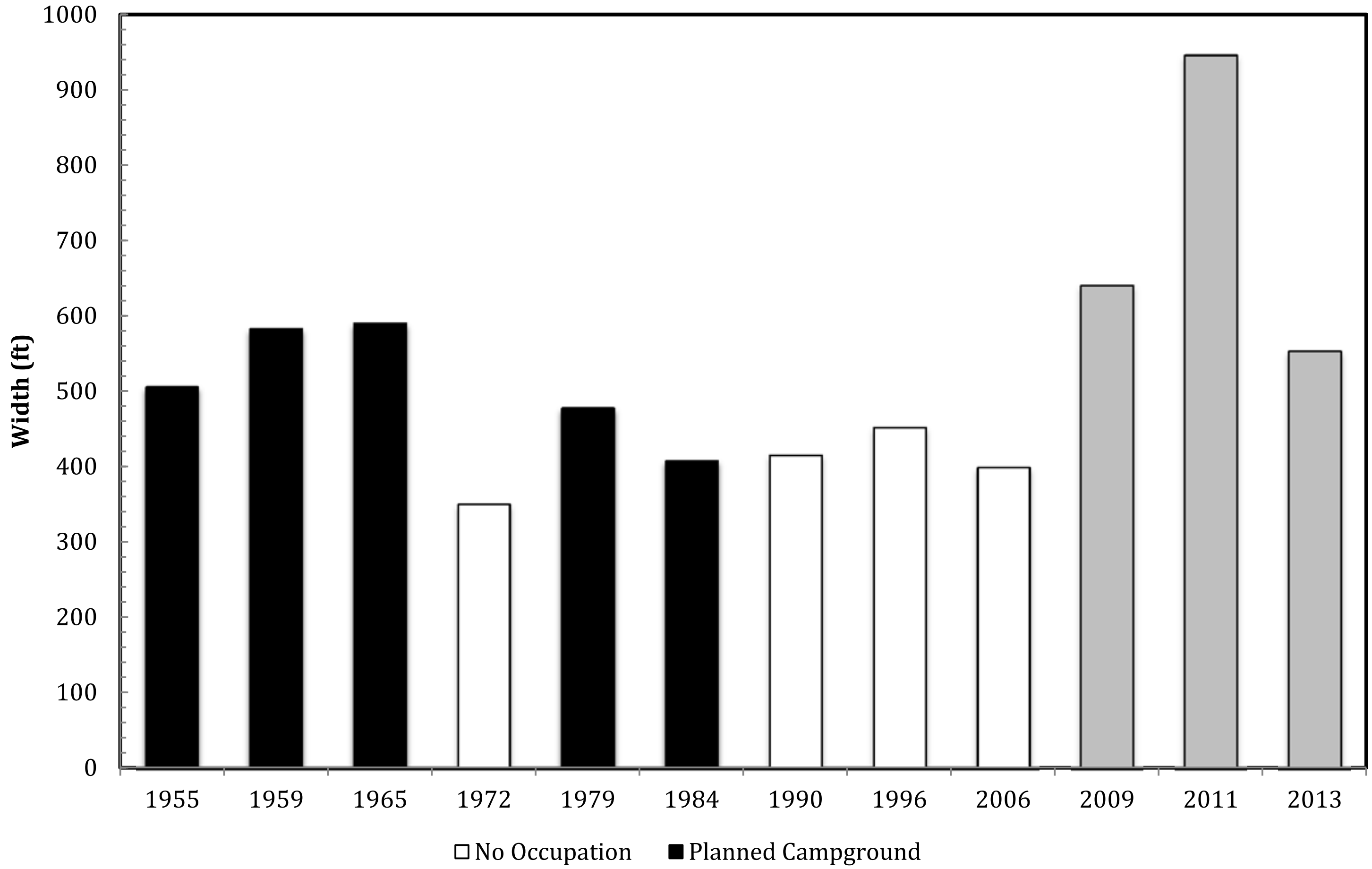

Figure 11. Active channel width in image year at Sunshine Point Campground (transect 33). Years that the Nisqually River has occupied the proposed campground are in black, years that the river occupied the pre-2006 campground are in gray; years that the river flow was restricted to the south are in white.

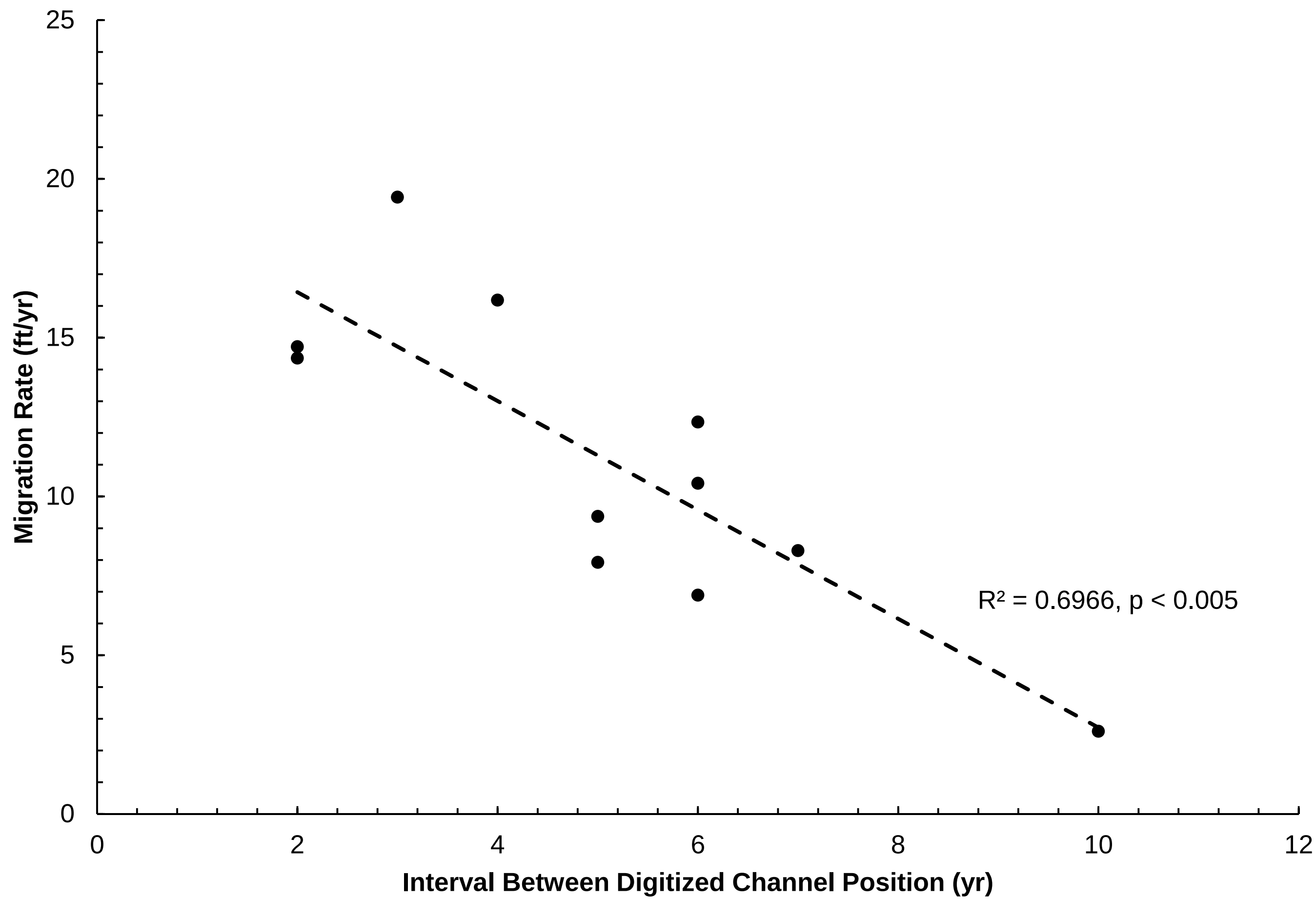

Figure 12. Scatter plot of annual reach averaged migration rates versus years between images with a best-fit linear regression. Mean interval is 5.3 years; median interval is six years (after O'Connor et al., 2002).

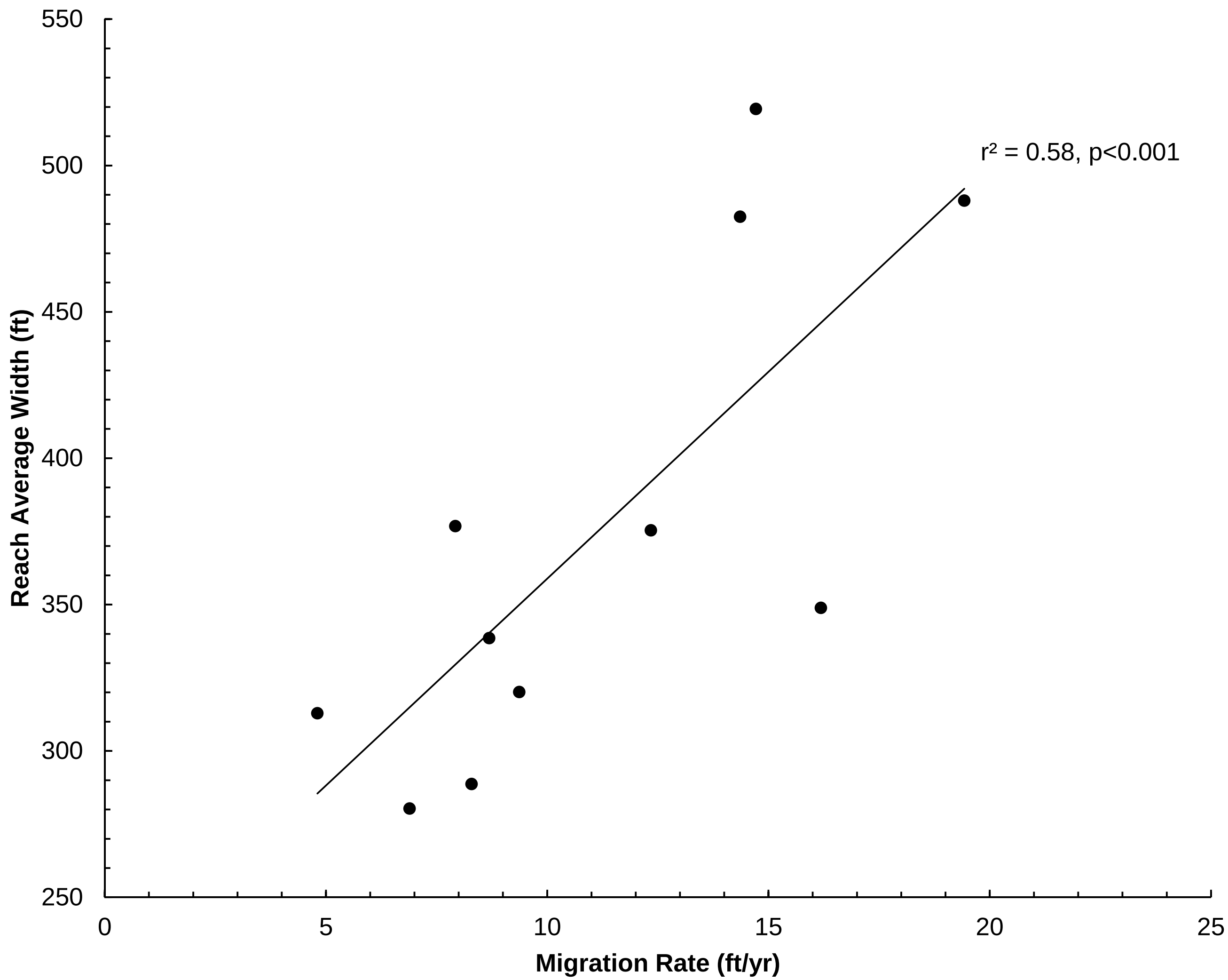

Figure 13. Active channel width versus centerline migration rate for each aerial image used in migration analysis. Width increases as migration rate increases along the study reach.

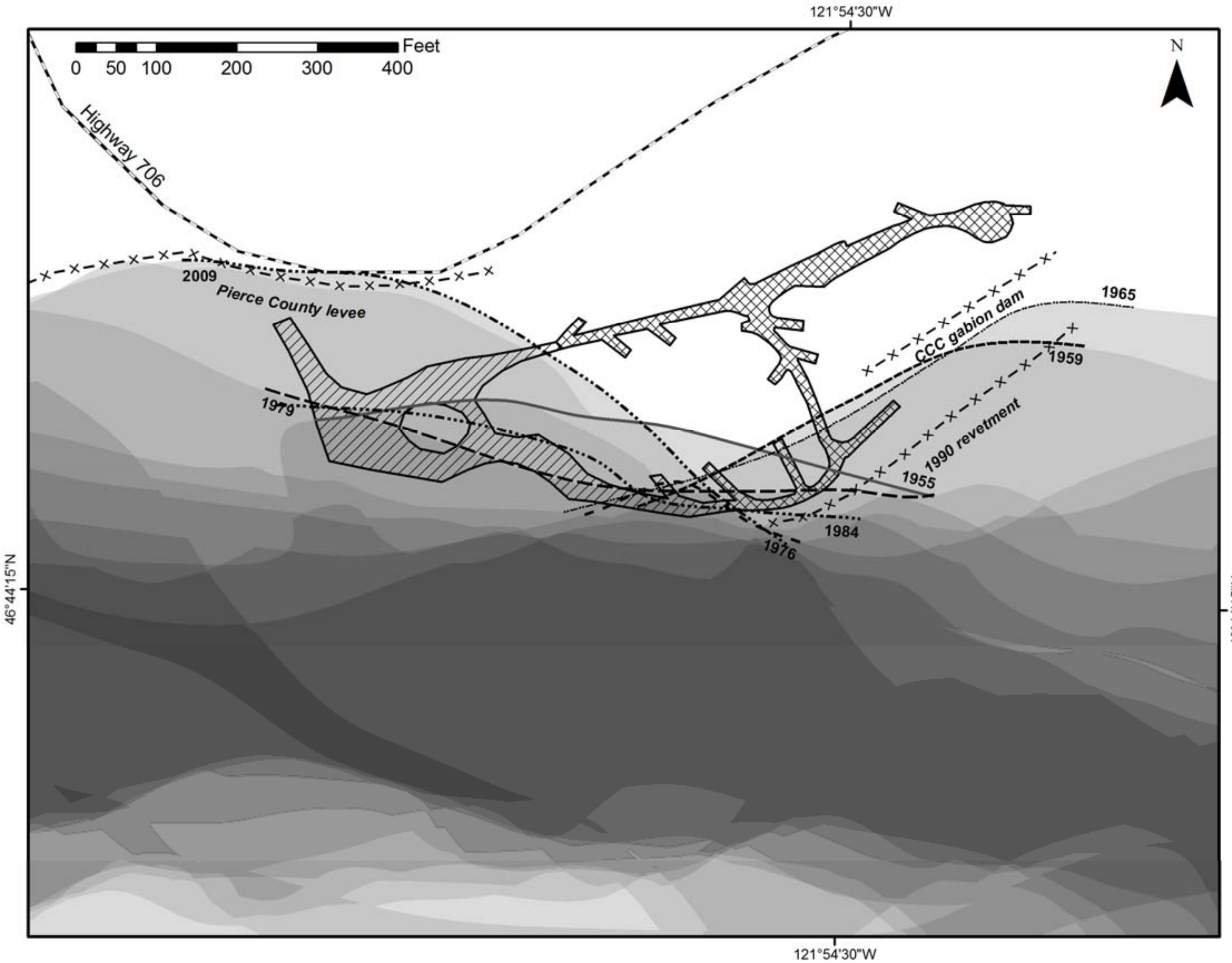

Figure 14. Occupation map at Sunshine Point. Remaining Sunshine Point campground infrastructure is shown (double cross-hatch) with the pre-2006 campground infrastructure (single cross-hatch). Dashed lines show the Nisqually River north bank in each year labeled. In 1959 and 1965, the north bank coincided with the 1938 CCC gabion revetment.

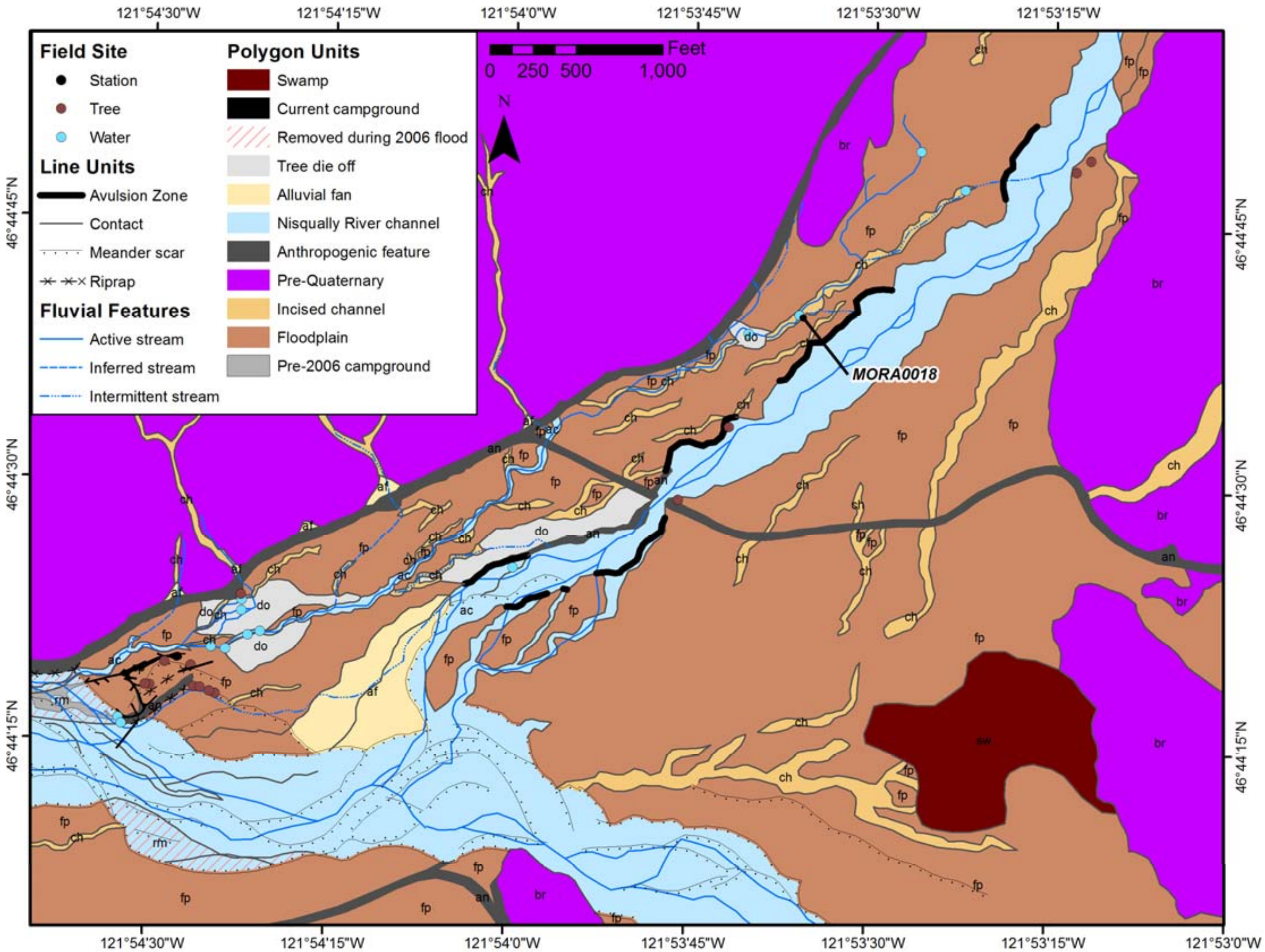

Figure 15. Geomorphic map of the Tahoma Creek fan compiled from fieldwork and 1-DEM analysis. All mapped channels on the Tahoma Creek west floodplain had some discharge or had evidence of alluvial deposits in them. Areas where Tahoma Creek has avulsed from the main channel are marked by bold black lines. Tree die-offs correspond channelized deposits and avulsion locations.

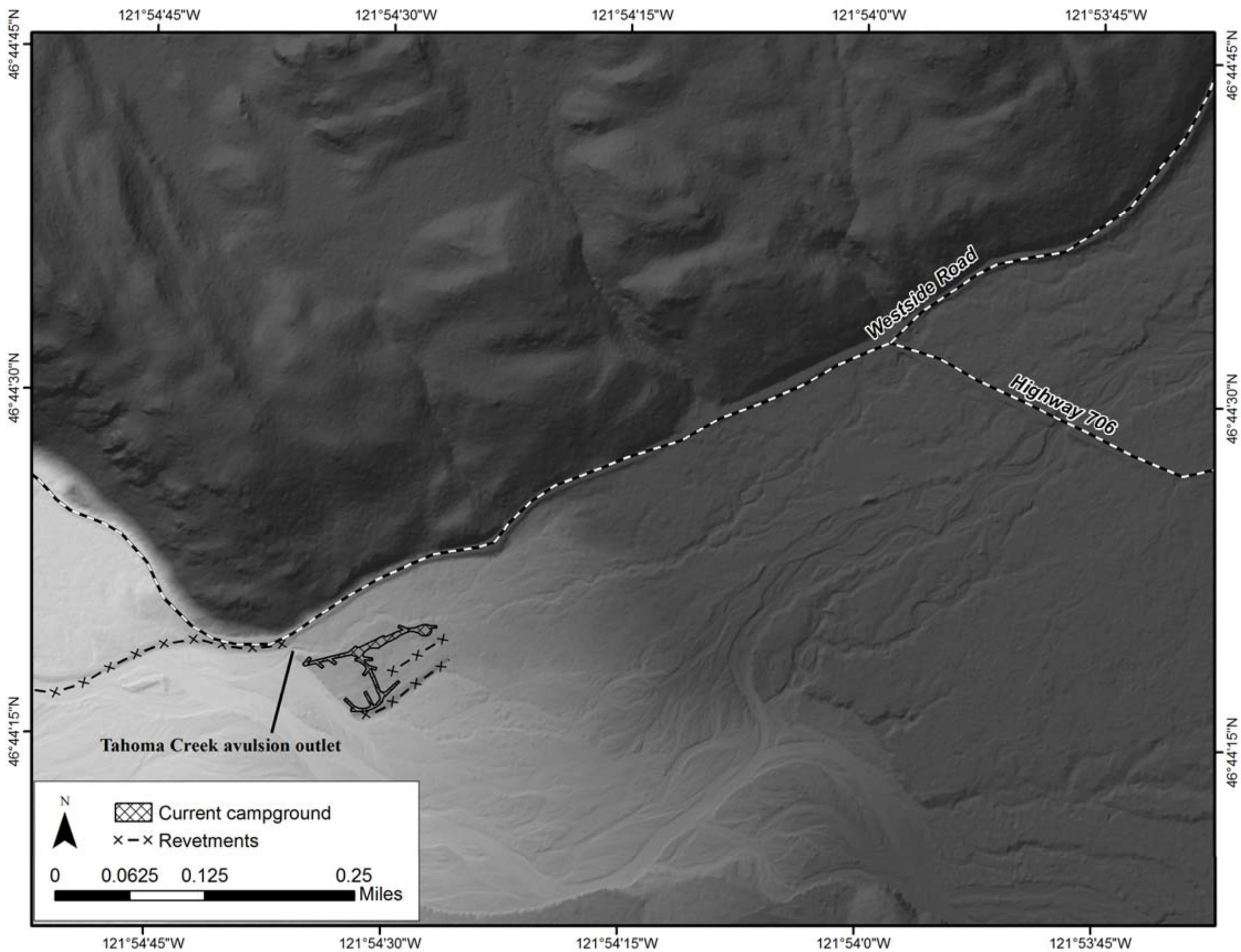

Figure 16. Tahoma Creek fan topography from 2009 1-meter LiDAR derived DEM. Avulsion channels are evident incised into the floodplain both east and west of the Tahoma Creek active channel. Tahoma Creek avulsion distributary re-enters the Nisqually River at the Tahoma Creek avulsion outlet.

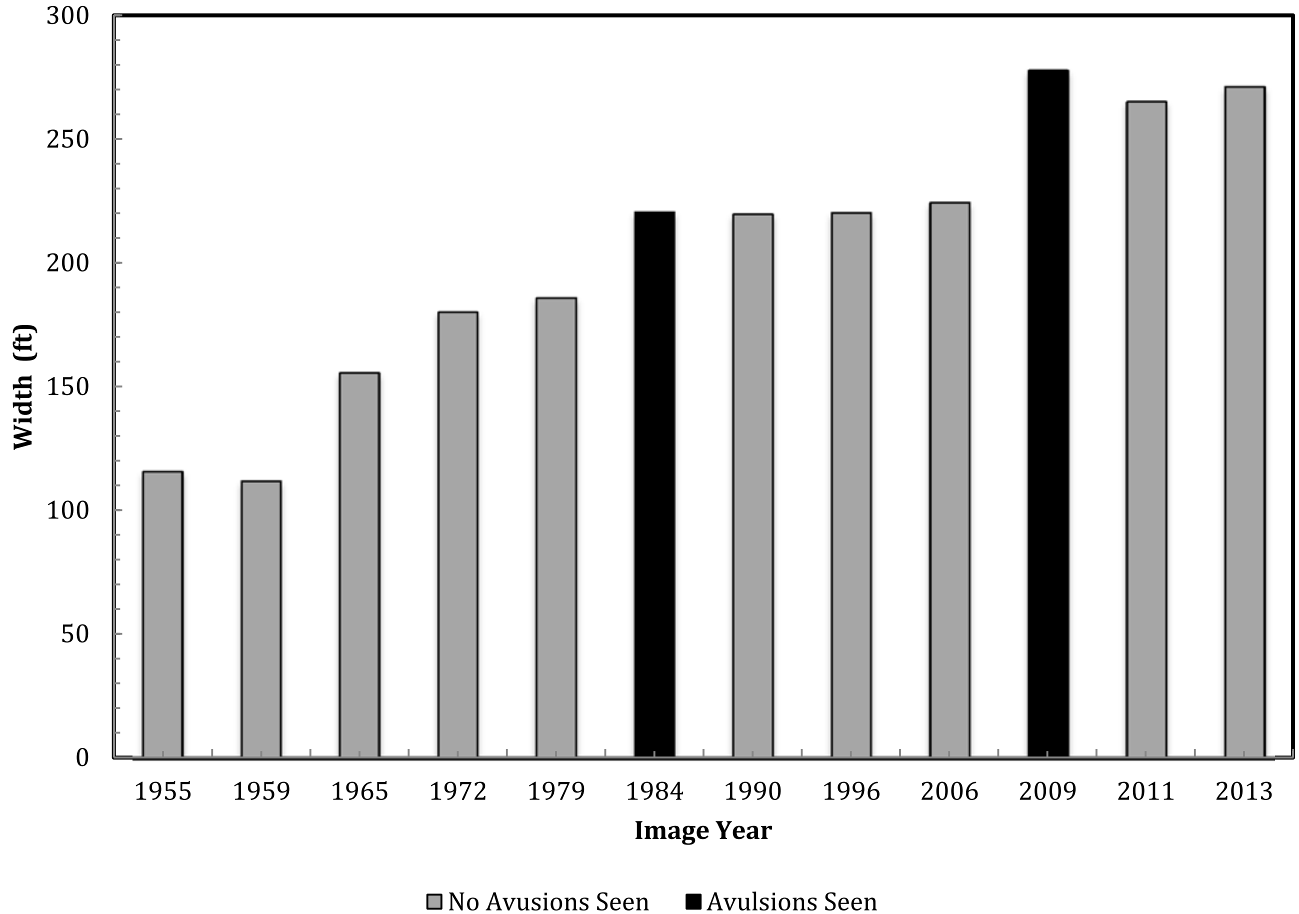

Figure 17. Tahoma Creek average channel width by image year. Width steadily increased between 1959 and 2009; 2011 was the first year since 1959 that average channel decreased. Images in which avulsions were seen occur after a period of relatively stable width (1972 to 1979) and (1990 to 2006).

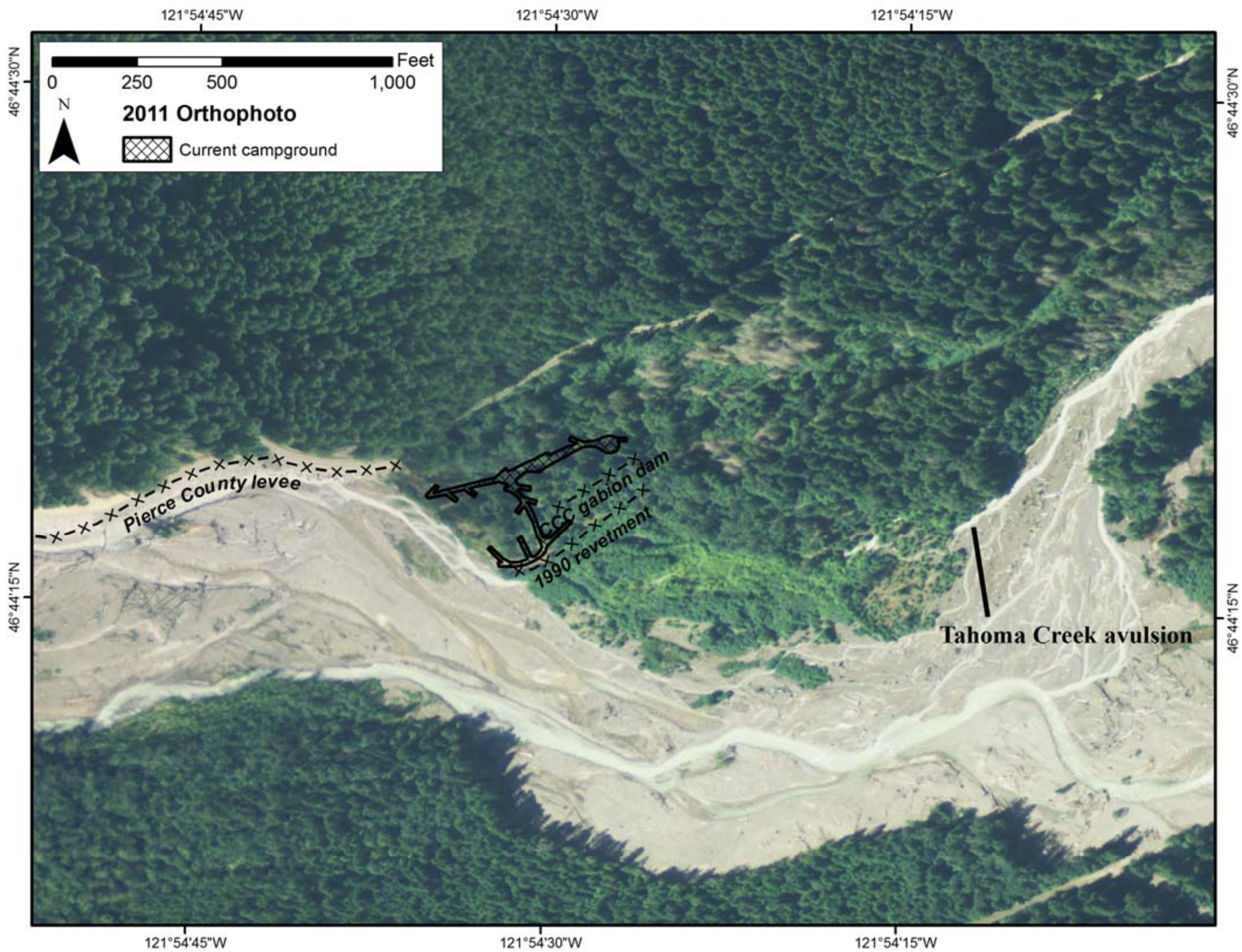

Figure 18. Orthophoto flown in 2011 shows Tahoma Creek avulsing from its channel 600 feet north of the Nisqually River confluence and flowing west toward the south boundary of Sunshine Point Campground. The avulsion flows along the south edge of the 1990 revetment and rejoins the main Nisqually River flow west of the image view.

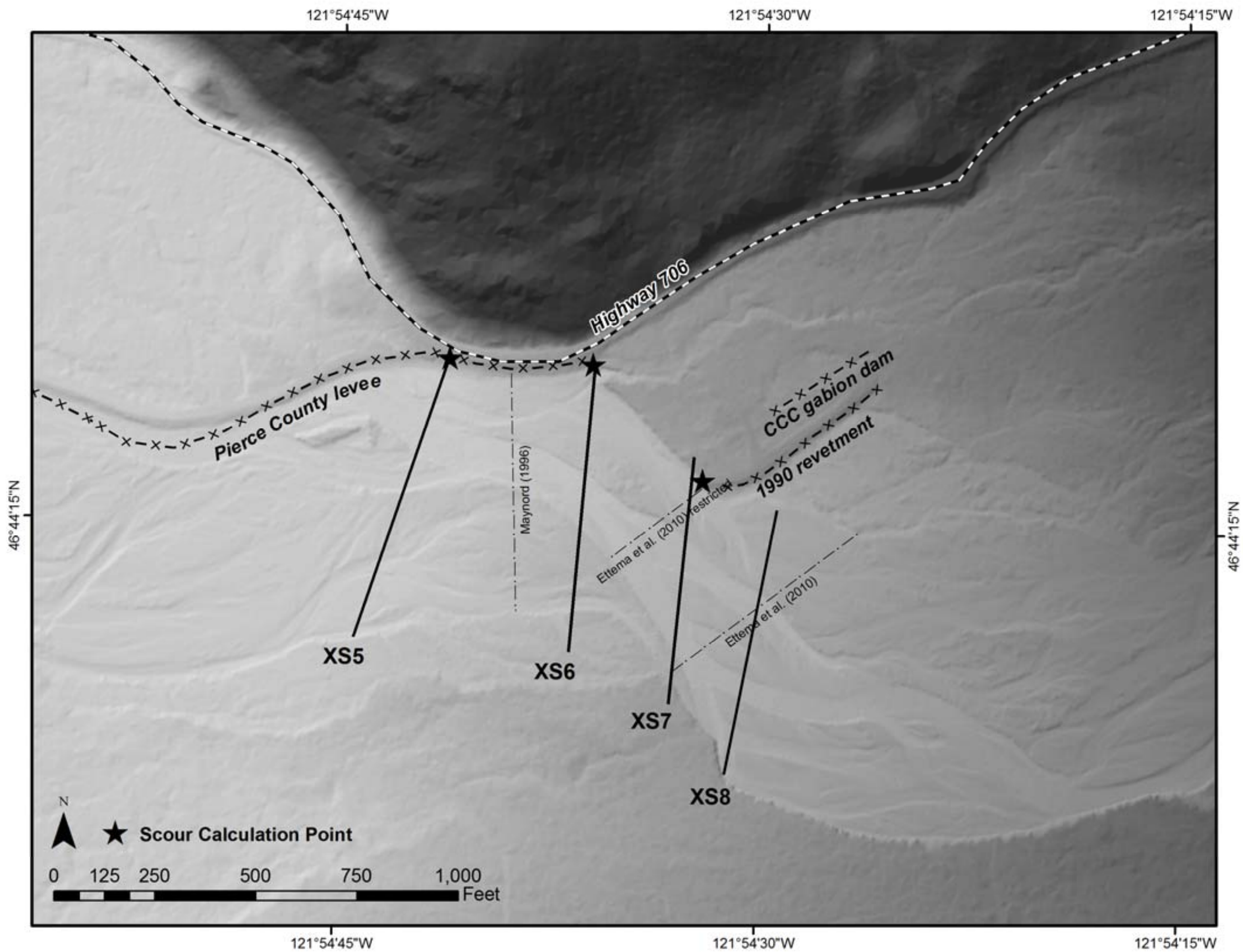

Figure 19. Channel geometry used for scour calculations with select cross-sections from Beason et al. (2014) and relevant infrastructure. Scour was calculated at the southwest tip of the 1990 rip-rap revetment, at the north end of XS 6 along Highway 706, and the north end of XS 5 where Highway 706 and the Pierce County levee meet.