National Park Service
U.S. Department of the Interior

Mount Rainier National Park
Ashford, WA

Geomorphic and Archaeological Study of the Ohanapecosh River: Estimating Anadromous Fish Distribution up to 7,000 Years Ago

ON THIS PAGE
Area where fish are re-introduced to the Ohanapecosh River in Packwood, WA, after being trucked above downstream dams.
Photograph by: April Kelly, NPS

ON THE COVER
Ohanapecosh River at the confluence of Carlton Creek.
Photograph by: April Kelly, NPS

Geomorphic and Archaeological Study of the Ohanapecosh River: Estimating Anadromous Fish Distribution up to 7,000 Years Ago

April Kelly[1,2], Paul Kennard[1]
[1]National Park Service
55210 238th Avenue East
Ashford, Washington 98304

[2]U.S. Army Corps of Engineers, Savannah District
100 W. Oglethorpe Ave
Savannah, GA 31401

April 2019

U.S. Department of the Interior
National Park Service
Mount Rainier National Park
Ashford, Washington

This report is available in digital format from the http://www.morageology.com/pubs.php

Please cite this publication as:

Kelly, A.L. and P. Kennard, 2019, Geomorphic and Archaeological Study of the Ohanapecosh River: Estimating Anadromous Fish Distribution up to 7,000 Years Ago to Aid Archaeological Investigations. Natural and Cultural Resources Publication, Geomorphology Program, Mount Rainier National Park Ashford, WA.

April 2019

Contents

Figures

Tables

Page

1. Introduction

The objective of this geomorphic study is to determine presence or absence of anadromous fish in the Ohanapecosh River during the early historic and pre-European contact periods up to 7,000 years ago. It does so by identifying fish barriers and habitat in the upper reaches of the Cowlitz-Ohanapecosh River watershed. Because anadromous fish were a critical resource staple for indigenous people in the Pacific Northwest for at least the last 4,000 years, information on salmonid presence and abundance in a watershed is important to developing accurate archaeological interpretations regarding site function and regional occupation patterns.

The present study area encompasses the confluence of the Ohanapecosh and Cowlitz Rivers (figure 1) near the southeast corner of Mount Rainier National Park (described in section 2, below). Anadromous fish species of particular interest include chinook, coho, and steelhead trout that existed in the project area prior to dam installation on the lower Cowlitz. Despite absence of clear visual evidence of major obstructions downstream of Silver Falls on the Ohanapecosh River, *Blue Hole* at the confluence with the Clear Fork Cowlitz River well downstream of Silver Falls appears to be the upper limit for fisheries as documented by historical research, the archaeological record, and Cowlitz Indian tribal members.

In this study, we develop a general approach that can be applied to a wide variety of river systems. This generic approach identifies operative landscape disturbance regimes (such as landslides or changing glaciers) that affect the geomorphic controls to fish presence or absence (such as physical fish blockages or unsuitable fish habitats), during the time-period of interest (centuries to millennia). This specific study identifies alpine glacial recession as the dominant disturbance type in the Ohanapecosh River canyon, and subsequent river incision over the last 7,000 years that exposed present-day fish barriers. The timing of barrier exposure is a key factor in determining whether or not anadromous fish were present or absent in the Ohanapecosh River. The research reveals that one true vertical barrier to fish passage, known as Slippery Falls, exists today. Based on our archeological, ethnographic, and geomorphic analyses, there were likely negligible anadromous fish runs beyond the current fish distribution (below Slippery Falls, near *Blue Hole*, Figure 2) starting at least 7000 years ago.

2. Study Area

2.1 Geographic Setting

The Ohanapecosh River is a part of the Upper Cowlitz watershed in southwestern Washington (Figure 3). It is located in both Mount Rainier National Park and the Gifford Pinchot National Forest, flowing southward for ~18 km until it merges with the Muddy Fork Cowlitz. The Cowlitz River at this confluence flows south and then westward for more than 140 km, entering the Columbia River at Longview, Washington (Riedel and Dorsch 2016).

The main focus of this project is a 9.5 km stretch of the Ohanapecosh River from Silver Falls within Mount Rainier National Park, downstream to *Blue Hole* at La Wis Wis Campground in Gifford Pinchot National Forest (Figure 1). Silver Falls, an 11.5 m waterfall within the park boundary, is a definite fish barrier to migrating salmonids (Figure 4). The project site continues

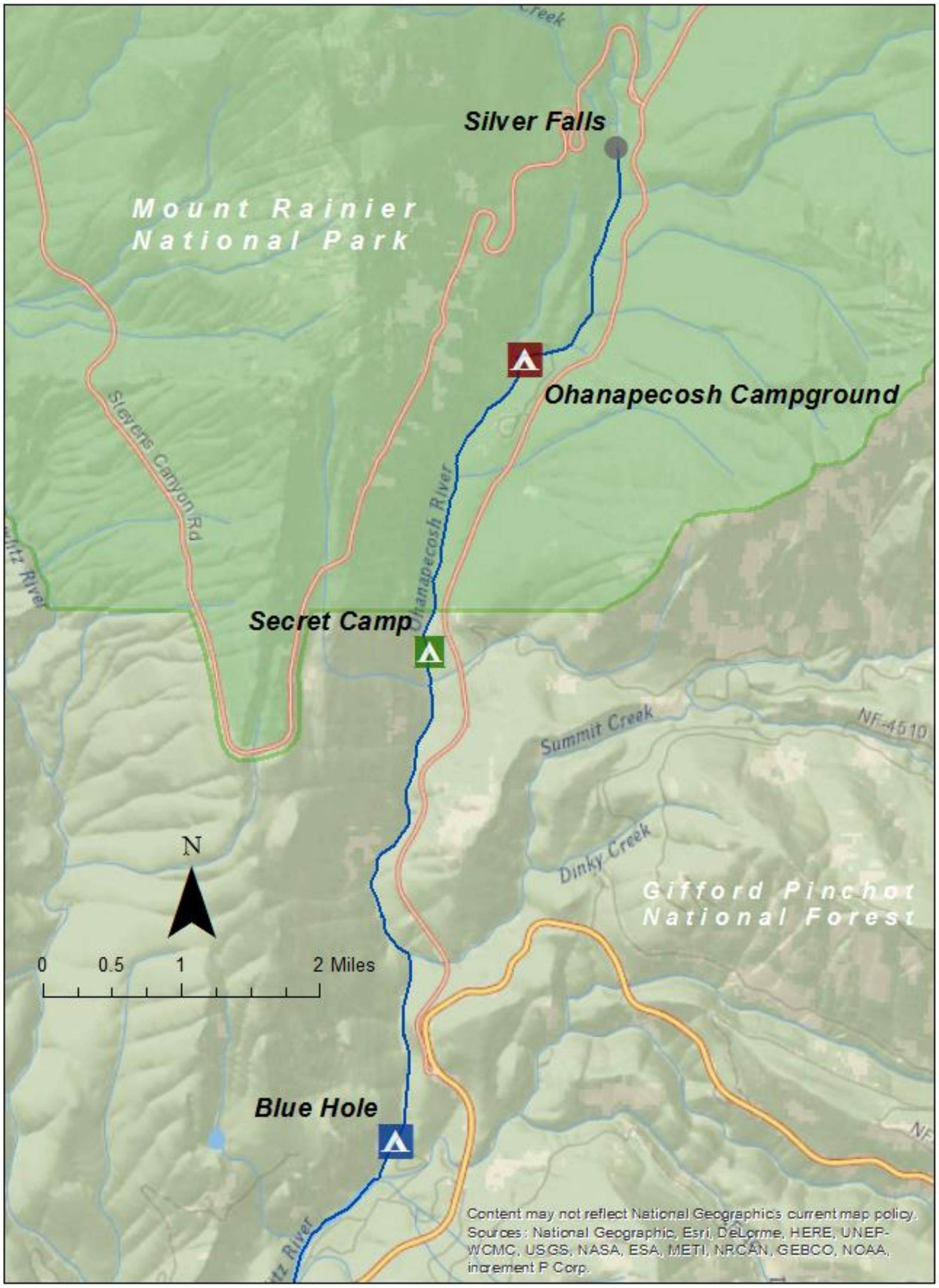


Figure 1. Map of the Ohanapecosh River project site, which extends from Silver Falls in Mount Rainier National Park, down to *Blue Hole* in Gifford Pinchot National Forest. River flows downstream to the south. Notable landmarks and access points include Secret Camp, in green, and the Ohanapecosh Campground in red.

downstream through the Ohanapecosh Campground at Mount Rainier, across the park boundary into Gifford Pinchot, past Secret Camp, and down to *Blue Hole*.

2.2 Anthropogenic Barriers

Anadromous fish that return to the Ohanapecosh River to spawn begin their journey in the Pacific Ocean. They migrate up the Columbia and Cowlitz Rivers before reaching the Ohanapecosh. Their migratory paths, however, were altered beginning in the 1960s with the construction of Mayfield Dam by Tacoma Power. Mayfield Dam, forming Mayfield Lake, was installed in 1963, followed by Tacoma Power's Mossyrock Dam, forming Riffe Lake, in 1968. The Lewis County Public Utility District (PUD) then built Cowlitz Falls Dam in 1994 (Figure 5), forming Lake Scanewa. Neither dam incorporated fish-ladders nor other technology designed to ensure unfettered anadromous fish passage. Rather, salmonids are brought up from the Cowlitz Salmon Hatchery, two miles downstream of Mayfield Dam, and dropped off at a stocking location in Packwood, WA (Paulu 2010) (Figure 5). Some fish runs are also brought to Lake Scanewa in an effort to allow the fish to self-select their migratory run; either ascending the Upper Cowlitz River and potentially to Ohanapecosh, or the Cispus River (Murphy 2017).

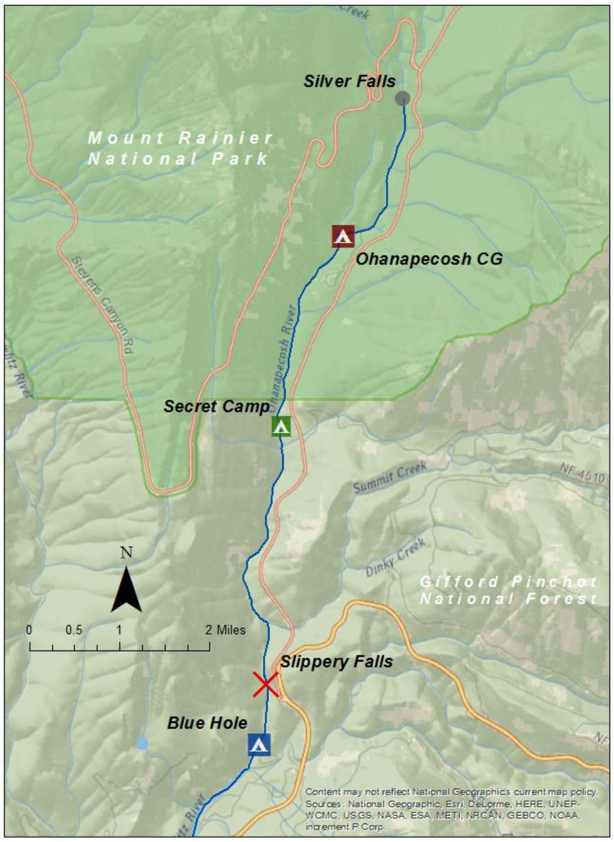


Figure 2. Location of Slippery Falls, a series of waterfalls recognized as the upper extent of current salmonid distribution, 0.5 miles upstream of *Blue Hole*.

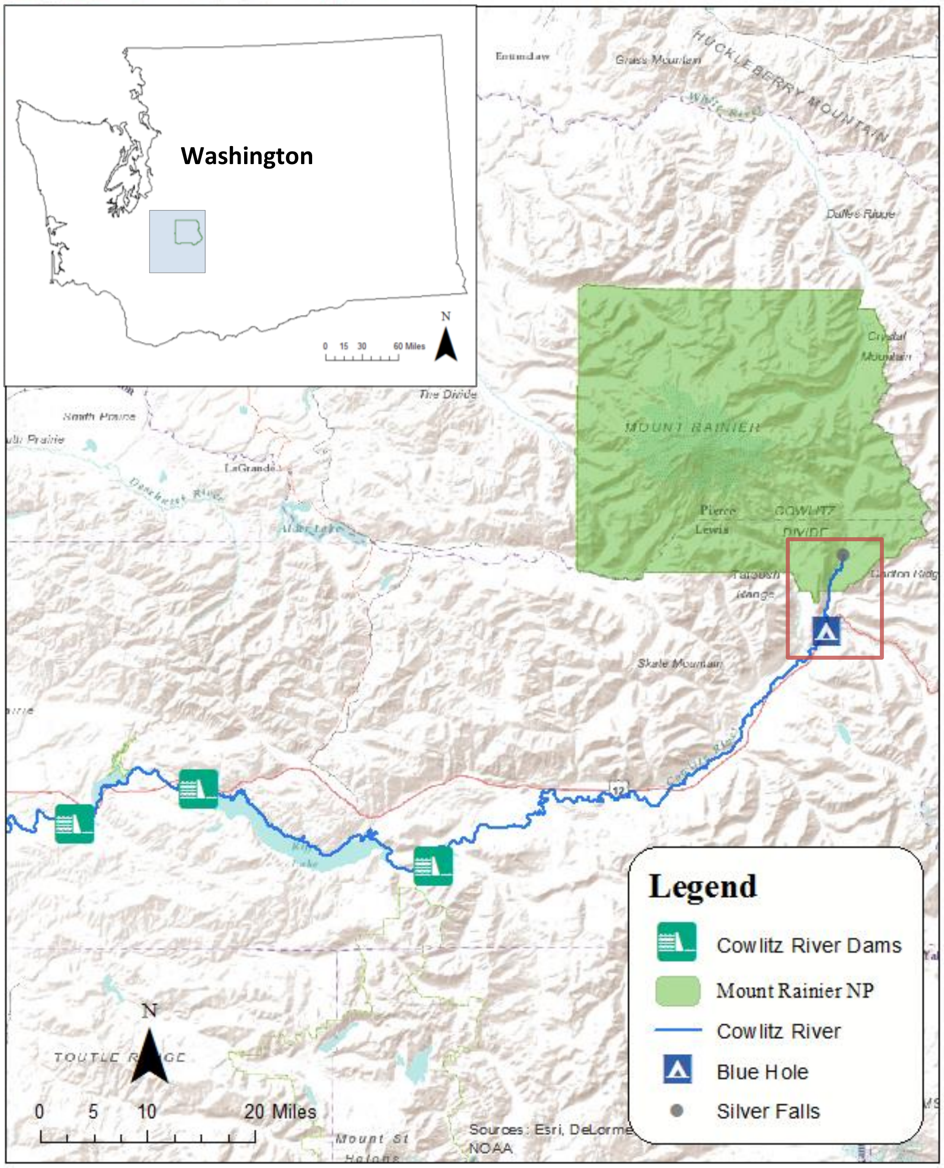


Figure 3. Map of the Cowlitz River in southwestern Washington, with the Ohanapecosh River and project site location, boxed in orange. The upstream half of the project site resides in Mount Rainier National Park. The Cowlitz River Dams are denoted along the Cowlitz, downstream of the Ohanapecosh River.

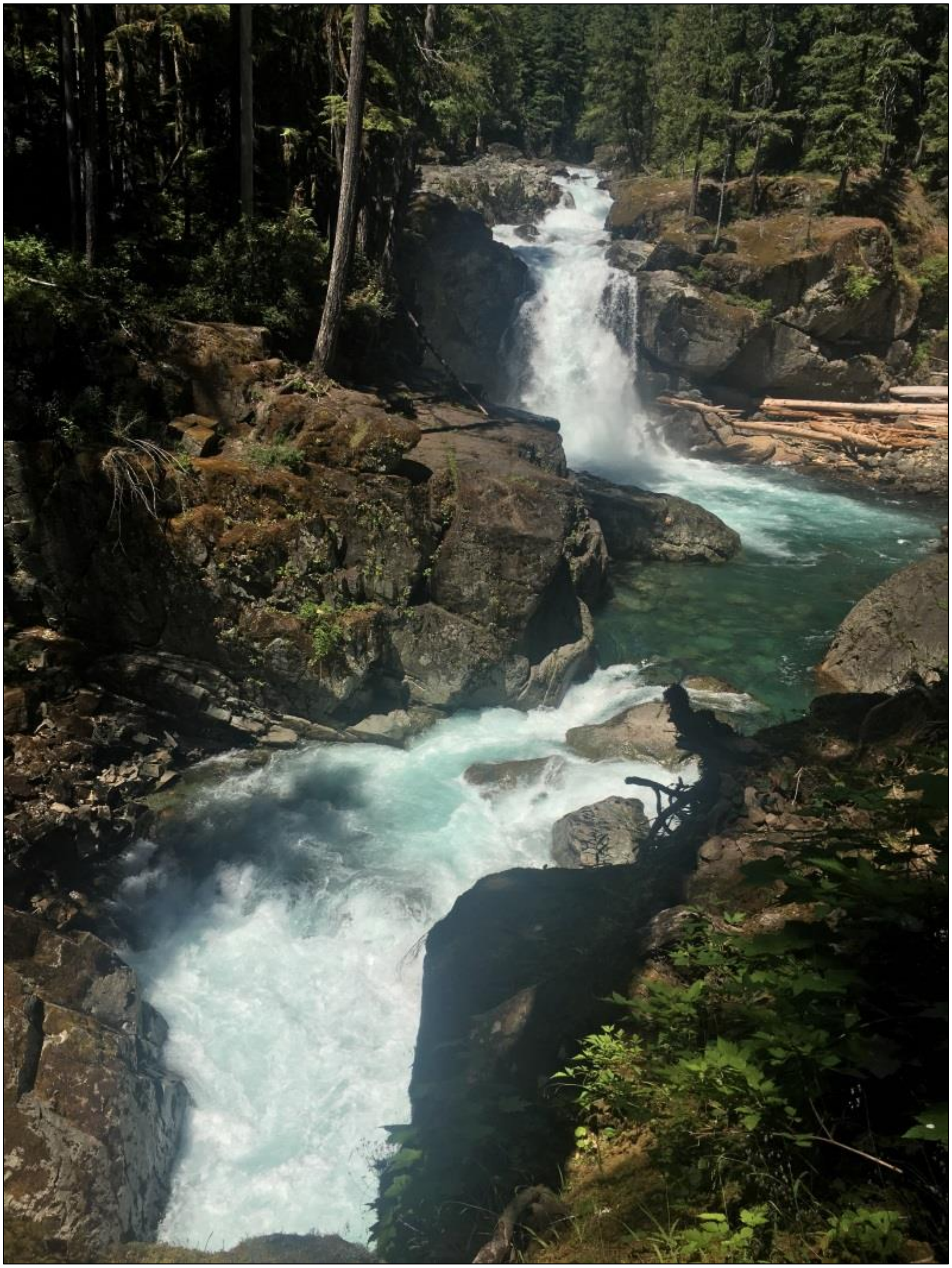


Figure 4. Photo of Silver Falls, an 11.5m vertical waterfall located in Mount Rainier National Park, and the upper limit of the project area. NPS photo.

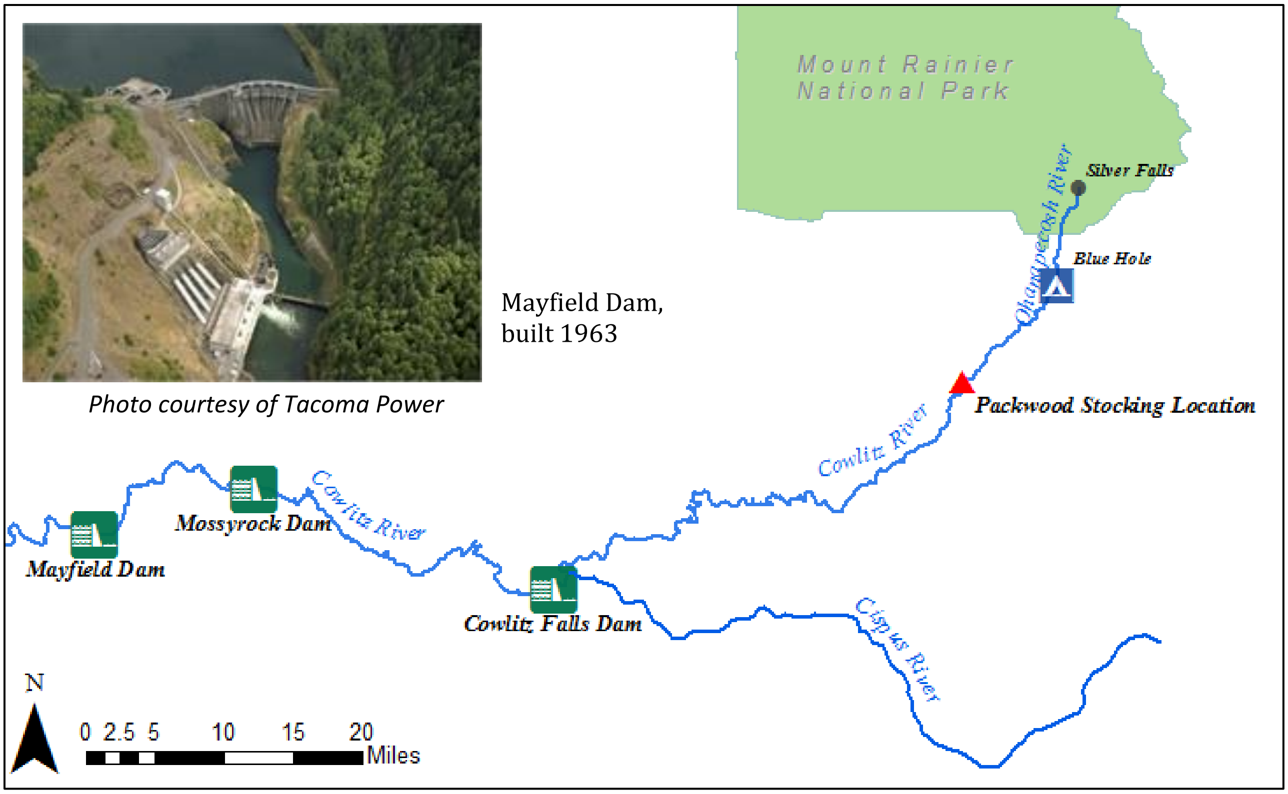


Figure 5. Map of the three Cowlitz River Dams and the stocking location in Packwood, WA where anadromous fish are brought up to continue their migratory ascents.

2.3 Ohanapecosh River

The Ohanapecosh River is the largest river in the park where the headwaters do not solely begin on Mount Rainier's flanks (Riedel and Dorsch 2016) (Figure 6). Tributaries on west side of the river are glacially-sourced by the Ohanapecosh and Fryingpan glaciers, which are at their historic minimum areal extent and continue to waste away, interconnected by withering snowfields and ice lobes (Riedel and Dorsch 2016). Most tributary headwaters of Ohanapecosh, however, originate in the Cascade Mountains to the east of Mount Rainier, and are not glacially sourced. In contrast, other park rivers are glacial-sourced rivers and are sediment transport limited and aggrading (Beason and Kennard 2007).A sediment transport limited river is one where the amount of sediment in the river exceeds the ability of the river to transport it downstream. Conversely, the Ohanapecosh River is sediment limited since much of the watershed is not glacier-sourced, and is less extensively mantled with glacial deposits.

In addition to being sediment limited, the Ohanapecosh River is the most confined of all the other major Mount Rainier rivers (Figure 7). (River channel confinement is a measure of the valley width relative to the river width.) The Ohanapecosh River has highest percentage of valley wall of any river in the park (71%) and a lowest percentage floodplain (0.7%) (Riedel and Dorsch 2016) (Table 1), consistent with its high level of valley wall confinement.

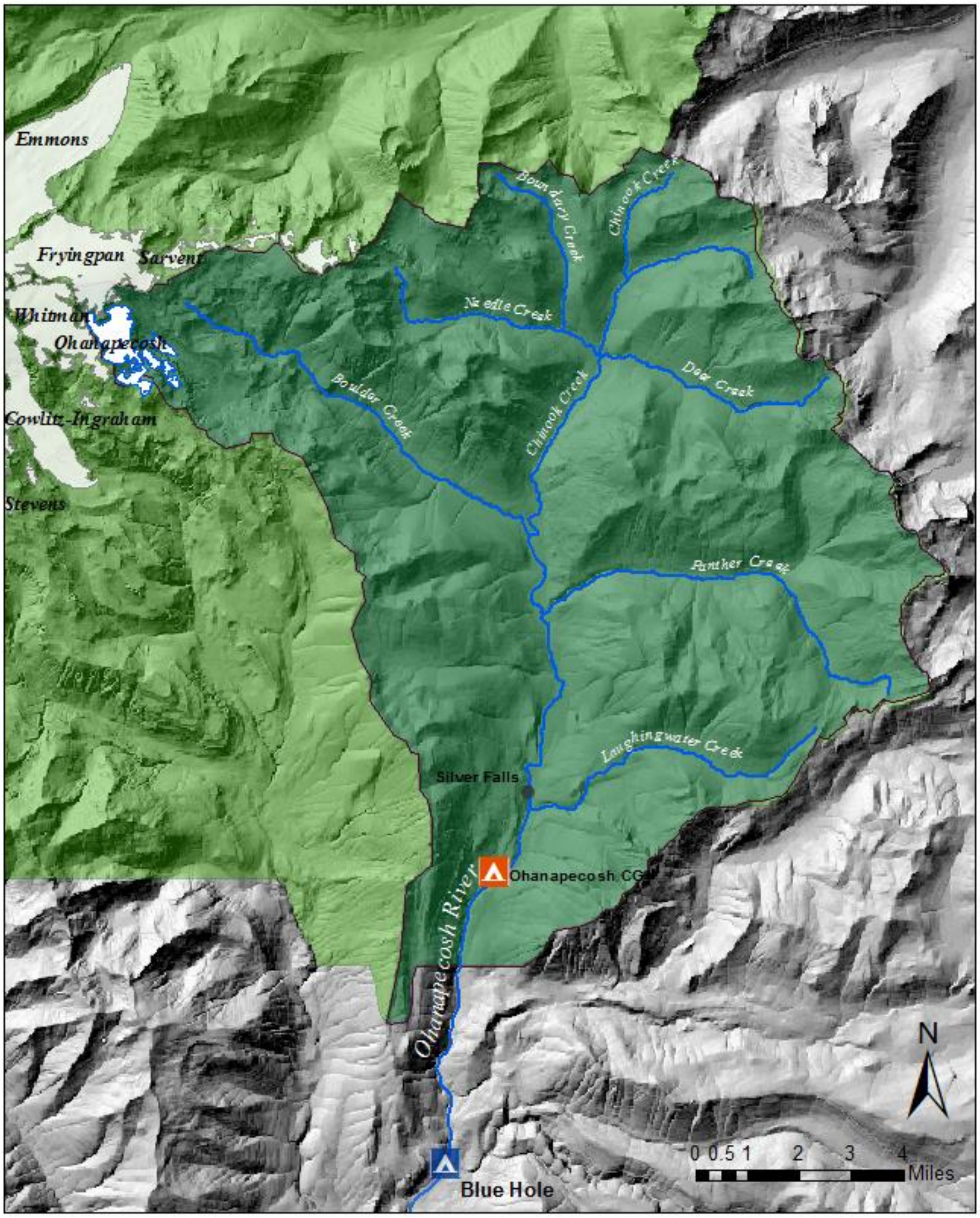


Figure 6. Map of the Ohanapecosh River watershed within Mount Rainier National Park, with connecting tributaries. The upper extent of the project area, Silver Falls, is denoted by a grey marker; the lower extent, *Blue Hole* by a blue camp sign; and the Ohanapecosh Campground by an orange camp sign. Glacially sourced sediment originates from the Ohanapecosh and Fryingpan glaciers to the west, and most other headwaters and nonglacial sources originate from the east, outside of park boundaries.

Figure 7. View of the Ohanapecosh River looking downstream towards Ohana Falls, a classic example of its confined and sediment limited character. NPS photo.

Table 1. Percentages of valley walls and flood plains of major river watersheds within Mount Rainier National Park (Riedel and Dorsch 2016).

Watershed	% Valley Wall	% Floodplain
Ohanapecosh	**71**	**0.7**
White	53.6	2.42
Puyallup	52.4	1.56
Carbon	47.2	5.28
Muddy Fork Cowlitz	45.5	1.1
Nisqually	40	3.57
Mount Rainier NP	**50.6**	**2.3**

2.3.1 Geomorphic History: Lahars and Lava Flows

Volcanic mudflows and lava flows could have prevented fish from ascending the Ohanapecosh River if deposited within the Ohanapecosh River itself. In the past 7,000 years, neither lava flows nor lahars significantly affected the project area (Vallance, personal communication, 2017). The Cowlitz watershed in general was less affected by lahars, lahar runout flows, and lava flows in comparison to other Mount Rainier rivers like the White River on the northeastern flank of Mount Rainier, and the Nisqually River on the southwestern side of the mountain.

Lava flows have erupted from Mount Rainier and built the summit cone within 5,600 years, yet likely did not influence the project site (Vallance, personal communication, 2017). Additionally, there is no evidence of lava flows within the last 7,000 years in the Ohanapecosh watershed from *Blue Hole* to Ohanapecosh Campground.

There were no major lahar events documented within the last 7,000 years that impacted the geomorphology of the Ohanapecosh River. Several small-scale lahars have been deposited upstream of the project area and further downstream via Muddy Fork (Scott and others 1995; Crandell 1971; Vallance, personal communication, 2017). However, these deposits are on the order of a small debris flow, likely having little to no influence on the project site (Vallance, personal communication, 2017).

Debris flow deposits, however, are known to locally create or influence aquatic habitat (Montgomery and others, 2003). Small local storm-driven debris flows can and have occurred, modifying salmonid habitat in the short term, in areas where salmon was present. The most recent debris flow (2006) was upstream of the study area (Legg 2013).

2.3.2 Late Pleistocene – Holocene Glaciation History

During the Pleistocene, the Cordilleran Ice Sheet extended from northern latitudes, sending ice lobes south into Washington State. The Puget lobe of this ice sheet reached its maximum extent 15,000 – 14,000 years ago, where it stopped about 15 miles south of Olympia (Pringle 2008), and did not directly affect the project area. The greatest extent of the Cascade Range alpine glaciers was 20,000 – 16,000 years ago (Crandell and Miller 1974). The most recent major alpine glaciation, known as the Evans Creek glaciation, a substage of the regional Fraser Glaciation, lasted from about 22,000 – 15,000 calibrated (cal.) yr before present (BP). (Radiocarbon dated years are converted to calendar years by calibration.)

The alpine glaciers originating in the highlands of Mount Rainier extended down the Cowlitz River about 38 miles, reaching at least 10 miles west-southwest of Randle, WA (Pringle 2008) (Figure 8). A Late Pleistocene moraine is located at the park boundary (Riedel and Dorsch 2016), indicating an alpine glacier covered half of the project area upon its retreat.

Alpine Pleistocene ice deposits on Mount Rainier are less well known, as they have not been studied in as much depth as the continental ice sheet deposits. Even so, a small ice advance, known as the Late Pleistocene McNeeley advance (12,000 – 10,000 years ago) is documented south of McNeeley Peak (Crandell and Miller 1974). This advance is congruent with the Younger Dryas (12,900 – 11,700 years ago), a marked cold period in Earth’s climatic history. It’s possible an advance in Ohanapecosh also occurred during this time. However, any evidence in the river valley of this advance (if it occurred) has likely been washed away.

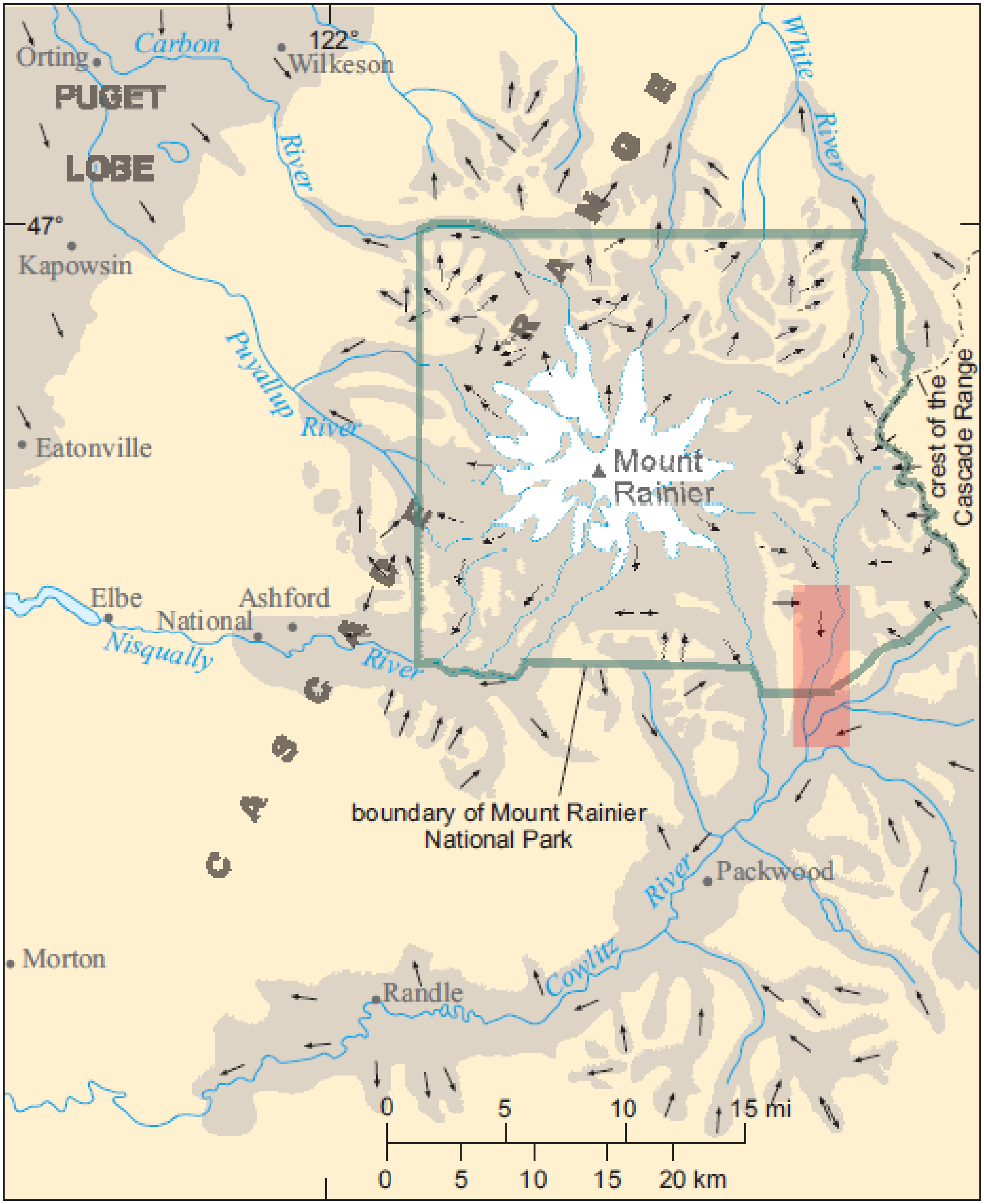


Figure 8. Alpine glacier extents at Mount Rainier and locally surrounding mountains during the most recent major glaciation. Late Pleistocene alpine glacier extents at Mount Rainier and locally surrounding mountains shaded in grey. The study area from *Blue Hole* to Silver Falls is shaded in red. Arrows show glacier flow direction, and white areas indicate today's glaciers. The Puget lobe is shown in the northeast. Adapted from Pringle (2008).

Minor glacial advances within the last 6,000 years, known as neoglacial advances (Riedel and Dorsch 2016) would have been the most influential to the Ohanapecosh project site within the last 8,000 years, potentially impacting the vegetation and geomorphology of the region, as well as pre-contact subsistence and settlement patterns. The two most studied advances are 2,800 – 2,600 years ago, and the Little Ice Age (LIA), from about A.D. 1450 until the about 1900 (Riedel and Dorsch 2016). During the LIA, Pringle (2008) notes that glaciers at Mount Rainier were thicker and generally extended about one mile farther down river valleys than they do today. Based on neoglacial moraines mapped in the Ohanapecosh watershed, the Ohanapecosh glacier appears to extend at least a half mile further downstream than today (Riedel and Dorsch 2016). In any case, the Ohanapecosh neoglacial advances did not affect the study area directly.

2.3.3 Geologic History

The geology of the project area is characterized by coarse volcanic clastic rocks, lava and mudflow deposits, and sparse rhyolites of the Ohanapecosh Formation, Eocene in age (Fiske and others,1963). Rocks of this formation underlie most of the eastern portion of Mount Rainier National Park and are older than the modern Mount Rainier volcano itself (Fiske and others, 1963, Pringle 2008). Massive and locally columnar andesite flows are seen along the Ohanapecosh River, along with locally voluminous mudflow breccias containing angular and subangular lava fragments of plagioclase and pyroxene (Fiske and others, 1963). A wide variety of pyroclastic rocks are present along the area drained by the Ohanapecosh River. From about 37 to 27 million years ago, early Cascade Range volcanoes in southwest Washington and near present day Rainier erupted piles of lava and volcanic debris, where most of the Ohanapecosh formation was deposited. As silica content and lava viscosity increased, more explosive eruptions occurred and caused more local subsidence, depositing the angular and fragmental rocks we see today (Pringle 2008). The robust nature and hardness of the volcanoclastics allows for a less erodible fluvial system, contributing to the current nature of the sediment limited condition of the Ohanapecosh River.

2.4 Archaeological and Ethnographic Evidence in the Ohanapecosh Region

In addition to investigating specific aspects of Ohanapecosh River morphology, the archaeological and enthnographic, or cultural, parameters of the Ohanapecosh River were explored. The presence of pre-European contact human settlements and presence or absence of fishing related remains in the archaeological record could additionally support or reject the presence of salmonids in the river system.

2.4.1 Archaeology

Earliest hard evidence of human presence at Ohanapecosh Campground presently dates to about 7,300 years ago (Burtchard, personal communication, 2017). It is important to note, however, that early Holocene pre-contact societies were dominated by highly mobile foraging groups, where human population density and competition for available food resources was low (Burtchard 2007). In turn, early Holocene pre-contact subsistence systems tended not to rely on mass-harvested salmonids as a major food source because of the time, labor and storage constraints involved. However, by the mid to late Holocene, population density and resource competition increased to a point that selected for a shift in the way pre-contact humans lived and retrieved their resources. Burtchard (2007) maintains that increasing population density accompanied by too few resources in too small of a space resulted in increased reliance on mass harvest and storage of resources ─ in this case, salmon. He notes that this logistical shift occurred about 4,000 years ago across the greater Pacific Northwest region. Accordingly, it is significant to note that mass fish harvest, and storage did not begin to take place in the region until this time, and did so in conjunction with the appearance of semi-sedentary village complexes located near significant salmon-producing rivers and/or other mass-harvestable and storable staples such as camas (Burtchard 2007).

Pre-contact archaeological sites exist at both Ohanapecosh Campground in Mount Rainier National Park as well as at *Blue Hole* at La Wis Wis Campground in Gifford Pinchot National Forest (Figure 1). The character of these sites, however, is quite different. Archaeological remains recovered from Ohanapecosh Campground consist of multiple small-scale sites with limited material remains; a pattern consistent with very short-term, temporary encampments. There is no evidence of fishing or fish harvest and storage (Burtchard, personal communication, 2017). At *Blue Hole*, however, fishery evidence was found in the form of abundant *Salmonidae* (Salmonid vertebrae), calcined fish bones leftover from the fish cooking process, and calcined bone points used for spear fishing (McClure and Mack 2016) (Figure 9). In contrast to Ohanapecosh Campground 7.3 km upstream, *Blue Hole* archaeological evidence supports longer-term, or permanent, pre- contact occupation and fish procurement by at least 3640 ±100 cal. years before present (BP) (McClure and Mack 2016).

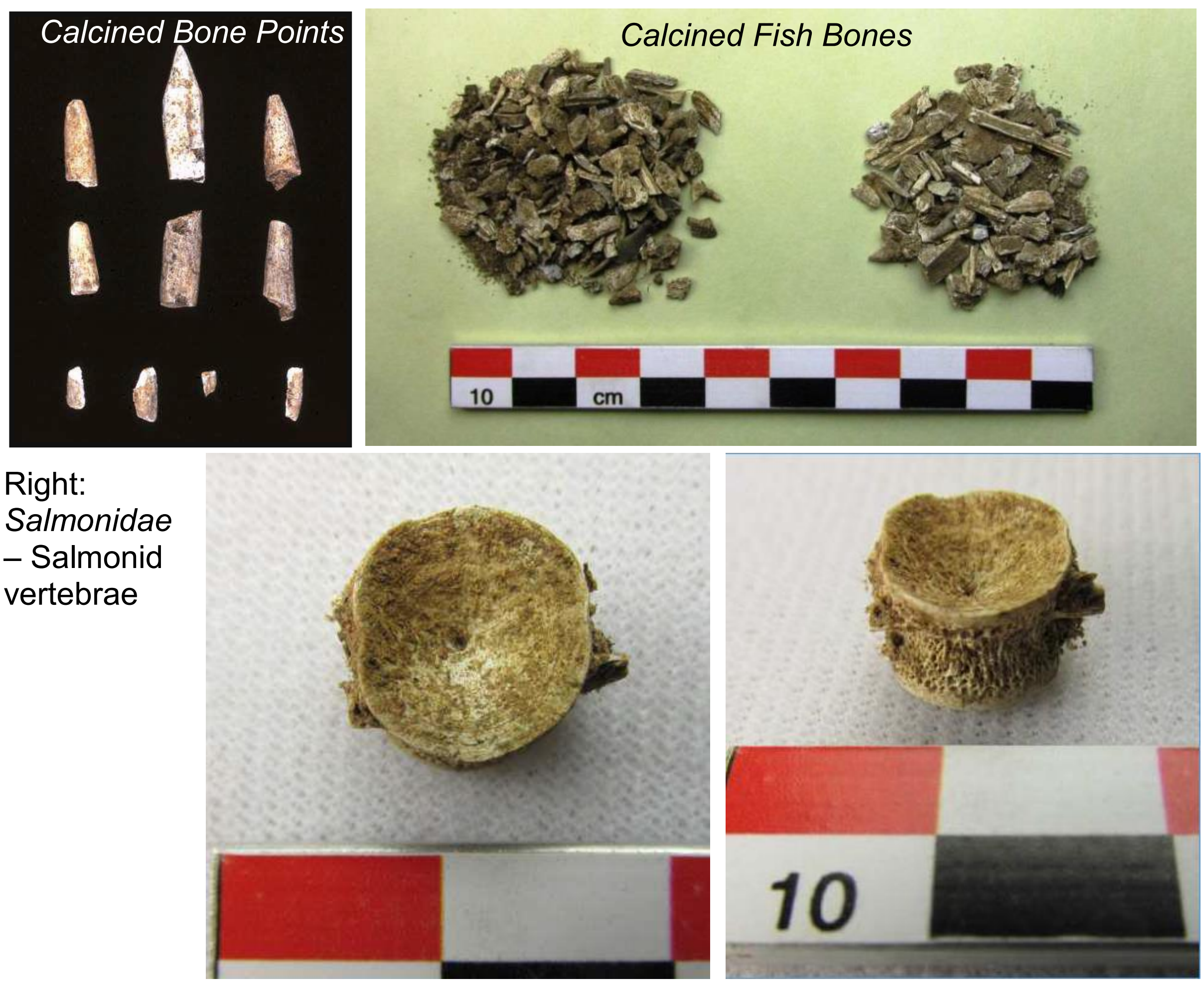


Figure 9. Evidence of fisheries at *Blue Hole*. Top left: calcined bone points, top right: calcined fish bones, and bottom left and right: salmonid vertebrae. Photos courtesy of Rick McClure, USFS Archaeologist.

2.4.2 Ethnography

Ethnographic information also can inform us as to certain aspects of Native American life near the time of Euro-American contact. For example, a coyote story, one meant to entertain or instruct, was told by Louis Costima (Figure 10), a Taytnapam (Upper Cowlitz) member in 1924-1926 (Jacobs 1934). This bit of cultural evidence states that fishing took place at *Blue Hole*, but not further upstream. Costima said:

> "At this place [*Blue Hole*] will be salmon, Chinook salmon, steelhead, silverside, grayling, Dolly Vardens, a great many large Dolly Vardens. They will not go further upstream, none will be above Ohanapecash [the name used at the time for Blue Hole], no people will ever dwell above there, there will be a great deal of snow in winter time. The people will always be here, at this place they will have salmon for food."

According to Louis Costima's statement, fishing did not take place in quantities sufficient to support sustained settlement, anywhere upstream of *Blue Hole*; which includes the Ohanapecosh Campground where only short-term encampments have been documented. The Costima coyote story is consistent with the absence of archaeologically recovered fisheries evidence at the Ohanapecosh Campground.

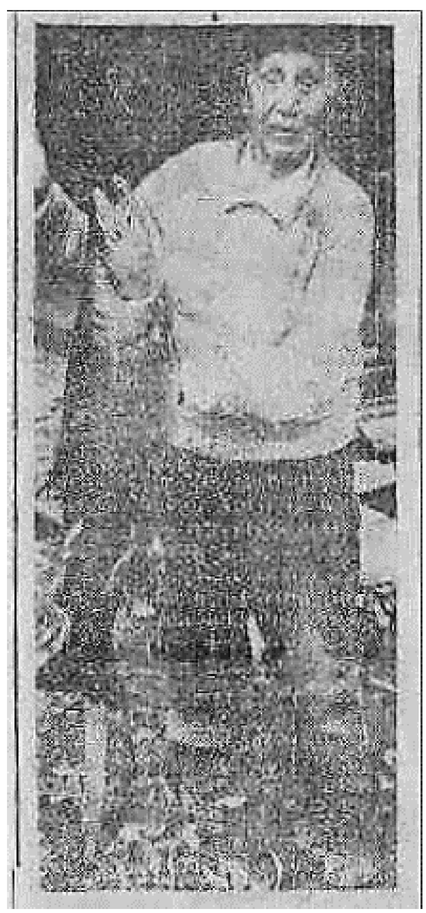


Figure 10. April 1939 photo of Louis Costima holding a salmonid. Photo courtesy of Rick McClure, USFS Archaeologist.

2.5 Pre- and Post-Dam Fish Distribution

Fish species currently present in the Upper Cowlitz and in lower reaches of the Ohanapecosh River are spring and fall chinook, winter steelhead, and coho (Wadsworth 2017, Murphy 2017). The same anadromous fish species are thought to be present in the Cowlitz watershed prior to the Mayfield and Mossyrock Dam installations in the 1960s (Wadsworth 2017, Murphy 2017). These species were reintroduced into the Upper Cowlitz in 1996 following the establishment of the fish collection facility, located just downstream of Cowlitz Falls Dam (Serl, personal communication, 2017). Anadromous fish have been brought up from this location by truck to Packwood, WA in an effort to re-populate the upper reaches of the Cowlitz (Murphy 2017, Paulu 2010) (Figure 5). The same species of fish are brought up above the dams as were there prior to dam installation (Wadsworth 2017, Murphy 2017), consistent with good fisheries practices.

2.5.1 Anadromous Fish and their Preferred Habitat

Anadromous fish are born in freshwater, migrate downstream to the sea where they spend the majority of their lives, and eventually return to their natal streams to spawn (Washington Department of Fish and Wildlife 2009). These fish become physically and sexually mature at sea before returning to freshwater. Spring and fall chinook typically range from 10 – 15 pounds, but can very rarely weigh in at more than 100 pounds. Chinook typically spawn in the river mainstem, as they are the largest of the anadromous fish species, and prefer pebble to cobble substrate for laying redds. Winter steelhead range from 8 – 11 pounds, but can reach up to about 40 lbs. Steelhead prefer medium-large tributaries and the mainstem for spawning. Coho salmon, ranging from 6 – 10 pounds and occasionally reaching up to ~30 pounds, prefer smaller tributaries and coastal streams (Washington Department of Fish and Wildlife 2017).

Salmonid species require specific habitats to successfully and comfortably spawn. They prefer cool, clear, and low turbidity waters for easier migration, spawning, and egg oxygenation. Other stream characteristics include water velocity, temperature, substrate size, riparian quality and pool and riffle frequency. Chinook typically spawn in areas with a flow velocity of 0.25 – 2.25 meters per second (Hanrahan and others, 2004), while coho prefer pools with slower velocities of less than 0.2 meters per second (Bisson and others, 1988). Steelhead utilize riffles as well as deep pools with relatively high velocities (Bisson and others, 1988). Salmonids have a water temperature threshold around the high 60s and into the low 70s degrees Fahrenheit. These temperatures can be exceeded and salmonids will survive for a time. However, salmonids cannot survive when excessive water temperature is sustained over a period of days (Wadsworth 2017). The Cowlitz River watershed and the Ohanapecosh River typically maintain temperature parameters suitable for salmonid spawning and rearing habitat.

Pool-riffle sequences are important for quality redd habitat and for salmonid rest and recovery during upstream migration. Pools provide proper resting places during fish runs, while riffles create suitable substrate conditions for lying eggs, additionally oxygenating the redds with continuous flowing water (Fukushima 2001). However, redds are vulnerable to suspended sediment that may deposit on the eggs, causing a decrease in oxygen and ultimate suffocation (Wood and Armitage 1997). Overhanging riparian vegetation offers additional protection and helps keep the river cool, additionally providing a more diverse food source.

The above listed river characteristics outline the elements needed for quality salmonid habitat. However, the intent of this study is primarily concerned with salmonid presence or absence.

Anadromous fish can surprisingly reproduce in less suitable and poor-quality spawning and rearing conditions.

2.5.2 Current Salmonid Fish Distribution

Spawning surveys and radio-tagging fall and spring chinook, winter steelhead and coho in the upper Cowlitz has been taking place most years since 2005 by the USGS Biological Resources Division of the Columbia River Research Laboratory (personal communications: Kock 2017, Serl 2017, and Heimbigner 2017). These surveys have confirmed fish presence, albeit in limited number, in the Ohanapecosh River at *Blue Hole* in 2005 - 2008, and just below *Blue Hole* in 2017 (Table 2).

Table 2. Number of radio tagged salmonids detected in the Ohanapecosh River at *Blue Hole* in 2005 – 2008, and 2017 (Ekstrom, personal communication, 2017).

Year	Spring Chinook	Winter Steelhead	Coho
2005	2	0	0
2006	3	1	0
2007	4	0	1
2008	0	2	0
2017	0	1	0

Spawning surveys conducted by fisheries biological science technicians of the Columbia River Research Laboratory also note that spawning of fall and spring chinook, coho, and winter steelhead have taken place 0.5 mi upstream of *Blue Hole* (Figure 2) (personal communications: Serl 2017 and Heimbigner 2017). There is no further fish migration beyond this point, as a 15 – 20 ft series of waterfalls exists in this location and more potential fish barriers are present further upstream (personal communications: Serl 2017 and Heimbigner 2017). This knickpoint is recognized as likely impassable to fish, unless steelheads can surpass this barrier at high flow (Serl, personal communication, 2017).

In sections 4.1 and 4.2, we further discuss this and other potential barriers within the Ohanapecosh River up to Silver Falls in Mount Rainier National Park, and the relative timing of barrier exposure.

3. Methods

3.1 Overview

A lack of previous work in using geomorphology to determine anadromous fish presence or absence encouraged us to develop our own conceptual method. This method identifies current natural barriers in the Ohanapecosh River, and looks at drivers and triggers to landscape response that would affect the morphology of the river system within the last 7,000 years that potentially control fish distribution. The most influential driver to landscape response in the Ohanapecosh River is alpine deglaciation. Limited evidence exists in the Ohanapecosh regarding the timing of river incision; however, terraces make reliable fingerprints to paleo river beds. Additionally, dateable volcanic ash (or tephra) layers within the terraces yields the relative timing of river abandonment and terrace formation. The Ohanapecosh River, was overridden by an alpine glacier during Evans Creek glaciation, about 22,000 – 15,000 cal. yr BP (Crandell and

Miller 1974) was also covered in glacial outwash deposits before subsequently incising and exposing potential fish barriers we see today. This method will identify impassable fish obstacles, map previously dated terraces, and use the terraces and their ages to determine paleo river bed height and timing of fish barrier exposure.

3.2 Geomorphic Evidence: A General Approach

Overall, this study utilizes a weight of the evidence approach to determine presence or absence of anadromous fish, comprising 3 components: (1) archeological evidence, (2) ethnographic information, and (3) geomorphic analyses. This section details the latter ─ a general geomorphic approach that we apply in to the Ohanapecosh River, and can be adapted to other areas.

We developed a general geomorphic approach to analyze the influence of landscape and riverine drivers and controls to fish passage. We initially: (1) identify the suite of disturbance processes operative in the watershed, (2) estimate the frequencies, magnitudes and durations of the processes, and (3) evaluate the landscape response and the relative influence of each on the physical and biologic criteria for fish passage. This results in a winnowing down to those processes significant over the spatial and temporal scales of interest.

Generally, there are many potential processes to consider over a large array of spatial and temporal scales; such as tectonics on a regional scale, to large wood inputs on a river reach scale. For the Ohanapecosh study, we initially considered the following drivers (disturbance regimes): lava flows; mass wasting (lahars, debris flows, and rockfall); and changes in sediment production to the river associated with glaciers, particularly alpine deglaciation. For landscape response, we considered changes to riverine inputs that potentially altered river morphology, and physically or biologically, affected salmonid fish passage. For this, we mainly consider changes sediment, flow, large wood, and temperature to stream channels.

A mass wasting event could increase sediment input, creating an initial channel blockage, and ultimately cause the river to become more transport limited and aggrade and/or avulse, altering the base level. In addition, a decrease in sediment input following a mass wasting event, could cause the river to incise and base level to go down. A sudden mass wasting event also could eradicate adjacent forests, negatively affecting spawning and rearing habitat, and potentially allowing water temperatures to increase. Additionally, mature stream-adjacent forests mediate sudden shifts (avulsions) of aggrading streams (Kennard and others 2011) and the loss of these trees strongly degrades fish habitat.

On the other hand, on a centennial time-scale, an emergence of forests long after a volcanic eruption could promote more suitable salmonid habitat with riparian tree cover, additionally providing more food resources. The cumulative effects of numerous drivers can greatly influence landscape response, modifying salmonid habitat on a small and large scale. Dependent upon the study area, time scale, local and regional geologic, biologic, ecologic and anthropogenic history, this method and select drivers can be used and further investigated for understanding changing salmonid habitat and determining fish presence or absence in a river system.

3.2.1 Application to the Ohanapecosh River

Below, we apply the geomorphic approach to the Ohanapecosh River.

3.2.2 Glacial Recession: A Key Driver in Changing River Morphology and Salmonid Habitat

In earlier sections (2.3.1; 2.3.2), it was shown that lahars and lava flows had little or no influence in the study area. The most influential driver in the Ohanapecosh River for the last 7,000 years has been alpine glacial recession, where the late Pleistocene alpine glacier retreated from the Ohanapecosh River canyon, leaving behind glacial outwash deposits. In terminal Pleistocene times, the river base level was much higher than it is today, as glacio-fluvial deposits would have filled the river canyon. Following glacial retreat sedimentation, the river incised through the glacial-fluvial deposits, subsequently revealing the present-day bedrock canyon, and the exposing present-day fish barriers.

The timing of the most recent alpine deglaciation and subsequent river incision determines the status of the Ohanapecosh fish barriers ─ whether they are buried or exposed ─ and therefore whether fish are present or absent. To understand this, we use dated river terraces to determine the paleo-river elevations relative to the bedrock fish barriers. This determines the extent to which anadromous fish could be expected to have migrated up the Ohanapecosh River, beyond Ohanapecosh Campground, to Silver Falls within the last 7,000 years. To do this, the fish barrier criteria must first be identified.

3.2.3 Natural Fish Barrier Criteria

For this project, we use the criteria identified by the Washington Department of Fish and Wildlife (2009), listed below, to estimate fish barriers within the Ohanapecosh River. The natural fish barrier criteria for the state of Washington are as follows:

1. Vertical waterfall >3.7 meters in height.
2. Stream reach >20% sustained gradient for 160 meters continuously.
3. Channel with sustained gradient >16% for 160 meters with a channel width <0.6 meters in Western Washington.

This barrier criterion is accepted for most adult salmonids. However, we should recognize that different anadromous fish species (and different species life stages) have varying migration abilities.

3.2.4 Identifying Potential Fish Barriers

Three methods were used to identify potential fish barriers from *Blue Hole* in Gifford Pinchot National Forest to Silver Falls in Mount Rainier National Park: (1) slope classification mapping; (2) stream channel longitudinal profile analysis; and (3) field identification. Each is discussed below.

The first method uses a slope classification map, where the Ohanapecosh stream gradients were measured using high resolution 10 m contour intervals on 2009 Light Detection and Ranging (LiDAR) in Geographic Information Systems (GIS). This method identifies barriers with >20% sustained gradient for a continuous 160 meters or more. Additionally, GIS was used to confirm that all channel widths exceed 0.6 meters in the study area, and the third fish barrier criteria listed above is not relevant to this study.

The second method involved creating a longitudinal profile (Figure 11) of the Ohanapecosh River using the 2009 LiDAR in GIS. This method identifies potential vertical barriers, looking for those > 3.7 meters, and confirms potential barriers found in the slope classification method.

After all potential barriers were identified in GIS and located on Google Earth Pro; field verification was conducted to measure the gradients and heights of each potential barrier using a distance range finder. All three methods gave the same results, however field verification was most useful in measuring potential vertical barriers.

3.2.5 Mapping Dated Terraces

Terraces were identified and mapped using LiDAR and field verification. Terraces within Mount Rainier National Park boundaries were previously mapped using the same method (Riedel and Dorsch 2016). Terraces outside of the park boundary in Gifford Pinchot National Forest were mapped for this project using the same criteria, based on 2009 LiDAR results. Terraces were partitioned based on terraces heights (Table 3), measured by distance range-finder. The only known terrace dates were from Ohanapecosh archaeological studies in 2015 and 2016 (Burtchard, personal communication, 2017), where tephra layers deposited by known past eruptions from Mount Rainier and surrounding volcanoes were exposed. Logistical constraints made it impossible to obtain additional terrace dates. For more information regarding potential dating methods, see section 5.1 Future Research.

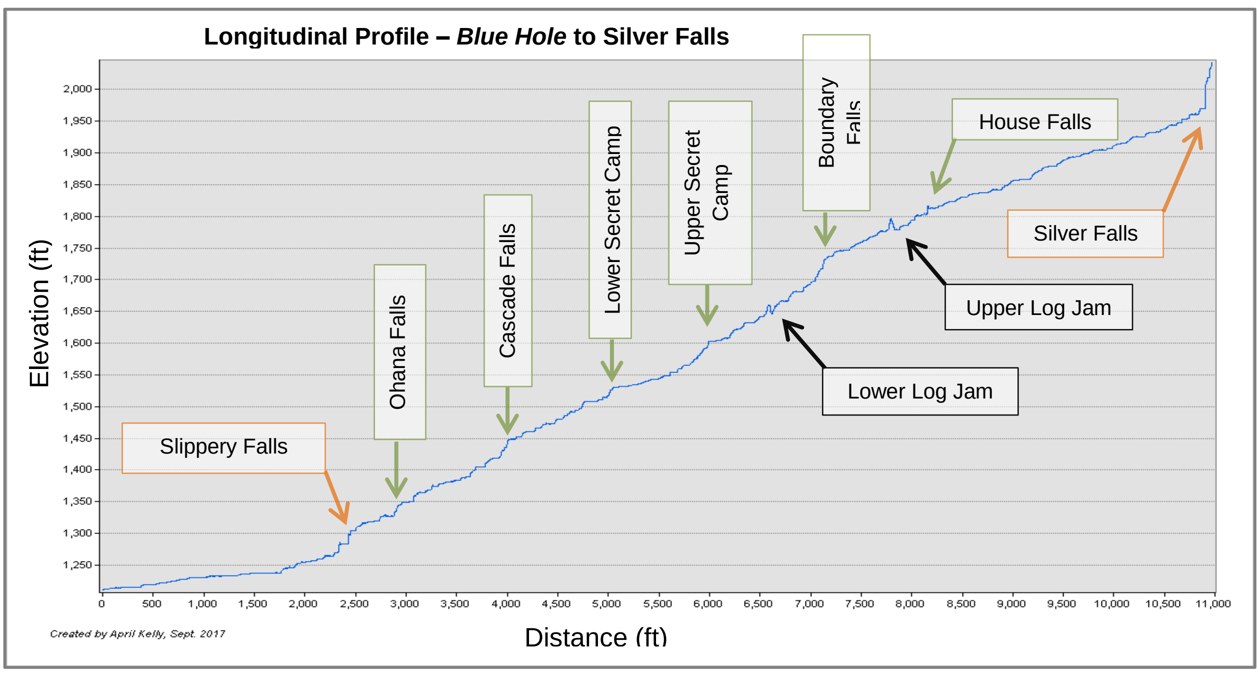


Figure 11. Longitudinal profile of the Ohanapecosh River from Blue Hole to Silver Falls with knickpoints and potential barriers identified. Potential vertical barriers are denoted with green arrows, and impassable vertical barriers to fish are denoted in orange. Log jams are marked in black.

Table 3. Terrace height classification system.

Terrace Height Classification	*Height (m)*
Low	0 – 5
High	>5 – 15
Very High	>15

4. Results

4.1 Slope Classification: Gradient Barriers

Nine potential bed-rock barriers in addition to two large wood log jams were found in the Ohanapecosh River from *Blue Hole* to Silver Falls using the slope classification and longitudinal profile methods. On the slope classification map (Figure 12), slope classes were divided by percent gradient and color coordinated. Steeper gradients are represented by warmer colors, and more shallow gradients are depicted by cooler colors. Reds, oranges and yellows mark the presence of potential barriers. Log jams were a concave feature and anomaly on the LiDAR, and are denoted in black on the slope classification map. Of these nine barriers, only Silver Falls and House Falls were confirmed to be true fish barriers based on the stream reach gradient criteria of >20% sustained gradient for a continuous 160m or more (Figure 12).

4.2 Longitudinal Profile: Vertical Barriers

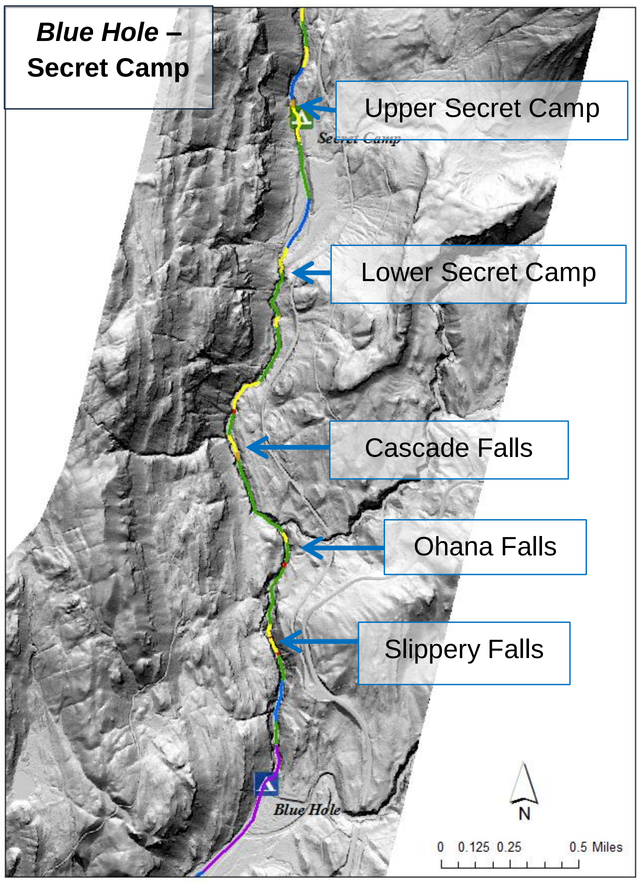
The same nine potential barriers and two log jams were found on the Ohanapecosh River longitudinal profile (Figure 11). Google Earth imagery also visually shows white-water and knickpoints at each of these nine locations, as well as stacks of logs present at the log jam locations. These were targeted for field investigation. Bedrock was identified on 2009 LiDAR imagery at each of the step-like features in the long profile where potential barriers and knickpoints are present. Log jams are revealed as concave features that dip down in the upstream direction.

Each potential barrier was field checked to verify if it was >3.7 meters vertical height and impassable to fish, and if the log jams were true fish barriers. The furthest downstream potential barrier, Slippery Falls, had a 4 m high waterfall at the top of a series of falls, qualifying it as a true barrier to fish migration (Figure 13). This barrier is 0.5 miles upstream from *Blue Hole*, and the same barrier described by fisheries biological science technicians of the Columbia River Research Laboratory. Slippery Falls and Silver Falls were found to be the only true vertical barriers in this study area.

Field investigation of the log jams demonstrated they do not constitute as fish barriers because fish are capable of swimming beneath and through the log jams, where debris-flow formed log jams may even provide high-quality habitat (Montgomery and others 2003) to continue their migratory path. In this study, we will focus on the exposure of Slippery Falls, as it is the most downstream fish barrier and therefore, the first obstacle anadromous fish would encounter in the Ohanapecosh drainage.

Figure 12. *Right:* Slope classification system, warmer colors indicate steeper gradients; cooler colors depict more shallow gradients. Black represents log jams. *Below: Blue Hole* to Secret Camp slope class map at left, and Secret Camp to Silver Falls slope class map at right. Gradients are denoted by according colors within the river channel. All potential barriers are boxed in blue and definite fish barriers, Silver Falls and House Falls, in orange. Log jams are boxed in black.

Percent Gradient	Color
>30%	Red
20-30%	Orange
8-20%	Yellow
4-8%	Green
2-4%	Blue
0.1-2%	Purple
Log jam	Black



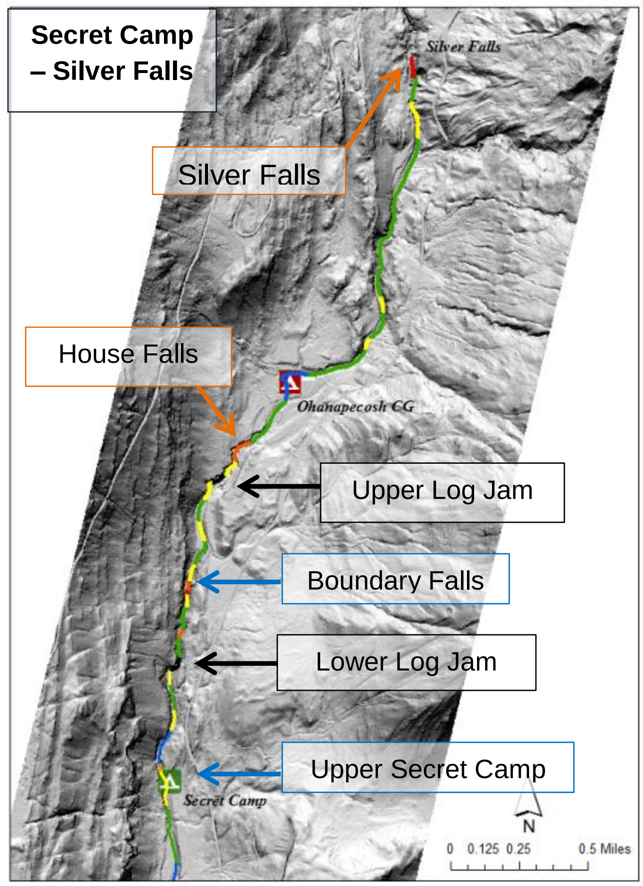


Figure 13. *Left:* Map of project site with Slippery Falls. Slippery Falls, the most downstream barrier, is about 0.5 miles upstream of *Blue Hole*. *Right:* Photo of Slippery Falls area looking upstream, with the 4 m waterfall at the top of the step-pool sequence denoted by the red arrow. NPS photo.

4.3 Existing Dated Terraces

A total of 14 terraces were identified in the project area using park landform maps, LiDAR, and field verification (Figure 14) (Table 3). Five of these 14 terraces contain previously dated tephra layers, and two of these five terraces have bounding dates younger than 8,000 years ago. This is important for understanding the timing of river incision and exposure of Slippery Falls within the last 7,000 years. The uppermost fluvial deposit within a terrace indicates the paleo bed height. A terrace date from an overriding ash layer constrains the relative time at which the river was at the previous height. This will determine if the paleo river bed was above Slippery Falls, thus covering the barrier, and at what time the river incised to expose Slippery Falls a total of 3.7 m, resulting in the now impassable fish barrier.

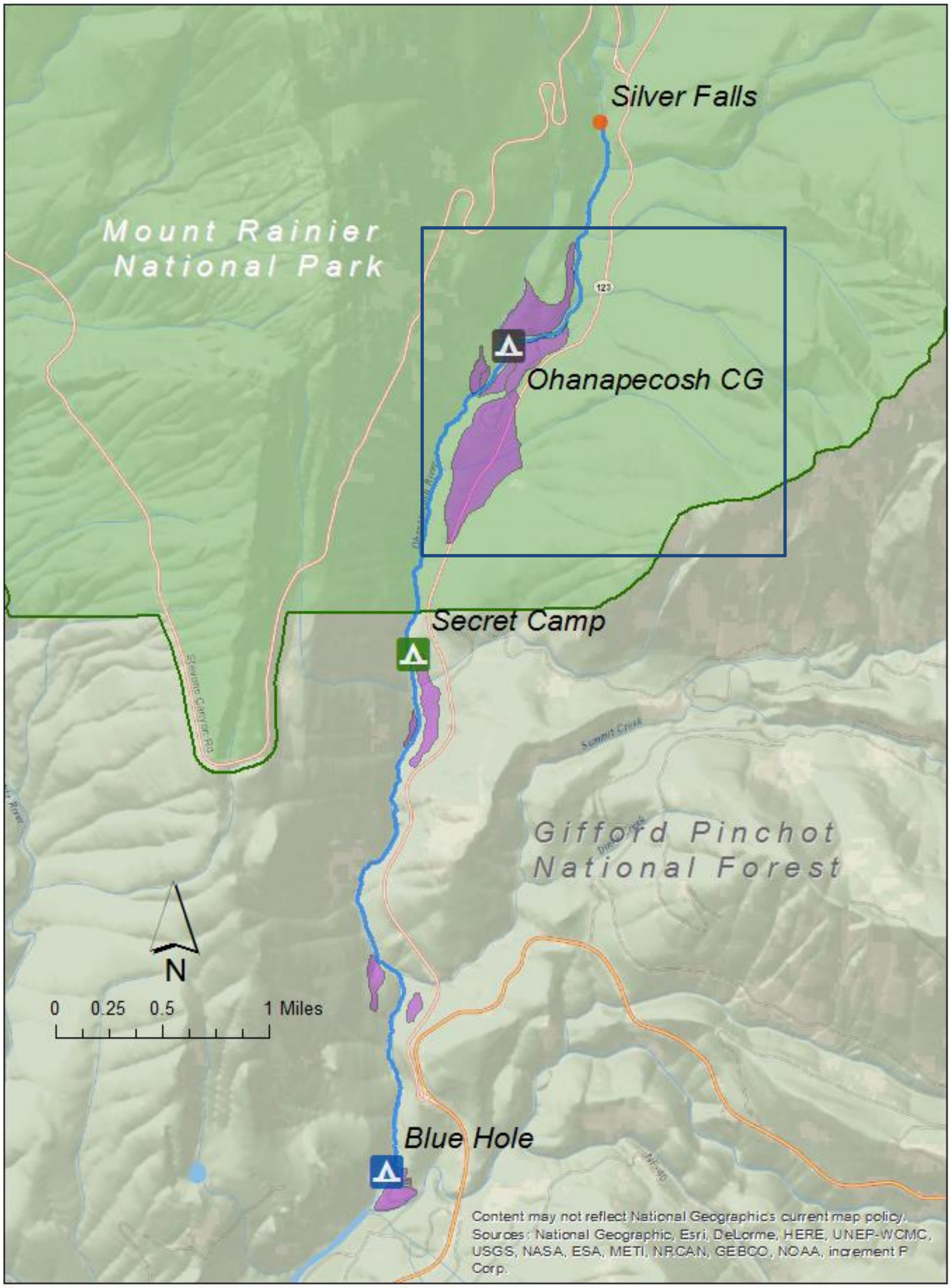


Figure 14. Map of project area with all identified terraces highlighted in purple. The dated terraces are boxed in blue, within the Ohanapecosh Campground.

Table 3. Identified terraces in the project area, separated by their regions within the study area; Ohanapecosh Campground, Secret Camp Region, and *Blue Hole*. Terrace names and heights are listed with according height classification. Terraces in **bold** contain previously dated tephra layers, and **orange** terraces contain bounding dates.

	Terrace Name	*Terrace Height Relative to River (m)*	*Height Classification*
Ohanapecosh Campground	**Upper F-Loop**	**14**	**High**
	Lower F-Loop	**4.5**	**Low**
	Upper C-Loop	**11.5**	**High**
	Lower C-Loop	3.5	Low
	Housing	~40	Very High
	Lower West Ohana	~3.5	Low
	Upper West Ohana	~15	High
Secret Camp Region	Upper East SC	~15	High
	Lower West SC	~3.5	Low
	Gifford Pinchot East	~24	Very High
	Gifford Pinchot West	~24	Very High
Blue Hole	**Lower BH**	**5**	**Low**
	Intermediate Hummocky	**9**	**High**
	Upper BH	15	High

4.3.1 Upper and Lower F-Loop and C-Loop Terraces

The dated terraces that are the focus of this study are the Lower and Upper F-Loop terraces, and the Upper C-Loop terrace in Ohanapecosh Campground. These terraces are in accordance with the names of the Ohanapecosh Campground Loops, shown in Figure 15. Located on the north and south sides of the Ohanapecosh River (Figure 16), these terraces are especially significant to this study due to the preserved, dateable tephra layers with dates at least 8,000 years old or younger.

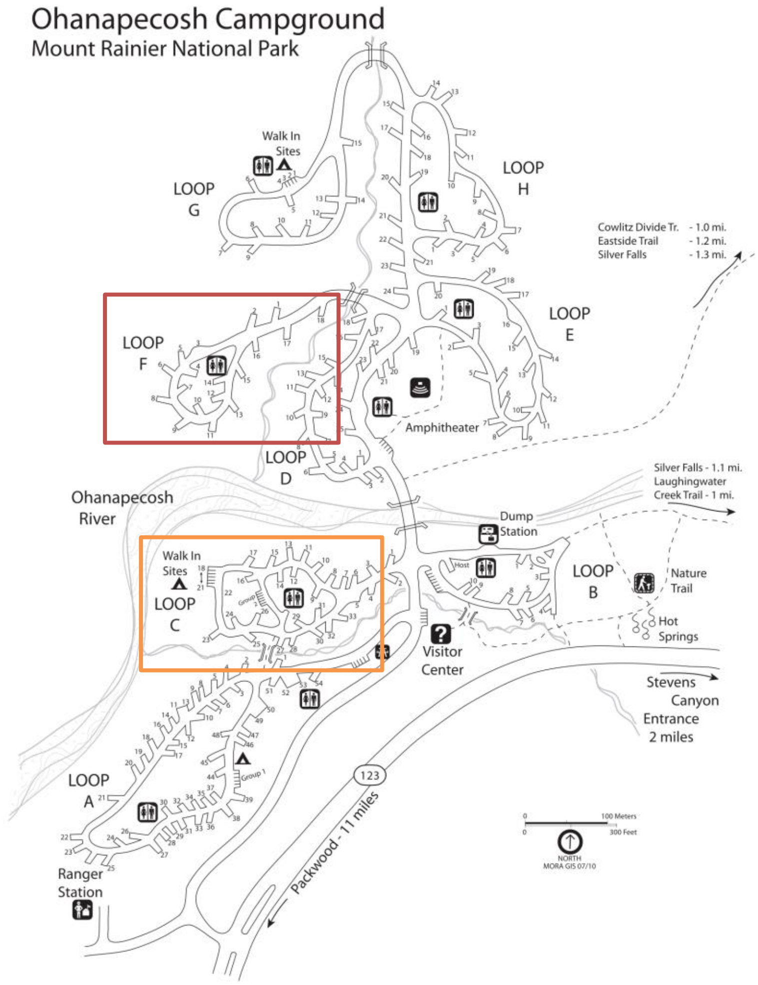


Figure 15. Ohanapecosh Campground map containing highlighted loops with dateable tephra layers in their terraces. F-Loop, boxed in red, is located north of the Ohanapecosh River. C-Loop, boxed in orange, is south and east of the Ohanapecosh River.

The Lower F-Loop terrace is 4.5 m above the current base level, and the Upper F-Loop terrace is 14 m above current base level (Table 4). The general stratigraphy of the high terraces in the Ohanapecosh Campground, including the Upper F-Loop terrace, is exhibited in Figure 16. This stratigraphy shows that ~1.4 m below the terrace surface consists of post-Pleistocene overbank flood deposits, sub rounded cobbles, and other fluvial deposits such as sandy-silts and gravels, and indicates the paleo bed was ~12.6 m higher than the current river bed (Table 4). These are the youngest fluvial deposits in the high terrace stratigraphy; as the rest of the column consists of seven tephras reside above the flood deposits.

The tephra directly overriding the early Holocene flood deposits is the Mazama-O layer, which is the oldest tephra in the stratigraphic sequence, dated to 7950 cal. BP (Mullineaux 1974) (Figure 17). The Lower F-Loop terrace stratigraphy differs in that the fluvial deposits are 0.5 m below the current surface, putting the paleo bed at 4.0 m above the current bed. The MR-L tephra layer, dated to 7320 cal. BP (Mullineaux 1974), lies above the fluvial deposits in the Lower F-Loop terrace with no fluvial deposits in the remaining upper stratigraphy.

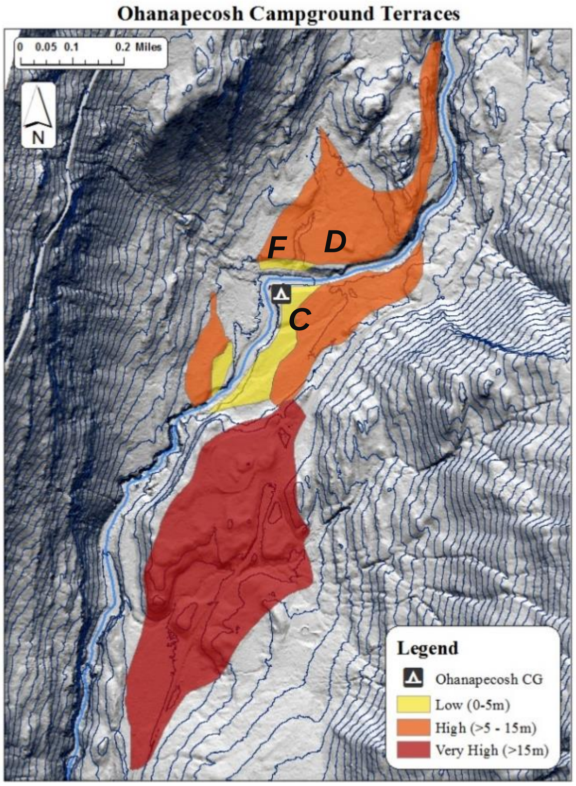


Figure 16. Ohanapecosh Campground Terraces, where low elevation terraces are in yellow, high elevation terraces are in orange, and very high terraces are denoted in red. F-, C-, and D-Loop locations are labeled in black, north and south of the Ohanapecosh River.

Table 4. Upper and Lower F-Loop, and Upper C-Loop terrace heights, relative ages of the terrace formation, and calculated paleo river bed height using fluvial deposit depths in each terrace.

Terrace	***Height (m)***	***Oldest Tephra Layer above Fluvial Deposits***	***Depth to Fluvial Deposits (m)***	***Paleo River Bed Height (m)***
Upper F-Loop	14.0	Mazama-O 7950 cal. BP	1.4	**12.6**
Lower F-Loop	4.5	MR-L 7320 cal. BP	0.5	**4.0**
Upper C-Loop	11.4	Mazama-O 7950 cal. BP	0.8	**10.6**

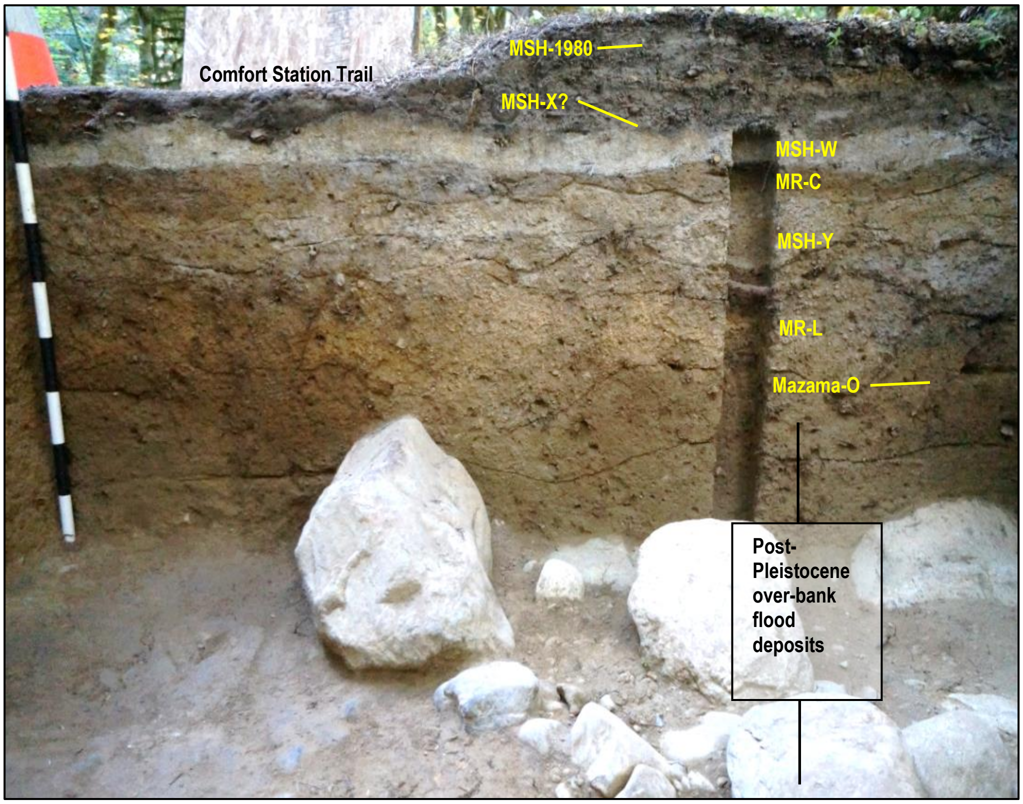


Figure 17. General high terrace stratigraphy of the Ohanapecosh Campgound Loop-C excavated by Mount Rainier archaeological staff in 2015. Meter stick at left is in 10 cm color increments. Stratigraphy contains post-Pleistocene fluvial deposits overlain by tephra layers, as labeled. Photo from Burtchard 2017.

4.4 Timing of Slippery Falls Exposure

In general, we estimated the landscape response and evolution of salmonid habitats in the Ohanapecosh River study area following a major glacier disturbance. River base level changes were used to estimate the timing and magnitude of bedrock exposure or burial, and whether fish passage was physically facilitated or blocked. Specifically, we investigated river channel response during the Holocene following the most recent major alpine glaciation, known as the Evans Creek glaciation, a substage of the regional Fraser Glaciation, which lasted from about 22,000 – 15,000 cal. yr BP (Crandell and Miller 1974). We assumed that the Ohanapecosh landscape responded similarly to other regional river systems studied after major deglaciation (Church and Ryder 1972), particularly the well documented South Fork Stillaguamish River in Northwest Washington State (Benda and others 1992).

Regionally, the affected areas initially experienced massive aggradation, as the valley filled with sediments, followed by river incision. In the Ohanapecosh, we focused on the effects on Slippery Falls in the study area. While the Ohanapecosh was responding to alpine glacier loss versus ice sheet melt in the Stillaguamish, the glacio-fluvial processes that the valley and river are responding to are identical, though the relative sequence timing differs. Based on the Benda and others' (1992) analysis, 90% of the erosion and export of glacial sediment occurred in the 1st several 1000s of years following deglaciation. This high rate of sediment yield lowered the river's base level as river sediment transport capacity vastly exceeded the sediment supply, and was facilitated by the absence of stabilizing vegetation. This period was followed by a reduced incision rate ─ estimated to be 15 times less than the postglacial period, based on the Stillaguamish data.

These sediment yields are closely comparable with postdeglaciation responses for several river basins in British Columbia (Church and Ryder 1972). A modern day analogue is the post May 18, 1980 Mount St. Hellens volcano eruption response of the North Fork Toutle River in Washington State (Janda and others 1984). At St. Helens, the sediment driver is not deglaciation, but the valley base level controlling processes are identical to those in the study area.

The Ohanapecosh River channel rapidly incised following the deposition of the post-Pleistocene flood deposits, as the light weight tephra layers are easily erodible. These overriding tephra layers surviving in the terraces yield a relative time at which the Ohanapecosh River began its subsequent incision into the remaining glacial outwash deposits. At the time of the Mazama-O layer deposition 7950 cal. BP, the Ohanapecosh River was ~12.6 m higher than today, and at the time of the MR-L layer deposition 7320 cal. BP, the Ohanapecosh River was 4 m higher than it is today. This indicates the Ohanapecosh incised 8.6 m over ~630 years, at an average rate of 1.36 meters per year. Since 7320 cal. BP, the river further incised 4 m to the present-day bed, likely on a slower decadal to centennial time-scale. If the river incised at the same pre-7,320 year rate (1.36 meters per year), the current base level would have been established in a mere 294 years.

Slippery Falls has a current height of 4 m, where its exposure began following the abandonment of the Lower F-Loop terrace ~7320 years ago. After the 3.7 m of the falls was exposed, it became impassable to anadromous fish. The 1.36 m incision rate suggests that the falls would have become a barrier after about 272 years of incision, approximately7,048 years ago. This is the time at which anadromous fish where blocked from upstream migration.

For this calculation, we assumed a linear incision rate. The actual incision rate is initially high (see above) and decays with time. Therefore we are slightly underestimating actual incision during the time period, meaning it is likely the barrier was exposed earlier. It is likely the underestimation is not significant, since we were in a period well after deglaciation, and the decay curve becomes relatively flat (tends toward linearity) with increasing time.

5. Discussion

This research study developed a conceptual approach that can be applied generally to other rivers to determine fish presence or absence across different geologic settings and over a variety of timescales. The method identifies the geologic drivers to landscape response affecting the river's morphology and its corresponding effects on determining the upper limits of anadromous fish migration. In this specific study, glacial retreat, terrace formation, and knickpoint development were found to be the dominant controls to fish barriers, and were evaluated to determine fish presence or absence in the Ohanapecosh River.

A current fish barrier 0.5 miles upstream of *Blue Hole*, Slippery Falls, was identified by others (Serl 2017, Heimbigner 2017), and by this study using slope classification, longitudinal profile methods, and field confirmation. Slippery Falls was covered by glacio-fluvial deposits, as the

Ohanapecosh River canyon aggraded, following alpine glacier retreat about 10,000 years ago. At that time, the Ohanapecosh was probably more like the other Mount Rainier rivers of today (Figure 18), with a larger valley width relative to channel width, and a higher sediment loads consisting of suspended sediment and glacial flour. This difference between the paleo and current Ohanapecosh River, compared to other Rainier rivers, was mediated by the facts that Ohanapecosh River is generally steeper and more confined than the other rivers.

This stream habitat was likely less favorable for salmonids than today. Over the next 1,000 – 2,000 years, rapidly declining sediment yields and forest development would have slightly improved salmonid habitat (Benda and others 1992). In addition, the Ohanapecosh abandoned its river bed, leaving behind remnant terraces and replacing a low-gradient stream with a higher gradient stream more suitable for salmonids (Benda and others 1992).

By approximately 7950 years ago, the Upper F and C-Loop terraces had formed and been abandoned by the river as indicated by Mazama-O tephra deposits atop overbank flood or lahar deposits. At that time, or somewhat earlier, the Ohanapecosh River was about 12.6 m higher than it is today. At that level, Slippery Falls would have been covered by about 8.6 m of glacial outwash deposits, probably making it passable to fish. Therefore, it is reasonable to infer that anadromous fish were present up to the Ohanapecosh Campground and potentially Silver Falls up to about 8000 years ago. Although, due to the high proportion of cobble and boulder substrate and high turbidity, salmonids would have had a low quality spawning habitat, likely impacting the abundance of fish present.

In short, our results suggest that salmonids were physically able to access the Ohanapecosh River above Slippery Falls, even if the habitat was relatively unsuitable for them during 1000 to 2000 year period following retreat of Mount Rainier’s Pleistocene alpine glaciers until about 8000 years ago. If salmonids intend on spawning, they will likely find ways to spawn in an area they can physically access (Heimbigner 2017). Salmonids continued to ascend the Ohanapecosh until ~7,000 years ago, when 3.7 m of Slippery Falls was exposed, probably marking it impassable to anadromous fish. Therefore, it is probable that significant anadromous fish runs did not pass beyond Slippery Falls after this time. Furthermore, the archeological and ethnographic data support the geomorphic data, suggesting that no mass salmon harvest took place above *Blue Hole* during the ca. 7000 year time-span reflected in Ohanapecosh Campground’s archaeological record.

Figure 18. Downstream view of the Nisqually River from the Longmire bridge, showing a typical Rainier river; wide valley relative to channel width, and transport limited with an overburden of substrate. NPS photo.

5.1 Further Research

The project's resolution (accuracy, and certainty) could be improved and the scope expanded with further research including: (1) dating additional terraces, (2) investigating other driving factors in the conceptual approach, and (3) estimating salmonid habitat quality.

In particular, collecting bounded terrace dates at *Blue Hole* would allow calculating a paleo-gradient in addition to a paleo-bed height. Having dates to all Ohanapecosh River terraces will result in a more detailed and accurate incision story. Radiocarbon dating could be used to date terraces that have not been previously dated. Further investigation of other drivers in the conceptual approach, such as rock falls and earthquakes, would add more variables to the equation and more accurately determine fish presence or absence along the Ohanapecosh.

Studying the quality of the Ohanapecosh River salmonid habitat would add more detail and depth to this project, and potentially provide additional archeological insights. For example, identifying fish abundance could help one understand if the amount of fish present in the region was a harvestable source to pre-European peoples.

Literature Cited

Beason, S., and P. Kennard, 2007, Environmental and ecological implications of aggradation in braided rivers at Mount Rainier National Park: Natural Resource Year in Review—2006, A portrait of the year in natural resource stewardship and science in the National Park System, p. 52-53.

Benda L., T. Beechie, R. Wissmar, and A. Johnson, 1992, Morphology and Evolution of Salmonid Habitats in a Recently Deglaciated River Basin, Washington State, USA. Can. J. Fish. Aquat. Sci. 49: 1246 – 1256.

Bisson, P., K. Sullivan and J. Nielsen, 1988, Channel hydraulics, habitat use, and body form of juvenile coho salmon, steelhead, and cutthroat trout in streams, Transactions of the American Fisheries Society, 117:3, p. 262-273.

Burtchard, G., 2017, Personal communications regarding results of 2014 and 2015 archaeological testing in Mount Rainier's Ohanapecosh Campground.

Burtchard, G., 2007, Holocene Subsistence and Settlement Patterns: Mount Rainier and the Montane Pacific Northwest. Archaeology in Washington, Vol. 13 (Printed and distributed in 2009).

Crandell, D., 1971. Postglacial Lahars From Mount Rainier Volcano, Washington. U.S. Geological Survey Professional Paper 677, U.S. Govt. Print. Off., Washington, D.C.

Crandell, D. and R. Miller, 1974, Quaternary stratigraphy and extent of glaciation in the Mount Rainier region, Washington, U.S. Geological Survey Professional Paper 847, U.S. Govt. Print. Off., Washington, D.C.

Church, M., and J. Ryder, 1972, Paraglacial Sedimentation: a Consideration of Fluvial Processes Conditioned by Glaciation, Geological Society of America Bulletin, Vol. 83, p. 3059-3071.

Ekstrom, B., 2017, October 16, Personal communication.

Fiske, R, C. Hopson, and A. Waters, 1963, Geology of Mount Rainier National Park, Washington, U.S. Geological Survey Professional Paper 444, U.S. Government Printing Office, Washington, D.C.

Fukushima, M., 2001, Salmonid habitat-geomorphology relationships in low-gradient streams. *Ecology*. 82(5), p. 1238-1246.

Hanrahan, T., D. Dauble, and D. Geist, 2004, An estimate of Chinook salmon (Oncorhynchus tshawytscha) spawning habitat and redd capacity upstream of a migration barrier in the upper Columbia River, Canadian Journal of Fisheries & Aquatic Sciences, 61, p. 23-33.

Heimbigner, W., 2017, October 17, Personal communication.

Jacobs, M., 1934. Northwest Sahaptin Texts: Upper Cowlitz Myth and Geographic Text. Columbia University Contributions to Anthropology, Vol. XIX, Part I, Columbia University Press, p. 238–246.

Janda, R., D. Meyer, and J. Childers, 1984, Sedimentation and Geomorphic Changes During and Following the 1980-1983 Eruptions of Mount St. Helens, Washington, Journal of the Japan Society of Erosion Control Engineering, Vol. 37, No. 2: p. 10-21.

Kennard, P., T. Abbe, M. Ericsson, J. Bjork, S. Beason, 2011, The role of riparian forests in river avulsion and floodplain disequilibrium in aggrading pro-glacial braided rivers; a newly recognized model in fluvial geomorphology: Abstracts with Programs - Geological Society of America, v. 43, p. 164-164.

Kock, T., 2017, October 16, Personal communication.

Legg, N., 2013, Debris Flows in Glaciated Catchments: A Case Study on Mount Rainier, Washington (master's thesis). Retrieved from Oregon State University. https://ir.library.oregonstate.edu/concern/graduate_thesis_or_dissertations/r781wj99n?locale=en

McClure, R. and C. Mack, 2016, Late pre-contact land use on the lower Ohanapecosh River: the archaeology of Awxanapakash (45LE220), Presented at the 69th Annual Northwest Anthropological Conference, Tacoma, Washington, March 24, 2016. Symposium: Archaeology of the Mount Rainier Area: Papers in Honor of Greg Burtchard.

Montgomery, D., Masson, T., and Hawley, S. (2003) Influence of debris flows and log jams on the location of pols and alluvial channel reaches, Oregon Coast Range. GSA Bulletin; v. 115; no. 1; p. 78–88.

Mullineaux, D.,1974, Pumice and other pyroclastic deposits in Mount Rainier National Park, WA., Geological Survey Bulletin 1326, Washington, D.C.

Murphy, J., 2017, October 10, Personal communication.

Paulu, T., 2010, Cowlitz Salmon Hatchery's two-year revamp complete, The Daily News, Accessed 2017, http://tdn.com/news/local/cowlitz-salmon-hatchery-s-two-year-revamp-complete/article_9e4c8db8-98f5-11df-b667-001cc4c002e0.html

Pringle, P., 2008, Roadside Geology of Mount Rainier National Park and Vicinity, Washington Division of Geology and Earth Resources, Information Circular 107, ftp://ww4.dnr.wa.gov/geology/pubs/ic107/

Riedel, J., and S. Dorsch, 2016, Geomorphology of Mount Rainier: Landform mapping at Mount Rainier National Park, Washington, Natural Resource Report NPS/MORA/NRR—2016/1234, National Park Service, Fort Collins, Colorado.

Scott, K., J. Vallance, and P. Pringle, 1995, Sedimentology, Behavior, and Hazards of Debris Flows at Mount Rainier, Washington. U.S. Geological Survey Professional Paper 1547, U.S. Govt. Print. Off., Washington, D.C.

Serl, J., 2017, October 16, Personal communication.

Vallance J., 2017, October 2, Personal communication.

Wadsworth, T., 2017, August 8, Personal communication.

Washington Department of Fish and Wildlife, 2009, Fish Passage and Surface Water Diversion Screening Assessment and Prioritization Manual, Washington Department of Fish and Wildlife, Olympia, Washington.

Washington Department of Fish and Wildlife, 2017, Salmon/Steelhead Species Information: Fishing and Shellfishing, accessed 2017, http://wdfw.wa.gov/fishing/salmon/species.html

Wood, P. and P. Armitage, 1997, Biological effects of fine sediment in the lotic environment, *Environmental Management*, 21(2), p. 203-217.

The U.S. Department of the Interior (DOI) is the nation's principal conservation agency, charged with the mission "*to protect and provide access to our Nation's natural and cultural heritage and honor our trust responsibilities to Indian tribes and our commitments to island communities."* More specifically, Interior protects America's treasures for future generations, provides access to our nation's natural and cultural heritage, offers recreation opportunities, honors its trust responsibilities to American Indians and Alaska Natives and its responsibilities to island communities, conducts scientific research, provides wise stewardship of energy and mineral resources, fosters sound use of land and water resources, and conserves and protects fish and wildlife. The work that we do affects the lives of millions of people; from the family taking a vacation in one of our national parks to the children studying in one of our Indian schools.

April 2019

National Park Service
U.S. Department of the Interior

Mount Rainier National Park
55210 238th Avenue East
Ashford, Washington 98304

www.nps.gov/mora

EXPERIENCE YOUR AMERICA ™