THE ENVIRONMENTAL IMPLICATIONS OF AGGRADATION IN MAJOR BRAIDED RIVERS AT MOUNT RAINIER NATIONAL PARK, WASHINGTON

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CHAPTER 1

INTRODUCTION

Mount Rainier (Figure 1.1) is the most prominent icon of the Pacific Northwest. Its image can be seen on billboards, signs, and advertisements and its likeness is displayed on the background of Washington State's license plates. "The Mountain," as it is known by those living near its flanks, rises almost two miles above the surrounding lowlands, affording a view for hundreds of miles. Due to its proximity to major population centers, it is a popular destination for campers, hikers and climbers. Its own National Park, founded in 1899, receives up to two million visitors annually, many during the busy summer months. Mount Rainier allows these visitors an up-close opportunity to see numerous biological and geological forces at work.

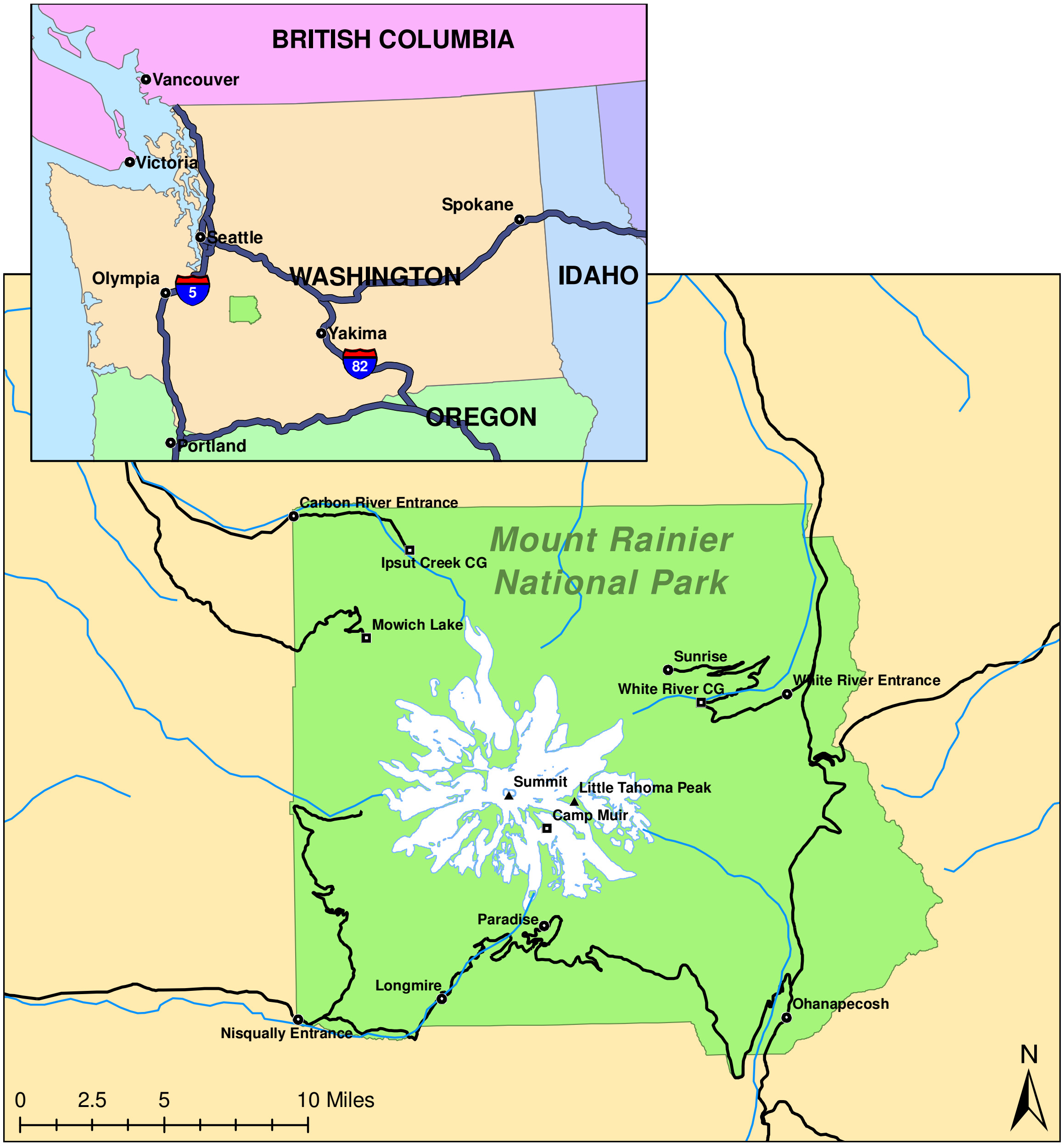
Since Mount Rainier is an active volcano, a great deal of research has gone into looking at the eruptive and non-eruptive hazards associated with the volcano. Following the 1980 eruption of the nearby Mount St. Helens, much research was conducted looking at the possibility of a similar volcanic event at the much larger Mount Rainier. The glaciers that are clad on the volcano's steep slopes feed braided rivers that radiate outward from the volcano. The erosive effects of ice and water on the active volcano provide great volumes of sediment to the braided rivers. Since most major rivers in the Park are confined in valleys surrounded by tall ridges, the natural alluvial fan deposits that would be expected are spread out laterally in the river channels. These valley-confined alluvial fans naturally drop out sediment when the river loses entrainment velocity. The bed elevation of the braided rivers has been continuously increasing in height over time, effectively decreasing river bank heights.

▲ FIGURE 1.1
Mount Rainier (14,410 ft) from the south (Photo: Scott Beason, 7/9/2003).

This study looks at the rate at which braided river channels at Mount Rainier are increasing in height over time, or aggrading. Specifically, the Nisqually and White Rivers, two rivers that are adjacent to Park infrastructure, have been singled out for detailed study. Other rivers in the Park have been analyzed via the use of topographic maps. Implications of the aggradation include: (1) determining the useful life of structures and areas near aggrading river channels; (2) finding hazard zones where floods may be particularly destructive; (3) understanding the evolution of valley bottoms, particularly the balance of river deposition, and recolonization of the flood plain by coniferous vegetation; and (4) further studying the processes of sediment transport in braided river channels on active volcanoes – an area of geomorphology that is not well studied.

Location & Geographic Setting

Mount Rainier is a 14,410 ft (4,392 m) composite volcano located in southwestern Washington State (Figure 1.2). The volcano is the tallest of the Cascade Range (Crandell, 1969a), a linear arrangement of volcanoes and mountains from Mount Garibaldi in British Columbia, Canada to Lassen Peak in California (Lillie and Driedger, 2001). The Cascades are a part of a broader volcanic arc known as the Ring of Fire, which spans nearly the entire Pacific Ocean basin. Locally, the volcanism seen in the Cascades is fueled by the 2 in/yr (5 cm/yr) subduction of the oceanic Juan de Fuca plate beneath the continental North American Plate (Lillie and Driedger, 2001).



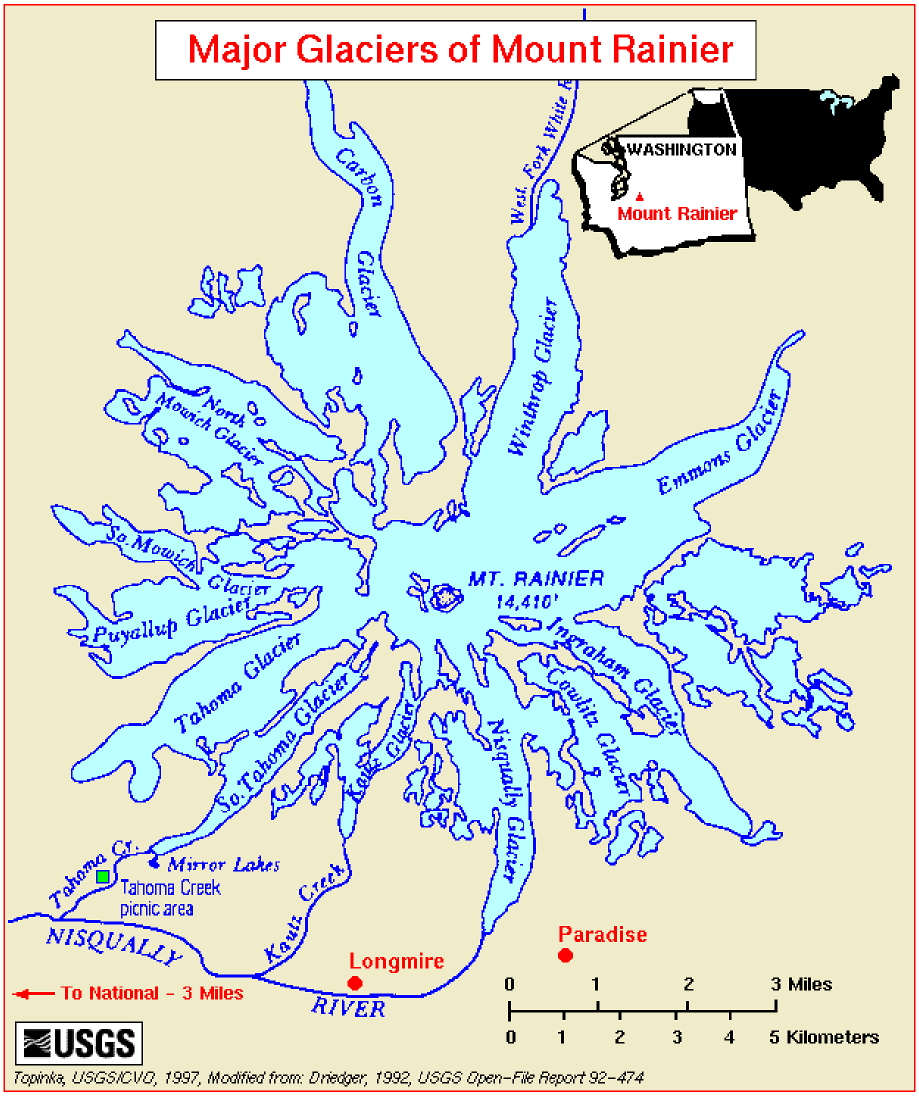
▲ FIGURE 1.2
Mount Rainier area map (Figure: Scott Beason).

Volcanoes in the Cascade Range have been episodically active in the last 4,000 years; some have been active even within the last 30 years. Mount St. Helens, a dacitic stratovolcano located near Mount Rainier suffered a destructive eruption on May 18, 1980 (Lombard et al., 1981). Some of the most explosive eruptions on the Earth's surface have occurred in this range as well, as evidenced by Mount Mazama's eruption approximately 7,700 years before present, which formed Crater Lake (Lillie, 2005; Harris et al., 2004). Many volcanoes in this range exhibit deformation, gas vents, hydrothermal activity and earthquakes (Lillie and Driedger, 2001). On calm days on the summit of Mount Rainier, a faint odor of sulfur can be smelled and steam usually escapes around the mountain's summit crater (Sisson, 1995).

Because of Mount Rainier's height above the surrounding ridges and valleys, which often exceed 7,000 ft (2,134 m), the mountain acts as a significant orographic barrier to landward air currents. Moist air from the Pacific Ocean is forced to rise vertically, often resulting in clouds, rain, and snow. The volcano is shrouded for much of the spring and fall due to this orographic effect, but does experience many weeks of clear weather during the summer (National Park Service, 2007b). In the winter months, enormous volumes of snow fall on the mountain. The Paradise area, at 5,400 ft (1,646 m), was at one time the world record holder for snow, receiving 1,122 in (28.5 m) in 1971-1972 (National Park Service, 2007a). In general, Mount Rainier receives a cool, rainy climate due to the influence of the Pacific Ocean (National Park Service, 2007b). Highs in the summer range from the 60s to 70s (Fahrenheit) and lows in the 20s to 30s in the winter. Weather is wildly variable, however. Late July and August are generally the warmest and driest months of the year (National Park Service, 2007b).

At 5,400 ft (1,646 m), winter snows melt out during each summer; however, at higher elevations, snow lingers all summer. Successive winters add more layers atop the snow and if conditions allow, glacial ice forms. Mount Rainier has 25 named glaciers (Figure 1.3) and has more ice than all other Cascade volcanoes combined (Driedger and Kennard, 1986). Several glaciers at Mount Rainier are record-holders: the Carbon Glacier has the greatest measured thickness (700 ft [213 m]), terminus elevation, and volume (0.2 mi^3 [0.83 km^3]) of any glacier in the continental United States, and the Emmons Glacier has the largest surface area (4.3 mi^2 [11 km^2]) in the continental United States (Driedger and Kennard, 1986). Approximately 1 mi^3 (4.167 km^3) of glacial ice and permanent snowfields exist on the mountain (Driedger and Kennard, 1986).

One interesting aspect about Mount Rainier is its accessibility. Major metropolitan areas are within a 2-hour drive from the volcano. Some of these cities (e.g., Orting, Puyallup, Enumclaw and others) actually lie on top of former lahar deposits from flank collapses of Mount Rainier (Crandell, 1971). The location of Mount Rainier allows for thousands of visitors annually, but it can also present serious hazard concerns for residents who live down slope of the volcano (Driedger and Scott, 2002). Since Mount Rainier is an active volcano and due to its proximity to major population centers, the National Research Council considers the volcano the most dangerous mountain in the United States (National Research Council, 1994).



Topinka, USGS/CVO, 1997, Modified from: Driedger, 1992, USGS Open-File Report 92-474

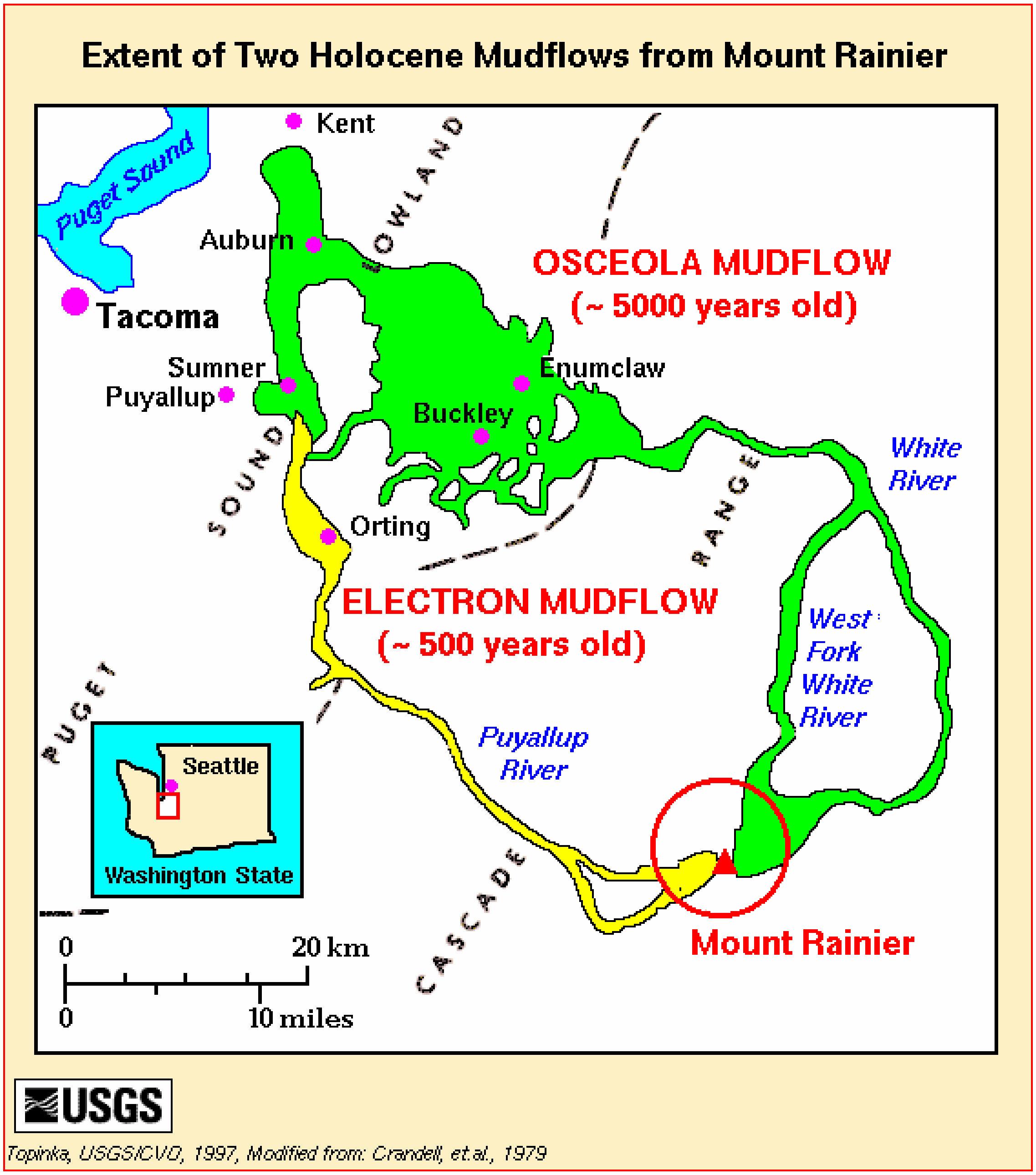
▲ FIGURE 1.3
Major glaciers at Mount Rainier (Modified from Topinka, 1997b).

Geologic History

The volcanism which built the modern Mount Rainier began approximately 650,000 years before present (Lillie and Driedger, 2001). Prior to this time, the region where the mountain now lies contained folded mountains of sedimentary and ancient volcanic rocks up to about 7,000 ft (2,134 m) in elevation (Lillie and Driedger, 2001). Some time during the late Pleistocene, voluminous eruptions of andesite – a porphyritic aphanitic igneous rock with an intermediate silica composition (~60%) – began to issue from a central vent (Lillie and Driedger, 2001). Most of the voluminous lava extrusions that built the modern Mount Rainier took place 500,000 to 420,000 and 280,000 to 180,000 years before present (Sisson et al., 2001; Sisson, 1995). Other extrusions occurred during the last 650,000 years but were not as voluminous as these two periods (Sisson, personal communication, 2007).

The largest mudflow from Mount Rainier during the Holocene was the Osceola Mudflow, which occurred between 5,500-5,800 years before present (Crandell, 1971). The Osceola removed the uppermost 2,000 ft (600 m) of Mount Rainier (Sisson, 1995). This event can be compared to, but was much larger than, the 1980 eruption of Mount St. Helens (Sisson, 1995). Before this point, Mount Rainier may have been between 15,000 to 16,000 ft (4,572 to 4,877 m) tall (Crandell, 1969). Later eruptions created the modern summit cone and crater.

The depth of the Osceola deposit is up to 100 ft (30 m) in the Park, and greater than 200 ft (61 m) in Greenwater, Washington (Crandell, 1971). The deposit's lateral expansion can be seen in Figure 1.4. The origin of the Osceola Mudflow was most likely an avalanche of hydrothermally-altered rock from the summit of Mount Rainier (Crandell, 1971). The deposit can be seen as an orangish-yellow mantle of material on Steamboat Prow (Figure 1.5) at 9,700 ft (2,957 m) between the Emmons and Winthrop Glaciers on the northeast side of the Park.



▲ FIGURE 1.4
Extent of major Holocene lahars from Mount Rainier (Modified from Topinka, 1997a).

▲ FIGURE 1.5
Evidence of Osceola Lahar from Camp Schurman (9,700 ft) on Steamboat Prow. The pale orange-yellow rubbly deposit in the upper left hand side of the outcrop (above the dashed line) is the remnants of the deposit. Arrow points to a human for scale (Photo: Scott Beason, 8/4/2004).

Since the Osceola Lahar flow, Mount Rainier has been quite active. From 2,200 to 700 years before present, lahar activity from the mountain was frequent with some events like the National Lahar traveling 59 mi (95 km) to the Puget Sound (Scott and Vallance, 1995). The latest very large mudflow, the Electron Mudflow (Figure 1.4), followed the path of the National Lahar and filled in the valley around the city of Orting. The Electron Mudflow is significant in that it occurred during a period of relative quiescence at Mount Rainier, indicating that large mudflows could occur anytime instead of exclusively as a byproduct of volcanic eruptions (Scott and Vallance, 1995). Sisson (1995) notes that the latest large eruptions took place approximately 1,000 and 2,300 years before present. Some less significant volcanic activity took place in the 1840s.

One of the most spectacular mudflows seen in the last 100 years occurred in the Kautz Creek drainage, on the southern side of the mountain (between the Tahoma and Nisqually drainage). During the nights of October 2-3, 1947, a major mudflow traveled downslope as a result of approximately 5.85 in (14.86 cm) of rain in a 24-hour period (Crandell, 1971). The first of several lahars occurred between 10-11 PM and lasted until 8 AM the morning of October 3. The lahars were described to have the consistency of wet concrete and entrained vegetation and boulders with diameters greater than 13 ft (4 m). When all was said and done, the total deposition from the debris flow was measured to about 28 ft (8.5 m) where the river crossed the Nisqually-Longmire Road (Crandell, 1971). A National Park Service estimate of the volume of materials deposited by the mudflow was at least 50 million cubic yards (Garter, 1948 *in* Crandell, 1971).

In December 1962, U.S. Forest Service Rangers working at the nearby Crystal Mountain Ski Area heard a loud boom in the direction of Mount Rainier (Crandell and Fahnestock, 1965). The mountain was mostly enshrouded in clouds; however, a few lifting clouds revealed a fresh, pink-colored scar on Little Tahoma peak, a 11,117 ft (3,388 m) spire of volcanic breccia interlayered with lava flows which lies just to the east of the main summit (Figure 1.2). Crandell and Fahnestock (1965) discovered that the collapse of a large buttress on the north side of the peak was the cause of up to five separate debris avalanches with a total volume of 14 million cubic yards. The research concluded that the debris avalanche traveled approximately 4 mi (6.5 km) down from the peak, over the Emmons Glacier and into the White River valley, losing just over 6,000 ft (1,829 m) of altitude (Crandell and Fahnestock, 1965). The material flowed as a "dry avalanche," or a surge of rock debris and air, provided by the buoyancy of air below the rock debris as it moved downslope. The speeds attained by these flows were estimated between 100 and 300 mi/hr (160 and 480 km/hr; Crandell and Fahnestock, 1965).

One of the most interesting of the three explanations posed by Crandell and Fahnestock (1965) for the collapse of Little Tahoma peak includes renewed volcanic activity or a steam explosion. A climber named Luther G. Jerstad was asleep at Camp Muir (10,188 ft [3,105 m]; southwest of Little Tahoma peak [Figure 1.2]) during a summit attempt in 1961 and awakened by "a loud noise and shaking of the ground." According to Jerstad, rock fragments were observed on the Cowlitz Glacier up to 0.75 mi (1.2 km) from a volcanic knob called Gibraltar Rock, where a fresh scar was present. Inside this scar, steam was venting approximately 200 ft (61 m) into the air under great pressure. This vent continued to issue steam for about 5 weeks until no longer active in the fall of 1962. During the collapse of Little Tahoma peak just a year later, evidence of steam and hydrothermal activity was observed which could have led to the collapse (Crandell and Fahnestock, 1965).

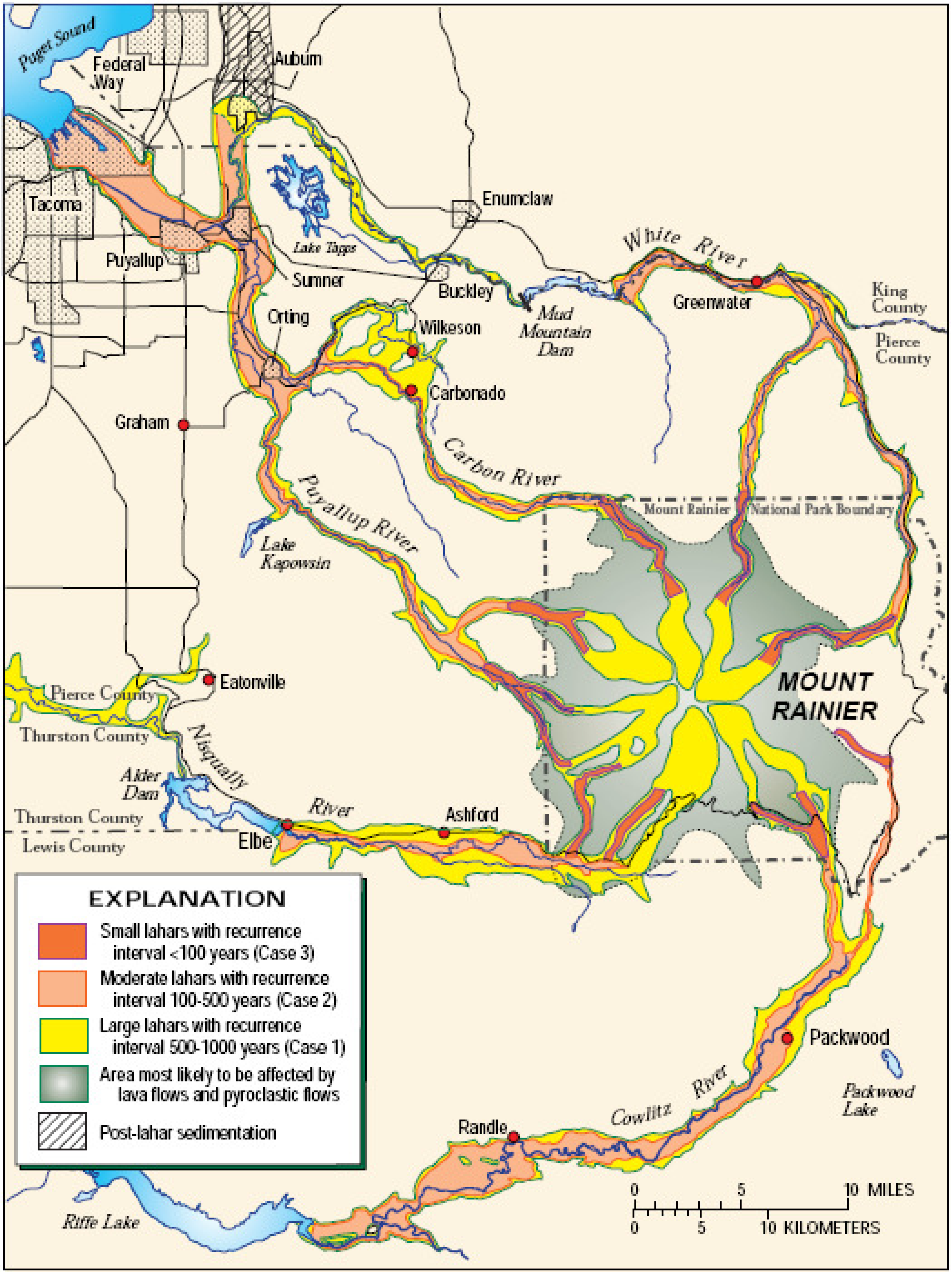
Tahoma Creek, on the southwest side of Mount Rainier, has seen significant debris flow activity since the late 1960s. Walder and Driedger (1995) suggest as many as 23 separate debris flows triggered by glacial outburst floods from the Tahoma Glacier from 1967 to 1995. Because of the nearly constant debris flow activity from Tahoma Creek, the Park has been forced to close off access to the West Side Road for visitors approximately 3 mi (4.8 km) from the junction of Nisqually-Longmire Road. On a field outing to the Tahoma Creek area during the course of this project, significant debris flow deposits (greater than 10 ft [3 m] in most places) within the previous year were noted. Debris flow events are becoming increasingly more common in this area, with at least one debris flow per year (Kennard, personal communication, 2006).

As evidenced by several authors, it seems as though the mountain is literally “falling apart.” Rock falls such as those which occur on warm days in the summertime, the collapses of the Osceola and Electron Mudflows, and the collapse of portions of Little Tahoma peak all provide evidence that the volcano is losing its battle to gravity. Crandell and Fahnestock (1965) note that it is surprising that more rock falls do not occur at Little Tahoma Peak. The presence of heat, gas, and water in various states can lead to degradation of andesite via hydrothermal alteration (Lillie and Driedger, 2001). Sulfur combines with meltwater near radial dikes and turns once strong andesite into an orange-yellow, crumbly mass of clay. Collapse of weakened andesite by hydrothermal alteration has been proposed as the cause of both the Osceola and Electron Mudflow (Lillie and Driedger, 2001).

Geologic Hazards

Mount Rainier is one of sixteen volcanoes worldwide to be declared a "Decade Volcano" (Sisson, 1995). The Decade Volcano program is a United Nations initiative to better understand the science and emergency management of volcanoes in order to minimize impacts to life and infrastructure from the hazards individual volcanoes present to nearby areas. At Mount Rainier, this allowed increased research, maps, and reports illustrating the hazards associated with the volcano (Sisson, 1995). An example of a product from the Decade Volcano study was written by Driedger and Scott (2002). Figure 1.6 shows the eruptive and non-eruptive hazards associated with Mount Rainier.

Volcanic hazards according to Lillie and Driedger (2001) include volcanic ash (tephra), lava flows, pyroclastic flows, and lahars. Additionally, Lillie and Driedger (2001) discuss shallow volcanic earthquakes and deep megathrust tectonic earthquakes caused by the subduction of the Juan de Fuca plate beneath the North American plate as additional hazards.

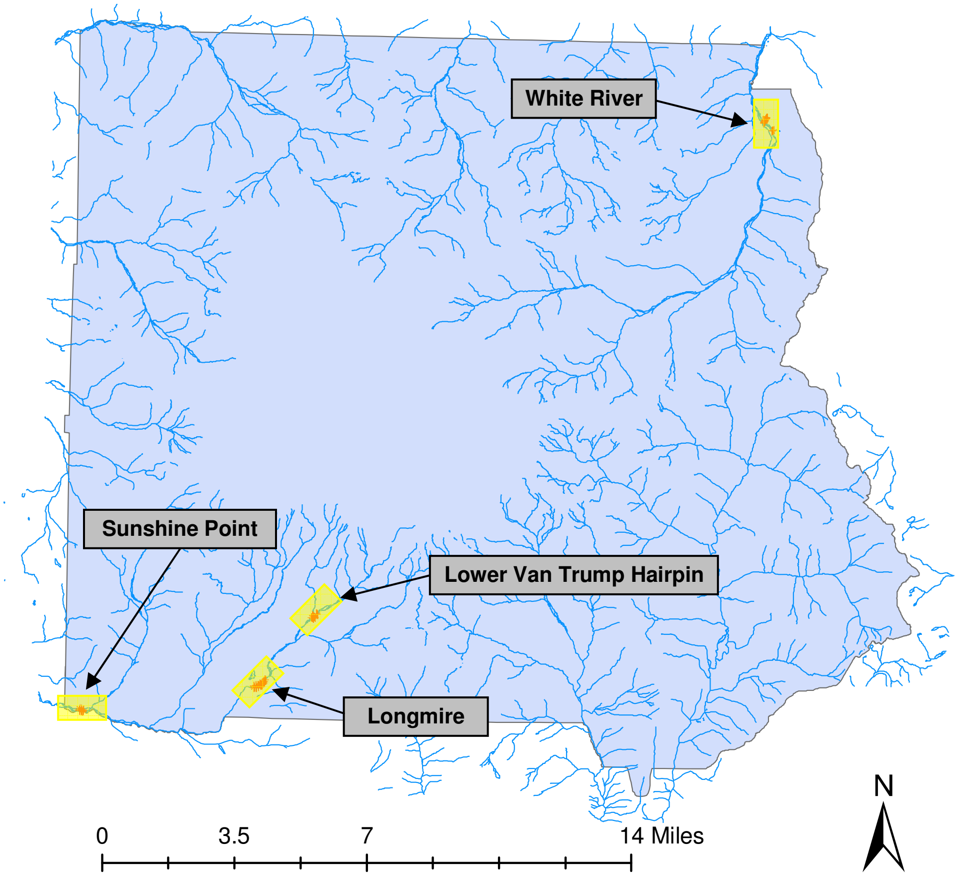


▲ FIGURE 1.6
Possible hazards to surrounding areas from Mount Rainier (Modified from Driedger and Scott, 2002).

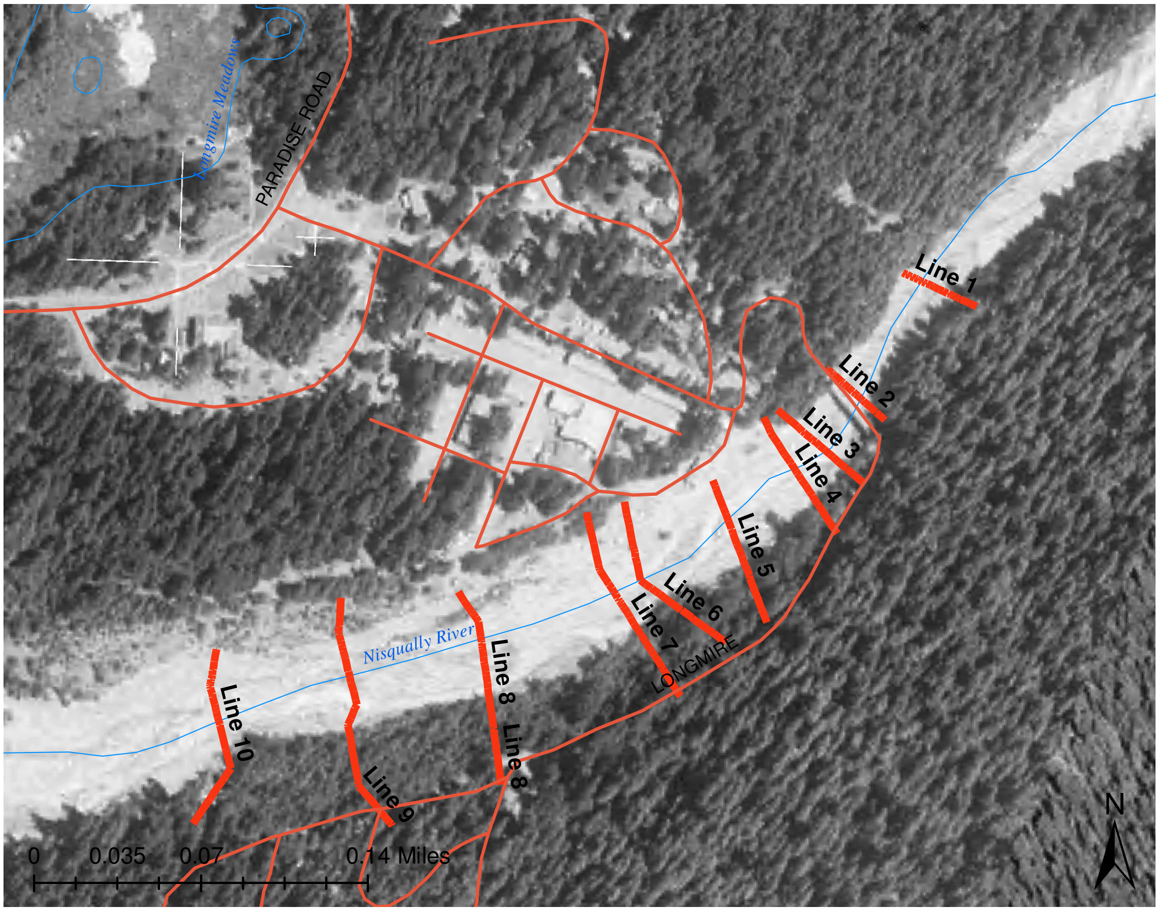
Study Areas

Since Mount Rainier encompasses such a large area, a summer-long study for the entire Park is virtually impossible. Instead, specific locations were picked for detailed study. These locations include places where there is a relatively high amount of human habitation or Park infrastructure. Detailed cross sections were measured in four locations (Figure 1.7); three along the Nisqually River (Longmire, Figure 1.8; Sunshine Point, Figure 1.9; and along the Lower Van Trump Hairpin, Figure 1.10) and one location along the White River (along State Highway 410, Figure 1.11). Cross Section data collected at these sites were used for longitudinal profile comparisons as well.

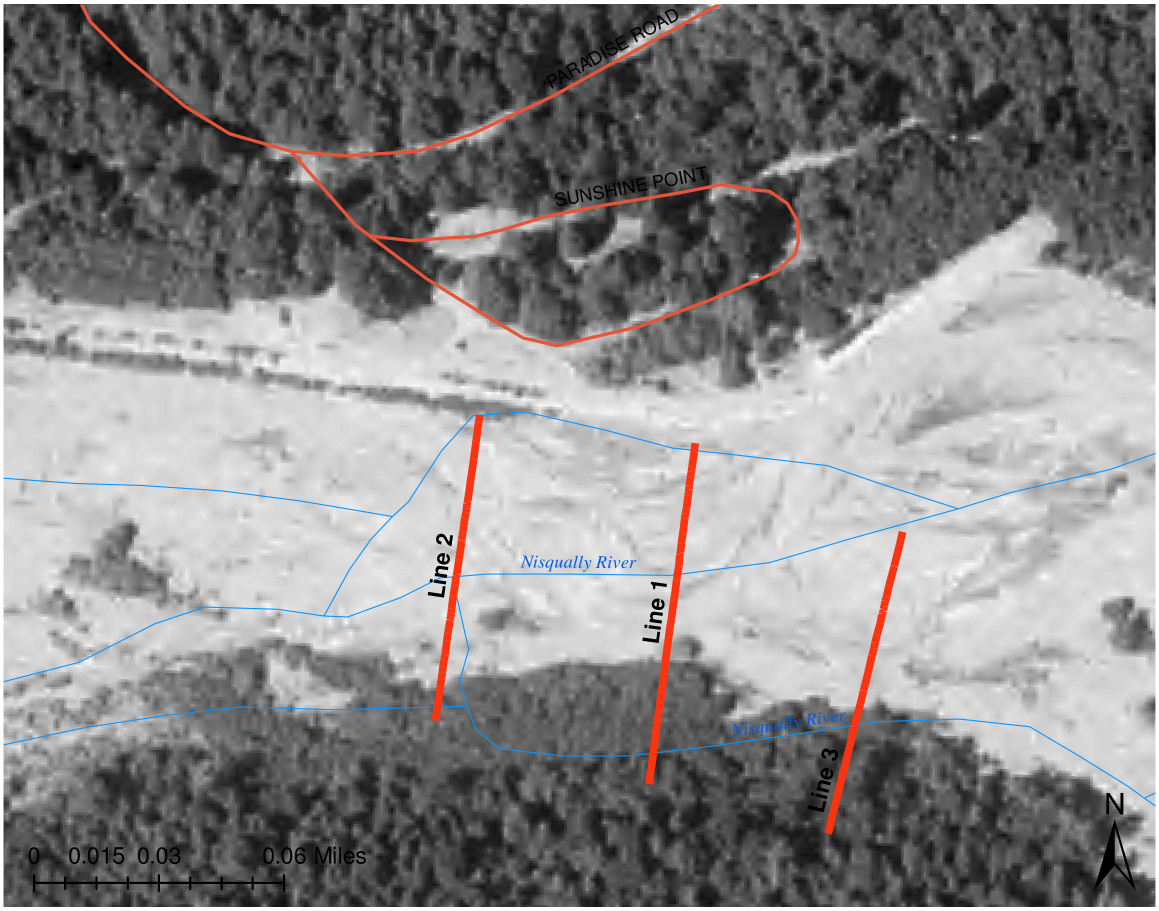
Historical topographic map analyses were carried out on five additional rivers (Carbon, Kautz, Nisqually, Tahoma and White; Figure 1.12) to determine historical rates of change in the braided river channels.



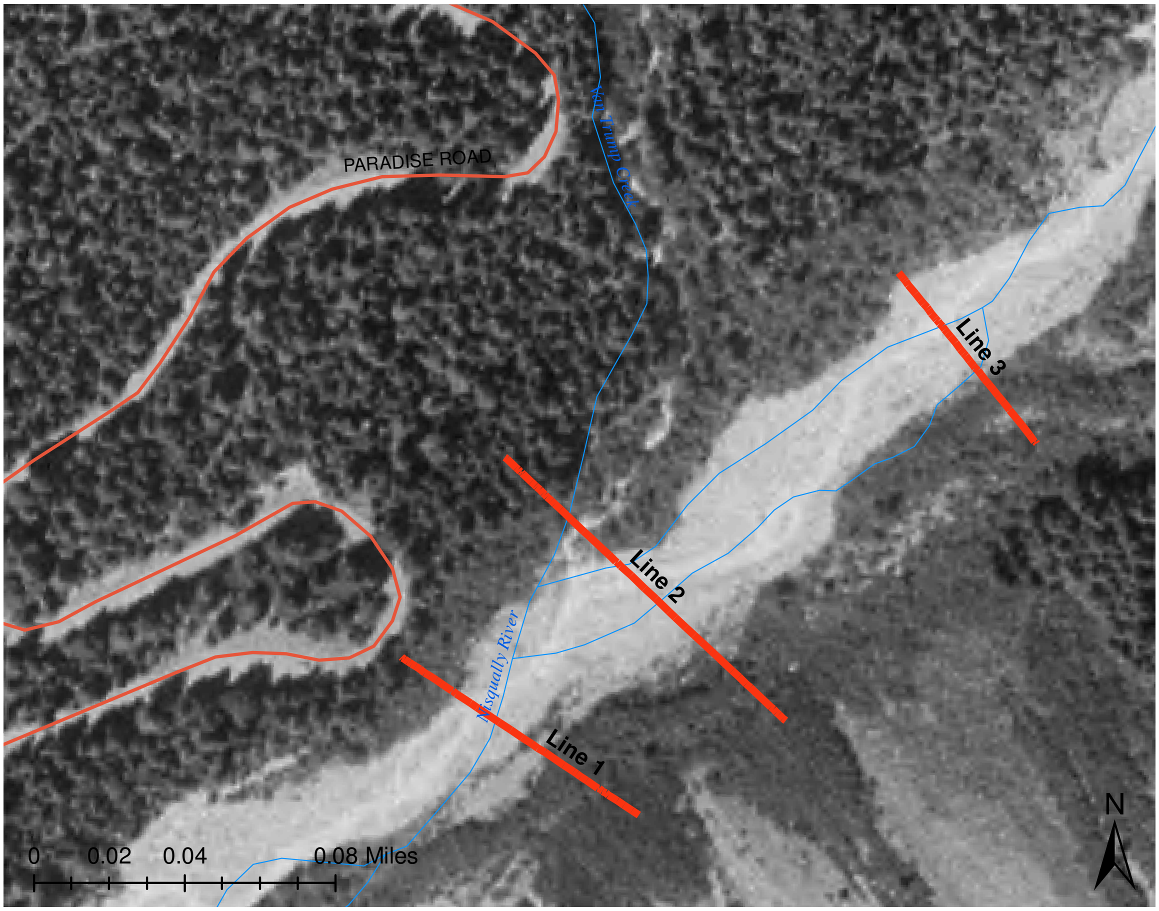
▲ FIGURE 1.7
Overview of detailed cross section locations.



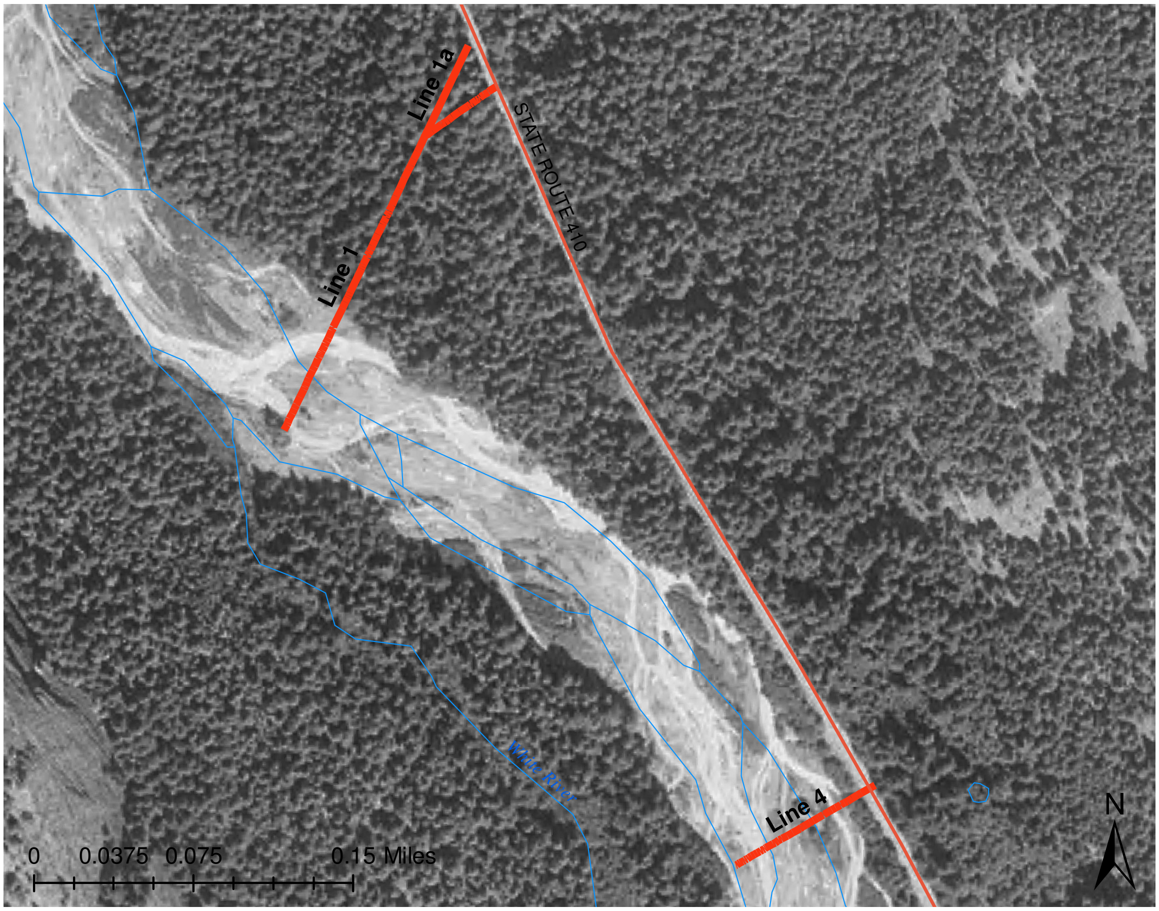
▲ FIGURE 1.8
Overview of cross sections at Longmire (Nisqually River). River flow is from upper right to lower left.



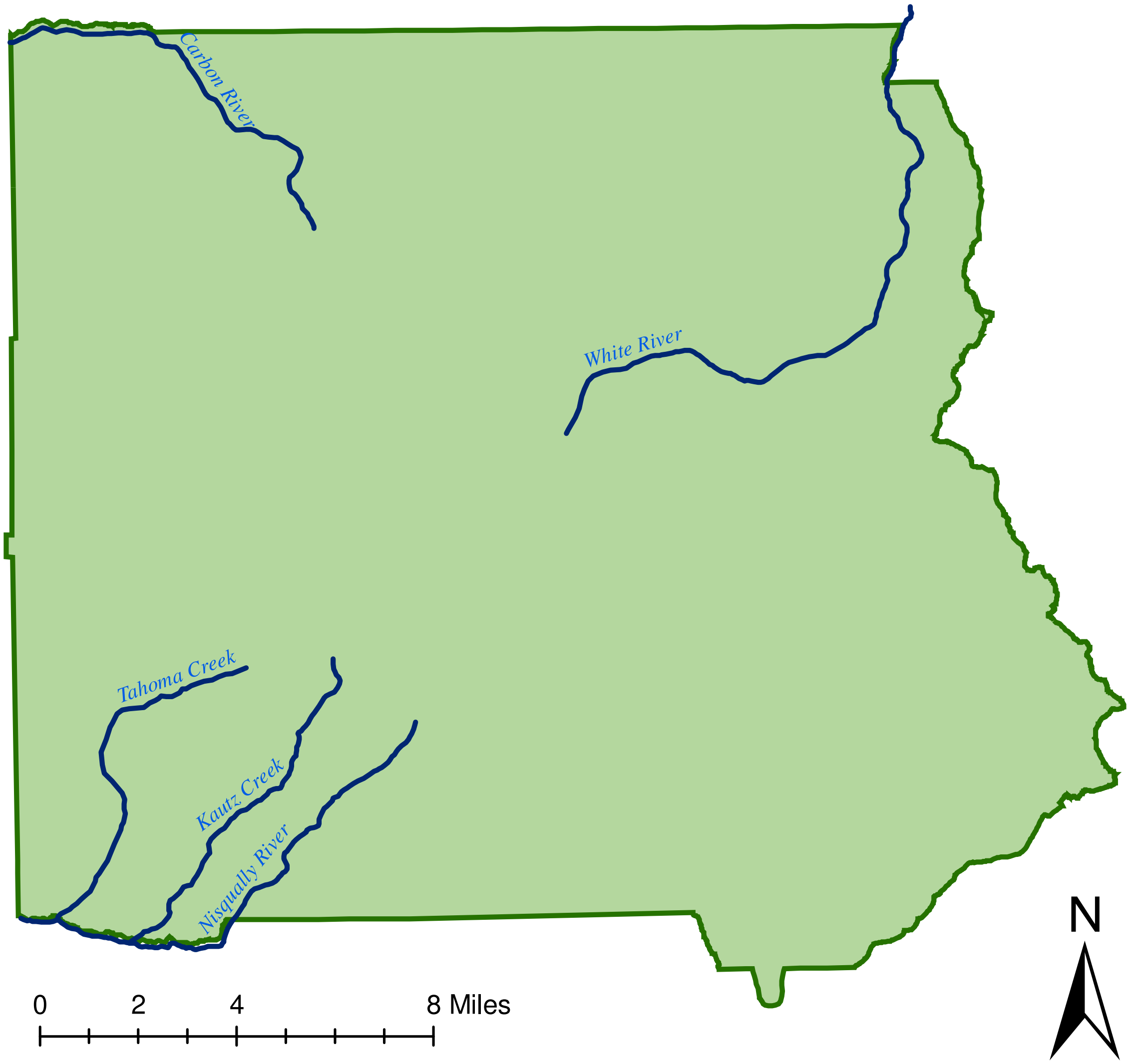
▲ FIGURE 1.9
Overview of cross sections at Sunshine Point (Nisqually River). River flow is from right to left.



▲ FIGURE 1.10
Overview of cross sections at Lower Van Trump Hairpin (Nisqually River/Van Trump Creek). River flow is from upper right to lower left.



▲ FIGURE 1.11
Overview of cross sections along Highway 410 (White River). Line 1 has a bend; Line 1a is straight. River flow is from lower right to upper left.



▲ FIGURE 1.12
Overview of rivers analyzed via historical topographic maps. Other rivers and creeks in the Park are not shown for clarity.

CHAPTER 2

PRIOR RESEARCH

Aggradation is defined as “the process of building up a surface by deposition” and an aggrading stream is “a stream that is actively building up its channel or floodplain by being supplied with more load than it is capable of transporting” (Bates and Jackson, 1984). Braided streams are a special type of river where sediment supplied to the stream is greater than it can remove (Bates and Jackson, 1984; Ritter et al., 2002). Because of the sediment load, bars and interlacing channels develop and change over time. By definition, aggradation is a natural geological process in a braided river system.

While many authors have discussed aggradation in various ways, aggradation in valley-confined alluvial fans on active volcanoes has been poorly studied. Mount Rainier has been studied by several authors in prior years looking at the geomorphic characteristics of the Nisqually and White Rivers.

The first major look at the rivers of Mount Rainier National Park occurred as part of a study conducted in 1910 looking at the hydroelectric possibilities in the Pierce and King county areas of Washington State (Henshaw and Parker, 1913). This included the White and Nisqually Rivers at Mount Rainier. This was also among the first surveys of the braided rivers in the Park (except for topographic maps). Henshaw and Parker conducted long profiles of the thalweg of both rivers from sink to source. These longitudinal profiles from 1910 provide the oldest set of historical data for this research project.

Perhaps one of the most famous historical geomorphologists in the Mount Rainier area was Robert K. Fahnestock. Fahnestock wrote several papers discussing various geomorphological concepts and published a comprehensive professional paper (1963) about the morphology and hydrology of the White River at Mount Rainier. The 70-page paper goes into great detail about the proglacial features observed in the outwash plain from the Emmons Glacier. The research includes several cross sections and discusses the observed rates of aggradation seen in the White River.

Leonard M. Nelson from the United States Geological Survey published a report (1982) about the flood characteristics for the Nisqually River and susceptibility of Sunshine Point and Longmire facilities to flooding. Nelson makes the point that flooding is generally not a problem unless dikes protecting infrastructure near the rivers are compromised (Nelson, 1982). Nelson also discusses peak flood flows and the expected flood elevation during 25, 50, 100 and 500 year flood flows.

As part of Mount Rainier's General Management Plan (GMP), a comprehensive geologic inventory of the Park was completed during the late 1990s. This part of the assessment was completed by Jon Riedel (1997), currently stationed at the North Cascades National Park in Northwestern Washington State. Cross sections surveyed at the Longmire Compound in Riedel's study were resurveyed in 2005 and 2006 in order to determine the change occurring in the rivers in the last 10 years. Riedel's study was primarily used to diagnose hazard risk analysis for many locations within the Park. These analyses use proximity to the volcano, visitor and employee use, and other factors to create a score for the geologic hazard associated with the location.

In October 2003, a large debris flow surged down Van Trump Creek, originating from the Van Trump Glaciers and ending in the Nisqually River valley. Katherine Donovan, a student from the School of Earth and Environmental Sciences at the University of Portsmouth, UK, studied these debris flows as part of a Bachelor's thesis (2005). Donovan discovered that the 2003 debris flows were caused by a small rock fall at 10,558 ft (3,218 m). The rock fall quickly entrained materials, and with a water composition of only 30%, mobilized into a debris flow. Much of this material was deposited in a debris fan adjacent to Lower Van Trump Hairpin in the Nisqually River's active channel. The volume estimate from the debris flow is 200,000 m^3. A similar debris flow occurred in this area in 2001, with a volume estimate of 160,000 m^3 (Donovan, 2005).

In 2005, Herrera Environmental Consultants, Inc., an interdisciplinary consulting firm based in Seattle, Washington, prepared a reach analysis of the White River for the Washington State Department of Transportation. The report identifies potential problem areas along State Route 410, including sections of the highway that fall within the borders of Mount Rainier National Park. The analysis found 16 areas that were either existing or potential problem locations. The research included several cross sections of the river itself. The Herrera Group was the first to document the fact that in at least one location, the elevation of the river is higher than State Route 410 running adjacent to the river. The current study reoccupied two cross sections Herrera Environmental Consultants occupied.

The 2006 survey team based measurements on the data supplied by a similar research team in 2005. Many of the cross sections measured by the 2005 team provided a baseline for surveying in 2006. For example, the 2005 team measured cross sections on a section of the Nisqually River that experienced a debris flow three months later. The 2006 team was able to successfully determine the exact amount of material that was deposited by this event because of the 2005 cross sections.

Much work has gone into the effects in stream channels in locations that have experienced recent denudation, either due to debris flows and landslides (Miller and Benda, 2000; Sutherland et al., 2002), fires (Hoffman and Gabet, 2007; Reneau et al., 2007) and volcanic eruption (Hayes et al., 2002; Lombard et al., 1981).

Shi (2004) found that slope differences upstream are more important than downstream controls in the rapidly aggrading Yellow River, China. Maren (2004) discusses the evolution of geomorphic processes in proglacial rivers. Lombard and others (1981) analyzed the channel conditions in the lower Toutle and Cowlitz Rivers following the 1980 eruption of Mount St. Helens. Several authors (Haritashya et al., 2006; Meunier et al., 2006; Hodgkins et al., 2003; Bhutiyani, 2000; and Hasnain and Thayyen, 1999) have worked at quantifying sediment load in proglacial streams from worldwide glaciers. Stott and Mount (2007) have investigated the implications of global warming on sediment flux from European glaciers.

The studies by other authors are quite different from the environment at Mount Rainier; however, the sedimentation rates observed and geomorphic characteristics can be compared for this study.

CHAPTER 3

MATERIALS AND METHODS

Several tools were used during the field research portion of this study, including a total station, Global Positioning System (GPS) receivers, and specialized chemical and physical water testing equipment.

Total Station

A Pentax PCS-2 electronic total station was used for construction of cross sections and long profiles during this research (Figure 3.1). A total station is an optical device that electronically calculates the horizontal angle, vertical angle and distance to a point of interest. Knowing the X, Y, and Z coordinates of the station and height of both the instrument and the height of a prism at the point of interest, the total station uses simple trigonometry to calculate the X, Y, and Z coordinates at the point of interest. A laser pulse is sent – or “shot” – out to a prism, a glass mirror that is attached to an adjustable height rod (this assembly will be called “the rod”; Figure 3.2). The station calculates the time taken to receive the pulse, and divides by the speed of light to calculate a distance.

A handheld TDS Recon data collector with Survey Pro version 4.2 software is tied in with the total station and receives information about each shot that is taken. The software stores the data and offers several useful functions for fieldwork. Positions for this study were recorded in the North American Datum (NAD) 1983 Washington State Plane South Zone coordinate system, with positions measured in U.S. Survey Feet.

▲ FIGURE 3.1
Pentax PCS-2 Electronic Total Station (Photo: Sharain Halmon, 7/27/2006).

▲ FIGURE 3.2
Prism and adjustable-height rod assembly (Photo: Scott Beason, 6/17/2006).

One of the first things the research team did was establish control points throughout the study area. A control point is a position marked with a nail driven into the ground. Flagging tape was attached to the control point for identification. Control points are temporary benchmarks that are used for measurements at locations away from established benchmarks. Some cross sections required the use of up to five or more control points due to interference of trees and other objects. The study incorporated USGS benchmarks where available (e.g. Longmire and Sunshine Point). Where USGS benchmarks were absent, a Trimble GPS Unit calculated the X, Y, and Z positions of at least two control points. Once two positions were known, the data could be georeferenced for analysis in GIS.

Setting up the total station can be an arduous task since the device must be almost perfectly level. A device that is even a little bit off level can give erroneous positions. Once the device is leveled, the next step is to tell the total station and data collector where it is actually sitting (i.e. the control point the station is standing over). Since the device has no reference to direction, the instrument must be “back sighted.” The rod is placed on another control point and a shot is taken to the prism. Distance is confirmed to ensure both positions and setup of the instrument are accurate. The device is then “zero-set,” meaning the horizontal angle is set to 0 degrees, 0 minutes, and 0 seconds in reference to the backsight location. The data collector’s software automatically adjusts all shots in reference to this location. If this step is not completed, all shots taken are shifted by some arbitrary direction (since the station assumes it is at the same position as its last use). These shots therefore have to be discarded and reshot.

After the total station is set up, leveled, back sighted and zero-set, it is ready to take shots. Shots are taken in one of two ways: sideshots or staking to a Line. A sideshot is a basic position measurement taken from the total station. One individual is assigned to the rod and one to the total station (with three workers, one is assigned to the data collector, speeding up the process). The total station is lined up with the prism and a shot is taken. Combined with the distance calculation, the total station calculates the horizontal and vertical angles to the prism. The data collector automatically downloads the information from the total station and a position identifier and description are entered in the data collector. Notes about the shot and a sketch of the area are entered in a field notebook. The person assigned to the rod then moves to the next position and the same process is repeated for the next shot.

Taking shots along a perfectly straight line is problematic, and when the shots for a line were downloaded after shooting several sideshots, sometimes positions would be a few feet off of the cross section's centerline. This problem is solved with a feature in the Survey Pro software called "stake to a line." At least two points (usually a start point and end point) are shot with the sideshot method. Then, in the software, the two points are entered into the stake to a line menu. The software calculates a line, and a shot is taken. The software runs through the trigonometry of the position in reference to the cross section transect and indicates if the position should move upstream, downstream or if it is on line. Positions that were within 0.1 ft of the cross section centerline were considered to be on line for the purpose of this study. When the position is on line with the cross section transect, the shot is saved and the rod person moves on to the next position on the transect.

Other useful functions of the total station and data collector include staking points, translating data, and rotating data. Staking a point is used if attempting to locate a surveyed position or control point. Translating and rotating data are used if no known benchmarks are present. An “imaginary” coordinate system is set up starting from the first surveyed position with made up X, Y, and Z positions (commonly, X = 5000, Y = 5000, and an estimate of the elevation based on topographic maps for the Z coordinate). If we happen to run into a benchmark or create a control point benchmark from the Trimble GPS, a position would be shot with the total station at that benchmark. The position coordinates (from the Trimble GPS or USGS benchmark data) are manually entered and the shots that were taken are shifted, or translated, to the actual coordinate system. The data would also be rotated to correct the difference between the assumed backsight direction and real direction that was estimated when originally setting up the job at that location. Once these functions are processed, the data are ready to download into a computer and imported into Geographic Information Software.

Trimble GPS

A Trimble Pathfinder Pro XR GPS device (Figure 3.3) was used many times during the course of the study. It has three main pieces: a receiver, a backpack-mounted battery pack and a handheld computer device. The Trimble GPS only takes positions when it sees enough satellites (more than 4) and when the signal strength is the greatest (Trimble, 2004). Signal strength is measured as Percent Dilution of Position (PDOP) and is the measure of the geometrical strength of the GPS satellite configuration (Trimble, 2004). This can be thought of as the amount of error in a position. If the PDOP is less than 6 (which equates to approximately 1 meter), the device is receiving the best accuracy. PDOPs of 4 to 8 are acceptable, and any PDOP greater than 8 indicates poor accuracy. The device will not take a position at PDOP value greater than 6 but can be custom configured to accept higher PDOP values (Trimble, 2004).

The Trimble was used in two ways for this study: finding positions and mapping positions. When the research team first was surveying positions in the active channel, the positions used were from both 1997 and 2005 data. These positions did not have a benchmark and had to be manually located. The GIS office at Mount Rainier National Park entered these positions into the Trimble and the positions were found and marked with a nail, later to be mapped with the total station. A handheld GPS also mapped these positions to make finding them easier when returning to map them with the total station.

The Trimble was also used in several areas to map locations where benchmarks were absent (Figure 3.3). The height of the receiver above the ground (mounted to a rod) is entered into the handheld computer. Then, several (usually more than 200) individual positions are taken in the same spot. These locations are downloaded and post-processed. Post processing of the data involves rectifying the locations and retrieving the average X, Y, and Z position of the location. This X, Y, and Z location was used as a control point benchmark. A rectified position has accuracies of around 0.5 m horizontally, and less than 1 m vertically (Trimble, 2004).

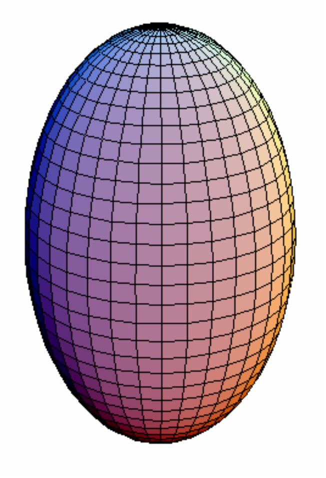
▲ FIGURE 3.3
Trimble Pathfinder Pro XR GPS shown mapping a control point (Photo: Scott Beason, 7/20/2006)

Handheld GPS

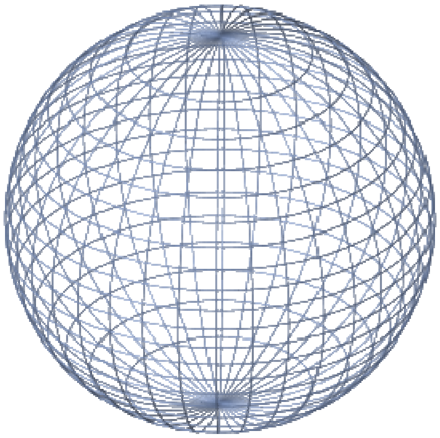
Handheld GPS units were extremely useful for this study; however, they were not used for the determination of critical position measurements. The GPS this study used was a Magellan eXplorist 210 (Figure 3.4). This GPS was primarily used to find control points and critical cross section points (endpoints and midpoints) in the active channel. One of the first things the study team noted in the braided river channel was how nearly impossible it was to find a nail with flagging tape in a boulder-dominated braided river channel. Despite position accuracies ranging between 7 and 30 feet on good days, the handheld GPS allowed us to find the control points much easier than wandering around the river channel looking for the point. The handheld GPS was also used to document locations of peculiar findings and to document locations of water samples taken for analysis for this study.

All three instruments – the total station, Trimble GPS and handheld GPS – worked in concert to make the field portion of this project proceed smoothly. Due to the provisions in the research permit with Mount Rainier National Park, control point benchmarks were required to be removed from the study area following completion of the data collection. Future study teams must relocate these positions.

▲ FIGURE 3.4
Magellan eXplorist 210 handheld GPS (Photo: Scott Beason).



▲ FIGURE 3.5
A prolate spheroid.



▲ FIGURE 3.6
A perfect sphere.

Accuracy of GPS and Total Station Units

One of the most important aspects of a study that is looking at rates of change in terms of feet per decade is accuracy of the surveying devices. We used three different devices for this study that had widely varying accuracies. Generally, the handheld GPS only had 7 ft (2.1 m) accuracy when standing in the middle of the braided channel with no cover; usually the positional error was around 30 ft (9.1 m). It was not unusual for a 100 to 200 ft (30 to 61 m) or more error to exist in areas with tree cover.

The volume of space a theoretical point could lie within as calculated by the various survey devices is expressed by a prolate spheroid[1] (Figure 3.5; Equation 1). Where the horizontal and vertical errors are the same (i.e. the total station and handheld GPS), Equation 1 generates the same volume as a perfect sphere (Figure 3.6; Equation 2). Therefore, the positional error of all devices can be calculated by Equation 1.

$$V = \frac{4}{3}\pi a b^2 \qquad \text{(Equation 1)}$$

$$V = \frac{4}{3}\pi r^3 \qquad \text{(Equation 2)}$$

In Equation 1, *a* represents the semi-major axis length (the horizontal error) and *b* represents the semi-minor axis length (the vertical error). Table 3.1 shows the accuracies of the various devices based on their horizontal and vertical errors. A small change in the horizontal and vertical error results in a very large area change. Obviously, for a study like this, the smallest area possible is ideal for the calculation of aggradation in a braided river channel.

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[1] Since the vertical error is greater than the horizontal error in the Trimble GPS, the resulting ellipsoid is a prolate spheroid. If the reverse were true, the ellipsoid would be an oblate spheroid.

Device Type	Horizontal Error, a (m)	Vertical Error, b (m)	Volume (m^3)
Handheld GPS (Typical)	9.14	9.14	3202.56
Handheld GPS (Best)	2.13	2.13	40.68
Trimble GPS	0.5	1	2.09
Total Station	0.0095	0.0095	0.0000036

▲TABLE 3.1
Positional accuracy in surveying equipment. Volume calculated as a prolate spheroid with Equation 1. Horizontal and vertical error data is from: Handheld GPS (Observed values), Trimble GPS (Trimble, 2004), Total Station (Dunn, personal communication, 2006).

The Trimble GPS unit had a much better positional accuracy than the handheld GPS, as it only took positions when it received a certain number of satellites and the quality of the signal was above a certain limit. Neither of the GPS devices had anywhere near the accuracy of the total station, which had a vertical and horizontal error of approximately 0.375 in (0.96 cm; Dunn, personal communication, 2006)[2].

Post Processing of Total Station Data

The process of actually getting the X, Y, and Z data into GIS is less than straightforward. Data are exported from Survey Pro and downloaded to a computer. The data are imported into Microsoft Access and saved as a database file. In ArcGIS, the data are added to a map of the area. A digitized cross section centerline transect is added to

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[2] Personal Communication from John Dunn, regarding the accuracy of the Total Station:

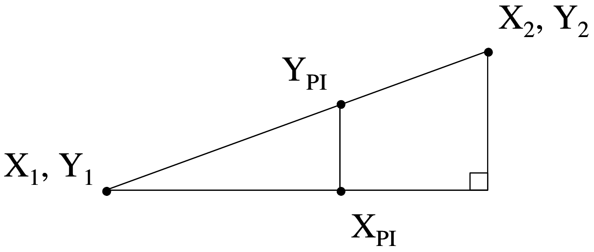
> "The instrument is a 5 second instrument, meaning it will measure a horizontal or vertical angle to the nearest 5 seconds of angular measurement. 5 seconds of error over 1000 feet of horizontal distance equates to an offset error in the coordinate value of the point of 0.02 feet or ¼ inch. The same value applies to vertical measurements as well. The ppm error applies to distance measurement and, while I don't know the exact specs of the Pentax instrument, is typically a 2 mm ± 2 ppm. This means there is always about 2 mm of error in any distance shot in addition to an error which is a function of the length of measurement. At the 1000 foot range, your total distance measurement error is about 3 mm or 0.01 feet (1/8 inch). Basically all of your measurements, discounting rod errors, should be better than 3/8-inch tolerance."

show the cross section line that is being measured. This line is then split at each surveyed point and the length of that line segment is calculated with a formula in GIS.

In Microsoft Excel, the point data (X, Y, and Z) and line data (length between each point) are added to a spreadsheet. A running total length of the cross section at each point is then calculated. The elevation at each point (Y-axis) and length along cross section (X-axis) are added to an X Y chart to graphically display the cross section. Data from previous years are added as well to show the change over time.

The data from Excel are added to another custom-written spreadsheet to calculate the area of each year's cross section (i.e., the area under the curve in the X Y graph described in the previous paragraph). The spreadsheet calculates the total area for each year (1997, 2005 and 2006) and then displays the net change between surveyed periods and the average change along the section per year (examples can be seen in Appendix A).

Occasionally when comparing cross sections, two lines may not end or start at the same location. Therefore, the lengths of cross sections cannot be compared unless the cross sections are clipped to the same start and end values. A measured cross section transect may also include areas adjacent to the river channel and thus will include data that is not relevant to the cross section. Using right angle trigonometry, a position along a line between two measured points can be calculated, clipping the transect to the necessary lengths (e.g. Point Y_{PI} in Figure 3.7). A mathematical formula can determine the elevation of a point along the line (Equation 3) or the position of an elevation along the line (Equation 4) between two points. It is important to note that no data loss occurs when clipping lines using this method.



▲ FIGURE 3.7
Diagram of right angle trigonometry used to find points Y_{PI} and X_{PI} given two surveyed X, Y positions, (X_1, Y_1) and (X_2, Y_2).

Generally, an X position is a distance along a constructed cross section, and a Y position is the elevation above a datum (also known as the Z position). Equation 3 finds an unknown Y position (Y_{PI}) at an X position (X_{PI}) based on an X, Y point before (X_1, Y_1) and after (X_2, Y_2), where $X_1 > X_{PI} < X_2$.

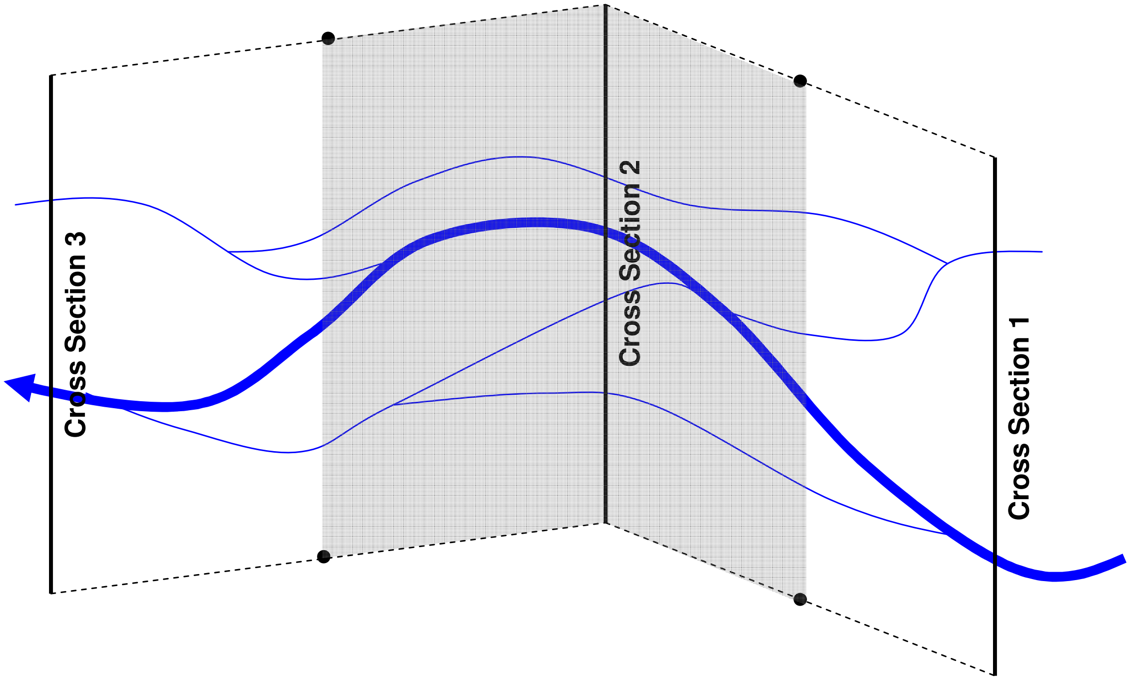
$$Y_{PI} = Y_1 + \left\{ (Y_2 - Y_1) \left[\frac{X_{PI} - X_1}{X_2 - X_1} \right] \right\} \qquad \text{(Equation 3)}$$

Equation 4 finds an unknown X position (X_{PI}) at a Y position (Y_{PI}) based on an X, Y point before (X_1, Y_1) and after (X_2, Y_2), where $Y_1 > Y_{PI} < Y_2$.

$$X_{PI} = X_1 + \left\{ (X_2 - X_1) \left[\frac{Y_{PI} - Y_1}{Y_2 - Y_1} \right] \right\} \qquad \text{(Equation 4)}$$

The area of the stream channel that each cross section represents is calculated in GIS. The midpoint between two cross sections is found and a polygon is digitized atop the active channel. The polygon for a cross section covers half of the area to the previous cross section and half of the area to the next cross section (Figure 3.8). The area of each polygon is then calculated with a formula in GIS. In a spreadsheet, the average yearly change for a cross section and the area the cross section represents are entered to calculate the area-weighted net aggradation along that stretch of the river.

The result of all these steps is a number that represents the average aggradation that any one spot along the surveyed region has changed over duration of time.



▲ FIGURE 3.8
Hypothetical map view showing area of a stream channel represented by Cross Section 2 (shaded in gray). The area is half of the area from Line 1 to 2 appended to half of the area from Line 2 to 3. Dots are the midway points between cross sections. Cross sections shown in this figure are examples only.

Historical Topographic Map Analysis

Historical topographic maps were analyzed in Geographic Information Software. Maps from 1907, 1915, 1924, 1938, 1955, and 1971 were digitized and georeferenced. A common stream centerline was created and whenever the stream crossed a contour line, the stream centerline was split at the intersection. Using a formula in GIS, the split centerline distance was calculated for each segment. Due to the accuracy of data, the 1907 topographic map was discarded as its contour lines had 1000 foot contour intervals. The datum used for the 1924, 1938, and 1955 maps were the same as used in 1915, so the 1924, 1938, and 1955 maps were discarded. The final comparison was calculated between the 1915 map (which had 100-foot accuracy) and the 1971 map (with 40 foot accuracy). The split distance and elevation data were added to a database in a custom written computer script which calculates the net change, yearly change, and graphs the longitudinal profile. It is important to note that the possible error with topographic maps is much greater than using a GPS or total station.

Chemical & Sediment Analysis

During the course of the summer 2006 study period at Mount Rainier, water samples were collected from several locations in the Park (Figure 3.9; Table 3.2). Eleven (11) 120-mL water samples were collected four times during the summer for chemical ion analysis (a total of 44 samples). Sixteen (16) 1-L water samples were collected randomly throughout the summer for suspended sediment analysis. The chemical samples were collected on June 19, July 5, July 21, and August 7. Seven (7) additional 120-mL chemical samples were collected during March 2006 from the Nisqually River at

Longmire for a winter to summer comparison. All samples were collected in High Density Polyethylene (HDPE) EPA level 1 plastic bottles.

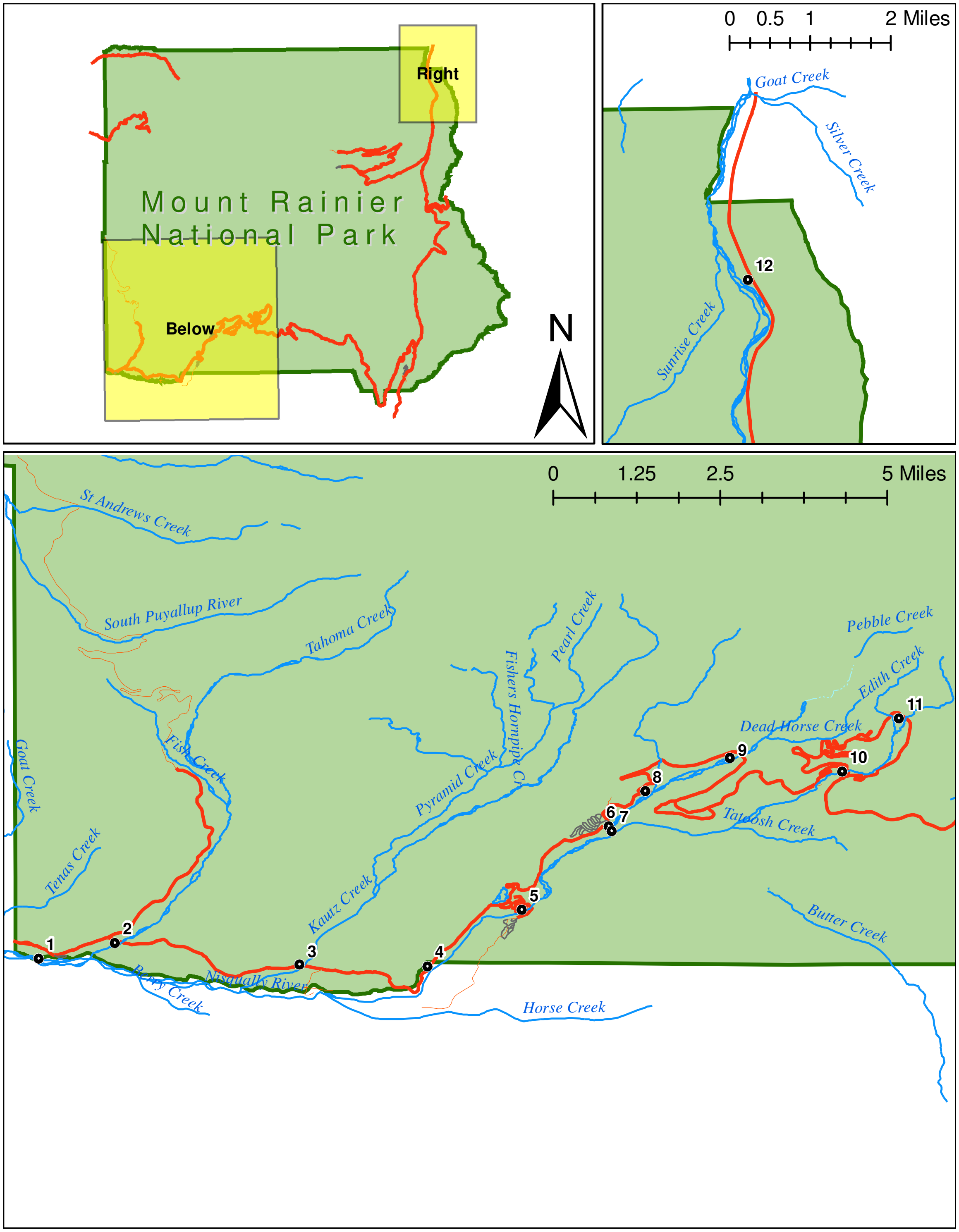
The first 11 sites were sampled during each of the four sample collection days in the field (site 12 was only sampled one time at the end of the summer research period). Field characteristics such as Total Dissolved Solids (TDS), Conductivity (EC), pH, and temperature were measured using a pH/EC/TDS probe (Hanna Instruments), and a double-junction pH probe (Oakton Instruments). A dissolved oxygen meter was also going to be used, but was damaged during shipment to the field location. A 120-mL bottle was labeled with the site location (1-11) and date of sampling (A-D – i.e.: sampling site 3 on the second collection day would give a sample identifier of 3B). The water bottle was filled and emptied, then filled again in order to get an uncontaminated sample. In a few specific locations, a 1-L bottle would be filled in a similar manner for suspended sediment analysis. Suspended samples were generally collected from sites 1 and 6 during the chemical water sampling. Site 1 was at the far reach of the Nisqually at Sunshine Point (the farthest location from the Nisqually Glacier along the Nisqually River while still in the Park) and site 6 was a particularly high energy location of the Nisqually River near Cougar Rock. Other sites were sampled for suspended sediments only when high sediment loads were noted. Site 12 was sampled late in the summer along a stretch of the White River that flowed near Highway 410.

During the first two sampling periods, TDS and EC values were so low that it was thought the equipment was malfunctioning. Because of this, the data were not recorded. However, after a second probe was sent and showed similar values, it was evident that there was not enough time to allow ion dissolution in the water to record any measurable TDS and EC values. This is expected given the proximity to the terminus of the glaciers and headwaters of the rivers in question.

The concentrations of chloride, nitrate and sulfate in water samples were determined with a Dionex ® (Model DX-120) ion chromatograph with suppressed conductivity. Ion elution was accomplished using a CO_3-HCO_3 solution. Before analyzing the samples, dionized water was injected to verify the stability of the machine. Flow rate was set at 1.75 mL/min. Known standards of target anions (5, 25, 50 ppm) were used for machine calibration, and a 25 ppm standard solution was used to check the validity of the calibration. Samples were filtered using a 0.2 µm syringe filter (Nalgene filter with polytetrafluoroethylene), which was attached to a 10 mL syringe. The syringe was thoroughly cleaned between sample injections. Approximately 0.3 mL of filtered sample was injected into the chromatograph to detect chloride, nitrate and sulfate. The samples flowed from the injection loop first to the guard column (AG14) and then to the anion exchange column (AS14) and finally to the ASRS (4 mm) suppressor to complete the cycle. The peak retention times for chloride, nitrate and sulfate were 2.5 min, 4.4 min and 8.6 min, respectively. The analytical margin of error was ± 0.5 mg/L.

The DX-120 IC system is a high precision ion analyzer, which controls the chromatograph procedure by using PeakNet bundled software from a workstation. All retention peaks are directly visible on the monitor during sample runs. The machine is suitable for a wide range of anions and cations found in both fresh and polluted surface water and groundwater samples. The equipment performs all types of isocratic IC separations using conductivity detection (Dionex, 1997). Its simple design, precision and reliability make it easy to take advantage of the applications and high performance. The DX-120 is compatible with all Dionex anion and cation exchange columns. Built-in digital conductivity detection and auto-suppression technology using the Dionex SRS Self-Regenerating Suppressor provide highly selective and sensitive analysis, superior detection limits, and a broad dynamic range with ease of use. The chromatography work station provides tools to control and automate data management. It wraps all aspects of data collection, data analysis, and reporting into an integrated multitasking Windows environment. PeakNet makes it possible to quickly optimize baselines, compare chromatograms, subtract backgrounds, fit calibration curves, reprocess data – and do it all at the same time on multiple samples.

Suspended sediment samples were analyzed using a force-fed vacuum filtration method. Filtration was accomplished using non-sterile Fisher Scientific Fisherbrand 0.2 μm Nitrocellulose general filtration membranes. The weight of the filter was measured using a high-precision Fisher EMD XE series (Model 100A) electronic balance with ten-thousandths gram accuracy (0.0001 g). The filter was placed in the funnel of the sampling apparatus and water was fed into the equipment. After passing through the filter, water accumulated in a 1000 mL glass Pyrex flask. Once all the water was emptied from the sample container, the volume of the water was computed. The filter was dried for 24 hours and the weight of the filter and sediment were measured with the balance. Measurements were converted into g/L and mg/L for comparison.



▲ Figure 3.9
Map of locations of water samples collected during summer 2006.

Site	River	Latitude	Longitude	Elevation
1	Nisqually	46.73805	-121.91318	2,040
2	Tahoma	46.74135	-121.89660	2,161
3	Kautz	46.73675	-121.85663	2,421
4	Nisqually	46.73633	-121.82895	2,581
5	Nisqually	46.74865	-121.80845	2,791
6	Nisqually	46.76667	-121.78963	3,175
7	Paradise	46.76568	-121.78902	3,134
8	Van Trump	46.77433	-121.78172	3,393
9	Nisqually	46.78152	-121.76340	3,814
10	Paradise	46.77853	-121.73912	4,828
11	Paradise	46.79007	-121.72682	5,270
12	White	46.96617	-121.53062	2,843

▲ TABLE 3.2

GPS positions, river name, and elevation of 12 water sampling locations in summer 2006 study. Refer to Figure 3.9 for location.

CHAPTER 4

RESULTS

Cross Section Results

Detailed cross sections were surveyed at four locations in the Park during the summer research period. These locations include 10 cross sections at Longmire, 3 at Sunshine Point, and 3 at the Lower Van Trump Hairpin for the Nisqually River and 2 locations along Highway 410 for the White River.

Nisqually River at Longmire

Ten cross sections were surveyed near the Longmire compound from June 12 – July 27, 2006 (Figure 1.8) and the results compared with surveys from 1997 and 2005. Figures 4.1 – 4.10 show the graphical representation of the cross sections. Data from these cross sections were imported into an Excel spreadsheet to calculate the net change over time (Appendix A). Seven of the 10 cross sections show a net increase in elevation, from 0.013 to 0.217 ft/yr (0.396 to 6.614 cm/yr) The remaining three cross sections showed a net decrease ranging from -0.021 to -0.073 ft/yr (-0.640 to 2.225 cm/yr).

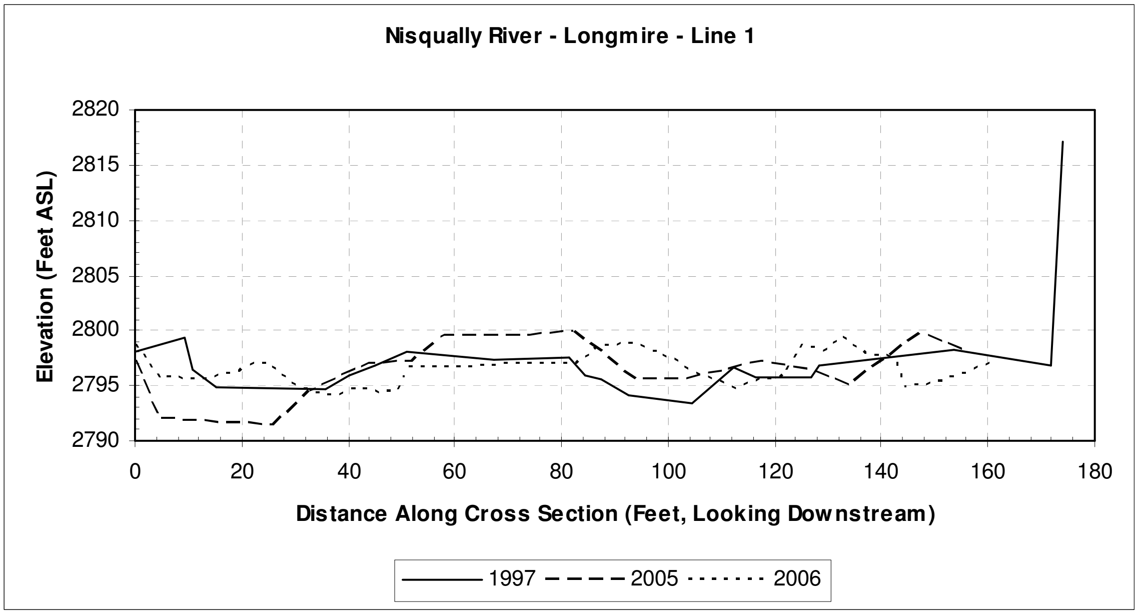
Table 4.1 shows the aggradation rate for each line at Longmire and the area the cross sections represent (Appendix B). The total weighted average aggradation rate is calculated as:

$$Ag_W = \frac{\sum_{i=1}^{n} A_i R_i}{\sum_{i=1}^{n} A_i} \qquad \text{(Equation 5)}$$

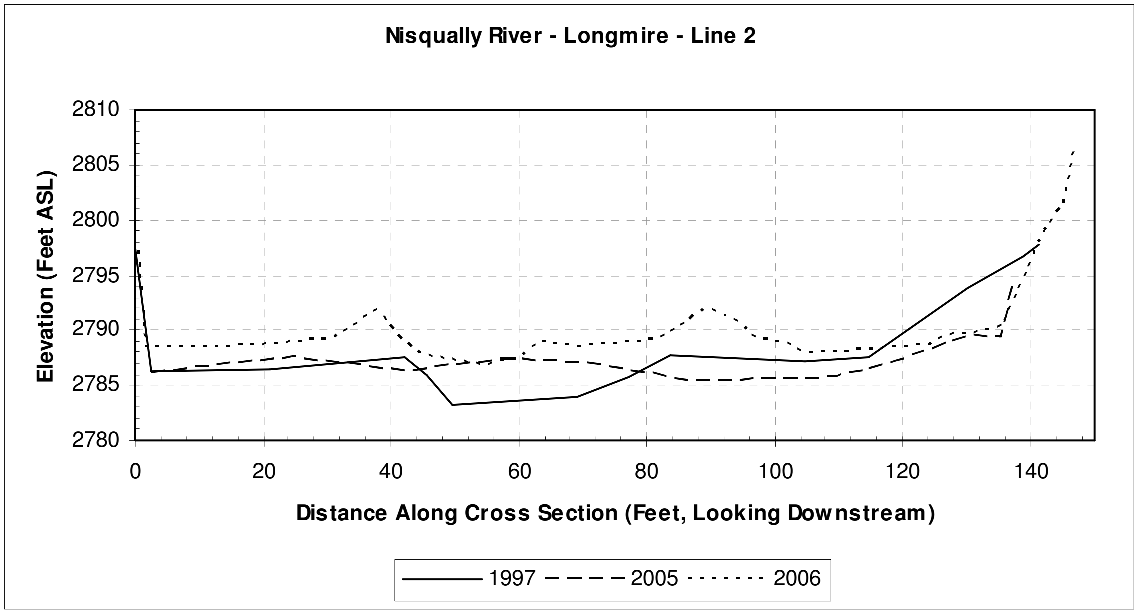
Where Ag_W is the weighted aggradation rate, A_i is area represented by a single cross section and R_i is the aggradation rate for n cross sections. This formula takes all cross sections into account for the summation of an aggradation rate. All weighted aggradation rates in this paper use Equation 5.

The aggradation rate for all cross sections at Longmire is 6.494 in/decade (16.495 cm/decade; Table 4.1). Assuming a 10-cubic yard dump truck, the rate equates to the volume of approximately 303 dump trucks worth of material accumulating in the reach in a decade. Cross sections near the man-made levee at Longmire showed a trend where, for the most part, the narrower the active channel, the higher the rate of aggradation. These cross sections were isolated and the rate was found to be higher, i.e., 12.139 in/decade (30.833 cm/decade), or 172 dump trucks (Table 4.2). The lower volume is due to a smaller area being analyzed.

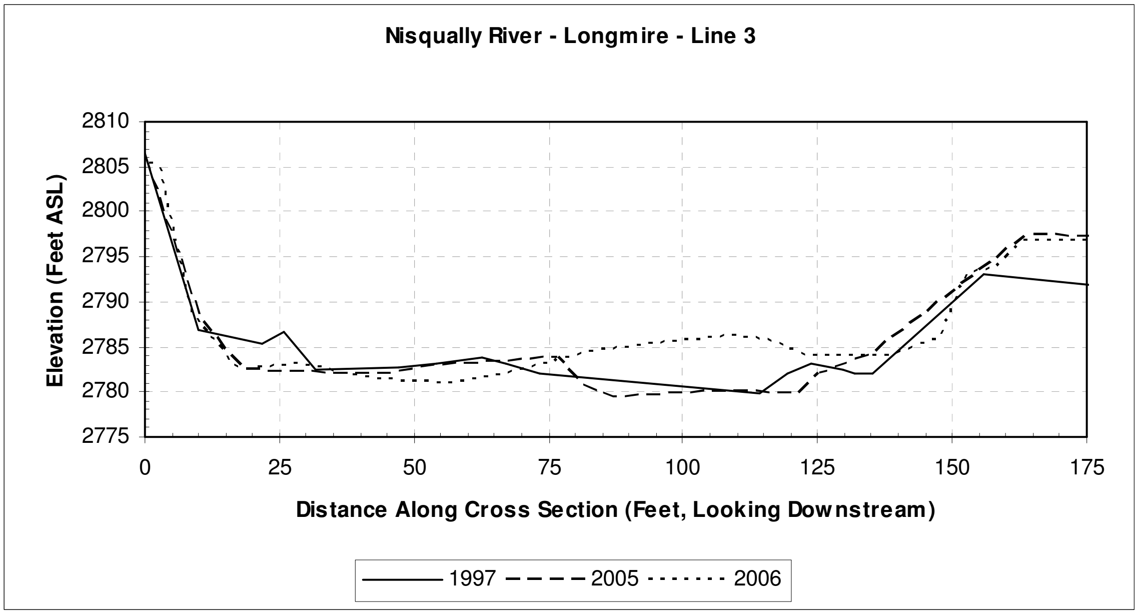
One observation noted when setting up control points for the locations at Longmire was that the river bed is higher than most of the adjacent Park infrastructure. For example, the lowest point on Cross section 3 is at 2781.02 ft (847.65 m). A control point in the compound approximately 1100 ft (335 m) to the west of cross section 3 has an elevation of 2751.67 ft (838.71 m), or approximately 29 ft (9 m) lower than the river bed. The height of the levee along that transect of the line is approximately 2797 ft (853 m), so the river would have to either have a significant flood or compromise the levee in that area in order to flood the Longmire area. It should be noted that the aggradation rate here is higher (Table 4.2) than the rest of the Longmire compound (Table 4.1) due to slope differences.



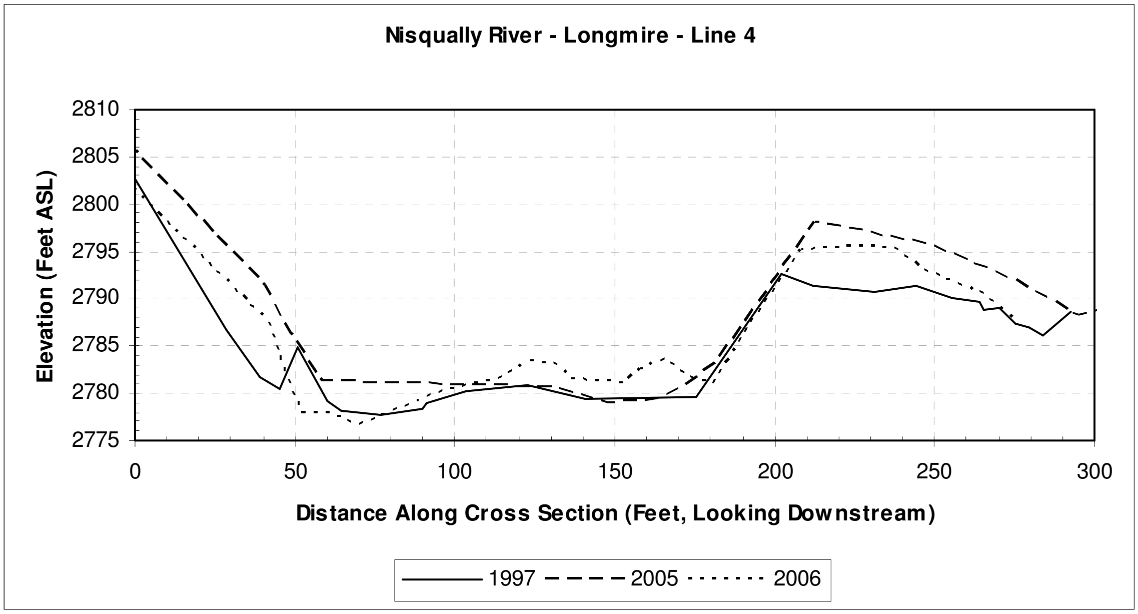
▲ FIGURE 4.1
Cross Section 1 at Longmire (Nisqually River). Vertical Exaggeration ≈ 2.0x.



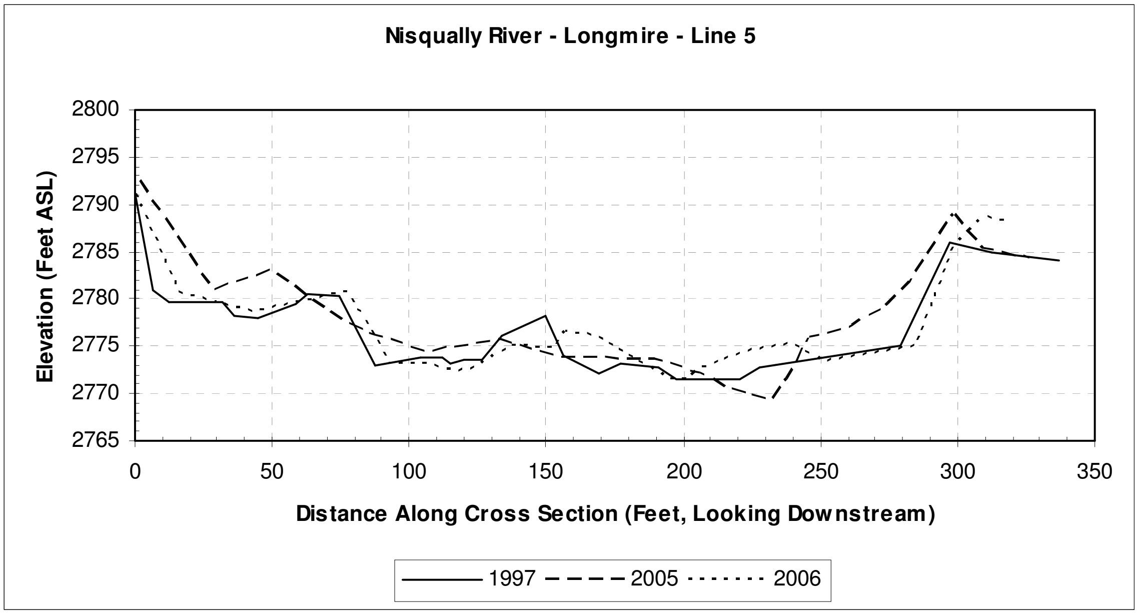
▲ FIGURE 4.2
Cross Section 2 at Longmire (Nisqually River). Vertical Exaggeration ≈ 1.7x.



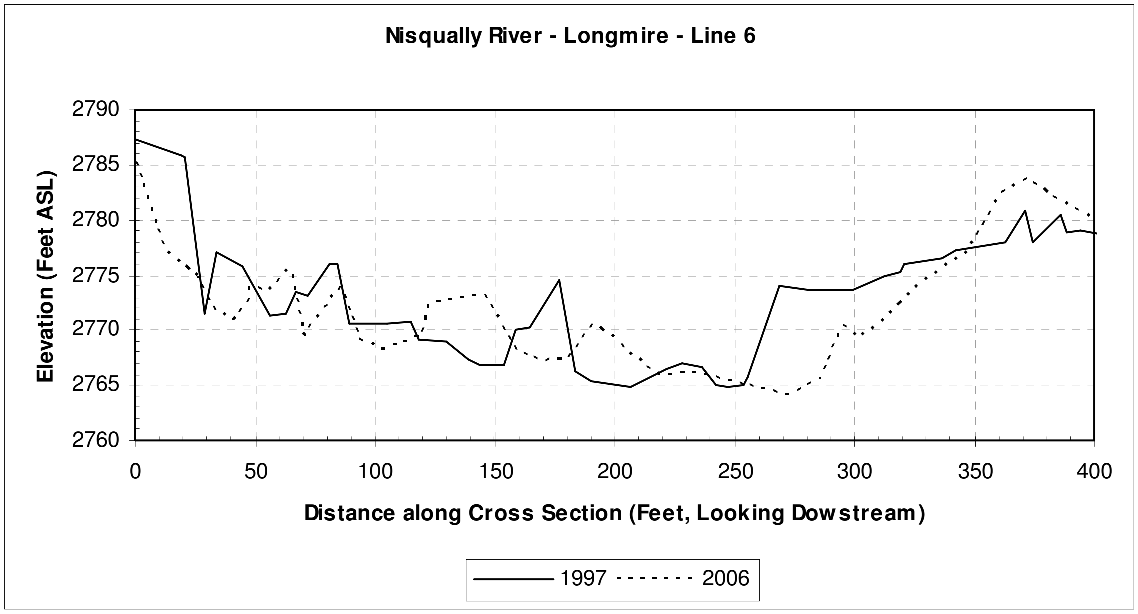
▲ FIGURE 4.3
Cross Section 3 at Longmire (Nisqually River). Vertical Exaggeration ≈ 1.7x.



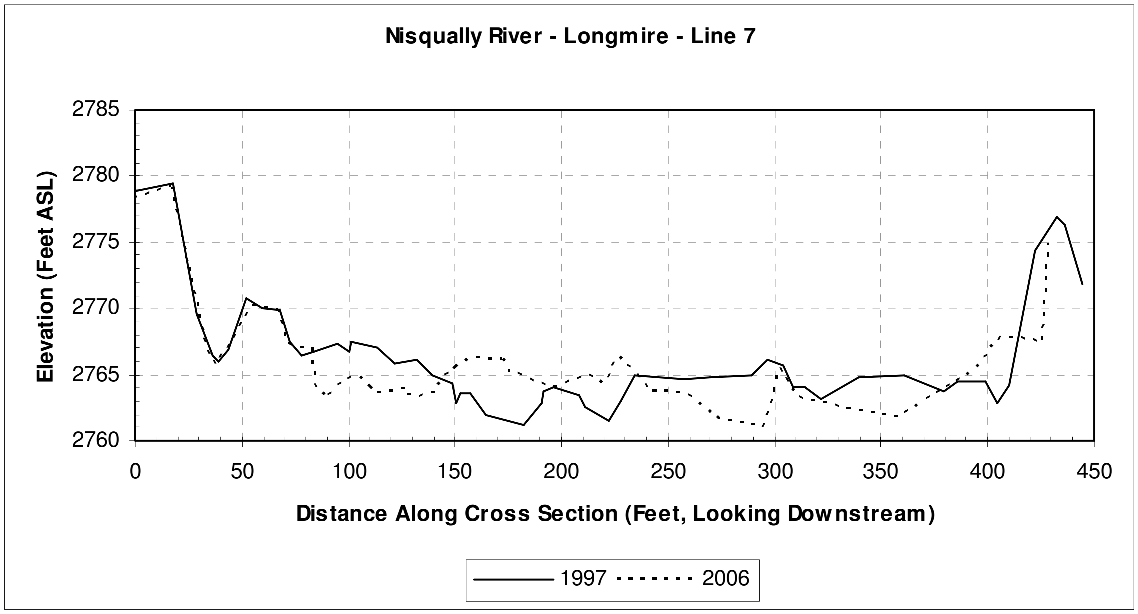
▲ FIGURE 4.4
Cross Section 4 at Longmire (Nisqually River). Vertical Exaggeration ≈ 3.0x.



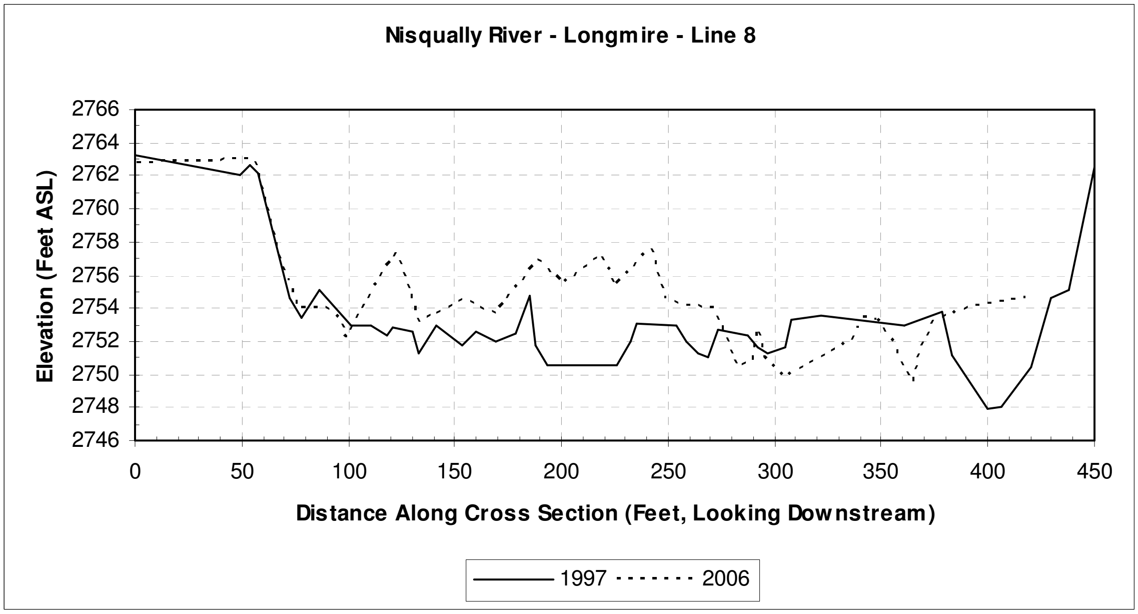
▲ FIGURE 4.5
Cross Section 5 at Longmire (Nisqually River). Vertical Exaggeration ≈ 3.3x.



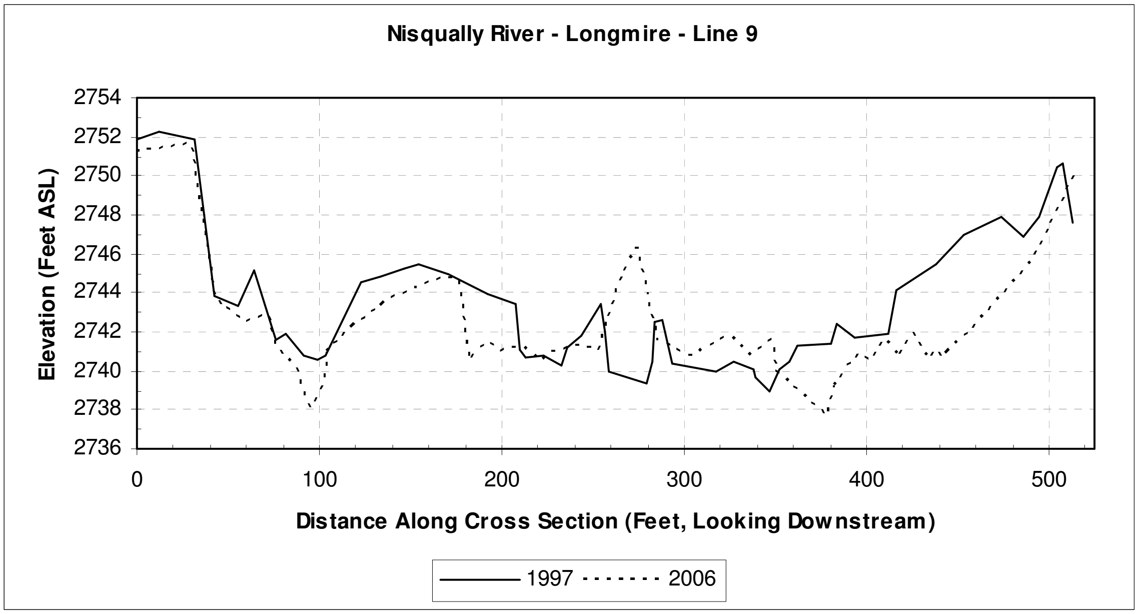
▲ FIGURE 4.6
Cross Section 6 at Longmire (Nisqually River). Vertical Exaggeration ≈ 4.6x.



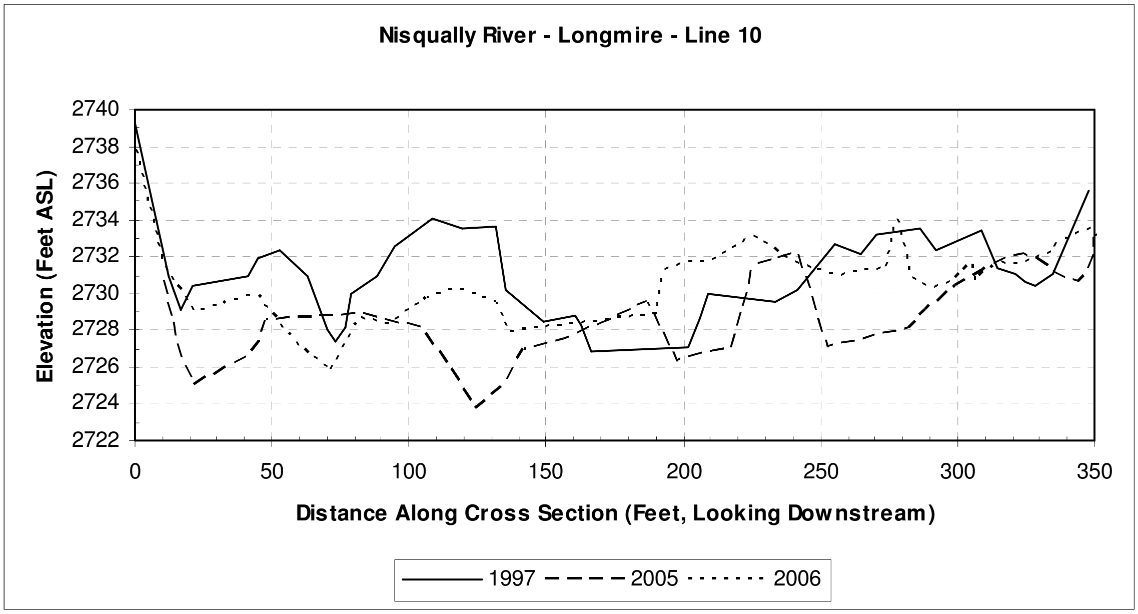
▲ FIGURE 4.7
Cross Section 7 at Longmire (Nisqually River). Vertical Exaggeration ≈ 6.0x.



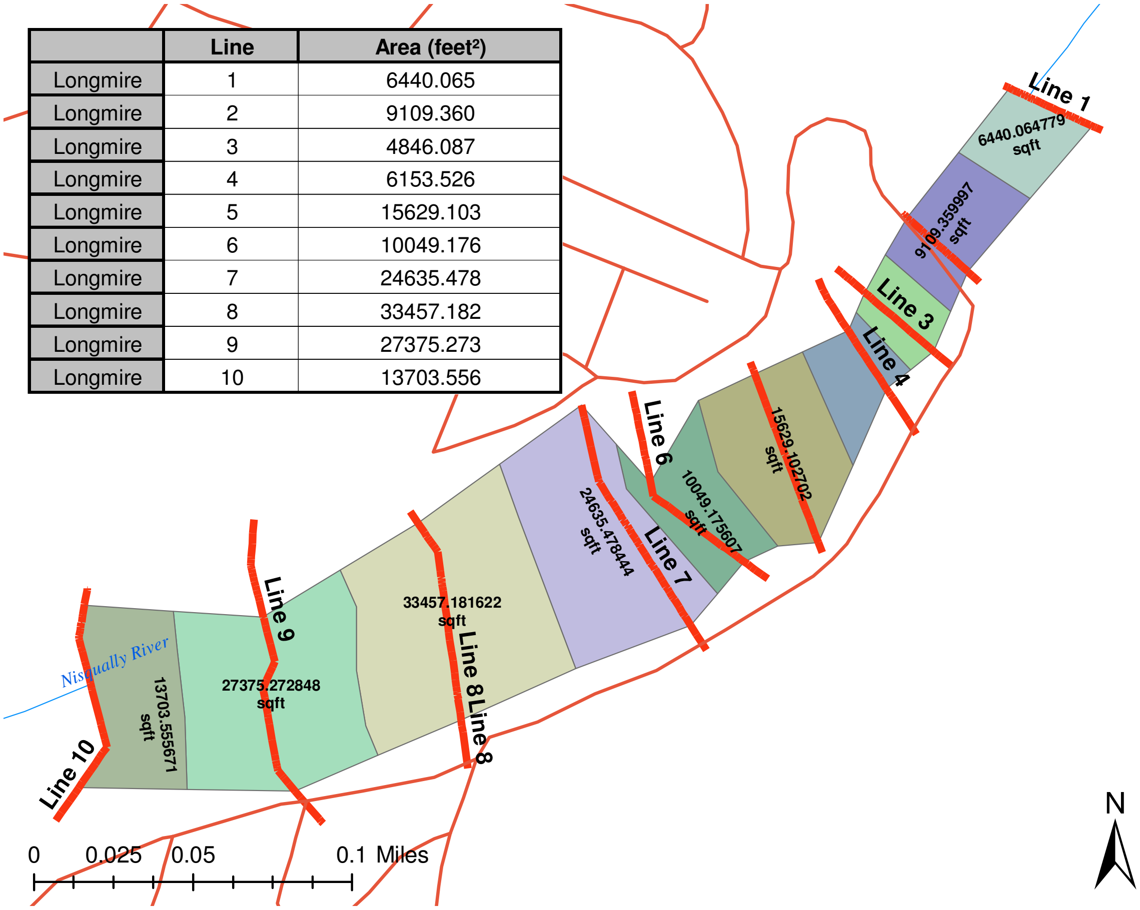
▲ FIGURE 4.8
Cross Section 8 at Longmire (Nisqually River). Vertical Exaggeration ≈ 7.7x.



▲ FIGURE 4.9
Cross Section 9 at Longmire (Nisqually River). Vertical Exaggeration ≈ 10.6x.



▲ FIGURE 4.10
Cross Section 10 at Longmire (Nisqually River). Vertical Exaggeration ≈ 6.6x.



	Line	Area (feet²)
Longmire	1	6440.065
Longmire	2	9109.360
Longmire	3	4846.087
Longmire	4	6153.526
Longmire	5	15629.103
Longmire	6	10049.176
Longmire	7	24635.478
Longmire	8	33457.182
Longmire	9	27375.273
Longmire	10	13703.556

▲ FIGURE 4.11
Area represented by individual cross sections at Longmire.

Line	Area (ft^2)	Aggradation Rate (1997-2006, ft/year)	Area * Rate (ft^3/year)	
1	6,440.065	0.013	85.202	
2	9,109.360	0.217	1,972.541	
3	4,846.087	0.037	181.050	
4	6,153.526	0.079	483.667	
5	15,629.103	0.049	768.327	
6	10,049.176	0.122	1,226.200	
7	24,635.478	-0.038	-946.495	
8	33,457.182	0.179	6,000.880	
9	27,375.273	-0.021	-583.093	
10	13,703.556	-0.073	-995.700	
Σ(Area):	151,398.805	**Σ(Area * Rate):**	8,192.578	**ft^3/year**

Weighted Average Aggradation:	0.054	**ft/year**
	0.649	**in/year**

Average Aggradation:	**6.494**	**in/decade**
	0.541	**ft/decade**

Volume in a Decade:	81,925.783	**ft^3**
Volume of Total Increase:	3,034.285	**yards^3**
Dump Trucks (10 yard^3 capacity):	**303.43**	**per decade**
Dump Trucks per year:	**30.34**	

▲ TABLE 4.1
Average aggradation amount for all cross sections at Longmire. Aggradation rates from Appendix A. Area represented by a cross section calculated by GIS (Figure 4.11).

Line	Area (ft^2)	Aggradation Rate (1997-2006, ft/year)	Area * Rate (ft^3/year)	
2	9,109.360	0.217	1,972.541	
3	4,846.087	0.037	181.050	
4	6,153.526	0.079	483.667	
5	15,629.103	0.049	768.327	
6	10,049.176	0.122	1,226.200	
Σ(Area):	45,787.251	**Σ(Area * Rate):**	4,631.785	**ft^3/year**

Weighted Average Aggradation:	0.101	**ft/year**
	1.214	**in/year**

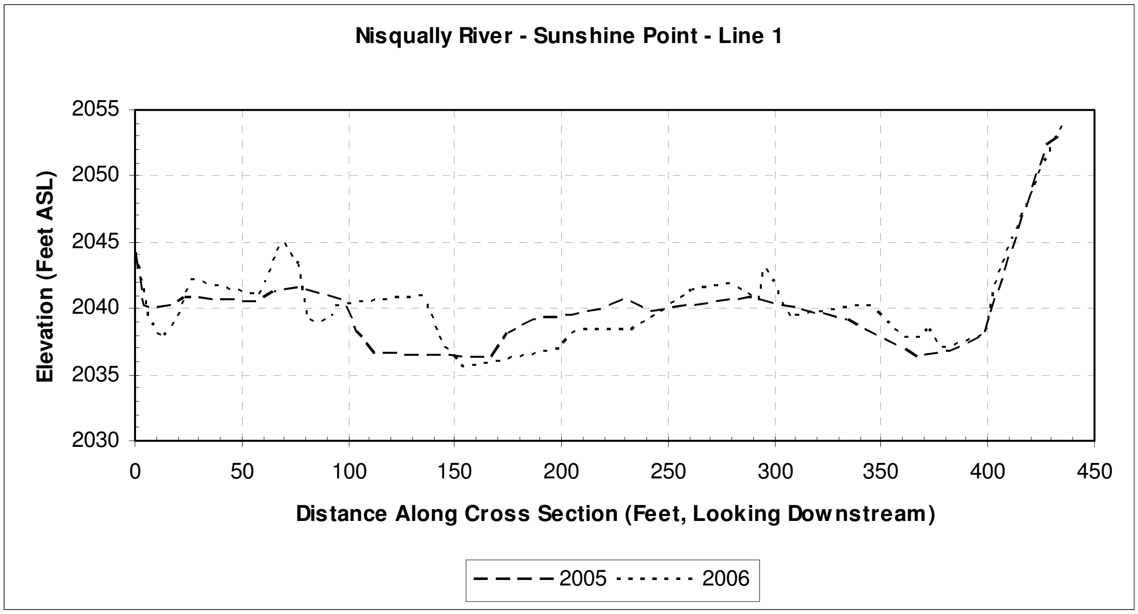
Average Aggradation:	**12.139**	**in/decade**
	1.012	**ft/decade**

Volume in a Decade:	46,317.849	**ft^3**
Volume of Total Increase:	1,715.474	**yards^3**
Dump Trucks (10 yard^3 capacity):	**171.55**	**per decade**
Dump Trucks per year:	**17.15**	

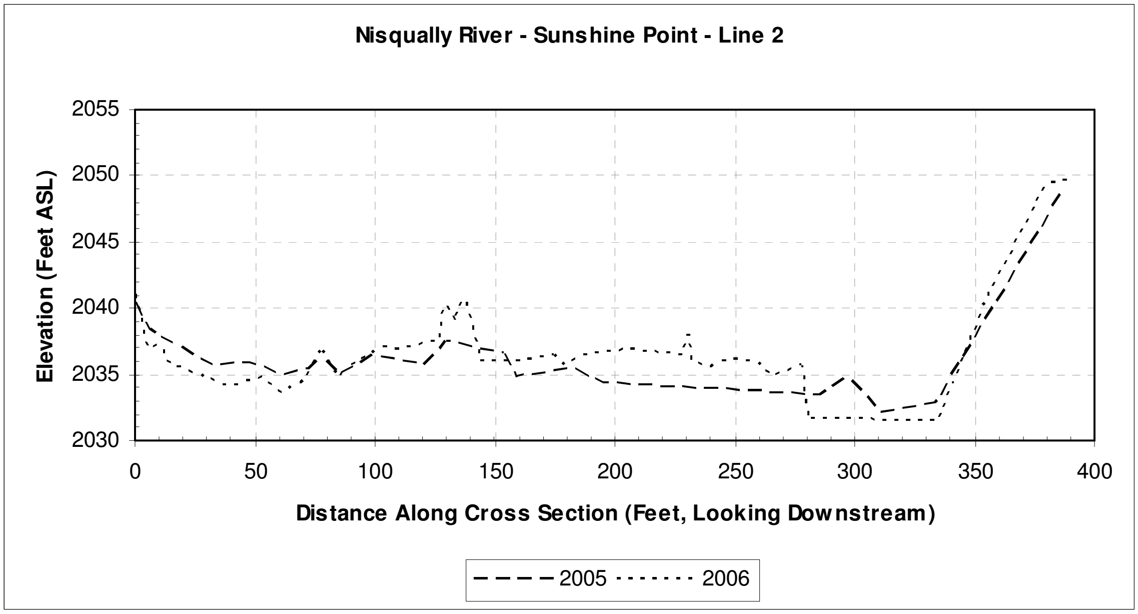
▲ TABLE 4.2
Average aggradation amount for cross sections near primary levee at Longmire (transects 2 – 6). Aggradation rates from Appendix A. Area represented by a cross section calculated by GIS (Figure 4.11).

Nisqually River at Sunshine Point

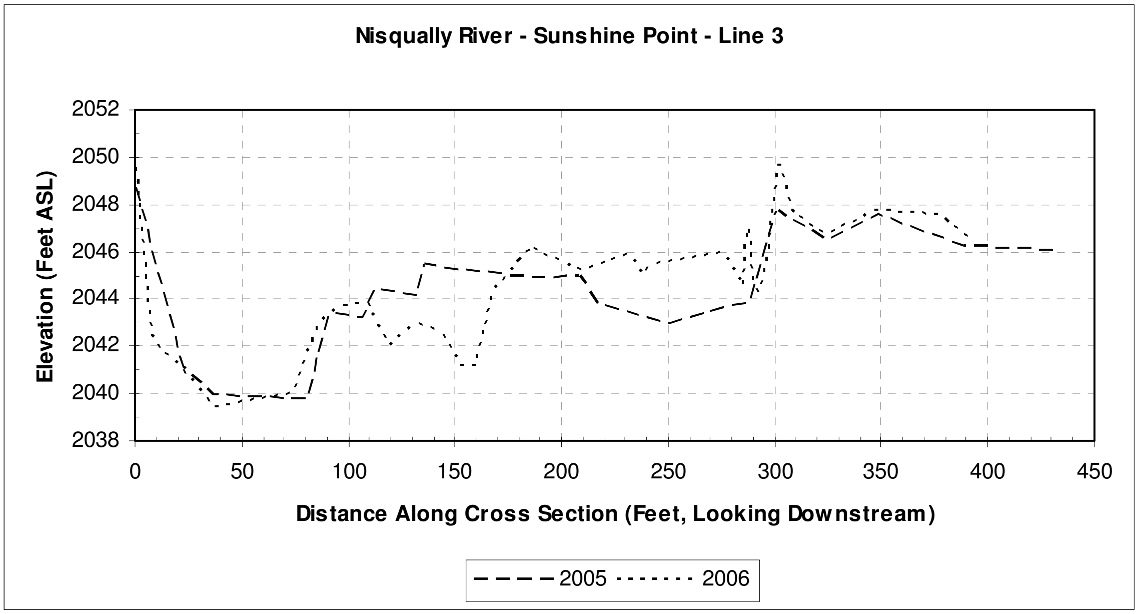
No surveying was completed at Sunshine Point prior to 2005 and observed rates can only be calculated for the last year of aggradation. The order of lines at this location is a little peculiar as the downstream order goes from line 3, 1, 2 (Figure 1.9). Surveying for Sunshine Point was completed August 1 – August 4, 2006. Significant aggradation was noted in cross sections 1 (0.291 ft/yr [8.870 cm/yr]; Figure 4.12) and 3 (0.221 ft/yr [6.736 cm/yr]; Figure 4.13), while significant degradation was noted in cross section 2 (-0.42 ft/yr [-12.802 cm/yr]; Figure 4.14). Using Equation 5 and areas calculated from GIS (Figure 4.15), the average aggradation rate observed in this location is 14.943 in/decade (37.953 cm/decade), or 266 dump trucks per decade (Table 4.3; the rate is based on a single year of data). This rate is higher than observed at Longmire. The Nisqually River at this location has the added influence of Kautz and Tahoma Creeks.



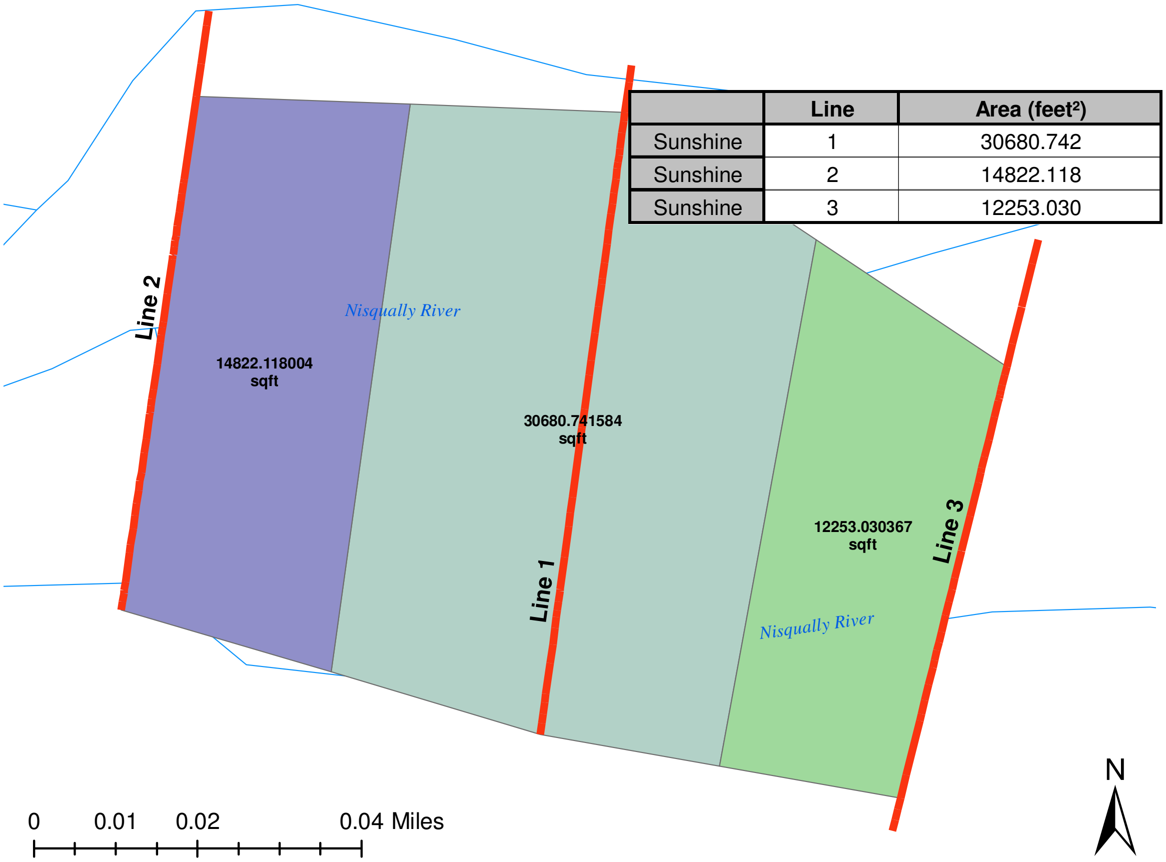
▲ FIGURE 4.12
Cross Section 1 at Sunshine Point (Nisqually River). Vertical Exaggeration ≈ 6.1x.



▲ FIGURE 4.13
Cross Section 2 at Sunshine Point (Nisqually River). Vertical Exaggeration ≈ 5.6x.



▲ FIGURE 4.14
Cross Section 3 at Sunshine Point (Nisqually River). Vertical Exaggeration ≈ 11.3x.



	Line	Area (feet²)
Sunshine	1	30680.742
Sunshine	2	14822.118
Sunshine	3	12253.030

▲ FIGURE 4.15
Area represented by individual cross sections at Sunshine Point.

Line	Area (ft²)	Aggradation Rate (2005-2006, ft/year)	Area * Rate (ft³/year)	
1	30,680.742	0.291	8,940.368	
2	12,253.030	-0.420	-5,147.919	
3	14,822.118	0.229	3,399.601	
Σ(Area):	57,755.890	**Σ(Area * Rate):**	7,192.050	**ft³/year**

Weighted Average Aggradation:	0.125	**ft/year**
	1.494	**in/year**

Average Aggradation:	**14.943**	**in/decade**
	1.245	**ft/decade**

Volume in a Decade:	71,920.503	**ft³**
Volume of Total Increase:	2,663.720	**yards³**
Dump Trucks (10 yard³ capacity):	**266.37**	**per decade**
Dump Trucks per year:	**26.64**	

▲ TABLE 4.3

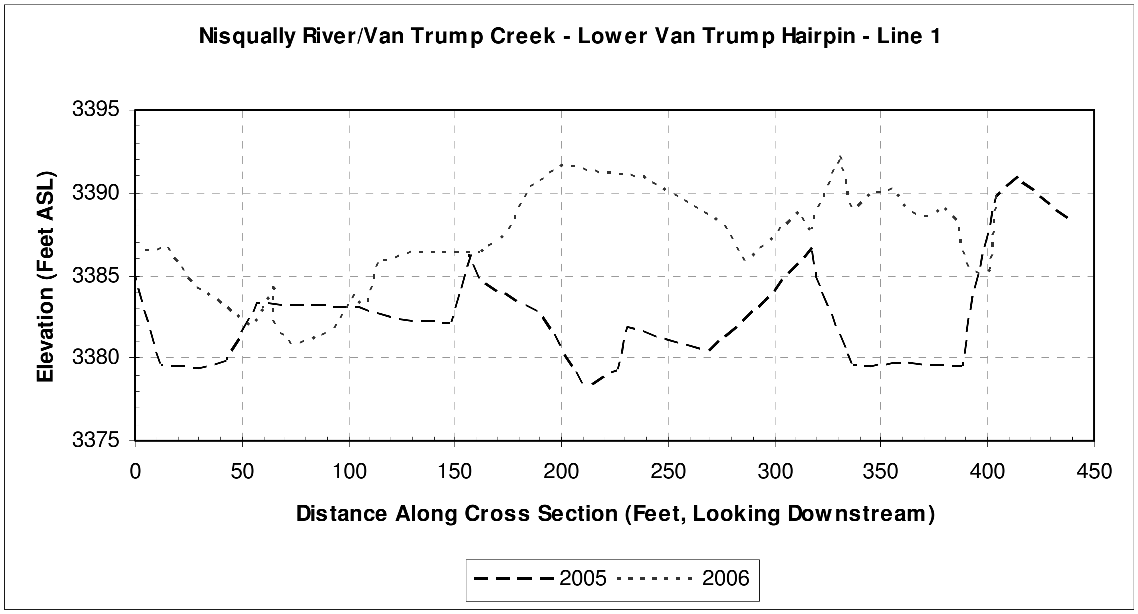
Average aggradation amount for all cross sections at Sunshine Point. Aggradation rates from Appendix A. Area represented by a cross section calculated by GIS (Figure 4.15). Aggradation rate based on two years of data.

Nisqually River and Van Trump Creek at Lower Van Trump Hairpin

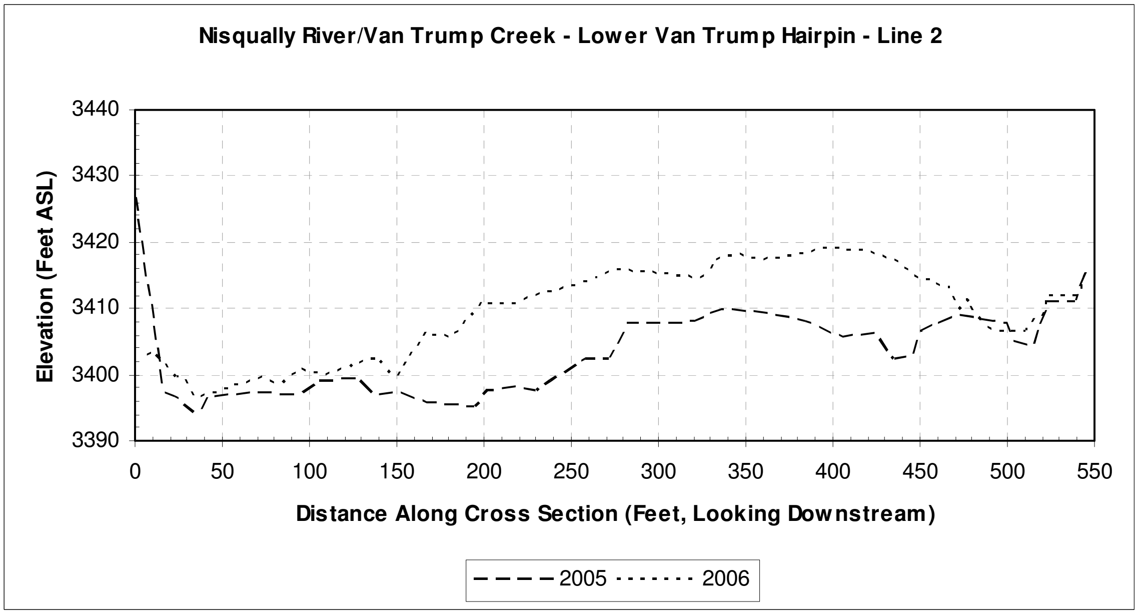
Between surveying in 2005 and 2006, a debris flow occurred in Van Trump Creek (Kennard, personal communication, 2006). The terminus of this debris flow came to rest directly in the survey area (Figure 1.9), which caused a much higher rate of aggradation (referred to as "hyperaggradation" in this paper). This is also an area that was not surveyed prior to 2005, so only 1 year of data exists for this location. We surveyed this location July 19 – 20, 2006.

Cross section 1 (Figure 4.16) showed an average net increase of 5.081 ft (1.549 m) of material across its 403 ft (123 m) length. Cross section 2 (Figure 4.17) showed a higher average net increase of 7.196 ft (2.193 m) across 544 ft (166 m). Finally, cross section 3 (Figure 4.18) showed a smaller net increase of 2.705 ft (0.824 m) across 294 ft (90 m). It should be noted that cross section 3 is upstream of the left (most upstream) edge of the fan from the 2005 debris flow.

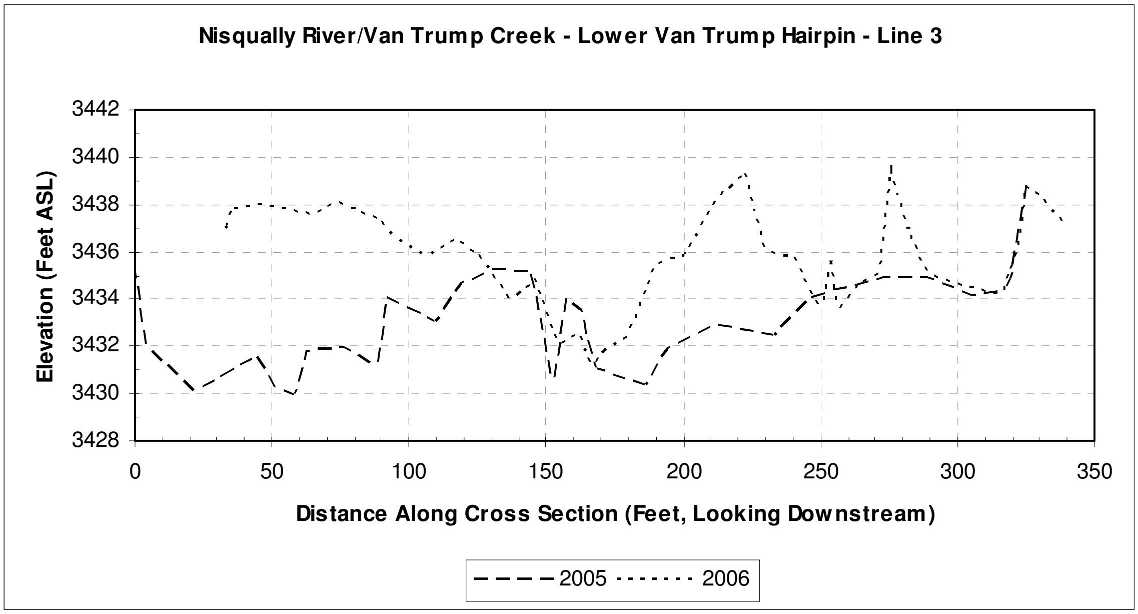
The weighted average net change in the river bed in this location is 5.610 ft (1.710 m) in 107,468 ft² (9,984 m²; Table 4.4). This equates to an influx of 2,233 dump trucks of material in a single event. Because of these deposits, the Nisqually River was pushed over to the far side of the channel, or left-most bank looking downstream. Van Trump Creek was pushed to the right bank, looking downstream, and ran adjacent to the lower hairpin for the entire study period.



▲ FIGURE 4.16
Cross Section 1 at Lower Van Trump Hairpin (Nisqually River/Van Trump Creek). Vertical Exaggeration ≈ 7.9x.



▲ FIGURE 4.17
Cross Section 2 at Lower Van Trump Hairpin (Nisqually River/Van Trump Creek). Vertical Exaggeration ≈ 3.9x.



▲ FIGURE 4.18
Cross Section 3 at Lower Van Trump Hairpin (Nisqually River/Van Trump Creek). Vertical Exaggeration ≈ 8.6x.

	Line	Area (feet²)
Van Trump	1	17786.139
Van Trump	2	60094.544
Van Trump	3	29587.094

▲ Figure 4.19
Area represented by individual cross sections at Lower Van Trump Hairpin.

Line	Area (ft^2)	Aggradation Rate (2005-2006, ft/year)	Area * Rate (ft^3/year)	
1	17,786.139	5.081	90,374.038	
2	60,094.544	7.196	432,447.549	
3	29,587.094	2.705	80,025.989	
Σ(Area):	107,467.777	Σ(Area * Rate):	602,847.576	**ft^3/year**

Weighted Average Aggradation:	5.610	**ft/year**
	67.315	**in/year**

Average Aggradation:	**673.148**	**in/decade**
	56.096	**ft/decade**

Volume in a Decade:	6,028,475.756	**ft^3**
Volume of Total Increase:	223,276.657	**$yards^3$**
Dump Trucks (10 $yard^3$ capacity):	**22327.67**	**per decade**
Dump Trucks per year:	**2232.77**	

▲ TABLE 4.4

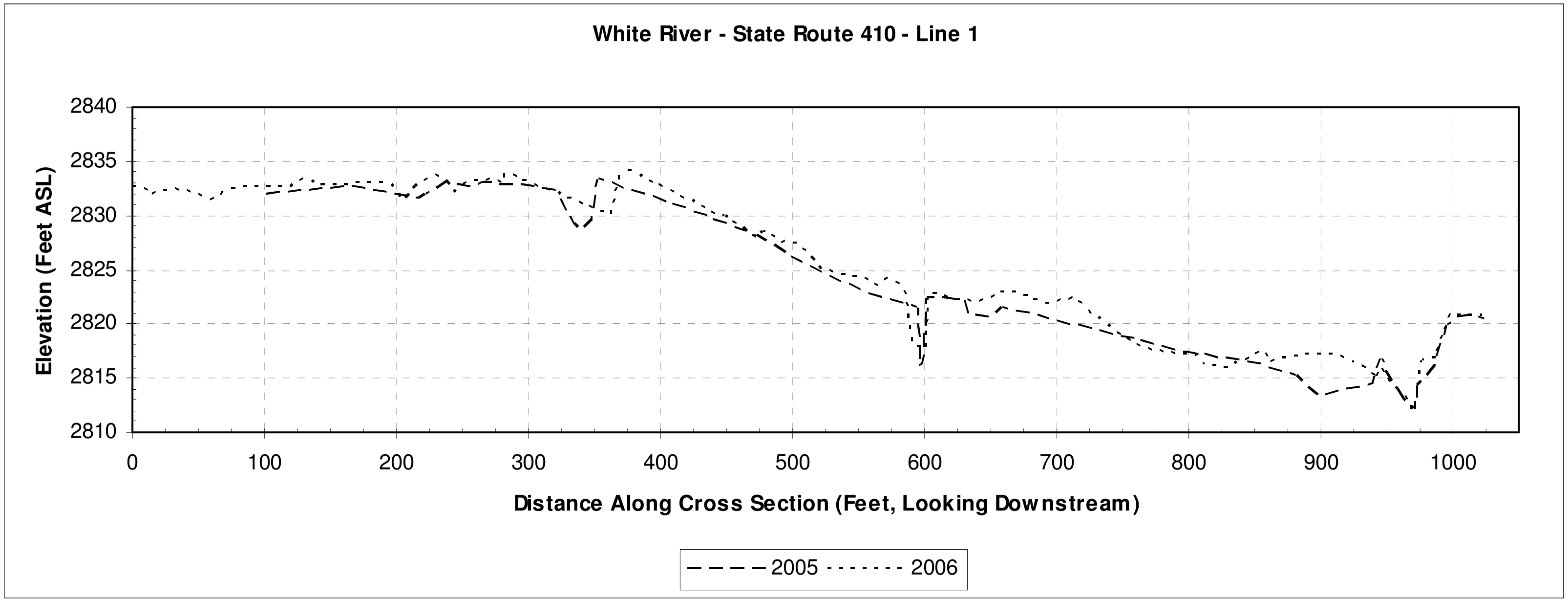
Average aggradation amount for all cross sections at Lower Van Trump Hairpin. Aggradation rates from Appendix A. Area represented by a cross section calculated by GIS (Figure 4.19). Aggradation rate based on two years of data.

White River along State Route 410

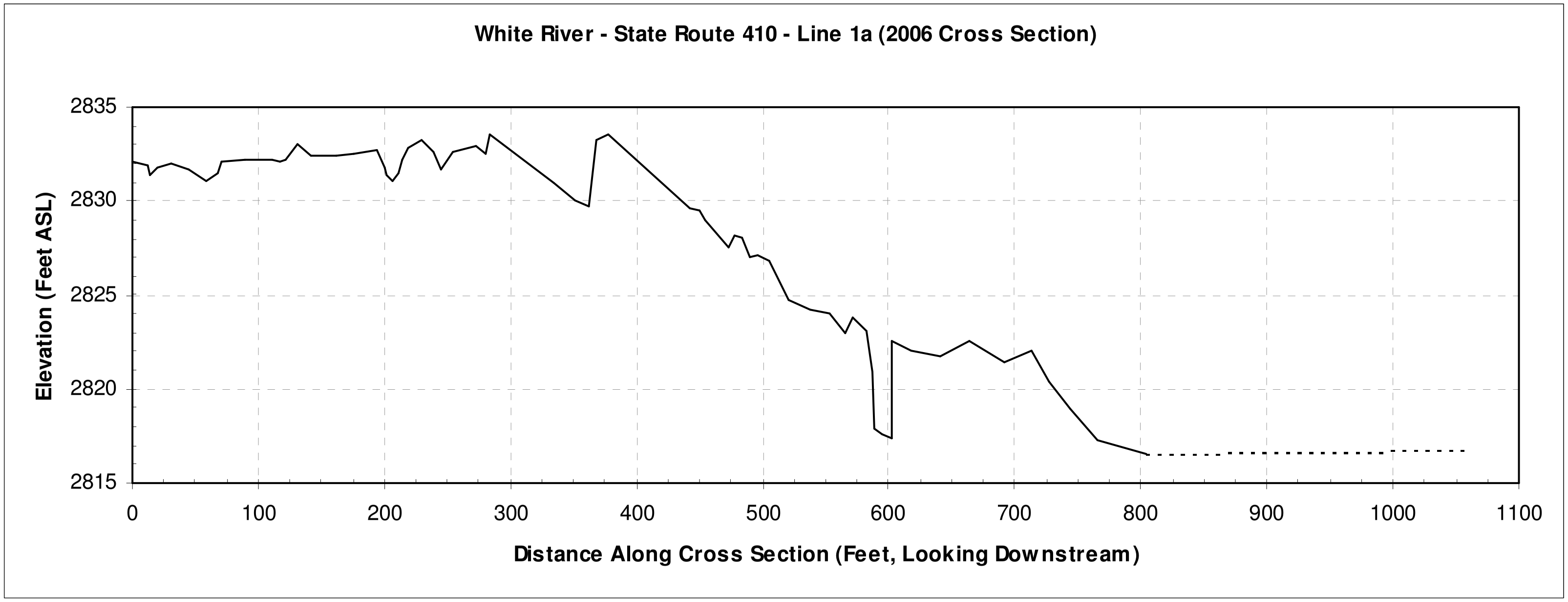
Surveying was conducted in this location August 9 – 11, 2006 in order to reoccupy the sites studied by the Herrera Group (2005; Figure 1.11). Specifically, we were interested in cross section 1, where Herrera showed that the White River was above the height of the road (a similar situation to what was previously discussed with Longmire). Cross section 1 (Figure 4.20) is the longest cross section we shot, just over 1000 ft (305 m) in length. The shot required multiple control points and the Total Station was repositioned several times. The first 350 ft (107 m) of the cross section in Figure 4.20 represent the stream channel, while the remaining cross section is old growth forest and finally, State Highway 410 at the far right (just beyond the 1000 ft mark).

The river elevation at cross section 1 is 2832.55 ft (863.36 m). Where the line meets the road, the elevation of the road is 2820.76 ft (859.77 m), or a difference of 11.79 ft (3.59 m). The river bank elevation in this situation is only 2833 ft (863.5 m). Line 1 included a bend in order to meet the road nearly perpendicular. We decided to shoot to a point on the road that was a continuation of Line 1 without a bend. This became cross section 1a (Figure 4.21). No positions were taken from the bend to the road due to thick tree cover. The river and bank elevations were the same. The road elevation at this point was 2816.79 ft (858.56 m), for a difference of 15.79 ft (4.81 m). In both situations, the river is between 11.8 and 15.8 ft (3.6 to 4.8 m) higher than the road. This is not obvious as old growth forest completely obscures the river channel from the road and vice versa. Just downstream from cross section 1a's final point, the National Park Service has constructed a berm to keep the river off of the road. A small side channel does flow next to the road by this point.

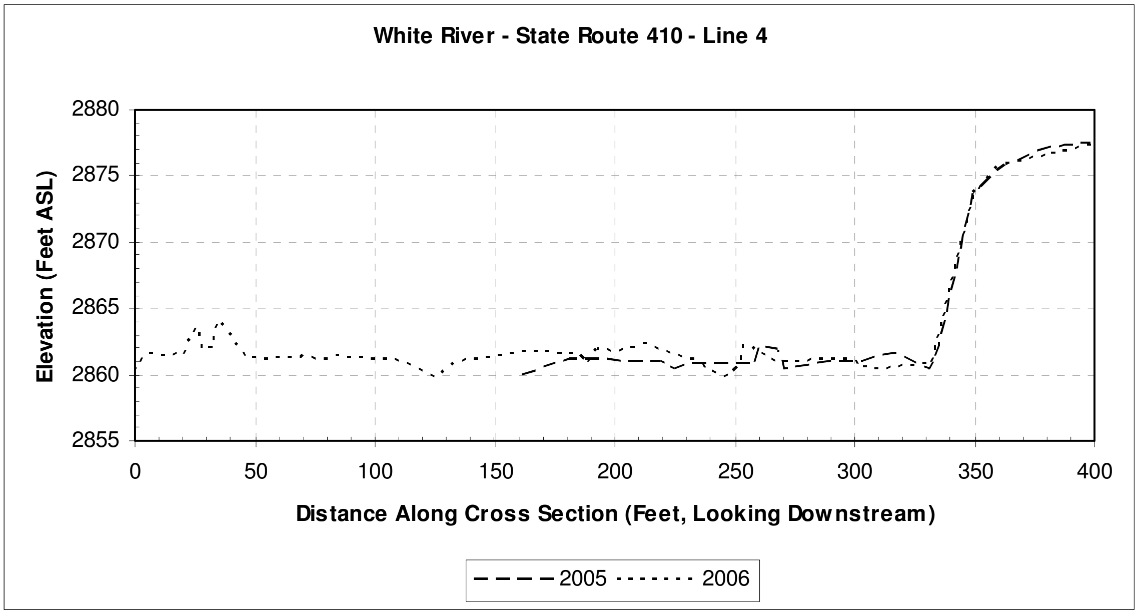
Cross section 1 and 4 (Figure 4.22) both showed a net increase in bed elevation (Table 4.5). The aggradation rate for cross section 1 is 0.642 ft/yr (19.568 cm/yr) and 0.309 ft/yr (9.418 cm/yr) for line 4. The weighted average net increase of materials is 0.475 ft/yr (14.478 cm/yr), or a total increase of 463 dump trucks of materials. These values are based only on a single year of change.



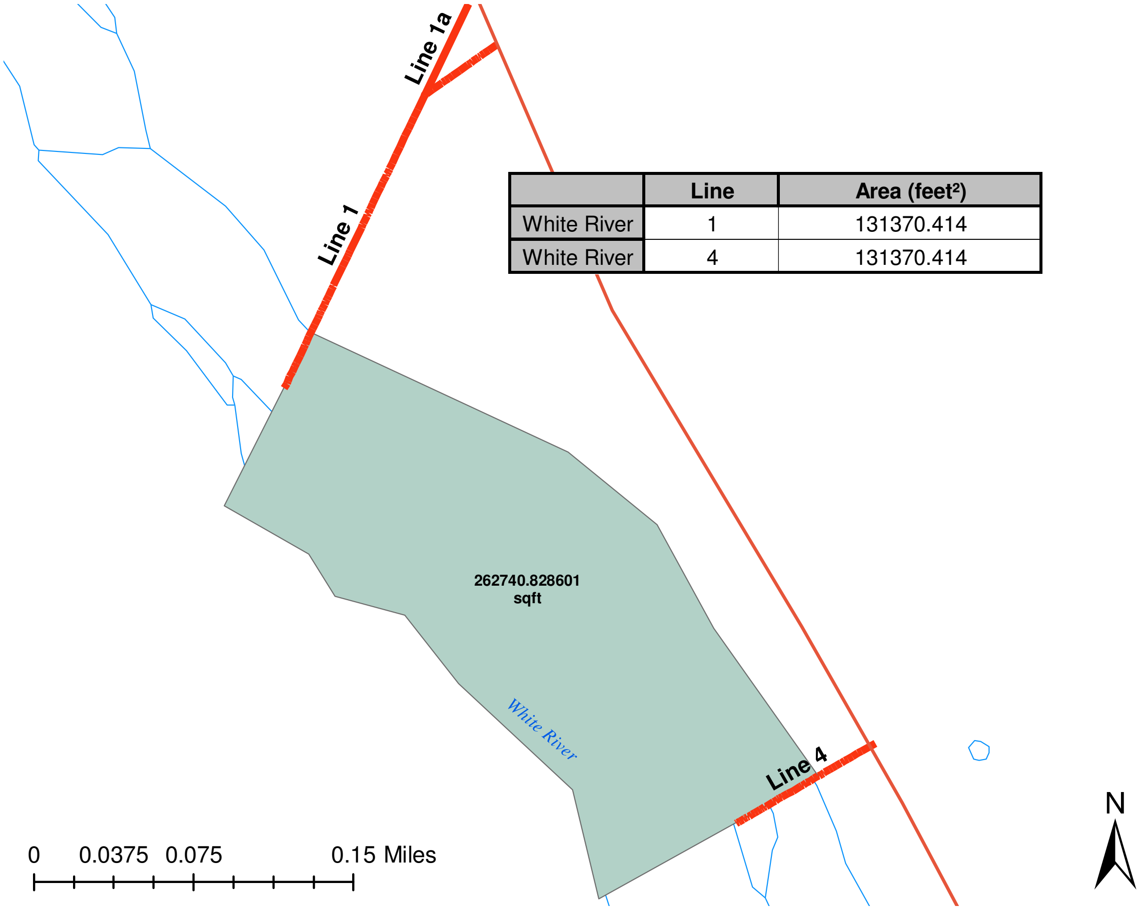
▲ FIGURE 4.20
Cross Section 1 at SR 410 (White River). Vertical Exaggeration ≈ 8.1x.



▲ FIGURE 4.21
Cross Section 1a at SR 410 (White River). Line 1a does not include a bend (see text for explanation). Cross section based on 2006 survey data. Except for the beginning and end, no positions were taken along the dashed section. Vertical Exaggeration ≈ 14.9x.



▲ FIGURE 4.22
Cross Section 4 at SR 410 (White River). Vertical Exaggeration ≈ 5.6x.



	Line	Area (feet²)
White River	1	131370.414
White River	4	131370.414

▲ FIGURE 4.23

Area represented by cross sections along State Route 410 (White River). Since only two cross sections were present, the area represented by each is the total area divided in half.

Line	Area (ft²)	Aggradation Rate (2005-2006, ft/year)	Area * Rate (ft³/year)	
1	131,370.414	0.642	84,301.709	
4	131,370.414	0.309	40,590.831	
Σ(Area):	262,740.829	Σ(Area * Rate):	124,892.539	ft³/year

Weighted Average Aggradation:	0.475	ft/year
	5.704	in/year

Average Aggradation:	**57.041**	in/decade
	4.753	ft/decade

Volume in a Decade:	1,248,925.392	ft³
Volume of Total Increase:	46,256.450	yards³
Dump Trucks (10 yard³ capacity):	**4625.64**	per decade
Dump Trucks per year:	**462.56**	

▲ TABLE 4.5
Average aggradation amount for cross sections along State Route 410 (White River). Aggradation rates from Appendix A. Area represented by a cross section calculated by GIS (Figure 4.23). Aggradation rate based on two years of data and only includes two cross section locations.

Longitudinal Profile Results

Longitudinal profiles were constructed from the lowest river elevations observed along cross sections in the Sunshine Point, Van Trump and White River data. A separate longitudinal profile for the Longmire area was constructed from surveyed data collected on July 31, 2006. The cooler weather experienced this day allowed the survey team to collect elevations in the thalweg of the stream, something nearly impossible to do with high flow conditions in the warmer summer months. These data were compared with a longitudinal profile conducted in the White and Nisqually Rivers in 1910 by Henshaw and Parker (1913).

The longitudinal profile at Longmire (Figure 4.24) includes positions from River Mile 78.19 to 77.59. The longitudinal profile starts just downstream of Line 10 and continues upstream to Line 1 (Figure 4.25). The overall aggradation rate observed in the Nisqually River at Longmire averages 0.008 ft/yr (0.244 cm/yr), or a net change of 0.759 ft (23.134 cm) in 96 years (Appendix A).

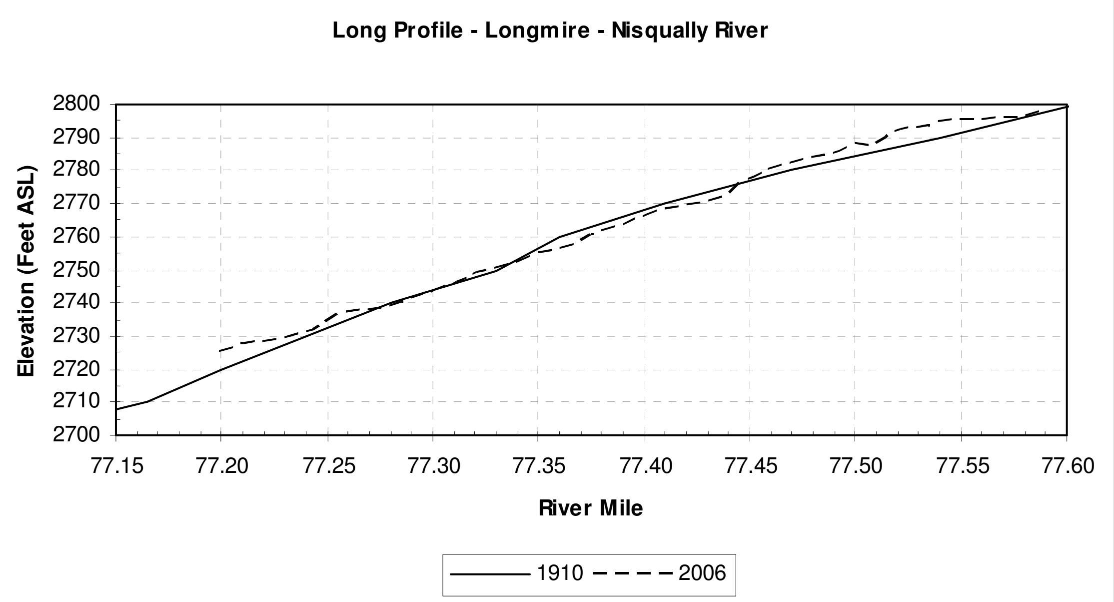
As the survey team was preparing to construct the longitudinal profile at Sunshine Point on August 4, 2006, the prism assembly broke on the adjustable-height rod. This is a vital component of the total station. The assembly was fixed approximately one week later; however, the survey team was at White River and unable to finish the planned longitudinal profiles at the remaining three locations. Therefore, the longitudinal profile at Sunshine Point was created using the lowest river elevation in each cross section. This does introduce an error into the longitudinal profile construction since the topography between cross sections is not known. This method was also used at the Lower Van Trump Hairpin and White River.

The Sunshine Point longitudinal profile (Figure 4.26) includes a single position from each of the three cross sections shot earlier in the season (Figure 1.9). The overall aggradation observed in the Nisqually River at Sunshine Point averages 0.015 ft/yr (0.457 cm/yr) with a total net change of 1.449 ft (44.166 cm) in 96 years (Appendix A).

Like the Sunshine Point longitudinal profile, the longitudinal profile of the Lower Van Trump Hairpin area (Figure 4.27) includes the lowest river elevation along 3 cross sections (Figure 1.10). Valley wide, this location has been influenced by several debris flows, including the debris flow in the fall of 2005, and similar debris flows in 2003 and 2001 (Donovan, 2005). The aggradation observed in the Nisqually River and Van Trump Creek at Lower Van Trump Hairpin averages 0.404 ft/yr (12.314 cm/yr). In 96 years, the river bed in the Lower Van Trump Hairpin area has increased an average of 38.753 ft (11.812 m; Appendix A).

The last location that had surveyed longitudinal profiles in the summer field season was along the White River and State Route 410 in the northeastern side of the Park (Figure 4.28). Two cross sections (Figure 1.11) were surveyed with the total station and the lowest river elevation was used for the long profile. In this location, the average rate of increase is 0.049 ft/yr (0.015 cm/yr) with a total net increase of 4.67 ft (1.423 m) of material in 96 years (Appendix A).

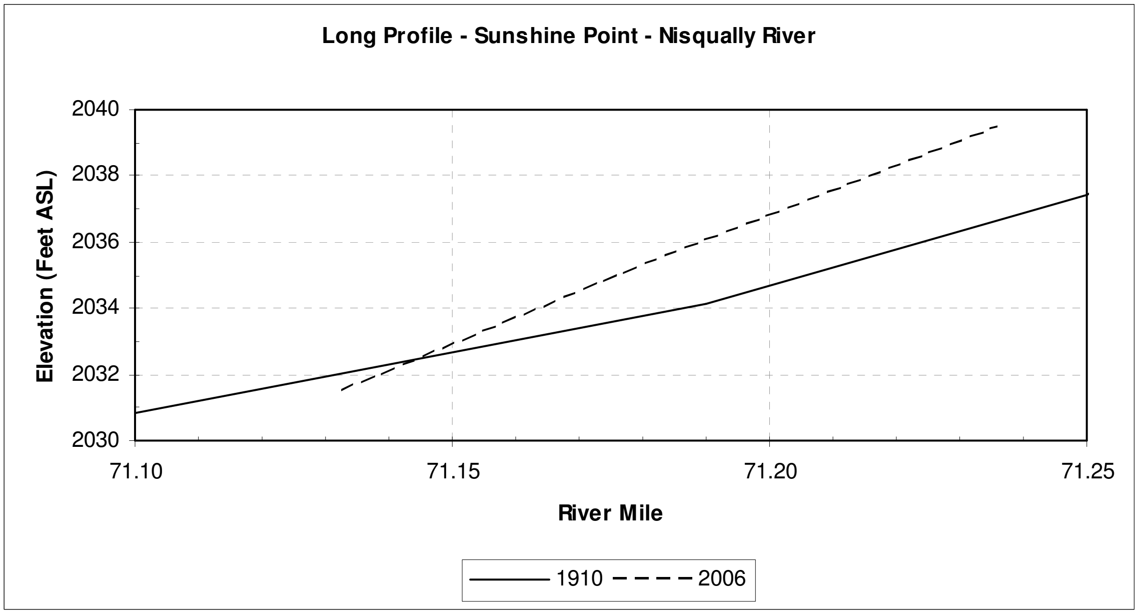
Combining the average aggradation rates (Appendix A) with area represented by cross sections in the study area (Figures 4.11, 4.15, 4.19, and 4.23), the weighted average increase can be calculated with Equation 5. For all four areas surveyed in the summer season, the weighted average increase in the last 96 years is 12.062 in/decade (30.637 cm/decade), or an increase of 216 dump trucks per year of material in the rivers (Table 4.6). Since the aggradation observed at Lower Van Trump Hairpin includes debris flow deposits, the rate without the Van Trump Hairpin deposits is calculated separately (Table 4.7). Not including these deposits, the average rate of aggradation seen since 1910 in the Park is 3.777 in/decade (9.594 cm/decade) or an increase of 55 dump trucks of material in the rivers per year. 3.777 in/decade (9.594 cm/decade) is considered the historical rate of aggradation in the Park since 1910.



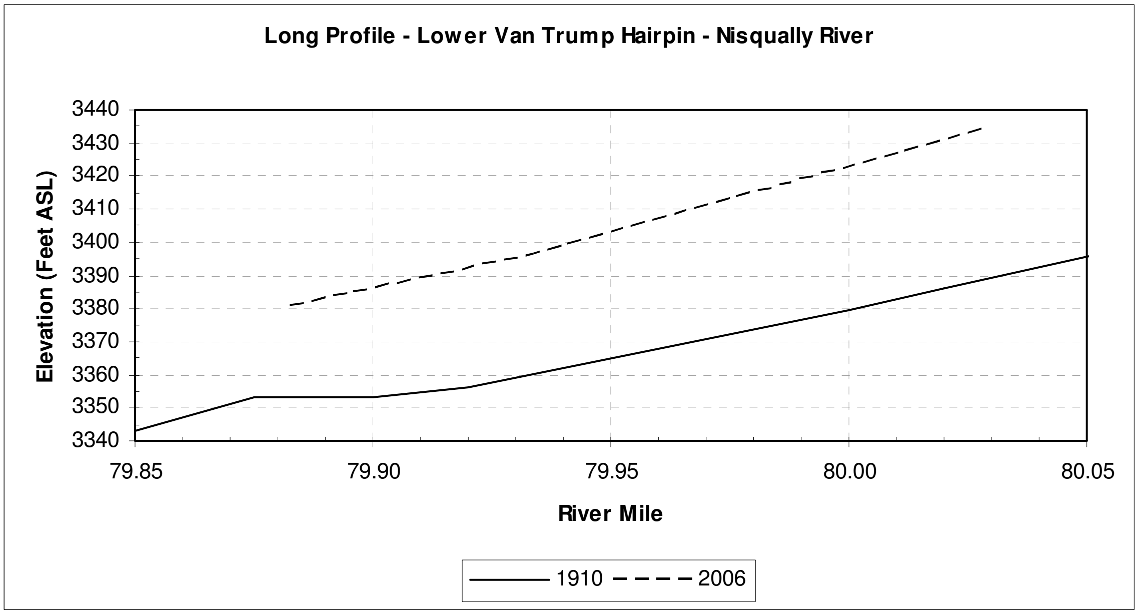
▲ FIGURE 4.24
Long Profile of Nisqually River at Longmire. Vertical Exaggeration ≈ 8.4x.

▲ FIGURE 4.25

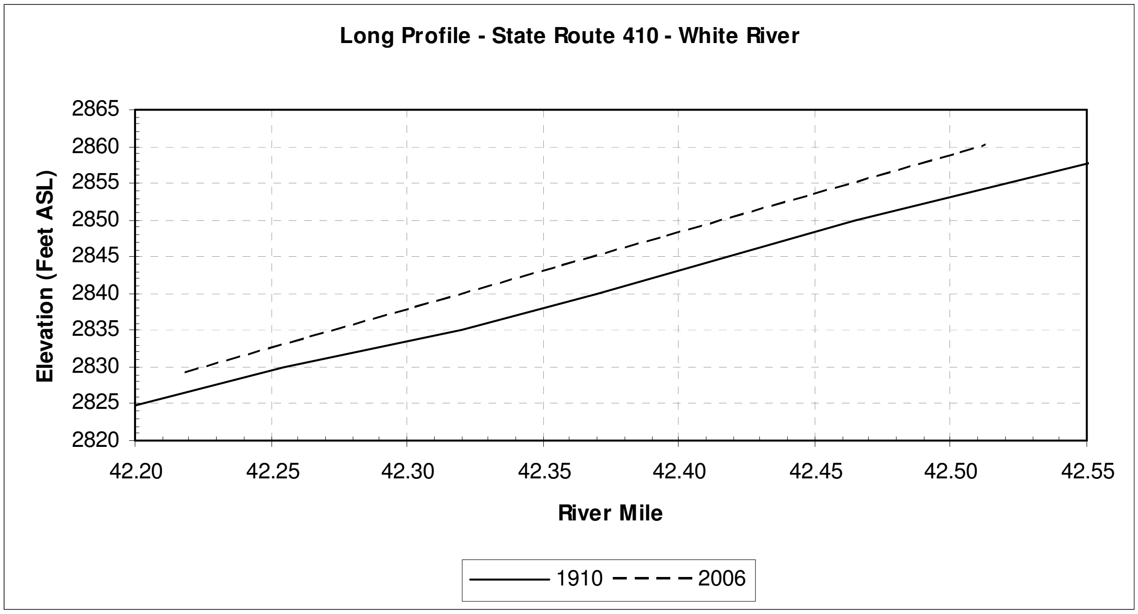
Map showing constructed long profile of Nisqually River at Longmire. Cross section lines included for reference.



▲ FIGURE 4.26
Long Profile of Nisqually River at Sunshine Point. Vertical Exaggeration ≈ 27.2x.



▲ FIGURE 4.27
Long Profile of Nisqually River at Lower Van Trump Hairpin. Vertical Exaggeration ≈ 3.6x.



▲ FIGURE 4.28
Long Profile of White River along State Route 410. Vertical Exaggeration ≈ 14.0x.

Location	Area (ft^2)	Aggradation Rate (1910-2006, ft/year)	Area * Rate (ft^3/year)	
Sunshine	57,755.890	0.015	872.114	
Longmire	151,398.805	0.008	1,197.565	
Van Trump	107467.777	0.404	43,382.592	
White River	262,740.829	0.049	12,784.969	
Σ(Area):	579,363.300	**Σ(Area * Rate)**	58,237.239	**ft^3/year**

Weighted Average Aggradation:	0.101	**ft/year**
	1.206	**in/year**

Average Aggradation:	**12.062**	**in/decade**
	1.005	**ft/decade**

Volume in a Decade:	582,372.393	**ft^3**
Volume of Total Increase:	21,569.326	**yards^3**
Dump Trucks (10 yard^3 capacity):	**2,156.93**	**per decade**
Dump Trucks per year:	**215.69**	

▲ TABLE 4.6
Average aggradation amount for long profiles in the Park. Aggradation rates from Appendix A. Area represented by a cross section calculated by GIS (Figures 4.11, 4.15, 4.19, and 4.23).

Location	Area (ft^2)	Aggradation Rate (1910-2006, ft/year)	Area * Rate (ft^3/year)	
Sunshine	57,755.890	0.015	872.114	
Longmire	151,398.805	0.008	1,197.565	
White River	262,740.829	0.049	12,784.969	
Σ(Area):	471,895.523	**Σ(Area * Rate)**	14,854.647	**ft^3/year**

Weighted Average Aggradation:	0.031	**ft/year**
	0.378	**in/year**

Average Aggradation:	**3.777**	**in/decade**
	0.315	**ft/decade**

Volume in a Decade:	148,546.472	**ft^3**
Volume of Total Increase:	5,501.716	**yards^3**
Dump Trucks (10 yard^3 capacity):	**550.17**	**per decade**
Dump Trucks per year:	**55.02**	

▲ TABLE 4.7
Average aggradation amount for long profiles in the Park. Aggradation rates from Appendix A. Area represented by a cross section calculated by GIS (Figures 4.11, 4.15, 4.19, and 4.23). This table ignores aggradation seen at Lower Van Trump Hairpin.

Historical Topographic Map Analysis

Historical Topographic Map analysis is useful because it allows the survey team to get an idea of the aggradation that is occurring in rivers that are not accessible during the field season. However, it is the least accurate way to measure aggradation due to uncertain elevation accuracy and requires a long period of time between map data. We looked at five major braided rivers in this study to determine the usefulness of topographic map analysis (Figure 1.12): Carbon River (northwest), Kautz Creek (southwest), Nisqually (southwest), Tahoma Creek (southwest), and the White River (northeast). Maps were analyzed between 1915 and 1971. A custom written computer script[3] provides the data analysis. River miles (x-axis) provided by the computer output start from the Park boundary and continue upstream to the glacier terminus.

One of the most surprising findings from the historical topographic map analysis was the results observed at Tahoma Creek (Figure 4.29). Most of the long profile derived from 1971 is at a higher elevation the 1915 longitudinal profile. Around river mile 8.2, the 1915 longitudinal profile jumps to a higher elevation than the 1971 profile. Because of this, the average yearly change derived from topographic maps for Carbon River is 0.559 ft/yr (17.038 cm/yr) or a total average increase of 31.329 ft (9.549 m) of material in the 39,809 ft (11.9 km) length of the profile (Table 4.8). This is the highest rate observed in topographic map analysis.

Kautz Creek's long profile showed interesting results (Figure 4.30). The river mile starts counting at the confluence of Kautz Creek and the Nisqually River. The first

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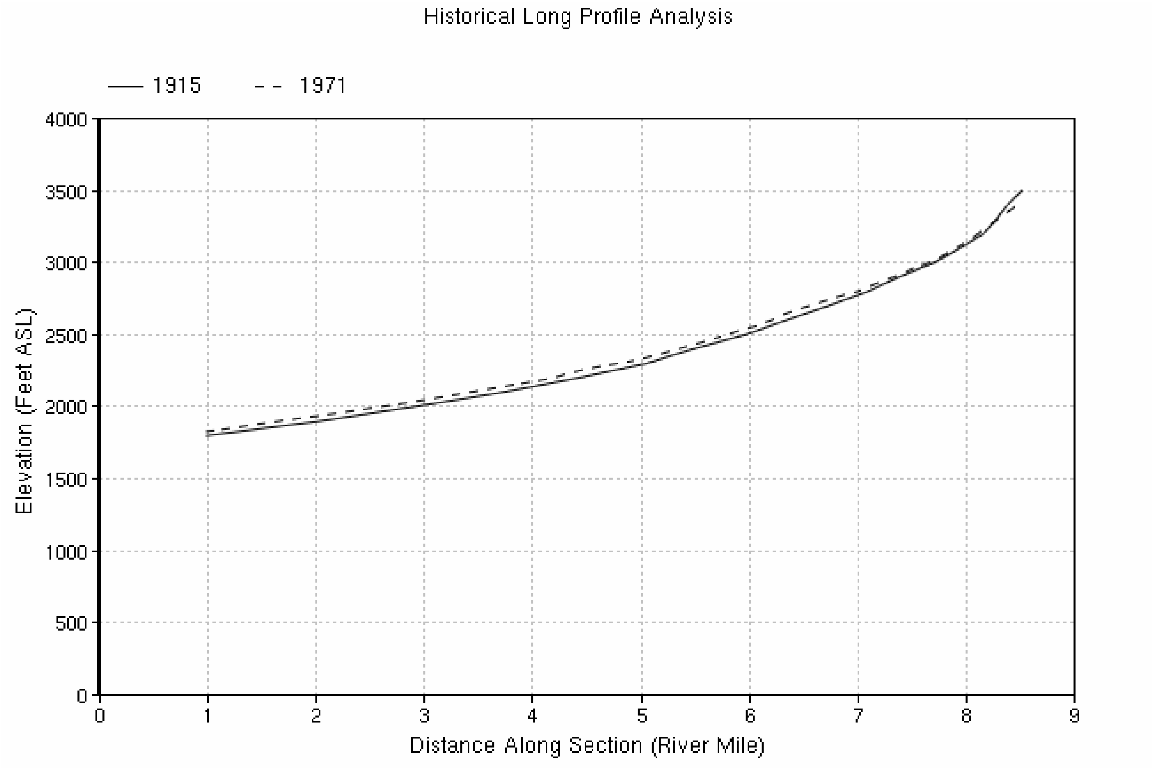
[3] This script is accessible by any web browser at: http://www.beezer.com/moraResearch/. Each river is included and has options to limit the analysis to the whole river or between river mile segments.

mile of the river's profile includes the deposit of the 1947 debris flow described earlier in this paper. According to the topographic analysis, between river mile 0.66 and 1, a total net increase of approximately 56 ft (17 m) of material has occurred between 1915 and 1971. Overall, the profile has increased 0.006 ft/yr (0.183 cm/yr) with a total increase of 0.345 ft (10.516 cm) along the 31,963 ft (9.7 km) longitudinal profile (Table 4.9).

The Nisqually River (Figure 4.31) shows a net decrease of 0.024 ft/yr (0.732 cm/yr) or a total decrease of 1.319 ft (42.398 cm) of material (Table 4.10). The 1971 topographic map shows no evidence of increases in material between river mile 8 and 9 (location of the Lower Van Trump Hairpin study area). Combined with the 1910 longitudinal profile analysis, we saw approximately 66 ft (20 m) of aggradation along this reach.

Since the late 1960s, Tahoma Creek (Figure 4.32) has been ravaged by several debris flows (Walder and Driedger, 1995). Evidence of this can be seen in the total net increase of material: 0.064 ft/yr (1.951 cm/yr) or a total increase of 3.574 ft (1.089 m) along the 33,843 ft (10.3 km) longitudinal profile (Table 4.11). Like Kautz Creek, the river mile count starts from the confluence of the Tahoma Creek with the Nisqually River.

The White River has also seen some debris avalanche deposits as evidenced by the 1962 collapse of Little Tahoma Peak. Despite the increase of material, the longitudinal profile (Figure 4.33) does not appear to show this deposit. The average net decrease in the 56 year period is 0.079 ft/yr (2.408 cm/yr) with a total decrease of 4.398 ft (1.341 m) of materials across 67,528 ft (20.6 km; Table 4.12).



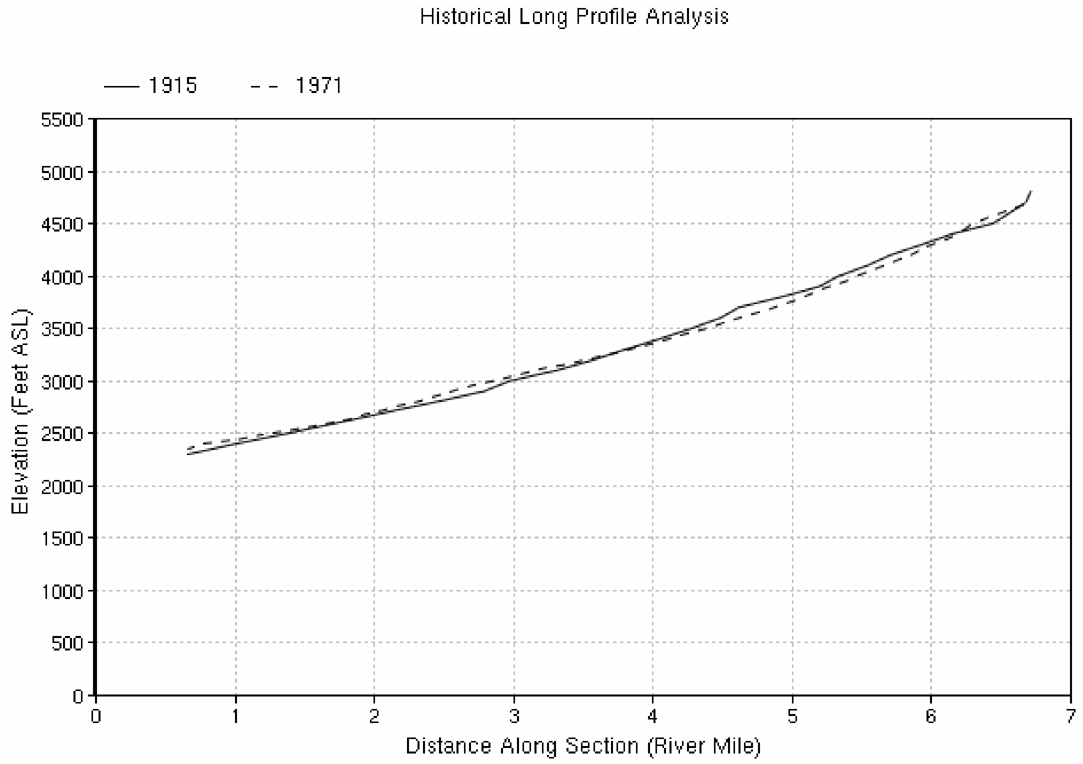
▲ FIGURE 4.29
Long profile of Carbon River derived from topographic maps. Vertical Exaggeration ≈ 7.0x.

	1915	1971
Total Area (ft²)	94,127,021.525	95,374,215.314
Total Length (ft)	39809.24595	

	Net Change		Average Yearly Change	
	Total Change	**Across Channel**	**Total Change**	**Across Channel**
1915 to 1971 (56 years)	1,247,193.789	31.329	22,271.318	0.559

Total Change in Square Feet
Across Channel Change in Feet

▲ TABLE 4.8
Average aggradation amount for Carbon River derived from topographic maps. Data calculated by computer script.



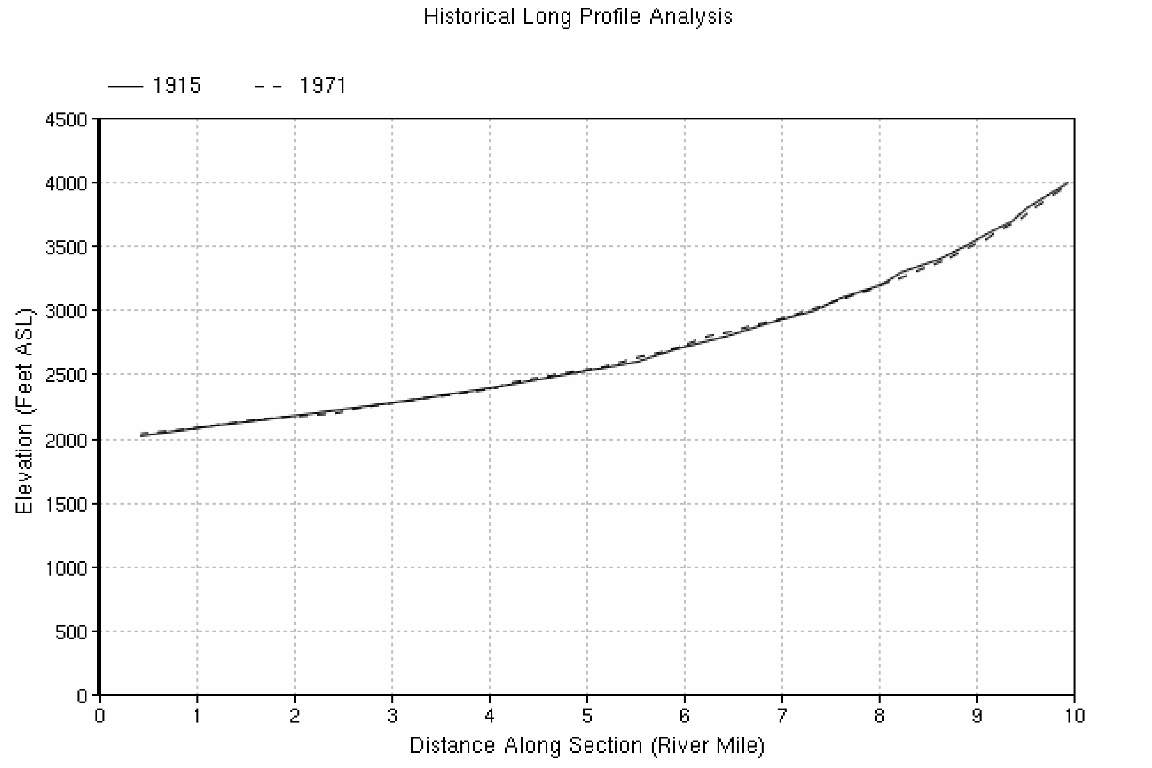
▲ FIGURE 4.30
Long profile of Kautz Creek derived from topographic maps. Vertical Exaggeration ≈ 1.9x.

	1915	1971
Total Area (ft²)	106,854,883.128	106,865,914.563
Total Length (ft)	31963.07562	

	Net Change		Average Yearly Change	
	Total Change	Across Channel	Total Change	Across Channel
1915 to 1971 (56 years)	11,031.436	0.345	196.990	0.006

Total Change in Square Feet
Across Channel Change in Feet

▲ TABLE 4.9
Average aggradation amount for Kautz Creek derived from topographic maps. Data calculated by computer script.



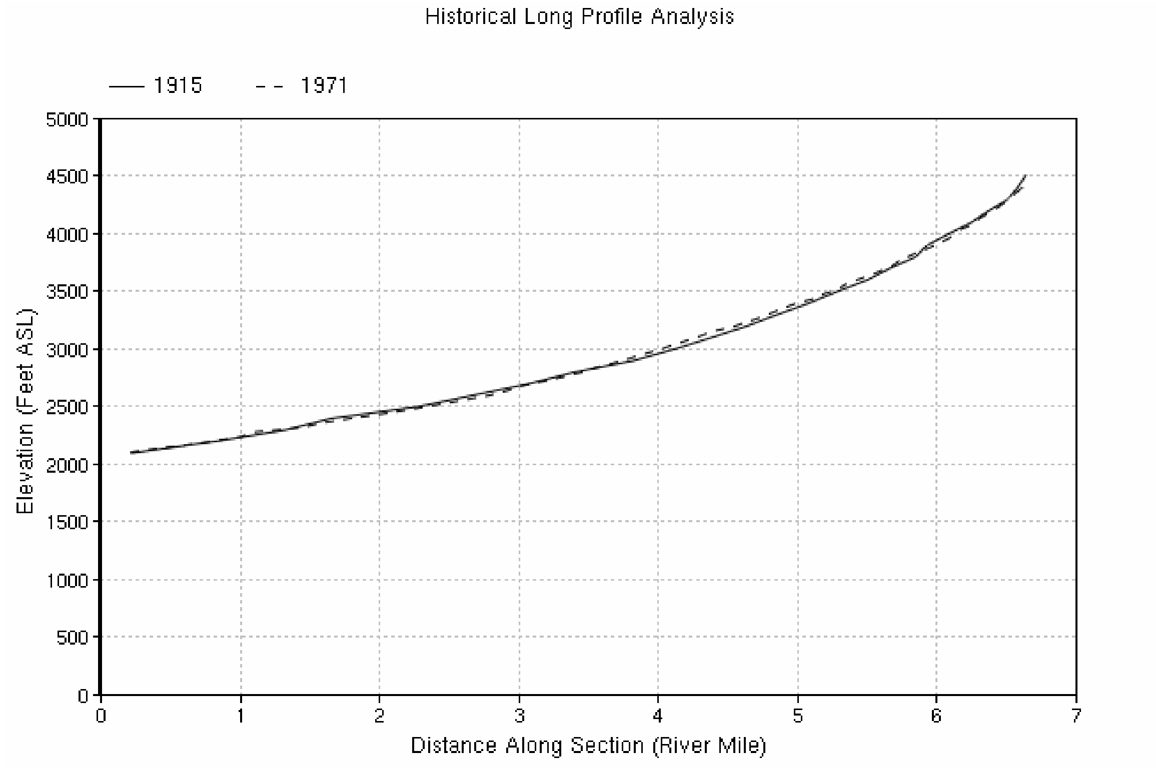
▲ FIGURE 4.31
Long profile of Nisqually River derived from topographic maps. Vertical Exaggeration ≈ 6.9x.

	1915	1971
Total Area (ft²)	135,984,494.473	135,918,231.384
Total Length (ft)	50244.37903	

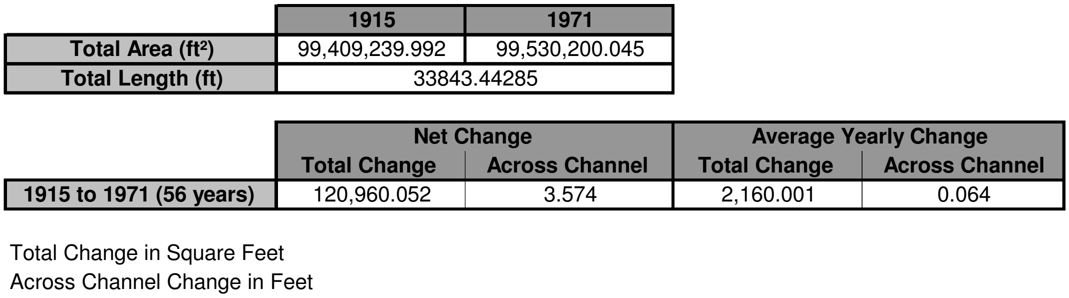
	Net Change		Average Yearly Change	
	Total Change	Across Channel	Total Change	Across Channel
1915 to 1971 (56 years)	-66,263.089	-1.319	-1,183.269	-0.024

Total Change in Square Feet
Across Channel Change in Feet

▲ TABLE 4.10
Average aggradation amount for Nisqually River derived from topographic maps. Data calculated by computer script.



▲ FIGURE 4.32
Long profile of Tahoma Creek derived from topographic maps. Vertical Exaggeration ≈ 2.1x.

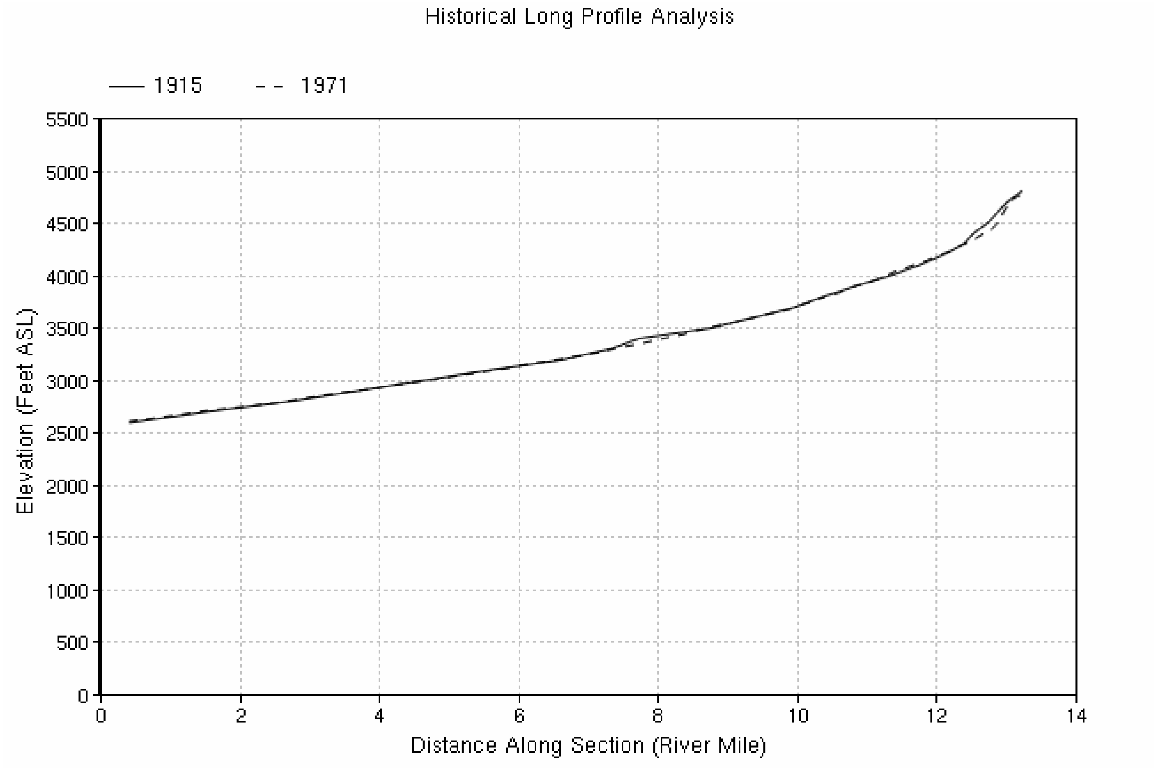


	1915	1971
Total Area (ft²)	99,409,239.992	99,530,200.045
Total Length (ft)	33843.44285	

	Net Change		Average Yearly Change	
	Total Change	**Across Channel**	**Total Change**	**Across Channel**
1915 to 1971 (56 years)	120,960.052	3.574	2,160.001	0.064

Total Change in Square Feet
Across Channel Change in Feet

▲ TABLE 4.11
Average aggradation amount for Tahoma Creek derived from topographic maps. Data calculated by computer script.



▲ FIGURE 4.33
Long profile of White River derived from topographic maps. Vertical Exaggeration ≈ 8.1x.

	1915	1971
Total Area (ft²)	226,350,153.516	226,053,151.503
Total Length (ft)	67528.27974	

	Net Change		Average Yearly Change	
	Total Change	**Across Channel**	**Total Change**	**Across Channel**
1915 to 1971 (56 years)	-297,002.013	-4.398	-5,303.607	-0.079

Total Change in Square Feet
Across Channel Change in Feet

▲ TABLE 4.12
Average aggradation amount for White River derived from topographic maps. Data calculated by computer script.

Chemical Analysis

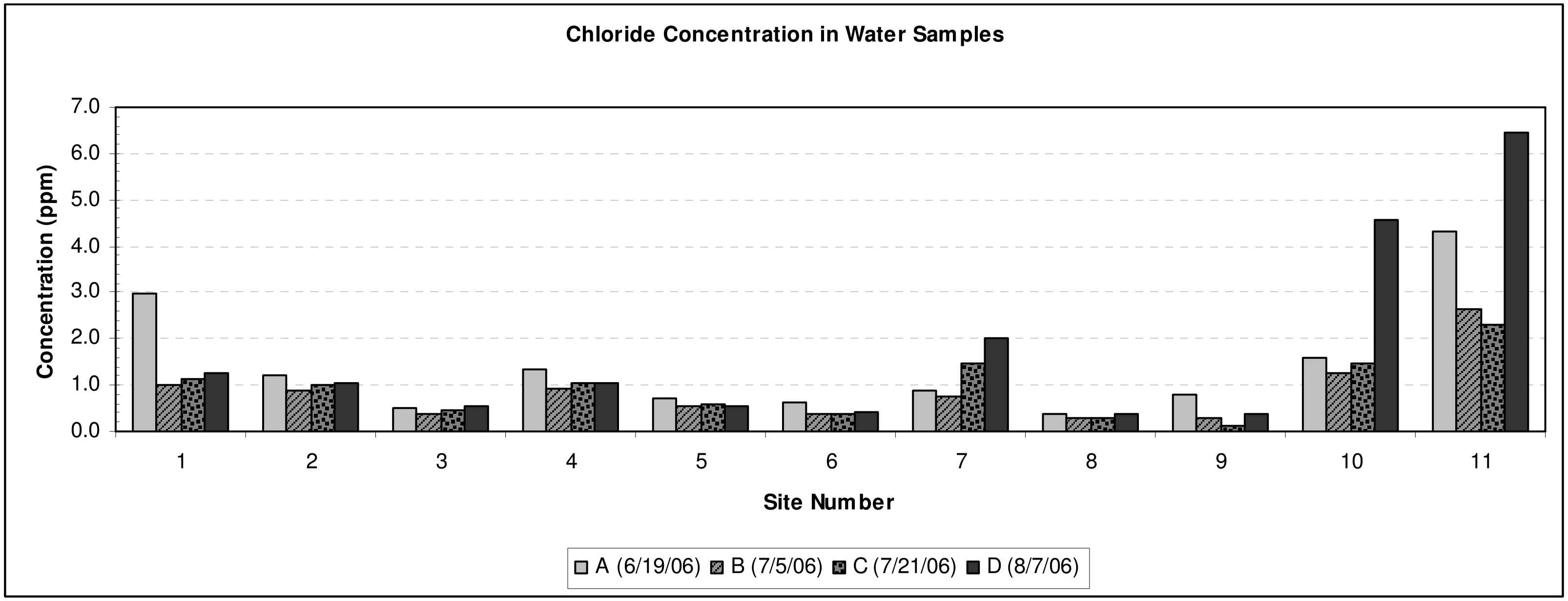
The concentration of chloride, nitrate and sulfate in water samples was determined by the use of ion chromatography. Hydrogen ion concentration (pH), total dissolved solids (TDS) and conductivity were determined by the use of field testing equipment. Table 4.13 shows the results of the chemical characteristics of 44 water samples collected for this study. As mentioned in Chapter 3, TDS and conductivity values for the first two collection periods were thought to be in error until a second probe showed similar values as the first probe. Because the data were thought to be in error, it was not entered in the field notebook and not available for analysis.

Chloride (Figure 4.34), nitrate, and sulfate (Figure 4.35) concentrations were all very low, with the highest concentration under 25 parts per million (ppm). Only one water sample (10B) had any measurable nitrate concentrations, and was under 1 ppm. With the exception of sites 7, 10, and 11, concentrations of chloride and sulfate appear to decrease over the summer for each locality. Sites 7, 10, and 11 are the three sampled locations of the Paradise River; the other locations are the Nisqually River or its major tributaries (Kautz and Tahoma Creek).

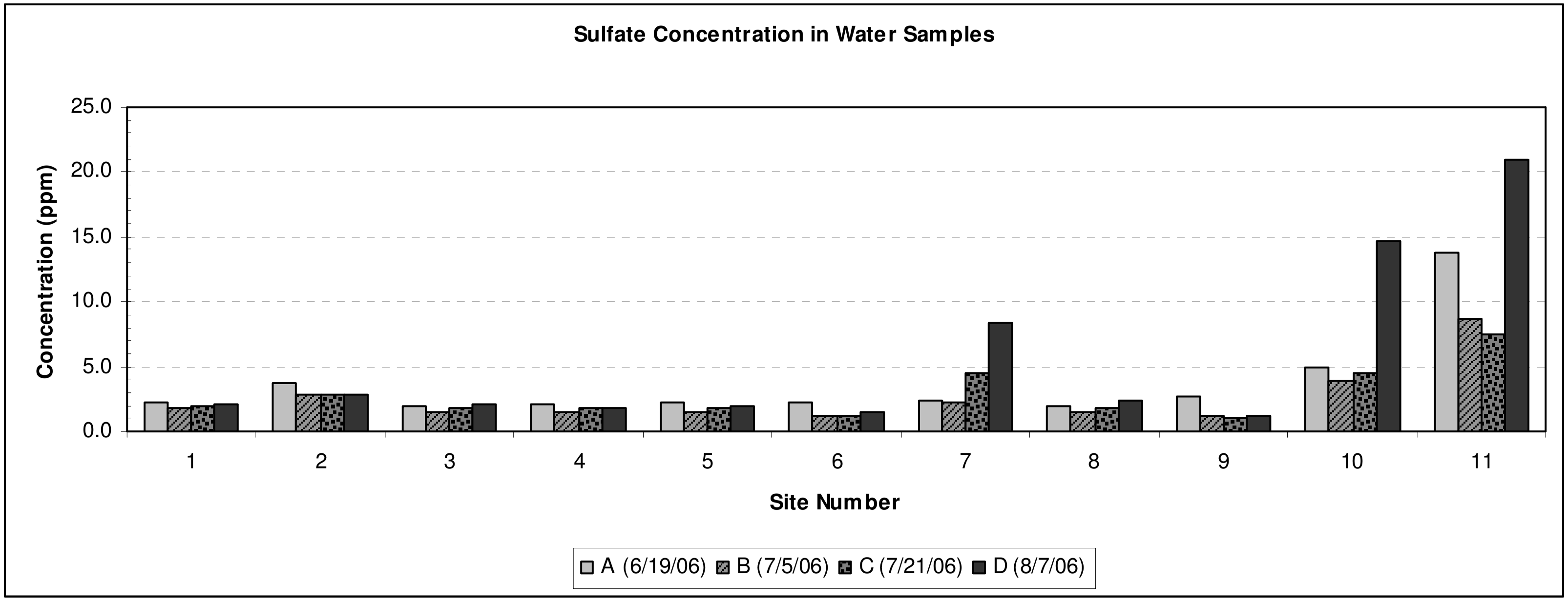
pH (Figure 4.36) generally decreased over the course of the summer. TDS (Figure 4.37) and conductivity (Figure 4.38) nearly mirrored each other in a decrease in concentration over time with the notable exception of the Paradise River localities (sites 7, 10, and 11). Similar to the chloride and sulfate concentrations, TDS and conductivity increased over time with the Paradise River samples.

Sample	Date	Chloride (ppm)	Nitrate (ppm)	Sulfate (ppm)	TDS (ppm)	Conductivity (μS/cm)	PH	Water Temp (℃)
1A	6/19/2006	2.9559		2.3041			8.36	10.9
2A	6/19/2006	1.1967		3.8027			8.27	10.1
3A	6/19/2006	0.4873		1.9019			8.35	9.3
4A	6/19/2006	1.3582		2.1320			8.29	8.6
5A	6/19/2006	0.7208		2.1888			8.27	8.1
6A	6/19/2006	0.6419		2.2541			8.31	7.3
7A	6/19/2006	0.8603		2.3910			8.36	6.6
8A	6/19/2006	0.3965		1.9666			8.41	7.6
9A	6/19/2006	0.8089		2.6854			8.32	6.5
10A	6/19/2006	1.5973		4.9621			7.79	5.8
11A	6/19/2006	4.3050		13.7242			7.93	5.8
1B	7/5/2006	1.0072		1.7756			8.01	10.8
2B	7/5/2006	0.8859		2.7985			8.22	10.5
3B	7/5/2006	0.3966		1.4797			8.03	9.7
4B	7/5/2006	0.9378		1.4447			7.79	9.4
5B	7/5/2006	0.5254		1.5060			7.73	9.3
6B	7/5/2006	0.3819		1.1664			7.92	8.3
7B	7/5/2006	0.7669		2.2916			7.89	9.7
8B	7/5/2006	0.2871		1.4855			7.68	10.3
9B	7/5/2006	0.2769		1.2408			7.59	8.9
10B	7/5/2006	1.2582	0.6499	3.8697			7.65	10.6
11B	7/5/2006	2.6461		8.7035			7.90	13.1
1C	7/21/2006	1.1353		1.9705	19	28	7.95	17.5
2C	7/21/2006	0.9860		2.9152	25	35	7.86	19.0
3C	7/21/2006	0.4422		1.8432	12	17	7.71	17.1
4C	7/21/2006	1.0533		1.7217	10	15	7.52	14.0
5C	7/21/2006	0.5811		1.7443	7	11	7.46	12.9
6C	7/21/2006	0.3929		1.2174	5	7	7.66	11.1
7C	7/21/2006	1.4806		4.4204	20	28	7.47	14.3
8C	7/21/2006	0.3042		1.7376	6	8	7.52	16.0
9C	7/21/2006	0.1163		0.9989	3	5	7.54	8.9
10C	7/21/2006	1.4488		4.4981	18	25	7.49	13.5
11C	7/21/2006	2.3059		7.5438	25	35	7.58	10.8
1D	8/7/2006	1.2678		2.0928	18	27	7.55	16.7
2D	8/7/2006	1.0593		2.8900	23	34	7.54	17.8
3D	8/7/2006	0.5368		2.0868	10	15	7.35	16.4
4D	8/7/2006	1.0652		1.7905	8	13	7.55	13.0
5D	8/7/2006	0.5647		1.9197	6	9	7.88	12.3
6D	8/7/2006	0.4087		1.4359	4	6	7.58	10.3
7D	8/7/2006	2.0295		8.3537	29	43	7.50	13.3
8D	8/7/2006	0.3787		2.3378	6	9	7.55	15.1
9D	8/7/2006	0.3888		1.2680	2	4	7.52	7.1
10D	8/7/2006	4.5849		14.6176	51	75	7.69	17.0
11D	8/7/2006	6.4613		21.0024	66	97	7.85	15.2

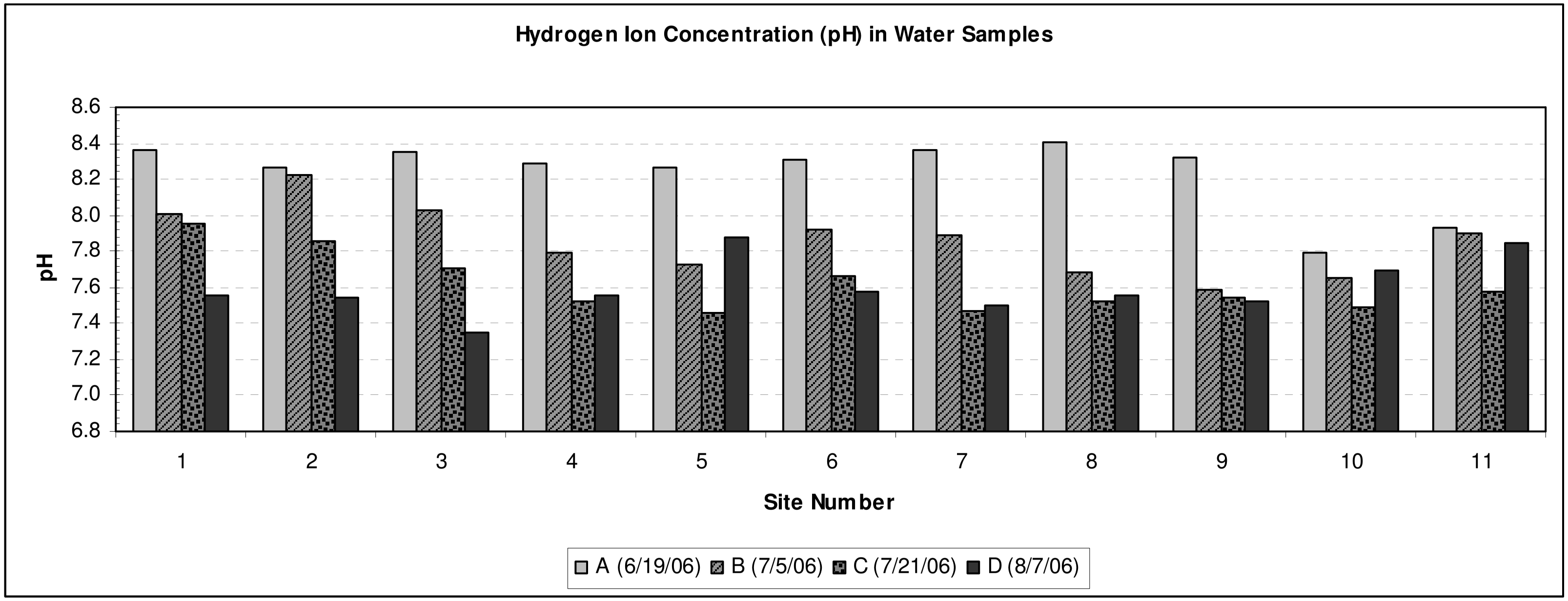
▲ TABLE 4.13
Results from chemical analysis on 44 water samples collected in summer 2006.



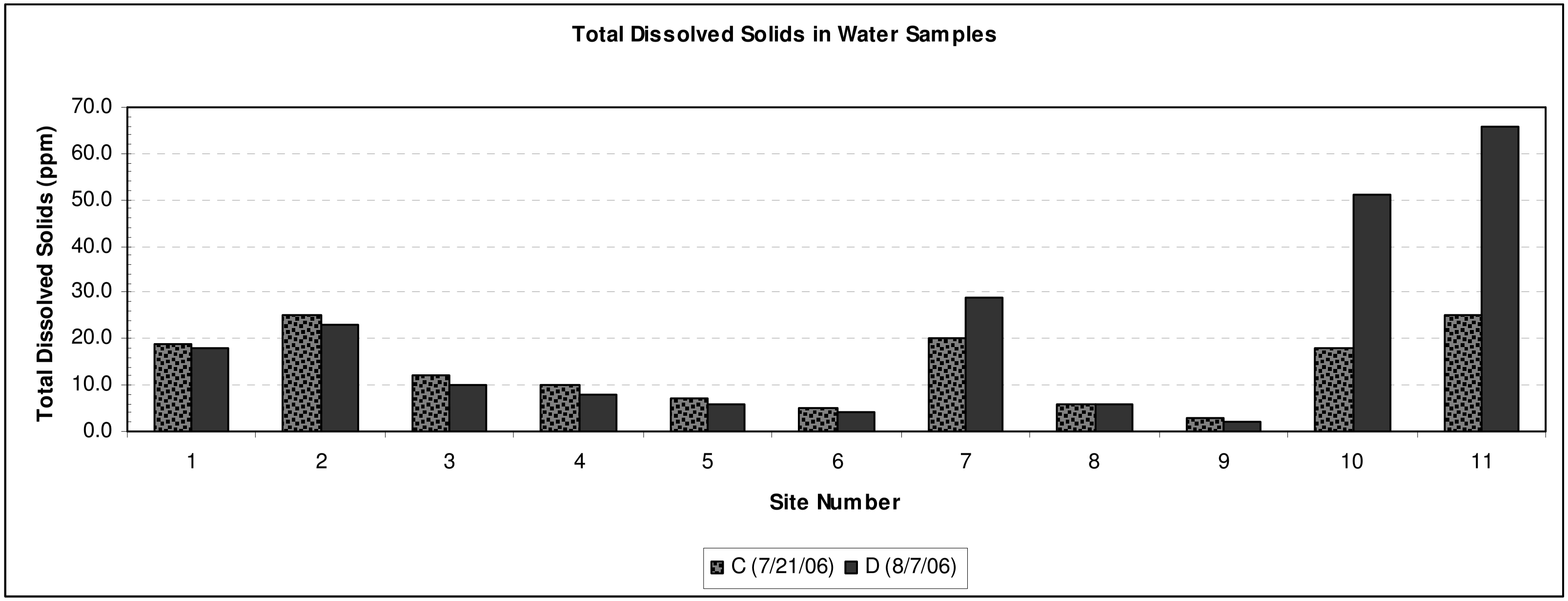
▲ FIGURE 4.34
Chloride (Cl^-) ion concentration in water samples from summer 2006.



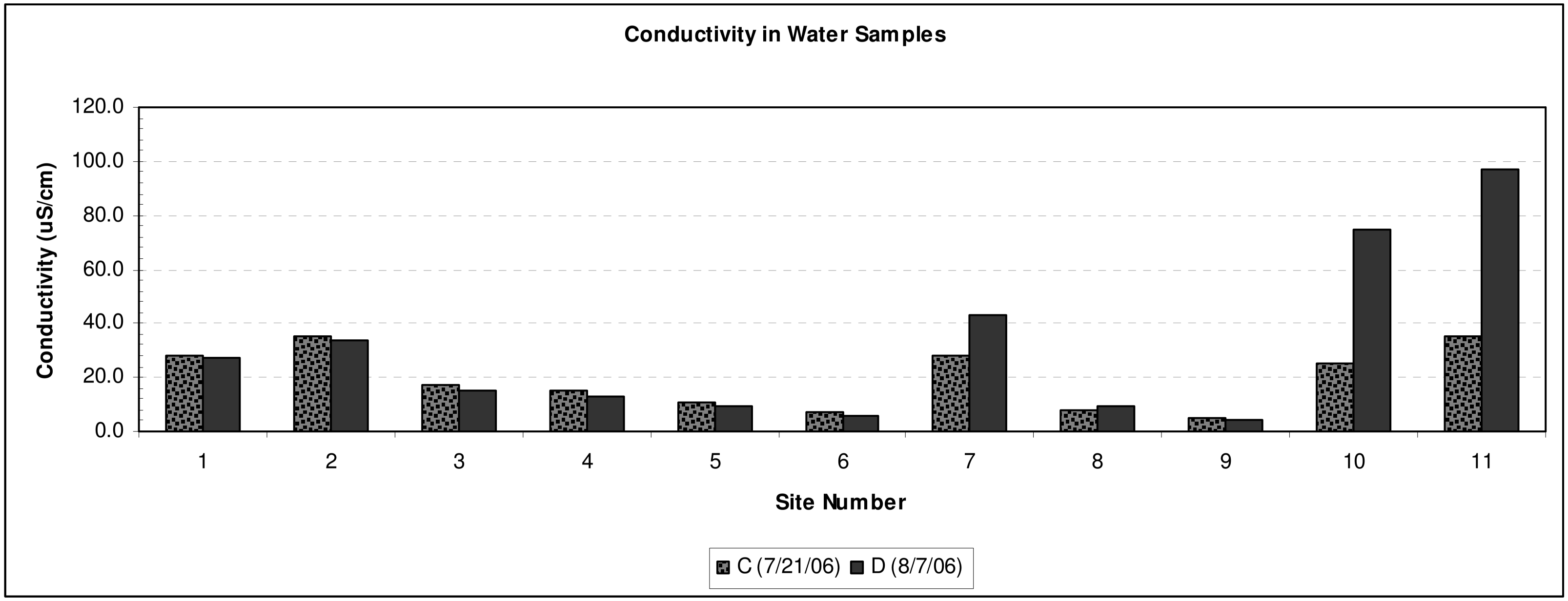
▲ FIGURE 4.35
Sulfate ($SO_4^{=}$) ion concentration in water samples from summer 2006.



▲ FIGURE 4.36
Hydrogen ion concentration (pH) in water samples from summer 2006.



▲ FIGURE 4.37
Total dissolved solids in water samples from summer 2006.



▲ FIGURE 4.38
Conductivity in water samples from summer 2006.

Suspended Sediment Analysis

Suspended sediment data analysis showed values that ranged from 172 mg/L to 5,055 mg/L (Table 4.14). Filtered sediment ranged in size from fine silt to coarse sand with a maximum observed grain size of approximately 4 mm. Site 9 (Figure 3.9) is located nearest to the glacier (approximately 1.25 mi [2 km]) and showed the highest sediment load in the study. The next highest values were from site 6 (Figure 3.9), a location near the Carter Falls Trailhead and Cougar Rock Campground. The river here is particularly active with high thalweg velocities.

Site 1 (Sunshine Point; Figure 3.9) was sampled the most times during this study. This site is around 10 mi (16 km) from the terminus of the Nisqually Glacier. All samples except #14 showed low suspended sediment values. Temperatures were higher on the day we collected sample #14.

Site 12 (Figure 3.9) was sampled three times over the course of one day; sample #15 in the morning, #16 around noon and #17 in the afternoon. This day was also much cooler and cloudier.

In all locations, especially on very warm days, a dull “thud” can be heard from time to time in the river bed from large boulders crashing into one another. The high water velocity at site six is particularly well suited for this. A log bridge crossed near this location and allowed visitors the unnerving chance to hear these crashing boulders firsthand.

Sample #	Location	Sediment Total (g)	Vol Water (mL)	x Factor	Sediment (gm/L)	Sediment (mg/L)
1	1	0.1778	520.0	1.923	0.342	341.923
2	6	0.6496	475.0	2.105	1.368	1367.579
3	1	0.6671	1058.5	0.945	0.630	630.231
4	6	4.4112	1019.5	0.981	4.327	4326.827
5	5	0.1758	1021.0	0.979	0.172	172.184
6	1	0.1881	998.0	1.002	0.188	188.477
7	2	0.3645	1022.0	0.978	0.357	356.654
8	1	0.3819	1003.0	0.997	0.381	380.758
9	1	0.3508	1019.0	0.981	0.344	344.259
10	5	1.9960	1001.0	0.999	1.994	1994.006
11	6	3.4139	1015.5	0.985	3.362	3361.792
12	9	5.0269	994.5	1.006	5.055	5054.701
13	4	2.3848	1023.5	0.977	2.330	2330.044
14	1	2.4886	1032.0	0.969	2.411	2411.434
15	12	0.6030	980.0	1.020	0.615	615.306
16	12	0.4852	966.5	1.035	0.502	502.018
17	12	0.7610	993.5	1.007	0.766	765.979

▲ TABLE 4.14

Suspended sediment results from 17 samples collected at Mount Rainier in summer 2006. Location refers to Figure 3.9.

CHAPTER 5

MAJOR FLOODING IN NOVEMBER 2006

During the first two weeks in November 2006, Mount Rainier received a record amount of precipitation for a period of record starting from 1948 (National Park Service, 2006). A storm total of 17.9 in of rain was recorded from 7:00 AM, 11/5/2006 to 7:00 AM, 11/7/06 (Table 5.1; National Park Service, 2006). The impact to the Park's rivers and infrastructure was the subject of national news attention. The Park was closed immediately following the storm and remains closed at the time of this writing. The projected opening is at least into May 2007, the longest closure of the Park in its 108-year history (National Park Service, 2006). Because of the impact of this event, follow-up research was conducted in the Park during November 20 – 25, 2006. Several areas of the Park were resurveyed to determine the effect the floods had on river channels and overbank areas.

1948-2005

November Average Precipitation	17.19 in (43.66 cm)
November Maximum Precipitation	32.36 in (82.19 cm) 1990
November Maximum Daily Precipitation	6.53 in (16.59 cm) 11/28/1995
All Time Maximum Daily Precipitation	7.76 in (19.71 cm) 12/02/1977

November 2006

Total Precipitation	41.3 in (104.90 cm)
Daily Maximum	9.7 in (24.64 cm) 11/6/2006
Storm Total	17.9 in (45.47 cm) 11/5/2006 7:00 AM – 11/7/2006 7:00 AM
Total Rain – 11/2/06 – 11/7/06	21.4 in (54.36 cm)

▲ TABLE 5.1
Precipitation statistics at Mount Rainier National Park. (Modified from National Park Service, 2006).

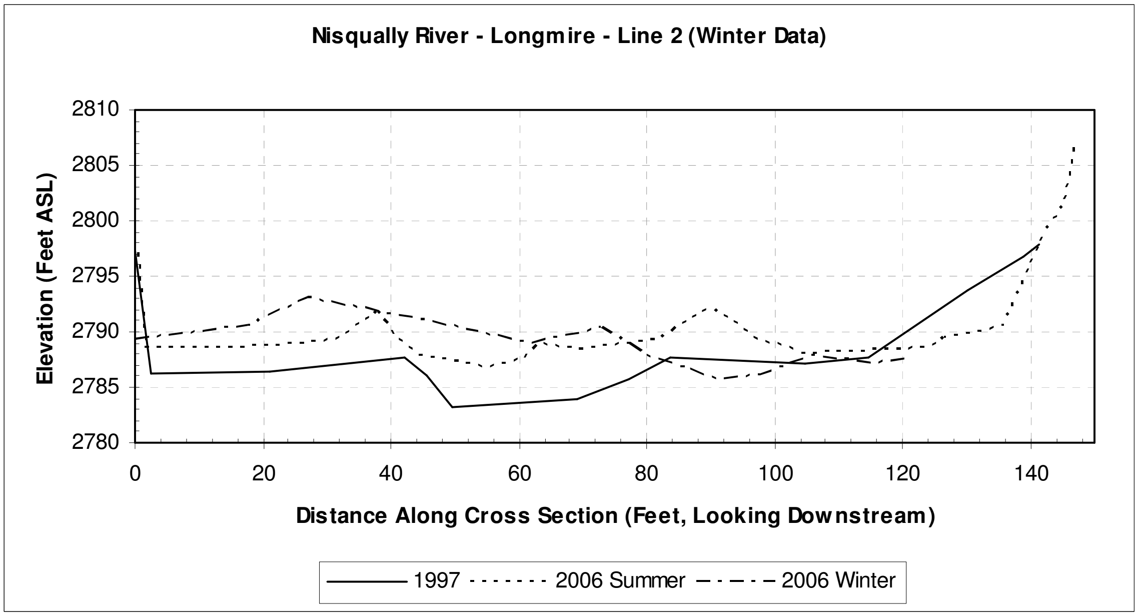
Longmire

During the flood event, a portion of the levee protecting the Longmire compound failed and damaged portions of a road and one corner of the newly-constructed Emergency Operations Center (EOC; Figure 5.1). On the opposite bank, a small grove of trees growing on the river channel was completely destroyed, opening up a much wider active channel. Electric, sewer, and water lines for the Longmire compound were significantly damaged during the flooding (National Park Service, 2006).

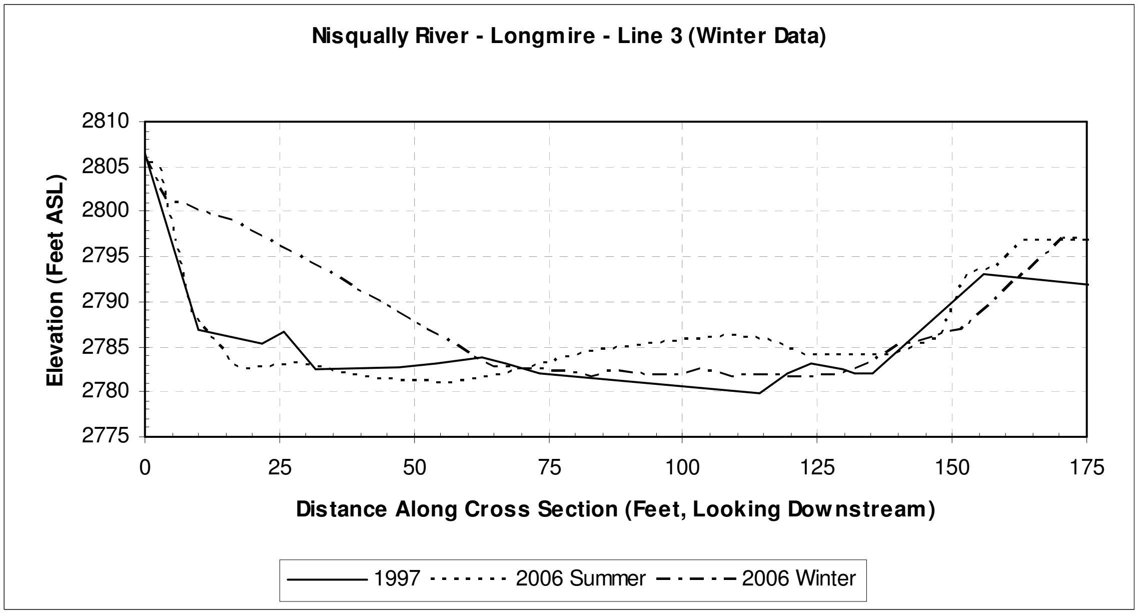
▲ FIGURE 5.1
Damage to Emergency Operations Center, levee and parking lot from flooding in November 2006. Dashed line shows approximate former levee boundary. (Photo: National Park Service, 11/17/2006).

Three cross sections at Longmire were surveyed (cross sections 2, 3 and 4; Figure 5.2 – 5.4) and the results were compared with the data observed from the summer 2006 data. The river channel had been significantly modified by post-flood maintenance personnel in heavy construction equipment (bulldozers and excavators). The maintenance workers were observed to be forcing the Nisqually River into the very center of the active channel and pushing bed material outwards to the sides of the channel. Since the personnel did not move significant amounts of material upstream, downstream, or out of the river channel, the cross sections contained the same pre-storm material, just in peculiar locations. Cross sections 3 and 4 showed this very phenomenon. Cross section 2 had not yet been modified by equipment and appeared to be unaltered in any way.

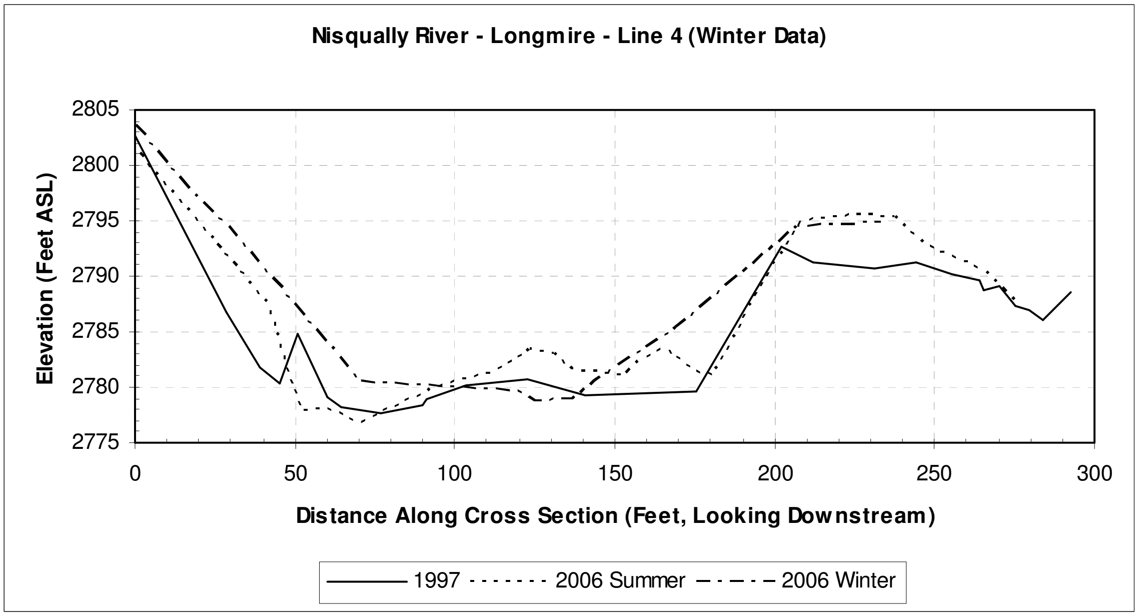
The results of the surveying indicate that Line 2 (Figure 5.2) aggraded an average of 1.18 ft (35.97 cm) along 121 ft (37 m; Appendix A). Line 3 (Figure 5.3) aggraded an average of 3.72 ft (113.39 cm) along 176 ft (54 m; Appendix A). Line 4 (Figure 5.4) aggraded an average of 0.17 ft (5.18 cm) along 254 ft (77 m; Appendix A). Using the same area calculations from the summer 2006 data, the total volume of materials that accumulated in the channel was computed (Table 5.2). The weighted average accumulation is 1.49 ft (45.42 cm) in an area of approximately 20,109 ft^2 (1868 m^2). This is approximately 111 dump trucks worth of material (assuming a typical 10-cubic yard dump truck).



▲ FIGURE 5.2
Cross Section 2 at Longmire (Nisqually River) showing change from November 2006 storm. Vertical Exaggeration ≈ 1.8x.



▲ FIGURE 5.3
Cross Section 3 at Longmire (Nisqually River) showing change from November 2006 storm. Vertical Exaggeration ≈ 1.7x.



▲ FIGURE 5.4
Cross Section 4 at Longmire (Nisqually River) showing change from November 2006 storm. Vertical Exaggeration ≈ 3.5x.

	Line 2	Line 3	Line 4	Totals	
Area - 2006 Summer (ft^2)	10,762.699	15,381.812	22,894.193	*(Appendix A)*	
Area - 2006 Winter (ft^2)	10,905.404	16,038.305	22,937.878		
Transect Width (ft)	120.742	176.324	253.880		
Net Change (ft^2)	142.705	656.492	43.685		
Average Across Transect (ft)	1.182	3.723	0.172		
Area (ft^2)	9,109.360	4,846.087	6,153.526	20,108.973	**ft^2**
Increase in Material (ft^3)	10,766.334	18,042.990	1,058.833	29,868.157	**ft^3**

Total Weighted Increase (Total Increase / Total Area): 1.485 **ft**

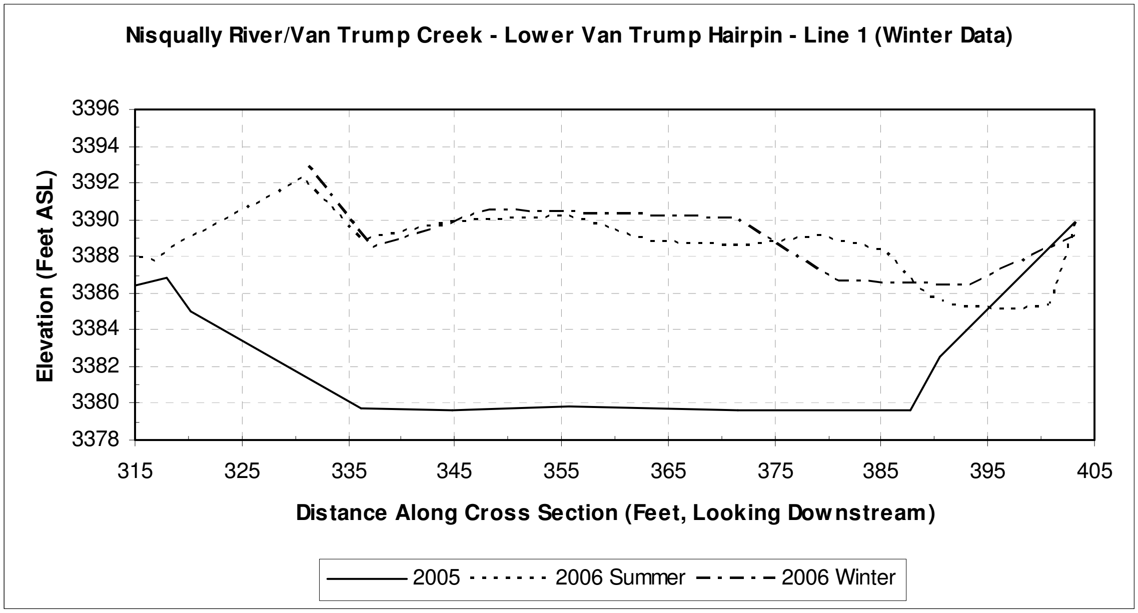
Volume of Total Increase: 1106.227 **yard^3**
Dump Trucks (10 yard^3 capacity): 110.62 **dump trucks**

▲ TABLE 5.2
Average increase of material from Summer 2006 to Winter 2006 for cross sections 2, 3 and 4 at Longmire. The total weighted increase is 1.49 ft or an increase of 111 10-cubic yard dump trucks of material.

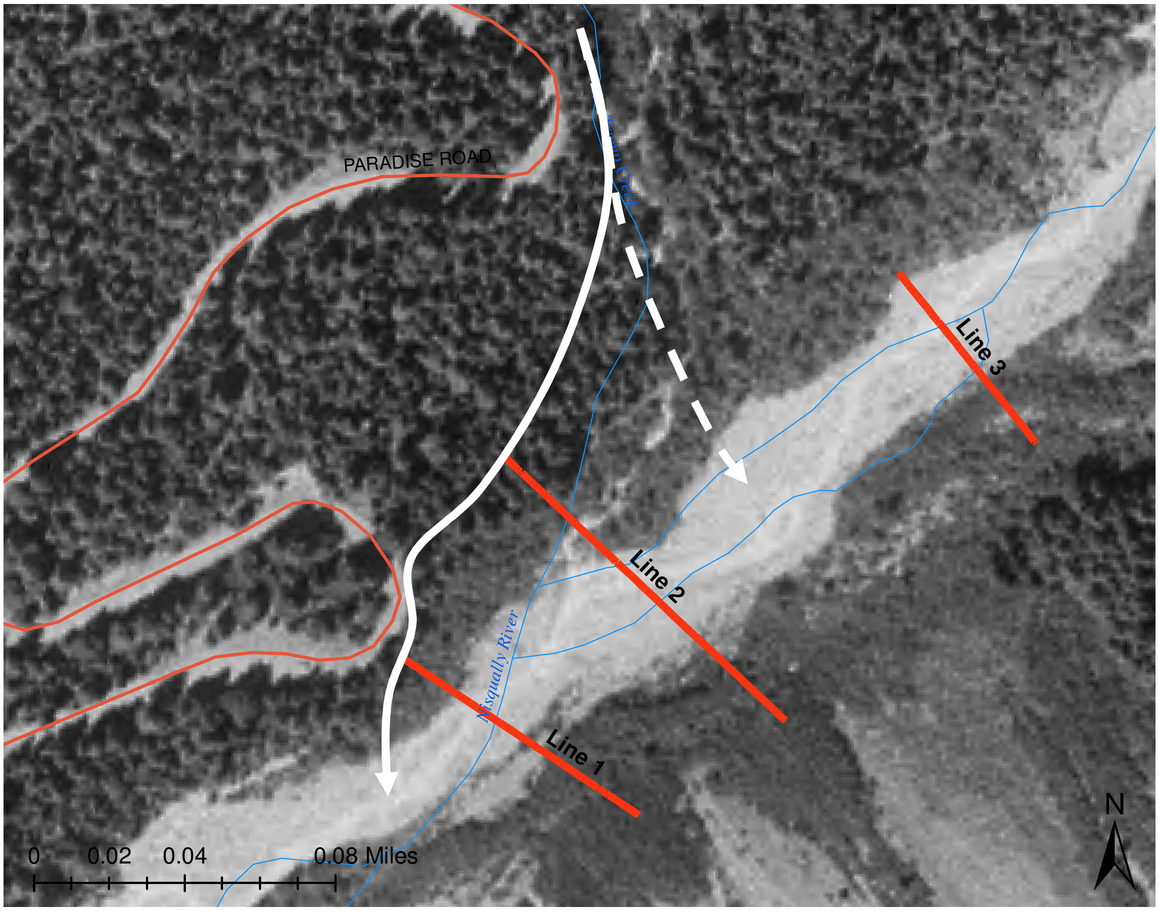
Lower Van Trump Hairpin

Little if any damage occurred in this area to Park Infrastructure. Valley-wide cross sections could not be constructed in this area due to depth of snow cover (approximately 5 ft) and the fact that snow was hiding the true location of the Nisqually River. The survey team was able to survey approximately 72 ft (22 m) of the 433 ft (132 m) first cross section (Figure 5.5). This is the first of 3 cross sections in the area. In that distance, the cross section aggraded approximately 0.73 ft (22.25 cm; Appendix A).

Van Trump Creek no longer follows its former channel near the lower hairpin (Figure 5.6). It now flows straight east from the upper hairpin into the Nisqually. Prior to this time, the debris flow deposit from September 2005 isolated the river into a channel which flowed near the lower Van Trump Hairpin.



▲ FIGURE 5.5
Cross Section 1 at Lower Van Trump Hairpin (Nisqually River/Van Trump Creek) showing change from November 2006 storm. Vertical Exaggeration ≈ 1.7x.



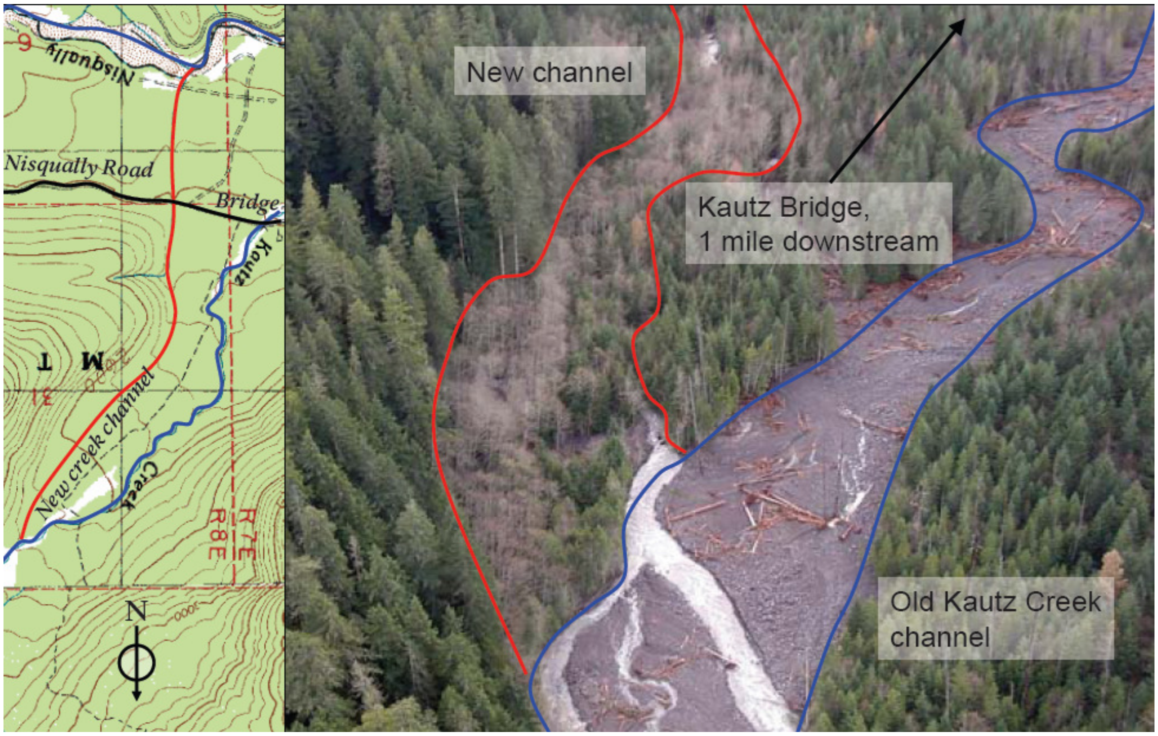
▲ FIGURE 5.6
Migration of Van Trump Creek at Lower Van Trump Hairpin between summer 2006 and November 2006. Solid line indicates flow during summer 2006 while dashed line indicates flow following major flooding that occurred in November 2006

Kautz Creek

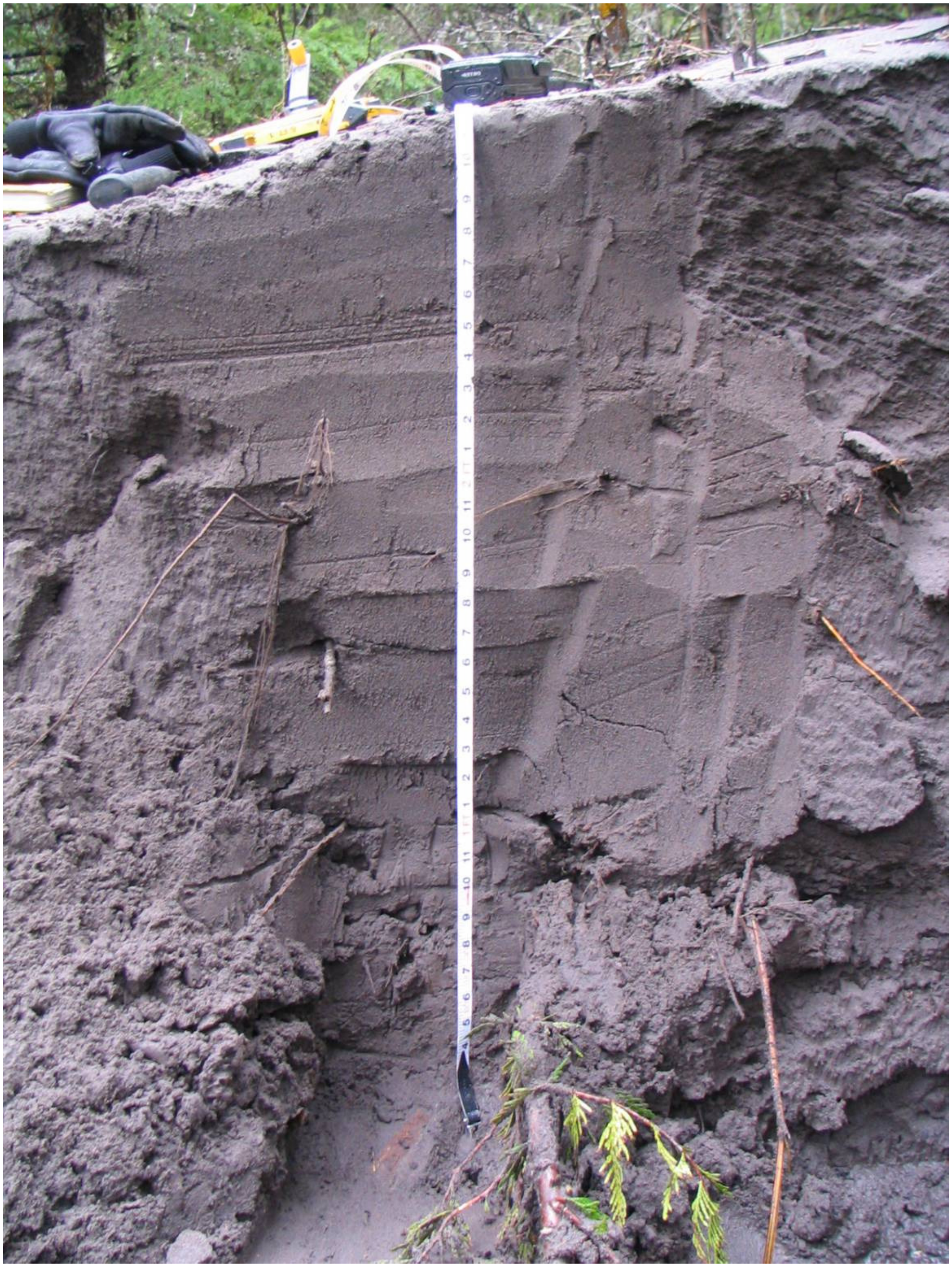
Kautz Creek, an area that was not surveyed in the summer research period, was one of the most heavily impacted locations on the south side of the Park. The river was diverted out of its channel approximately 1 mi upstream of the main Park road and the river now flows through mature old growth forest (Figure 5.7). At the Nisqually-Longmire Road, the creek no longer flowed in its former channel, instead carving a new channel in a debris flow deposit from 1947 (Crandell, 1971). Water flooded over the Nisqually-Longmire Road during and after the event until Park staff were able to unblock culverts under the road.

Water carried significant amounts of sediment from the diversion point until it hit the main Park road. Along this area, overbank aggradation occurred as the water hit the road and lost entrainment velocity. An informal survey of the overbank aggradation was conducted next to the Nisqually-Longmire Road, east of the original river channel. In many places, the amount of material was estimated. Several locations were measured using a contractor’s tape (Figure 5.8). In the majority of the places surveyed, the interface between the former ground level and base of overbank aggradation could not be observed due to liquefaction of the overbank material. In situations like this, the minimum possible depth was calculated, though, the true depth was greater than the depth we measured.

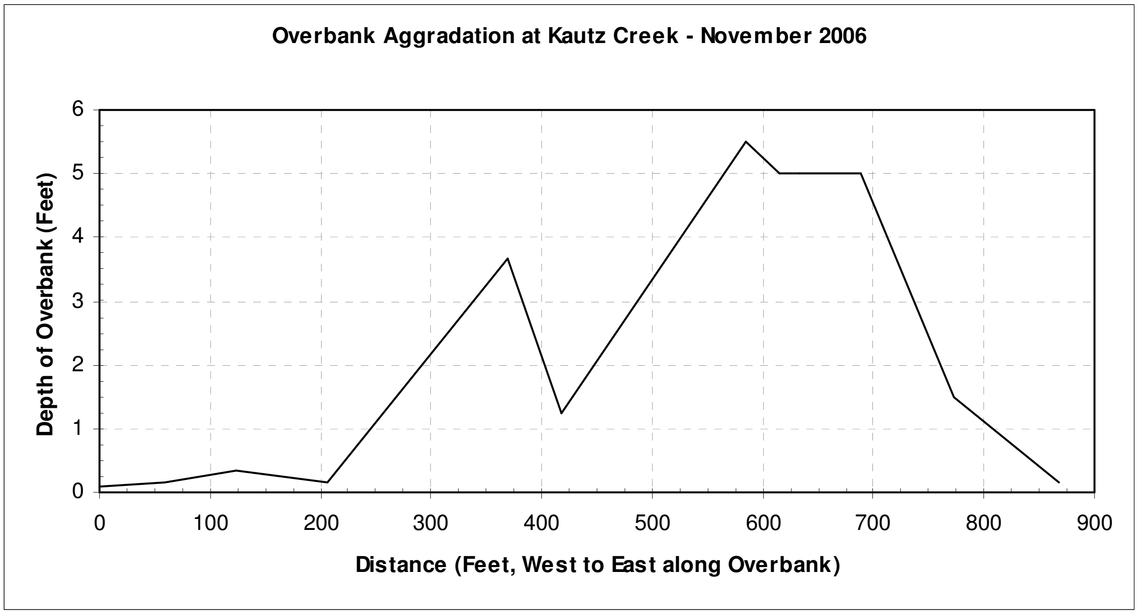
The area of the overbank aggradation along the main Park road was 1915.76 ft^2 (177.98 m^2; Figure 5.9). Assuming this sedimentation continues north of the main Park road for 50 feet, the volume of overbank aggradation measured here was 95,788 ft^3 (2,712 m^3), or 355 dump-trucks worth of material. This fluvial (non-debris flow) aggradation is the highest amount of sedimentation measured during the course of the study.



▲ FIGURE 5.7
Photo showing diversion of Kautz Creek off of former bed into new channel approximately 1 mile upstream from Nisqually-Longmire Road (Photo modified from National Park Service publication, 11/2006).



▲ FIGURE 5.8
3.92 ft (1.19 m) of overbank aggradation along Nisqually-Longmire Road at Kautz Creek deposited from the November 2006 flood. Scale in inches/feet (Photo: Scott Beason, 11/22/2006).



▲ FIGURE 5.9
Cross section view of overbank aggradation depth along Nisqually-Longmire Road at Kautz Creek following November 2006 flooding. Vertical Exaggeration ≈ 5.8x.

Tahoma Creek

Surveying was not conducted in this area in the summer research period. A significant increase of materials in the creek at the junction of the river and the main Park road was observed. Visual estimation of the material that accumulated is at least 5 ft (1.5 m) across the channel (estimating on the low side). As it stands now, the river and lower portions of the bridge are only separated by less than 5 ft (1.5 m) of space (Figure 5.10). This was not the case during the summer. However, since this area was not surveyed in the summer, the exact height difference is not available.

Just downstream from the main Park road, in the river channel, was an area that was heavily modified by Park maintenance personnel prior to 2006. The personnel channelized the river into the center of the channel and pushed excess material outwards, creating berms. Observations revealed the berms were removed early in the flood (by 9:30 A.M.; Kennard, personal communication, 2007), and showed that the entire area had filled in with material from Tahoma Creek after the flood. Using a photo taken during the flood event, looking downstream from the bridge and one taken during the November survey period, a comparison of the river channel's aggradation can be made. No height reference was made during the research period; however, using the height of a known object which was photographed in the stream channel in January, the change in river elevation can be calculated. The absolute minimum the riverbed increased at that point was determined to be 4.44 ft (1.35 m).

Much like the case at the Longmire compound, at Tahoma Creek, one heads downhill from the river to the west toward the junction of the Nisqually-Longmire Road and West Side Road. Damage did occur to this location from overbank flooding.

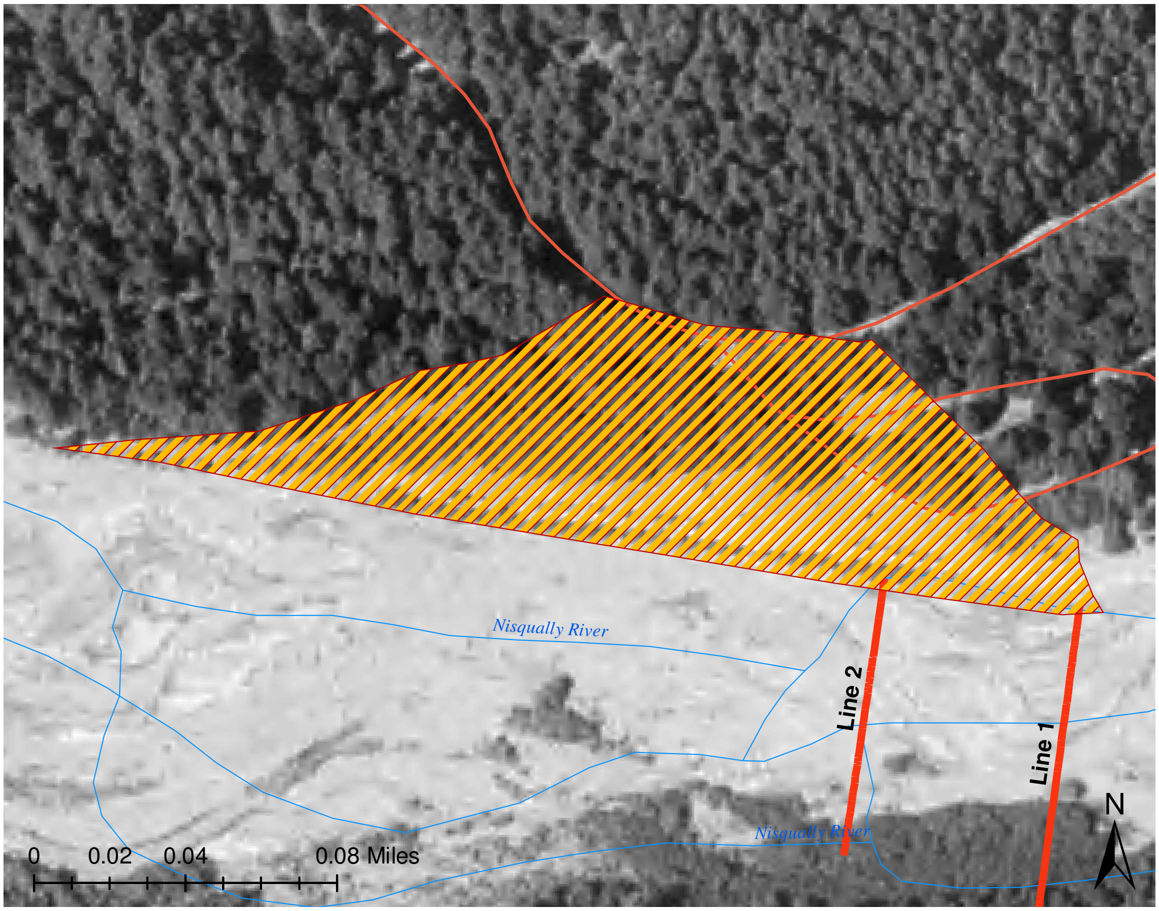
▲ FIGURE 5.10
Evidence of rapid aggradation in Tahoma Creek under the Nisqually-Longmire Road bridge. Prior to the November storm, there was at least two times the open space between the bottom of the bridge and river bed (Photo: Scott Beason, 11/22/2006).

Sunshine Point

By far, the most damage in the Park occurred to the Sunshine Point Campground, a quarter of a mile from the main Park entrance (Figure 5.11). The campground was completely destroyed and no longer exists except for a small island of materials with several vacant campsites in it. The rest of the campground was heavily eroded and is now part of the active channel of the Nisqually River. A quarter of a mile of Park road was also destroyed during the flooding.

Using a handheld GPS, the new bank position was mapped and the positions were brought into GIS software. The area lost to the river was calculated after digitizing a polygon atop a digital orthophoto of the area (Figure 5.12). The total area lost to the river is approximately 296,467 ft^2 (27,542 m^2). Assuming the river eroded 15 ft (4.6 m) of material in the vertical direction (the average height from riverbed to former surface at Sunshine Point surveyed from summer 2006), the total material lost and mobilized by the Nisqually River is approximately 4,447,000 ft^3 (125,925 m^3; 16,470 dump trucks worth of material).

▲ FIGURE 5.11
Damage to Sunshine Point Campground. Dashed line approximates former river/campground boundary. Longmire-Nisqually Road curves on the left (Photo: Scott Beason, 11/23/2006).



▲ FIGURE 5.12
Area of material lost from Sunshine Point campground and mobilized downstream by the Nisqually River. Area of hachured polygon is 296,466.72 ft². Campsites are along the loop road in this figure. The western half of the campground had space for picnic tables, bathrooms and parking.

CHAPTER 6

INTERPRETATION AND DISCUSSION

Nisqually River at Longmire

The data from the Nisqually River at Longmire showed some very interesting results. This was the most studied area in the Park since there happens to be quite a bit of Park infrastructure near the study area. Access to the study area is also quite easy. Within a quarter of a mile of the Nisqually River at this location lie Park housing, a maintenance yard, an administration building, historical structures, visitor centers, and the National Park Inn, which is open all year.

The very first – and most troubling – fact discovered in this research is that nearly all structures mentioned in the last paragraph lie under the current bed elevation of the Nisqually River. We suspected this when initially establishing control points for the study but it was not until analysis of cross section points when the true height difference was noted. The administration building lies approximately 29 ft (9 m) below the bed height of the Nisqually River, 1,100 ft (335 m) away. This is readily apparent as one walks uphill from the administration building to the Nisqually River.

The Nisqually's active channel just upstream and adjacent to Longmire happens to be among the narrowest areas the river occupies in the Park. We were expecting to see degradation in these areas since, it was thought, a confined channel would have a higher velocity which would entrain sediment. Upon analysis of our data, however, we discovered the very opposite. The Nisqually in the more confined channel has a higher rate of aggradation than the more spread-out channel downstream of cross section 6. This strongly suggests sediment supply and not channel geometry controls aggradation. This was a surprising and troubling find, since a man-made levee on the right bank (looking downstream) near cross section 3 is all that protects the Longmire compound from the river. In several places, the levee appeared to be thinning and getting undercut (Figure 6.1).

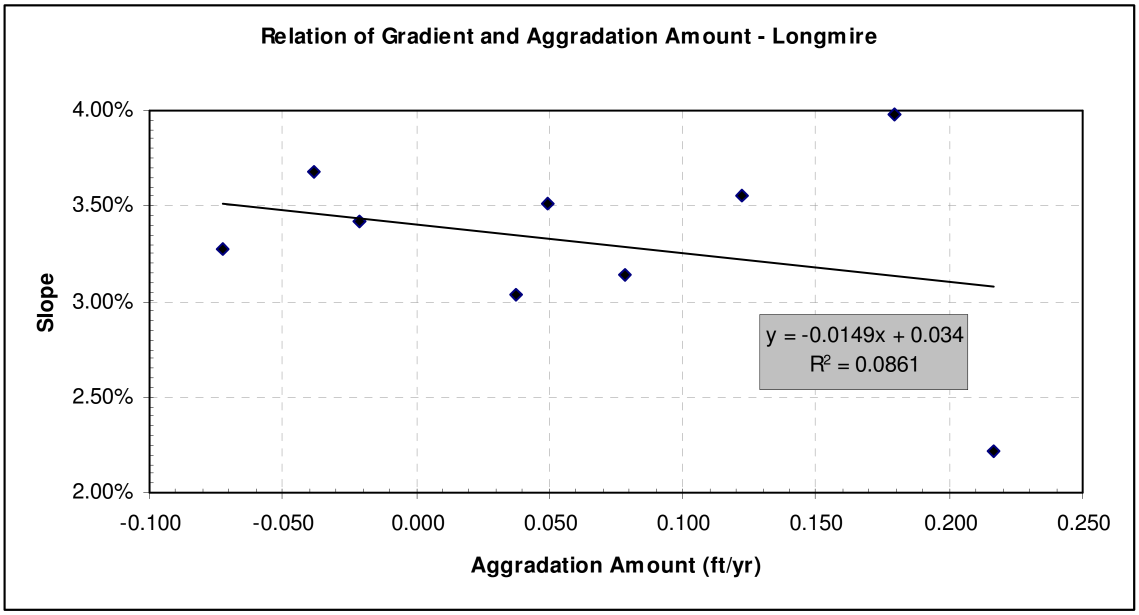
One possible explanation for the unexpected aggradation rate is the slope observed in the active channel at Longmire. Table 6.1 shows the lowest river elevations in each line, the distance between each line, calculated gradient and observed aggradation rates (ft/yr) in the cross sections at Longmire. Plotting slope and aggradation rate (Figure 6.2), a very rough approximation can be made (as evidenced by the best-fit line in Figure 6.2). The R^2 value for this line is 0.086. Removing the uppermost outlier (Slope of 3.98% with an aggradation rate of 0.179 ft/yr) gives an R^2 value of 0.454, a better relationship. If this trend is true, however, it explains the data we observed (i.e., a steeper slope results in decreased aggradation). This would be expected since, all things being equal, steeper slopes generally experience more degradation and gentler slopes experience more aggradation.

The minimum aggradation that should be expected for all cross sections at Longmire is 6.494 in/decade (16.495 m/decade). Areas with lower gradients (i.e., areas in the more confined channel near the levee – lines 2 to 6) should expect to see aggradation of around 12.139 in/decade (30.833 m/decade). Since debris flows have occurred upstream and have deposited over 300,000 m^3, it should be expected that this material will be brought downstream by regular flows and flood events.

▲ FIGURE 6.1
Undercutting of levee protecting Longmire compound. Photo is taken from the suspension bridge crossing the Nisqually, looking downstream at the right bank (Photo: Scott Beason, 8/16/2006).

Line	Elevation	Distance between Lines	Gradient	Aggradation Rate
1	2794.81			0.013
2	2788.55	282.526	2.22%	0.217
3	2784.05	147.915	3.04%	0.037
4	2781.55	79.561	3.14%	0.079
5	2775.16	181.819	3.52%	0.049
6	2766.20	252.431	3.55%	0.122
7	2761.01	141.129	3.68%	-0.038
8	2749.59	286.754	3.98%	0.179
9	2737.74	346.894	3.42%	-0.021
10	2726.31	348.858	3.28%	-0.073

▲ TABLE 6.1
Characteristics of cross sections at Longmire. Columns include: cross section transect, lowest river elevation (ft) in each transect, distance (ft) between transects, gradient between cross sections, and aggradation rate (ft/yr) observed at each cross section.



▲ FIGURE 6.2
Relationship between gradient and aggradation amount in cross sections at Longmire. Removing the uppermost outlier results in a better R² relationship (0.454).

Nisqually River at Sunshine Point

Cross sections from Sunshine Point showed some of the highest rates of aggradation but one cross section showed very negative aggradation across its width. Gradients in this location are much lower (around 2%). The hypothesis for this area was a higher rate of aggradation due to its lower gradient and lower entrainment velocity. The data observed in this location do show this relationship, but poorly. The upper two cross sections in this area show higher rates of aggradation, whereas the furthest downstream cross section shows a decrease of material. This is based on only one year of data.

The Nisqually River at this location has the additional influence of both Kautz Creek and Tahoma Creek. Tahoma Creek flows though an area that is seeing relatively extreme debris flow activity compared to the rest of the Park. Because the creek flows through this location, it is possible that more material is making its way to the Nisqually River and influencing the active channel. Kautz Creek also has experienced major mudflows in the last century and certainly has supplied a great deal of material to the Nisqually River.

It is unknown why the very negative aggradation rate was observed in this location. Further study would benefit the current work and help answer why this observation was noted. However, because of the damage which occurred to this area in November 2006, future work may be difficult at best based on the much larger braided channel at Sunshine Point. It is expected that the material provided by the debris flows from Tahoma Creek will positively influence aggradation rates at Sunshine Point in the coming decade.

Nisqually River at Van Trump Creek

Exact rates of aggradation at this location are not known due to the influence of debris flows from Van Trump Creek. Surveying resulted in cross sections that looked vastly different in the last year. The amounts of material that have accumulated in this river channel far exceed any aggradation amounts noted anywhere else in this study. Because the aggradation noted here is from a debris flow, the term hyperaggradation is used to describe these deposits.

Surveying also allowed calculation of a very rough estimate of total volume of material from the 2005 debris flow. The total volume of material accumulating in all 3 cross sections in this area is 602,847.576 ft^3 (17,070.742 m^3). Using only cross sections 1 and 2 (since the debris flow fan thins out upstream of line 2), we have found that approximately 522,811.711 ft^3 (14,804.379 m^3) of materials accumulated from the debris flow. This amount is much lower than the 2001 and 2003 debris flows, but also does not take into account the material which accumulated off of the active channel. Additionally, locations between the three cross sections may have higher or lower total increases.

Since this was a smaller debris flow and larger debris flows have been seen in this location in the last 5 years, similar sized or even larger sized events may be expected. Field surveying by Donovan (2005) on the upper mountain source area for this event found a large area of loose, unconsolidated materials that may be easily entrained as a debris flow. Given this area’s history, future debris flow events would not be surprising.

Continual monitoring in this area is essential, especially if debris flow activity continues. As observed in the current study, the maximum river channel height in cross section 1 is several feet higher than the Lower Van Trump Hairpin. At this point, the Nisqually River and Van Trump Creek are still lower than the road elevation; however, further debris flow activity in this area may change that. During the debris flow in 2005, waters from Van Trump Creek did flow across Lower Van Trump Hairpin (Figure 6.3).

▲ FIGURE 6.3
Van Trump Creek flowing across Lower Van Trump Hairpin during the fall 2005 debris flow. (Photo: National Park Service, 9/29/2005)

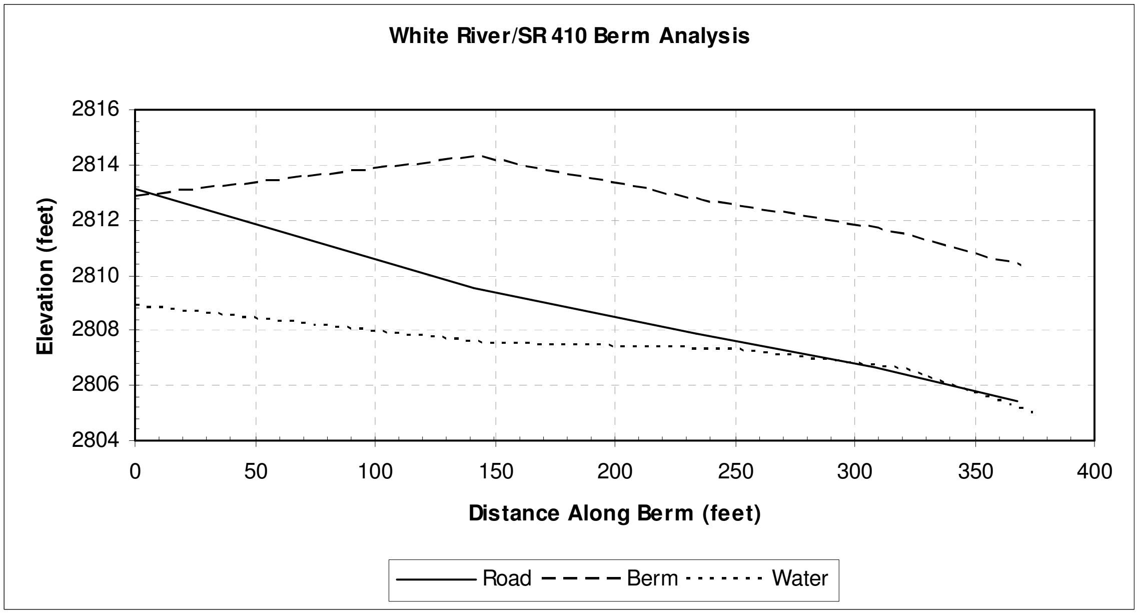
White River along State Route 410

Herrera (2005) documented the fact that State Route 410 was below the elevation of the river bed, a fact that we confirmed. Our data also indicated that the river bed in this location is also aggrading at a much higher rate than observed in similar gradient locations in the Park. This is a troubling finding, especially when compared to other rivers in similar situations at the Park (e.g. Tahoma Creek, discussed in the next section).

An old growth forest occupies areas between the river channel and State Route 410 in this location. Evidence of flood water flow is plainly visible since the entire forest floor is covered with several inches of overbank river sediment. This sediment is at such a depth and cover that it appears to be killing old growth forest. Some of these trees are hundreds of feet tall, which present a risk to automobile traffic on State Route 410.

A side channel of the White River flows off of the main active channel, through the old growth forest area and runs parallel to State Route 410. The river has flooded across State Route 410 several times, and recently the Park has built a concrete reinforced, rock armored berm (Figure 6.4). We analyzed this berm on a cool, cloudy day to determine if the water in the side channel would be flowing across the road if the berm were not present (Figure 6.5). We found that at a low flow condition, the water would indeed be flowing across the road. The berm is at a location that is approximately 15 ft (4.6 m) below the bed elevation of the White River. It is unlikely that the berm would stop a large flood of the White River.

▲ FIGURE 6.4
Berm constructed by National Park Service to keep flooding from occupying State Route 410. A side channel of the White River flows near the road necessitating construction of the berm. Photo taken at the end of the berm (approximately the 350 ft point in Figure 6.5) looking upstream (south; Photo: Scott Beason, 8/10/2006)



▲ FIGURE 6.5
Analysis of road, berm and side channel elevation along State Route 410, constructed by Total Station. If it were not for the berm, the river would be flowing over the road at higher discharges than were observed during the construction of the transects for the analysis.

Carbon River, Kautz Creek and Tahoma Creek

Historical topographic map analysis showed that Carbon River is experiencing the highest aggradation rate of all the rivers analyzed using this method. This method may have a significant margin of error since it depends on topographic contours and the accuracy of maps. This indicates aggradation or hyperaggradation in this area may be at a higher rate than observed in the rest of the Park. This area should be a priority to be studied by future workers at Mount Rainier.

Analysis of Kautz Creek historical topographical maps show locations that have both aggraded and degraded significantly. The most accessible of these locations is right along the Nisqually-Longmire Road from the 1947 debris flow deposit. Further upstream, locations have both aggraded and degraded. There is weak evidence for these degraded areas being the source materials for the 1947 debris flow. Since the survey team was unable to visit this area to verify the data, future work in this location needs to be done to confirm this finding.

Tahoma Creek was not analyzed in detail during this study. Instead, we looked at historical topographic maps to determine rates of change occurring in this area. Tahoma Creek has been experiencing numerous debris flows since the late 1960s, a trend that appears to be increasing with time. Many debris flows have impacted the West Side Road, now closing the road off to Park visitors. Even in the last year, significant debris has accumulated in the river channel, probably as result of debris flow activity. This material significantly damaged portions of the road during early summer 2006 (Figure 6.6). Maintenance staff were able to temporarily repair the damage. The work performed by maintenance staff will continue to be destroyed by future flows. The current trend of short-term fixes in this and many other locations in the Park does provide access to destroyed places but such practices may be costly in comparison to more permanent solutions.

Visual observations of Tahoma Creek at the Nisqually-Longmire Road bridge indicate that it is at a higher elevation than areas adjacent to it, especially as one travels west to the intersection of the West Side Road and Nisqually-Longmire Road. This is the case for many locations in the active channel as observed in Figure 6.7. Due to aggradation and hyperaggradation, many sections of the active channel of Tahoma Creek are at elevations much higher than lower-lying forests. Because of this, much of the creek's active channel is quite dry.

▲ FIGURE 6.6

Discussion occurring among Park staff along Tahoma Creek and the West Side Road. Thick dashed line shows the former river and road boundary; thin dashed line shows the current boundary (the road was fixed by maintenance staff shortly after this meeting). At its narrowest point in this photo, the road is less than 1 ft in width, shown by the arrow. The main creek channel is seen in the middle of the picture. Hyperaggradation in this area was visually estimated around 10 to 15 ft (Photo: Elizabeth Beaulieu/NPS, 7/2006).

▲ FIGURE 6.7
Tahoma Creek as it flows off of its active channel into the forest, due to vertical growth of the channel over time. When the river encounters areas like this, it is natural for the river to flow downhill and off of the river channel. (Photo: Scott Beason, 7/8/2004).

November Flooding

The floods that struck Mount Rainier in November were the result of a record event that led to flooding and infrastructure damage to many locations in the Pacific Northwest. Mount Rainier was heavily damaged by the flood flows. Thankfully for the Park, events of this magnitude are not frequent; however, at least one rain-on-snow event seems to be common in the fall season. These rain-on-snow events can be especially bad since warm rain melts snow at higher elevations, which adds to the volume of water in the river channels. Also, rain-on-snow events may be a trigger for debris flows, as evidenced in the Tahoma Creek area and Van Trump area from the 2005 debris flow.

As bad as the event was, it could have been much worse. Field evidence for another debris flow during the rain event was inconclusive and possibly incomplete. Kennard (personal communication, 2007) indicated that there probably was another debris flow and resurveying the location will likely determine if there was a debris flow (it should be noted that we are discussing an additional debris flow event which possibly occurred in November 2006). The presence of the Van Trump debris flow fan from 2005 appears to have saved the Lower Van Trump Hairpin. The Nisqually River was isolated to the far left of the river channel, when looking downstream. To the right, the debris flow deposit provided a barrier which protected the lower hairpin area. A significant portion of the 2005 material may have been mobilized downstream as a result of undercutting by the Nisqually. Unfortunately, the survey team was unable to survey this area due to the amount of snow in the braided channel. We did see evidence of aggradation in the section of line 1 at Van Trump that was surveyed. This was unexpected and indicates that a sediment flux filled in the area in the three months between summer and winter surveying. This suggests a very dynamic sediment supply system.

The hypothesis before the late November surveying – with a rainstorm that dropped almost 18 in of rain on the Park – was that this was going to be a significant degradation event in the Park's rivers. This was expected because flood flows tend to increase the velocity in a river, which can more easily entrain bed and suspended sediment, carrying this sediment downstream. The result would be channels that had been eroded away by the floodflows. No evidence was observed that any surveyed location had degraded (with the exception of Kautz Creek, a special case, mentioned later). In fact, observed locations aggraded between 0.4 and 2 ft (12 and 61 cm) in areas surveyed with the total station, and up to 5 ft (1.5 m) or more in other areas. This is a very troubling finding and indicates that the "hyperaggradation" that occurred because of possible debris flows overcompensated the assumed incision forces in the flood flows.

One should never have to walk uphill to get to a river channel. Rivers follow gravity as a rule and always flow downhill. Any situation where a river is higher than the surrounding land is a serious problem – this is the case in at least four major areas in the Park (Tahoma Creek, Longmire, the upper Kautz Creek drainage, and the White River). It is fortunate that more damage did not occur in these areas due to the river's elevated position.

The Kautz Creek overbank aggradation that occurred was probably due to incision of a new river channel upstream from the Park road (Kennard, personal communication, 2007). Because of this, major degradation occurred upstream of the surveyed location which led to major aggradation in the surveyed location along the main Park road. The road most likely acted as a sediment dam – when the water, carrying the sediment, hit the road, it lost all of its energy and sediment was deposited upstream of the road. The diversion point itself is a function of an aggrading stream. The stream, over time, had built its bed elevation higher than the surrounding land. Following the flooding in November, the floodwaters found a way off of the active channel into the nearby forest. This phenomenon has been noted in the Tahoma Creek area in the past.

As observed at Tahoma Creek, the area that was channelized filled in with material very effectively (greater than 4.44 feet in a single event). The mechanism for this is natural: aggradation occurs where the river loses energy to entrain bed and suspended materials. The area channelized by Park maintenance personnel thus represents an area where the gradient of the river suddenly changes. When the river hits this area, it loses the ability to entrain sediment. Aggradation will therefore occur at a much higher rate than previously experienced (Figure 6.8). The implications of this effect are substantial, especially considering what occurred in the Nisqually River at Longmire following the event (Figure 6.9). Maintenance personnel were observed in the channel with bulldozers channelizing the stream. One piece of equipment was observed to be digging a large hole in the river channel for unknown reasons. These actions will most likely affect the slope of the river channel and lead to increasing aggradation as evidenced at Tahoma Creek.

Park personnel were heard saying what a success the channelized river segment at Tahoma Creek was following this event. This is in fact not true, for two reasons: (1) the rechannelized stream bed promoted accelerated aggradation (by reducing the stream gradient), placing the Tahoma Creek Bridge, the Nisqually-Longmire Road, and the West Side Road in imminent danger if another event were to occur before remediation; and (2) the constructed berm afforded no protection to the downstream Sunshine Point campground, as the entire berm had washed away at least 8 hours before the flood peaked. Additionally, the safety of facilities at Longmire is in question given the work that has occurred in the Nisqually River channel following the flooding.

Bank and levee failure at both Sunshine Point and Longmire occurred along areas of rip-rap protection. A review of published literature has found very few articles discussing failure of levees and similar structures because of rip-rap. However during the entire study period, rivers at Mount Rainier seem to be attracted to rip-rap banks rather than being deflected away from the channel sides into the middle of the active channel (this is because rip-rap provides less “roughness” than a natural, forested stream bank). We did not conduct a forensic study as to why these locations failed. In fact, at Longmire, the channel was modified by post-flood maintenance personnel so quickly that analysis as to why failure occurred in these locations was not possible. This is understandable at Longmire since infrastructure was at significant risk. However, it is inaccurate to assume the rechannelization provides meaningful infrastructure protection. It is interesting to note that the Park appropriated funds to build engineered barbs to divert the erosive power of the river from the rip-rap at Longmire following flood damage the previous year. It is extremely unfortunate that these barbs were not constructed prior to the 2006 flood.

A study looking at the possible reasons of failure of the Sunshine Point rip-rap protection (possibly looking at Manning's *n* values) would be very useful to the engineering of protective structures in the Park and at many other locations that rely on rip-rap protection.

▲ FIGURE 6.8
Evidence of anthropogenic alteration to Nisqually River channel at Mount Rainier following November 2006 flooding (photo looking upstream). Dashed line shows division of natural stream channel (upstream) and modified channel (downstream). Slope is increased around the nick point but decreases immediately after it, allowing entrainment velocity to decrease. During high flow events, locations like this can fill in with sediment. (Photo: Scott Beason, 11/22/2006)

▲ FIGURE 6.9
Bulldozers and heavy equipment channelizing and altering the natural active channel of the Nisqually River at Longmire following November 2006 flooding. (Photo: Scott Beason, 11/21/2006)

Chemical Analysis

Chloride can be dissolved in water in a variety of ways. Chloride is one of the ingredients used in road salt during the winter in a variety of locations. It can be the degraded product of pesticides used to control invasive weeds. It may also naturally occur as scattered fragments from halite in the topsoil.

Chloride concentrations were quite low in water samples analyzed during the summer 2006 research period. The maximum concentration observed was less than 10 parts per million (ppm). The author is not aware of Mount Rainier National Park using road salt during the winter time (the Park generally uses sand and gravel only). Also, the presence of chloride ions in samples within a few miles of the Nisqually Glacier tends to indicate that road salts are not a primary contributor. The exact source of chloride ions in the water samples is unknown.

Sources of nitrate in the environment include decayed organic material and animal wastes. Nitrates are also part of fertilizers that are applied to fields in agricultural areas. Decayed organic material includes natural nitrate which may undergo nitrification to nitrate. Solid wastes contain nitrate which may enter surface and ground waters; decayed materials enter the environment in similar ways.

Nitrates were not expected to be part of the dissolved load at the Park. Results from the ion analysis strongly confirmed this hypothesis. Only one sample showed nitrates and the concentration was less than 1 ppm. The sample was from a location near a road and bridge. Upstream (site 11) and downstream (site 7) locations showed no nitrates in their samples. The presence of nitrate in this sample may also be explained as animal waste from a variety of animals that live in the Park.

Sulfate is a natural ion in soil, caused by the breakdown of gypsum. It can also be found in groundwater from very deep sources. It may also occur in a volcanic environment from the breakdown of sulfur dioxide.

Water samples showed much higher concentrations of sulfate ions than chloride ions. The exact source of these ions is unknown. A possible scenario is sulfate moving up along fractures and interfaces between volcanic intrusions and country rock due to high pressure gradients. Microfractures may also contribute to the upward movement of sulfate ions. Sulfate ions tended to increase in samples throughout the course of the summer, especially in the Paradise River. The exact reason for the increase is unknown, but may be related to the breakdown of hydrothermally-altered rocks.

The pH in water samples showed a very general decrease over the course of the summer. This indicates that the water was becoming more acidic and is not a surprising finding given the volcanic nature of the mountain. Acid compounds, water, and heat have been proposed for the collapse of large portions of Mount Rainier’s edifice over time.

Total dissolved solids (TDS) and conductivity results mirrored each other, an expected result. As TDS concentrations increase, the conductivity of water increases. TDS values also showed a positive correlation with chloride and sulfate concentrations in water samples in all locations.

Suspended Load

When suspended load was graphed with observed air temperature (Table 6.2), a logarithmic relation was observed (Figure 6.10). The equation of the best-fit line in Figure 6.10 is:

$$T = 4.1325 * \ln(S) - 10.517 \qquad \text{(Equation 6)}$$

Assuming suspended load (mg/L) is the x-axis and air temperature (Celsius) is the y axis, the formula can be rearranged in the following way:

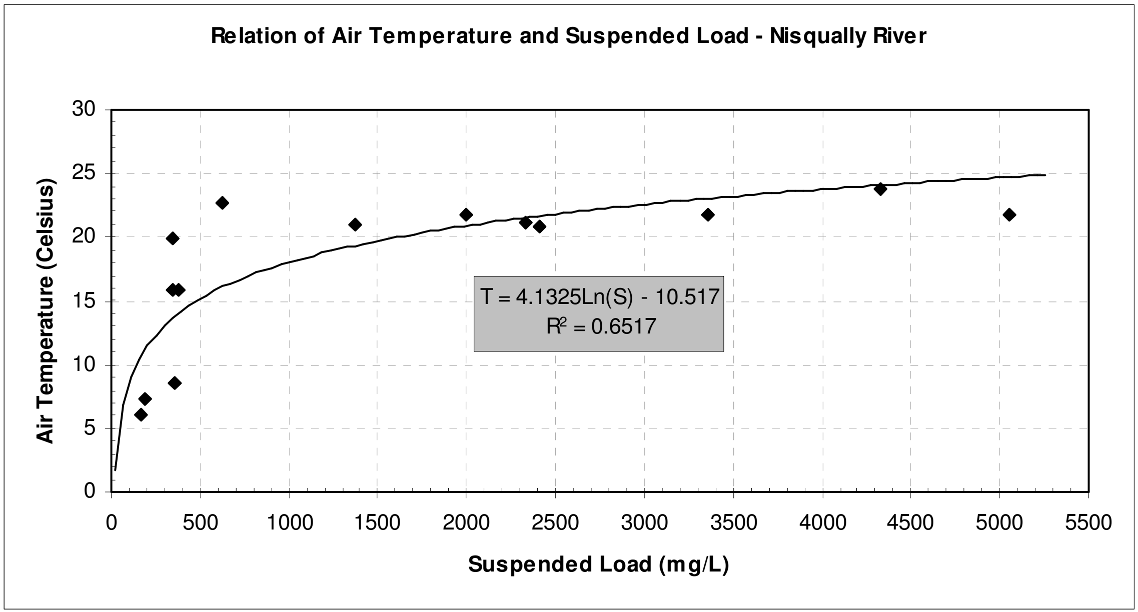
$$S = e^{\left(\frac{T+10.517}{4.1325}\right)} \qquad \text{(Equation 7)}$$

Where *S* is the Suspended Load in mg/L based on an air temperature *T* in degrees Celsius. The e value is Euler's number, a mathematical constant. The R^2 value of the plotted data is 0.6517, suggesting a strong relationship. This relation does need further refinement with more data but the fit with a logarithmic line seems to suggest a possible correlation of the two values. Suspended sediment load is derived from subglacial material (47%), channel banks (47%), and supraglacial material (6%; Hammer and Smith, 1983 *in* Haritashya et al., 2006). At higher temperatures, more melting occurs which lubricates the base of the glacier. The glacier speeds up and erodes the bed which provides more sediment to the river system (Ritter, 2002). Suspended and bed load studies have been extensively carried out in the Himalayas. Since glaciers provide sediment and water to braided rivers in both the Himalayas and at Mount Rainier, the same approximations can be made about streams at the Mount Rainier based on the observations of streams in the Himalayas.

ID	Site	Date	Time	Susp Sed (mg/L)	Water Temp (C)	Air Temp (C)	Discharge (cfs)
1	1	7/5/06	9:03 AM	342	10.8	19.9	970.6986
2	6	7/5/06	10:23 AM	1368	8.3	21.1	940.3222
3	1	7/21/06	1:40 PM	630	17.5	22.7	609.8234
4	6	7/21/06	3:00 PM	4327	11.1	23.8	606.2746
5	5	7/31/06	12:30 PM	172	10.5	6.1	407.9273
6	1	8/2/06	8:25 AM	188	9.4	7.3	342.4146
7	2	8/2/06	11:55 AM	357	12.1	8.5	336.9635
8	1	8/4/06	10:30 AM	381	11.1	15.8	390.3407
9	1	8/4/06	3:10 PM	344	16.6	15.8	381.6739
10	5	8/7/06	2:30 PM	1994	12.3	21.8	422.8441
11	6	8/7/06	2:45 PM	3362	10.3	21.8	422.8441
12	9	8/7/06	3:25 PM	5055	7.1	21.8	419.8453
13	4	8/7/06	4:30 PM	2330	13.0	21.2	416.8465
14	1	8/7/06	4:55 PM	2411	16.7	20.8	416.8465

▲ TABLE 6.2

Suspended loads, water temperature, air temperature and discharge for each suspended load sample collected in the Park in summer 2006. Air temperature data is from Paradise[4] and discharge data is from a gauging station along the Nisqually River outside the Park[5].



▲ FIGURE 6.10

Relation of air temperature and suspended load as observed along the Nisqually River at Mount Rainier during the summer 2006 study period. Data is from Table 6.2.

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[4] Paradise weather data courtesy of Northwest Weather and Avalanche Center, http://www.nwac.noaa.gov.

[5] United States Geological Survey gauging station 12082500 near National, Washington, http://waterdata.usgs.gov/wa/nwis/uv/?site_no=12082500.

This is not the first time a relation between sediment load and air temperature has been established. Haritashya and others (2006) discovered a relation between air temperature and suspended load in the Gangotri Glacier, Himalayas. The R^2 number seen in their work was 0.98, suggesting a very strong relationship between the two factors. Bhutiyani (2000) also discovered such a relation in the Nubra Valley, Karakoram Himalayas, India, with an R^2 factor of 0.82. Other workers (Hodgkins et al., 2003; Hasnain and Thayyen, 1999) have related suspended sediment load with discharge and the relationship is very well established.

Entrainment velocity in any fluvial system is a relation of the object's particle size and the velocity of the water in question. Entrainment velocities can be determined using the Hjulström Curve. The velocity required to transport sediment of a certain size is between the particle's deposition velocity and erosion velocity – this provides a lower and upper limit to the velocity required. The maximum grain size observed in filtered samples was approximately 4 mm. Using the Hjulström curve, the maximum velocity associated with these flows is 30 to 45 cm/s.

Limitations

This is the first study to present firm rates of aggradation as measured in the Park (prior researchers had estimated rates of aggradation). As previously established, positions measured with the total station have error margins of ± 0.375 in (0.95 cm; Dunn, personal communication, 2006). In places where judgments had to be made regarding positions or heights of materials observed, we attempted to estimate on the low side (thus indicating that there was most likely more material or higher rates than we established). Further data regarding aggradation rates observed over time in the Park or in other locations would only help tighten up the aggradation rates.

Aggradation is not a straightforward geomorphic process and as observed in an aggrading stream, locations can both aggrade or degrade. For instance, 30% of the cross sections at Longmire were observed to be degrading over their width. However, even in those cross sections, many places had positive elevation changes (which were negated by degradation elsewhere in the cross section). Additionally, when it comes to hyperaggradation due to debris flows, no attempt was made to quantify the rates of background aggradation versus hyperaggradation due to debris fan deposits. These events can bias data and show higher rates of aggradation than are actually occurring in river channels.

Ignoring depth of flow, any change in slope can result in aggradation, whether it is provided by gravels and boulders in the stream or the presence of large woody debris. Longmire and other places provided superb examples of wood jams that accumulated material upstream where flowing water lost entrainment velocity. Small scale changes observed in cross sections are not nearly as important as the weighted change observed across a large area of concern.

Implications of Climate Change

Since this is the first study to look at rates of aggradation in the Park, trying to determine, unambiguously, if the rate of aggradation is accelerating or decelerating is problematic. However, the current research has benefited by the longitudinal profile and historical topographic map analysis. As evidenced by these historical rates, which are either negative or under 3 inches per decade, there appears to be an increasing rate of aggradation in the Park in the last ten years. It is likely that this rate has been increasing as global temperatures have been increasing.

One mechanism for increased aggradation is lateral moraine failure. As glaciers in the Park recede, they leave behind over-steepened lateral moraine walls that are prone to failure. As evidenced on warm summer days, steep walls on either side of the active channel near the glacier termini tend to collapse easily. During high precipitation events, a river cutting into these deposits can also provide a mechanism for slope failure. Donovan (2005) described the initiation of the 2003 Van Trump debris flow as a rock fall from a moraine wall near the Van Trump Glaciers. In several areas of the Park, debris flows are becoming increasingly more frequent (Kennard, personal communication, 2006), many of which are caused by moraine failure. Another related trigger is erosion of till deposited on hill slopes, exposed as ice melts.

Glaciers and permanent bodies of snow at Mount Rainier have been in a continual recession for the last decade. The lead climbing ranger at Mount Rainier, Mike Gauthier, has been working at the Park for the last 18 years and has had a unique perspective of recession and thinning of ice and snowfields. According to Gauthier:

> “My honest observations are that both the Muir Snowfield and Inter Glacier are BOTH receding. I can't scientifically measure this observation, but from a causal 18 years of hiking up and down these snowfields/glaciers, there is DEFINITELY less snow and ice than what I first saw [in] 1990. I particularly noticed it on the Muir Snowfield this fall” (Gauthier, personal communication, 2007).

Gauthier discussed the recession on his climbing website[6] in early October 2006:

> “I had a good conversation with a senior RMI guide about the level of the snow pack on the snowfield. We both felt that there was a noticeable drop in how it measured against the rocks. That is, the surface of the snow seems to have lowered, thus exposing more bare ground. It appears to my untrained scientific eyes that the ice mass underneath is melting and diminishing, leaving less ice-volume throughout the snowfield. The surface appearance seems normal for this time of year with ice, some fresh snow, and a few crevasses, but the overall snow level seems to have decreased. In essence, we noticed more exposed mounds of sand, pumice and volcanic rock” (Gauthier, 2006).

The observations noted by Gauthier are backed up by work conducted by Thomas Nylen (2001). In his thesis, Nylen notes that the area of Mount Rainier’s glaciers have decreased by 19.2% and total glacier volume has decreased by 25.8% between 1913 and 1994.

One of the implications of increased global warming is increased ablation in the glaciers that flank Mount Rainier. Recall that Figure 6.10 shows the expected sediment load in a braided stream for a given air temperature. As air temperature increases, the suspended sediment load expected in the river is increased by an exponential value (as seen in Equation 7). Since this relation is not linear, an increase in 1°C can result in a big change. For instance, between 20 and 21°C, sediment load increases by approximately 450 mg/L. The same change between 30 and 31°C results in an increase of almost 5000 mg/L of suspended sediment available to the braided river. Global warming seen in this way may result in an exponentially increasing amount of sediment being introduced to the river system. This exponential amount of sediment will certainly result in faster aggradation rates than have been found in this study. Stott and Mount (2007) showed that

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[6] Mount Rainier Climbing, http://www.mountrainierclimbing.blogspot.com.

in Southeastern France, an increase of 1.2°C resulted in a suspended sediment load between 3.1 to 4.1 times higher, a finding similar to what we have found at Mount Rainier.

Because the rates of aggradation depend on total sediment load (suspended and bed loads) in braided rivers and because further sediment is available via moraine failure and air temperature/suspended sediment relations, it is expected that the rates of aggradation observed at the Park will only increase. Unless global temperature begins to cool and glaciers at the Park begin to advance, aggradation rates will continue to be high.

CHAPTER 7

RECOMMENDATIONS FOR FUTURE WORK

This is an introductory study and further work is needed to refine the rates of aggradation that are occurring in streams at Mount Rainier. Also, due to the limited resources and time available to the research team, only a few rivers were studied. Studies looking at all major braided rivers in the Park would be a benefit to both the Park and other workers in the fluvial geomorphology discipline. Continual monitoring of the river aggradation rate would provide a wealth of information about the sedimentation that is occurring in rivers at the Park. If an increase in rate is observed, the implications of global warming or debris flows would be more significant. Historical topographic map analysis showed that the Carbon River area may have the highest rate of aggradation in the Park. Because of this finding, development of continuous monitoring in the Carbon River area should be a priority for future research teams.

The methods of research in the Park were straightforward, but the use of Light Detection and Ranging (LIDAR) equipment would provide much better data. LIDAR would provide a three-dimensional look at the river channels, and the increase of material provided by aggradation would be much easier to measure in GIS with the use of LIDAR-derived heights. LIDAR is expensive; however, but the cost-benefit of the data would help to pin-point exact locations that are at most risk in the Park. LIDAR data do exist for the upper Tahoma Creek area. Since these data exist, any further development in the Park with LIDAR technology would provide an immense amount of data to future researchers.

A provision of the research permit at Mount Rainier required the removal of any benchmarks that were installed or flagging tape used in the Park. This presents the issue of finding the cross section locations for further research teams when they reoccupy the locations in the river channels. The installation of permanent benchmarks (at least showing the start and end positions of the cross sections) would eliminate a potential major error in the determination of height increases in the river.

Our study shows a couple of possible relations to climate change and the influence of increased temperatures on aggradation in the Park. Further work in this direction could provide additional support for this relationship or show that the relationship we observed was a random circumstance. Another possible study would be to differentiate between the background rate of aggradation and the rates of hyperaggradation due to debris flows in the Park. The sedimentological record from the river channels could provide the necessary data for this study. This would be an important study to show how fast rivers are filling at the lowest possible rate. Also, since debris flows add a huge amount of material to the stream channel, a study showing the influence of (increasing) debris flows will show how much more quickly material will fill in the braided river channels.

The relation identified between air temperature and suspended load observed in the river needs further refinement. This relation has been shown in other locations around the world. A possible study relating the influence of air temperature at the glacier terminus and suspended load in several locations downstream throughout the course of the year would be ideal to refine the observation noted in this study. This should be a high priority since the data have direct relations to global warming (whereby higher temperatures will relate to exponentially higher amounts of sediment supplied to the channel).

It is not the intent of the research team to offend any employees at the Park, but there needs to be a change in the maintenance of stream channels at Mount Rainier. In the past, short-term fixes have been shown over and over again to fail and with the threat of increasing sedimentation in river channels. Carefully studied solutions to the pressing management concerns with aggradation in braided rivers in the Park need to be developed. As shown by the recent record-long closure of the Park following a major storm, the Park is facing a situation that is not getting better. Possible remediation methods that need further study include “barbs,” large woody debris and, most importantly, engineered log jams. Barbs are described by Kennard (personal communication, 2006) and Matsurra and Townsend (2004) as obstacles oriented at 45° upstream in the river channels that direct the river flow away from levees and other features. The goal is to keep the river confined in the center of the channel.

In the opinion of the research team, the use of rip-rap should be minimized and replaced by other technologies because the usefulness and effectiveness of such practices have been unsuccessful at Mount Rainier (Kennard, personal communication, 2007). Any permanent solution to the problem of aggradation will require a serious commitment of time, energy, and most importantly, money.

In places where aggrading rivers are near or above the height of roads adjacent to the rivers, the Park should take a serious look at constructing roads on armored elevated concrete structures (Figure 7.1). With such a structure, aggradation can occur around the piers without compromising the road. This will allow access to previously inaccessible areas despite the problem of aggradation. Roads constructed in this manner will be expensive and will have a certain life expectancy based on background aggradation rates. However, this is probably the only way to allow unimpeded access in areas that are seeing rapid aggradation.

▲ FIGURE 7.1
Concrete-piered elevated highway. A similar structure built near aggrading rivers in the Park can allow access to presently damaged and rapidly aggrading areas without moving the road a significant distance.

CHAPTER 8

CONCLUSION

Mount Rainier is a superb example of an active and dynamic geological environment that is capable of dramatic change. The volcano has built itself up over the last 650,000 years to its present height, and during the quiet periods of time where the volcano is not erupting, it is continuously weathering. The mountain provides enormous quantities of sediment that fill in valley-confined alluvial fans in braided river channels. Aggradation is a completely natural and expected outcome in this area during the volcano’s dormant periods.

As soon as humans settled in the areas around Mount Rainier, they looked for the easiest places to build infrastructure. These locations happened to be adjacent to major rivers that radiated from the volcano. When the National Park was originally founded in 1899, the same mentality occurred: build in areas that are easy to access. This was to be expected given the lack of geological knowledge about hazards such as aggradation. Therefore, roads, housing, visitor centers, campgrounds and other infrastructure were placed in locations near major river channels. Over time, these structures have remained in the same location while rivers have been slowly and seemingly unnoticeably aggrading.

Recently, the effects of aggradation have been making itself known. Flooding, damage to Park infrastructure and a record-long Park closure have been directly attributed to the aggradation that is occurring in the Park. Following a major rainstorm that deposited 17.9 inches of rain on the volcano, severe damage which occurred in many places within the Park brought the true seriousness of this problem to light. Despite the heavy rain that occurred in the Park, rivers are aggrading up to a foot per decade without the influence of debris flows. This rate appears to be increasing, which is bad news for Park infrastructure near braided rivers.

Aggradation is a problem that will not go away; indeed, it will only get worse for the Park. As the rivers slowly fill in the valleys that radiate away from the volcano, the problems associated with flooding, visitor and employee safety and potential damage to Park infrastructure will only continue. An additional complication to the problem is the idea of increased debris associated with unbuttressed lateral moraine failure from receding glaciers due to global warming. As the volumes of ice disappear on the mountain, the possibility of debris flows that "hyper aggrade" the river channels will only increase.

This is an important time for Mount Rainier and the administrative staff in charge of the Park. As the November 2006 event illustrated, the Park is facing a force of nature that will not change. It is critical that the Park staff and maintenance personnel have the correct and accurate data about river bed filling in order to maximize the useful life for structures that will be occupying areas adjacent to aggrading river channels. It is hoped that these data will supply the key Park personnel with the necessary information to make wise decisions about the future of Mount Rainier National Park.

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APPENDIX A

RIVER AGGRADATION RESULTS FOR EACH TRANSECT

Area:	Nisqually River at Longmire
Cross Section Number:	1

Notes:

Data has been reviewed - FINAL COPY

RESULTS

	1982	1997	2005	2006
Total Area	0.00000	15122.72303	15187.14552	15141.33830
Total Length of Cross Section*	0.00000	156.29300	156.29300	156.29300

	Net Change		Average Yearly Change	
	Total Change	Across Channel	Total Change	Across Channel
1982 to 1997	N/A	N/A	N/A	N/A
1982 to 2005	N/A	N/A	N/A	N/A
1982 to 2006	N/A	N/A	N/A	N/A
1997 to 2005	64.42249	0.41219	8.05281	0.05152
1997 to 2006	18.61527	0.11910	2.06836	0.01323
2005 to 2006	-45.80723	-0.29309	-45.80723	-0.29309

* = Should all be exactly the same

Total Change in Square Feet
Across Channel Change in Feet

Area:	Nisqually River at Longmire
Cross Section Number:	2

Notes:

Data has been reviewed - FINAL COPY

RESULTS

	1982	1997	2005	2006
Total Area	0.00000	11608.29628	11590.54015	11867.63767
Total Length of Cross Section*	0.00000	133.07500	133.07500	133.07500

	Net Change		Average Yearly Change	
	Total Change	Across Channel	Total Change	Across Channel
1982 to 1997	N/A	N/A	N/A	N/A
1982 to 2005	N/A	N/A	N/A	N/A
1982 to 2006	N/A	N/A	N/A	N/A
1997 to 2005	-17.75613	-0.13343	-2.21952	-0.01668
1997 to 2006	259.34138	1.94884	28.81571	0.21654
2005 to 2006	277.09751	2.08227	277.09751	2.08227

* = Should all be exactly the same

Total Change in Square Feet
Across Channel Change in Feet

Area:	Nisqually River at Longmire
Cross Section Number:	3

Notes:

Data has been reviewed - FINAL COPY

RESULTS

	1982	1997	2005	2006
Total Area	0.00000	12306.90100	12150.04823	12355.97612
Total Length of Cross Section*	0.00000	145.96000	145.96000	145.96000

	Net Change		Average Yearly Change	
	Total Change	Across Channel	Total Change	Across Channel
1982 to 1997	N/A	N/A	N/A	N/A
1982 to 2005	N/A	N/A	N/A	N/A
1982 to 2006	N/A	N/A	N/A	N/A
1997 to 2005	-156.85277	-1.07463	-19.60660	-0.13433
1997 to 2006	49.07512	0.33622	5.45279	0.03736
2005 to 2006	205.92789	1.41085	205.92789	1.41085

* = Should all be exactly the same

Total Change in Square Feet
Across Channel Change in Feet

Area:	Nisqually River at Longmire
Cross Section Number:	4

Notes:

Data has been reviewed - FINAL COPY

RESULTS

	1982	1997	2005	2006
Total Area	9898.46960	10058.77564	10224.79239	10147.35709
Total Length of Cross Section*	125.22000	125.22000	125.22000	125.22000

	Net Change		Average Yearly Change	
	Total Change	**Across Channel**	**Total Change**	**Across Channel**
1982 to 1997	160.30604	1.28020	10.01913	0.08001
1982 to 2005	326.32280	2.60600	14.18795	0.11330
1982 to 2006	248.88749	1.98760	10.37031	0.08282
1997 to 2005	166.01675	1.32580	20.75209	0.16573
1997 to 2006	88.58144	0.70741	9.84238	0.07860
2005 to 2006	-77.43531	-0.61839	-77.43531	-0.61839

* = Should all be exactly the same

Total Change in Square Feet
Across Channel Change in Feet

Area:	Nisqually River at Longmire
Cross Section Number:	5

Notes:

Data has been reviewed - FINAL COPY

RESULTS

	1982	1997	2005	2006
Total Area	0.00000	20368.26040	20743.67140	20487.03639
Total Length of Cross Section*	0.00000	268.45900	268.45900	268.45900

	Net Change		Average Yearly Change	
	Total Change	**Across Channel**	**Total Change**	**Across Channel**
1982 to 1997	N/A	N/A	N/A	N/A
1982 to 2005	N/A	N/A	N/A	N/A
1982 to 2006	N/A	N/A	N/A	N/A
1997 to 2005	375.41100	1.39839	46.92637	0.17480
1997 to 2006	118.77599	0.44244	13.19733	0.04916
2005 to 2006	-256.63501	-0.95596	-256.63501	-0.95596

* = Should all be exactly the same

Total Change in Square Feet
Across Channel Change in Feet

Area:	Nisqually River at Longmire
Cross Section Number:	6

Notes:

Data has been reviewed - FINAL COPY

RESULTS

	1982	1997	2005	2006
Total Area	0.00000	14479.12414	0.00000	14707.21587
Total Length of Cross Section*	0.00000	207.69509	0.00000	207.69509

	Net Change		Average Yearly Change	
	Total Change	**Across Channel**	**Total Change**	**Across Channel**
1982 to 1997	N/A	N/A	N/A	N/A
1982 to 2005	N/A	N/A	N/A	N/A
1982 to 2006	N/A	N/A	N/A	N/A
1997 to 2005	-14479.12414	-69.71337	-1809.89052	-8.71417
1997 to 2006	228.09172	1.09820	25.34352	0.12202
2005 to 2006	N/A	N/A	N/A	N/A

* = Should all be exactly the same

Total Change in Square Feet
Across Channel Change in Feet

Area:	Nisqually River at Longmire
Cross Section Number:	7

Notes:

Data has been reviewed - FINAL COPY

RESULTS

	1982	1997	2005	2006
Total Area	0.00000	25934.70500	0.00000	25798.95490
Total Length of Cross Section*	0.00000	392.62000	0.00000	392.62000

	Net Change		Average Yearly Change	
	Total Change	**Across Channel**	**Total Change**	**Across Channel**
1982 to 1997	N/A	N/A	N/A	N/A
1982 to 2005	N/A	N/A	N/A	N/A
1982 to 2006	N/A	N/A	N/A	N/A
1997 to 2005	-25934.70500	-66.05549	-3241.83813	-8.25694
1997 to 2006	-135.75010	-0.34575	-15.08334	-0.03842
2005 to 2006	N/A	N/A	N/A	N/A

* = Should all be exactly the same

Total Change in Square Feet
Across Channel Change in Feet

Area:	Nisqually River at Longmire
Cross Section Number:	8

Notes:

Data has been reviewed - FINAL COPY

RESULTS

	1982	1997	2005	2006
Total Area	0.00000	18006.02363	0.00000	18557.17640
Total Length of Cross Section*	0.00000	341.42951	0.00000	341.42951

	Net Change		Average Yearly Change	
	Total Change	**Across Channel**	**Total Change**	**Across Channel**
1982 to 1997	N/A	N/A	N/A	N/A
1982 to 2005	N/A	N/A	N/A	N/A
1982 to 2006	N/A	N/A	N/A	N/A
1997 to 2005	-18006.02363	-52.73716	-2250.75295	-6.59215
1997 to 2006	551.15277	1.61425	61.23920	0.17936
2005 to 2006	N/A	N/A	N/A	N/A

* = Should all be exactly the same

Total Change in Square Feet
Across Channel Change in Feet

Area:	Nisqually River at Longmire
Cross Section Number:	9

Notes:

Data has been reviewed - FINAL COPY

RESULTS

	1982	1997	2005	2006
Total Area	0.00000	13145.88130	0.00000	13086.99399
Total Length of Cross Section*	0.00000	307.25392	0.00000	307.25392

	Net Change		Average Yearly Change	
	Total Change	**Across Channel**	**Total Change**	**Across Channel**
1982 to 1997	N/A	N/A	N/A	N/A
1982 to 2005	N/A	N/A	N/A	N/A
1982 to 2006	N/A	N/A	N/A	N/A
1997 to 2005	-13145.88130	-42.78507	-1643.23516	-5.34813
1997 to 2006	-58.88731	-0.19166	-6.54303	-0.02130
2005 to 2006	N/A	N/A	N/A	N/A

* = Should all be exactly the same

Total Change in Square Feet
Across Channel Change in Feet

Area:	Nisqually River at Longmire
Cross Section Number:	10

Notes:

Data has been reviewed - FINAL COPY

RESULTS

	1982	1997	2005	2006
Total Area	0.00000	10078.98786	9323.34773	9867.28406
Total Length of Cross Section*	0.00000	323.71600	323.71600	323.71600

	Net Change		Average Yearly Change	
	Total Change	**Across Channel**	**Total Change**	**Across Channel**
1982 to 1997	N/A	N/A	N/A	N/A
1982 to 2005	N/A	N/A	N/A	N/A
1982 to 2006	N/A	N/A	N/A	N/A
1997 to 2005	-755.64013	-2.33427	-94.45502	-0.29178
1997 to 2006	-211.70380	-0.65398	-23.52264	-0.07266
2005 to 2006	543.93633	1.68029	543.93633	1.68029

* = Should all be exactly the same

Total Change in Square Feet
Across Channel Change in Feet

Area:	Longmire Long Profile
Cross Section Number:	

Notes:

Data has been reviewed - FINAL COPY

RESULTS

	1910	2006
Total Area	128786.45849	130339.35957
Total Length of Cross Section*	2046.25190	2046.25190

	Net Change		Average Yearly Change	
	Total Change	**Across Channel**	**Total Change**	**Across Channel**
1910 to 2006 (96 years)	1552.90108	0.75890	16.17605	0.00791

* = Should all be exactly the same

Total Change in Square Feet
Across Channel Change in Feet

Area:	Sunshine Point
Cross Section Number:	1

Notes:

Data has been reviewed - FINAL COPY

RESULTS

	1982	1997	2005	2006
Total Area	0.00000	0.00000	15817.90260	15933.77529
Total Length of Cross Section*	0.00000	0.00000	397.63600	397.63600

	Net Change		Average Yearly Change	
	Total Change	Across Channel	Total Change	Across Channel
1982 to 1997	N/A	N/A	N/A	N/A
1982 to 2005	N/A	N/A	N/A	N/A
1982 to 2006	N/A	N/A	N/A	N/A
1997 to 2005	N/A	N/A	N/A	N/A
1997 to 2006	N/A	N/A	N/A	N/A
2005 to 2006	115.87269	0.29140	115.87269	0.29140

* = Should all be exactly the same

Total Change in Square Feet
Across Channel Change in Feet

Area:	Sunshine Point
Cross Section Number:	2

Notes:

Data has been reviewed - FINAL COPY

RESULTS

	1982	1997	2005	2006
Total Area	0.00000	0.00000	10180.38004	10178.76257
Total Length of Cross Section*	0.00000	0.00000	277.88683	277.88683

	Net Change		Average Yearly Change	
	Total Change	Across Channel	Total Change	Across Channel
1982 to 1997	N/A	N/A	N/A	N/A
1982 to 2005	N/A	N/A	N/A	N/A
1982 to 2006	N/A	N/A	N/A	N/A
1997 to 2005	N/A	N/A	N/A	N/A
1997 to 2006	N/A	N/A	N/A	N/A
2005 to 2006	-1.61747	-0.00582	-1.61747	-0.00582

* = Should all be exactly the same

Total Change in Square Feet
Across Channel Change in Feet

Area:	Sunshine Point
Cross Section Number:	3

Notes:

Data has been reviewed - FINAL COPY

RESULTS

	1982	1997	2005	2006
Total Area	0.00000	0.00000	16541.32802	16626.33733
Total Length of Cross Section*	0.00000	0.00000	370.64116	370.64116

	Net Change		Average Yearly Change	
	Total Change	Across Channel	Total Change	Across Channel
1982 to 1997	N/A	N/A	N/A	N/A
1982 to 2005	N/A	N/A	N/A	N/A
1982 to 2006	N/A	N/A	N/A	N/A
1997 to 2005	N/A	N/A	N/A	N/A
1997 to 2006	N/A	N/A	N/A	N/A
2005 to 2006	85.00930	0.22936	85.00930	0.22936

* = Should all be exactly the same

Total Change in Square Feet
Across Channel Change in Feet

Area:	Sunshine Point Long Profile
Cross Section Number:	

Notes:

Only 3 positions to compare with. Data has been reviewed - FINAL COPY

RESULTS

	1910	2006
Total Area	18656.62099	19449.57591
Total Length of Cross Section*	547.14690	547.14690

	Net Change		Average Yearly Change	
	Total Change	Across Channel	Total Change	Across Channel
1910 to 2006 (96 years)	792.95492	1.44925	8.25995	0.01510

* = Should all be exactly the same

Total Change in Square Feet
Across Channel Change in Feet

Area:	Lower Van Trump Hairpin
Cross Section Number:	1

Notes:

Definite Debris Flow Influence across section. Data has been reviewed - FINAL COPY

RESULTS

	1982	1997	2005	2006
Total Area	0.00000	0.00000	33080.01750	35106.76502
Total Length of Cross Section*	0.00000	0.00000	398.87609	398.87609

	Net Change		Average Yearly Change	
	Total Change	Across Channel	Total Change	Across Channel
1982 to 1997	N/A	N/A	N/A	N/A
1982 to 2005	N/A	N/A	N/A	N/A
1982 to 2006	N/A	N/A	N/A	N/A
1997 to 2005	N/A	N/A	N/A	N/A
1997 to 2006	N/A	N/A	N/A	N/A
2005 to 2006	2026.74753	5.08115	2026.74753	5.08115

* = Should all be exactly the same

Total Change in Square Feet
Across Channel Change in Feet

Area:	Van Trump Hairpin
Cross Section Number:	2

Notes:

Definite Debris Flow Influence across section. Data has been reviewed - FINAL COPY

RESULTS

	1982	1997	2005	2006
Total Area	0.00000	0.00000	55874.75862	59745.58201
Total Length of Cross Section*	0.00000	0.00000	537.90436	537.90436

	Net Change		Average Yearly Change	
	Total Change	Across Channel	Total Change	Across Channel
1982 to 1997	N/A	N/A	N/A	N/A
1982 to 2005	N/A	N/A	N/A	N/A
1982 to 2006	N/A	N/A	N/A	N/A
1997 to 2005	N/A	N/A	N/A	N/A
1997 to 2006	N/A	N/A	N/A	N/A
2005 to 2006	3870.82339	7.19612	3870.82339	7.19612

* = Should all be exactly the same

Total Change in Square Feet
Across Channel Change in Feet

Area:	Van Trump Hairpin
Cross Section Number:	3

Notes:

Definite Debris Flow Influence across section. Data has been reviewed - FINAL COPY

RESULTS

	1982	1997	2005	2006
Total Area	0.00000	0.00000	39351.71541	40147.84350
Total Length of Cross Section*	0.00000	0.00000	294.34333	294.34333

	Net Change		Average Yearly Change	
	Total Change	Across Channel	Total Change	Across Channel
1982 to 1997	N/A	N/A	N/A	N/A
1982 to 2005	N/A	N/A	N/A	N/A
1982 to 2006	N/A	N/A	N/A	N/A
1997 to 2005	N/A	N/A	N/A	N/A
1997 to 2006	N/A	N/A	N/A	N/A
2005 to 2006	796.12808	2.70476	796.12808	2.70476

* = Should all be exactly the same

Total Change in Square Feet
Across Channel Change in Feet

Area:	Van Trump Long Profile
Cross Section Number:	

Notes:

Data could be skewed by definate debris flow signatures in the last few years. Data has been reviewed - FINAL COPY

RESULTS

	1910	2006
Total Area	52215.97078	82228.71617
Total Length of Cross Section*	774.46030	774.46023

	Net Change		Average Yearly Change	
	Total Change	Across Channel	Total Change	Across Channel
1910 to 2006 (96 years)	30012.74539	38.75311	312.63276	0.40368

* = Should all be exactly the same

Total Change in Square Feet
Across Channel Change in Feet

Area:	White River
Cross Section Number:	1

Notes:

Data has been reviewed - FINAL COPY

RESULTS

	1982	1997	2005	2006
Total Area	0.00000	0.00000	8697.94340	8868.99832
Total Length of Cross Section*	0.00000	0.00000	266.56304	266.56304

	Net Change		Average Yearly Change	
	Total Change	Across Channel	Total Change	Across Channel
1982 to 1997	N/A	N/A	N/A	N/A
1982 to 2005	N/A	N/A	N/A	N/A
1982 to 2006	N/A	N/A	N/A	N/A
1997 to 2005	N/A	N/A	N/A	N/A
1997 to 2006	N/A	N/A	N/A	N/A
2005 to 2006	171.05493	0.64171	171.05493	0.64171

* = Should all be exactly the same

Total Change in Square Feet
Across Channel Change in Feet

Area:	White River
Cross Section Number:	4

Notes:

Data has been reviewed - FINAL COPY

RESULTS

	1982	1997	2005	2006
Total Area	0.00000	0.00000	2198.87561	2256.91645
Total Length of Cross Section*	0.00000	0.00000	187.84365	187.84365

	Net Change		Average Yearly Change	
	Total Change	Across Channel	Total Change	Across Channel
1982 to 1997	N/A	N/A	N/A	N/A
1982 to 2005	N/A	N/A	N/A	N/A
1982 to 2006	N/A	N/A	N/A	N/A
1997 to 2005	N/A	N/A	N/A	N/A
1997 to 2006	N/A	N/A	N/A	N/A
2005 to 2006	58.04083	0.30898	58.04083	0.30898

* = Should all be exactly the same

Total Change in Square Feet
Across Channel Change in Feet

Area:	White River Long Profile
Cross Section Number:	

Notes:

Data has been reviewed - FINAL COPY

RESULTS

	1910	2006
Total Area	62377.31167	69654.00358
Total Length of Cross Section*	1557.80000	1557.75329

	Net Change		Average Yearly Change	
	Total Change	Across Channel	Total Change	Across Channel
1910 to 2006 (96 years)	7276.69191	4.67113	75.79887	0.04866

* = Should all be exactly the same

Total Change in Square Feet
Across Channel Change in Feet

Area:	Longmire - Winter Surveying
Cross Section Number:	2

Notes:

Data has been reviewed - FINAL COPY

RESULTS

	2006 Summer	2006 Winter
Total Area	10762.69897	10905.40370
Total Length of Cross Section*	120.74201	120.74201

	Net Change		Average Yearly Change	
	Total Change	Across Channel	Total Change	Across Channel
2006 Summer - 2006 Winter	142.70473	1.18190	142.70473	1.18190

* = Should all be exactly the same

Total Change in Square Feet
Across Channel Change in Feet

Area:	Longmire - Winter Surveying
Cross Section Number:	3

Notes:

Data has been reviewed - FINAL COPY

RESULTS

	2006 Summer	2006 Winter
Total Area	15381.81204	16038.30454
Total Length of Cross Section*	176.32442	176.32442

	Net Change		Average Yearly Change	
	Total Change	Across Channel	Total Change	Across Channel
2005 to 2006	656.49250	3.72321	656.49250	3.72321

* = Should all be exactly the same

Total Change in Square Feet
Across Channel Change in Feet

Area:	Longmire - Winter Surveying
Cross Section Number:	4

Notes:

Data has been reviewed - FINAL COPY

RESULTS

	2006 Summer	2006 Winter
Total Area	22894.19283	22937.87779
Total Length of Cross Section*	253.87996	253.87996

	Net Change		Average Yearly Change	
	Total Change	Across Channel	Total Change	Across Channel
2005 to 2006	43.68496	0.17207	43.68496	0.17207

* = Should all be exactly the same

Total Change in Square Feet
Across Channel Change in Feet

Area:	Lower Van Trump Hairpin - Winter Surveying
Cross Section Number:	1

Notes:

RESULTS

	2006 Summer	2006 Winter
Total Area	6419.19873	6471.86115
Total Length of Cross Section*	72.10251	72.10251

	Net Change		Average Yearly Change	
	Total Change	Across Channel	Total Change	Across Channel
2005 to 2006	52.66242	0.73038	52.66242	0.73038

* = Should all be exactly the same

Total Change in Square Feet
Across Channel Change in Feet