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Aggradation of glacially-sourced braided rivers at Mount Rainier National Park, Washington

Summary Report for 1997-2012

Natural Resource Technical Report NPS/MORA/NRTR—2014/910

ON THE COVER
Nisqually River at Longmire, Mount Rainier National Park, Washington
Photograph by: Scott Beason/NPS/MORA

Aggradation of glacially-sourced braided rivers at Mount Rainier National Park, Washington

Summary report for 1997-2012

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Executive Summary

Rivers are dynamic forces of nature whose form and function are driven by sediment inputs balanced with stream flow. When sediment production overwhelms stream flow in a river, excess sediment accumulates across the river bed, in a geologic process called aggradation. If stream flow exceeds sediment production, the river incises. All rivers go through episodes of aggradation and incision in an attempt to equilibrate stream flow and sediment inputs. However, when a river is continually provided more sediment than it can transport, sediment is deposited in the active channel, floodplain size increases and threats like flooding and debris flows can be of greater consequence over time. Combined with uncertainties in future climates, geologic hazards from aggradation can increase threats to infrastructure placed near aggrading rivers.

Mount Rainier is a spectacular example of geologic forces at work – from the eruptions that built up the volcano over the last half million years, to the erosive forces that combine to tear down the mountain. In times of relative volcanic quiet, the forces of glaciers, freeze/thaw cycles, water, and wind all work to tear the mountain down. As the mountain falls apart via these forces, sediment is provided to rivers. This sediment routes through the river system in a variety of time scales. This study examines the effects of sediment movement in a 15 year period between 1997 and 2012.

Given that much of the infrastructure at Mount Rainier National Park (MORA) is built adjacent to proglacial braided rivers, it is critical to understand the rates of aggradation in these areas to anticipate the geologic future for these areas. For instance, what are the threats to roads and buildings in areas next to aggrading streams? In order to gauge these threats, we must first know the “health” of the braided river systems: are they at equilibrium, aggrading, or incising? Additionally, what do we anticipate future aggradation trends to be based on what we’ve observed thus far and forecasts for regional climate change in the next century?

Sediment is provided to rivers in a variety of ways, including glacial runoff, rock fall, and debris flows. The latter can provide large amounts of sediment in a very short time frame. At Mount Rainier, debris flows occur with some frequency and the park has seen at least 12 separate debris flows initiated in six drainages during events in 2001, 2003, 2005, and 2006. All of the debris flows since 2006 have initiated in areas that have been recently deglaciated, a worrisome prospect considering that retreating glaciers are continuing to expose vast areas of loose, unstable sediment on steep slopes. Given that Mount Rainier has much steep, loose terrain above 2,500 m, the potential sediment budget at Mount Rainier is very high. Additionally, some of the largest floods on record have occurred in the last two decades. The combined extremes we are seeing in the weather, hydrology, and glacial recession at Mount Rainier are consistent with models for increasing climate change in the Pacific Northwest.

In order to gauge the threats to infrastructure at MORA, cross sections were surveyed in developed locations at the park. We surveyed 27 cross sections on the Nisqually River, located on the southwest side of Mount Rainier: eight at Sunshine Point (Figure 6), ten at Longmire (Figure 8), six at Carter Falls (Figure 10) and three at Lower Van Trump Hairpin (Figure 11). Eight cross sections were surveyed on the White River, on the park’s Northeastern side (Figure 12). Each cross section

represents a snapshot of the geomorphic landscape at that point in time. These cross sections are re-surveyed yearly in order to identify the geomorphic landscape associated with aggradation or incision in the reach. Cross-sections are measured using a TopCon Total Station with sub-centimeter accuracy.

Sunshine Point is located just within the southwest boundary of Mount Rainier National Park, alongside the Nisqually River. The Nisqually River has received a tremendous sediment input from the South Tahoma Glacier via Tahoma Creek in the vicinity of Sunshine Point. Tahoma Creek has experienced massive sediment influx due to the occurrence of over 25 separate debris flows since 1967. This sediment input has led to high aggradation rates in the Nisqually River at Sunshine Point. Aggradation was observed in the intervals 2005-2006, 2006-2008, 2009-2011, and 2011-2012, with weighted aggradation rates ranging from 0.03 to 0.36 $m \times yr^{-1}$ (0.10 – 1.18 $ft \times yr^{-1}$). Only one year within the survey period showed net incision. The interval of 2008-2009 showed incision of -0.16 $m \times yr^{-1}$ (-0.52 $ft \times yr^{-1}$), much lower than the aggradation rates occurring before and after. Overall, the Sunshine Point reach has accumulated 26,740 m^3 (944,100 ft^3) of sediment from 2005 to 2012, one of the highest amounts observed in this study. Sunshine Point has been greatly affected by the Nisqually River and Tahoma Creek, especially in 2006 when a large flood destroyed the infrastructure at the campground. It should be expected that aggradation will continue to affect the Sunshine Point area due to continual sediment moving downstream in Tahoma Creek and river dredging at the Tahoma Creek Bridge (Anderson, 2013). Additionally, the riverbed in this area is "tilted" toward park infrastructure, meaning that the river will preferentially flow toward the campground remains and road. The Nisqually River here is by no means in equilibrium and it may take decades for the river to adjust to increasing sediment loads.

Longmire is home to many park maintenance facilities, visitor destinations, and employee housing. The Longmire area was also greatly affected by the 2006 flood: levees were destroyed and the park nearly lost its Emergency Operations Center. Upstream sediment delivery and sediment routing through the Longmire reach cause large variations in the sediment-to-discharge balance of the Nisqually River at this location. Aggradation and incision rates here are much more variable year-to-year compared to other locations in the park. Aggradation was observed in 2005-2006, 2009-2010, and 2011-2012 ranging from 0.05 to 0.14 $m \times yr^{-1}$ (0.16 – 0.46 $ft \times yr^{-1}$). Incision occurred in the reach between 1997-2005, 2006-2008, and 2010-2011 ranging between 0.00 to -0.04 $m \times yr^{-1}$ (0 – 0.13 $ft \times yr^{-1}$). Overall, the Longmire reach has accumulated 2,185 m^3 (77,170 ft^3) of sediment from 1997 to 2012. However, most areas in the Longmire reach have incised since 2006, with the notable exception of Longmire cross section 7, which has showed a rather large increase in sediment – likely relicts from dredging efforts upstream of the line. Longmire is located downstream of areas that have seen large increases in sediment delivery and as this sediment sluices downstream, it is likely that the aggradation rate here will increase in the coming years to decades, depending on timing and magnitude of large floods that move the sediment downstream.

New cross sections were added on the Nisqually River in the vicinity of the Cougar Rock Campground in 2011 and resurveyed in 2012, a location in this study referred to as Carter Falls. The Carter Falls reach is just downstream of massive sediment inputs from debris flows from Van Trump

Creek and was added in an attempt to trace the downstream movement of this reworked sediment over time. In one year, the weighted aggradation in this reach was 0.10 $m \times yr^{-1}$ (0.33 $ft \times yr^{-1}$), with an influx of 2,850 m^3 (100,700 ft^3) of sediment between 2011 and 2012. The upper four cross sections here have strong increases in sediment volume, decreasing in magnitude downstream. The lower two cross sections both show incision; this trend is consistent with a wave of sediment moving into the survey reach from the upstream sediment deposition. Carter Falls will be a critical location to define sediment transport rates, especially its implications to downstream localities like Longmire.

The Nisqually River at the Lower Van Trump Hairpin has seen some of the most dramatic and variable changes in channel morphology since the early 2000s. This area was affected by debris flows in 2001, 2003, 2005, and 2006; as well as by numerous landslides, most notably a large landslide in 2008. Because of the large sediment delivery in this location, channel equilibrium is unlikely to be exhibited here for decades. Reach-weighted aggradation was strongly observed here in 2005-2006 as result of a 2005 debris flow that deposited an impressive 15,500 m^3 (547,500 ft^3) of material, an aggradation rate corresponding to 1.55 m (5.09 ft) in a one year period. Some incision has occurred in this area, namely in the intervals 2006-2008 and 2010-2011, and ranging between -0.03 to -0.18 $m \times yr^{-1}$ (-0.10 to -0.59 $ft \times yr^{-1}$). However, the periods 2008-2009, 2009-2010, and 2011-2012 have seen aggradation ranging from 0.01 to 0.12 $m \times yr^{-1}$ (0.03 – 0.39 $ft \times yr^{-1}$). Overall, 13,130 m^3 (463,700 ft^3) of sediment have accumulated in this area since 2005. It is anticipated that, without further sediment inputs, the Nisqually River will continually erode away at these deposits, mobilizing them downstream. However, future debris flow deposition here is very likely, so this area is not expected to return to equilibrium in the near future.

The White River is fed by the Emmons glacier on Mount Rainier, and flows 121 km (75 mi) from its source, joining the Puyallup River at Sumner. The stretch of the White River along State Route 410 on the park’s northeastern side has seen rather large increases in aggradation. The riverbed here is up to 3.6 m (12 ft) above the road in some places, a floodplain disequilibrium also found elsewhere throughout the park that can have devastating consequences during high flow. Cross sections measured since 2005 have shown overall aggradation of about 0.04 $m \times yr^{-1}$ (0.13 $ft \times yr^{-1}$) during the 2005-2007 and 2008-2011 periods. Incision occurred in 2007-2008 at the rate of -0.09 $m \times yr^{-1}$ (-0.30 $ft \times yr^{-1}$). During the study period, 54,670 m^3 (1,930,000 ft^3) of sediment has accumulated in this reach (this reach has a much larger area than the other areas analyzed in the park). Mature old growth and forested floodplains are preventing a massive channel avulsion for now. However, aggradation of the stream channel could slowly overwhelm the stabilizing forces of the old growth forest and monitoring of this area is necessary to maintain park and state infrastructure through this study reach. Massive sediment delivery has occurred upstream as result of the Little Tahoma Peak collapse in 1963. That sediment is likely moving down-stream and may be impacting the study reach at this time.

Park-wide aggradation rates are highly variable and depend on multiple factors including location, time period, and sediment inputs. However, every location in this study has seen overall aggradation during the study, despite periods of incision. Additionally, despite the largest floods on record in the park’s history occurring recently, rivers continue to aggrade, which indicates sediment delivery is overwhelming erosive forces in rivers. These results indicate that river systems at Mount Rainier are strongly driven by sediment production, a trend that we expect to remain constant or increase. Increasing aggradation rates observed at Mount Rainier are an example of the complex interactions of a glaciated landscape responding to climate change. As glacial retreat occurs in alpine areas, new unvegetated, unstable sediment is exposed and continually transported into braided rivers already choked with material. Aggrading rivers – especially those mechanically confined and not allowed to move about their natural floodplains – develop unstable convex profiles, prone to avulsion to lower-lying floodplains. Much infrastructure has been built in low-lying areas near braided rivers at MORA. As climate change occurs and as aggradation rates increase, river beds build up progressively higher, increasing flood danger to infrastructure. Flooding, damage to park infrastructure, and a record-long park closure have been attributed to the aggradation and associated avulsion occurring in Park rivers. Rivers are aggrading even without the influence of debris flows, and even during recent flood events despite heavy rain and anticipated erosive forces. It is anticipated that aggradation will have progressively detrimental consequences to areas farther away as sediment budgets increase. This is important not only to development within the park, but to the fluvial environments more distant from the park. Aggradation will present new problems to planning and engineering in glacially-sourced rivers here and in other glacial environments in the Pacific Northwest.

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Introduction

Mount Rainier is a 4,392 m (14,410 ft) volcano located within Mount Rainier National Park (MORA), located approximately 70 km (43 mi) southeast of Tacoma and 90 km (56 mi) south-southeast of Seattle, Washington (Figure 1). MORA was established in 1899 as the nation's fifth national park. MORA receives approximately 1.8 million visitors annually, many of them coming in the busy summer months (National Park Service, 2011). Mount Rainier is considered an active volcano by the United States Geological Survey and features fumaroles at the summit, summit areas that are ice-free year-around despite sub-zero temperatures, background earthquakes, an extensive eruptive history, and a magma source from the subducting oceanic Juan de Fuca plate under the continental North American Plate (Crandell, 1969; Scott and Vallance, 1995; Sisson, 1995; Walder and Driedger, 1995; Riedel, 1997; Lillie and Dridger, 2001; Sission et al., 2001; Driedger and Scott, 2002; Vallance et al., 2002; Vallance et al., 2003; Harris et al., 2004; Lillie, 2005).

Given the proximity of major populated areas on and near the volcano's flanks, the active nature of the volcano, the history of destructive events from Mount Rainier, and the future potential of magma-water interaction and sector collapse, the volcano has been called one of the most dangerous volcanoes in the United States (National Research Council, 1994). Mount Rainier is one of 16 "decade volcanoes," identified by the International Association of Volcanology and Chemistry of the Earth's Interior (IAVCEI) as being worthy of particular study in light of their history of large, destructive eruptions combined with their proximity to populated areas (Swanson et al., 1992). Mount Rainier's rich volcanic history has been the subject of many studies by other researchers (Crandell and Fahnestock, 1965; Crandell, 1969; Crandell, 1971; Scott and Vallance, 1995; Sisson, 1995; Walder and Driedger, 1995; Riedel, 1997; Topinka, 1997a; Topinka, 1997b; Lillie and Dridger, 2001; Sission et al., 2001; Driedger and Scott, 2002; Vallance et al., 2002; Vallance et al., 2003; Harris et al., 2004; Lillie, 2005). These dramatic and catastrophic events are certainly exciting, but have very long recurrence intervals. The other hazards like rock fall, debris flows, flooding, glacial outburst floods, and other events occur over a much shorter time frame and are of principle importance to this study (Fahnestock, 1963; Crandell and Fahnestock, 1965; Nelson, 1987; Scott and Vallance, 1995; Vallance and Driedger, 1995; Riedel, 1997; Driedger and Scott, 2002; Vallance et al., 2002; Abbe et al., 2003; Vallance et al., 2003; Donovan, 2005; Abbe et al., 2010).

Mount Rainier stands out above the lower ridges and mountains in the region with a topographic prominence of 4,023 m (13,199 ft), the highest topographic prominence in the United States and the 21st highest prominence in the world (Metzler and Jurgalski, 2007). Because of the orographic barrier the mountain presents to prevailing westerly winds coming from the Pacific Ocean and Puget Sound, the mountain receives a great deal of precipitation. Much of this precipitation falls as snow in the winter. Snow that does not melt in the summer forms into glaciers on the mountain's upper slopes. Twenty-five named glaciers clad 9.21×10^7 m^2 (9.91×10^8 ft^2) of the volcano, amounting to 4.42×10^9 m^3 (1.56×10^9 ft^3) of perennial ice – more ice than all other Cascade volcanoes combined (Driedger and Kennard, 1986).

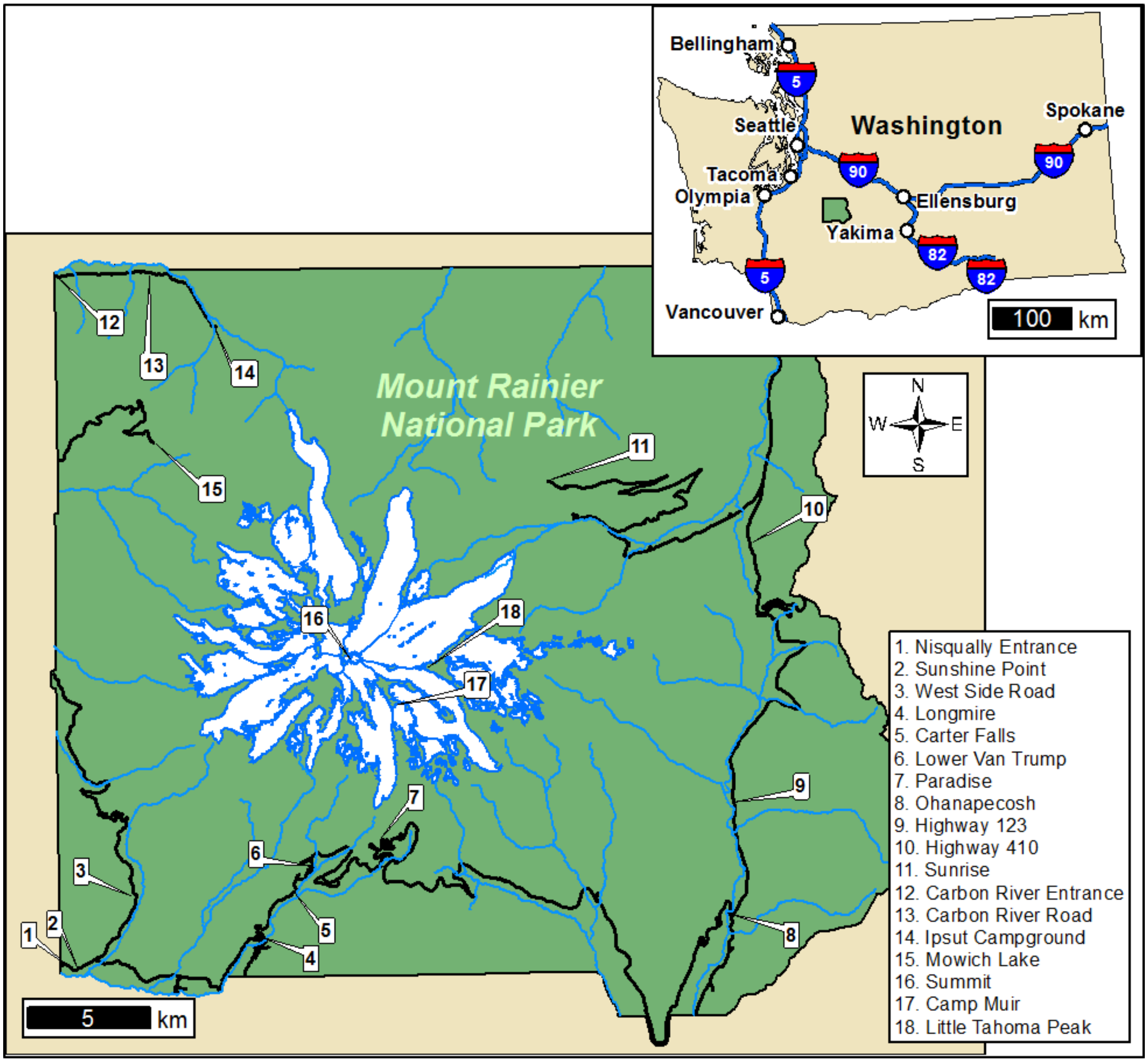


Figure 1: Location map of Mount Rainier volcano and Mount Rainier National Park within Washington State. Major areas discussed in the text are labeled.

Glaciers act as giant conveyor belts, collecting rock fall and other sediment on the glacier, encasing it in ice and slowly carrying it down to the terminus of the glacier (Driedger, 1993; Patterson, 2000). At the terminus, melt water and sediment escape the glacier and become rivers. Many large rivers emanate from the base of the glaciers and radiate away from the volcano like spokes on a wheel. At Mount Rainier, the White, West Fork White, Carbon, Mowich, Puyallup, Tahoma, Kautz, Nisqually, Cowlitz, and Ohanpecosh Rivers begin at glacial termini and flow away from the mountain (Figure 2). Sediment is a major contribution to rivers near their glacial source, and a surfeit of sediment leads to the development of a braided or braided-anastomosing river form.

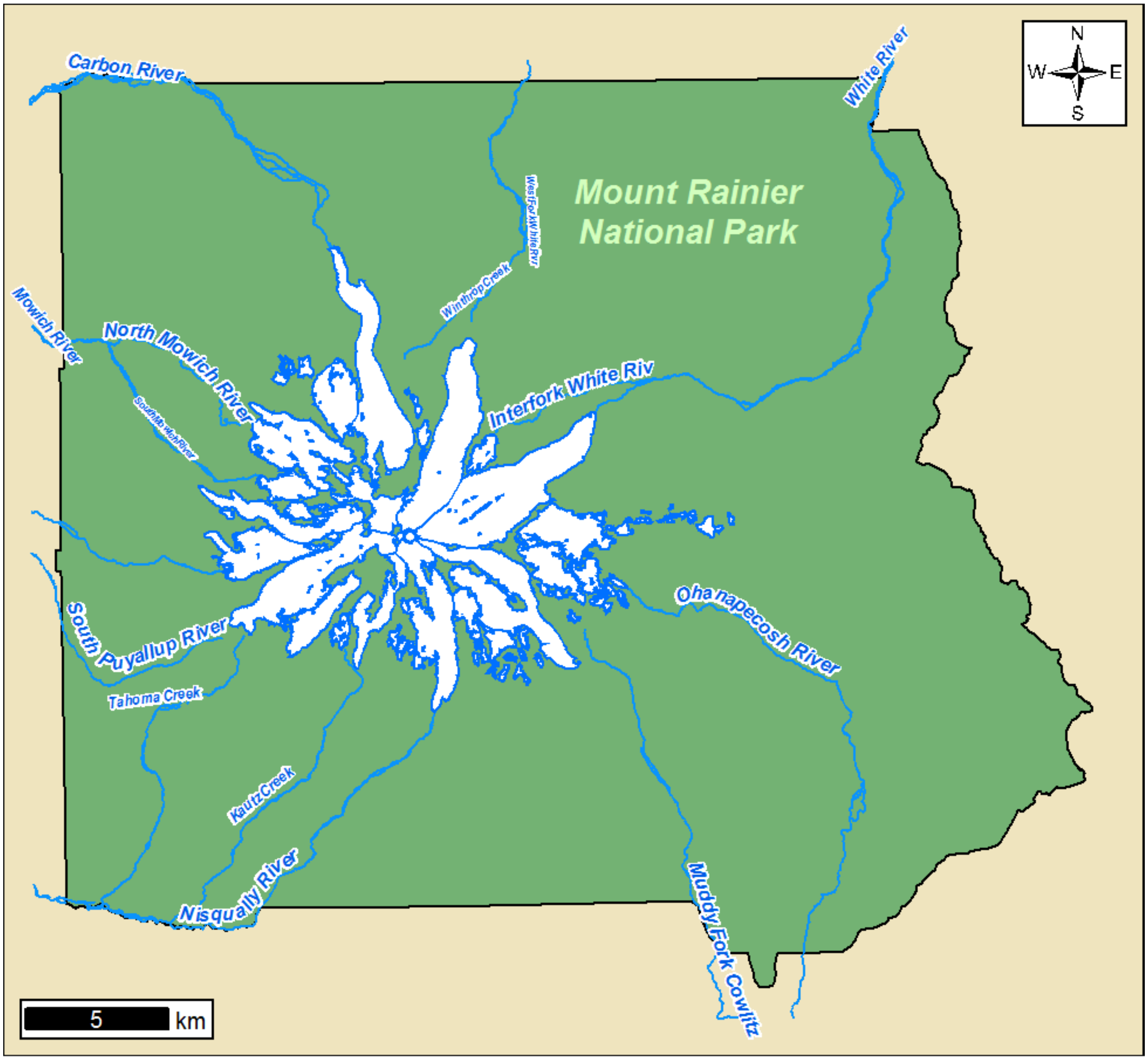


Figure 2: Major proglacial braided rivers at Mount Rainier National Park. Other perennial and intermittent rivers in the park are omitted for clarity.

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 alluvial rivers are exceedingly diverse and dynamic, their form is largely determined by the interplay between sediment deposition and sediment erosion. These two processes, in turn, are largely governed by four factors: stream slope, stream discharge, sediment size, and sediment load. The first two factors – slope and discharge – determine the energy available to move sediment while the second two factors – sediment size and load – determine the energy needed to move the sediment. Lane (1955) and Rosgen (1996) describe conceptually how a balance between these four factors leads to an overall stable channel form, and how an imbalance results in aggradation or degradation (incision) as shown in Figure 3. This conceptual model is called “Lane’s balance.”

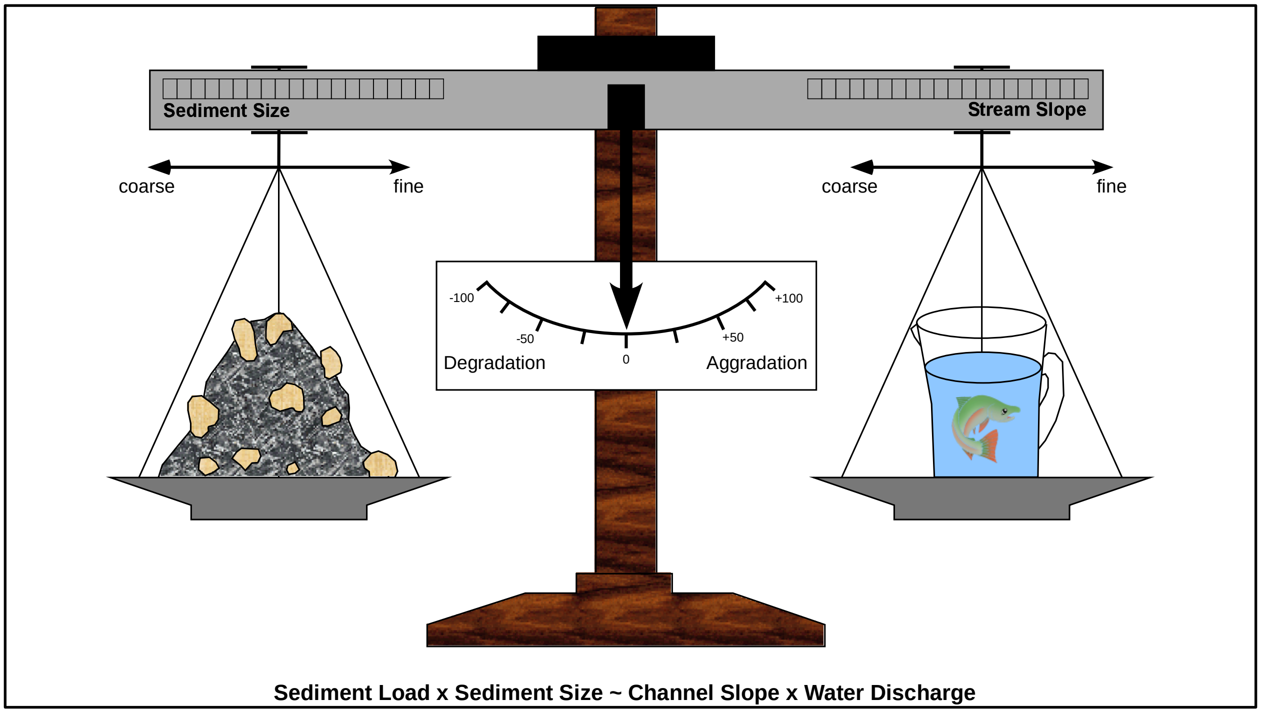


Figure 3: Lane’s balance (Lane, 1955; Rosgen, 1996), a way of simplifying sediment and flow dynamics in a river to stream slope, flow, sediment size and sediment volume. A change in any of these four characters can change the equilibrium of a river, resulting in aggradation or incision.

When the energy available to move sediment (the right side Lane’s balance) is in balance, on average, with the energy required to move the sediment (the left side of the Lane’s balance), the river is said to be in dynamic equilibrium. Some alluvial rivers are characterized by long-term dynamic equilibrium, and when a disturbance changes one of the four factors depicted in Lane’s balance, the other three factors will adjust in order to reestablish the equilibrium. For example, if a debris flow deposits a large wedge of sediment in a river previously at equilibrium, the channel slope will locally increase as the water works its way around the sediment deposit, and the streambed surface may become less coarse, exposing more fine sediment to be carried away. This results in increased sediment transport rates, which erode away the new sediment deposit, eventually leading to streambed coarsening, and reduction in slope as the channel returns to equilibrium.

Many alluvial rivers are not, however, in equilibrium. Where more sediment, or coarser sediment, is delivered to the channel than it is capable of transporting, the channel will aggrade and must eventually change either its form, its location in the valley, or both. This produces a segment of the valley characterized by long-term deposition and storage of alluvial sediment as channels aggrade and migrate in response. Conversely, when the river has more hydraulic energy than needed to transport its sediment load, it will erode the bed and banks. This can result in channel incision.

Channel incision, in turn, results in increased bank erosion, which locally increases the sediment load in response. A large flood can cause the streambed to erode, but floods often also mobilize large amounts of sediment from bank erosion or hillslope failures, and thus do not always result in channel incision.

Aggradation in Park rivers has been studied in detail in the last decade due to increasing infrastructure damage, especially during the 2006 flood at Mount Rainier (National Park Service, 2006; Beason, 2007; Beason and Kennard, 2007). On November 6-7, 2006, Mount Rainier received 45.5 cm (17.9 in) of rain and had a freezing level greater than 3,000 m (10,000 ft) (NPS, 2006). Rivers in the park responded to this event by flooding (RI = 100 yr at USGS stream gage at National, WA), and the associated peak flows caused severe bank erosion and infrastructure damage. Mount Rainier National Park was closed from November 6, 2006 to May 6, 2007, the longest closure in the park's history. Despite the record stream flows, Beason (2007) found that many rivers aggraded. This indicates that sediment production overwhelmed the erosive forces in Park rivers (Beason and Kennard, 2007). This flood was an eye-opening experience for many Park staff and it highlighted the hazard of aggradation in Park rivers, especially in locations near major Park infrastructure.

Increasing aggradation and sediment production may be related to overall glacial recession, a possible climate signal at Mount Rainier (Beason, 2007; Abbe et al., 2010; Marren and Toomath, 2014). Aggradation has also been studied in the rivers that drain Mount Rainier outside of MORA, primarily as they interact with populated areas outside the park (Czuba et al., 2010; Czuba et al., 2011; Czuba et al., 2012a; Czuba et al., 2012b). Observed aggradation may also indicate that many of the valley segments in and around Mount Rainier are in fact depositional response reaches, which store alluvial sediment over the long term, and are not well characterized by the equilibrium depicted in Lane's balance. In addition, when large amounts of sediment are delivered by processes other than fluvial transport, such as via lahars or debris flows, the river channel may never establish an equilibrium form because it remains in a state of recovery from the last disturbance, and valley bottom topography may be dominated by the legacy of these non-fluvial processes.

This study looks at the rate at which the beds of braided river channels at Mount Rainier are changing in height over time, i.e., aggrading or incising. The Nisqually and White Rivers have been singled out for detailed study, mainly because of their proximity to Park infrastructure. These rivers have affected nearby Park infrastructure within the last decade and have contributed to some of the longest closures in the Park's century-long history (National Park Service, 2006). Anticipated results of understanding rates of 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.

Study Areas

Study locations were selected based on: (1) availability of historical data (Henshaw and Parker, 1913; Fahnestock, 1963; Nelson, 1987; Ridel, 1997; Herrera, 2005); (2) accessibility; (3) proximity to park infrastructure; (4) aspect; and (5) river size. The primary study locations are on the Nisqually River. This includes: (1) Sunshine Point campground; (2) Longmire; (3) Carter Falls; and (4) Lower Van Trump Hairpin (at the confluence of Van Trump Creek and the Nisqually River). Other study locations include cross sections on the White River that were first occupied by Herrera (2005). The watersheds represented by study reaches are included in Figure 4 for Sunshine Point (Table 2), Longmire (Table 4), Carter Falls (Table 6) and Lower Van Trump (Table 8) and Figure 5 for the White River (Table 10).

Sunshine Point

Sunshine Point is located just within the Southwest boundary of MORA, approximately 0.6 km (0.4 mi) from the Nisqually Entrance on the Nisqually-Paradise Road (Figure 6). The survey area is located between river kilometer (RK) 0.39 and 0.90 (river mile, RM, 0.25 to 0.56) on the Nisqually River[1]. The location is named for the former Sunshine Point Campground, one of two former year-round campgrounds in the park. The Sunshine Point area was originally established as a Civilian Conservation Corps campground beginning in October 1938 and required the use of basket dams (gabions) and log cribbing to armor the campground from flood erosion by the Nisqually River (Burtchard et al., 2013). Sunshine Point Campground offered camping from 1953 to 2006 with 18 campsites, a dedicated picnic area with covered shelter, drinking water, and vault toilet facilities (Burtchard et al., 2013). The campground was located along a narrow section of the active channel of the Nisqually River just downstream of the confluence of Tahoma Creek. The channel was as wide as 200 m (660 ft) upstream, but narrowed to around 100 m (330 ft) in the vicinity of the campground. A hillslope drainage stream ran between the Nisqually-Paradise road and campground and emptied into the Nisqually River just downstream of the campground.

[1] River kilometer (RK) (and river mile, RM), for purposes of this study, will assume the starting point is at the park boundary and ending point is at the glacial terminus. For the Nisqually River, the range is RK/RM 0.00 at the Park Boundary and RK 19.26 (RM 11.96) at the Nisqually Glacier. For the White River, the range is RK/RM 0.00 at the North Park Boundary and RK 21.66 (RM 13.46) at the Emmons Glacier.

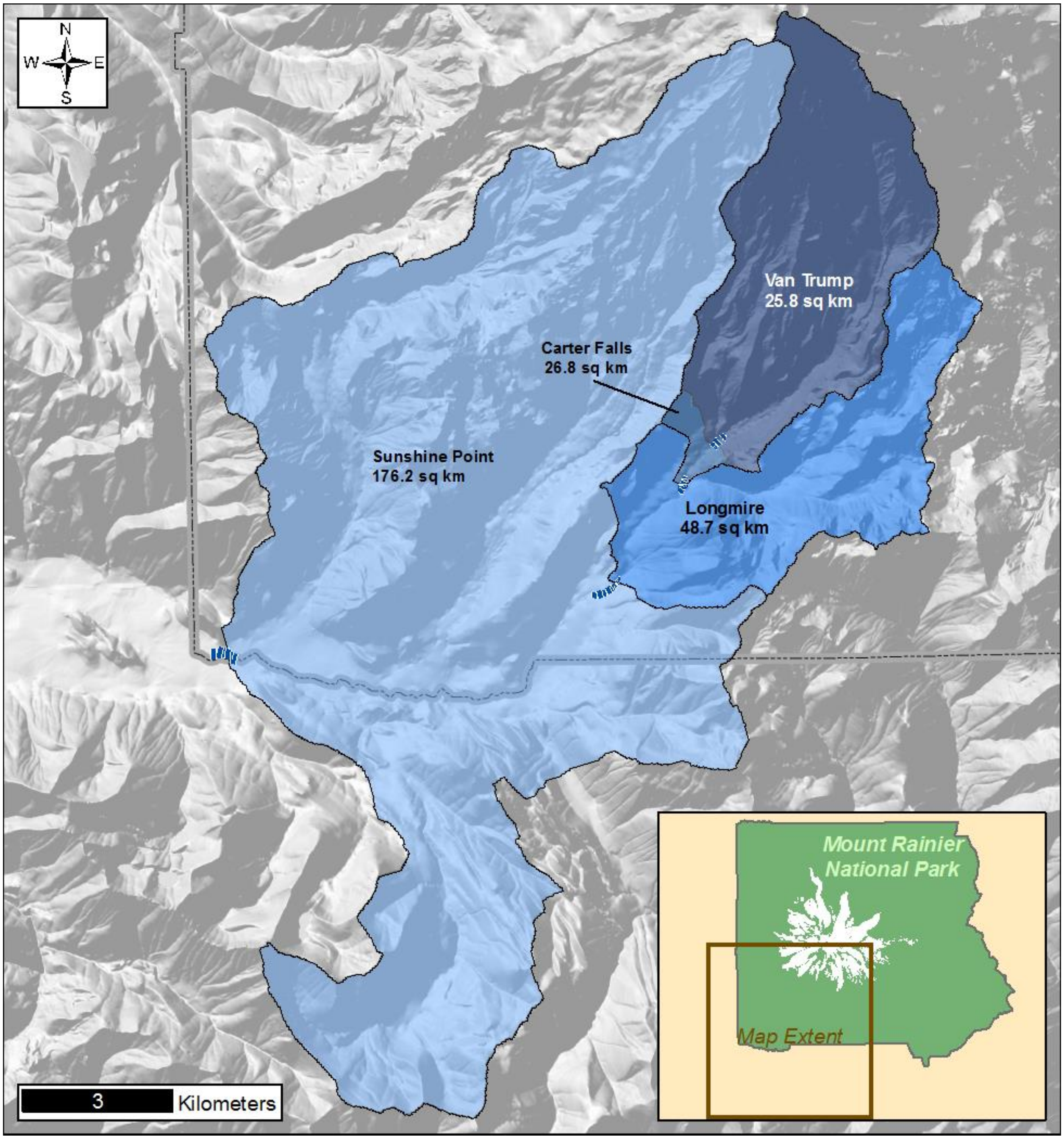


Figure 4: Delineated watersheds represented by cross section locations on the Nisqually River. Cross sections are included at the downstream end of each watershed for reference. Background hillshade is based on regional 10 m digital elevation model (DEM). Watershed delineation computed by USGS StreamStats for Washington (USGS, 2013b). Scale: 1:119,059.

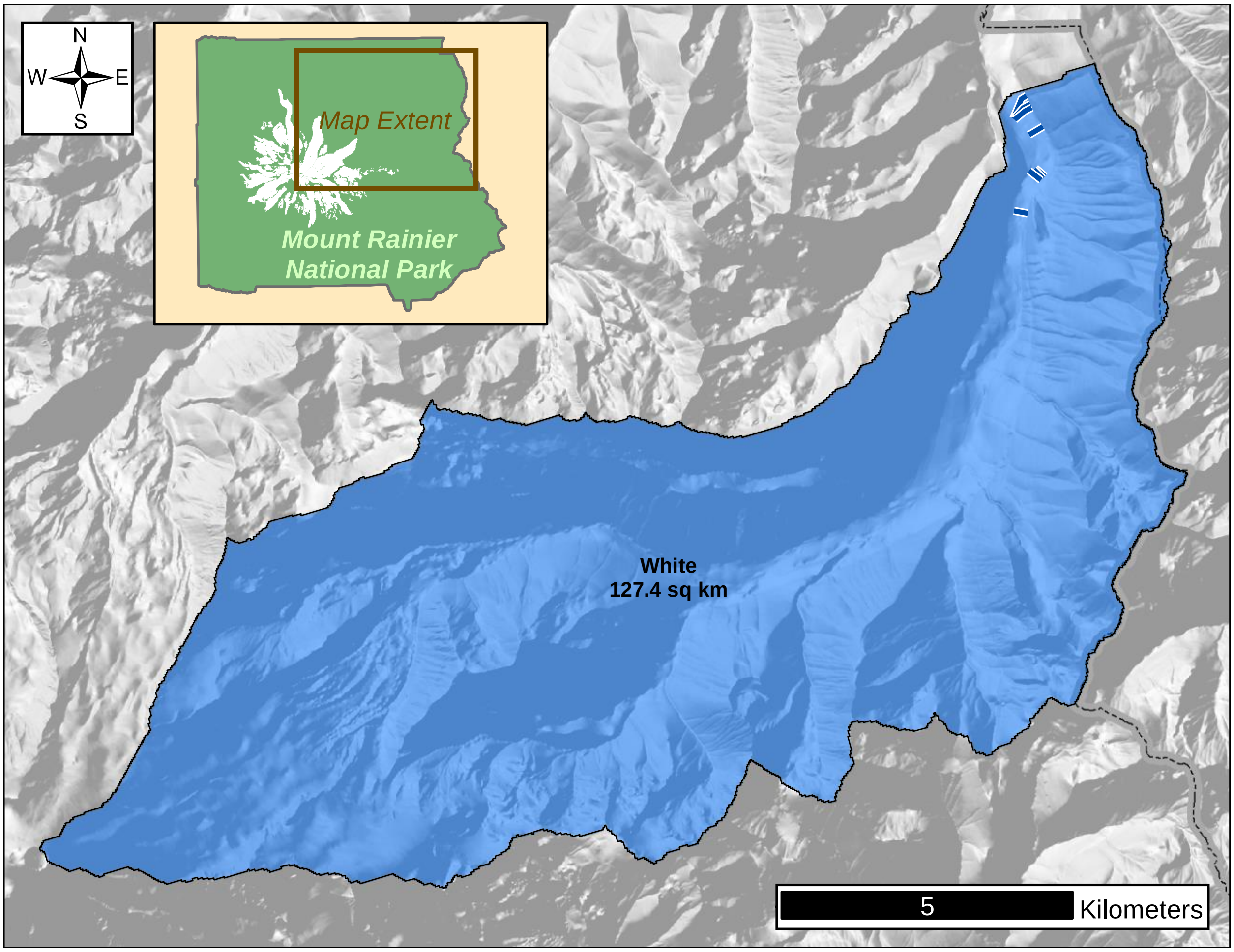


Figure 5: Delineated watersheds represented by cross section locations on the White River. Cross sections are included at the downstream end of the watershed for reference. Background hillshade is based on regional 10 m digital elevation model (DEM). Watershed delineation computed by USGS StreamStats for Washington (USGS, 2013b). Scale: 1:127,744.

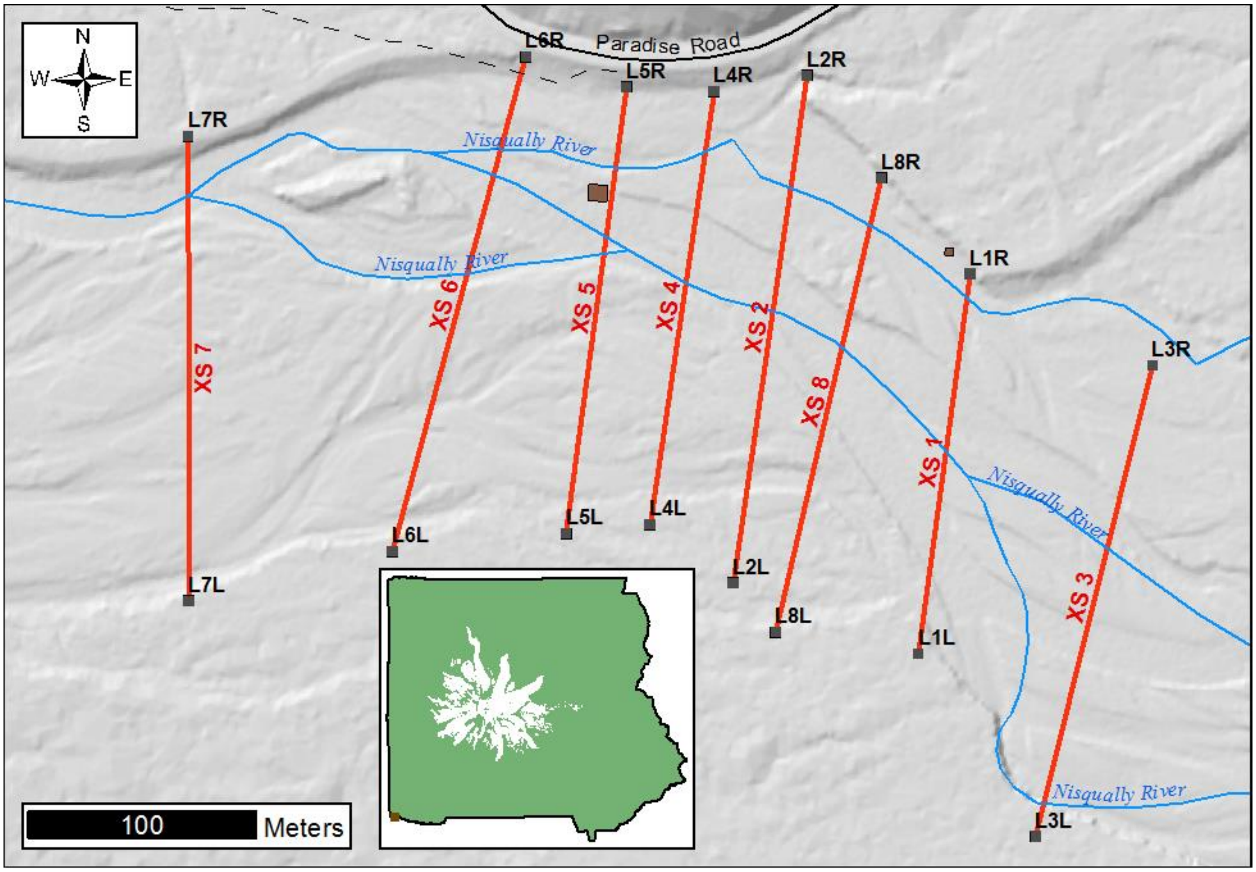


Figure 6: Sunshine Point area map showing cross section numbers and alignment points (Table 1) along the Nisqually River just downstream of the confluence of Tahoma Creek. River flow is from right to left in this figure. Background hillshade is based on 2008 park-wide LiDAR. Scale: 1:3,322.

The Sunshine Point Campground had a long history of bank erosion along the Nisqually River (Burtchard et al., 2013). The park had armored the right bank of the river with large rip-rap, building upon the flood control revetments of the CCC. Additionally, a levee was maintained by the park and Pierce County, starting at the campground and extending downstream past the park boundary to the Nisqually Park subdivision. During the record flood in November 2006, the park's levee catastrophically bank eroded and failed, and the park lost five campsites, the picnic area, vault toilet facilities, and a portion of the Nisqually-Paradise Road (Figure 7). The loss of this road, compounded with other major damage in the park, contributed to the longest closure of the park in its history, from November 6, 2006 to May 6, 2007. The estimated loss of the campground and associated land amounted to approximately 27,540 m^2 (296,500 ft^2), and a loss of approximately 125,900 m^3 (4,447,000 ft^3) of overbank and floodplain material (Figure 5.12 *in* Beason, 2007). This loss occurred in less than 12 hours during the peak of the storm as witnessed by the last departing park staff on November 6 and first arriving park staff on November 7, 2006. At its maximum flow, the river widened from 105 m (344 ft) to 223 m (732 ft), effectively doubling its active channel width in a single event (Beason, 2007).

Figure 7: National Agriculture Imagery Program (NAIP) true-color aerial photos from summer 2006 (above) to summer 2009 (below) showing the dramatic change at Sunshine Point Campground due to flood damage on November 6-7, 2006. Approximate bank erosion is 27,540 m^2 (296,500 ft^2) (Beason, 2007). Scale: 1:4,109.

During the 2006 flood, a portion of Tahoma Creek, estimated at about 25% by Kennard (Personal Communication, 2006), flooded into the right overbank floodplain 0.9 km (0.6 mi) upstream of the Tahoma Creek Bridge on the Nisqually-Paradise Road. Aggradation of the stream bed, likely due to a sediment wave (discussed later in this paper) likely exacerbated the height of the flood. These forces activated a high-flow channel that paralleled Tahoma Creek, overtopping a culvert at the intersection of the West Side Road and Nisqually-Paradise Road. The stream then paralleled the Nisqually-Paradise Road and Tahoma Creek, eventually flooding a small stream channel at the entrance of Sunshine Point Campground. The flooding of this side channel (commonly called "New Tahoma Creek" by park staff) likely contributed to the destruction of the campground by the erosive effects of the Nisqually River.

Sunshine Point was originally surveyed by researchers in 2005, establishing 3 cross sections, numbered 3, 1 and 2 in upstream to downstream order. The cross sections were reestablished in 2006 by Beason (2007). Following the flooding and major bank erosion in 2006, cross sections were lengthened along the newly-established stream channel and former campground area. Additional cross sections (4-7) were added in 2008 and resurveyed in 2009, 2010, 2011, and 2012. It should be noted that Nelson (1987) surveyed the Sunshine Point area to develop a hydraulic model of stream flow to predict flood flows. The cross sections Nelson surveyed were in a much larger area than our study, both upstream and downstream on the Nisqually River and upstream on Tahoma Creek to an area just upstream of the Tahoma Creek Bridge. However, the original data for these cross sections has not been found despite searching by United States Geological Survey staff and an exhaustive search by the authors of this study. Nelson's published study only references the locations of the lines, not the raw cross section data. Therefore, Nelson's data cannot be used for the purposes of this study.

Post 2006-flood levee repair in 2011 by Pierce County contractors damaged or destroyed control points on the levee. Because of the loss of these control points, a vertical and horizontal datum loss occurred (i.e., we had no points to reestablish for occupying the total station and back-sighting, which are needed in order to resurvey the cross sections). We made numerous attempts to reestablish this datum but have been unsuccessful in doing so. Therefore, data compared between the periods of 2005-2011 and 2011-2012 must be analyzed independent of one another. Numerous benchmarks have been established in this area to prevent this problem from occurring in the future.

The Nisqually River watershed at Sunshine Point (Figure 4) drains a significant portion of the southwest aspect of MORA, including the Nisqually River, Tahoma Creek, Kautz Creek, Van Trump Creek and Paradise River within MORA boundaries. The Nisqually also receives water from Horse Creek and Berry Creek from Gifford Pinchot National Forest, just south of the park. The watershed is 176.2 km^2 (68.05 mi^2), draining from the summit of Mount Rainier (4,392 m; 14,410 ft) to the downstream end of the survey reach (622 m; 2,040 ft) (Table 2). The elevation range is between 622 m (2,041 ft) in the upstream end and 613 m (2,012 ft) in the lower end of the reach, resulting in an average gradient of 1.95%, based on survey data in 2012. Other watershed facts for the Nisqually River at Sunshine Point are included in Table 2 (USGS, 2013b).

Table 1: Alignment points for cross sections at Sunshine Point. All coordinates are in North American Datum (NAD) 1983 Washington State Plane South Zone coordinate system (FIPS = 4602) with coordinates measured in U.S. Survey Feet. Lines are shown in upstream to downstream order. Directions (left and right) assume the reader is viewing the cross sections facing downstream. Cross section lines and left and right points correspond to Figure 6.

Line	Left Point	Left Northing	Left Easting	Right Point	Right Northing	Right Easting
3	L3L	514,501.426	1,287,274.451	L3R	515,182.056	1,287,443.119
1	L1L	514,766.058	1,287,105.857	L1R	515,313.980	1,287,180.211
8	L8L	514,796.776	1,286,900.067	L8R	515,452.406	1,287,052.196
2	L2L	514,867.957	1,286,838.305	L2R	515,600.057	1,286,945.143
4	L4L	514,942.132	1,286,718.323	L4R	515,576.920	1,286,811.072
5	L5L	514,939.007	1,286,597.114	L5R	515,583.184	1,286,685.058
6	L6L	514.913.503	1,286,346.839	L6R	515.627.136	1,286,539.091
7	L7L	514,842.354	1,286,053.843	L7R	515,512.488	1,286,052.548

Table 2: Watershed statistics for the Nisqually River at Sunshine Point (USGS, 2013b).

Attribute	Value	Units
Watershed Size:	176.249	Square kilometers
Mean Basin Elevation:	1,435	Meters
Minimum Basin Elevation:	622	Meters
Maximum Basin Elevation:	4,392	Meters
Relief (maximum – minimum):	3,770	Meters
Mean basin slope:	43.9	Percent
Percent of area with slope greater than 30%:	68.0	Percent
Percent of area with slope greater than 30% and north facing:	9.99	Percent
Area-weighted forest canopy:	56.8	Percent
Mean annual precipitation:	248.7	Centimeters

Longmire

The Longmire complex is one of the primary year-round administrative areas of the park. It is located on the southwest corner of MORA approximately 10.5 km (6.5 miles) from the park entrance. The survey area is between RK 10.33 to 10.96 (RM 6.42 to 6.81) on the Nisqually River. Longmire is home to the National Park Inn - a year-round hotel, employee housing, maintenance facilities, and employee offices. Longmire was named after, and established by, James Longmire, a mountain guide and pioneer who had moved from Indiana to Yelm, WA via the Oregon Trail in 1858 (Catton, 1996). Longmire cleared a road from the Succotash Valley (present day Ashford, WA) in 1884. In 1887, he filed a mineral claim and by 1889, the Longmire family had established a development consisting of bath-houses and guest cabins. In 1890, the Longmires built a rustic hotel in the present site of the Longmire Meadows. As the park became established and grew, the Longmire area became one of the large hubs for visitor and employee access in the park.

The Nisqually River flows through a relatively confined stretch upstream of Longmire with Tertiary-age intrusive bedrock exposures on both the right and left bank (Pringle, 2008). After flowing under the Longmire suspension bridge, the river loses its bedrock confinement and widens out. Channel widths here vary from 40 meters in the upstream zone to around 100 meters at the downstream end.

Longmire has an impressive floodplain disequilibrium; that is, the elevation of the river through Longmire is higher than most of the Longmire compound. This is likely due to a lahar that affected the Longmire area sometime before 1860 (Pringle, 2008). The National Park Inn is as much as 15 m (50 ft) lower than the Nisqually River, requiring one to walk uphill to get to the river. The park has recently constructed a buried concrete wall in the right bank levee that protects the Longmire compound. A significant flood would be required to overtop this levee.

Longmire has one of the longest histories of cross section surveys in the park, starting in 1982 with surveys by Nelson (1987) and continuing in 1997 with surveys by Riedel (1997). Similar caveats with Nelson's study at Sunshine Point preclude its inclusion for analysis in the Longmire area. Riedel established the cross sections, still in use to this day, in the Longmire area to develop a hydraulic model of stream flows at various hydraulic conditions, including anticipated debris flow enhanced stream flows. 10 cross sections were put in place by Riedel, numbered sequentially from 1 to 10 in upstream to downstream order (Figure 8). Riedel's original cross sections had numerous kinks and bends in them which were straightened in surveys in 2008. Cross sections and analyses since 2008 use these straightened cross sections through Longmire. Cross sections at Longmire were surveyed in 1997, 2005, 2006, 2008, 2009, 2010, 2011 and 2012.

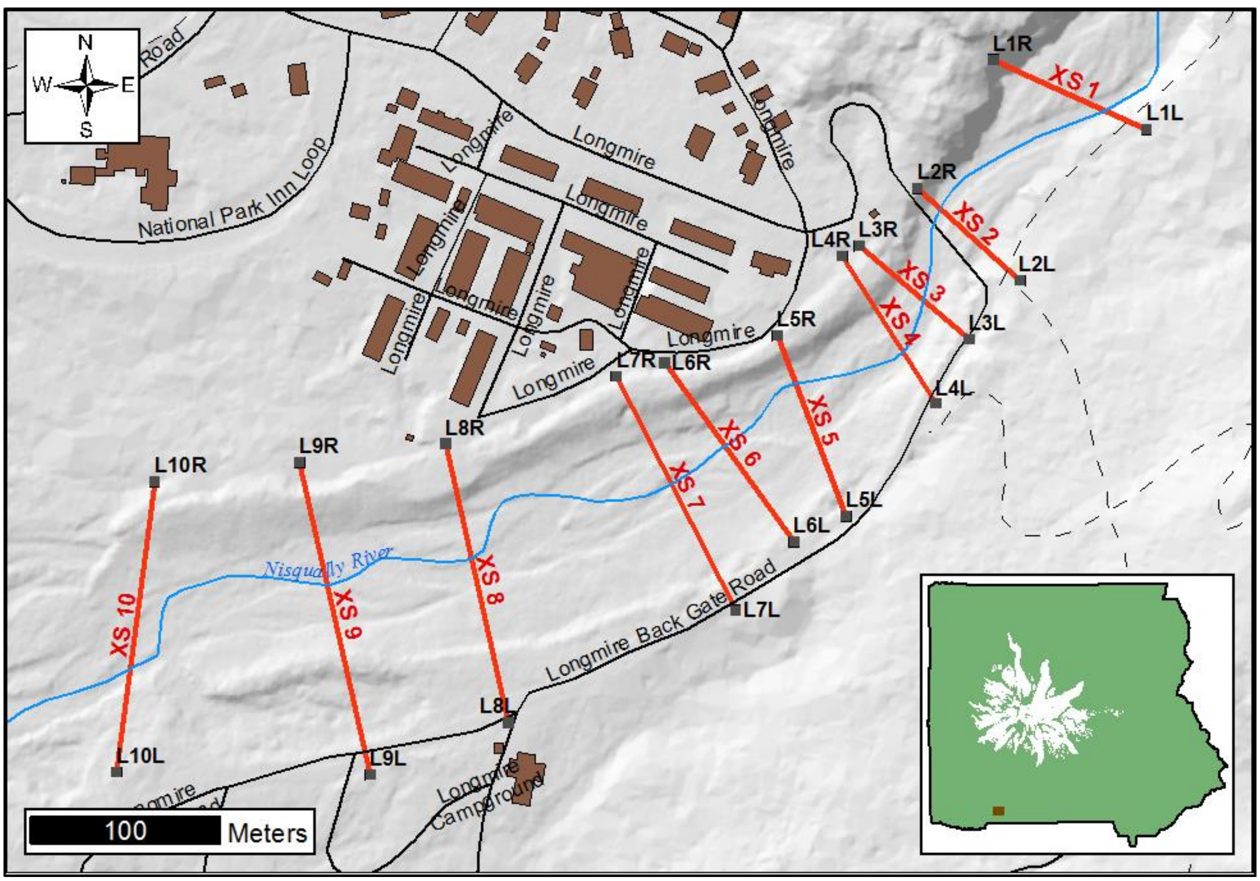


Figure 8: Longmire area map showing cross section numbers and alignment points (Table 3) along the Nisqually River. River flow is from upper right to lower left in this picture. Background hillshade is based on 2008 park-wide LiDAR. Scale: 1:4,000.

The Longmire reach was significantly affected by the 2006 flood, but resulting damage was to a lesser extent than that at Sunshine Point. The right bank levee experienced significant bank erosion and the park nearly sustained structural damage to its Emergency Operations Center (Figure 9). In order to protect the compound, heavy construction equipment was used to push material from the river bed back up to the levee to re-form it. Because of this anthropogenic alteration of the channel, exact sedimentation rates are somewhat uncertain; however, construction equipment did not remove stream sediment from the reach. The material was still in the channel, just in different configurations than were deposited by the river. We are reasonably confident that the cross sections still show the sediment deposited, though much of it was moved to the edges of the river in order to fix the right and left bank levees that protect the Longmire compound and community building.

Figure 9: Bank erosion and damage to park infrastructure during the November 2006 flood at Mount Rainier. Photo taken at 9:39 AM on November 7, 2006, after the peak of the flood. Photo: National Park Service.

The Nisqually River watershed at Longmire (Figure 4) receives water from the Nisqually Glacier, Van Trump Creek, and Paradise River within MORA boundaries. The watershed is 49.67 km^2 (18.79 mi^2), extending from the summit of Mount Rainier (4,392 m; 14,410 ft) to the survey reach (853 m; 2,798 ft) (Table 4). The elevation range is between 851 m (2,793 ft) in the upstream end and 831 m (2,726 ft) in the lower end of the reach, resulting in an average gradient of 3.36%, based on survey data in 2012. Other watershed facts for the Nisqually River at Longmire are included in Table 4 (USGS, 2013b).

Table 3: Alignment points for cross sections at Longmire. All coordinates are in North American Datum (NAD) 1983 Washington State Plane South Zone coordinate system (FIPS = 4602) with coordinates measured in U.S. Survey Feet. Lines are shown in upstream to downstream order. Directions (left and right) assume the reader is viewing the cross sections facing downstream. Cross section lines and left and right points correspond to Figure 8.

Line	Left Point	Left Northing	Left Easting	Right Point	Right Northing	Right Easting
1	L1L	519,169.236	1,312,947.851	L1R	519,290.541	1,312,681.809
2	L2L	518,907.640	1,312,727.483	L2R	519,067.981	1,312,550.351
3	L3L	518,805.221	1,312,639.609	L3R	518,967.486	1,312,449.545
4	L4L	518,693.249	1,312,581.848	L4R	518,950.291	1,312,419.144
5	L5L	518,496.978	1,312,425.840	L5R	518,811.600	1,312,306.827
6	L6L	518,453.115	1,312,335.329	L6R	518,763.692	1,312,110.709
7	L7L	518,334.743	1,312,234.462	L7R	518,740.656	1,312,027.030
8	L8L	518,139.032	1,311,838.995	L8R	518,623.301	1,311,730.085
9	L9L	518,047.972	1,311,598.833	L9R	518,591.094	1,311,475.820
10	L10L	518,052.829	1,311,157.432	L10R	518,557.256	1,311,225.103

Table 4: Watershed statistics for the Nisqually River at Longmire (USGS, 2013b).

Attribute	Value	Units
Watershed Size:	48.665	Square kilometers
Mean Basin Elevation:	1,813	Meters
Minimum Basin Elevation:	853	Meters
Maximum Basin Elevation:	4,392	Meters
Relief (maximum – minimum):	3,539	Meters
Mean basin slope:	48.2	Percent
Percent of area with slope greater than 30%:	75.7	Percent
Percent of area with slope greater than 30% and north facing:	9.65	Percent
Area-weighted forest canopy:	39	Percent
Mean annual precipitation:	261.62	Centimeters

Carter Falls

The name "Carter Falls" refers to the Carter Falls trail, which is a section of the larger Wonderland Trail, a 150 km (93 mi) trail that encircles Mount Rainier. The Carter Falls trail leads from the Nisqually-Paradise Road 13.7 km (8.5 mi) from the park entrance near the Cougar Rock Campground, crosses over the Nisqually River just upstream of the river's confluence with the Paradise River, then goes uphill 5.8 km (3.6 mi) to Carter and Madcap Falls. The survey area is between RK 13.68 to 13.95 (RM 8.50 to 8.67) on the Nisqually River. A former stream monitoring site with a channel spanning cable and tram existed in the vicinity of the study reach but has been abandoned (B. Diaz, personal communication, 2013). The Cougar Rock/Carter Falls area was also historically a popular location for the base of mining operations on Eagle Peak, a 1,816 m (5,958 ft)

Tertiary Tatoosh granodiorite mountain just southeast of the site (Pringle, 2008). Several mine adits remain on Eagle Peak but have not been used for some time.

This location was chosen for study for two reasons: (1) the presence of a year-round maintained log bridge to facilitate easy stream crossing, and (2) tracking the downstream migration of the Van Trump debris flow deposit from 2005 (mentioned later in this chapter). Six cross sections were initially surveyed in 2011, numbered sequentially from upstream to downstream (Figure 10). Horizontal and vertical elevation control comes from the Longmire area as part of a longitudinal profile completed from Longmire upstream to the Carter Falls reach in 2011. The cross sections at Carter Falls were resurveyed in 2012. With only two years of data in this location, the assessment of the area is still continuing.

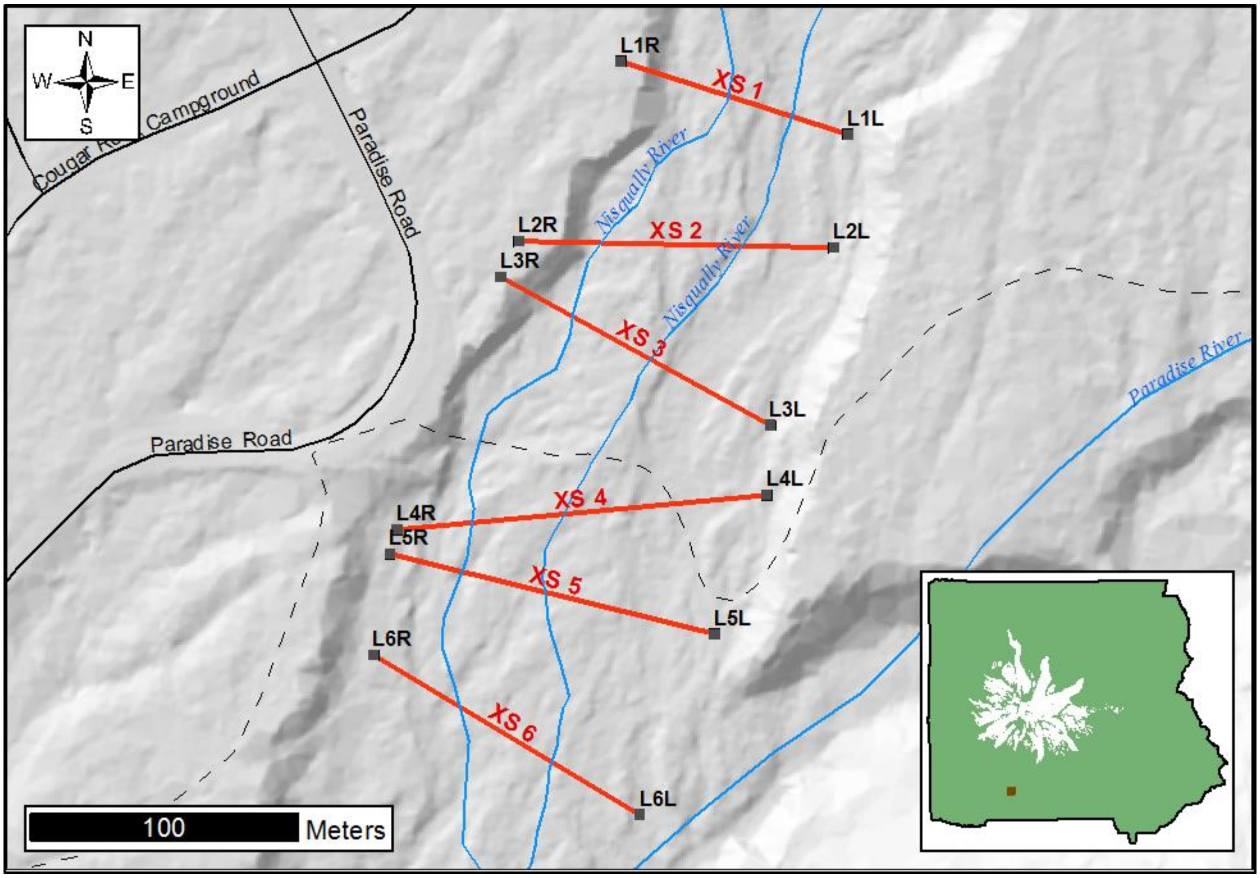


Figure 10: Carter Falls area map showing cross section numbers and alignment points (Table 5) along the Nisqually River just above of the confluence of Paradise River. River flow is from top to bottom in this picture. Background hillshade is based on 2008 park-wide LiDAR. Scale: 1:2,829.

The Nisqually River watershed at Carter Falls (Figure 4) receives water from the Nisqually Glacier and Van Trump Creek; Paradise River enters the Nisqually River just downstream of the survey reach. The watershed is 26.83 km^2 (10.36 mi^2), draining from the summit of Mount Rainier (4,392 m; 14,410 ft) to the survey reach (966 m; 3,169 ft) (Table 6). The elevation range is between 969 m (3,181 ft) in the upstream end and 953 m (3,126 ft) in the lower end of the reach, resulting in an average gradient of 6.57%, based on survey data in 2012. Other watershed facts for the Nisqually River at Carter Falls are included in Table 6 (USGS, 2013b).

Table 5: Alignment points for cross sections at Carter Falls. All coordinates are in North American Datum (NAD) 1983 Washington State Plane South Zone coordinate system (FIPS = 4602) with coordinates measured in U.S. Survey Feet. Lines are shown in upstream to downstream order. Directions (left and right) assume the reader is viewing the cross sections facing downstream. Cross section lines and left and right points correspond to Figure 10.

Line	Left Point	Left Northing	Left Easting	Right Point	Right Northing	Right Easting
1	L1L	525,674.539	1,317,503.148	L1R	525,764.321	1,317,224.344
2	L2L	525,535.367	1,317,486.303	L2R	525,543.440	1,317,098.596
3	L3L	525,317.213	1,317,408.036	L3R	525,499.574	1,317,077.090
4	L4L	525,231.584	1,317,403.751	L4R	525,189.198	1,316,949.424
5	L5L	525,060.915	1,317,340.328	L5R	525,159.146	1,316,940.616
6	L6L	524,839.038	1,317,248.256	L6R	525,035.011	1,316,920.307

Table 6: Watershed statistics for the Nisqually River at Carter Falls (USGS, 2013b).

Attribute	Value	Units
Watershed Size:	26.832	Square kilometers
Mean Basin Elevation:	2,115	Meters
Minimum Basin Elevation:	966	Meters
Maximum Basin Elevation:	4,392	Meters
Relief (maximum – minimum):	3,426	Meters
Mean basin slope:	50.7	Percent
Percent of area with slope greater than 30%:	81.9	Percent
Percent of area with slope greater than 30% and north facing:	2.39	Percent
Area-weighted forest canopy:	22.3	Percent
Mean annual precipitation:	279.4	Centimeters

Lower Van Trump Hairpin

Lower Van Trump Hairpin is the name for a tight hairpin on the Nisqually-Paradise road 15.1 km (9.4 mi) from the park entrance, at the confluence of Van Trump Creek and the Nisqually River. The survey area is between RK 14.96 to 15.26 (RM 9.30 to 9.48) on the Nisqually River. Van Trump Creek is sourced at the Van Trump Glaciers, a group of 0.5 km^2 (0.2 mi^2) perennial snowfields and glaciers on the south flank of Mount Rainier between about 2,100 m (7,000 ft) and 3,000 m (9,800 ft). The disappearing Van Trump Glaciers have left behind large areas of steep, loose material that is susceptible to mass wasting events. Debris flows have surged down from the Van Trump Glaciers in 2001, 2003, 2005, and 2006, some of which have covered the Nisqually-Paradise road (Donovan, 2005; Copeland, 2008; Copeland, 2009). Additionally, Beason (2007) found that the river bed adjacent to the apex of the Nisqually-Paradise Road has aggraded almost 12 m (39 ft) in a 96-year period from 1910-2006.

Because of the recent history of mass wasting events and accumulation of sediment in the reach, three cross sections were added in the summer of 2005 in the Lower Van Trump hairpin area (Figure 11). The cross sections are numbered sequentially from the downstream line to upstream (i.e., cross section 3 is at the upstream end and cross section 1 is at the lower end). Cross sections were resurveyed in 2006, 2008, 2009, 2010, 2011 and 2012. No new cross sections have been added, however, due to vandalism of control points in the area, new control points are generally added each survey year.

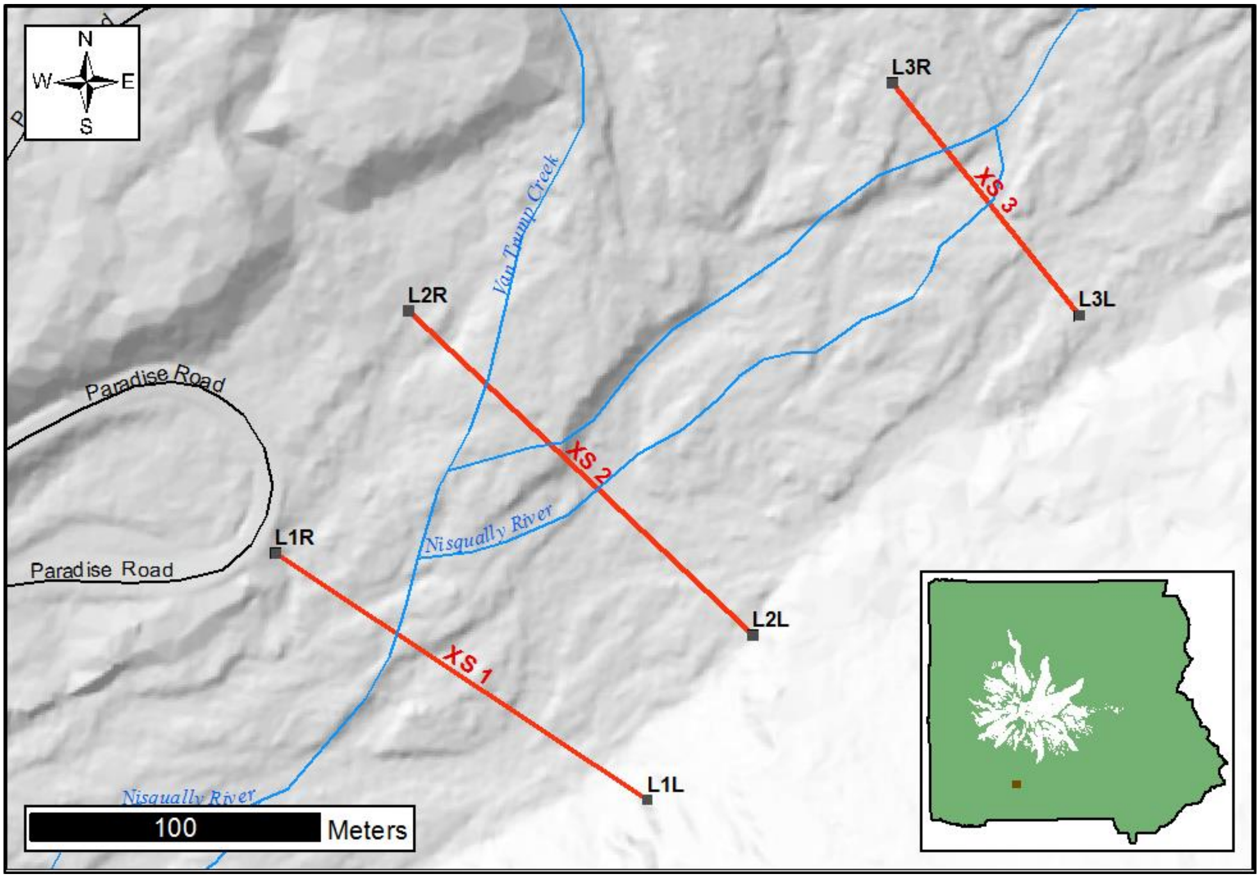


Figure 11: Lower Van Trump area map showing cross section numbers and alignment points (Table 7) along the Nisqually River. Lower Van Trump Creek enters from the top and joins the Nisqually River between cross sections 2 and 1. River flow is from upper right to lower left in this picture. Background hillshade is based on 2008 park-wide LiDAR. Scale: 1:2,616.

On September 29, 2005, Mount Rainier recorded 15.3 cm (6.02 in) of rain in a period of 48 hours with minimal snow pack (Copeland, 2008). During the event, a debris flow initiated by excessive melt water and precipitation in a steep area of loose glacial till just down slope of the Van Trump Glaciers, surged down Van Trump Creek, over Christine Falls, and finally deposited in the Nisqually River in the Lower Van Trump Hairpin survey area. Most of the debris was deposited in the vicinity of cross sections 1 and 2. This was most fortunate for the survey, as it allowed a detailed measurement of the debris flow deposition by Beason (2007). Less than a year after this event, the park was hit by the November 2006 flood. The location of the cross sections with respect to the debris flow deposit allowed for the analysis of transport of this sediment mass through the reach by flood flows. However, it should be noted that it is extremely likely that additional debris flows were spawned during the 2006 flood in the Van Trump Glacier area. If this is the case, they likely affected the sediment balance at this location.

During a ~13 year RI flood on November 12, 2008 (the 6th largest event on record, Table 12), the Nisqually River bank eroded into the left bank of Ricksecker point, initiating a landslide that deposited into the cross sectional reach at cross section 1. The landslide narrowed the active portion of the channel, causing significant channel change in the location of the landslide deposit, as well as directly upstream and downstream.

In addition to the Total Station cross-section surveys, Longmire, Carter Falls, and Lower Van Trump have been surveyed in 2008 and 2012 via airborne LiDAR (Light Detection and Ranging). The 2008 survey was part of a bigger project to generate LiDAR topography for the entire park; whereas, the 2012 study was flown on the main stem Nisqually and Carbon Rivers to analyze the passage of sediment through park rivers. Because of the extensive recent history with debris flows and landslides, LiDAR data allows a more detailed analysis of the landscape interactions here. This topic will be explored later in this paper.

The Nisqually River watershed at Lower Van Trump (Figure 4) receives water from the Nisqually Glacier and Van Trump Creek, which enters the reach between cross sections 2 and 3. The watershed is 25.77 km^2 (9.95 mi^2), draining from the summit of Mount Rainier (4,392 m; 14,410 ft) to the survey reach (1,027 m; 3,369 ft) (Table 8). The elevation range is between 1,047 m (3,436 ft) in the upstream end and 1,031 m (3,381 ft) in the lower end of the reach, resulting in an average gradient of 6.77%, based on survey data from 2012. Other watershed facts for the Nisqually River at Lower Van Trump are included in Table 8 (USGS, 2013b).

Table 7: Alignment points for cross sections at Lower Van Trump. All coordinates are in North American Datum (NAD) 1983 Washington State Plane South Zone coordinate system (FIPS = 4602) with coordinates measured in U.S. Survey Feet. Lines are shown in upstream to downstream order. Directions (left and right) assume the reader is viewing the cross sections facing downstream. Cross section lines and left and right points correspond to Figure 11.

Line	Left Point	Left Northing	Left Easting	Right Point	Right Northing	Right Easting
3	L3L	528,235.595	1,320,130.651	L3R	528,499.085	1,319,917.873
2	L2L	527,872.065	1,319,760.016	L2R	528,240.319	1,319,367.932
1	L1L	527,684.309	1,319,640.023	L1R	527,964.891	1,319,216.986

Table 8: Watershed statistics for the Nisqually River at Lower Van Trump (USGS, 2013b).

Attribute	Value	Units
Watershed Size:	25.770	Square kilometers
Mean Basin Elevation:	2,155	Meters
Minimum Basin Elevation:	1,027	Meters
Maximum Basin Elevation:	4,392	Meters
Relief (maximum – minimum):	3,365	Meters
Mean basin slope:	50.9	Percent
Percent of area with slope greater than 30%:	82.6	Percent
Percent of area with slope greater than 30% and north facing:	2.19	Percent
Area-weighted forest canopy:	20.3	Percent
Mean annual precipitation:	279.4	Centimeters

White River

The White River study site refers to eight cross sections surveyed along State Route 410 in the White River on the northeast corner of the park. These cross sections occur between SR410 mile post 58.42 and 58.86, approximately 1.2 km (0.8 mi) to 3.6 km (2.2 mi) from the north park boundary. The survey area is between RK 3.75 to 5.88 (RM 2.33 to 3.65) on the White River. SR410 is seasonally closed from the park boundary to Cayuse Pass each winter and open throughout the summer.

The White River in the study area has a wide alluvial channel and mature riparian old growth forest. In many areas throughout this reach, the river is topographically perched above the surrounding floodplain. In the vicinity of Cross Section 1, State Route 410 is about 3.6 m (11.8 ft) below the river channel (Beason, 2007).

Eight cross sections were originally surveyed by Herrera Environmental Consultants in 2005, as part of a reach analysis of the SR410 corridor contracted by the Washington State Department of Transportation (WSDOT) (Figure 12). During high precipitation events, water from the White River often floods the road. Since most floods at Mount Rainier occur after this portion of the road through the park is closed for the winter, there is generally no vehicle traffic on this stretch of highway at the time of the floods. However, flood waters have historically exited the park and run onto Crystal Mountain Boulevard, which affects Crystal Mountain Ski Area traffic. Additionally, damage from over bank sedimentation and bank erosion has occurred in these floods. Numerous studies have been undertaken by other park researchers mapping avulsion channels and studying the impact of large woody debris and mature old growth forests in stabilizing the floodplain in this area (P. Kennard, Personal Communication, 2012). Cross sections at White River have been occupied and resurveyed in 2005, 2006 (partially, and not included in this study), 2007, 2008, and 2011.

The White River watershed along State Route 410 (Figure 5) receives runoff from the Emmons Glacier, Inter Fork White River, Fryingpan Creek, Shaw Creek, Klickitat Creek, Deadwood Creek, and Crystal Creek. The watershed is 127.4 km^2 (49.19 mi^2), from the summit of Mount Rainier (4,392 m; 14,410 ft) to the survey reach (856 m; 2,808 ft) (Table 10). The elevation range is between 902 m (2,959 ft) in the upstream end and 862 m (2,828 ft) in the lower end of the reach, resulting in an average gradient of 1.90%, based on survey data in 2011. Other watershed facts for the White River along State Route 410 are included in Table 10 (USGS, 2013b).

Table 9: Alignment points for cross sections at White River. All coordinates are in North American Datum (NAD) 1983 Washington State Plane South Zone coordinate system (FIPS = 4602) with coordinates measured in U.S. Survey Feet. Lines are shown in upstream to downstream order. Directions (left and right) assume the reader is viewing the cross sections facing downstream. Cross section lines and left and right points correspond to Figure 12.

Line	Left Point	Left Northing	Left Easting	Right Point	Right Northing	Right Easting
8	L8L	591,147.104	1,382,059.024	L8R	590,991.442	1,382,812.420
7	L7L	593,393.839	1,382,983.120	L7R	592,858.083	1,383,648.674
6	L6L	593,475.310	1,383,269.255	L6R	592,964.173	1,383,738.688
5	L5L	593,539.853	1,383,344.820	L5R	593,069.553	1,383,850.995
4	L4L	595,413.302	1,383,036.104	L4R	595,866.940	1,383,849.759
3L[1]	L3L	596,295.077	1,382,251.230	L3M	596,791.189	1,382,870.183
3R[1]	L3M	596,791.189	1,382,870.183	L3R	596,956.559	1,383,229.025
2L[1]	L2L	596,355.106	1,382,194.904	L2M	596,948.713	1,382,756.643
2R[1]	L2M	596,948.713	1,382,756.643	L2R	597,151.907	1,383,168.685
1L[1]	L1L	596,372.257	1,382,178.811	L1M	597,447.880	1,382,691.413
1R[1]	L1M	597,447.880	1,382,691.413	L1R	597,644.520	1,382,982.615

[1] Lines 3, 2 and 1 at White River have a bend. For example, Line 3L is the left portion of the line to the bend, and 3R is the portion of the line to the right of the bend.

Table 10: Watershed statistics for the White River along State Route 410 (USGS, 2013b).

Attribute	Value	Units
Watershed Size:	127.402	Square kilometers
Mean Basin Elevation:	1,710	Meters
Minimum Basin Elevation:	856	Meters
Maximum Basin Elevation:	4,392	Meters
Relief (maximum – minimum):	3,536	Meters
Mean basin slope:	50.2	Percent
Percent of area with slope greater than 30%:	82.5	Percent
Percent of area with slope greater than 30% and north facing:	21.5	Percent
Area-weighted forest canopy:	50.5	Percent
Mean annual precipitation:	232.7	Centimeters

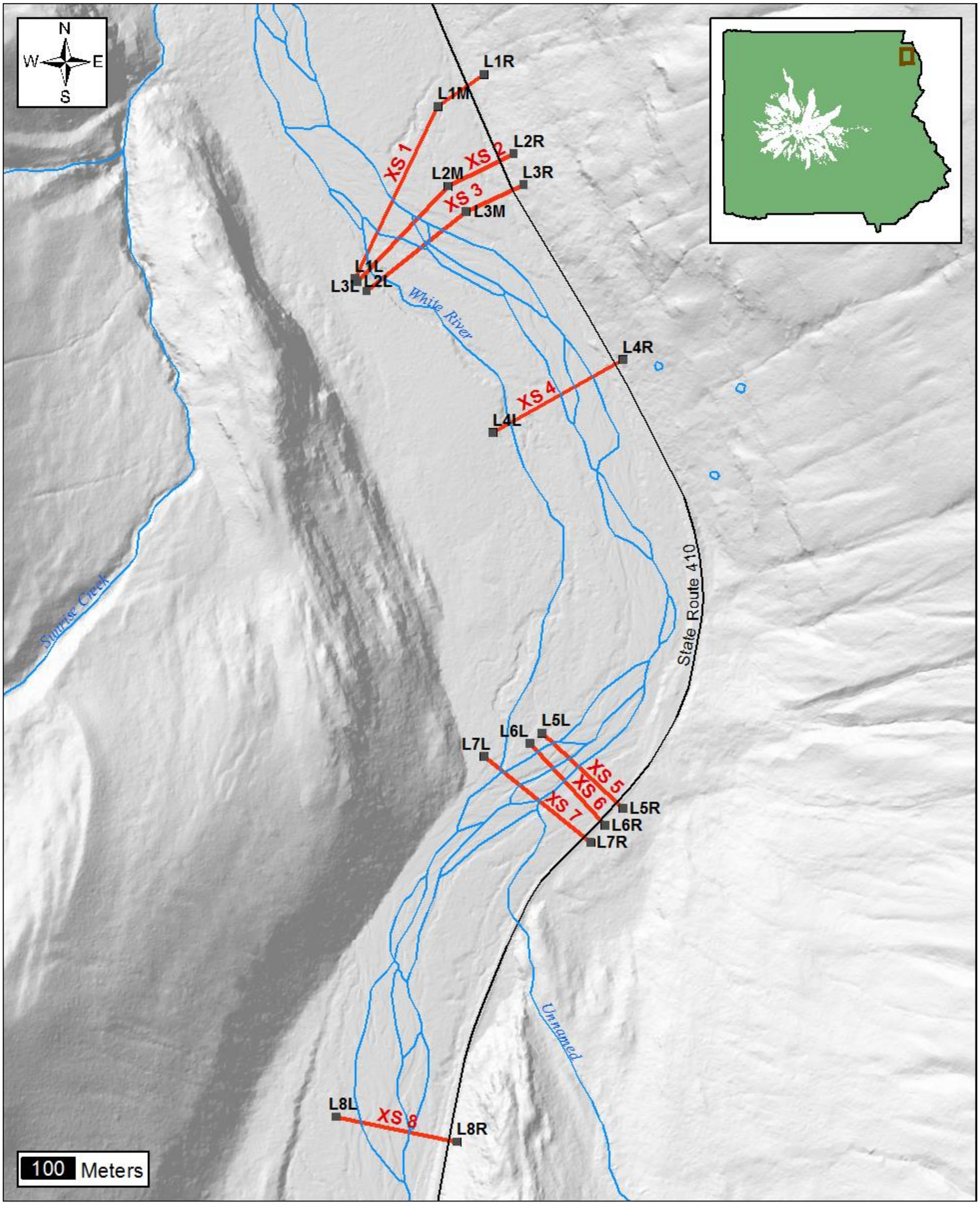


Figure 12: White River/SR410 area map showing cross section numbers and alignment points (Table 9) along the White River just south of the north park boundary. See text for description about lines 1-3. River flow is from bottom to top in this picture. Background hillshade is based on 2008 park-wide LiDAR. Scale: 1:11,223.

Peak Floods and Seasonality of Flooding

The climate of Mount Rainier, like that of the Pacific Northwest as a whole, is temperate maritime and is strongly bimodal, with a distinct rainy season in the fall, winter, and spring, and a separate dry season in the summer (Mass, 2008). Flooding from Mount Rainier most often occurs in the autumn and winter seasons, and these two seasons alone account for approximately 87% of the annual peak flows as measured at the USGS stream gaging station on the Nisqually River at National, located approximately 13.7 km (8.5 mi) downstream from the park boundary (Table 11). The months of November to January account for most of these floods, 48 out of 70 of the annual peak flows since water year 1943. While Park rivers do have an increase in average daily discharge in the summer due to snow melt, they rarely record the annual peak flow during that time. For example, only 2 of the peak flows on the Nisqually River have occurred in the summer months (June, July and August; both of the peaks occurred in June) and the recurrence interval for the events has been less than a 2-year return period (Table 12).

Most of the largest floods have occurred as result of atmospheric rivers (ARs; sometimes called "Pineapple Express" storms), which are long (> 2,000 km), narrow (< 1,000 km) fluxes or plumes of warm water vapor from tropical latitudes that jet into the coast of western North America (Neiman et al., 2011). ARs are unusually moisture-rich plumes that also have strong low level flow and high freezing levels, and as such are predisposed to significant orographic precipitation enhancement upon landfall, especially if the AR moves slowly or stalls over a given region (Neiman et al., 2011). Landfalling winter storms with AR attributes have been shown to produce almost twice as much precipitation as non-AR storms. Some of these events have produced record 24 hour increases in stream flow, particularly in mountainous regions near the coast (Neiman et al., 2008; Neiman et al., 2011).

The largest flood on record at the park has been mentioned previously and occurred on November 6, 2006. The flood had a recurrence interval of 100 years and a peak discharge at the USGS National stream gage of 617 $m^3 \times s^{-1}$ (21,800 $ft^3 \times s^{-1}$) (Table 12). This storm was attributed to a particularly intense AR that affected the Pacific Northwest (Figure 2 *in* Neiman et al., 2008). Neiman and others (2008) discuss this event in detail and discuss how the event caused major flooding with record rainfall and debris flows. Rainfall in the Cascades and coastal mountains from the 2006 AR ranged from 250 to 750 mm (10 to 30 in) and the freezing level for the storm was greater than 3,000 m (9,800 ft), a level that was anomalously high and allowed precipitation to fall as rain rather than snow (Neiman et al., 2008). The storm timing also coincided with a low snow pack at Mount Rainier and these three factors (low snow pack, high freezing level, and excessive rainfall) presented a "perfect storm" that enhanced sediment production during the event.

Table 11: Seasonality of annual peak floods on the Nisqually River from Water Year 1943-2012 (N = 70). Data from USGS (2013a).

Month	Total Annual Peak Floods	Percentage
WINTER	45	64.29%
December	16	22.86%
January	21	30.00%
February	8	11.43%
SPRING	7	10.00%
March	4	5.71%
April	1	1.43%
May	2	2.86%
SUMMER	2	2.86%
June	2	2.86%
July	0	0.00%
August	0	0.00%
AUTUMN	16	22.86%
September	1	1.43%
October	4	5.71%
November	11	15.71%

AR events are particularly important to Mount Rainier when the timing of the event coincides with low or non-existent snowpacks on the mountain. AR events that occur before significant accumulations of snow allow sediment to be mobilized as debris flows. AR events like the one that occurred in 2006 mobilized significant sediment sources and overwhelmed the erosive forces of floodwaters in park rivers (Beason, 2007). Other AR events that have occurred since 2006 have generally occurred when snow packs were thick enough to not be melted by falling rain and high freezing levels. The events do contribute to runoff of water from snowmelt, but sediment stores are locked underneath the snow. In general, AR events that occur with high snow packs may result in net incision in park rivers (stream flow > sediment production); whereas, AR events with low snow packs may lead to aggradation of park rivers (sediment production > stream flow). With that said, however, many other factors govern the rate of mass wasting, including rainfall intensity and antecedent soil saturation. Therefore, relating only snow packs, AR events, and incision/aggradation may be problematic.

It should be noted that until 2008, there were no permanent gaging stations within the park on the White or Nisqually Rivers. The stream gage information mentioned in this report is based on the Nisqually River at National (USGS Gaging Station #12082500. USGS gaging stations on the White River are several kilometers from the park and influenced by the Mud Mountain Dam (USGS, 2013a). A long- term stream gage has been installed at Longmire in MORA, but its period of record is only available since 2008 and has suffered numerous outages due to flood damage and excessive sedimentation.

Table 12: Annual peak floods with recurrence intervals greater than 2 years (n=39 out of 70) as measured on the Nisqually River at National, just outside of Ashford, WA, approximately 13.7 km (8.5 mi) outside of the Park. Period of record is from water year 1943 to current. The data is sorted by flood magnitude. Recurrence interval is calculated based on the Log Pearson III method. Data from USGS (2013a).

Water Year	Date	Peak Discharge m^3/s	Peak Discharge ft^3/s	LP III Recurrence Interval	Rank
2007	11/06/2006	617	21,800	100	1
1996	02/08/1996	600	21,200	86.6	2
1978	12/02/1977	484	17,100	31.0	3
1974	01/15/1974	425	15,000	18.0	4
1990	01/09/1990	411	14,500	15.8	5
2009	11/12/2008	394	13,900	13.5	6
1976	12/04/1975	374	13,200	11.2	7
1981	12/26/1980	328	11,600	7.33	8
1965	01/29/1965	311	11,000	6.25	9
1991	11/24/1990	311	11,000	6.25	9
1960	11/23/1959	309	10,900	6.09	11
2003	01/31/2003	306	10,800	5.93	12
1963	11/20/1962	294	10,400	5.33	13
1987	11/24/1986	278	9,830	4.59	14
1997	03/19/1997	278	9,820	4.58	15
1988	12/09/1987	261	9,200	3.90	16
2011	01/16/2011	255	9,020	3.72	17
2000	11/25/1999	248	8,750	3.47	18
2002	01/08/2002	244	8,630	3.37	19
2008	12/03/2007	240	8,470	3.23	20
1998	10/30/1997	236	8,330	3.12	21
1982	02/20/1982	234	8,280	3.08	22
1986	02/23/1986	232	8,180	3.00	23
2005	01/18/2005	230	8,140	2.97	24
1947	12/11/1946	229	8,100	2.94	25
1968	12/25/1967	229	8,070	2.92	26
1984	01/25/1984	227	8,020	2.88	27
1983	12/03/1982	227	8,000	2.87	28
1973	12/21/1972	218	7,700	2.66	29
1975	01/18/1975	217	7,660	2.64	30
1943	11/23/1942	212	7,500	2.53	31
1956	12/12/1955	212	7,470	2.52	32
1972	01/20/1972	211	7,460	2.51	33
1995	01/31/1955	208	7,340	2.44	34
1950	11/27/1949	207	7,310	2.42	35
1980	12/17/1979	200	7,050	2.27	36
2006	01/10/2006	199	7,030	2.26	37
1954	12/09/1953	188	6,640	2.07	38
1969	01/04/1969	187	6,620	2.06	39

Previous Research

Aggradation in park rivers has been either directly or indirectly measured by many researchers, and the data from these researchers have been combined in this and other studies to quantify rates of aggradation at Mount Rainier. While aggradation and sediment loads in braided rivers have been studied in depth by other researchers (Hoffman and Gabet, 2007; Miller and Benda, 2007; Reneau et al., 2007; Haritashya et al., 2006; Meunier et al., 2006; Maren, 2004; Shi, 2004; Hodgkins et al, 2003; Hayes et al., 2002; Sutherland et al., 2002; Bhutiyani, 2000; Hasnain and Thayyen, 1999; Lombard et al., 1981), the direct study of aggradation in rivers at Mount Rainier is critical to establish rates of geomorphic change in park 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. With the exception of topographic maps, this was also among the first surveys of the braided rivers in the Park. Henshaw and Parker conducted longitudinal profiles of the thalweg of both rivers from sink to source. These longitudinal profiles from 1910 provide the oldest set of historical data for the park.

Robert K. 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 upper White River. These cross sections are now located under meters of ice from an advance of the Emmons Glacier due to the collapse of Little Tahoma Peak in 1962. Debris from this rock fall accumulated on the glacier, shielding it from the sun and decreasing its melt rate, which resulted in an advance of the glacier. Therefore, these cross sections are not able to be resurveyed. They do, however, give insight to the rates of aggradation in in the upper White River.

Leonard M. Nelson from the United States Geological Survey published a report (1987) mentioned previously 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, 1987). Nelson also discusses peak flood flows and the expected flood elevation during 25, 50, 100 and 500 year flood flows. Original data from Nelson's study have not been found, despite an exhaustive search, and are not included in this study.

As part of Mount Rainier National Park'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), who is now currently stationed at the North Cascades National Park in northwestern Washington State. Riedel's study was primarily used to diagnose geologic hazards and risks 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.

Cross sections surveyed at the Longmire Compound in Riedel's study have been reoccupied and resurveyed in order to determine river changes during the last 15 years and serve as a baseline for cross sections at Longmire.

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 erosion hazard areas along State Route 410, including sections of the highway that fall within the borders of Mount Rainier National Park. Their analysis found 16 areas that were either existing or potential problem locations, both in and out of the park. The research included several cross sections of the river itself, which serve as a baseline for the cross sections on White River included in this study. The Herrera Group was the first to document a floodplain topographically below its river in this reach. In one location, the elevation of the river channel is 3.6 m (11.8 ft) higher than State Route 410, which runs adjacent to the river.

Cross sections were either originally occupied (e.g., Sunshine Point and Lower Van Trump Hairpin) or resurveyed (e.g., Longmire) by a survey team consisting of Holly Brunkal and Christina Forbes during the summer of 2005. The timing and locations of the cross sections occupied by the 2005 team was fortuitous, as they were able record massive geomorphic change in some rivers within two years of their surveys. For example, they measured cross sections on a section of the Nisqually River at Lower Van Trump Hairpin 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. Additionally, the Sunshine Point Cross sections experienced massive bank erosion following the 2006 floods. While Brunkal and Forbes did not publish findings from their work, their original data has been provided for this study.

A comprehensive look at aggradation in Mount Rainier rivers was completed via historical topographic maps, longitudinal profiles and cross sections as part of a M.S. thesis by Beason (2007). This study used data from all the previous authors in this section and established aggradation rates based on these data from 1910 to 2006. The study also took advantage of the timing of the 2006 flood and partially reoccupied cross sections to examine the rate of change due to flooding and debris flows from the event. Beason found an elevated rate of aggradation in the last decade compared to historical rates. The study also found no evidence of incision during the 2006 flood, a finding indicating that sediment production during the 2006 flood exceeded the erosive forces of the river (Beason, 2007). The current study builds on those initial findings and refines rates of aggradation in the park; however, the methodologies are the same. Due to flood damage outside of the park in recent large storms, Pierce County and the United States Geological Survey has undertaken several studies seeking to understand how aggradation affects rivers and infrastructure outside of Mount Rainier National Park (Czuba et al., 2010; Czuba et al., 2011; Czuba et al., 2012a; Czuba et al., 2012b).

Methods

Cross sections, benchmarks, longitudinal profiles, and other topographic data were surveyed with a variety of instruments during this study. Originally, a Pentax PCS-2 electronic total station with a hand held TDS Recon data collector with Survey Pro 4.2 software was used in surveys from 2005-2009. Later, in 2010-2012, we used a Topcon GPT-3105W wireless electronic total station with a Topcon FC-250 data collector with TopSurv Basic surveying software. Both total stations are 5-arcsecond instruments with a positional accuracy of ± 5 arcseconds, or 5/3,600th of a degree. Positions for this study were recorded in the North American Datum (NAD) 1983 Washington State Plane South Zone coordinate system (FIPS = 4602), with positions measured in U.S. Survey Feet. Vertical elevation control was based on USGS benchmarks, previously surveyed benchmarks, or established benchmarks corrected by GPS survey.

Surveying

Several tools were used during the field research portion of this study, including two different types of total stations and Global Positioning System (GPS) receivers.

A Pentax PCS-2 electronic total station and TopCon GPT-3105W electronic total station were used for construction of cross sections for this research. 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 (easting), Y (northing), and Z (elevation) 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"). 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, and later, Topcon FC-250 with Topcon TopSurv Basic software were tied in with the total station and received information about each shot that was taken. The software stores the data and offers several useful functions for fieldwork.

Locations and timing of individual cross section surveys are included in Table 13.

Table 13: Summary table of locations, cross section lines and when they were surveyed for this study. Lines are shown in upstream to downstream order. "X" indicates the location and line were surveyed in the year of interest, whereas "-" indicates the line was not surveyed that year.

Line	1997	2005	2006	2007	2008	2009	2010	2011	2012
Sunshine Point									
3	-	X	X	-	X	X	-	X	X
1	-	X	X	-	X	X	-	X	X
8	-	-	-	-	X	X	-	X	X
2	-	X	X	-	X	X	-	X	X
4	-	-	-	-	X	X	-	X	X
5	-	-	-	-	X	X	-	X	X
6	-	-	-	-	X	X	-	X	X
7	-	-	-	-	X	X	-	X	X

(continued)

Table 13 *(Continued)*: Summary table of locations, cross section lines and when they were surveyed for this study. Lines are shown in upstream to downstream order. “X” indicates the location and line were surveyed in the year of interest, whereas “-” indicates the line was not surveyed that year.

Line	1997	2005	2006	2007	2008	2009	2010	2011	2012
Longmire									
1	X	X	X	-	X	X	-	-	X
2	X	X	X	-	X	X	X	X	X
3	X	X	X	-	X	X	X	X	X
4	X	X	X	-	X	X	X	X	X
5	X	X	X	-	X	X	X	X	X
6	X	X	X	-	X	X	X	X	X
7	X	X	X	-	X	X	X	X	X
8	X	X	X	-	X	X	X	X	X
9	X	X	X	-	X	X	X	X	X
10	X	X	X	-	X	X	X	X	X
Carter Falls									
1	-	-	-	-	-	-	-	X	X
2	-	-	-	-	-	-	-	X	X
3	-	-	-	-	-	-	-	X	X
4	-	-	-	-	-	-	-	X	X
5	-	-	-	-	-	-	-	X	X
6	-	-	-	-	-	-	-	X	X
Lower Van Trump									
3	-	X	X	-	X	X	X	X	X
2	-	X	X	-	X	X	X	X	X
1	-	X	X	-	X	X	X	X	X
White River									
8	-	X	-	X	X	-	-	X	-
7	-	X	-	X	X	-	-	X	-
6	-	X	-	X	X	-	-	X	-
5	-	X	-	X	X	-	-	X	-
4	-	X	X	X	X	-	-	X	-
3	-	X	-	X	X	-	-	X	-
2	-	X	-	X	X	-	-	X	-
1	-	X	X	X	X	-	-	X	-

Post-Processing of Field Data

The total station surveys of cross sections provide northings, eastings and elevations of numerous positions along cross sections, within a tolerance of 0.076 m (0.25 ft) of the line, as delineated by the left bank and right bank positions of alignment points. From these surveys, individual cross sections can be constructed for each year of the survey and for each line. A custom written web-based PHP script was developed, utilizing a MySQL database to store all survey data. In the past, analysis was completed with individual Microsoft Excel spreadsheets; however, the PHP/MySQL method is much less time consuming and produces more consistent results.

The web application allows a user to select a location, cross section, and time period to analyze. The script takes the cross section and time period and selects the corresponding data from the database. Individual points are plotted along the line formed from the alignment points and displayed on a dynamically generated graph. Statistics are also dynamically generated from the input variables and dynamically generated output. In doing this, individual points are plotted on the line, even if they were surveyed off of the line within the line tolerance noted earlier. An assumption is made that the elevation of the point surveyed within the line tolerance and the elevation of a similar point on the hypothetical line are the same.

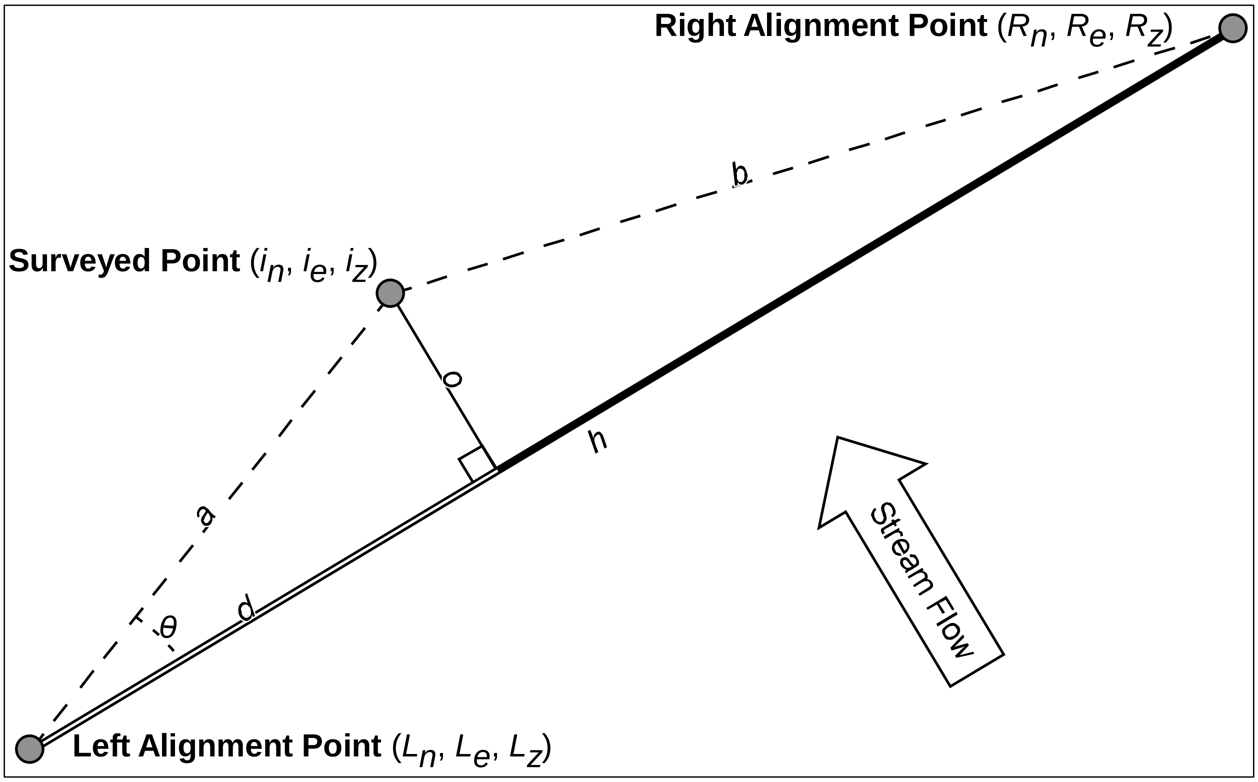


Figure 13: Labeled plot of variables used to place surveyed points along a cross section line.

Figure 13 shows the following distances and angles that are calculated by the web application in the next few steps. The first calculation that must occur to place surveyed points along a cross section is to determine the total length of the cross section, from left alignment point to right alignment point. The total length of cross section, *h*, is calculated with the Pythagorean Theorem rewritten to:

$$h = \sqrt{|L_n - R_n|^2 + |L_e - R_e|^2} \qquad \text{(Equation 1)}$$

Where:

h = Total length of cross section from left bank alignment point to right bank alignment point,
L_n = Northing position of the left bank alignment point,
L_e = Easting position of the left bank alignment point,
R_n = Northing position of the right bank alignment point, and
R_e = Easting position of the right bank alignment point.

Next, the distance between the left bank alignment point and a surveyed point, a, is calculated with the rewritten Pythagorean theorem used to calculate h:

$$a = \sqrt{|L_n - i_n|^2 + |L_e - i_e|^2} \qquad \text{(Equation 2)}$$

Where:

a = Distance between left bank alignment point and a surveyed point along a cross section,
L_n = Northing position of the left bank alignment point,
L_e = Easting position of the left bank alignment point,
i_n = Northing position of the surveyed point, and
i_e = Easting position of the surveyed point.

The distance between the surveyed point and right bank alignment point, or b, is calculated in the same form as a and h:

$$b = \sqrt{|i_n - R_n|^2 + |i_e - R_e|^2} \qquad \text{(Equation 3)}$$

Where:

b = Distance between a surveyed point along a cross section and the right bank alignment point,
i_n = Northing position of the surveyed point,
i_e = Easting position of the surveyed point,
R_n = Northing position of the right bank alignment point, and
R_e = Easting position of the right bank alignment point.

At this point, a, b, and h represent the three sides of a non-right triangle shown on Figure D. In order to calculate the distance along the line and offset from the line, it is necessary to know one interior angle, θ, within the non-right triangle. The rewritten law of cosines accomplishes this as such:

$$\theta = \cos^{-1}\left(\frac{b^2 - a^2 - h^2}{-2\,a\,h}\right) \qquad \text{(Equation 4)}$$

Where:

θ = Interior angle of a non-right triangle, and
a, b, h = Length of sides of the non-right triangle, calculated previously.

This interior angle, θ, represents the angle between the surveyed point, left alignment point and right alignment point. We now know the angle, θ, and the hypotenuse, a, of a right triangle whose adjacent side is the distance along the cross section line and opposite side is the offset of the surveyed point from the cross section line. Finally, the remaining two variables for the surveyed point are calculated:

$$d = a\,\cos\theta \qquad \text{(Equation 5)}$$

$$o = a\,\sin\theta \qquad \text{(Equation 6)}$$

Where:

d = Distance of a surveyed point along the cross section,
o = Offset distance of the surveyed point from the cross section,
a = Distance from left bank alignment point to surveyed point on the cross section, and
θ = Interior angle of the triangle, calculated previously.

The variables a, b, θ, d, and o are calculated for every surveyed point along the cross section, whereas h can be calculated once and shared with all calculations. The offset distance, o, is also calculated in real time by the total station's data collector when surveying every point to ensure the point falls within the 0.076 m (0.25 ft) tolerance of the line.

The surveyed point also includes an elevation, z, above sea level. An array is created by the program with d and z and values within the array, and sorted by d ascending, which can also be known as "station" along the line; or the x-axis of a graph. The elevation, or z, of a point along the line is therefore on the y-axis of the same graph. When plotted on this graph, the cross section is now shown with station on the x-axis, increasing to the right, and elevation on the y-axis, increasing upwards.

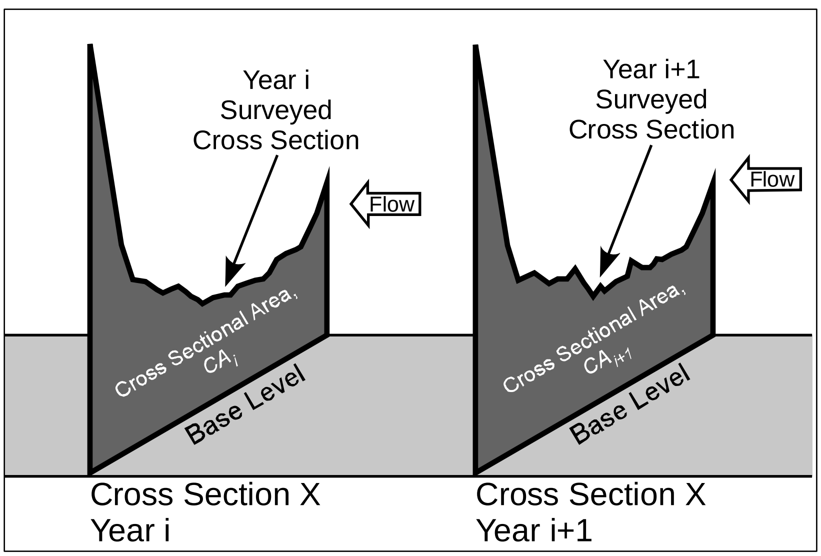


Figure 14: The method employed in this study to determine area change in individual cross sections from one year to another. Cross Sectional Area, *CA*, is the area represented by a closed irregular polygon whose top is the surveyed cross section and bottom is at some base level, assumed in this study to be sea level. Once each year's cross sectional area is tabulated, they can be compared with one another. In the above hypothetical example, the changes in cross section *X* from year *i* to *i+1* is simply $CA_{i+1} - CA_i$.

In order to compare various years of cross sections with one another, the area beneath the cross section is calculated. This volume can then be analyzed from year to year. The cross section line can be equated to a closed irregular polygon, whose base is at 0, or sea level, whose tops are the surveyed elevations, and various points along the top of the polygon are the stations from the surveyed points (Figure 14). The cross sectional area, *CA*, is calculated as:

$$CA = \frac{|(x_1y_2 + x_2y_3 + x_3y_4 + \cdots + x_ny_1) - (x_2y_1 + x_3y_2 + x_4y_3 + \cdots + x_1y_n)|}{2} \quad \text{(Equation 7)}$$

Where:

CA = Cross sectional area,
x_i = Station position, *d*, along line for *n* positions on the cross section, and
y_i = Elevation position, *z*, along line for *n* positions on the cross section.

It is especially important to note that cross sectional area, *CA*, and area represented by a cross section, A_i, are not the same variable. Cross sectional area represents the area "underneath" the cross section line in map view (Figure 14), while area represented by cross section is the area of the active braided channel that is represented by the cross section in map view (Figure 15).

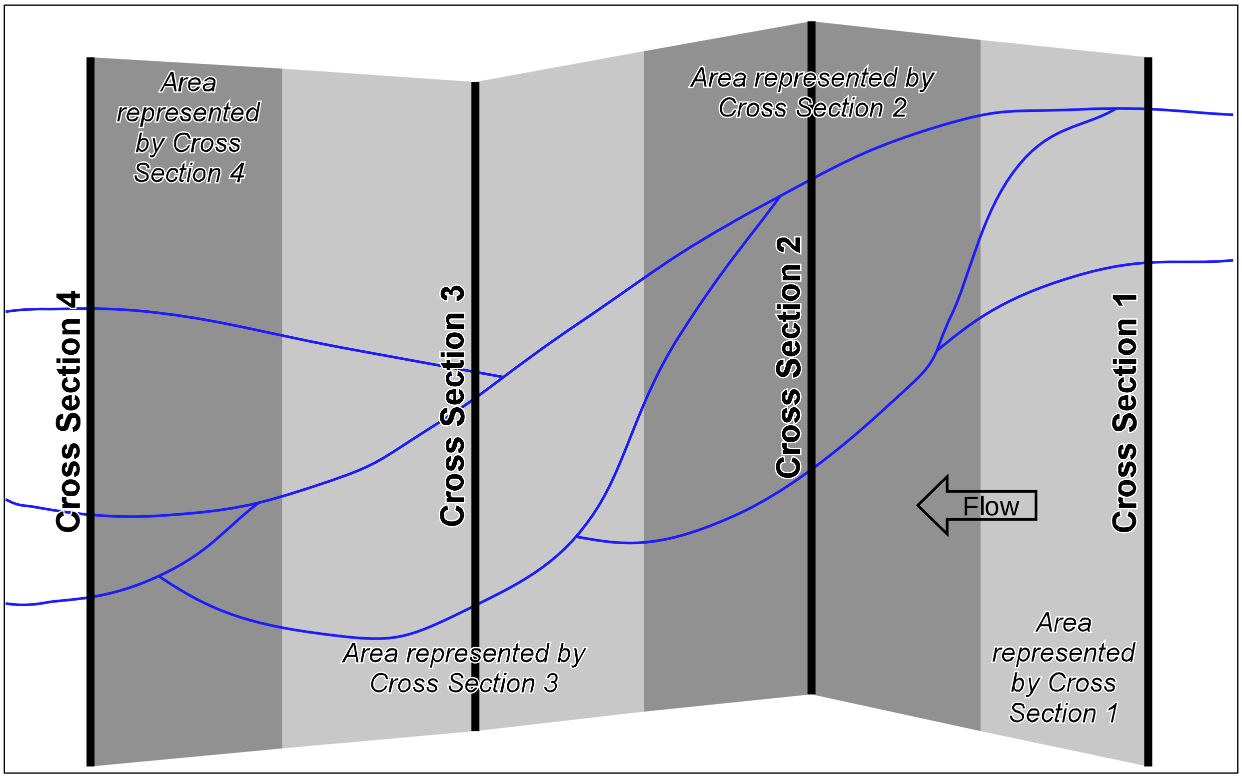


Figure 15: Ac**tive channel a**reas represented by hypothetical cross sections. Generally, the area represented by a cross section is half of the active channel upstream to the next cross section added to half of the active channel downstream to the next cross section. In the case of cross sections at the upstream and downstream extents, the area represented by the cross section is simply half of the active channel to the next upstream or downstream cross section.

We can now calculate cross sectional area changes between years by simply subtracting the area of the cross section in one year from another (Figure 14). The average change, in this sense, a rate of aggradation in the period between the two cross section years along the line, R_i, can be calculated as:

$$R_i = \frac{(CA_i - CA_n)}{h} \qquad \text{(Equation 8)}$$

Where:

R_i = Aggradation rate for a cross section between years *i* and *n*,
CA_i = Cross sectional area in year $_i$,
CA_n = Cross sectional area in previous year *n*, and
h = Length of cross section (calculated above).

Length of cross section, *h*, may be variable from year to year, depending on disturbance events like bank erosion, debris flows, landslides, or other geologic events. Therefore, *h* in Equation 8 only accounts for similar extents within the cross section between surveyed years. For example, a cross section may be 100 m in length in one year, and could expand to 125 m due to bank erosion. Only the common extents of the 100 m cross section length would be compared when analyzing these two years. Subsequent surveys, however, can take advantage of the longer (or shorter) cross sections. This method ensures that artificial error is not introduced into the equation.

Appendix A shows tables of aggradation results from surveyed locations during specific time periods. "Net cross sectional area change" column represents $CA_i – CA_n$ in the above equation. The "Line Length" column is the variable *h*. The "Net change across line" column is simply ($CA_i – CA_n$) ÷ *h*. And finally, the "aggradation rate" column, or R_i, is the net change across the line divided by the time period between surveys. Negative cross sectional area change, net change across line and rates represent incision while positive values represent aggradation in the cross section in the analyzed time period. Aggradation rates for each cross section line over various intervals are graphically shown in Appendix B.

Volumetric changes in areas represented by cross sections are calculated using the variable A_i for specific time periods. Area represented by a cross section is generally half of active channel area from the cross sectional line to the next upstream cross section added to half of the active channel area from the cross sectional line to the next downstream cross section (Figure 15). In instances where the cross section is either the most upstream or most downstream cross section, the area is calculated as half of the active channel area to the next cross section, whether upstream or down (Figure 15). Tables K-O show area represented by individual cross sections, A_i. Appendix C shows tabular data related to volumetric changes in individual cross sections for specific time periods. The "Rate" column is the same variable as R_i, calculated above, for various time periods. The "Area" column is the area represented by cross section, A_i, from Tables K-O. The "Volume" column is simply calculated as: $R_i \times A_i$. The net volume column is a running sum of the volume from the first year of survey through last.

Since aggradation is extremely variable, reach-scale aggradation rates were calculated. Mean cross section aggradation rates were reach-averaged by:

$$Ag_w = \sum_{i=1}^{n}(A_i\ R_i)\ \div \sum_{i=1}^{n} A_i \qquad \text{(Equation 9)}$$

Where:

Ag_W is the weighted aggradation rate;
A_i is area represented by a single cross section in map view; and
R_i is the corresponding aggradation rate,
for n cross sections.

Area represented by a single cross section, A_i, may change from year to year, in a similar way that cross section length, h, can change due to bank erosion and other forces. Therefore, only common areas between survey periods are factored into this equation in order to avoid introducing error into the calculation.

Equation 9 is the formula used to calculate reach-averaged aggradation in Tables Q-U for various time periods.

Accuracy and Error in Total Station Surveys

The magnitude of probable error in total station surveys is related to the error of individual components in development of cross sections. The total error is calculated as the square root of the sum of squares of individual error components, a method used by Czuba and others (2010) to define error in surveys (Specifically, Dally et al., 1984 *in* Czuba et al., 2010). Error may be introduced as systematic or random errors. Systematic errors arise from a flaw in the measurement scheme which is repeated each time a measurement is made. Sources of systematic error can include errors in calibration of the measurement instrument, incorrect measurement technique, or bias of the surveyor. Random errors arise from fluctuations that are most easily observed by making multiple trails of a given experiment. Random errors can include uncontrollable fluctuations in measurements, limitations imposed by the precision of the measurement device and lack of precise definition of the quantity being measured.

Error in this study can be introduced in three ways: (1) Total Station equipment error, (2) survey variability in a single year and (3) distance off line and topography differences in that distance. Total station error is stated by the manufacturer as 0.0015 m (0.005 ft) (Topcon, 2008). Survey variability is based on the location where individual points are taken along the cross section line, which may change depending on the surveyor, even in the same year. Survey variability is estimated at 0.076 m (0.25 ft) (C. Magirl, Personal Communication, 2013). Finally, during individual surveys, we considered a position to be on-line if it was within 0.076 m (0.25 ft) of the line.

The overall estimated error in total station surveys based on these factors is ±0.11 m (±0.35 ft). This is a similar error rate used by Beason (J. Dunn, personal communication, 2006 *in* Beason, 2007). Adding in a factor of safety, we consider positions that fall outside of 0.15 m (0.50 ft) to be indicative of conclusive aggradation or incision. For example, a location that has greater than 0.15 m of aggradation between survey periods has a higher confidence of aggradation that a location that is less than 0.15 m based on the total error introduced into the measurement of the cross section. However, rates that are between 0 and 0.15 m may be considered to be aggradational or incisional when compared to other cross sections in a reach that that show clear aggradation or incision trends. Specific aggradation rates stated in this paper will be rounded to 2 significant figures.

The following terms will be used when describing aggradation rates in the text:

- "No discernible change outside of the error margin" for rates of -0.15 to 0.15 m (-0.50 to 0.50 ft);
- "Weak Aggradation" for rates of 0.15 to 0.25 m (0.50 to 0.82 ft);
- "Moderate Aggradation" for rates of 0.25 to 0.50 m (0.82 to 1.64 ft);
- "Pronounced aggradation" for rates greater than 0.50 m (1.64 ft);
- "Weak Incision" for rates of -0.15 to -0.25 m (-0.50 to -0.82 ft);
- "Moderate Incision" for rates of -0.25 to -0.50 m (-0.82 to -1.64 ft); and
- "Pronounced incision" for rates greater than -0.50 m (-1.64 ft).

Results

Sunshine Point

The Nisqually River flows through a relatively unconfined stretch of river upstream, through and downstream of the survey reach. Mature riparian forest exists on floodplain terraces on both right and left banks. There is an exposure of bedrock on the right bank in the vicinity of cross sections 4-6, but the bedrock has little, if any, control on the form of the river. Hardened and maintained levees, especially the Pierce County levee starting around Cross Section 6 and leaving the park on the right bank of the Nisqually, bound the right bank of the river's active channel. The main stem generally flows along this levee once it is encountered. Channel widths through the Sunshine Point reach varied from 118-131 m (387-430 ft) in 2005-2006 and, due to bank erosion during the 2006 Flood, widened to 168-225 m (551-738 ft). The elevation range in the upstream end is 622 m (2,041 ft) and 613 m (2,011 ft) in the downstream end of the reach, resulting in an overall gradient of 1.95% based on 2012 survey data. Other watershed facts are found in Table 2.

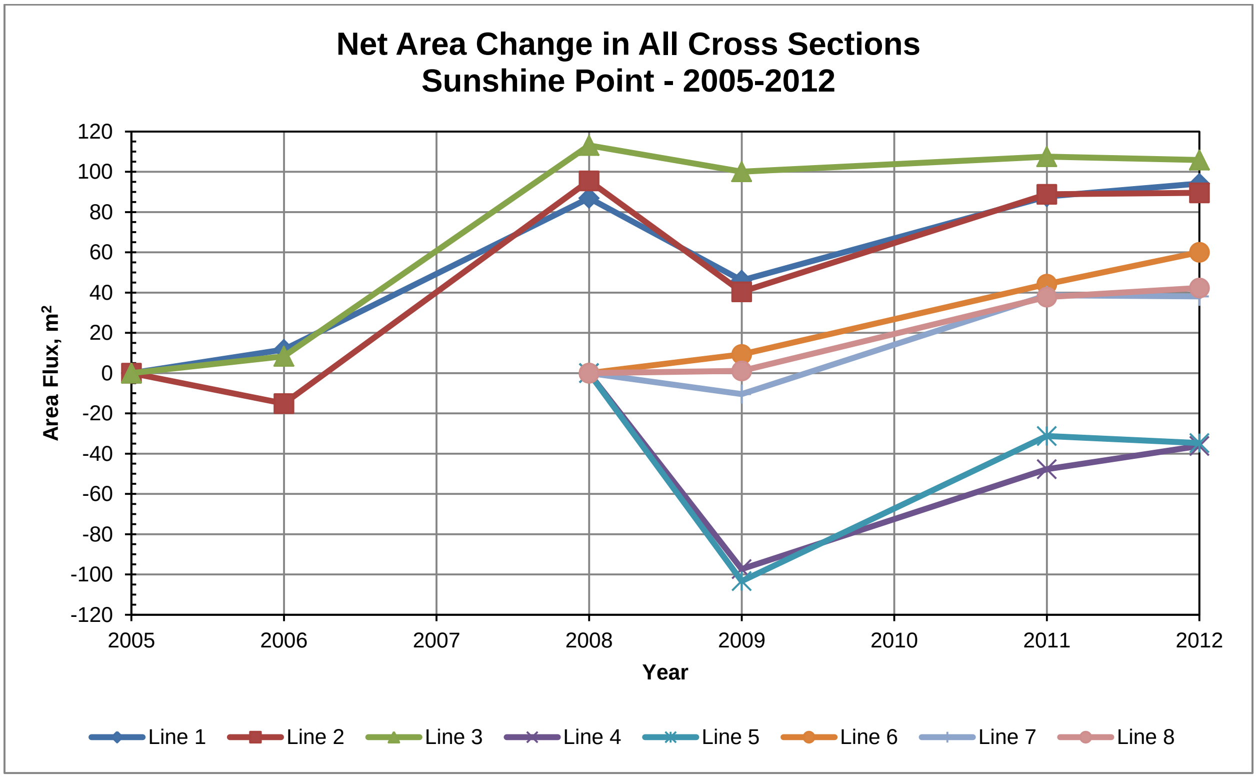


Figure 16: Net area change in all Sunshine Point cross sections. Net area change represents the increase or decrease in sediment in a single cross section and does not factor in area represented by cross section. This can also be thought of as the change in the average elevation in each cross section from year-to-year. The first year is plotted as zero and additional years either add or subtract areas from the cross sections.

Overall, the Sunshine Point reach is aggradational, having some of the highest aggradation observed in any of our reaches in this study (Figures 16, 17, and 18; Appendix A.1-A.8; Appendix B.1-B.8; Appendix C.1-C.8). Cross sectional aggradation rates vary depending on survey period and line. Rates, cross sectional areas, and volume changes in the active channel are analyzed between individual survey years, which allows us to analyze aggradation or incision independently from one year to another. This is beneficial, especially in the Sunshine Point reach, as cross sections widened after the 2006 flood event. Two cross sections, lines 6 and 8 show constant aggradation, whereas lines 4 and 5 show incision. Cross sections 1, 2, 3, 6, 7 and 8 all show net aggradation despite periods of incision. Between 2008 and 2009, six of the eight cross sections showed net incision, and the remaining two showed only very modest aggradation. Individual cross section results are discussed in depth in the next sections. Cross section lengths and areas represented by cross sections are shown in Table 14.

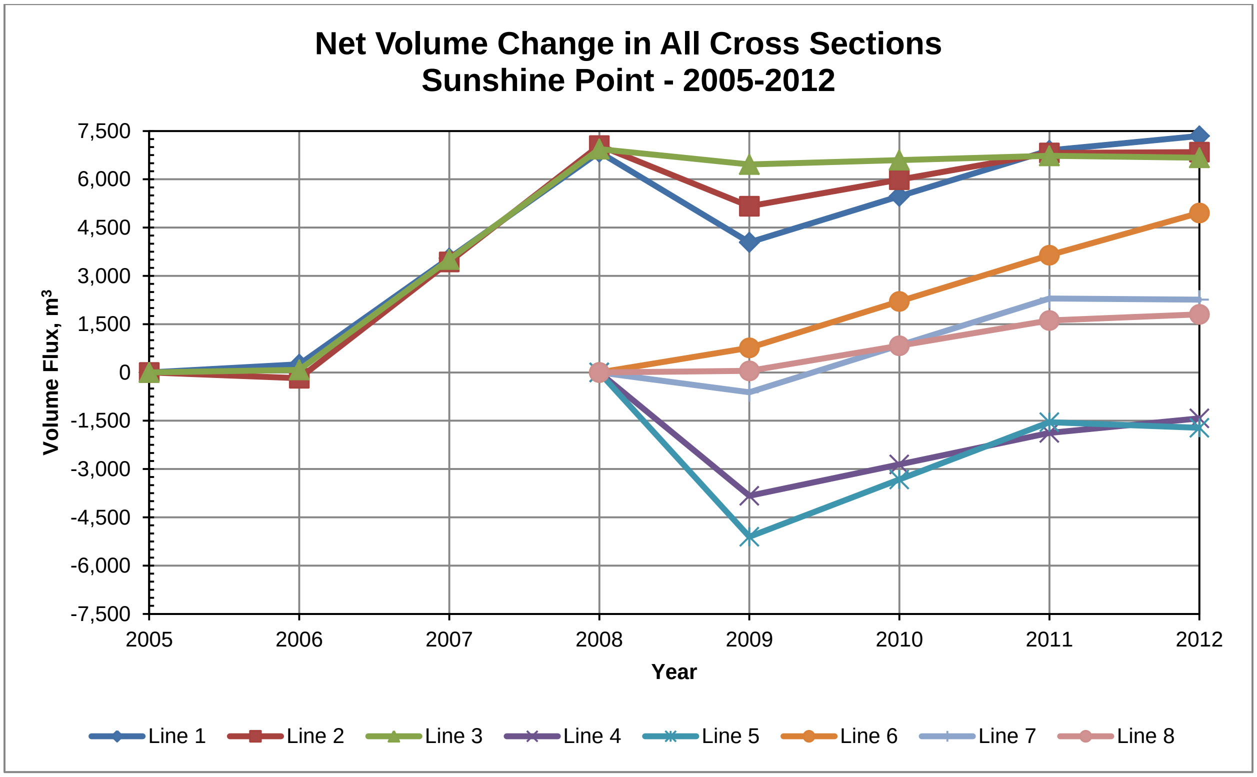


Figure 17: Net volume change in all Sunshine Point cross sections. Net volume change accounts for aggradation rate and area occupied by all cross sections and shows a running total of sediment volume in the reach over time. The first year a cross section is surveyed is plotted as zero, then additional years either add or subtract sediment volume.

In order to classify aggradation in the reach among extremely variable cross sections, aggradation rate and area represented by cross sections in a given time period is weighted using Equation 9 in Section 4.2, resulting in a weighted aggradation rate for the reach. Table 15 shows the reach-averaged aggradation rates for various time periods at Sunshine Point. The rate is almost completely aggradational with one period of incision (2008-2009). Rates vary from -0.17 $m \times yr^{-1}$ (-0.55 $ft \times yr^{-1}$) to 0.36 $m \times yr^{-1}$ (1.19 $ft \times yr^{-1}$) (Figure 19).

Table 14: Cross section lengths and area represented by individual cross sections at Sunshine Point. Areas are used for reach averaging cross section aggradation rates. Lines are shown in upstream to downstream order. Areas in the time period of 2005-2006 were computed by Beason (2007). Later areas were calculated in ArcGIS by the author.

Cross Section	Length, m	Area Represented by Cross Section, m^2
Time Period of 2005 to 2006[1]		
3	119.55	1,138.34
1	131.81	2,850.33
2	118.02	1,377.02
Time Period of 2006 to 2012[1]		
3	213.73	7,825.11
1	168.54	11,551.03
8	205.15	8,756.80
2	225.51	7,704.06
4	192.52	7,582.16
5	198.17	9,793.86
6	225.27	18,581.95
7	204.26	12,126.77

[1] Significant bank erosion occurred during the November 2006 flood, and therefore, cross section lengths and areas represented by cross sections changed. Additionally, Lines 4-8 were added in 2008.

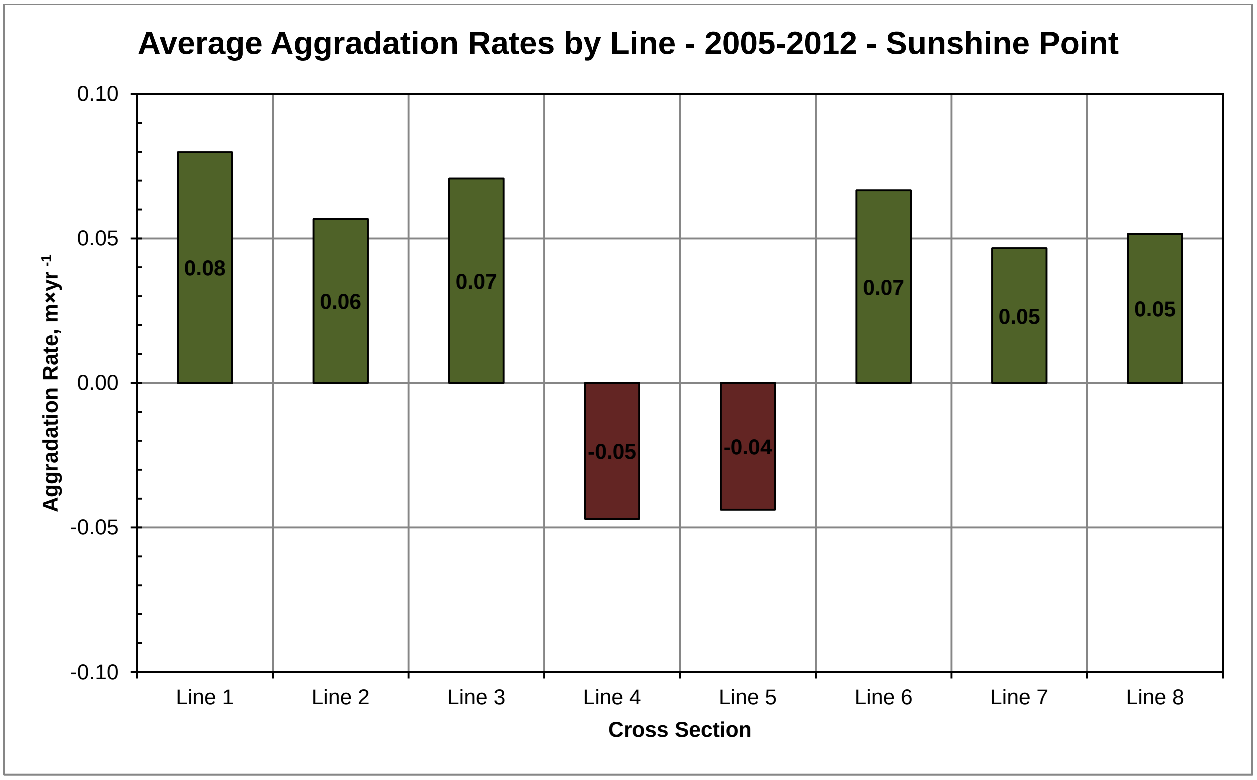


Figure 18: Average aggradation rate for Sunshine Point cross sections. Note that lines 1-3 have a longer period of record (2005-2012) than lines 4-8 (2008-2012). See Appendix A.1 – A.8 for individual cross section line aggradation rates.

Table 15: Reach averaged aggradation rates for various time periods at Sunshine Point

Line	Area, *m^2*	Rate, *$m \times yr^{-1}$*	Area×Rate *$m^3 \times yr^{-1}$*	Reach averaged Aggradation *$m \times yr^{-1}$*
2005-2006 (1 Year) (Beason, 2007)				
1	2,850.33	0.09	252.86	-
2	1,138.34	-0.13	-145.73	-
3	1,377.02	0.07	96.12	-
Sum	**5,365.69**	**-**	**203.25**	**0.04**
2006-2008 (2 Years)				
1	2,850.33	0.29	813.52	-
2	1,138.34	0.47	533.52	-
3	1,377.02	0.44	603.28	-
Sum	**5,365.69**	**-**	**1,950.32**	**0.36**
2008-2009 (1 Year)				
1	11,551.03	-0.24	-2,803.75	-
2	7,704.06	-0.24	-1,882.17	-
3	7,825.11	-0.06	-476.60	-
4	7,582.16	-0.51	-3,833.28	-
5	9,793.86	-0.52	-5,105.83	-
6	18,581.95	0.04	765.33	-
7	12,126.77	-0.05	-615.84	-
8	8,756.80	0.01	49.17	-
Sum	**83,921.72**	**-**	**-13,902.96**	**-0.17**
2009-2011(2 Years)				
1	11,551.03	0.12	1,427.87	-
2	7,704.06	0.11	827.40	-
3	7,825.11	0.02	136.07	-
4	7,582.16	0.13	976.97	-
5	9,793.86	0.18	1,781.23	-
6	18,581.95	0.08	1,440.09	-
7	12,126.77	0.12	1,455.83	-
8	8,756.80	0.09	782.30	-
Sum	**83,921.72**	**-**	**8,827.75**	**0.11**
2011-2012 (1 Year)				
1	11,551.03	0.04	445.26	-
2	7,704.06	0.00	23.70	-
3	7,825.11	-0.01	-61.33	-
4	7,582.16	0.06	454.57	-
5	9,793.86	-0.02	-174.61	-
6	18,581.95	0.07	1,308.13	-
7	12,126.77	-0.00	-36.18	-
8	8,756.80	0.02	190.68	-
Sum	**83,921.72**	**-**	**2,150.21**	**0.03**

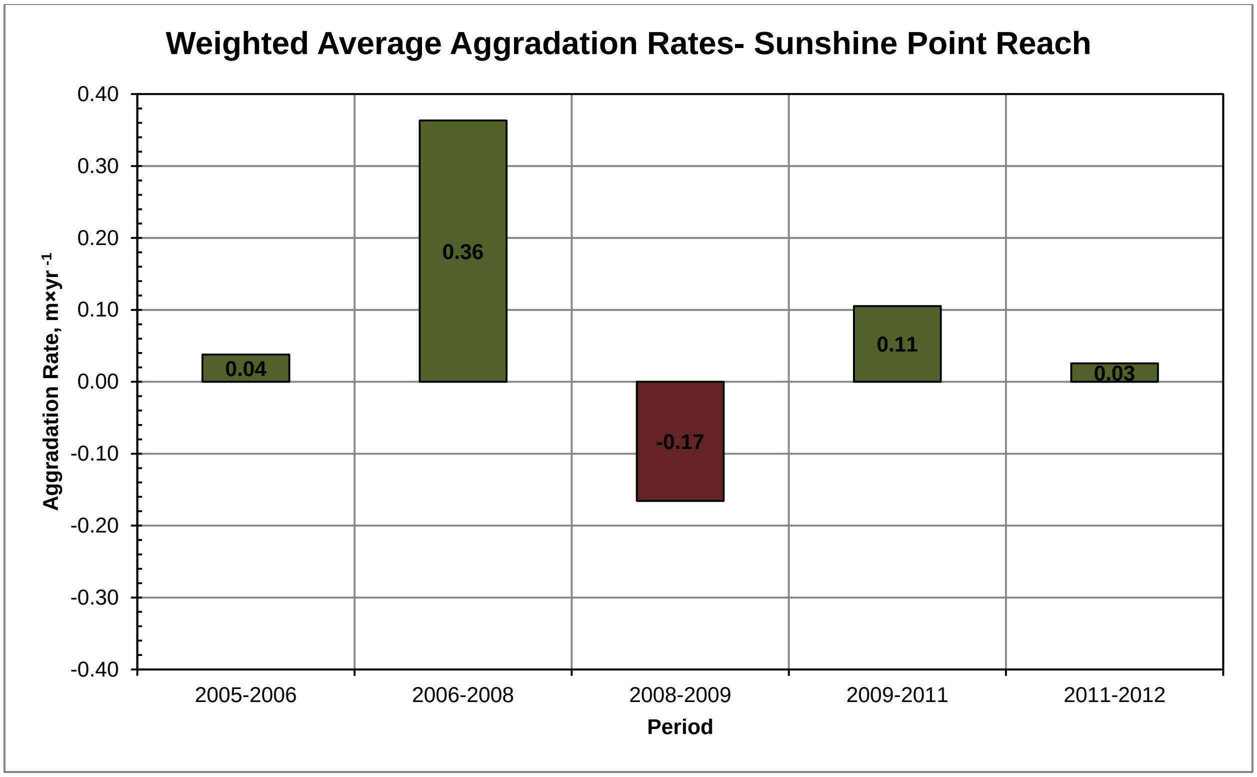


Figure 19: Weighted average aggradation rate for the entire Sunshine Point Reach during the study period, accounting for all available lines and cross sectional areas.

Sunshine Point – Line 1

Sunshine Point cross section line 1 is the second most upstream line in the study reach, about 90 m (295 ft) downstream of cross section 3 and about 57 m (187 ft) upstream of cross section 8 (Figure 6). The line originally was surveyed in 2005 and has since been surveyed in 2006, 2008, 2009, 2011, and 2012 (Table 13). The cross section is 168.5 m (552.9 ft) in length and represents 11,550 m^2 (124,300 ft^2) of the main channel area (Table 14). Because of bank erosion, this cross section has increased in length and area represented since 2006 (Table 14). The cross section alignment points for line 1 are included in Table 1. The left bank position is in the forest on a terrace above the Nisqually River. The right bank position was formerly on the Sunshine Point Campground levee but now ends in the campground, just downstream of the most upstream bank erosion in the campground.

Like most cross sections in the Sunshine Point area, cross section 1 is highly variable, with individual survey periods seeing aggradation rates varying from -0.24 $m \times yr^{-1}$ (-0.80 $ft \times yr^{-1}$) to 0.29 $m \times yr^{-1}$ (0.94 $ft \times yr^{-1}$) (Appendix A.1; Appendix B.1). Net cross section area change varies from -40.91 m^2 (-440.3 ft^2) to 75.24 m^2 (809.9 ft^2). The overall aggradation rate from 2005 to 2012 is 0.08 $m \times yr^{-1}$ (0.26 $ft \times yr^{-1}$) (Figure 18) and the net cross section area change from 2005 to 2012 is 94.19 m^2 (1,014 ft^2) (Figure 16). Accounting for the area represented by the cross section (Table 14), the overall aggradation in the active channel represented by cross section 1 from 2005 to 2012 is 7,344 m^3 (259,300 ft^3) (Appendix C.1). This is the highest aggradation rate (Figure 18) and volume change (Figure 17) at Sunshine Point from 2005 to 2012.

Sunshine Point – Line 2

Sunshine Point cross section line 2 is the fourth most upstream line in the study reach, about 30 m (98 ft) downstream of cross section 8 and about 39 m (128 ft) upstream of cross section 4 (Figure 6). The line was originally surveyed in 2005 and has since been surveyed in 2006, 2008, 2009, 2011, and 2012 (Table 13). The cross section is 225.5 m (739.9 ft) in length and represents 7,704 m^2 (82,930 ft^2) of the main channel area (Table 14). Because of bank erosion, this cross section has increased in length and area represented since 2006 (Table 14). The cross section alignment points for line 2 are included in Table 1. The left bank position is in the forest on a terrace above the Nisqually River. The right bank position was formerly on the Sunshine Point Campground levee but now ends on the uphill lane of the Nisqually-Paradise road prism just downstream of a small creek.

Cross section 2 is highly variable, with individual survey periods seeing aggradation rates varying from -0.24 $m \times yr^{-1}$ (-0.80 $ft \times yr^{-1}$) to 0.47 $m \times yr^{-1}$ (1.54 $ft \times yr^{-1}$) (Appendix A.2; Appendix B.2). Net cross section area change varies from -55.09 m^2 (-593.0 ft^2) to 110.6 m^2 (1,191 ft^2). The overall aggradation rate from 2005 to 2012 is 0.06 $m \times yr^{-1}$ (0.19 $ft \times yr^{-1}$) (Figure 18) and the net cross section area change from 2005 to 2012 is 89.56 m^2 (964.0 ft^2) (Figure 16), the third highest of the Sunshine Point cross sections. Accounting for the area represented by the cross section (Table 14), the overall aggradation in the active channel represented by cross section 2 from 2005 to 2012 is 6,842 m^3 (241,600 ft^3) (Appendix C.2). This is the second highest active channel volume change at Sunshine Point (Figure 17) and the fourth highest aggradation rate in the reach (Figure 18).

Sunshine Point – Line 3

Sunshine Point cross section line 3 is the most upstream cross section in the survey area, approximately 80 m (262 ft) upstream of cross section 1 (Figure 6). The line was originally surveyed in 2005 and has since been surveyed in 2006, 2008, 2009, 2011, and 2012 (Table 13). The cross section is 205.1 m (673.1 ft) in length and represents 7,825 m^2 (84,230 ft^2) of the main channel area (Table 14). Because of bank erosion, this cross section has increased in length and area represented since 2006 (Table 14). The cross section alignment points for line 3 are included in Table 1. The left bank position is in the forest on a terrace above the Nisqually River. The right bank position ends in an Alder forest just east of Sunshine Point Campground on a terrace above the active channel.

Cross section 3 is mostly aggradational with a few periods of incision between 2005 and 2012. Individual survey periods have aggradation rates that vary from -0.06 $m \times yr^{-1}$ (-0.20 $ft \times yr^{-1}$) to 0.44 $m \times yr^{-1}$ (1.44 $ft \times yr^{-1}$) (Appendix A.3; Appendix B.3). Net cross section area change varies from -13.02 m^2 (-140.1 ft^2) to 104.75 m^2 (1,127.54 ft^2). The overall aggradation rate from 2005 to 2012 is 0.07 $m \times yr^{-1}$ (0.23 $ft \times yr^{-1}$) (Figure 18) and the net cross section area change from 2005 to 2012 is 105.8 m^2 (1,139 ft^2) (Figure 16), the highest cross sectional area change at Sunshine Point. Accounting for the area represented by the cross section (Table 14), the overall aggradation in the active channel represented by cross section 1 from 2005 to 2012 is 6,670 m^3 (235,600 ft^3) (Appendix C.3). Cross section 3 has the third highest active channel volume change, just 673.5 and 171.5 m^3 (23,790 and 6,055 ft^3) behind cross sections 1 and 2, respectively (Figure 17) and second highest aggradation rate in the reach (Figure 18).

Sunshine Point – Line 4

Sunshine Point cross section line 4 is the fourth most downstream line in the study reach, about 37 m (121 ft) downstream of cross section 2 and about 40 m (131 ft) upstream of cross section 5 (Figure 6). The line was initially surveyed in 2008 and has since been surveyed in 2009, 2011, and 2012 (Table 13). The cross section is 192.5 m (631.6 ft) in length and represents 7,582 m^2 (81,610 ft^2) of the main channel area (Table 14). The cross section alignment points for line 4 are included in Table 1. The left bank position is in the forest on a terrace above the Nisqually River. The right bank position is on the uphill fog line of the Nisqually-Paradise Road upstream the apex of the bend as the road rounds a bedrock knob.

Cross section 4 is aggradational in two of the three study periods with one period of incision between 2008 and 2009. It is one of two of the eight cross sections at Sunshine Point that displays net incision over the study period. Individual aggradation rates vary from -0.51 $m \times yr^{-1}$ (-1.66 $ft \times yr^{-1}$) to 0.13 $m \times yr^{-1}$ (0.42 $ft \times yr^{-1}$) (Appendix A.4; Appendix B.4). Net cross section area change varies from -97.33 m^2 (-1,408 ft^2) to 46.61 m^2 (501.7 ft^2). The overall aggradation rate from 2005 to 2012 is -0.05 $m \times yr^{-1}$ (0.15 $ft \times yr^{-1}$) (Figure 18) and the net cross section area change from 2008 to 2012 is -36.18 m^2 (-389.4 ft^2) (Figure 16), indicating incision over the survey period. Accounting for the area represented by the cross section (Table 14), the overall incision in the active channel represented by cross section 4 from 2008 to 2012 is -1,424 m^3 (-50,320 ft^3) (Appendix C.4). Cross section 4 has the lowest net area change (Figure 16), the second lowest net volume change for the active channel (Figure 17) and has the lowest aggradation rate (highest incision rate) (Figure 18).

Sunshine Point – Line 5

Sunshine Point cross section 5 is the third most downstream line in the study reach, about 40 m (131 ft) downstream of cross section 4 and about 55 m (180 ft) upstream of cross section 6 (Figure 6). The line was initially surveyed in 2008 and has since been surveyed in 2009, 2011, and 2012 (Table 13). The cross section is 198.2 m (650.2 ft) in length and represents 9,794 m^2 (105,400 ft^2) of the main channel area (Table 14). The cross section alignment points for line 5 are included in Table 1. The left bank position is in the forest on a terrace above the Nisqually River. The right bank position is on the uphill fog line of the Nisqually-Paradise Road at the apex of the bend as the road rounds a bedrock knob.

Cross section 5 is incisional in two of the three study periods with one period of aggradation between 2009 and 2011. It is one of the two cross sections at Sunshine Point that is incisional over the study period. Individual aggradation rates vary from -0.52 $m \times yr^{-1}$ (-1.71 $ft \times yr^{-1}$) to 0.18 $m \times yr^{-1}$ (0.60 $ft \times yr^{-1}$) (Appendix A.5; Appendix B.5). Net cross section area change varies from -103.3 m^2 (-1,112 ft^2) to 72.08 m^2 (775.9 ft^2). The overall aggradation rate from 2005 to 2012 is -0.04 $m \times yr^{-1}$ (-0.14 $ft \times yr^{-1}$) (Figure 18) and the net cross section area change from 2008 to 2012 is -34.76 m^2 (-374.8 ft^2) (Figure 16). Accounting for the area represented by the cross section (Table 14), the overall incision in the active channel represented by cross section 4 from 2008 to 2012 is -1,718 m^3 (-60,670 ft^3) (Appendix C.5). Cross section 5 has the second lowest net area change (Figure 16), the lowest net volume change for the active channel (Figure 17) and has the second lowest aggradation rate (second highest incision rate) (Figure 18).

Sunshine Point – Line 6

Sunshine Point cross section 6 is the second most downstream line in the study reach, about 55 m (180 ft) downstream of cross section 5 and about 129 m (423 ft) upstream of cross section 7 (Figure 6). The line was initially surveyed in 2008 and has since been surveyed in 2009, 2011, and 2012 (Table 13). The cross section is 225.3 m (739.1 ft) in length and represents 18,580 m^2 (200,000 ft^2) of the main channel area (Table 14), the most of any cross section at Sunshine Point. The cross section alignment points for line 1 are included in Table 1. The left bank position is in the forest on a terrace above the Nisqually River. The right bank is on the most upstream point of the Pierce County levee near the Nisqually-Paradise Road.

Cross section 6 is completely aggradational in all survey periods, with individual periods seeing aggradation rates varying from 0.04 $m \times yr^{-1}$ (0.14 $ft \times yr^{-1}$) to 0.08 $m \times yr^{-1}$ (0.25 $ft \times yr^{-1}$) (Appendix A.6; Appendix B.6). Net cross section area change varies from 9.28 m^2 (99.87 ft^2) to 34.92 m^2 (375.8 ft^2). The overall aggradation rate from 2008 to 2012 is 0.07 $m \times yr^{-1}$ (0.22 $ft \times yr^{-1}$) (Figure 18) and the net cross section area change from 2008 to 2012 is 60.05 m^2 (646.4 ft^2) (Figure 16). Accounting for the area represented by the cross section (Table 14), the overall aggradation in the active channel represented by cross section 1 from 2008to 2012 is 4,953 m^3 (174,900 ft^3) (Appendix C.6). Cross section 6 has the fourth highest net area change in its cross section (Figure 16), the fourth highest net volume change in its active channel (Figure 17) and the third highest average aggradation rate for the entire study period (Figure 18).

Sunshine Point – Line 7

Sunshine Point cross section line 7 is the most downstream cross section in the study reach, about 129 m (423 ft) downstream of cross section 6 (Figure 6). The line was initially surveyed in 2008 and has since been surveyed in 2009, 2011, and 2012 (Table 13). The cross section is 204.3 m (670.1 ft) in length and represents 12,130 m^2 (130,500 ft^2) of the main channel area (Table 14). The cross section alignment points for line 1 are included in Table 1. The left bank position is in the forest on a terrace above the Nisqually River. The right bank position is on the Pierce County levee 160 m (525 ft) from its most upstream point near the Nisqually-Paradise Road.

Cross section 7 is incisional in two of the three study periods with one period of aggradation between 2009 and 2011. Individual survey period aggradation rates vary from -0.05 $m \times yr^{-1}$ (-0.17 $ft \times yr^{-1}$) to 0.12 $m \times yr^{-1}$ (0.39 $ft \times yr^{-1}$) (Appendix A.7; Appendix B.7). Net cross section area change varies from -10.37 m^2 (-111.7 ft^2) to 49.04 m^2 (527.9 ft^2). The overall aggradation rate from 2008 to 2012 is 0.05 $m \times yr^{-1}$ (0.15 $ft \times yr^{-1}$) (Figure 18) and the net cross section area change from 2008 to 2012 is 38.06 m^2 (409.67 ft^2) (Figure 16). Accounting for the area represented by the cross section (Table 14), the overall aggradation in the active channel represented by cross section 8 from 2008 to 2012 is 2,260 m^3 (79,800 ft^3) (Appendix C.7). Cross section 7 is ranked sixth in terms of net area change in cross section view (the lowest of the aggradational cross sections) (Figure 16), ranked fifth for net volume change in area represented by cross sections (second lowest of the aggradational cross sections) (Figure 17), and has the sixth lowest average aggradation rate (also the lowest of the aggradational cross sections) (Figure 18).

Sunshine Point – Line 8

Sunshine Point cross section 8 is the third most upstream line in the study reach, about 57 m (187 ft) downstream of cross section 1 and about 30 m (98 ft) upstream of cross section 2 (Figure 6). The line was initially surveyed in 2008 and has since been surveyed in 2009, 2011, and 2012 (Table 13). The cross section is 205.1 m (673.1 ft) in length and represents 8,757 m^2 (94,260 ft^2) of the main channel area (Table 14). The cross section alignment points for line 1 are included in Table 1. The left bank position is in the forest on a terrace above the Nisqually River. The right bank position is on the cut bank formed from the erosion of Sunshine Point campground, about half way along the cut bank from the Nisqually-Paradise Road prism to the rip-rap levee protecting the former campground.

Like cross section 6, cross section 8 is completely aggradational, with individual survey periods seeing aggradation rates varying from 0.01 $m \times yr^{-1}$ (0.02 $ft \times yr^{-1}$) to 0.09 $m \times yr^{-1}$ (0.29 $ft \times yr^{-1}$) (Appendix A.8; Appendix B.8). Net cross section area change varies from 1.15 m^2 (12.44 ft^2) to 36.65 m^2 (394.5 ft^2). The overall aggradation rate from 2008 to 2012 is 0.05 $m \times yr^{-1}$ (0.17 $ft \times yr^{-1}$) (Figure 18) and the net cross section area change from 2008 to 2012 is 42.27 m^2 (455.0 ft^2) (Figure 16). Accounting for the area represented by the cross section (Table 14), the overall aggradation in the active channel represented by cross section 8 from 2008 to 2012 is 1,804 m^3 (63,720 ft^3) (Appendix C.8). Cross section 8 has the fifth highest net area change in cross sectional area (second lowest for aggradational lines) (Figure 16), sixth lowest net volume change in active channel area (lowest for aggradational lines) (Figure 17), and ranks fifth in terms of overall aggradation rate from 2008-2012 (second lowest for aggradational lines) (Figure 18).

Longmire

The Nisqually River flows through a relatively confined stretch upstream of Longmire with Tertiary-age intrusive bedrock exposures on both the right and left bank (Pringle, 2008). After flowing under the Longmire suspension bridge, the river loses its bedrock confinement and widens out (Cover photo). However, the river is leveed on the right bank from the suspension bridge down to Line 10. Additionally, the park constructed a buried “wall” in this levee consisting of concrete and in-situ boulders in September, 2007, to prevent bank erosion and flood damage in future events. Channel widths in Longmire vary from 72.82 m (238.92 ft) in the upstream confined zone to 169.74 m (556.9 ft) at the downstream end (Table 16). The elevation range in the upstream end is 851 m (2,792 ft) and 835 m (2,738 ft) in the downstream of the reach, resulting in an average gradient of 3.356% based on 2012 survey data. Other watershed facts for the Nisqually River at Longmire are included in Table 4.

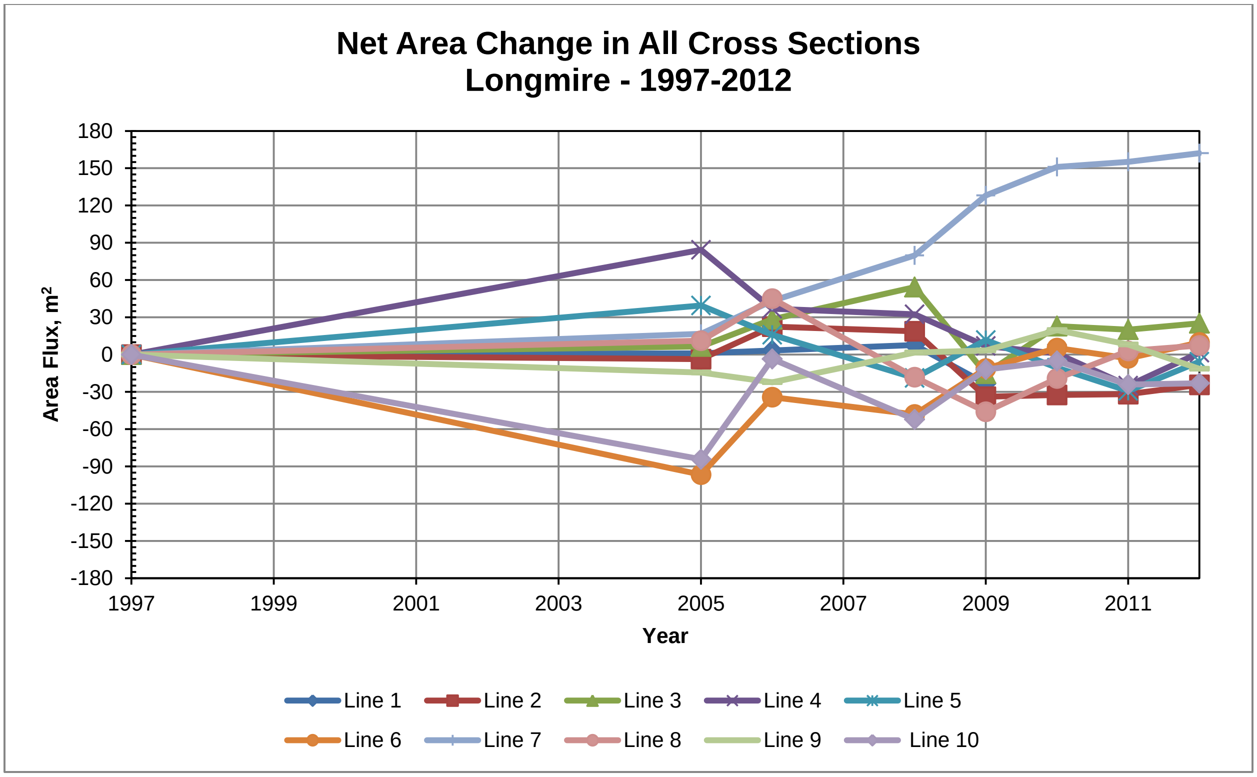


Figure 20: Net area change in all Longmire cross sections. Net area change represents the increase or decrease in sediment in a single cross section and does not factor in area represented by cross section. This can also be thought of as the change in the average elevation in each cross section from year-to-year. The first year is plotted as zero and additional years either add or subtract areas from the cross sections.

The Longmire reach of the Nisqually River displays episodic aggradation and incision, but overall remains nearly at equilibrium to slightly incisional (Figures 20, 21, and 22; Appendix A.9-A.18; Appendix B.9-B.18; Appendix C.9-C.18). Aggradation was noted in a majority of the cross sections between 2005 and 2006, but since then cross sections have been undergoing incision. The only exception to this is Cross Section 7, which has been experiencing an ambiguously high rate of aggradation in stark contrast to most other cross sections in this reach. Rates, cross sectional areas, and volume changes in the active channel are analyzed between individual survey years. Individual cross section results are discussed in depth on the following pages.

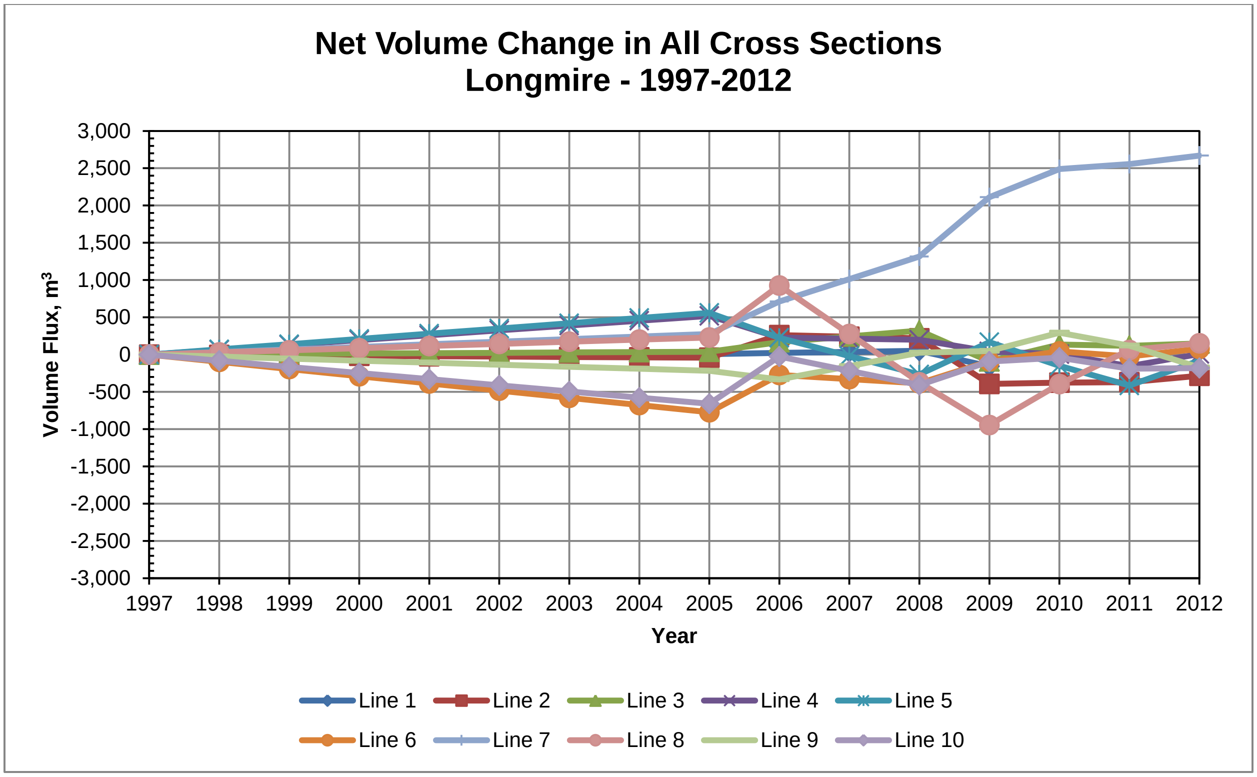


Figure 21: Net volume change in all Sunshine Point cross sections. Net volume change accounts for aggradation rate and area occupied by all cross sections and shows a running total of sediment volume in the reach over time. The first year a cross section is surveyed is plotted as zero, then additional years either add or subtract sediment volume.

Weighted aggradation rates for the Longmire reach were calculated using Equation 9 as in previous study areas. Table 17 shows the reach averaged aggradation rates for various time periods at Longmire. With the exception of the period of 2005 to 2006, reach averaged aggradation and incision amounts are very small, ranging between -0.04 $m \times yr^{-1}$ (-0.14 $ft \times yr^{-1}$) to 0.10 $m \times yr^{-1}$ (0.33 $ft \times yr^{-1}$) (Figure 23). The time period between 2005 and 2006 has a rate of 0.14 $m \times yr^{-1}$ (0.47 $ft \times yr^{-1}$). The aggradation noted here, while small, still overwhelms the incision for the reach.

Table 16: Cross section lengths and area represented by individual cross sections at Longmire. Areas are used for reach averaging cross section aggradation rates. Lines are shown in upstream to downstream order. Areas were computed by Beason (2007).

Cross Section	Length, m	Area Represented by Cross Section, m^2
1	89.12	598.30
2	72.82	846.29
3	76.17	450.22
4	92.72	571.68
5	102.53	1,451.99
6	116.83	933.60
7	138.94	2,288.71
8	151.29	3,108.27
9	169.74	2,543.25
10	155.13	1,214.57

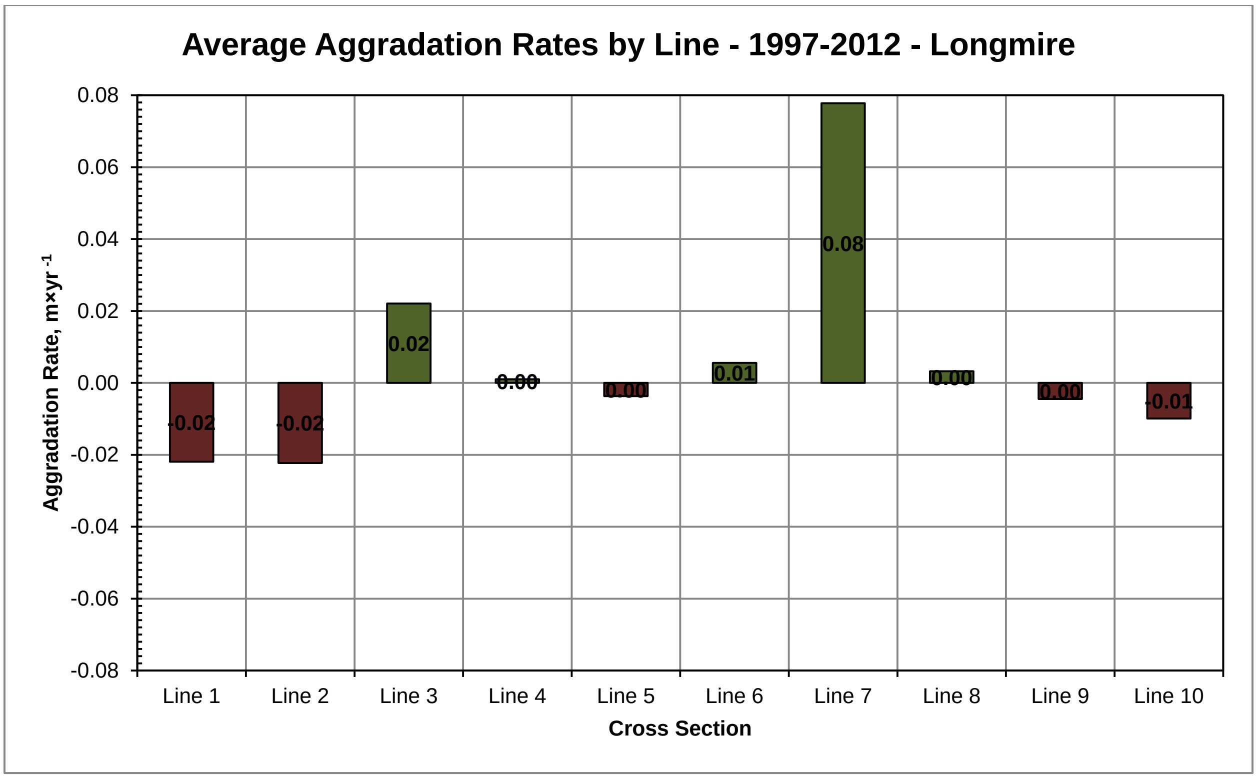


Figure 22: Average aggradation rate for Longmire cross sections. Note that line 1 was not surveyed in 2010-2012. See Appendix A.9 – A.18 for individual cross section lines.

Table 17: Reach averaged aggradation rates for various time periods at Longmire.

Line	Area, m^2	Rate, $m \times yr^{-1}$	Area×Rate $m^3 \times yr^{-1}$	Reach averaged Aggradation $m \times yr^{-1}$
1997-2005 (8 Years) (Beason, 2007)				
1	598.30	0.00	0.89	-
2	846.29	-0.01	-5.26	-
3	450.22	0.01	4.87	-
4	571.68	0.11	64.98	-
5	1,451.99	0.05	70.02	-
6	933.60	-0.10	-96.51	-
7	2,288.71	0.02	34.56	-
8	3,108.27	0.01	28.75	-
9	2,543.25	-0.01	-27.07	-
10	1,273.10	-0.07	-86.36	-
Sum	**14,065.41**	**-**	**-11.13**	**-0.00**
2005-2006 (1 Year) (Beason, 2007)				
1	598.30	0.03	15.44	-
2	846.29	0.36	304.37	-
3	450.22	0.29	129.11	-
4	571.68	-0.51	-292.32	-
5	1,451.99	-0.23	-334.55	-
6	933.60	0.53	498.48	-
7	2,288.71	0.19	434.98	-
8	3,108.27	0.22	696.32	-
9	2,543.25	-0.05	-117.50	-
10	1,273.10	0.52	662.51	-
Sum	**14,065.41**	**-**	**1,996.84**	**0.14**
2006-2008 (2 Years)				
1	598.30	0.02	14.42	-
2	846.29	-0.03	-21.66	-
3	450.22	0.17	76.52	-
4	571.68	-0.02	-13.87	-
5	1,451.99	-0.17	-245.85	-
6	933.60	-0.06	-55.96	-
7	2,288.71	0.13	302.10	-
8	3,108.27	-0.21	-649.38	-
9	2,543.25	0.07	179.31	-
10	1,273.10	-0.16	-199.66	-
Sum	**14,065.41**	-	**-614.04**	**-0.04**

(Continued)

Table 17 (Continued): Reach averaged aggradation rates for various time periods at Longmire

Line	Area, *m^2*	Rate, *$m \times yr^{-1}$*	Area×Rate *$m^3 \times yr^{-1}$*	Reach averaged Aggradation *$m \times yr^{-1}$*
2009-2010 (1 Year)				
2	846.29	0.02	17.34	-
3	450.22	0.50	225.41	-
4	571.68	-0.07	-37.98	-
5	1,451.99	-0.22	-315.78	-
6	933.60	0.14	131.59	-
7	2,288.71	0.16	377.63	-
8	3,108.27	0.18	549.35	-
9	2,543.25	0.10	245.59	-
10	1,273.10	0.04	55.68	-
Sum	**13,467.11**	**-**	**1,248.83**	**0.09**
2010-2011 (1 Year)				
2	846.29	0.01	7.36	-
3	450.22	-0.04	-16.42	-
4	571.68	-0.28	-158.90	-
5	1,451.99	-0.18	-264.89	-
6	933.60	-0.07	-66.03	-
7	2,288.71	0.03	66.79	-
8	3,108.27	0.15	456.39	-
9	2,543.25	-0.07	-174.03	-
10	1,273.10	-0.12	-155.01	-
Sum	**13,467.11**	**-**	**-304.73**	**-0.02**
2011-2012 (1 Year)				
2	846.29	0.10	86.56	-
3	450.22	0.07	30.47	-
4	571.68	0.28	162.84	-
5	1,451.99	0.23	333.91	-
6	933.60	0.11	101.55	-
7	2,288.71	0.05	115.51	-
8	3,108.27	0.03	90.18	-
9	2,543.25	-0.11	-292.24	-
10	1,273.10	0.01	8.37	-
Sum	**13,467.101**	-	**637.17**	**0.05**

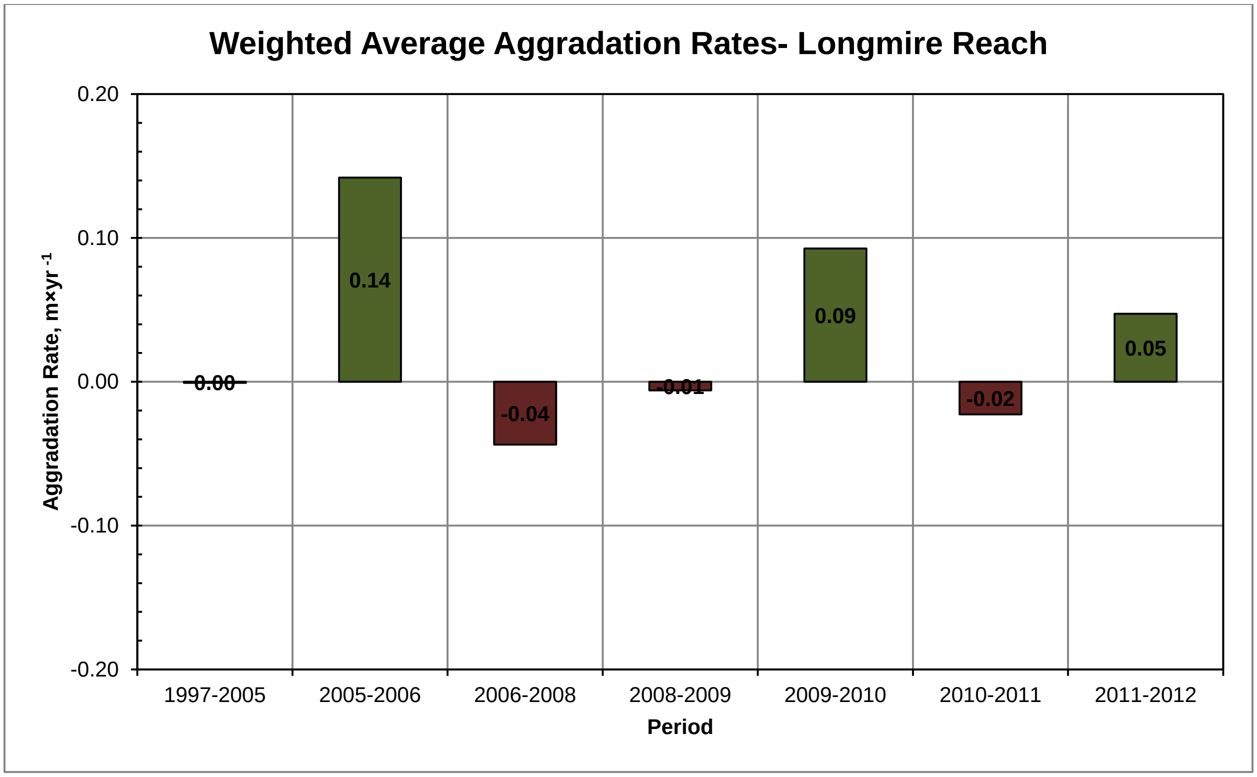


Figure 23: Weighted average aggradation rate for the entire Longmire Reach during the study period, accounting for all available lines and cross sectional areas.

Longmire – Line 1

Longmire cross section 1 is the most upstream line in the study reach, about 32 m (106 ft) upstream of cross section 2 (Figure 8). The line was originally surveyed in 1997 and was resurveyed in 2005, 2006, 2008, 2009, and 2012 (Table 13). The cross section is 89.12 m (292.4 ft) in length and represents 598.3 m^2 (6,440 ft^2) of the main channel area (Table 16). The cross section alignment points for line 1 are included in Table 3. The left bank position is on top of a bedrock exposure well above the active channel. The right bank position is also on a bedrock exposure above the active channel. Due to the bedrock confinement on both banks and the position of the channel, resurveying cross section 1 can be problematic and thus was not surveyed in 2010 and 2011.

Between 1997 and 2008, Longmire cross section 1 was very slightly aggradational, seeing rates of aggradation that vary between 0.00 $m \times yr^{-1}$ (0.00 $ft \times yr^{-1}$) to 0.03 $m \times yr^{-1}$ (0.09 $ft \times yr^{-1}$) (Appendix A.9; Appendix B.9). Between 2008 and 2009, the cross section incised with a rate of -0.35 $m \times yr^{-1}$ (-1.15 $ft \times yr^{-1}$) (Appendix A.9; Appendix B.9). Net cross sectional area change varies from -31.10 m^2 (-334.8 ft^2) to 4.30 m^2 (46.24 ft^2) (Appendix A.9). The overall aggradation rate from 1997 to 2009 is -0.02 $m \times yr^{-1}$ (-0.07 $ft \times yr^{-1}$) (Figure 22) and the net cross section area change from 1997 to 2009 is -23.44 m^2 (-252.3 ft^2) (Figure 20). Accounting for area represented by cross section (Table 16), the overall aggradation in the active channel represented by cross section 1 from 1997 to 2009 is -157.4

m^3 (-5,558 ft^3) (Appendix C.9). This is the second lowest aggradation rate in the reach (Figure 22) and the fourth lowest volume change (Figure 21) in the Longmire reach.

Longmire – Line 2

Longmire cross section 2 is the second most upstream line in the study reach, about 15 m (51 ft) upstream of cross section 3 and about 32 m (106 ft) downstream of cross section 1 (Figure 8). The line was originally surveyed in 1997 and has been resurveyed in 2005, 2006, 2008, 2009, 2011, and 2012 (Table 13). The cross section is 72.82 m (238.9 ft) in length and represents 846.3 m^2 (9,109 ft^2) of the main channel area (Table 16). The cross section alignment points for line 2 are included in Table 3. The left bank position is on top of a bedrock exposure well above the active channel. The right bank position is on a concrete footing for a suspension bridge at a USGS brass benchmark labeled “29FMK”.

Longmire cross section 2 has aggradation rates that are generally very close to no change from year to year, but also has had episodes of significant aggradation (2005-2006 and 2011-2012) and incision (2008-2009). Rates of aggradation vary between -0.72 $m \times yr^{-1}$ (-2.38 $ft \times yr^{-1}$) and 0.36 $m \times yr^{-1}$ (1.18 $ft \times yr^{-1}$) (Appendix A.10; Appendix B.10). Net cross sectional area change varies from -52.75 m^2 (-567.8 ft^2) to 26.19 m^2 (281.92 ft^2) (Appendix A.10). The overall aggradation rate from 1997 to 2012 is -0.02 $m \times yr^{-1}$ (-0.07 $ft \times yr^{-1}$) (Figure 22) and the net cross section area change from 1997 to 2012 is -24.34 m^2 (-261.98 ft^2) (Figure 20), indicating overall incision in the line. Accounting for area represented by cross section (Table 16), the overall aggradation in active channel represented by cross section 2 from 1997 to 2012 is -282.8 m^3 (-9,988 ft^3) (Appendix C.10). This is the lowest aggradation rate (or, highest incision rate) in the reach (Figure 22) and the lowest volume change (Figure 21) in the Longmire reach.

Longmire – Line 3

Longmire cross section 3 is the third most upstream line in the study reach, about 10 m (32 ft) upstream of cross section 4 and about 15 m (51 ft) downstream of cross section 2 (Figure 8). The line was originally surveyed in 1997 and has been resurveyed in 2005, 2006, 2008, 2009, 2011, and 2012 (Table 13). The cross section is 76.17 m (249.9 ft) in length and represents 450.2 m^2 (4,846 ft^2) of the main channel area (Table 16). The cross section alignment points for line 3 are included in Table 3. The left bank position is on east edge of the Longmire Back Gate Road. The right bank position is on a reinforced levee constructed by the park to separate the Nisqually River active channel from the remaining Longmire complex.

Longmire cross section 3 shows more periods of aggradation than lines 1 and 2 and has significant periods of aggradation (2005-2006 and 2009-2010) as well as a significant period of incision (2008-2009). Rates of aggradation vary between -0.91 $m \times yr^{-1}$ (-3.00 $ft \times yr^{-1}$) and 0.50 $m \times yr^{-1}$ (1.64 $ft \times yr^{-1}$) (Appendix A.11; Appendix B.11). Net cross sectional area change varies from -69.62 m^2 (-749.4 ft^2) to 38.14 m^2 (410.5 ft^2) (Appendix A.11). The overall aggradation rate from 1997 to 2012 is 0.02 $m \times yr^{-1}$ (0.07 $ft \times yr^{-1}$) (Figure 22) and the net cross section area change from 1997 to 2012 is 25.23 m^2 (271.5 ft^2) (Figure 20). Accounting for area represented by cross section (Table 16), the overall aggradation in active channel represented by cross section 3 from 1997 to 2012 is 149.1 m^3 (5,265 ft^3) (Appendix C.11). This is the second highest aggradation rate in the reach (Figure 22) and the third highest volume change (Figure 21) in the Longmire reach.

Longmire – Line 4

Longmire cross section 4 is the fourth most upstream line in the study reach, about 21 m (69 ft) upstream of cross section 5 and about 10 m (32 ft) downstream of cross section 3 (Figure 8). The line was originally surveyed in 1997 and has been resurveyed in 2005, 2006, 2008, 2009, 2011, and 2012 (Table 13). The cross section is 92.72 m (304.2 ft) in length and represents 571.7 m^2 (6,154 ft^2) of the main channel area (Table 16). The cross section alignment points for line 4 are included in Table 3. The left bank position is on east edge of the Longmire Back Gate Road. The right bank position is on a reinforced levee discussed previously.

Longmire cross section 4 is mostly incisional with two periods of aggradation (1997-2005 and 2011-2012). Rates of aggradation vary between -0.51 m×yr^{-1} (-1.68 ft×yr^{-1}) and 0.29 m×yr^{-1} (0.94 ft×yr^{-1}) (Appendix A.12; Appendix B.12). Net cross sectional area change varies from -47.41 m^2 (-510.4 ft^2) to 84.32 m^2 (907.6 ft^2) (Appendix A.12). The overall aggradation rate from 1997 to 2012 is 0.00 m×yr^{-1} (0.00 ft×yr^{-1}) (Figure 22) and the net cross section area change from 1997 to 2012 is 1.46 m^2 (15.46 ft^2) (Figure 20). Accounting for area represented by cross section (Table 16), the overall aggradation in active channel represented by cross section 4 from 1997 to 2012 is 9.02 m^3 (318.6 ft^3) (Appendix C.12). This is the fifth highest aggradation rate in the reach (Figure 22) and the fifth highest volume change (Figure 21) in the Longmire reach.

Longmire – Line 5

Longmire cross section 5 is the fifth most upstream line in the study reach, about 17 m (55 ft) upstream of cross section 6 and about 21 m (69 ft) downstream of cross section 4 (Figure 8). The line was originally surveyed in 1997 and has been resurveyed in 2005, 2006, 2008, 2009, 2011, and 2012 (Table 13). The cross section is 102.5 m (336.4 ft) in length and represents 1,452 m^2 (15,630 ft^2) of the main channel area (Table 16). The cross section alignment points for line 5 are included in Table 3. The left bank position is on west edge of the Longmire Back Gate Road. The right bank position is on a reinforced levee discussed previously.

Longmire cross section 5 shows episodic periods of aggradation (1997-2005, 2008-2009 and 2011-2012) and incision (2005-2008 and 2009-2011). Rates of aggradation vary between -0.23 m×yr^{-1} (-0.76 ft×yr^{-1}) and 0.30 m×yr^{-1} (0.98 ft×yr^{-1}) (Appendix A.13; Appendix B.13). Net cross sectional area change varies from -34.72 m^2 (-373.7 ft^2) to 39.55 m^2 (425.7 ft^2) (Appendix A.13). The overall aggradation rate from 1997 to 2012 is -0.00 m×yr^{-1} (-0.01 ft×yr^{-1}) (Figure 22) and the net cross section area change from 1997 to 2012 is -5.68 m^2 (-61.17 ft^2) (Figure 20). Accounting for area represented by the cross section (Table 16), the overall aggradation in active channel represented by cross section 5 from 1997 to 2012 is -80.49 m^3 (-2,842 ft^3) (Appendix C.13). This is the fifth lowest aggradation rate in the reach (Figure 22) and the fifth lowest volume change (Figure 21) in the Longmire reach.

Longmire – Line 6

Longmire cross section 6 is the fifth most downstream line in the study reach, about 14 m (45 ft) upstream of cross section 7 and about 17 m (55 ft) downstream of cross section 5 (Figure 8). The line was originally surveyed in 1997 and has been resurveyed in 2005, 2006, 2008, 2009, 2011, and 2012 (Table 13). The cross section is 116.83 m (383.3 ft) in length and represents 933.6 m^2 (10,050 ft^2) of the main channel area (Table 16). The cross section alignment points for line 6 are included in Table 3. The left bank position is on west edge of the Longmire Back Gate Road. The right bank position is on a reinforced levee discussed previously.

Longmire cross section 6 shows mostly periods of aggradation with some periods of incision in 1997-2005, 2006-2008, and 2010-2011. Rates of aggradation vary between -0.10 $m \times yr^{-1}$ (-0.34 $ft \times yr^{-1}$) and 0.53 $m \times yr^{-1}$ (1.75 $ft \times yr^{-1}$) (Appendix A.14; Appendix B.14). Net cross sectional area change varies from -96.61 m^2 (-1,040 ft^2) to 62.38 m^2 (671.4 ft^2) (Appendix A.14). The overall aggradation rate from 1997 to 2012 is 0.01 $m \times yr^{-1}$ (0.02 $ft \times yr^{-1}$) (Figure 22) and the net cross section area change from 1997 to 2012 is 9.74 m^2 (104.8 ft^2) (Figure 20). Accounting for area represented by cross section (Table 16), the overall aggradation in active channel represented by cross section 6 from 1997 to 2012 is 77.83 m^3 (2,748 ft^3) (Appendix C.14). This is the third highest aggradation rate in the reach (Figure 22) and the third highest volume change (Figure 21) in the Longmire reach.

Longmire – Line 7

Longmire cross section 7 is the fourth most downstream line in the study reach, about 41 m (133 ft) upstream of cross section 8 and about 14 m (45 ft) downstream of cross section 6 (Figure 8). The line was originally surveyed in 1997 and has been resurveyed in 2005, 2006, 2008, 2009, 2011, and 2012 (Table 13). The cross section is 138.9 m (455.8 ft) in length and represents 2,289 m^2 (24,640 ft^2) of the main channel area (Table 16). The cross section alignment points for line 7 are included in Table 3. The left bank position is on east edge of the Longmire Back Gate Road. The right bank position is on a reinforced levee discussed previously.

Longmire cross section 7 is one of the most unusual lines in the Longmire reach due to its completely aggradational nature. No time period in the study showed incision in cross section 7, even in years where other lines showed strong incision. Rates of aggradation vary between 0.02 $m \times yr^{-1}$ (0.05 $ft \times yr^{-1}$) and 0.35 $m \times yr^{-1}$ (1.14 $ft \times yr^{-1}$) (Appendix A.15; Appendix B.15). Net cross sectional area change varies from 4.05 m^2 (43.64 ft^2) to 48.26 m^2 (519.4 ft^2) (Appendix A.15). The overall aggradation rate from 1997 to 2012 is 0.08 $m \times yr^{-1}$ (0.26 $ft \times yr^{-1}$) (Figure 22) and the net cross section area change from 1997 to 2012 is 162.1 m^2 (1,745 ft^2) (Figure 20). Accounting for area represented by cross section (Table 16), the overall aggradation in active channel represented by cross section 7 from 1997 to 2012 is 2,670 m^3 (94,310 ft^3) (Appendix C.15). This is the highest aggradation rate in the reach (Figure 22) and the highest volume change (Figure 21) in the Longmire reach.

Longmire – Line 8

Longmire cross section 8 is the third most downstream line in the study reach, about 28 m (92 ft) upstream of cross section 9 and about 41 m (133 ft) downstream of cross section 7 (Figure 8). The line was originally surveyed in 1997 and has been resurveyed in 2005, 2006, 2008, 2009, 2011, and 2012 (Table 13). The cross section is 151.3 m (496.4 ft) in length and represents 3,108 m^2 (33,460 ft^2) of the main channel area (Table 16). The cross section alignment points for line 8 are included in Table 3. The left bank position is in the parking lot for the Longmire Community Building. The right bank position is on a reinforced levee discussed previously.

Longmire cross section 8 is a mostly aggradational line with two periods of incision between 2006-2008 and 2008-2009. Rates of aggradation vary between -0.21 m×yr^{-1} (-0.69 ft×yr^{-1}) and 0.22 m×yr^{-1} (0.74 ft×yr^{-1}) (Appendix A.16; Appendix B.16). Net cross sectional area change varies from -63.22 m^2 (-680.5 ft^2) to 33.89 m^2 (364.8 ft^2) (Appendix A.16). The overall aggradation rate from 1997 to 2012 is 0.00 m×yr^{-1} (0.01 ft×yr^{-1}) (Figure 22) and the net cross section area change from 1997 to 2012 is 7.37 m^2 (79.31 ft^2) (Figure 20). Accounting for area represented by the cross section (Table 16), the overall aggradation in active channel represented by cross section 8 from 1997 to 2012 is 151.4 m^3 (5,346 ft^3) (Appendix C.16). This is the fourth highest aggradation rate in the reach (Figure 22) and the second highest volume change (Figure 21) in the Longmire reach.

Longmire – Line 9

Longmire cross section 9 is the second most downstream line in the study reach, about 29 m (96 ft) upstream of cross section 10 and about 28 m (92 ft) downstream of cross section 8 (Figure 8). The line was originally surveyed in 1997 and has been resurveyed in 2005, 2006, 2008, 2009, 2011, and 2012 (Table 13). The cross section is 169.7 m (556.9 ft) in length and represents 2,543 m^2 (27,380 ft^2) of the main channel area (Table 16). The cross section alignment points for line 9 are included in Table 3. The left bank position is on the south side of the Longmire Back Gate Road. The right bank position is on a reinforced levee discussed previously.

Longmire cross section 9 shows episodic incision (1997-2006 and 2010-2012) and aggradation (2006-2010) but is an overall incisional line. Rates of aggradation vary between -0.12 m×yr^{-1} (-0.38 ft×yr^{-1}) and 0.10 m×yr^{-1} (0.32 ft×yr^{-1}) (Appendix A.17; Appendix B.17). Net cross sectional area change varies from -19.50 m^2 (-209.9 ft^2) to 16.39 m^2 (176.4 ft^2) (Appendix A.17). The overall aggradation rate from 1997 to 2012 is -0.01 m×yr^{-1} (-0.02 ft×yr^{-1}) (Figure 22) and the net cross section area change from 1997 to 2012 is -11.45 m^2 (-123.3 ft^2) (Figure 20). Accounting for area represented by the cross section (Table 16), the overall aggradation in active channel represented by cross section 9 from 1997 to 2012 is -171.6 m^3 (-6,061 ft^3) (Appendix C.17). This is the fourth lowest aggradation rate in the reach (Figure 22) and the third lowest volume change (Figure 21) in the Longmire reach.

Longmire – Line 10

Longmire cross section 10 is the most downstream line in the study reach, about 29 m (96 ft) downstream of cross section 9 (Figure 8). The line was originally surveyed in 1997 and has been resurveyed in 2005, 2006, 2008, 2009, 2011, and 2012 (Table 13). The cross section is 155.1 m (508.9 ft) in length and represents 1,215 m^2 (13,070 ft^2) of the main channel area (Table 16). The cross section alignment points for line 10 are included in Table 3. The left bank position is on the north side of the Longmire Back Gate Road. The right bank position is near the most downstream point of a reinforced levee discussed previously. The cross section line runs parallel to and near power lines that cross the Nisqually River from the Longmire Campground to the Longmire administrative area.

Longmire cross section 10 shows varied aggradation and incision from year-to-year but is an overall incisional line. Rates of aggradation vary between -0.16 m×yr^{-1} (-0.52 ft×yr^{-1}) and 0.52 m×yr^{-1} (1.71 ft×yr^{-1}) (Appendix A.18; Appendix B.18). Net cross sectional area change varies from -84.18 m^2 (-906.1 ft^2) to 80.73 m^2 (868.9 ft^2) (Appendix A.18). The overall aggradation rate from 1997 to 2012 is -0.01 m×yr^{-1} (-0.03 ft×yr^{-1}) (Figure 22) and the net cross section area change from 1997 to 2012 is -23.03 m^2 (-247.9 ft^2) (Figure 20). Accounting for area represented by the cross section (Table 16), the overall aggradation in active channel represented by cross section 10 from 1997 to 2012 is -180.3 m^3 (-6,368 ft^3) (Appendix C.18). This is the third lowest aggradation rate in the reach (Figure 22) and the second lowest volume change (Figure 21) in the Longmire reach.

Carter Falls

The Nisqually River valley in the Carter Falls reach is relatively unconfined in a wide valley bounded on either side by the Rampart Ridge lava flow (to the west) and the southern-most extent of the Ricksecker Point lava flow (Pringle, 2008). The Ricksecker Point lava flow is one of the youngest large lava flows extending away from the Mount Rainier volcano, with an age of about 40 ka (Pringle, 2008). The Paradise River enters the Nisqually River just downstream of the study reach. A large pullout and trailhead is on the right bank of the Nisqually River adjacent to the Longmire-Paradise Road. Additionally, the Cougar Rock Campground is near the survey reach (Figure 10). The river bed is composed of sediment that includes fine grained materials as well as coarse gravel to cobble and larger grain sizes. This is typical of the braided channels as channel gradient and proximity to the glacial source of the river increase. Channel widths through the Carter Falls reach vary from 89-139 m (292-456 ft). The elevation range in the upstream end is 969 m (3,181 ft) and 953 m (3,125 ft) in the downstream of the reach, resulting in an overall gradient of 6.57% based on 2012 survey data. Other watershed facts for the Nisqually River at Carter Falls are found in Table 6. This study reach was added in 2011 and resurveyed in 2012, so only a single year of data exists for this location.

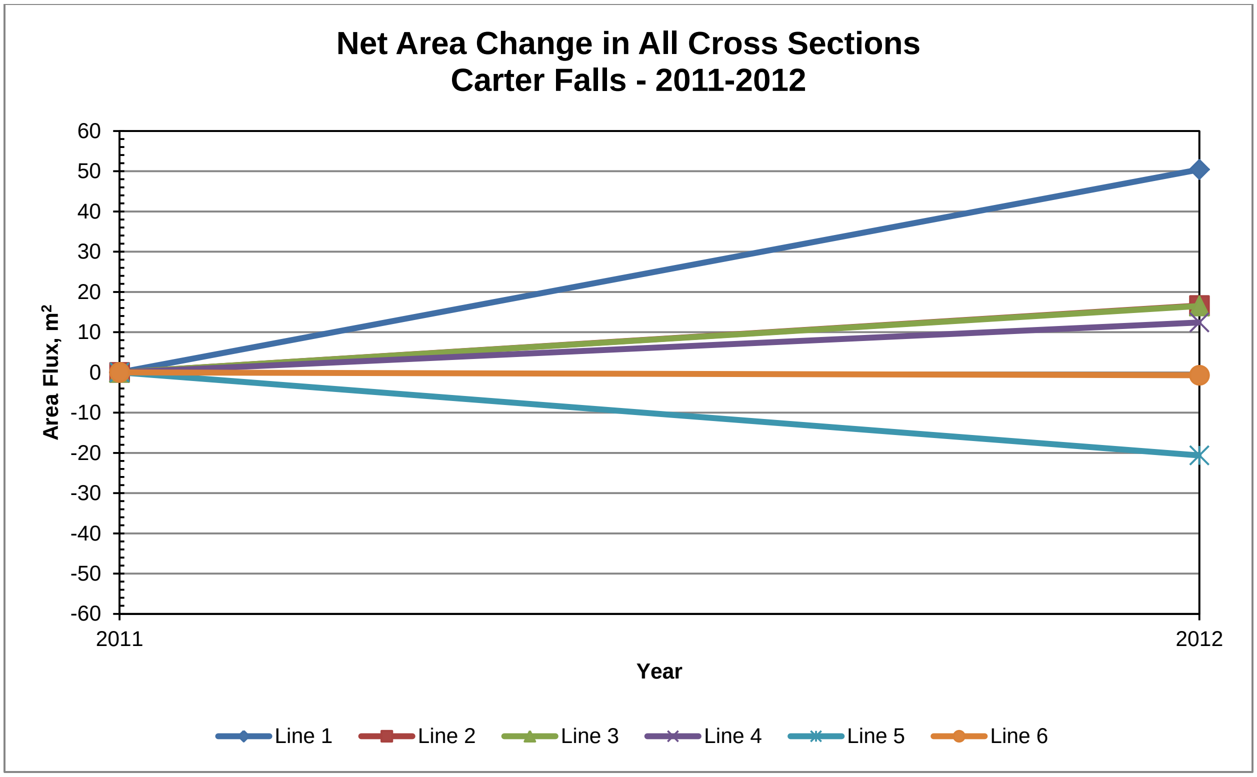


Figure 24: Net area change in all Carter Falls cross sections. Net area change represents the increase or decrease in sediment in a single cross section and does not factor in area represented by cross section. This can also be thought of as the change in the average elevation in each cross section from year-to-year. The first year is plotted as zero and additional years either add or subtract areas from the cross sections.

The Carter Falls reach is aggradational in its upper end and becomes increasingly less aggradational to incisional in the downstream end of the reach (Figures 24, 25, and 26; Appendix A.19; Appendix B.19; Appendix C.19-C.24). Rates, cross sectional areas, and volume changes in the active channel are analyzed between 2011 and 2012. Cross section width and area represented by individual cross sections are included in Table 18. Individual cross section results are discussed in depth in the next few pages.

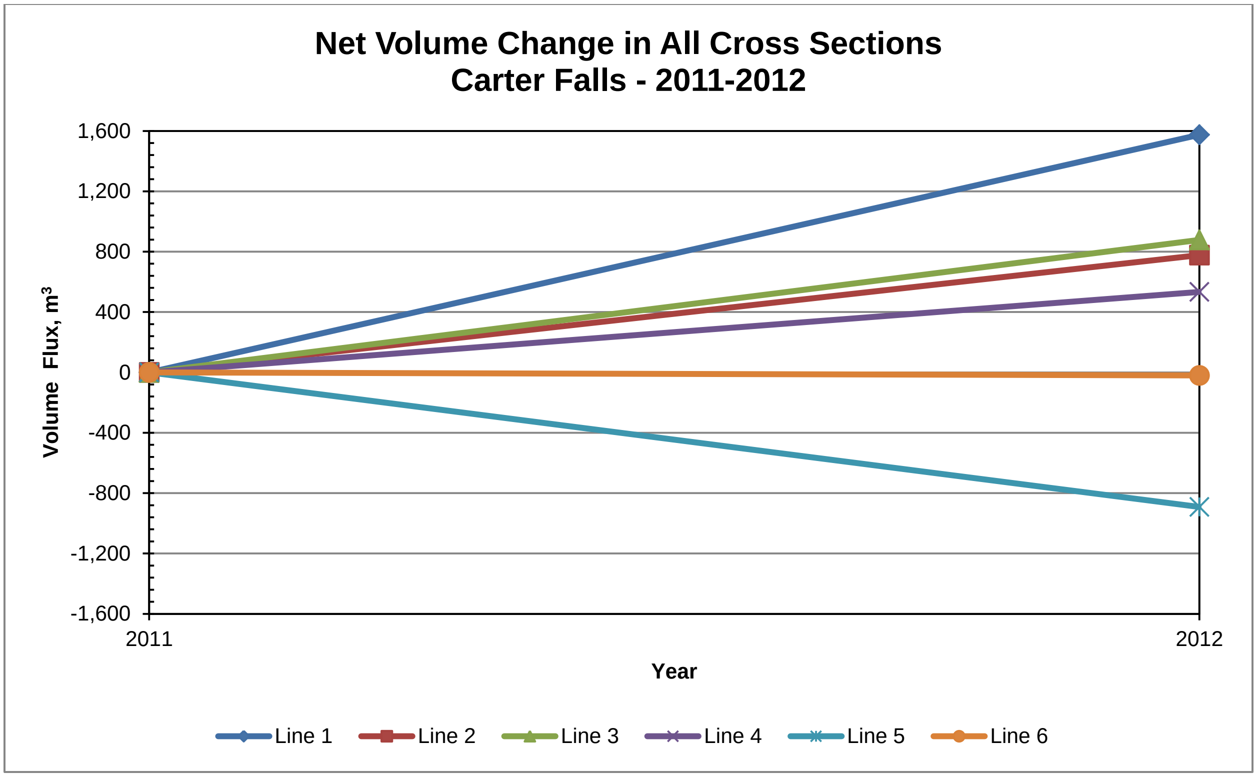


Figure 25: Net volume change in all Carter Falls cross sections. Net volume change accounts for aggradation rate and area occupied by all cross sections and shows a running total of sediment volume in the reach over time. The first year a cross section is surveyed is plotted as zero, then additional years either add or subtract sediment volume.

Weighted aggradation rates for the Longmire reach were calculated using Equation 9 as in previous study areas. Table 19 shows the reach averaged aggradation rates for the time period between 2011-2012 at Carter Falls. Four of the six cross sections in this location show aggradation while the remaining two show incision. Factoring in the area represented by the individual cross sections, the reach-averaged aggradation rate at Carter Falls from 2011 to 2012 is 0.10 $m \times yr^{-1}$ (0.33 $ft \times yr^{-1}$) (Table 19; Figure 27).

Table 18: Cross section lengths and area represented by individual cross sections at Carter Falls. Areas are used for reach averaging cross section aggradation rates. Lines are shown in upstream to downstream order. Areas were calculated in ArcGIS by the author.

Cross Section	Length, m	Area Represented by Cross Section, m^2
1	89.28	2,788.89
2	118.20	5,518.02
3	115.17	6,124.47
4	139.08	5,979.54
5	125.46	5,421.16
6	116.45	3,227.46

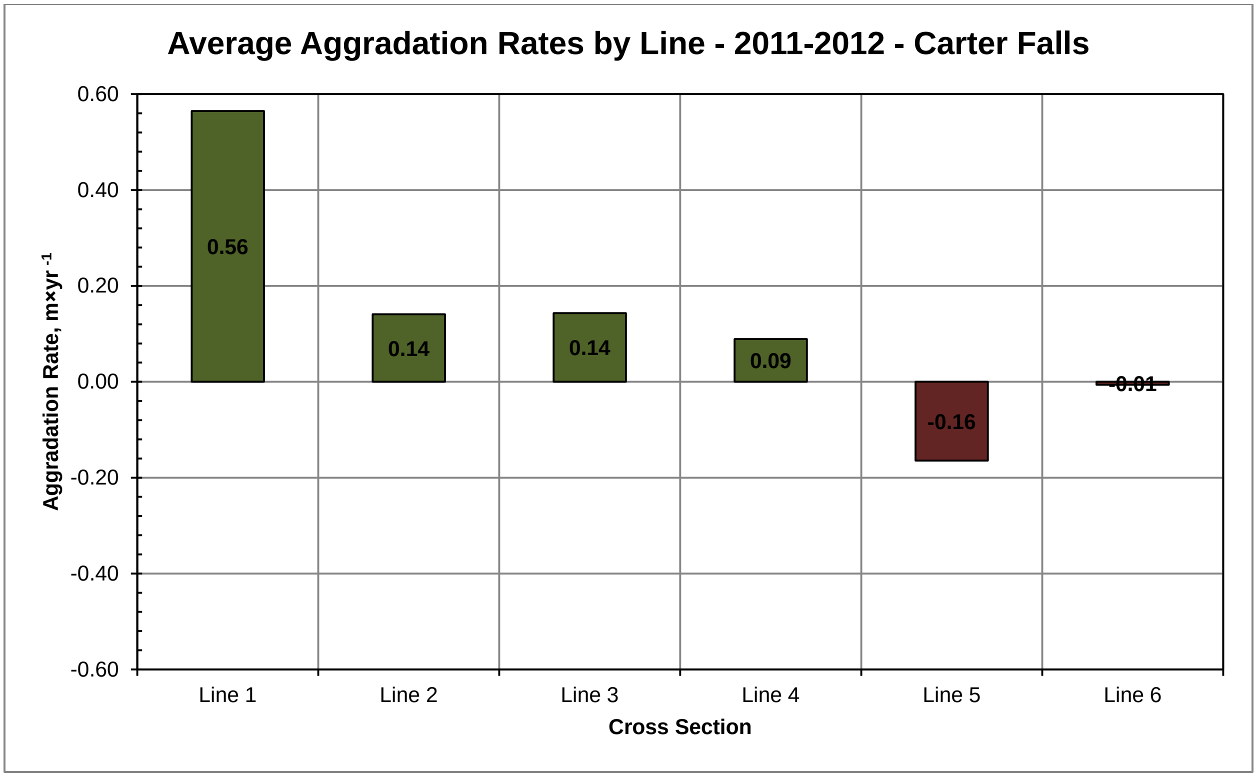


Figure 26: Average aggradation rate for Carter Falls cross sections between 2011-2012.

Table 19: Reach averaged aggradation rates for various time periods at Carter Falls.

Line	**Area,** ***m²***	**Rate,** ***m×yr⁻¹***	**Area×Rate** ***m³×yr⁻¹***	**Reach averaged Aggradation** ***m×yr⁻¹***
2011-2012 (1 Year)				
1	2,788.89	0.56	1,574.67	-
2	5,518.02	0.14	776.80	-
3	6,124.47	0.14	877.97	-
4	5,979.54	0.09	533.08	-
5	5,421.16	-0.16	-891.90	-
6	3,227.46	-0.01	-20.17	-
Sum	**29,059.52**	**-**	**2,850.45**	**0.10**

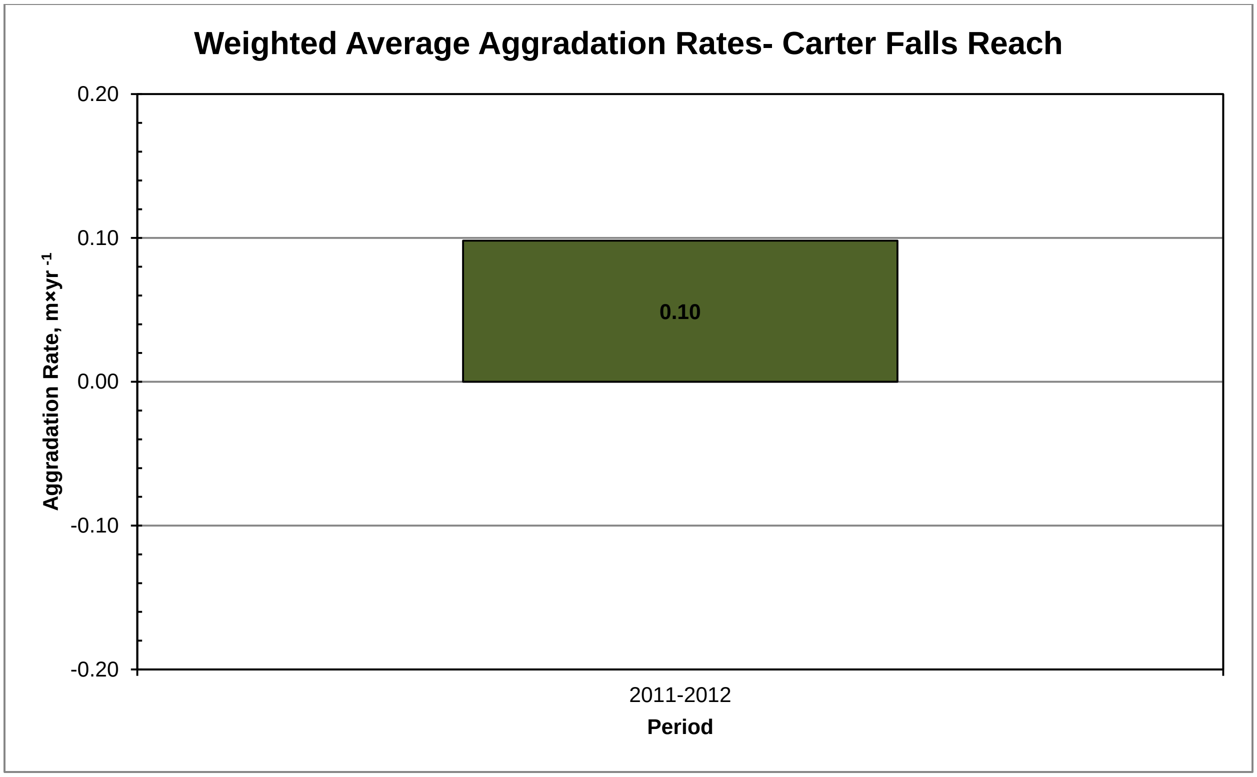


Figure 27: Weighted average aggradation rate for the entire Carter Falls Reach during the study period, accounting for all available lines and cross sectional areas.

Carter Falls – Line 1

Carter Falls cross section 1 is the most upstream line in the study reach, about 59 m (195 ft) upstream of cross section 2 (Figure 9). The line was originally surveyed in 2011 and was resurveyed in 2012 (Table 13). The cross section is 89.28 m (292.9 ft) in length and represents 2,789 m^2 (30,020 ft^2) of the main channel area (Table 18). The cross section alignment points for line 1 are included in Table 5. The left bank and right bank positions are on river terraces several meters above the active channel.

Carter Falls cross section 1 shows the highest rate of aggradation in the reach between 2011 and 2012, a rate of 0.57 $m \times yr^{-1}$ (1.86 $ft \times yr^{-1}$) (Appendix B.19; Figure 26). The net cross sectional area change increases by 50.41 m^2 (542.6 ft^2) between 2011 and 2012 (Appendix A.19). The net volume increase between 2011 and 2012 is 1,575 m^3 (55,610 ft^3) (Appendix C.19), the highest volume change observed in the reach.

Carter Falls – Line 2

Carter Falls cross section 2 is the second most upstream line in the study reach, about 42 m (139 ft) upstream of cross section 3 and about 59 m (195 ft) downstream of cross section 1 (Figure 9). The line was originally surveyed in 2011 and was resurveyed in 2012 (Table 13). The cross section is 118.2 m (387.8 ft) in length and represents 5,518 m^2 (59,400 ft^2) of the main channel area (Table 18). The cross section alignment points for line 2 are included in Table 5. The left bank and right bank positions are on river terraces several meters above the active channel.

Carter Falls cross section 2 shows the third highest rate of aggradation in the reach between 2011 and 2012, a rate of 0.14 $m \times yr^{-1}$ (0.46 $ft \times yr^{-1}$) (Appendix B.19; Figure 26). The net cross sectional area change increases by 16.64 m^2 (179.1 ft^2) between 2011 and 2012 (Appendix A.19). The net volume increase between 2011 and 2012 is 776.8 m^3 (27,430 ft^3) (Appendix C.20), the third highest volume change observed in the reach.

Carter Falls – Line 3

Carter Falls cross section 3 is the third most upstream line in the study reach, about 76 m (251 ft) upstream of cross section 4 and about 42 m (139 ft) downstream of cross section 2 (Figure 9). The line was originally surveyed in 2011 and was resurveyed in 2012 (Table 13). The cross section is 115.2 m (377.9 ft) in length and represents 6,124 m^2 (65,920 ft^2) of the main channel area (Table 18). The cross section alignment points for line 3 are included in Table 5. The left bank and right bank positions are on river terraces several meters above the active channel.

Carter Falls cross section 3 shows the second highest rate of aggradation in the reach between 2011 and 2012, a rate of 0.14 $m \times yr^{-1}$ (0.47 $ft \times yr^{-1}$) (Appendix B.19; Figure 26). The net cross sectional area change increases by 16.51 m^2 (177.7 ft^2) between 2011 and 2012 (Appendix A.19). The net volume increase between 2011 and 2012 is 878.0 m^3 (31,010 ft^3) (Appendix C.21), the second highest volume change observed in the reach.

Carter Falls – Line 4

Carter Falls cross section 4 is the third most downstream line in the study reach, about 28 m (93 ft) upstream of cross section 5 and about 76 m (251 ft) downstream of cross section 3 (Figure 9). The line was originally surveyed in 2011 and was resurveyed in 2012 (Table 13). The cross section is 139.1 m (456.3 ft) in length and represents 5,980 m^2 (64,360 ft^2) of the main channel area (Table 18). The cross section alignment points for line 4 are included in Table 5. The left bank and right bank positions are on river terraces several meters above the active channel. The cross section runs roughly parallel to the Carter Falls/Wonderland Trail as it crosses the Nisqually River active channel.

Carter Falls cross section 4 shows the fourth highest rate of aggradation in the reach between 2011 and 2012, a rate of 0.09 $m \times yr^{-1}$ (0.29 $ft \times yr^{-1}$) (Appendix B.19; Figure 26). The net cross sectional area change increases by 12.40 m^2 (133.5 ft^2) between 2011 and 2012 (Appendix A.19). The net volume increase between 2011 and 2012 is 533.1 m^3 (18,830 ft^3) (Appendix C.22), the fourth highest volume change observed in the reach.

Carter Falls – Line 5

Carter Falls cross section 5 is the second most downstream line in the study reach, about 57 m (186 ft) upstream of cross section 6 and about 28 m (93 ft) downstream of cross section 4 (Figure 9). The line was originally surveyed in 2011 and was resurveyed in 2012 (Table 13). The cross section is 125.5 m (411.6 ft) in length and represents 5,421 m^2 (58,350 ft^2) of the main channel area (Table 18). The cross section alignment points for line 5 are included in Table 5. The left bank and right bank positions are on river terraces several meters above the active channel.

Carter Falls cross section 5 shows the highest rate of incision in the reach between 2011 and 2012, a rate of -0.16 $m \times yr^{-1}$ (-0.54 $ft \times yr^{-1}$) (Appendix B.19; Figure 26). The net cross sectional area change decreases by -20.64 m^2 (-222.2 ft^2) between 2011 and 2012 (Appendix A.19). The net volume decrease between 2011 and 2012 is -891.9 m^3 (-31,500 ft^3) (Appendix C.23), the lowest volume change observed in the reach.

Carter Falls – Line 6

Carter Falls cross section 6 is the most downstream line in the study reach, about 57 m (186 ft) downstream of cross section 5 (Figure 9). The line was originally surveyed in 2011 and was resurveyed in 2012 (Table 13). The cross section is 116.4 m (382.0 ft) in length and represents 3,227 m^2 (34,740 ft^2) of the main channel area (Table 18). The cross section alignment points for line 6 are included in Table 5. The left bank position is on a terrace that separates the Nisqually River from the Paradise River, whose confluence occurs just downstream of the study reach. The right bank position is on a river terraces several meters above the active channel.

Carter Falls cross section 6 shows the second highest rate of incision in the reach between 2011 and 2012, a rate of -0.01 $m \times yr^{-1}$ (-0.02 $ft \times yr^{-1}$) (Appendix B.19; Figure 26). The net cross sectional area change decreases by -0.73 m^2 (-7.84 ft^2) between 2011 and 2012 (Appendix A.19). The net volume decrease between 2011 and 2012 is -20.17 m^3 (-712.3 ft^3) (Appendix C.24), the second lowest volume change observed in the reach.

Lower Van Trump

The Nisqually River is confined on the left bank by steep talus slopes from Ricksecker Point and mostly unconfined on the right bank throughout the study reach. Riparian forest sits on the right bank flood terraces throughout the study reach. Van Trump Creek joins with the Nisqually River in the vicinity of cross section 2 and flows as a clear-running stream most of the year despite its source at the Van Trump Glaciers. The Longmire-Paradise Road makes a sweeping bend in the vicinity of cross section 1; a feature nicknamed “Lower Van Trump Hairpin” for park staff (Figure 11). Due to excessive sedimentation in this location, typical stream banks are difficult to discern in the study reach. However, stream banks are exposed both upstream and downstream. Alder and Cedar trees help distinguish the active channel from overbank floodplain. Channel widths through the Lower Van Trump reach vary from 103-164 m (338-538 ft). The elevation range in the upstream end is 1,045 m (3,430 ft) and 1,030 m (3,380 ft) in the downstream of the reach, resulting in an overall gradient of 6.77% based on 2012 survey data. Other watershed facts for the Nisqually River at Lower Van Trump Hairpin are found in Table 8. Cross section widths and areas represented by cross sections are included in Table 20.

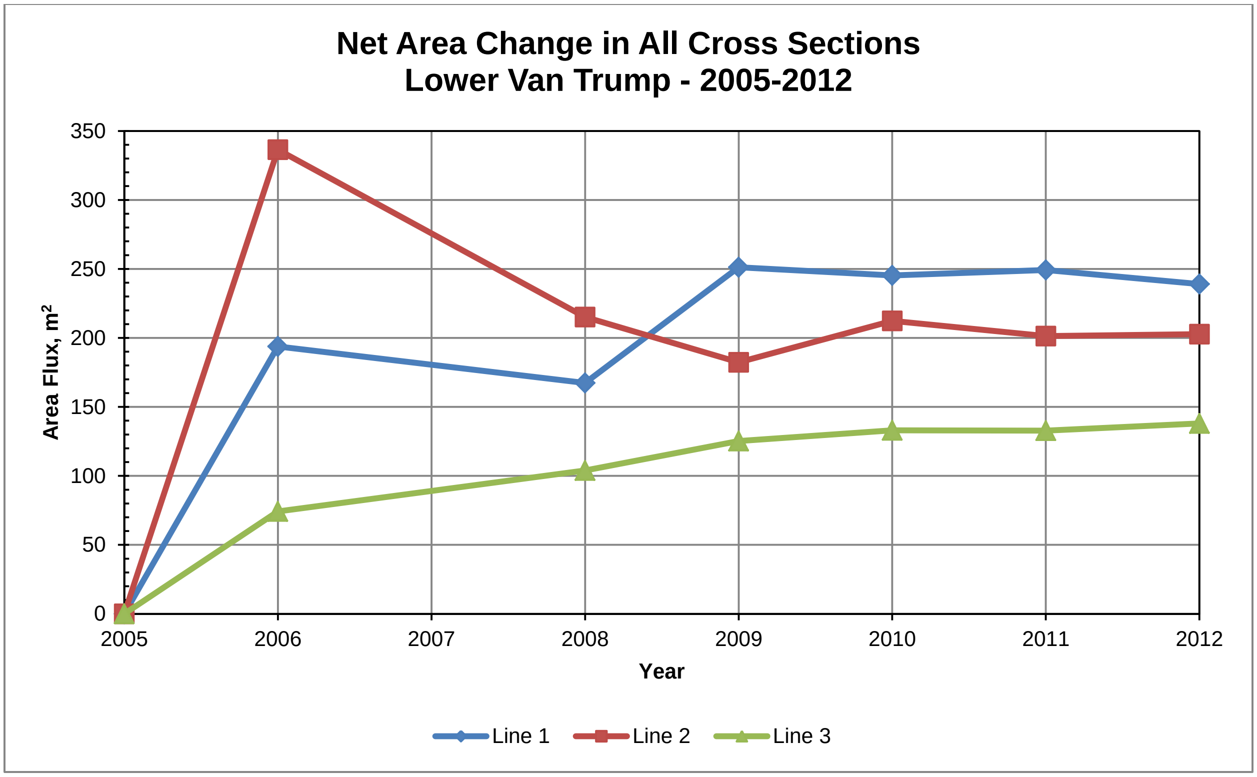


Figure 28: Net area change in all Lower Van Trump cross sections. Net area change represents the increase or decrease in sediment in a single cross section and does not factor in area represented by cross section. This can also be thought of as the change in the average elevation in each cross section from year-to-year. The first year is plotted as zero and additional years either add or subtract areas from the cross sections.

The Lower Van Trump reach is exceptionally aggradational due to both debris flow and landslide influence (Figures 28, 29, and 30; Appendix A.20-A.22; Appendix B.20-B.22; Appendix C.25-C.27). Most aggradation observed during the study occurred as result of the 2005 Van Trump debris flows, but other debris flows in 2001 and 2003 have added great volumes of sediment to the reach. Rates, cross sectional areas, and volume changes in the active channel are analyzed between individual survey years. All cross sections show net aggradation in this reach with some periods of incision. However, due to the surfeit of sediment that accumulated due to the 2005 and 2006 debris flows as well as the 2008 landslide, aggradation overwhelms any incision that occurred in this area. Individual cross section results are discussed in depth in the next sections.

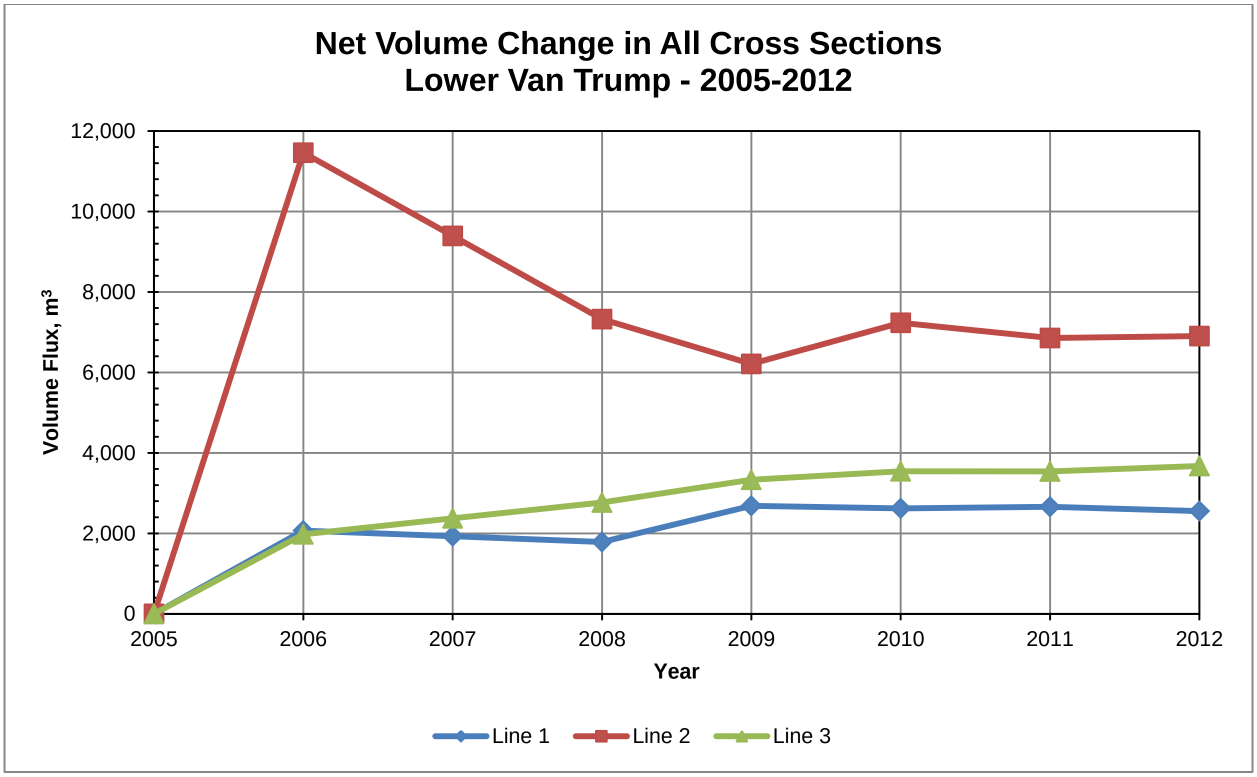


Figure 29: Net volume change in all Lower Van Trump cross sections. Net volume change accounts for aggradation rate and area occupied by all cross sections and shows a running total of sediment volume in the reach over time. The first year a cross section is surveyed is plotted as zero, then additional years either add or subtract sediment volume.

Weighted aggradation rates for the Longmire reach were calculated using Equation 9 as in previous study areas. Table 21 shows the reach-averaged aggradation rates for various time periods at Lower Van Trump. The rate is aggradational for four of the six analysis periods, including the 2005-2006 debris flow influenced rate of 1.55 m×yr^{-1} (5.10 ft×yr^{-1}) and the net accumulation of material in 2008-2009 due to the influence of the Ricksecker Point landslide. Two periods of incision occur in this location between 200-2008 and 2010-2011. Rates vary from -0.18 m×yr^{-1} (-0.59 ft×yr^{-1}) to 1.55 m×yr^{-1} (5.10 ft×yr^{-1}) (Table 21; Figure 31).

Table 20: Cross section lengths and area represented by individual cross sections at Lower Van Trump. Areas are used for reach averaging cross section aggradation rates. Lines are shown in upstream to downstream order. Areas were computed by Beason (2007).

Cross Section	Length, m	Area Represented by Cross Section, m^2
3	103.23	2,748.73
2	163.95	5,582.97
1	154.73	1,652.39

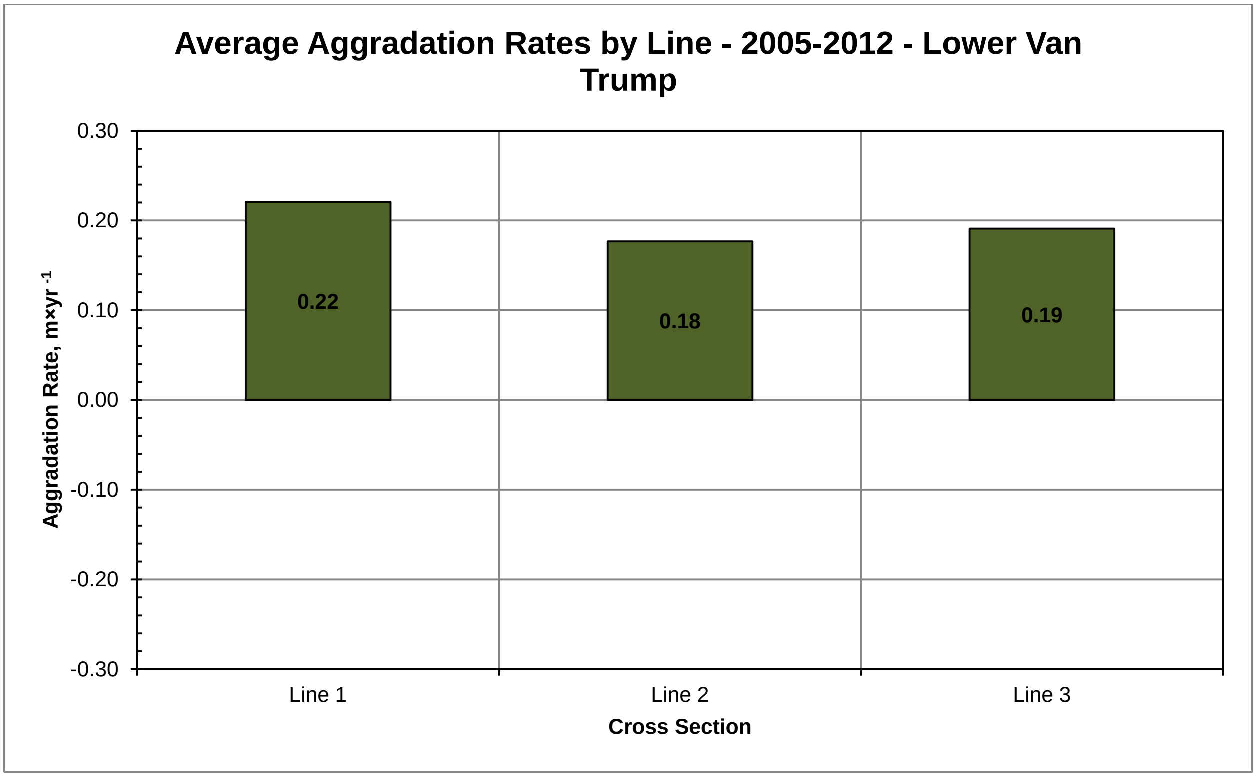


Figure 30: Average aggradation rate for Lower Van Trump cross sections.

Table 21: Reach averaged aggradation rates for various time periods at Lower Van Trump Hairpin

Line	**Area,** m^2	**Rate,** $m \times yr^{-1}$	**Area×Rate** $m^3 \times yr^{-1}$	**Reach averaged Aggradation** $m \times yr^{-1}$
2005-2006 (1 Year) (Beason, 2007)				
1	1,652.39	1.25	2,069.47	-
2	5,582.97	2.05	11,457.64	-
3	2,748.73	0.72	1,976.10	-
Sum	**9,984.08**	**-**	**15,503.21**	**1.55**
2006-2008 (2 Years)				
1	1,652.39	-0.09	-140.94	-
2	5,582.97	-0.37	-2,066.76	-
3	2,748.73	0.14	396.20	-
Sum	**9,984.08**	**-**	**-1,811.49**	**-0.18**
2008-2009 (1 Year)				
1	1,652.39	0.54	895.26	-
2	5,582.97	-0.20	-1,114.99	-
3	2,748.73	0.21	565.51	-
Sum	**9,984.08**	**-**	**345.78**	**0.03**

(Continued)

Table 21 (Continued): Reach averaged aggradation rates for various time periods at Lower Van Trump Hairpin

Line	Area, m^2	Rate, $m \times yr^{-1}$	Area×Rate $m^3 \times yr^{-1}$	Reach averaged Aggradation $m \times yr^{-1}$
2009-2010 (1 Year)				
1	1,652.39	-0.04	-62.80	-
2	5,582.97	0.18	1,023.39	-
3	2,748.73	0.08	208.83	-
Sum	**9,984.083**	**-**	**1,169.42**	**0.12**
2010-2011 (1 Year)				
1	1,652.39	0.03	41.85	-
2	5,582.97	-0.07	-378.49	-
3	2,748.73	-0.00	-5.35	-
Sum	**9,984.083**	**-**	**-341.99**	**-0.03**
2011-2012 (1 Year)				
1	1,652.39	-0.07	-109.29	-
2	5,582.97	0.01	49.88	-
3	2,748.73	0.05	136.42	-
Sum	**9,984.083**	**-**	**77.01**	**0.01**

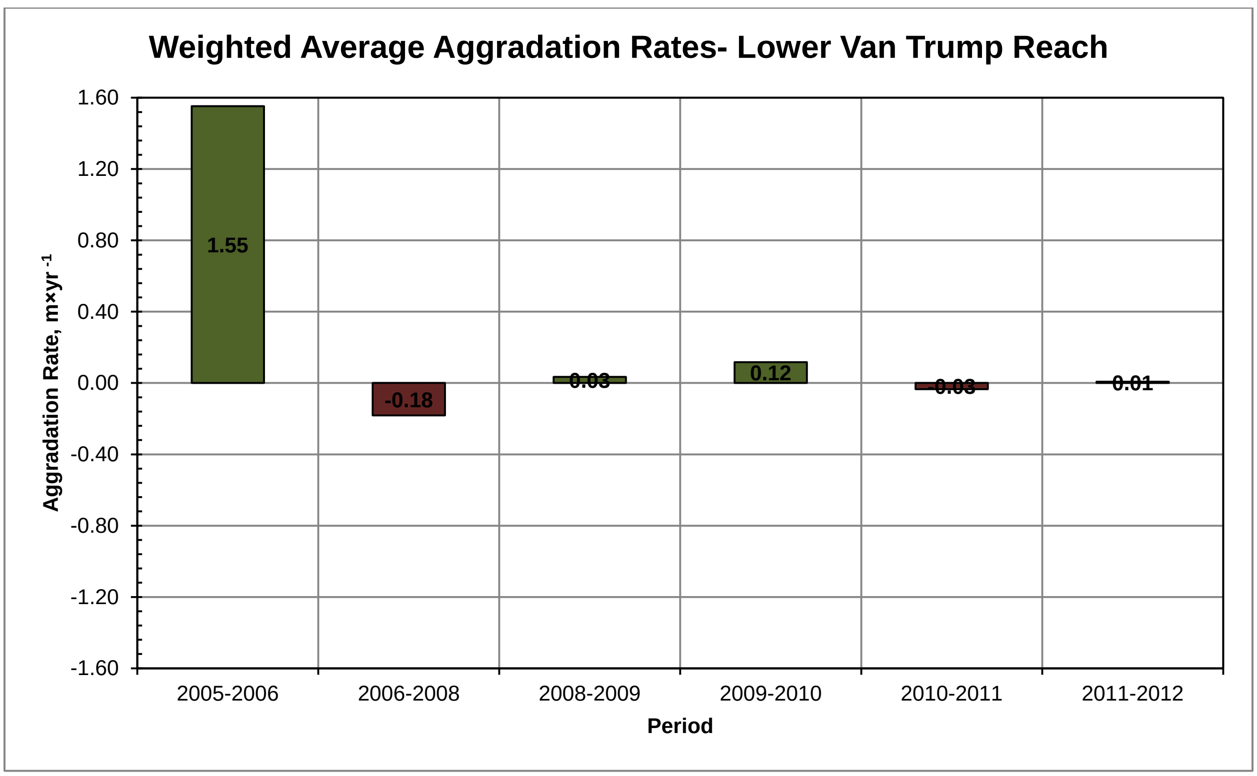


Figure 31: Weighted average aggradation rate for the entire Lower Van Trump Reach during the study period, accounting for all available lines and cross sectional areas.

Lower Van Trump – Line 1

Lower Van Trump cross section 1 is the most downstream line in the study reach, about 83 m (273 ft) downstream of cross section 2 (Figure 11). The line was originally surveyed in 2005 and has been resurveyed in 2006, 2008, 2009, 2011, and 2012 (Table 13). The cross section is 154.7 m (507.6 ft) in length and represents 1,652 m^2 (17,790 ft^2) of the main channel area (Table 20). The cross section alignment points for line 1 are included in Table 7. The left bank position is near the landslide deposit/scar from Ricksecker Point uphill from the active channel. The right bank position is on the road prism for the Longmire-Paradise Road.

Lower Van Trump cross section 1 is highly variable, with individual survey periods seeing aggradation rates varying from -0.09 $m \times yr^{-1}$ (-0.28 $ft \times yr^{-1}$) to 1.25 $m \times yr^{-1}$ (4.11 $ft \times yr^{-1}$) (Appendix A.20; Appendix B.20). However, there are two distinct periods of intense aggradation, between 2005-2006 and 2008-2009. Net cross section area change varies from -26.39 m^2 (-284.1 ft^2) to 193.8 m^2 (2,086 ft^2). The overall aggradation rate from 2005 to 2012 is 0.22 $m \times yr^{-1}$ (0.73 $ft \times yr^{-1}$) (Figure 30) and the net cross section area change from 2005 to 2012 is 239.0 m^2 (2,573 ft^2) (Figure 28). Accounting for the area represented by the cross section (Table 20), the overall aggradation in the active channel represented by cross section 1 from 2005 to 2012 is 2,553 m^3 (90,140 ft^3) (Appendix C.25). This is the highest aggradation rate (Figure 30), but lowest volume change since it occupies a smaller area in map view (Figure 29) at Lower Van Trump.

Lower Van Trump – Line 2

Lower Van Trump cross section line 2 is the middle line of the three cross sections in the study reach, about 167 m (547 ft) downstream of cross section 3 and 83 m (273 ft) upstream of cross section 1 (Figure 11). The line was originally surveyed in 2005 and has been resurveyed in 2006, 2008, 2009, 2011, and 2012 (Table 13). The cross section is 164.0 m (537.9 ft) in length and represents 5,583 m^2 (60,090 ft^2) of the main channel area (Table 20). The cross section alignment points for line 2 are included in Table 7. The left bank position is on the talus slope extending down from Ricksecker Point. The right bank position is on a floodplain terrace in riparian forest adjacent to Van Trump Creek.

Lower Van Trump cross section 2 shows the highest single rate of aggradation in this study due to the immediate influence of deposition from the 2005 Van Trump debris flow. The cross section has since experienced relative incision with a few periods of aggradation since 2006. Individual survey periods have aggradation rates that vary from -0.37 $m \times yr^{-1}$ (-1.21 $ft \times yr^{-1}$) to 2.05 $m \times yr^{-1}$ (6.73 $ft \times yr^{-1}$) (Appendix A.21; Appendix B.21). Net cross section area change varies from -121.4 m^2 (-1,307 ft^2) to 336.5 m^2 (3,622 ft^2). The overall aggradation rate from 2005 to 2012 is 0.18 $m \times yr^{-1}$ (0.58 $ft \times yr^{-1}$) (Figure 30) and the net cross section area change from 2005 to 2012 is 202.8 m^2 (2,182 ft^2) (Figure 28). Accounting for the area represented by cross section 2 (Table 20), the overall aggradation in the active channel from 2005 to 2012 is 6,904 m^3 (243,800 ft^3) (Appendix C.26). This is the lowest aggradation rate (Figure 30), but highest volume change since line 2 occupies the largest area of active channel (Figure 29) at Lower Van Trump.

Lower Van Trump – Line 3

Lower Van Trump cross section line 3 is the most upstream line in the study reach, about 167 m (547 ft) upstream of cross section 2 (Figure 11). The line was originally surveyed in 2005 and has been resurveyed in 2006, 2008, 2009, 2011, and 2012 (Table 13). The cross section is 103.2 m (338.7 ft) in length and represents 2,749 m^2 (29,590 ft^2) of the main channel area (Table 20). The cross section alignment points for line 3 are included in Table 7. The left bank position is on the talus slope extending down from Ricksecker Point. The right bank position is on a floodplain terrace in riparian forest upstream of Van Trump Creek.

Lower Van Trump cross section 3 has lower ranges of aggradation and incision than the other two cross sections in this area, likely due to its location upstream of the confluence of Van Trump Creek and the Nisqually River. Almost all survey periods here are aggradational with rates that vary from -0.00 $m \times yr^{-1}$ (-0.01 $ft \times yr^{-1}$) to 0.72 $m \times yr^{-1}$ (2.36 $ft \times yr^{-1}$) (Appendix A.22; Appendix B.22). Net cross section area change varies from -0.20 m^2 (-2.16 ft^2) to 74.21 m^2 (798.8 ft^2). The overall aggradation rate from 2005 to 2012 is 0.19 $m \times yr^{-1}$ (0.63 $ft \times yr^{-1}$) (Figure 30) and the net cross section area change from 2005 to 2012 is 138.0 m^2 (1,485 ft^2) (Figure 28). Accounting for the area represented by the cross section (Table 20), the overall aggradation in the active channel represented by cross section 1 from 2005 to 2012 is 3,674 m^3 (129,700 ft^3) (Appendix C.27). This is the second highest aggradation rate (Figure 30) and volume change (Figure 29) at Lower Van Trump between 2005 and 2012.

White River

The White River is confined on the right bank by steep forest-covered ridges and mostly unconfined on the left bank throughout the study reach. There are steep ridges on the left bank a few hundred meters west of the end of each cross section. Riparian old-growth forest occupies the overbank flood terraces throughout the study reach. A small unnamed stream enters the reach between cross section 8 and 7, and other spring-fed and hill-slope drainages enter the White River throughout the reach. The White River flows along State Route 410, and the study reach is located between road miles 58.42-59.86 in the park, approximately 1.24 km (0.77 mi) south of the north-park boundary. Channel widths through the White River reach vary from 211-470 m (690-1,543 ft). The elevation ranges from 902 m (2,959 ft) in the upstream end to 862 m (2,828 ft) in the downstream of the reach, resulting in an overall gradient of 1.90% based on 2011 survey data. Other watershed facts for the White River along State Route 410 are found in Table 10. Cross section widths and areas represented by cross sections are included in Table 22.

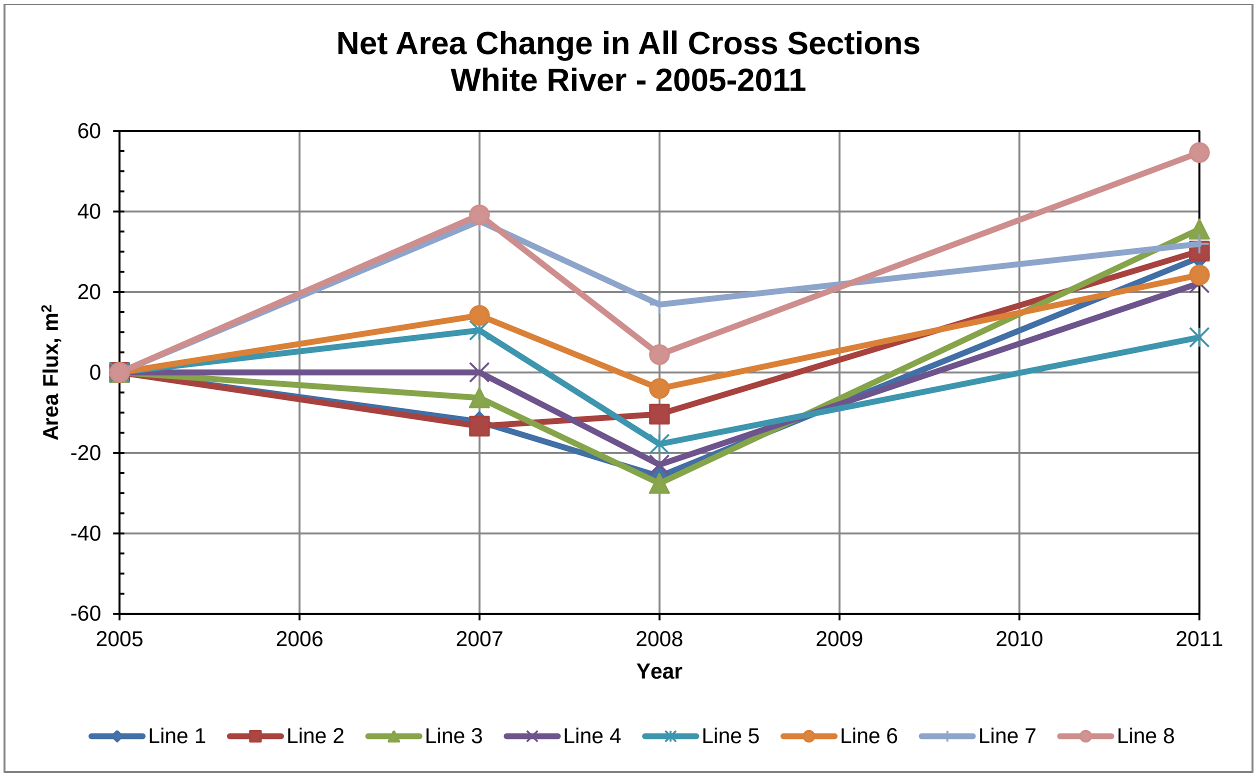


Figure 32: Net area change in all White River cross sections. Net area change represents the increase or decrease in sediment in a single cross section and does not factor in area represented by cross section. This can also be thought of as the change in the average elevation in each cross section from year-to-year. The first year is plotted as zero and additional years either add or subtract areas from the cross sections.

Despite some periods of incision, all cross sections at White River show net aggradation between 2005 and 2011 (Figures 32, 33, and 34; Appendix A.23-A.30; Appendix B.23-B.30; Appendix C.28-C.35). Rates, cross sectional areas, and volume changes in the active channel are analyzed between individual survey years.

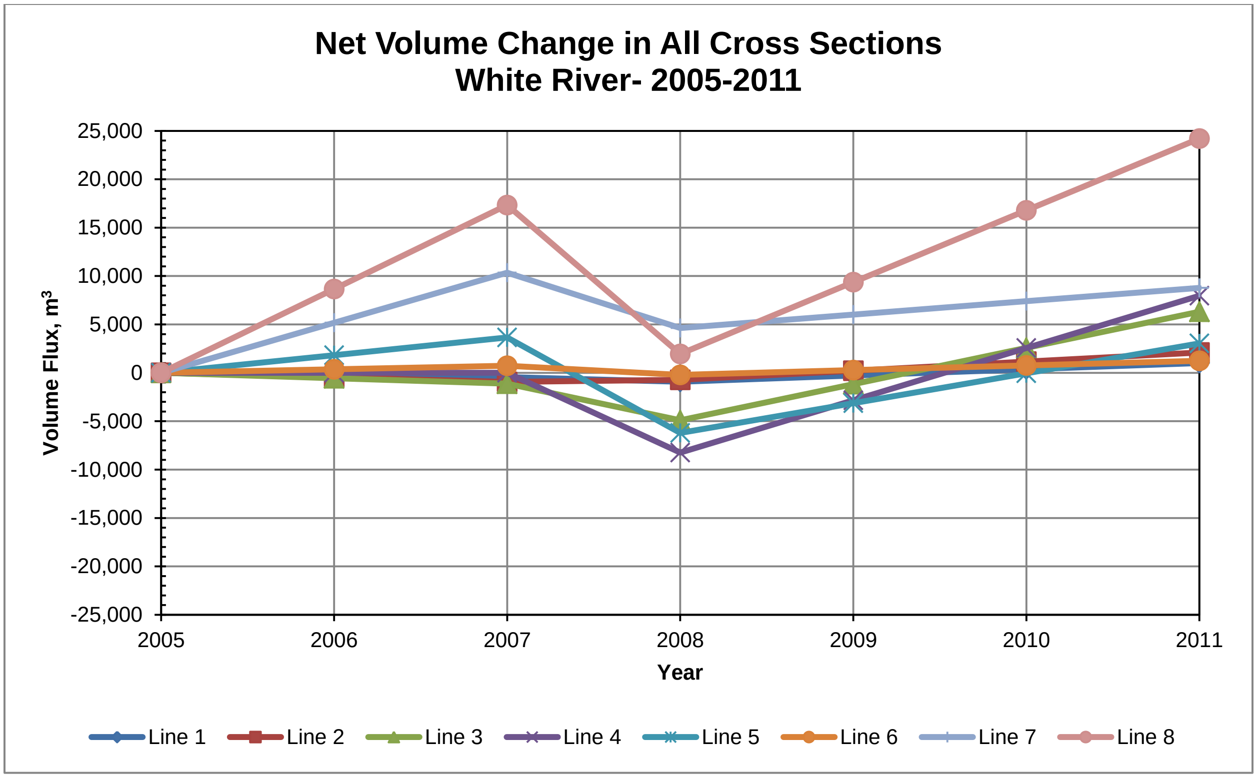


Figure 33: Net volume change in all White River cross sections. Net volume change accounts for aggradation rate and area occupied by all cross sections and shows a running total of sediment volume in the reach over time. The first year a cross section is surveyed is plotted as zero, then additional years either add or subtract sediment volume.

Weighted aggradation rates for the Longmire reach were calculated using Equation 9 as in previous study areas. Table 23 shows the reach averaged aggradation rates for various time periods on the White River. With the exception of the time period between 2007 and 2008, the reach-averaged aggradation rates vary between 0.04 m×yr^{-1} (0.13 ft×yr^{-1}) to 0.05 m×yr^{-1} (0.16 ft×yr^{-1}). The incision rate between 2007 and 2008 was -0.09 m×yr^{-1} (-0.31 ft×yr^{-1}) (Table 23; Figure 35). Aggradation in the five-year period of 2005-2007 and 2008-2011 overwhelms the incision observed in the one-year period between 2007 and 2008.

Table 22: Cross section lengths and area represented by individual cross sections at White River. Areas are used for reach averaging cross section aggradation rates. Lines are shown in upstream to downstream order. Areas were calculated in ArcGIS by the author.

Cross Section	Length, m	Area Represented by Cross Section, m^2
8[1]	234.49	103,848.08
7[1]	260.42	71,620.81
6	211.53	10,852.52
5[1]	210.60	73,573.56
4[1]	283.94	101,966.74
3[1,2]	362.21	64,315.01
2[2]	389.13	27,116.56
1[2]	470.28	16,659.39

[1] There is large gaps of space between lines 8 and 7, lines 5 and 4, and lines 4 and 3. Therefore, the area represented by cross sections 8, 7, 5, 4, and 3 are much larger than 6, 2 and 1.
[2] Lines 3, 2 and 1 at White River have a bend and the cross section length includes this bend.

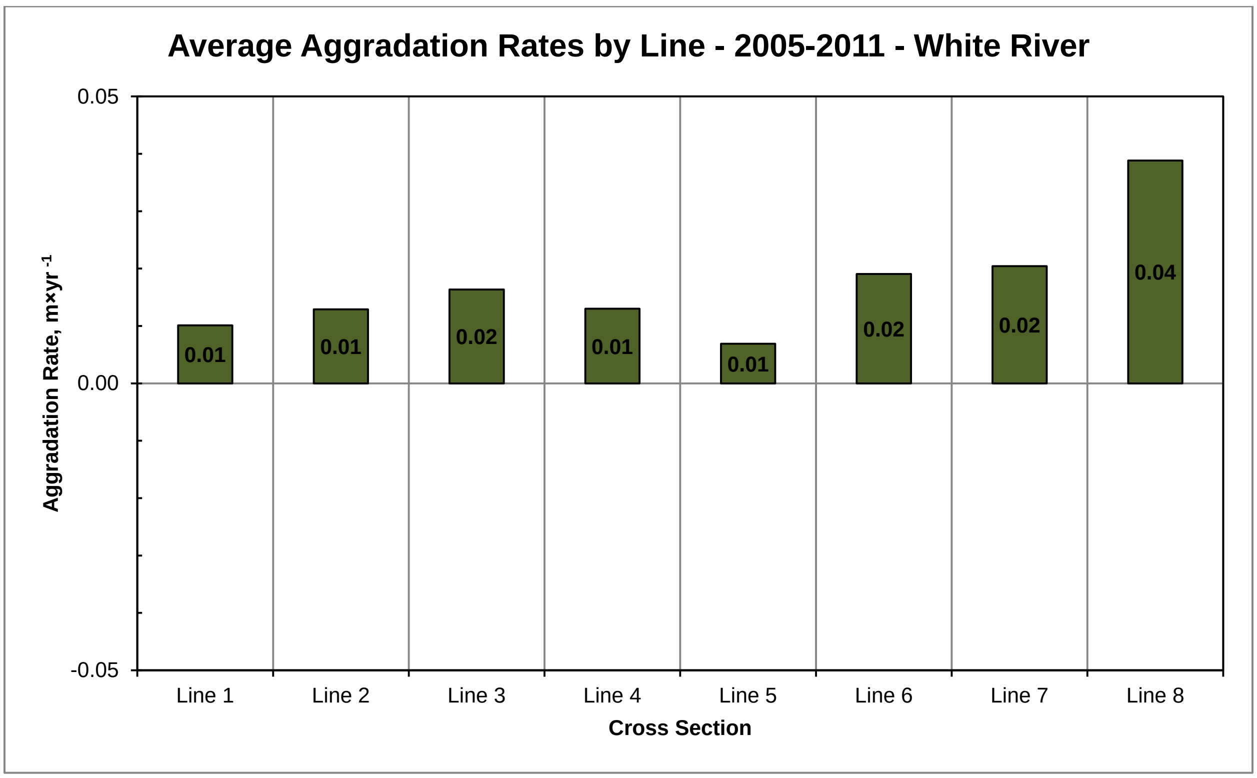


Figure 34: Average aggradation rate for White River cross sections.

Table 23: Reach averaged aggradation rates for various time periods at White River.

Line	**Area,** m^2	**Rate,** $m \times yr^{-1}$	**Area×Rate** $m^3 \times yr^{-1}$	**Reach averaged Aggradation** $m \times yr^{-1}$
2005-2007(2 Years)				
1	16,659.39	-0.01	-217.16	-
2	27,116.56	-0.02	-465.66	-
3	64,315.01	-0.01	-561.58	-
4	101,966.74	0.00	0.00	-
5	73,573.56	0.02	1,824.38	-
6	10,852.52	0.03	363.23	-
7	71,620.81	0.07	5,169.92	-
8	103,848.08	0.08	8,665.50	-
Sum	**367,985.92**	**-**	**14,778.63**	**0.04**
2007-2008(1 Year)				
1	16,659.39	-0.03	-480.55	-
2	27,116.56	0.01	208.96	-
3	64,315.01	-0.06	-3,777.19	-
4	101,966.74	-0.08	-8,244.22	-
5	73,573.56	-0.13	-9,864.99	-
6	10,852.52	-0.09	-932.28	-
7	71,620.81	-0.08	-5,702.43	-
8	103,848.08	-0.15	-15,381.61	-
Sum	**367,985.92**	**-**	**-44,174.32**	**-0.09**
2008-2011 (3 Years)				
1	16,659.39	0.04	641.93	-
2	27,116.56	0.04	941.12	-
3	64,315.01	0.06	3,738.89	-
4	101,966.74	0.05	5,404.20	-
5	73,573.56	0.04	3,088.20	-
6	10,852.52	0.04	482.44	-
7	71,620.81	0.02	1,382.13	-
8	103,848.08	0.08	7,416.66	-
Sum	**367,985.92**	-	**23,095.56**	**0.05**

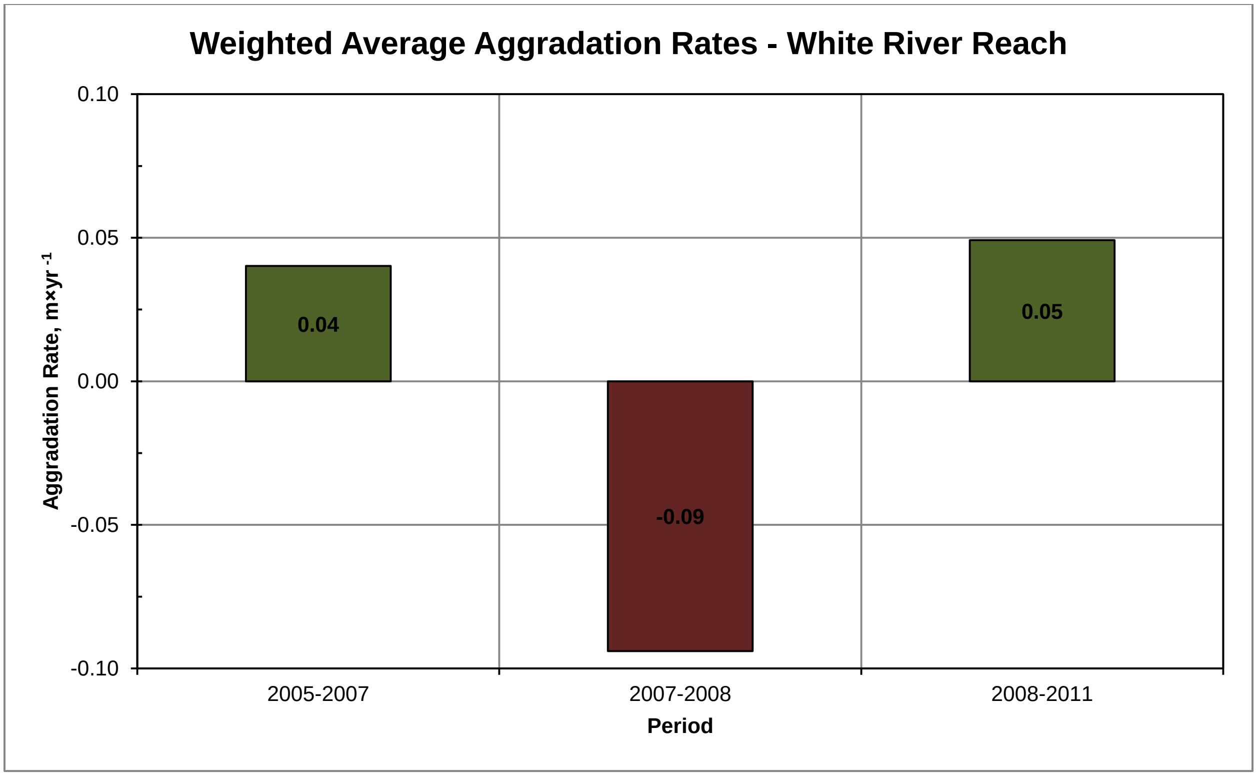


Figure 35: Weighted average aggradation rate for the entire White River during the study period, accounting for all available lines and cross sectional areas.

White River – Line 1

White River cross section 1 is the most downstream line in the study reach, about 40 m (131 ft) downstream of cross section 2 (Figure 12). The cross section is located at mile post (MP) 58.42 on State Route 410. The line was originally surveyed in 2005 and has been resurveyed in 2006, 2007, 2008, and 2011 (Table 13). The cross section is 470.3 m (1,543 ft) in length and represents 16,660 m^2 (179,300 ft^2) of the main channel area (Table 22). The cross section alignment points for line 1 are included in Table 9. Cross section 1 is one of three lines in the White River reach that has a bend in the line (represented by point L1M on Figure 12). This bend occurs in the riparian floodplain on the right bank of the active channel. The left bank position (L1L on Figure 12) is on a terrace in a riparian floodplain. The right bank position (L1R on Figure 12) is on an elevated terrace just east of State Route 410. An old growth riparian forest is between the mid-point and right bank positions with evidence of flood flows across the surface.

White River cross section 1 showed incision in the first part of its record and then later showed aggradation, with individual survey periods seeing aggradation rates varying from -0.03 $m \times yr^{-1}$ (-0.10 $ft \times yr^{-1}$) to 0.04 $m \times yr^{-1}$ (0.13 $ft \times yr^{-1}$) (Appendix A.23; Appendix B.23). Net cross section area change varies from -13.57 m^2 (-146.0 ft^2) to 54.36 m^2 (585.2 ft^2). The overall aggradation rate from 2005 to 2012 is 0.01 $m \times yr^{-1}$ (0.03 $ft \times yr^{-1}$) (Figure 34) and the net cross section area change from 2005 to 2012 is 28.54 m^2 (307.2 ft^2) (Figure 32). Accounting for the area represented by the cross section (Table 22), the overall aggradation in the active channel represented by cross section 1 from 2005 to 2011 is 1,011 m^3 (35,700 ft^3) (Appendix C.28). This is the second lowest aggradation rate

(Figure 34) and lowest volume change (Figure 33) at the White River along State Route 410 from 2005 to 2011.

White River – Line 2

White River cross section 2 is the second most downstream line in the study reach, about 55 m (180 ft) downstream of cross section 3 and 40 m (131 ft) upstream of cross section 1 (Figure 12). The cross section is located at MP 58.52 on State Route 410. The line was originally surveyed in 2005 and has been resurveyed in 2006, 2007, 2008, and 2011 (Table 13). The cross section is 389.1 m (1,277 ft) in length and represents 27,120 m^2 (291,900 ft^2) of the main channel area (Table 22). The cross section alignment points for line 2 are included in Table 9. Cross section 2 is one of three lines in the White River reach that has a bend in the line (represented by point L2M on Figure 12). This bend occurs in the riparian floodplain on the right bank of the active channel. The left bank position (L2L on Figure 12) is on a terrace in a riparian floodplain. The right bank position (L2R on Figure 12) is on an elevated terrace just east of State Route 410. An old growth riparian forest is between the mid-point and right bank positions with evidence of flood flows across the surface.

White River cross section 2 showed one period of incision in the first part of its record but was mostly aggradational, with individual survey periods seeing aggradation rates varying from -0.02 $m \times yr^{-1}$ (-0.06 $ft \times yr^{-1}$) to 0.04 $m \times yr^{-1}$ (0.12 $ft \times yr^{-1}$) (Appendix A.24; Appendix B.24). Net cross section area change varies from -13.37 m^2 (-143.9 ft^2) to 40.52 m^2 (436.1 ft^2). The overall aggradation rate from 2005 to 2012 is 0.01 $m \times yr^{-1}$ (0.03 $ft \times yr^{-1}$) (Figure 34) and the net cross section area change from 2005 to 2012 is 30.15 m^2 (324.5 ft^2) (Figure 32). Accounting for the area represented by the cross section (Table 22), the overall aggradation in the active channel represented by cross section 1 from 2005 to 2011 is 2,101 m^3 (74,200 ft^3) (Appendix C.29). This is the third lowest aggradation rate (Figure 34) and third lowest volume change (Figure 33) measured at the White River along State Route 410 during this study.

White River – Line 3

White River cross section 3 is the third most downstream line in the study reach, about 400 m (1,312 ft) downstream of cross section 4 and 55 m (180 ft) upstream of cross section 2 (Figure 12). The cross section is located at MP 58.56 on State Route 410. The line was originally surveyed in 2005 and has been resurveyed in 2006, 2007, 2008, and 2011 (Table 13). The cross section is 362.2 m (1,188 ft) in length and represents 64,320 m^2 (692,300 ft^2) of the main channel area (Table 22). The cross section alignment points for line 3 are included in Table 9. Cross section 3 is one of three lines in the White River reach that has a bend in the line (represented by point L3M on Figure 12). This bend occurs in the riparian floodplain on the right bank of the active channel. The left bank position (L3L on Figure 12) is on a terrace in a riparian floodplain. The right bank position (L3R on Figure 12) is on an elevated terrace just east of State Route 410. An old growth riparian forest is located between the mid-point and right bank positions and there is evidence of flood flows through the forested area. Cross section 3 is separated from line 4 by some distance and thus the area represented by the cross section is rather large.

White River cross section 3 showed initial incision in the first part of its record and then one period of aggradation, with individual survey periods seeing aggradation rates varying from -0.06 $m \times yr^{-1}$ (-

0.19 ft×yr^{-1}) to 0.06 m×yr^{-1} (0.190 ft×yr^{-1}) (Appendix A.25; Appendix B.25). Net cross section area change varies from -21.27 m^2 (-229.0 ft^2) to 63.17 m^2 (680.0 ft^2). The overall aggradation rate from 2005 to 2012 is 0.02 m×yr^{-1} (0.05 ft×yr^{-1}) (Figure 34) and the net cross section area change from 2005 to 2012 is 35.57 m^2 (382.9 ft^2) (Figure 32). Accounting for the area represented by the cross section (Table 22), the overall aggradation in the active channel represented by cross section 1 from 2005 to 2011 is 6,316 m^3 (223,060 ft^3) (Appendix C.30). This is the fourth highest aggradation rate (Figure 34) and fourth highest volume change (Figure 33) measured at the White River along State Route 410 during this study.

White River – Line 4

White River cross section 4 is the fourth most downstream line in the study reach, about 830 m (2,723 ft) downstream of cross section 3 and 400 m (1,312 ft) upstream of cross section 5 (Figure 12). The cross section is located at MP 58.79 on State Route 410. The line was originally surveyed in 2005 and has been resurveyed in 2006, 2007, 2008, and 2011 (Table 13). The cross section is 283.9 m (931.6 ft) in length and represents 102,000 m^2 (1,097,000 ft^2) of the main channel area (Table 22). The cross section alignment points for line 4 are included in Table 9. The left bank position is on a terrace in a riparian floodplain. The right bank position is on an elevated terrace just east of State Route 410. Cross section 4 is separated from lines 3 and 5 by some distance and thus the area represented by the cross section is rather large.

When Cross Section 4 was originally surveyed in 2005, the cross section that was generated did not have any common areas to compare with 2007 and successive survey years. Because of this issue, a comparison cannot be made between the years of 2005-2007, but 2007-2008 and 2008-2011 data all have common extents and can be analyzed without issue. This is the only cross section that had this anomalous error in the entire study.

White River cross section 4 initially showed incision followed by aggradation, with individual survey periods seeing aggradation rates varying from -0.08 m×yr^{-1} (-0.27 ft×yr^{-1}) to 0.05 m×yr^{-1} (0.17 ft×yr^{-1}) (Appendix A.26; Appendix B.26). Net cross section area change varies from -22.96 m^2 (-247.1 ft^2) to 45.15 m^2 (486.0 ft^2). The overall aggradation rate from 2005 to 2012 is 0.01 m×yr^{-1} (0.04 ft×yr^{-1}) (Figure 34) and the net cross section area change from 2005 to 2012 is 22.19 m^2 (238.8 ft^2) (Figure 32). Accounting for the area represented by the cross section (Table 22), the overall aggradation in the active channel represented by cross section 1 from 2005 to 2011 is 7,968 m^3 (281,400 ft^3) (Appendix C.31). This is the fourth lowest aggradation rate (Figure 34) but third highest volume change (Figure 33) measured at the White River along State Route 410 during the study period.

White River – Line 5

White River cross section 5 is the fourth most upstream line in the study reach, about 45 m (148 ft) downstream of cross section 6 and 830 m (2,723 ft) upstream of cross section 4 (Figure 12). The cross section is located at MP 59.43 on State Route 410. The line was originally surveyed in 2005 and has been resurveyed in 2006, 2007, 2008, and 2011 (Table 13). The cross section is 210.6 m (690.9 ft) in length and represents 73,570 m^2 (791,900 ft^2) of the main channel area (Table 22). The cross section alignment points for line 5 are included in Table 9. The left bank position is on a terrace in a riparian floodplain. The right bank position is on an elevated terrace just east of State Route 410.

Cross section 5 is separated from line 4 by some distance and thus the area represented by the cross section is rather large.

White River cross section 5 showed periods of aggradation, incision and then aggradation, with individual survey periods seeing aggradation rates varying from -0.13 $m\times yr^{-1}$ (-0.44 $ft\times yr^{-1}$) to 0.04 $m\times yr^{-1}$ (0.14 $ft\times yr^{-1}$) (Appendix A.27; Appendix B.27). Net cross section area change varies from -28.24 m^2 (-304.0 ft^2) to 26.52 m^2 (285.5 ft^2). The overall aggradation rate from 2005 to 2012 is 0.01 $m\times yr^{-1}$ (0.02 $ft\times yr^{-1}$) (Figure 34) and the net cross section area change from 2005 to 2012 is 8.73 m^2 (93.93 ft^2) (Figure 32). Accounting for the area represented by the cross section (Table 22), the overall aggradation in the active channel represented by cross section 1 from 2005 to 2011 is 3,048 m^3 (107,700 ft^3) (Appendix C.32). This is the lowest aggradation rate (Figure 34) but fourth lowest volume change (Figure 33) measured at the White River along State Route 410 during this study.

White River – Line 6

White River cross section 6 is the third most upstream line in the study reach, about 70 m (230 ft) downstream of cross section 7 and 45 m (148 ft) upstream of cross section 5 (Figure 12). The cross section is located at MP 59.46 on State Route 410. The line was originally surveyed in 2005 and has been resurveyed in 2006, 2007, 2008, and 2011 (Table 13). The cross section is 211.5 m (694.0 ft) in length and represents 10,850 m^2 (116,800 ft^2) of the main channel area (Table 22). The cross section alignment points for line 6 are included in Table 9. The left bank position is on a terrace in a riparian floodplain. The right bank position is on an elevated terrace just east of State Route 410.

White River cross section 6 showed periods of aggradation, incision and then aggradation similar to cross section 5, with individual survey periods seeing aggradation rates varying from -0.09 $m\times yr^{-1}$ (-0.28 $ft\times yr^{-1}$) to 0.04 $m\times yr^{-1}$ (0.14 $ft\times yr^{-1}$) (Appendix A.28; Appendix B.28). Net cross section area change varies from -18.17 m^2 (-195.6 ft^2) to 28.21 m^2 (303.7 ft^2). The overall aggradation rate from 2005 to 2012 is 0.02 $m\times yr^{-1}$ (0.06 $ft\times yr^{-1}$) (Figure 34) and the net cross section area change from 2005 to 2012 is 24.20 m^2 (260.5 ft^2) (Figure 32). Accounting for the area represented by the cross section (Table 22), the overall aggradation in the active channel represented by cross section 1 from 2005 to 2011 is 1,241 m^3 (43,840 ft^3) (Appendix C.33). This is the third highest aggradation rate (Figure 34) but second lowest volume change (Figure 33) measured at the White River along State Route 410 during this study.

White River – Line 7

White River cross section 7 is the second most upstream line in the study reach, about 750 m (2,461 ft) downstream of cross section 7 and 70 m (230 ft) upstream of cross section 5 (Figure 12). The cross section is located at MP 59.48 on State Route 410. The line was originally surveyed in 2005 and has been resurveyed in 2006, 2007, 2008, and 2011 (Table 13). The cross section is 260.4 m (854.4 ft) in length and represents 71,620 m^2 (770,900 ft^2) of the main channel area (Table 22). The cross section alignment points for line 7 are included in Table 9. The left bank position is on a terrace in a riparian floodplain. The right bank position is on an elevated terrace just east of State Route 410. Cross section 7 is separated from line 8 by some distance and thus the area represented by the cross section is rather large.

White River cross section 7 showed periods of aggradation, incision, and then aggradation again, similar to cross sections 5-6, with individual survey periods seeing aggradation rates varying from -0.08 $m \times yr^{-1}$ (-0.26 $ft \times yr^{-1}$) to 0.07 $m \times yr^{-1}$ (0.24 $ft \times yr^{-1}$) (Appendix A.29; Appendix B.29). Net cross section area change varies from -20.74 m^2 (-233.19 ft^2) to 37.60 m^2 (404.7 ft^2). The overall aggradation rate from 2005 to 2012 is 0.02 $m \times yr^{-1}$ (0.07 $ft \times yr^{-1}$) (Figure 34) and the net cross section area change from 2005 to 2012 is 31.94 m^2 (343.8 ft^2) (Figure 32). Accounting for the area represented by the cross section (Table 22), the overall aggradation in the active channel represented by cross section 1 from 2005 to 2011 is 8,784 m^3 (310,200 ft^3) (Appendix C.34). This is the second highest aggradation rate (Figure 34) and second highest volume change (Figure 33) at the White River along State Route 410 from 2005 to 2011.

White River – Line 8

White River cross section 8 is the most upstream line in the study reach, about 750 m (2,461 ft) upstream of cross section 7 (Figure 12). The cross section is located at MP 59.86 on State Route 410. The line was originally surveyed in 2005 and has been resurveyed in 2006, 2007, 2008, and 2011 (Table 13). The cross section is 234.5 m (769.3 ft) in length and represents 103,800 m^2 (1,118,000 ft^2) of the main channel area (Table 22). The cross section alignment points for line 8 are included in Table 9. The left bank position is on a terrace in a riparian floodplain. The right bank position is on an elevated terrace just east of State Route 410. Cross section 8 is separated from line 7 by some distance and thus the area represented by the cross section is rather large.

White River cross section 8 showed periods of aggradation, incision and then aggradation similar to cross sections 5-7, with individual survey periods seeing aggradation rates varying from -0.15 $m \times yr^{-1}$ (-0.49 $ft \times yr^{-1}$) to 0.08 $m \times yr^{-1}$ (0.27 $ft \times yr^{-1}$) (Appendix A.30; Appendix B.30). The rate of aggradation in the period of 2008-2011 is the highest for any line at White River during this time frame. Net cross section area change varies from -34.73 m^2 (-233.2 ft^2) to 50.24 m^2 (404.7 ft^2). The overall aggradation rate from 2005 to 2012 is 0.04 $m \times yr^{-1}$ (0.13 $ft \times yr^{-1}$) (Figure 34) and the net cross section area change from 2005 to 2012 is 54.64 m^2 (588.2 ft^2) (Figure 32). Accounting for the area represented by the cross section (Table 22), the overall aggradation in the active channel represented by cross section 1 from 2005 to 2011 is 24,200 m^3 (854,600 ft^3) (Appendix C.35). This is the highest aggradation rate (Figure 34) and volume change (Figure 33) at the White River along State Route 410 from 2005 to 2011. This volume change is so high due to line 8's large area of influence and high aggradation rates, especially in the 2008 to 2011 period.

Discussion

Overall Trends and Rates

Aggradation and incision rates in survey reaches across the park vary but the overall trend noted park-wide in the last 15 years is slightly aggradational. Table 24 shows the overall aggradation rates for survey locations, cross section lines, and survey years. Cross sections that represent longer intervals span multiple columns (e.g., if a survey was conducted in 2006 and in 2008, but no survey was conducted in 2007, the average rate for that area must occur between 2006 and 2008, not 2006-2007 and 2007-2008). Aggradation rates that are ±0.15 m are included in italics in order to highlight larger trends in aggradation in specific reaches.

With the exception of the 2007-2008 period, most recent periods at the park have been aggradational (Table 24). The 2007-2008 period was highlighted as mostly incisional in about 60% of the cross sections surveyed in this study. The period of 2009-2010 was remarkably aggradational, with almost 90% of the cross sections studied in the park showing aggradation.

Table 24 (Next Page): Overall aggradation rate analysis for cross sections in this study. Rates are shown by location, cross section line and time period. Areas that are aggradational are green while areas that are incisional are red; the more intense the color, the higher the rate of aggradation or incision. "Agg" means aggradation while "Inc" means incision. Values in the last 3 columns represent the total number of time periods, those with aggradation and those with incision for each location and cross section line.

Color ramp for aggradation rates in Table 24

Incision	Rate ($m \times yr^{-1}$)	Aggradation
See Note	0.00 - 0.15	*See Note*
	0.15 - 0.25	
	0.25 - 0.50	
	0.50 - 1.00	
	> 1.00	

Note: Rates within ±0.15 are considered to have no discernible change outside of the error margin. They are shown in the table only for reference and comparison to other lines in the survey reach.

Color ramp for summary percentages and totals in Table 24

Aggradation/Incision Ratio	Color
100% / 0%	
90% / 10%	
80% / 20%	
70% / 30%	
60% / 40%	
50% / 50%	
40% / 60%	
30% / 70%	
20% / 80%	
10% / 90%	
0% / 100%	

Cross Section	1997 to 2005	2005 to 2006	2006 to 2007	2007 to 2008	2008 to 2009	2009 to 2010	2010 to 2011	2011 to 2012	Total	Total Agg	Total Inc
Sunshine Point											
1		0.09	0.29		-0.24	0.12		0.04	7	6	1
2		-0.13	0.47		-0.24	0.11		0.00	7	5	2
3		0.07	0.44		-0.06	0.02		-0.01	7	5	2
4					-0.51	0.13		0.06	4	3	1
5					-0.52	0.18		-0.02	4	2	2
6					0.04	0.08		0.07	4	4	0
7					-0.05	0.12		-0.00	4	2	2
8					0.01	0.09		0.02	4	4	0
Longmire											
1	0.00	0.03	0.02		-0.35				5	3	2
2	-0.01	0.36	-0.03		-0.72	0.02	0.01	0.10	8	4	4
3	0.01	0.29	0.17		-0.91	0.50	-0.07	0.07	8	5	3
4	0.11	-0.51	-0.02		-0.27	-0.07	-0.29	0.29	8	1	7
5	0.05	-0.23	-0.17		0.30	-0.22	-0.18	0.23	8	2	6
6	-0.10	0.53	-0.06		0.32	0.14	-0.07	0.11	8	4	4
7	0.02	0.19	0.13		0.35	0.17	0.03	0.05	8	7	1
8	0.01	0.22	-0.21		-0.18	0.18	0.15	0.03	8	4	4
9	-0.01	-0.05	0.07		0.01	0.10	-0.07	-0.12	8	4	4
10	-0.07	0.52	-0.16		0.26	0.04	-0.12	0.01	8	4	4
Carter Falls											
1								0.57	1	1	0
2								0.14	1	1	0
3								0.14	1	1	0
4								0.09	1	1	0
5								-0.17	1	0	1
6								-0.01	1	0	1
Lower Van Trump											
1		1.25	-0.09		0.54	-0.04	0.03	-0.07	7	3	4
2		2.05	-0.37		-0.20	0.18	-0.07	0.01	7	3	4
3		0.72	0.14		0.21	0.08	-0.00	0.05	7	6	1
White River											
1		-0.01		-0.03	0.04				6	3	3
2		-0.02		0.01	0.04				6	4	2
3		-0.01		-0.06	0.06				6	3	3
4				-0.08	0.05				4	3	1
5		0.03		-0.13	0.04				6	5	1
6		0.03		-0.09	0.04				6	5	1
7		0.07		-0.08	0.02				6	5	1
8		0.08		-0.15	0.07				6	5	1
SUMMARY – all data, including rates without discernible change (> ±0.15 m)											
Total	10	23	23	24	29	28	28	26	191	118	73
Total Agg	6	16	12	9	17	25	20	19			
% Agg	60%	70%	52%	38%	59%	89%	71%	73%			
Total Inc	4	7	11	15	12	3	8	7			
% Inc	40%	30%	48%	62%	41%	11%	29%	27%			

There is no clear spatial or temporal trend between aggradation/incision rates observed in our study and the combination of yearly floods (greater than 70 m^3/s; 2,600 cfs) and snowpack at Paradise. For instance, in Table 24, the 2006 flood at Mount Rainier appears to show no change in stream profiles - neither aggradation nor incision. Beason (2007) found that cross sections surveyed in the winter of 2006 showed net aggradation at Longmire, Lower Van Trump, and Sunshine Point. It is likely that later storms incised this material before additional cross section surveys could be completed.

The lack of surveys of established cross sections in 2007 in many locations represents a lost snapshot of the geomorphic conditions in rivers at that time. It is likely that many smaller floods with relatively low sediment inputs lead to overall incision, which artificially shows a trend of incision in the rivers during this time period. Langbein and Leopold (1964) found that while high stream flows transfer large quantities of sediment, smaller flows accomplish geomorphic work through higher frequency, and thus serve as an important contributor to total sediment load. After the November 6, 2006 flood, there were four flows in water year 2007 and three flows in water year 2008 greater than 70 m^3/s (2,600 cfs) at the USGS stream gage in National, WA. One of the floods that occurred in December 2007 was a particularly strong atmospheric river that impacted the region just south of Mount Rainier. The USGS stream gage at National recorded a 3 year recurrence interval for that flood. These flows occurred between the 2006 and 2008 cross section surveys.

Basin-scale or local geomorphic factors may have a larger influence on aggradation and incision than does the timing or magnitude of storms. While our data does not conclusively prove or disprove the hypothesis, it is still believed that the timing of storms at the park has an influence on the geomorphic response in park rivers. Strong storms that occur with high freezing levels and little seasonal snow have a greater ability to erode lose, unconsolidated sediment at greater elevation ranges and provide that sediment to park streams (these are referred to as “muddy storms”). Storms that occur in winter months with high snow packs do not move as much sediment because the deep snow locks in sediment stores and prevents them from being eroded (referred to as “clear water storms”).

Aggradation is best viewed as a long-term trend, rather than an immediate response. The hill slopes produce sediment in sporadic events, which is routed downstream in storms. Sediment movement rates are dependent on sediment supply and storm patterns, which are likely to be highly variable. If mass wasting is a major process for sediment supply, then antecedent soil moisture conditions may be more important than storm magnitude or snowpack. If surface erosion is the main driver for “muddy” storms when the soil and unconsolidated sediment is not “protected” by snow, that would produce mostly wash load that does not overly contribute to aggradation. If bank erosion is the main contributor to sediment in motion during storms, this would result in aggradation phase differences or time lags between sites (i.e., one site erodes and the sediment comes to rest, temporarily, on the next site downstream). Further research into these areas may establish a better relationship between all of these forces the future.

Czuba and others (2012a) found that the best estimates of total sediment loads on the Nisqually River that leave Mount Rainier National Park are approximately 1,200,000 ± 180,000 tonnes/year between 1945 and 2011. Total sediment loads were high in the years after the 1947 Kautz Creek mudflow, but decreased between 1956 and 1985. However, sediment production has been increasing on the mountain due to a series of large floods and debris flows (Czuba et al., 2012a). Our cross sections on the Nisqually River show aggradation in a transport-limited fluvial system. This system is indicative of a river that has seen increasing sediment production and concurs with the findings of Czuba and others.

Czuba and others (2012a) also state that the White and Nisqually Rivers have likely developed a longitudinal channel profile that can more effectively sluice sediment as result of repeated lahars and debris flows. This indicates that the river systems transmit much of the available sediment load through the system instead of storing it in channel bars (like the Carbon River, for example). The authors state that despite this “equilibrium” channel profile, there is some potential for aggradation to develop along the upper Nisqually River between the glacial source to just downstream of the park boundary if large sediment pulses arrive from the mountain. This indicates that sediment deposition that occurs on the Nisqually River is likely in the form of transitory sediment waves that can potentially be tracked by repeat LiDAR or other technologies as they move downstream.

Overall Trends - Sunshine Point

Cross section results on the Nisqually River at Sunshine Point indicate a river system that is almost completely aggradational, with the exception of one period of incision from 2008 to 2009 (Table 24). All other periods show overall aggradation. Some years, like between 2006 – 2008 and 2009-2011, are completely aggradational – every cross section at the location has seen aggradation during those periods.

The Sunshine Point location is just upstream of the confluence of the Nisqually River with Tahoma Creek. Tahoma Creek flows from the South Tahoma Glacier. This area of the park has been especially active in the last 40 years, with repeated glacial outburst floods and debris flows. Tahoma Creek widened dramatically as a result of the outburst floods and debris flows, to the point that it closed the West Side Road 5 km (3 mi) from its intersection with the Nisqually-Longmire Road. This sediment has worked its way down Tahoma Creek and is, for most of its length, a system that is remarkably at equilibrium (Anderson, 2013).

Tahoma Creek is severely constricted as it flows underneath the Nisqually-Longmire Road Bridge, changing its active channel width from over 60 m (200 ft) to just 20 m (66 ft) at the bridge opening. The channel in the vicinity of the bridge has been repeatedly cleared out with heavy equipment to increase the channel capacity, especially after large storms. This has occurred approximately ten times since 1988 and every other year since 2006 (Anderson, 2013). During channel maintenance operations, channel soils are piled up alongside the creek in the active channel, in areas designated above the ordinary high water mark.

According to Anderson (2013), park management of the bridge has led to aggradation in the vicinity of Tahoma Creek Bridge and upstream approximately 0.5 – 1 km and downstream to the confluence of the Nisqually River. Changing the channel profile enhances aggradation, and stockpiling sediment on stream banks in the reach leads to preferentially more sediment production in the reach. It is likely that in addition to sediment coming down from the Nisqually River, sediment provided by channel maintenance at Tahoma Creek Bridge is providing the Nisqually River with enhanced sediment and leading to an aggradational system in the Sunshine Point reach. Anderson (2013) states that "dredging provides little benefit to the long-term maintenance of the Tahoma Creek Bridge, and likely plays a role in the persistence of local aggradation." This aggradation leads to sediment transport that may directly affect the Sunshine Point location in the future.

Comparisons of cross-valley and down-valley gradients at Sunshine Point (Table 25) show that the down-valley gradient is steeper than the cross-valley gradient. However, the negative cross-valley gradients indicate that the river preferentially flows toward the Nisqually-Paradise Road. The stream also tends to flow into and along the Pierce County Levee from the apex of the Nisqually-Paradise Road to well outside the park. In the last five years, the river has rarely flowed away from the levee, instead flowing adjacent to it. It is likely that the rip-rap used to construct the levee has a lower roughness than the channel roughness. This encourages the river to flow against the levee and could enhance damage, especially as smoother surfaces encourage faster flows and local incision, which only increases the possibility that the river will preferentially flow along the levee.

Table 25: Cross-valley and down-valley gradients for cross sections at Sunshine Point Campground based on a linear average best fit of 2012 survey points for each cross section. Cross sections are in order from upstream to downstream. Positive Average and Negative Average refer to the averages of those cross sections that are either only positive or only negative. Negative gradients mean the cross section is sloped toward the right bank; Positive gradients are sloped toward the left bank. Down-valley gradient is based on water surface elevation between extreme upstream and downstream cross sections in the reach.

Cross Section	Gradient (Percent)
3	-0.29%
1	-0.29%
8	0.30%
2	-0.31%
4	-0.79%
5	-0.94%
6	-0.16%
7	-0.15%
Average – All	-0.33%
Average – Negative	-0.42%
Average – Positive	0.30%
Down-valley Gradient	1.95%

Overall Trends - Longmire

The Longmire reach of the Nisqually River is best classified as "at equilibrium" in the last 15 years. Individual years show distinct periods of aggradation and incision at repeating intervals (Table 24). Beason (2007) described aggradation at Longmire that appeared to be increasing. Since that work, the reach incised (especially in 2008-2009) but has since begun to aggrade again in 2011-2012. It is likely that, as described by Czuba and others (2012a), the stretch of river in the Longmire reach is at equilibrium in longitudinal view and the river effectively sluices material through the reach during high flows.

Many of the upper cross sections have had relatively high incision, especially in cross sections 2-4. Field evidence of this includes a large bedrock knob that has been exposed in the stream bed in the vicinity of cross section 4. The bedrock knob is one of many ways to observe aggradation or incision in the reach from year to year.

Cross section 7 at Longmire has continually aggraded in all surveys, even in years where all other cross sections were experiencing incision. Aggradation was especially noted in the 2008-2009 period (Table 24). A likely explanation for the aggradation noted here is due to mechanical alteration of the channel by park staff following the 2006 flood. The channel was altered to increase channel conveyance in the areas between cross sections 2 and 6. It is likely that sediment has naturally accumulated in the zones downstream of cross section 6 as result of the alteration of the channel.

It is unlikely that the gravel fraction of the 2005 debris flow deposit from Lower Van Trump hairpin has entered the Longmire reach at this point. Prior debris flow deposits, especially those from 2001 and 2003, were likely sluiced through the Longmire reach in the 2006 flood. The 2005 debris flow material is still likely upstream of Longmire. It is anticipated that the upper cross sections will begin to aggrade as the debris flow deposit sediment wave enters the Longmire reach.

There has been little increase in the volume of material in the Longmire reach in the last 15 years. This is good news for park management and allows for a maximum natural channel conveyance. Continual monitoring of the reach will be necessary to track sediment pulses entering the Nisqually River upstream as they move downstream through the Longmire reach. It is still important to watch this area carefully given the proximity of park infrastructure and visitor facilities at Longmire.

Cross valley gradient in the Longmire reach is mostly oriented toward the right bank through most of the reach, with the exception of the last two cross sections which are oriented toward the left bank (Table 26). The cross-valley gradients do not exceed the down-valley gradient in any location. Cross-valley gradients are important, especially when the channel flows toward park infrastructure. At Mile Post 6, just downstream of the Longmire compound and survey reach, deposition of sediment on the left side of the active channel caused the river’s position to shift toward the right. In this case, the river had a dramatic bend back downstream, which eroded into the road prism for the Nisqually-Longmire Road. At this bend, the Park responded by building an Engineered Log Jam (ELJ) to prevent future bank erosion. To this date, the ELJ has been untested by additional flows.

Table 26: Cross-valley and down-valley gradients for cross sections at Longmire based on a linear average best fit of 2012 survey points for each cross section. Cross sections are in order from upstream to downstream. Positive Average and Negative Average refer to the averages of those cross sections that are either only positive or only negative. Negative gradients mean the cross section is sloped toward the right bank; Positive gradients are sloped toward the left bank. Down-valley gradient is based on water surface elevation between extreme upstream and downstream cross sections in the reach.

Cross Section	Gradient (Percent)
1	-1.80%
2	-0.85%
3	-1.76%
4	-3.17%
5	-0.60%
6	-0.98%
7	-0.38%
8	-0.98%
9	1.42%
10	1.85%
Average – All	-0.73%
Average – Negative	-1.32%
Average – Positive	1.64%
Down-valley Gradient	3.36%

Overall Trends - Carter Falls

The Carter Falls reach is a new location added in 2011 to monitor the routing of sediment from Lower Van Trump Hairpin down the Nisqually River. In the 2011-2012 period, it appears that sediment is entering the system in the upstream end of the reach. This would be consistent with sediment working its way down from Lower Van Trump, but it is only based on two years of data. Careful analysis and repeat surveys in this location will be necessary to trace sediment transport through the Carter Falls reach.

Cross-valley gradients for the Carter Falls reach are shown in Table 27. The cross-valley gradient does not exceed the down-valley gradient at any point and appears to wag from left-facing to right-facing on alternating cross sections. The wetted stream occupies the middle of the active channel throughout the reach and it does not appear that park infrastructure is at risk from cross-valley gradients at this time.

Table 27: Cross-valley and down-valley gradients for cross sections at Carter Falls based on a linear average best fit of 2012 survey points for each cross section. Cross sections are in order from upstream to downstream. Positive Average and Negative Average refer to the averages of those cross sections that are either only positive or only negative. Negative gradients mean the cross section is sloped toward the right bank; Positive gradients are sloped toward the left bank. Down-valley gradient is based on water surface elevation between extreme upstream and downstream cross sections in the reach.

Cross Section	Gradient (Percent)
1	3.20%
2	-0.42%
3	2.04%
4	-1.53%
5	0.30%
6	2.49%
Average – All	1.01%
Average – Negative	-0.98%
Average – Positive	2.01%
Down-valley Gradient	6.57%

Overall Trends - Lower Van Trump

One of the most compelling and complicated stories of landscape response during the study period occurs at the Lower Van Trump Hairpin. This location has been subject to numerous debris flows, most notably for this study, a debris flow that occurred in the fall of 2005. Placement of cross sections at Lower Van Trump Hairpin in 2005 was most fortuitous as it allowed for detailed study of landscape response to the 2005 debris flow, as well as a landslide that occurred in 2010. Beason (2007) describes the deposition of the 2005 debris flows, thanks to cross sections surveyed between 2005 and 2006 at Lower Van Trump. This represents the highest rate of cross section change observed anywhere in the study, up to 2 m per year (Table 24). Since 2006, and with the exception of cross section 1 in 2009, the Van Trump reach has been almost completely incisional, as the river reworks the debris flow deposit and mobilizes it downstream. Cross section 1 in 2009 shows the influence of the landslide deposit that occurred in November 2008. Other cross sections in that year incised as flows jetted through the constriction (cross section 2) and aggraded as water slowed for the constriction (cross section 3).

The presence of the debris flow deposit constricted the Nisqually River and Van Trump Creek into a reach about 35 m (110 ft) wide at its narrowest (Figure 36). During a ~14 year RI storm on November 12, 2008, increased stream flows incised into the left bank at the constriction (Ricksecker Point area). A landslide issued from the undercut bank and steep hillside above the river, depositing about 18,000 m^3 (630,000 ft^3) of material into the river bed (Figure 36). This likely either blocked the river for a short time or concentrated the river into a very narrow channel that widened as stream velocities and shear stresses increased. The river also likely pooled behind the constriction just after the landslide deposited in the active channel.

A differencing map between the 2008 and 2012 LiDAR-derived bare earth surfaces (Watershed Sciences, 2012; Watershed Sciences, 2009) is shown in Figure 37. LiDAR differencing “subtracts” the 2012 bare earth surface from the 2008 surface to highlight changes in the topography between time periods. Green colors show aggradation while red colors show incision; the more intense the color, the higher the rate. Zone "A" on Figure 37 is the 2005 debris flow deposit mantling the right bank of the active channel. Zone "B" highlights the landslide scar (20,000 m^3; 710,000 ft^3; Figure 36) while Zone "C" shows the landslide deposit in the active channel (18,000 m^3; 630,000 ft^3). Zone "D" on Figure 37 likely represents aggradation that occurs as water slows and pools up behind the physical impedance presented by both the landslide and debris flows deposit. Zone "E" shows the forces of incision that occur through the narrow reach between the debris flow and landslide deposits. This zone includes head cutting that occurs upstream from the narrow impedance and incision caused by the jetting of water downstream of it. Zone "F" represents aggradation that occurs behind the landslide deposit as water eddies and loses entrainment velocity. The aggradation upstream, incision through the reach, and aggradation downstream of the debris flow/landslide boundary is similar to effects of sediment pulses on channel morphology noted in rivers affected by debris flows in Montana by Hoffman and Gabet (2007).

It is important that fluvial aggradation rates in this reach are not confused with large, instantaneous deposits made by debris flows and landslides. The period from 2005-2006 measures a significant debris flow deposit that spread across the study area (Table 24). Determining rates of fluvial aggradation within the 2005 debris flow deposit is essentially impossible. The rates presented between the time period of 2008 and 2009 are heavily influenced by the landslide deposit and associated fluvial disturbance from the deposit. All other rates are likely more indicative of aggradation or incision in the fluvial systems in response to the large slug of sediment that was deposited during the two mass wasting events.

The presence of the 2005 debris flow in the active channel has moved the primary thread of the river well away from the Longmire-Paradise Road. Therefore, the road is relatively safe as long as this buffer remains in place. Events like the 2008 landslide encouraged incision into the debris flow deposit and both deposits will continue to be reworked by fluvial sediment transport. This sediment will continue to work its way downstream, passing through the Carter Falls, Longmire, and eventually, Sunshine Point reach. It remains to be seen how cohesive the sediment wave will be as it moves laterally away from the source area.

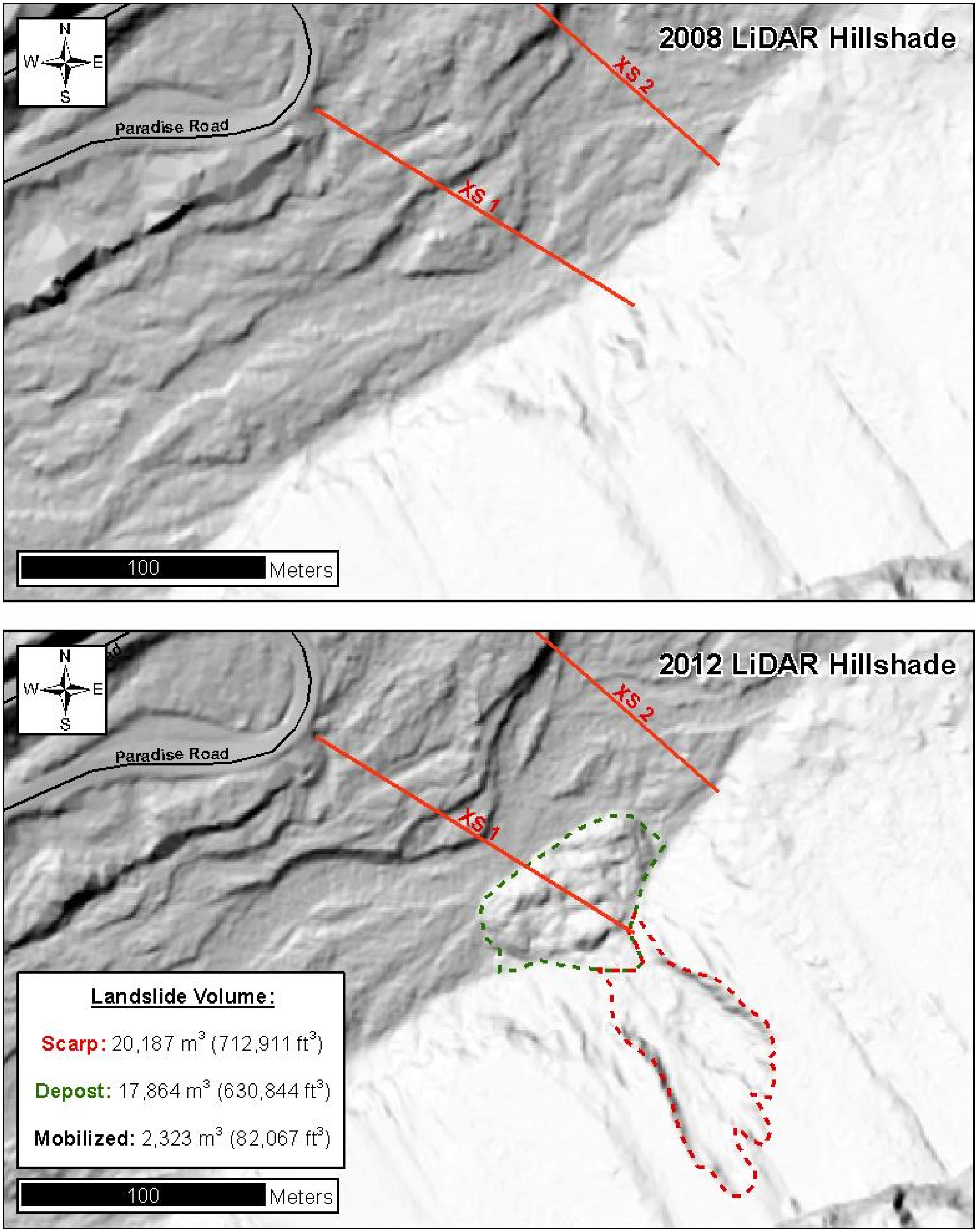


Figure 36: Ricksecker landslide at Lower Van Trump hairpin, which occurred November 12, 2008 during a ~14 year RI flood. LiDAR differencing between 2008 and 2012 LiDAR layers gives exact volumes from the scarp, deposit and material mobilized downstream by the Nisqually River and Van Trump Creek. Scale: 1:2,426.

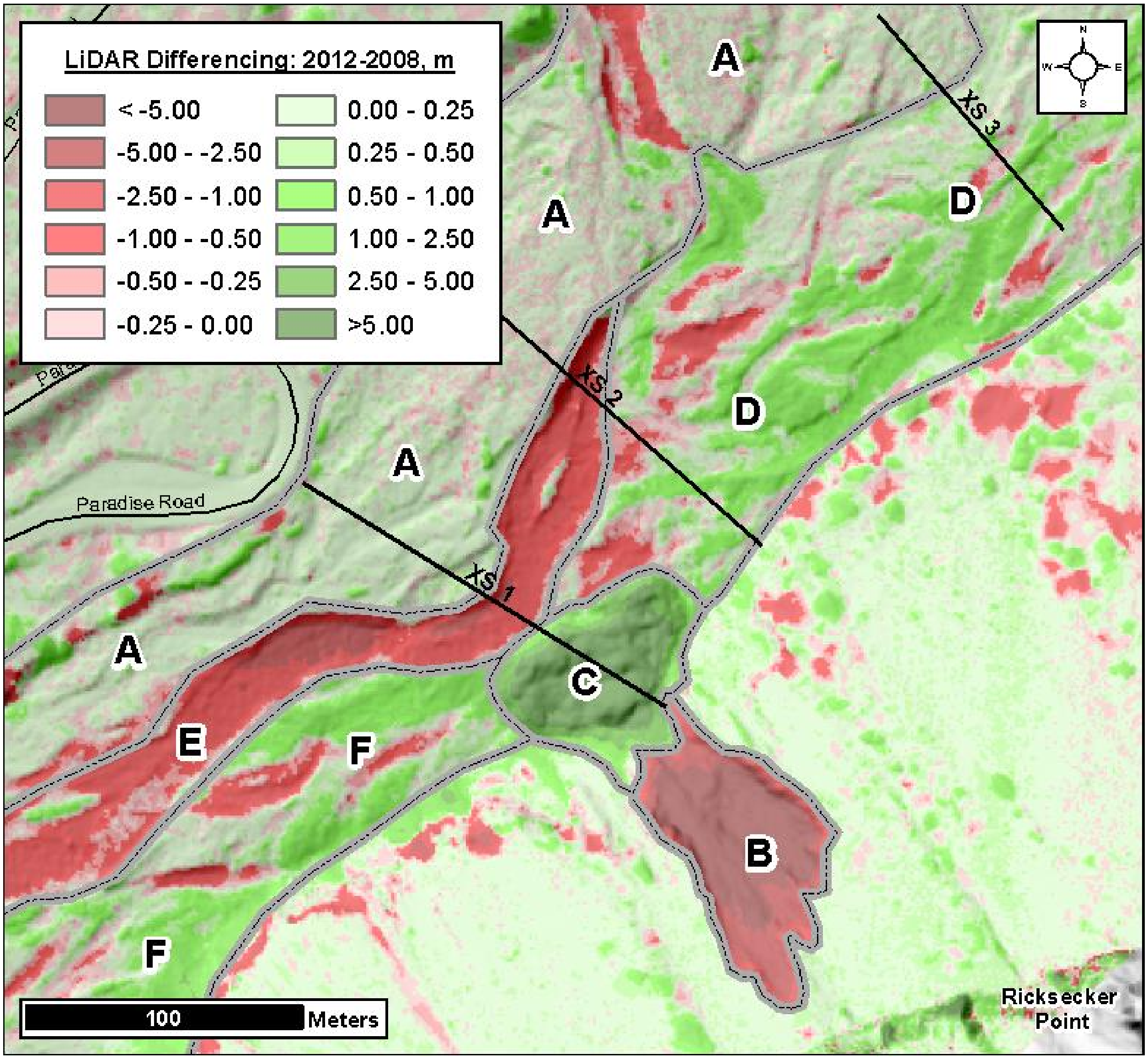


Figure 37: LiDAR differencing map of the area around the Ricksecker landside, which occurred November 12, 2008 during a ~14 year RI flood. The colors represent the 2012 LiDAR bare earth surface minus the 2008 LiDAR bare earth surface, in meters. Clearly visible are zones of aggradation upstream of the landslide deposit, incision past the deposit, incision downstream of the deposit where flow was jetted into the 2005 Van Trump debris flow deposit and aggradation behind the landslide deposit. See text for description of zones. Scale: 1:2,500.

The cross-valley gradient at Lower Van Trump Hairpin is strongly tilted toward the left bank, which tends to indicate the river's energy is still aimed at the Ricksecker Point side of the valley (Table 28). Overall cross-valley gradients do not exceed the down-valley gradient, but the gradient in line 2 is strongly titled toward the left bank, almost at the down-stream gradient. Park infrastructure in this area is mostly on the right bank and includes a road and buried utility lines. Park infrastructure is also located up on the Ricksecker Point pull off and includes a road, but it is unlikely that bank erosion would lead to consequences to the infrastructure at the top of the ridge.

Table 28: Cross-valley and down-valley gradients for cross sections at Lower Van Trump based on a linear average best fit of 2012 survey points for each cross section. Cross sections are in order from upstream to downstream. Positive gradients are sloped toward the left bank. Down-valley gradient is based on water surface elevation between extreme upstream and downstream cross sections in the reach.

Cross Section	Gradient (Percent)
1	1.80%
2	5.12%
3	2.05%
Average – All	2.99%
Down-valley Gradient	6.77%

Overall Trends - White River

Sedimentation rates on the White River along State Route 410 appear to be nearly at equilibrium, to slightly aggradational (Table 24). Only three time periods are available for detailed study. The time period from 2007-2008 is almost entirely incisional, which mirrors the trend noted at Longmire and Lower Van Trump. The other time periods are essentially steady but show slight evidence for aggradation, all within the error of our survey equipment.

As evidenced by other authors (Herrera, 2005; Beason, 2007), the White River in the vicinity of these lines is as much as 4.5 m (15 ft) higher than the surrounding old-growth forest and State Route 410 to the west. Because of the prevailing geomorphic and topographic setting, significant aggradation is not necessary to tip the river into an overbank flooding state that would cause significant monetary damage to Park Service and Washington State Department of Transportation infrastructure.

ENTRIX (2010) documented numerous significant head cut channels between the river and road, some as few as 3 m (10 ft) from connecting to the active channel. Stream banks are almost non-existent in these locations and a flood activating the head cut channel could lead to relatively major damage from a relatively small head cut in comparison to the size of the active channel. Because of the floodplain disequilibrium and the potential for damage from overbank flows, it is recommended that cross sections continue to be measured in this location to trace sediment inputs as they enter or depart the reach. If a significant sediment input is noted, short-term solutions like those proposed by ENTRIX (2010) can be deployed to minimize damage to park and state infrastructure.

Despite head cuts and the floodplain disequilibrium, Kennard and others (2011) found that standing and fallen (dead) old growth forests effectively dissipate enough of the river's energy and prevent it from moving into the riparian forest. While the river occupies its historic channel, aggradation can lead to an elevated channel surface as well as a floodplain surface that creates a more stable surface for new forest communities. The relatively low-lying floodplain forests play a fundamental role in river morphology by precluding major channel avulsions (Kennard et al., 2011).

Sediment sources in this reach are likely exasperated by the 1963 Little Tahoma Peak collapse (Czuba et al., 2012a). Czuba and others state that a pulse of sediment from this event is likely causing the aggradation in the White River in this stretch. However, given the relatively modest aggradation noted in this reach, it is likely that either the sediment has arrived and not moved or is not yet within the reach at this point. Given relatively extreme disequilibrium and lack of stream banks in the affected reaches, it is more likely that the sediment from the collapse of Little Tahoma peak has arrived in the reach but has not yet exited the area. Further study in the future here would answer this question with better certainty.

Cross-valley gradients in the White River reach are much less than the down-valley gradient (Table 29). In fact, the average cross-valley gradient is 0% and those cross sections with higher rates are very modest. However, the one major exception to this rule is cross section 1, which is oriented very strongly (compared to the down-valley gradient) toward the right bank. Cross section 1 has the highest amount of floodplain disequilibrium and the fact the river is "tilted" toward the right bank (the side with State Route 410) is concerning. This is another are that needs to be monitored in the coming years.

Table 29: Cross-valley and down-valley gradients for cross sections at White River based on a linear average best fit of 2011 survey points for each cross section. Cross sections are in order from upstream to downstream. Positive Average and Negative Average refer to the averages of those cross sections that are either only positive or only negative. Negative gradients mean the cross section is sloped toward the right bank; Positive gradients are sloped toward the left bank. Down-valley gradient is based on water surface elevation between extreme upstream and downstream cross sections in the reach.

Cross Section	Gradient (Percent)
8	0.35%
7	-0.07%
6	0.40%
5	0.40%
4	0.20%
3	0.01%
2	-0.09%
1	-1.20%
Average – All	0.00%
Average – Negative	0.27%
Average – Positive	-0.46%
Down-valley Gradient	1.90%

Sediment Sources

As Mount Rainier succumbs to the effects of weathering, it is a very prodigious sediment producer. This sediment production can occur in many ways; however, the primary sources that we are interested in this study are rock fall and debris flows.

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 3,388 m (11,117 ft) spire of volcanic breccia interlayered with lava flows which lies just to the east of the main summit. 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 6.5 km (4 mi) down from the peak, over the Emmons Glacier and into the White River valley, losing just over 1,800 m (6,000 ft) of altitude (Crandell and Fahnestock, 1965).

This rock fall provided a tremendous amount of material for the Emmons Glacier. Much of the rock fall that accumulated on the glacier lead to decreased ablation of glacial ice and a rapid advance of the glacier following the event until the late 1990s (Driedger, 1993; Fountain et al., 2003). As the sediment was provided to the White River, it was transported down into the fluvial reaches, one of which is along State Route 410 and where our eight cross sections are. Czuba and others (2012a) state that the pulse of sediment that is causing aggradation in the White River along State Route 410 may be predominately sourced by the 1963 rock fall.

Similar rock falls occur with frequency on Mount Rainier. On June 25, 2011, a rock fall was recorded by hikers on the Muir Snowfield coming from the Nisqually Cleaver. The rock fall was estimated at 0.5-1.0 million cubic yards and traveled more than a mile from its source area onto the Nisqually Glacier (C. Magirl, personal communication, 2013). These and other rock falls contribute significant sediment volumes to glaciers, which eventually provide the sediment to rivers to carry out of the park.

Glacial retreat is exposing vast stores of sediment in areas on the mountain that were previously locked into the ice. Debris flows have initiated in these areas, some of which did not see any before the 2000's but have now seen numerous debris flows (Copeland, 2008). Copeland also states that there is a "seemingly limitless supply of un-vegetated, unconsolidated material remaining from Pleistocene and Little Ice Age glacier retreat." This tends to indicate that with current climate warming, sediment production from the mountain will likely remain high. Debris flows initiate close to glacier margins due to the concentrated water flow which can be quickly delivered to adjacent steep, unstable slopes (Copeland, 2008; Lancaster et al, 2012). There is also a general correlation between increasing debris flow activity and increasing glacial retreat with strong autumnal atmospheric rivers as the primary triggering mechanism of debris flows (Copeland, 2009; Lancaster et al, 2012).

Mount Rainier will continue to provide sediment via rock falls and debris flows to glaciers, which in turn provide the sediment to braided rivers. While this sediment likely effectively routes through these systems, it is the transitory phases where rivers build up sediment in bars and along the active channel that can be worrisome for park management. If rapid channel aggradation occurs because of increased sediment production, active channel floodplains can increase in size and affect riparian areas and developed locations near park rivers. These sediment pulses may then move downstream, affecting different areas as they move. These dynamic systems require routine monitoring to determine threats to facilities and better trace the path of sediment transport throughout the system.

Future Research

This is among the first few studies to quantify rates of aggradation in the park. Ongoing surveying in Mount Rainier National Park should be expanded to include rivers not previously studied. Continual monitoring of previously studied reaches will be necessary to determine when channel conditions change to highlight the arrival of a new wave of sediment from upstream source areas. These data should be coupled with data at other Cascade volcanoes in order to provide information regarding sedimentation budgets and to quantify the regional scope of aggradation.

This study just looks at a few key areas at Mount Rainier, especially those areas that are near infrastructure. The phenomena of aggradation is most certainly occurring in other rivers at Mount Rainier, but the lack of park infrastructure in these locations means the risk to the areas is lower compared to other areas like Longmire and White River. Expanding the research into areas where there is little or no infrastructure would give a more complete look at the effects of aggradation on a larger area. The advent of aerial surveying with LiDAR and other technologies are allowing for remote sensing of aggradation and generate far more data than a traditional ground survey. Enhancing the aggradation data with LiDAR datasets would most certainly improve the story of aggradation at Mount Rainier.

Conclusions

A river's form and function are broadly driven by sediment inputs balanced with stream flow. When either sediment production or stream flow increase, the river comes out of equilibrium causing either aggradation or incision. Aggradation and incision cause changes to a river's floodplain size, which can exasperate hazards like flooding and debris flows. Much infrastructure at MORA is built in and near proglacial braided rivers and their associated floodplains. It is critical to understand the rates of aggradation in these areas to anticipate future use of these areas.

At Mount Rainier, debris flows occur with some frequency and the park has seen at least 12 separate debris flows initiated in 6 drainages during events in 2001, 2003, 2005 and 2006. All of the debris flows since 2006 have occurred in areas that have been recently deglaciated. Retreating glaciers are exposing vast areas of loose, unstable sediment on steep slopes. Given that Mount Rainier has many areas of terrain like this above 2,500 m, the potential sediment budget at Mount Rainier is very high. Additionally, some of the largest floods on record have occurred in the last two decades. The combined extremes we are seeing in the climate and geology at Mount Rainier are consistent with models for increasing climate change in the Pacific Northwest.

Cross sections have been surveyed in developed locations in MORA. On the Nisqually River on the southwest face of Mount Rainier, we surveyed 8 cross sections at Sunshine Point, 10 at Longmire, 6 at Carter Falls and 3 at Lower Van Trump Hairpin. On the White River on the northeast side of the park, we surveyed 8 cross sections. Each cross section represents a snapshot of the geomorphic landscape at that point in time, a baseline for the system. Each year after, we reoccupied these cross sections to see trends in the geomorphic landscape associated with aggradation or incision in the reach. These cross sections were constructed with extremely accurate surveying equipment called a total station that has sub-centimeter accuracy.

Park-wide aggradation rates are highly variable and depend on location, time period and sediment inputs. However, every location in this study has seen overall aggradation, despite periods of incision. Additionally, despite the largest floods of record in the park's history, rivers continue to aggrade, which indicates sediment delivery is overwhelming erosive forces in rivers. These results indicate that river systems at Mount Rainier are strongly driven by sediment production, a trend that we expect to remain constant or increase. Increasing aggradation rates observed at Mount Rainier are an example of the complex interactions of a glaciated landscape responding to climate change. As glacial retreat occurs in alpine areas, new unvegetated and unstable sediment is exposed and continually transported to braided rivers already choked with material. Aggrading rivers – especially those mechanically confined and not allowed to move about their natural floodplains – develop unstable convex profiles, prone to avulsion to lower-lying floodplains. Much infrastructure has been built in low-lying areas near braided rivers at MORA.

Climate change, glacial recession and the timing of atmospheric rivers are causing aggradation rates to increase, which in turn causes river beds to build up progressively higher, thereby increasing flood danger to infrastructure. Flooding, damage to park infrastructure and a record-long park closure has been attributed to the aggradation and avulsion that is occurring in the park rivers. "Muddy" storms or those that occur with low snow packs and high precipitation will be favored by future climate conditions. These climatic extremes will lead to aggradation, which will have progressively detrimental consequences to areas farther away as sediment budgets increase. This finding is important not only to development within the park, but to the fluvial environments more distant from the park. Aggradation will present new problems to planning and engineering in glacially-sourced rivers here and in other glacial environments in the Pacific Northwest.

Literature Cited

Abbe, T.B., J. Bountry, G. Ward, L. Piety, M. McBride and P.M. Kennard, 2003, Forest influence on floodplain development and channel migration zones. Geological Society of America Abstracts with Programs, Vol. 35, p. 352.

Abbe T.B., S.R. Beason, P.M. Kennard and J. Park, 2010, Rivers gone wild: Mountain river response to a warming climate in the Pacific Northwest: Freshwater, Vol. 2, No. 2, p. 10-13.

Anderson, S., 2013, Tahoma Creek: Aggradation and resource management: Unpublished internal report, Mount Rainier National Park, 43 p.

Bates, R.L. and J.A. Jackson, 1984, Dictionary of Geological Terms, 3rd Edition: Anchor Books, New York, NY, 571 p.

Beason, S.R., 2007, The environmental implications of aggradation in major braided rivers at Mount Rainier National Park, Washington: M.S. Environmental Science Thesis, University of Northern Iowa, 165 p.

Beason, S.R. and P.M. Kennard, 2007, Environmental and ecological implications of aggradation in braided rivers at Mount Rainier National Park, p. 52-53 *in* J.Selleck, ed., Natural Resources Year in Review—2006, Publication D-1859, National Park Service, Denver, CO, 136 p.

Bhutiyani, M.R., 2000, Sediment Load Characteristics of a Proglacial Stream of Siachen Glacier and the Erosion Rate in Nubra Valley in the Karakoram Himalayas, India: Journal of Hydrology, v. 227, p. 84-92.

Burtchard, G., M. Redmond, S. Makar, V. Houser and J. Cleary, 2013, Camp Sunshine Point: Mount Rainier National Park Archaeological Reconnaissance Report ARR2012-05, 27 p.

Catton, T., 1996, Wonderland: An administrative history of Mount Rainier National Park: National Park Service Cultural Resources Program, Seattle, WA, 723 p.

Copeland, E.A., 2008, Initiation of recent debris flows on Mount Rainier, Washington: A climate warming signal? American Geophysical Union 2008 Fall Meeting, San Francisco, CA.

Copeland, E.A., 2009, Recent periglacial debris flows from Mount Rainier, Washington: M.S. Thesis, Oregon State University, 124 p.

Crandell, D.R., 1969, The Geologic Story of Mount Rainier: United States Geological Survey Bulletin 1292, 43 p.

Crandell, D.R., 1971, Post Glacial Lahars from Mount Rainier National Park, Washington: United States Geological Survey Professional Paper 667, 80 p.

Crandell, D.R. and R.K. Fahnestock, 1965, Rockfalls and Avalanches from Little Tahoma Peak on Mount Rainier, Washington: United States Geological Survey Bulletin 1221-A, 30 p.

Czuba, J.A., C.S. Magirl, C.R. Czuba, C.A. Curran, K.H. Johnson, T.D. Olsen, H.K. Kimball and C.C. Gish, 2012a, Geomorphic analysis of the river response to sedimentation downstream of Mount Rainier Washington: United States Geological Survey Open File Report 2012-1242, 134 p.

Czuba, J.A., T.D. Olsen, C.R. Czuba, C.S. Magirl, and C.S. Gish, 2012b, Changes in sediment volume in Alder Lake, Nisqually River Basin, Washington, 1945-2011: United States Geological Survey Open-File Report 2012-1068, 30 p.

Czuba, J.A., C.S. Magirl, C.R. Czuba, E.E. Grossman, C.A. Curran, A.S. Gendaszek, and R.S. Dinicola, 2011, Sediment load from major rivers into Puget Sound and its adjacent waters: United States Geological Survey Fact Sheet 2011-3083, 4 p.

Czuba, J.A., C.R. Czuba, C.S. Magirl and F.D. Voss, 2010, Channel conveyance capacity, channel change, and sediment transport in the lower Puyallup, White and Carbon Rivers, Western Washington: United States Geological Survey Scientific Investigations Report 2010-5240, 104 p.

Donovan, K.H.M., 2005, An Investigation into the 2003 Van Trump Creek Debris Flow, Mount Rainier, Washington, United States of America: BSc thesis, School of Earth & Environmental Sciences, University of Portsmouth, UK, 58 p.

Driedger, C.L., 1993, Glaciers on Mount Rainier: United States Geological Survey Open-File Report 92-474, 2 p.

Driedger, C.L. and P.M. Kennard, 1986, Ice Volumes on Cascade Volcanoes: Mount Rainier, Mount Hood, Three Sisters, and Mount Shasta: United States Geological Survey Professional Paper 1365, 28 p.

Driedger, C.L. and K.M. Scott, 2002, Mount Rainier: Learning to Live with Volcanic Risk: United States Geological Survey Fact Sheet 034-02, 4 p.

ENTRIX Environmental Consultants, 2010, White River geomorphic reach analysis: Phase 1 report, Mount Rainier National Park: Project #42543001, WA PRA MORA ES(3), Task Order Number T-09-001, Seattle, WA.

Fahnestock, R.K, 1963, Morphology and Hydrology of a Glacial Stream – White River, Mount Rainier, Washington: United States Geological Survey Professional Paper 422-A, 70 p.

Fountain, A.G., D. Percy and F. Granshaw, 2003, Glaciers of the American West: Geological Society of America Abstracts with Programs, Vol. 35, No. 6, p. 131.

Haritashya, U.K., P. Singh, N. Kumar and R.P. Gupta, 2006, Suspended Sediment from the Gangotri Glacier: Quantification, Variability and Associations with Discharge and Air Temperature: Journal of Hydrology, Vol. 321, p. 116-130.

Harris, A.G., E. Tuttle and S.D. Tuttle, 2004, Geology of National Parks, 6th Edition: Kendall/Hunt Publishing Company, Dubuque, IA, 882 p.

Hasnain, S.I. and R.J. Thayyen, 1999, Discharge and Suspended Sediment Concentrations of Meltwaters Draining from the Dokriani Glacier, Garhwal Himalaya, India: Journal of Hydrology, Vol. 218, p. 191-198.

Hayes, S.K., D.R. Montgomery and C.G. Newhall, 2002, Fluvial Sediment Transport and Deposition Following the 1991 Eruption of Mount Pinatubo: Geomorphology Vol. 45, p. 211-224.

Henshaw, F.F. and G.L. Parker, 1913, Water Powers of the Cascade Range, Part II: Cowlitz, Nisqually, Puyallup, White, Green and Cedar River Drainage Basins: United States Geological Survey Water Supply Paper 313, 170 p.

Herrera Environmental Consultants, 2005, Reach Analysis, White River, Pierce County, Washington: Herrera Environmental Consultants, Inc., 123 p.

Hodgkins, R., R. Cooper, J. Wadham and M. Tranter, 2003, Suspended Sediment Fluxes in a High-Arctic Glacerised Catchment: Implications for Fluvial Sediment Storage: Sedimentary Geology, Vol. 162, p. 105-117.

Hoffman, D.E. and E.J. Gabet, 2007, Effects of Sediment Pulses on Channel Morphology in a Gravel-Bed River: Bulletin of the Geological Society of America, Vol. 119, No. 1/2, p. 116-125.

Kennard, P.M., T.B. Abbe, M. Ericsson, J. Bjork and S.R. Beason, 2011, The role of riparian forests in river avulsion and floodplain disequilibrium in aggrading pro-glacial braided rivers: A newly recognized model in fluvial geomorphology: Geological Society of America Abstracts with Programs, Vol. 43, No. 5, p. 164.

Lancaster, S.T., A.W. Nolin, E.A. Copeland and G.E. Grant, 2012, Periglacial debris-flow initiation and susceptibility and glacier recession from imagery, airborne LiDAR, and ground-based mapping: Geosphere, Vol. 8, No. 2, p. 417-430; doi: 10.1130/GES00713.1.

Lane, E.W., 1955, The importance of fluvial morphology in hydraulic engineering: Proceedings of the American Society of Civil Engineers 81, p. 745-761.

Langbein, W.B. and L.B. Leopold, 1964, Quasi-equilibrium states in channel morphology: American Journal of Science, Vol. 262, p. 782-794.

Lillie, R.J., 2005, Parks and Plates: The Geology of Our National Parks, Monuments, and Seashores: W. W. Norton and Company, New York, NY, 298 p.

Lillie, R.J. and C.L. Driedger, 2001, Subduction, Volcanism and Natural Hazards: Geology Training Manual for Mount Rainier National Park: Unpublished Internal Document for Mount Rainier National Park, 68 p.

Lombard, R.E., M.B. Miles, L.M. Nelson, D.L. Kresch and P.J. Carpenter, 1981, Channel Conditions in the Lower Toutle and Cowlitz Rivers Resulting from the Mudflows of May 18, 1980: United States Geological Survey Circular 850-C, 15 p.

Marren, P.M., 2004, Magnitude and Frequency in Proglacial Rivers: a Geomorphological and Sedimentological Perspective: Earth Science Reviews, Vol. 70, p. 203-251.

Marren, P.M. and S.C. Toomath, 2014, Channel pattern of proglaical rivers: Topographic forcing due to glacier retreat: Earth Surface Processes and Landforms, doi: 10.1002/esp.3545.

Mass, C., 2008, The weather of the Pacific Northwest: University of Washington Press, Seattle, WA, 336 p.

Meunier, P., F. Métivier, E. Lajeunesse, A.S. Mériaux and J. Faure, 2006, Flow Pattern and Sediment Transport in a Braided River: The "Torrent de St Pierre" (French Alps): Journal of Hydrology, Vol. 330, p. 496-505.

Metzler, D. and E. Jurgalski, 2007, 50 most prominent peaks on Earth [Online]: Last Updated December 10, 2007, Retrieved June 30, 2013 from http://www.peaklist.org/WWlists/WorldTop50.html.

Miller, D.J. and L.E. Benda, 2007, Effects of Punctuated Sediment Supply on Valley-Floor Landforms and Sediment Transport: Geological Society of America Bulletin, Vol. 112, No. 12, p. 1814-1824.

National Park Service, 2011, Mount Rainier Annual Visitor Statistics 1967-2010 [Online]: Last Updated January 2011, Retrieved June 30, 2012 from http://www.nps.gov/mora/parkmgmt/upload/vis-stats-1967-2010-2.pdf.

National Park Service, 2006, Rebuilding Rainier: Mount Rainier National Park, Park News, no. 3, December 20, 2006, 3 p.

National Park Service, 1998, Road to Paradise, Mount Rainier National Park: National Park Service Cultural Landscape Inventory, 99 p.

National Research Council, 1994, Mount Rainier, Active Cascade Volcano: Research Strategies for Mitigating Risk from a High Snow-Clad Volcano in a Populous Region: National Academy Press, Washington D.C. 114 p.

Neiman, P.J., F.M. Ralph, G.A. Wick, Y-H. Kuo, T-K. Wee, Z. Ma, G.H. Taylor and M.D. Dettinger, 2008, Diagnosis of an intense atmospheric river impacting the Pacific Northwest: Storm summary and offshore vertical structure observed with COSMIC satellite retrievals: Monthly Weather Review, American Meterological Society, Vol. 136, p. 4398-4420.

Neiman, P.J., L.J. Schick, F.M. Ralph, M. Hughes, and G.A. Wick, 2011, Flooding in Western Washington: The connections to atmospheric rivers: Journal of Hydrometerology, Vol. 12, No. 6, p 1337-1358, doi: 10.1175/2011JHM1358.1.

Nelson, L.M., 1987, Flood Characteristics for the Nisqually River and Susceptibility of Sunshine Point and Longmire Facilities to Flooding in Mount Rainier National Park, Washington: United States Geological Survey Water Resources Investigations Report 86-4179, 18 p.

Patterson, W.S.B., 2000. The physics of glaciers: Butterworth-Heinemann, 496 p.

Pringle, P.T., 2008, Roadside geology of Mount Rainier National Park and vicinity: Washington Division of Geology and Earth Resources Information Circular 107, 191 p.

Reneau, S.L., D. Katzman, G.A. Kuyumjian, A. Lavine, and D.V. Malmon, 2007, Sediment Delivery after a Wildfire: Geology, Vol. 35, No. 2, p. 151-154.

Rosgen, D., 1996, Applied fluvial geomorphology: Wildland Hydrology Books, Pagosa Springs, Co.

Riedel, J.L., 1997, Geologic Hazards and Floodplain Management, Mount Rainier General Management Plan: Unpublished Internal Document, National Park Service, 91 p.

Ritter, D.F., R.C. Kochel and J.R. Miller, 2002, Process Geomorphology: McGraw Hill Publishers, Dubuque, IA, 560 p.

Scott, K.M. and J.W. Vallance, 1995, History of Landslides and Debris Flows at Mount Rainier: United States Geological Survey Open File Report 93-111, 2 p.

Shi, C., 2004, Causes for continuous siltation of the Lower Yellow River: Geomorphology: Vol. 68, p. 213-223.

Sisson, T.W., 1995, History and hazards of Mount Rainier, Washington: United States Geological Survey Open File Report 95-642, 2 p.

Sisson, T.W., J.W. Vallance and P.T. Pringle, 2001, Progress Made in Understanding Mount Rainier's Hazards: EOS, Transactions of the American Geophysical Union, p. 113-120.

Sutherland, D.G., M.H. Ball, S.J. Hilton and T.E. Lisle, 2002, Evolution of a Landslide-Induced Sediment Wave in the Navarro River, California: Geological Society of America Bulletin, Vol. 114, No. 8, p. 1036-1048.

Swanson, D.A., S.D. Malone and B.A. Samora, 1992, Mount Rainier: A decade volcano: EOS, Transactions of the American Geophysical Union, Vol. 73, No. 16, p. 177-186.

Topcon, 2008, Instruction manual non-prism total station GPT-3100W series: Topcon, West Sacramento, CA, 184 p.

Topinka, L., 1997a, Mount Rainier, Washington Extent of the Osceola and Electron Mudflows [Online]: United States Geological Survey Cascade Volcano Observatory, Updated 9/10/2002, Retrieved February 21, 2007 from http://vulcan.wr.usgs.gov/Volcanoes/Rainier/Maps/osceola_map.html

Topinka, L, 1997b, Mount Rainier, Washington Glaciers [Online]: United States Geological Survey Cascade Volcano Observatory, Updated 9/10/2002, Retrieved February 21, 2007 from http://vulcan.wr.usgs.gov/Volcanoes/Rainier/Maps/map_rainier_glaciers.html

United States Geological Survey, 2013a, USGS 12082500 Nisqually River near National, WA [Online]: United States Geological Survey National Water Information System, Updated 8/15/2013, Retrieved August 15, 2013 from: http://waterdata.usgs.gov/wa/nwis/uv?site_no=12082500.

United States Geological Survey, 2013b, The StreamStats Program for Washington [Online]: United States Geological Survey, Updated 1/17/2013, Retrieved June, 15, 2013 from http://water.usgs.gov/osw/streamstats/washington.html.

Vallance, J.W., Cunico, M.L. and Shilling, S.P., 2003, Debris-flow hazards caused by hydrologic events at Mount Rainier, Washington: USGS Open File Report 03-368, 10 p.

Vallance, J.W., Driedger, C.L. and Scott, W.E., 2002, Diversion of meltwater from Kautz Glacier initiates small debris flows near Van Trump Park, Mount Rainier, Washington: Washington Geology Vol. 30, p. 17-19.

Walder, J.S. and C.L. Driedger, 1995, Glacier-Generated Debris Flows at Mount Rainier: United States Geological Survey Open File Report 93-124, 2 p.

Watershed Sciences, 2009, LiDAR remote sensing data collection: Mount Rainier, WA: Final Report: Corvallis, OR, 31 p.

Watershed Sciences, 2012, Carbon and Nisqually Rivers: Technical Data Report: Corvallis, OR, 29 p.

Appendix A: Tabular data of aggradation rates for individual cross sections during specific time periods during this study. Aggradation rates from each cross section and for time periods listed below are plotted in Appendix B.

Appendix A.1: Overall aggradation results from Sunshine Point cross section 1 for the time period between 2005-2012.

Time Period	Years	Net Cross Sectional Area Change, *m^2*	Line Length, *m*	Net Change Across Line, *m*	Rate, *$m \times yr^{-1}$*
2005-2006	1	11.69	131.81	0.09	0.09
2006-2008	2	75.24	131.81	0.57	0.29
2008-2009	1	-40.91	168.54	-0.24	-0.24
2009-2011	2	41.67	168.54	0.25	0.12
2011-2012	1	6.50	168.54	0.04	0.04
2005-2012	**7**	**94.19**	**168.54**	**0.56**	**0.08**

Appendix A.2: Overall aggradation results from Sunshine Point cross section 2 for the time period between 2005-2012.

Time Period	Years	Net Cross Sectional Area Change, *m^2*	Line Length, *m*	Net Change Across Line, *m*	Rate, *$m \times yr^{-1}$*
2005-2006	1	-15.11	118.02	-0.13	-0.13
2006-2008	2	110.63	118.02	0.94	0.47
2008-2009	1	-55.09	225.51	-0.24	-0.24
2009-2011	2	48.44	225.51	0.21	0.11
2011-2012	1	0.69	225.51	0.00	0.00
2005-2012	**7**	**89.56**	**225.51**	**0.40**	**0.06**

Appendix A.3: Overall aggradation results from Sunshine Point cross section 3 for the time period between 2005-2012.

Time Period	Years	Net Cross Sectional Area Change, *m^2*	Line Length, *m*	Net Change Across Line, *m*	Rate, *$m \times yr^{-1}$*
2005-2006	1	8.34	119.55	0.07	0.07
2006-2008	2	104.75	119.55	0.88	0.44
2008-2009	1	-13.02	213.73	-0.06	-0.06
2009-2011	2	7.43	213.73	0.03	0.02
2011-2012	1	-1.68	213.73	-0.01	-0.01
2005-2012	**7**	**105.84**	**213.73**	**0.50**	**0.07**

Appendix A.4: Overall aggradation results from Sunshine Point cross section 4 for the time period between 2008-2012.

Time Period	Years	Net Cross Sectional Area Change, m^2	Line Length, *m*	Net Change Across Line, *m*	Rate, $m \times yr^{-1}$
2008-2009	1	-97.33	192.52	-0.51	-0.51
2009-2011	2	49.61	192.52	0.26	0.13
2011-2012	1	11.54	192.52	0.06	0.06
2008-2012	**4**	**-36.18**	**192.52**	**-0.19**	**-0.05**

Appendix A.5: Overall aggradation results from Sunshine Point cross section 5 for the time period between 2008-2012.

Time Period	Years	Net Cross Sectional Area Change, m^2	Line Length, *m*	Net Change Across Line, *m*	Rate, $m \times yr^{-1}$
2008-2009	1	-103.31	198.17	-0.52	-0.52
2009-2011	2	72.08	198.17	0.36	0.18
2011-2012	1	-3.53	198.17	-0.02	-0.02
2008-2012	**4**	**-34.76**	**198.17**	**-0.18**	**-0.04**

Appendix A.6: Overall aggradation results from Sunshine Point cross section 6 for the time period between 2008-2012.

Time Period	Years	Net Cross Sectional Area Change, m^2	Line Length, *m*	Net Change Across Line, *m*	Rate, $m \times yr^{-1}$
2008-2009	1	9.28	225.27	0.04	0.04
2009-2011	2	34.92	225.27	0.15	0.08
2011-2012	1	15.86	225.27	0.07	0.07
2008-2012	**4**	**60.05**	**225.27**	**0.27**	**0.07**

Appendix A.7: Overall aggradation results from Sunshine Point cross section 7 for the time period between 2008-2012.

Time Period	Years	Net Cross Sectional Area Change, m^2	Line Length, *m*	Net Change Across Line, *m*	Rate, $m \times yr^{-1}$
2008-2009	1	-10.37	204.26	-0.05	-0.05
2009-2011	2	49.04	204.26	0.24	0.12
2011-2012	1	-0.61	204.26	-0.00	-0.00
2008-2012	**4**	**38.06**	**204.26**	**0.19**	**0.05**

Appendix A.8: Overall aggradation results from Sunshine Point cross section 8 for the time period between 2008-2012.

Time Period	Years	Net Cross Sectional Area Change, *m^2*	Line Length, *m*	Net Change Across Line, *m*	Rate, *$m \times yr^{-1}$*
2008-2009	1	1.15	205.15	0.01	0.01
2009-2011	2	36.65	205.15	0.19	0.09
2011-2012	1	4.47	205.15	0.02	0.02
2008-2012	**4**	**42.27**	**205.15**	**0.20**	**0.05**

Appendix A.9: Overall aggradation results from Longmire cross section 1 for the time period between 1997-2012.

Time Period	Years	Net Cross Sectional Area Change, *m^2*	Line Length, *m*	Net Change Across Line, *m*	Rate, *$m \times yr^{-1}$*
1997-2005	8	1.06	89.12	0.01	0.00
2005-2006	1	2.30	89.12	0.03	0.03
2006-2008	2	4.30	89.12	0.05	0.02
2008-2009	1	-31.10	89.12	-0.35	-0.35
1997-2009	**12**	**-23.44**	**89.12**	**-0.26**	**-0.02**

Appendix A.10: Overall aggradation results from Longmire cross section 2 for the time period between 1997-2012.

Time Period	Years	Net Cross Sectional Area Change, *m^2*	Line Length, *m*	Net Change Across Line, *m*	Rate, *$m \times yr^{-1}$*
1997-2005	8	-3.62	72.82	-0.05	-0.01
2005-2006	1	26.19	72.82	0.36	0.36
2006-2008	2	-3.73	72.82	-0.05	-0.03
2008-2009	1	-52.75	72.82	-0.72	-0.72
2009-2010	1	1.49	72.82	0.02	0.02
2010-2011	1	0.63	72.82	0.01	0.01
2011-2012	1	7.45	72.82	0.10	0.10
1997-2012	**15**	**-24.34**	**72.82**	**-0.33**	**-0.02**

Appendix A.11: Overall aggradation results from Longmire cross section 3 for the time period between 1997-2012.

Time Period	Years	Net Cross Sectional Area Change, m^2	Line Length, *m*	Net Change Across Line, *m*	Rate, $m \times yr^{-1}$
1997-2005	8	6.60	76.17	0.09	0.01
2005-2006	1	21.84	76.17	0.29	0.29
2006-2008	2	25.89	76.17	0.34	0.17
2008-2009	1	-69.62	76.17	-0.91	-0.91
2009-2010	1	38.14	76.17	0.50	0.50
2010-2011	1	-2.78	76.17	-0.04	-0.04
2011-2012	1	5.16	76.17	0.07	0.07
1997-2012	**15**	**25.23**	**76.17**	**0.33**	**0.02**

Appendix A.12: Overall aggradation results from Longmire cross section 4 for the time period between 1997-2012.

Time Period	Years	Net Cross Sectional Area Change, m^2	Line Length, *m*	Net Change Across Line, *m*	Rate, $m \times yr^{-1}$
1997-2005	8	84.32	92.72	0.91	0.11
2005-2006	1	-47.41	92.72	-0.51	-0.51
2006-2008	2	-4.50	92.72	-0.05	-0.02
2008-2009	1	-25.42	92.72	-0.27	-0.27
2009-2010	1	-6.16	92.72	-0.07	-0.07
2010-2011	1	-25.77	92.72	-0.28	-0.28
2011-2012	1	26.41	92.72	0.28	0.28
1997-2012	**15**	**1.46**	**92.72**	**0.02**	**0.00**

Appendix A.13: Overall aggradation results from Longmire cross section 5 for the time period between 1997-2012.

Time Period	Years	Net Cross Sectional Area Change, m^2	Line Length, *m*	Net Change Across Line, *m*	Rate, $m \times yr^{-1}$
1997-2005	8	39.55	102.53	0.39	0.05
2005-2006	1	-23.62	102.53	-0.23	-0.23
2006-2008	2	-34.72	102.53	-0.34	-0.17
2008-2009	1	30.53	102.53	0.30	0.30
2009-2010	1	-22.30	102.53	-0.22	-0.22
2010-2011	1	-18.71	102.53	-0.18	-0.18
2011-2012	1	23.58	102.53	0.23	0.23
1997-2012	**15**	**-5.68**	**102.53**	**-0.05**	**-0.00**

Appendix A.14: Overall aggradation results from Longmire cross section 6 for the time period between 1997-2012.

Time Period	Years	Net Cross Sectional Area Change, m^2	Line Length, *m*	Net Change Across Line, *m*	Rate, $m \times yr^{-1}$
1997-2005	8	-96.61	116.83	-0.83	-0.10
2005-2006	1	62.38	116.83	0.53	0.53
2006-2008	2	-14.01	116.83	-0.12	-0.06
2008-2009	1	37.07	116.83	0.32	0.32
2009-2010	1	16.47	116.83	0.14	0.14
2010-2011	1	-8.26	116.83	-0.07	-0.07
2011-2012	1	12.71	116.83	0.11	0.11
1997-2012	**15**	**9.74**	**116.83**	**0.08**	**0.01**

Appendix A.15: Overall aggradation results from Longmire cross section 7 for the time period between 1997-2012.

Time Period	Years	Net Cross Sectional Area Change, m^2	Line Length, *m*	Net Change Across Line, *m*	Rate, $m \times yr^{-1}$
1997-2005	8	16.78	138.94	0.12	0.02
2005-2006	1	26.41	138.94	0.19	0.19
2006-2008	2	36.68	138.94	0.26	0.13
2008-2009	1	48.26	138.94	0.35	0.35
2009-2010	1	22.93	138.94	0.16	0.16
2010-2011	1	4.05	138.94	0.03	0.03
2011-2012	1	7.01	138.94	0.05	0.05
1997-2012	**15**	**162.12**	**138.94**	**1.17**	**0.08**

Appendix A.16: Overall aggradation results from Longmire cross section 8 for the time period between 1997-2012.

Time Period	Years	Net Cross Sectional Area Change, m^2	Line Length, *m*	Net Change Across Line, *m*	Rate, $m \times yr^{-1}$
1997-2005	8	11.19	151.29	0.07	0.01
2005-2006	1	33.89	151.29	0.22	0.22
2006-2008	2	-63.22	151.29	-0.42	-0.21
2008-2009	1	-27.84	151.29	-0.18	-0.18
2009-2010	1	26.74	151.29	0.18	0.18
2010-2011	1	22.21	151.29	0.15	0.15
2011-2012	1	4.39	151.29	0.03	0.03
1997-2012	**15**	**7.37**	**151.29**	**0.05**	**0.00**

Appendix A.17: Overall aggradation results from Longmire cross section 9 for the time period between 1997-2012.

Time Period	Years	Net Cross Sectional Area Change, *m^2*	Line Length, *m*	Net Change Across Line, *m*	Rate, *$m \times yr^{-1}$*
1997-2005	8	-14.45	169.74	-0.09	-0.01
2005-2006	1	-7.84	169.74	-0.05	-0.05
2006-2008	2	23.93	169.74	0.14	0.07
2008-2009	1	1.63	169.74	0.01	0.01
2009-2010	1	16.39	169.74	0.10	0.10
2010-2011	1	-11.62	169.74	-0.07	-0.07
2011-2012	1	-19.50	169.74	-0.11	-0.11
1997-2012	**15**	**-11.45**	**169.74**	**-0.07**	**-0.00**

Appendix A.18: Overall aggradation results from Longmire cross section 10 for the time period between 1997-2012.

Time Period	Years	Net Cross Sectional Area Change, *m^2*	Line Length, *m*	Net Change Across Line, *m*	Rate, *$m \times yr^{-1}$*
1997-2005	8	-84.18	155.13	-0.54	-0.07
2005-2006	1	80.73	155.13	0.52	0.52
2006-2008	2	-48.66	155.13	-0.31	-0.16
2008-2009	1	40.16	155.13	0.26	0.26
2009-2010	1	6.79	155.13	0.04	0.04
2010-2011	1	-18.89	155.13	-0.12	-0.12
2011-2012	1	1.02	155.13	0.01	0.01
1997-2012	**15**	**-23.03**	**155.13**	**-0.15**	**-0.01**

Appendix A.19: Overall aggradation results from Carter Falls cross sections 1-6 for the time period between 2011-2012.

Time Period	Line	Years	Net Cross Sectional Area Change, *m^2*	Line Length, *m*	Net Change Across Line, *m*	Rate, *$m \times yr^{-1}$*
2011-2012	1	1	50.41	89.28	0.56	0.56
2011-2012	2	1	16.64	118.20	0.14	0.14
2011-2012	3	1	16.51	115.17	0.14	0.14
2011-2012	4	1	12.40	139.08	0.09	0.09
2011-2012	5	1	-20.64	125.46	-0.16	-0.16
2011-2012	6	1	-0.73	116.45	-0.01	-0.01

Appendix A.20: Overall aggradation results from Lower Van Trump cross section 1 for the time period between 2005-2012.

Time Period	Years	Net Cross Sectional Area Change, m^2	Line Length, *m*	Net Change Across Line, *m*	Rate, $m \times yr^{-1}$
2005-2006	1	193.78	154.73	1.25	1.25
2006-2008	2	-26.39	154.73	-0.17	-0.09
2008-2009	1	83.83	154.73	0.54	0.54
2009-2010	1	-5.88	154.73	-0.04	-0.04
2010-2011	1	3.92	154.73	0.03	0.03
2011-2012	1	-10.23	154.73	-0.07	-0.07
2005-2012	**7**	**239.02**	**154.73**	**1.54**	**0.22**

Appendix A.21: Overall aggradation results from Lower Van Trump cross section 2 for the time period between 2005-2012.

Time Period	Years	Net Cross Sectional Area Change, m^2	Line Length, *m*	Net Change Across Line, *m*	Rate, $m \times yr^{-1}$
2005-2006	1	336.48	163.95	2.05	2.05
2006-2008	2	-121.39	163.95	-0.74	-0.37
2008-2009	1	-32.74	163.95	-0.20	-0.20
2009-2010	1	30.05	163.95	0.18	0.18
2010-2011	1	-11.12	163.95	-0.07	-0.07
2011-2012	1	1.47	163.95	0.01	0.01
2005-2012	**7**	**202.75**	**163.95**	**1.24**	**0.18**

Appendix A.22: Overall aggradation results from Lower Van Trump cross section 3 for the time period between 2005-2012.

Time Period	Years	Net Cross Sectional Area Change, m^2	Line Length, *m*	Net Change Across Line, *m*	Rate, $m \times yr^{-1}$
2005-2006	1	74.21	103.23	0.72	0.79
2006-2008	2	29.76	103.23	0.29	0.14
2008-2009	1	21.24	103.23	0.21	0.21
2009-2010	1	7.84	103.23	0.08	0.08
2010-2011	1	-0.20	103.23	-0.00	-0.00
2011-2012	1	5.12	103.23	0.05	0.05
2005-2012	**7**	**137.97**	**103.23**	**1.34**	**0.19**

Appendix A.23: Overall aggradation results from White River cross section 1 for the time period between 2005-2011.

Time Period	Years	Net Cross Sectional Area Change, m^2	Line Length, *m*	Net Change Across Line, *m*	Rate, $m \times yr^{-1}$
2005-2007	2	-12.26	470.27	-0.03	-0.01
2007-2008	1	-13.57	470.27	-0.03	-0.03
2008-2011	3	54.36	470.27	0.12	0.04
2005-2011	**6**	**28.54**	**470.27**	**0.06**	**0.01**

Appendix A.24: Overall aggradation results from White River cross section 2 for the time period between 2005-2011.

Time Period	Years	Net Cross Sectional Area Change, m^2	Line Length, *m*	Net Change Across Line, *m*	Rate, $m \times yr^{-1}$
2005-2007	2	-13.37	389.13	-0.03	-0.02
2007-2008	1	3.00	389.13	0.01	0.01
2008-2011	3	40.52	389.13	0.11	0.03
2005-2011	**6**	**30.15**	**389.13**	**0.08**	**0.01**

Appendix A.25: Overall aggradation results from White River cross section 3 for the time period between 2005-2011.

Time Period	Years	Net Cross Sectional Area Change, m^2	Line Length, *m*	Net Change Across Line, *m*	Rate, $m \times yr^{-1}$
2005-2007	2	-6.33	362.21	-0.02	-0.01
2007-2008	1	-21.27	362.21	-0.06	-0.06
2008-2011	3	63.17	362.21	0.17	0.06
2005-2011	**6**	**35.57**	**362.21**	**0.10**	**0.02**

Appendix A.26: Overall aggradation results from White River cross section 4 for the time period between 2005-2011.

Time Period	Years	Net Cross Sectional Area Change, m^2	Line Length, *m*	Net Change Across Line, *m*	Rate, $m \times yr^{-1}$
2005-2007	2	---	283.94	---	---
2007-2008	1	-22.96	283.94	-0.08	-0.08
2008-2011	3	45.15	283.94	0.16	0.05
2005-2011	**6**	**22.19**	**283.94**	**0.08**	**0.01**

Appendix A.27: Overall aggradation results from White River cross section 5 for the time period between 2005-2011.

Time Period	Years	Net Cross Sectional Area Change, *m^2*	Line Length, *m*	Net Change Across Line, *m*	Rate, *$m \times yr^{-1}$*
2005-2007	2	10.44	210.60	0.05	0.02
2007-2008	1	-28.29	210.60	-0.13	-0.13
2008-2011	3	26.52	210.60	0.13	0.04
2005-2011	**6**	**8.73**	**210.60**	**0.04**	**0.01**

Appendix A.28: Overall aggradation results from White River cross section 6 for the time period between 2005-2011.

Time Period	Years	Net Cross Sectional Area Change, *m^2*	Line Length, *m*	Net Change Across Line, *m*	Rate, *$m \times yr^{-1}$*
2005-2007	2	14.16	211.5	0.07	0.03
2007-2008	1	-18.17	211.5	-0.09	-0.09
2008-2011	3	28.21	211.5	0.13	0.04
2005-2011	**6**	**24.20**	**211.5**	**0.11**	**0.02**

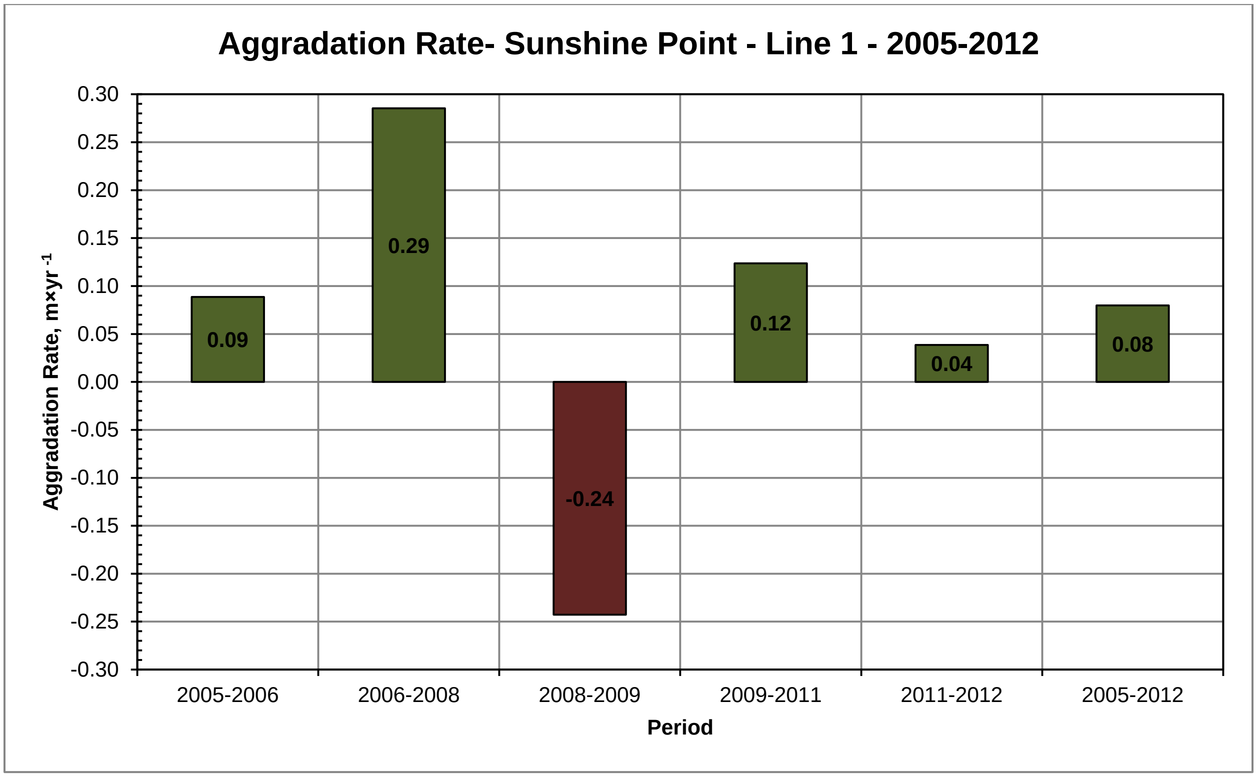
Appendix A.29: Overall aggradation results from White River cross section 7 for the time period between 2005-2011.

Time Period	Years	Net Cross Sectional Area Change, *m^2*	Line Length, *m*	Net Change Across Line, *m*	Rate, *$m \times yr^{-1}$*
2005-2007	2	37.60	260.42	0.14	0.07
2007-2008	1	-20.74	260.42	-0.08	-0.08
2008-2011	3	15.08	260.42	0.06	0.02
2005-2011	**6**	**31.94**	**260.42**	**0.12**	**0.02**

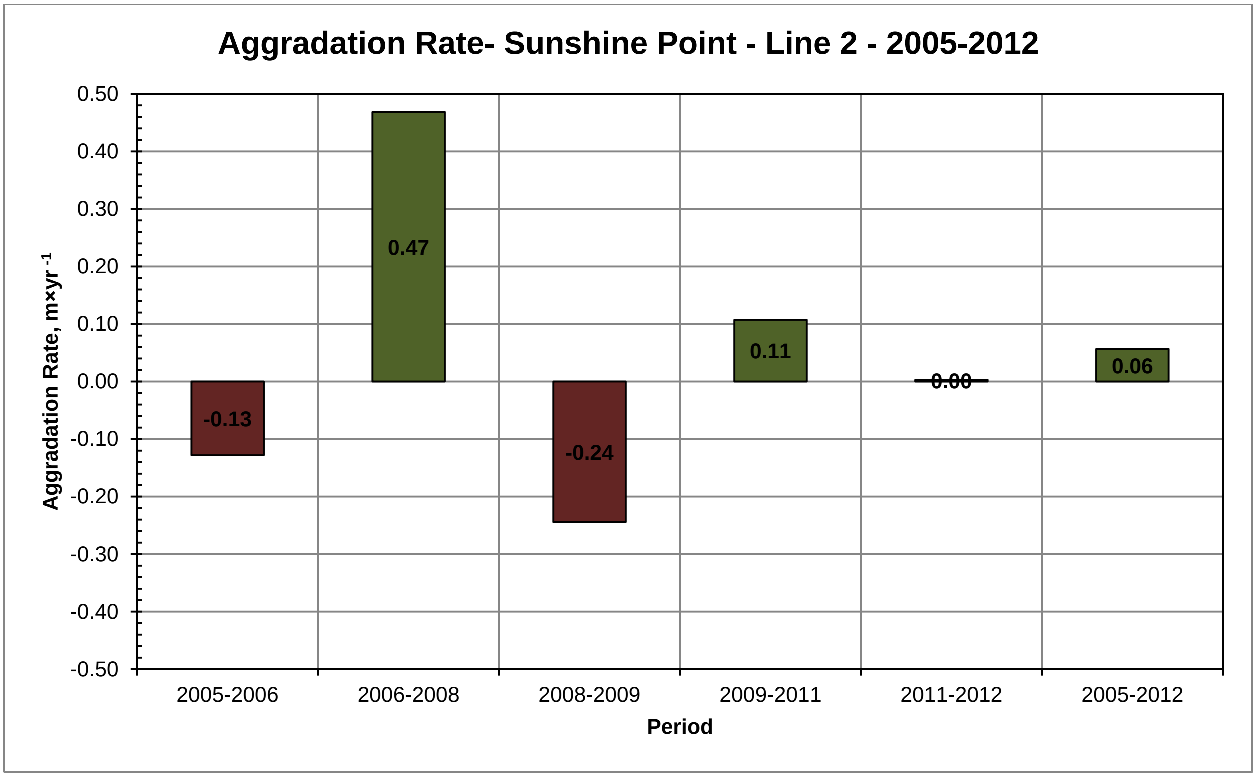
Appendix A.30: Overall aggradation results from White River cross section 8 for the time period between 2005-2011.

Time Period	Years	Net Cross Sectional Area Change, *m^2*	Line Length, *m*	Net Change Across Line, *m*	Rate, *$m \times yr^{-1}$*
2005-2007	2	39.13	234.49	0.17	0.08
2007-2008	1	-34.73	234.49	-0.15	-0.15
2008-2011	3	50.24	234.49	0.21	0.07
2005-2011	**6**	**54.64**	**234.49**	**0.23**	**0.04**

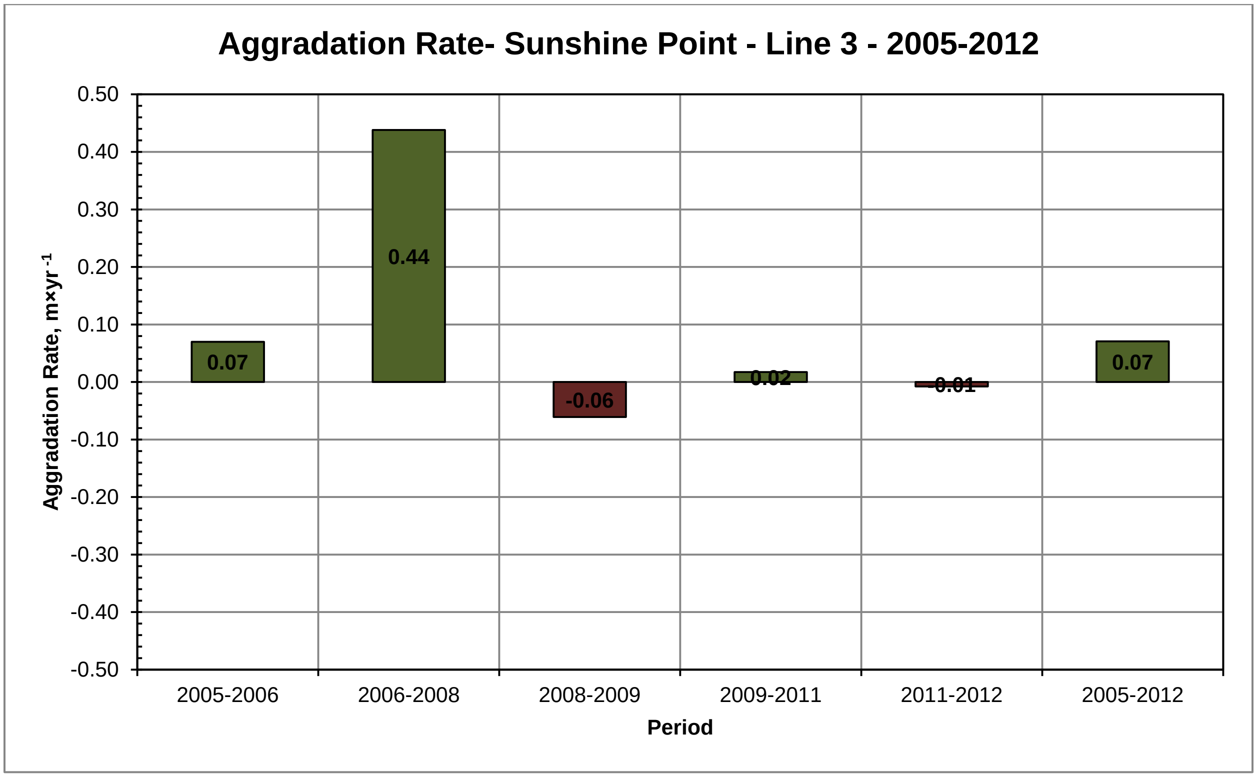
Appendix B: Graphical representations of aggradation rates for individual cross sections during specific time periods during this study, based on data from Appendix A. The column on the far right on all graphs with the exception of Carter Falls is the average aggradation rate for all periods of study. Since Carter Falls cross sections have only 1 year of analysis (2011-2012), the rates for all lines at Carter Falls are included on one graph.



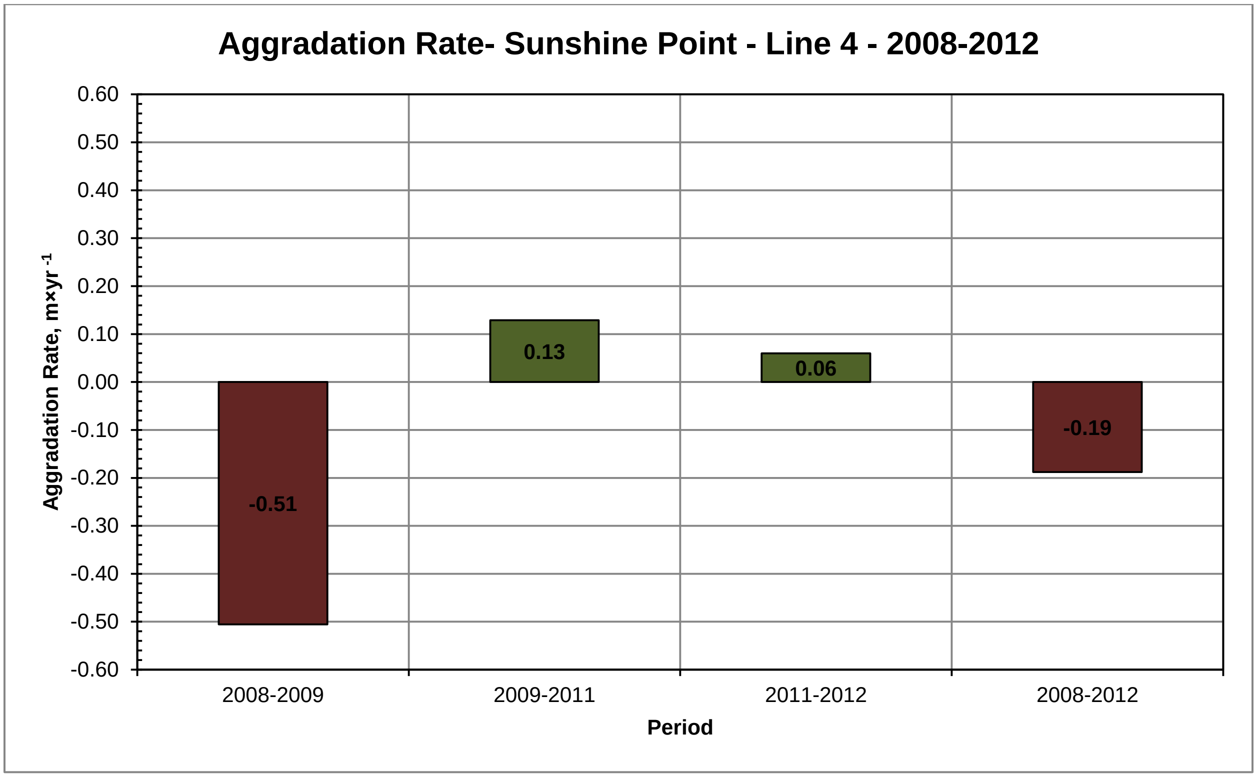
Appendix B.1: Aggradation rates for Sunshine Point, Cross Section 1, 2005-2012.



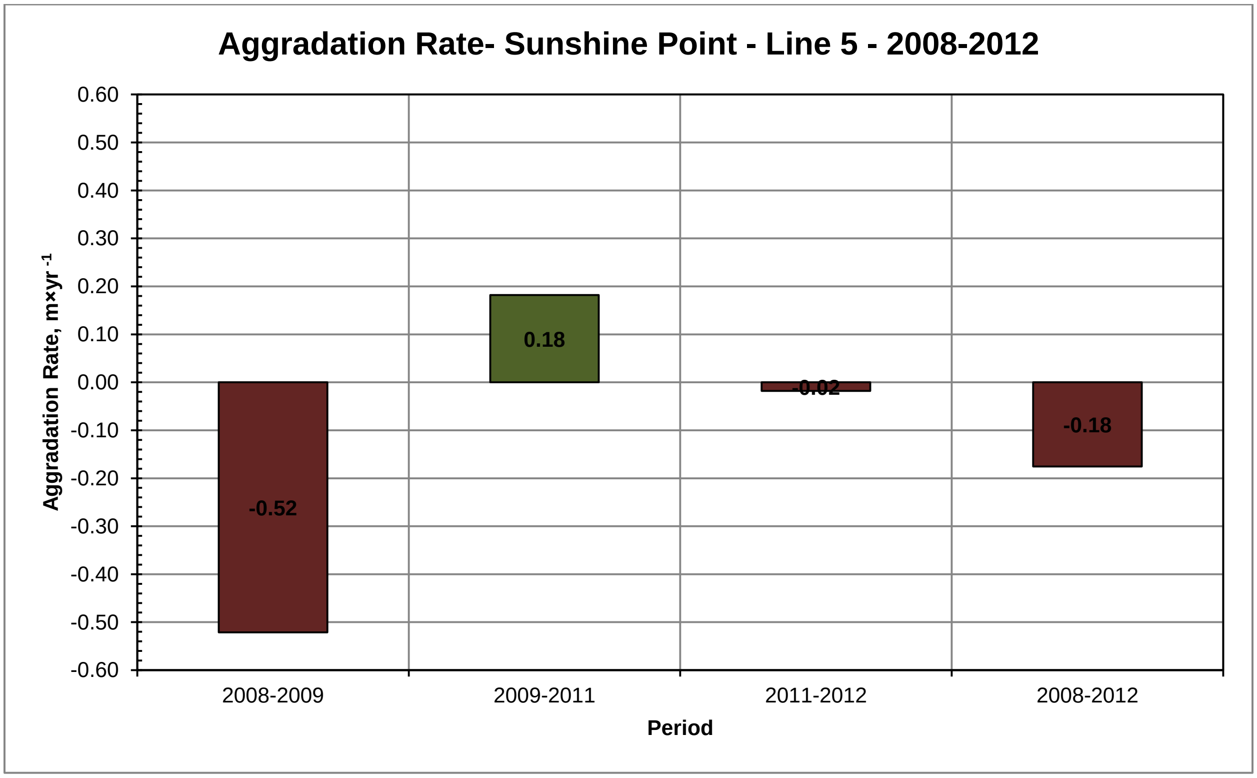
Appendix B.2: Aggradation rates for Sunshine Point, Cross Section 2, 2005-2012.



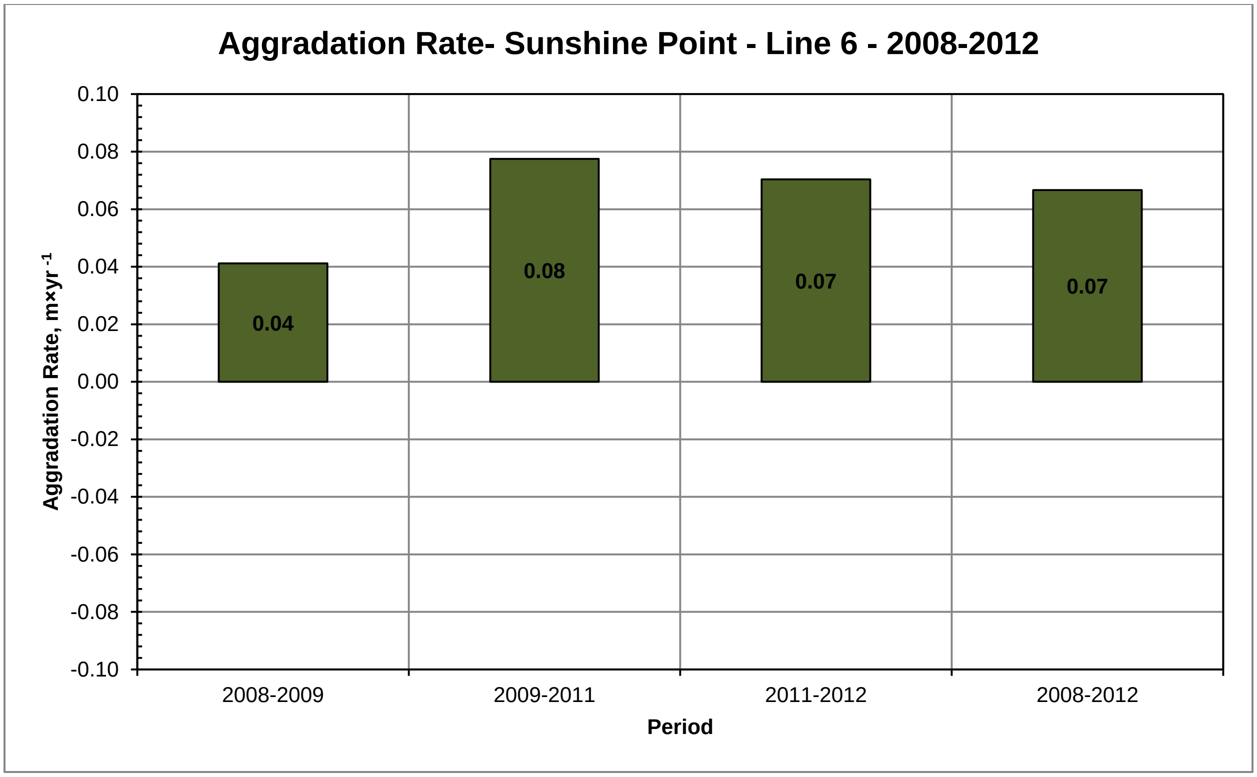
Appendix B.3: Aggradation rates for Sunshine Point, Cross Section 3, 2005-2012.



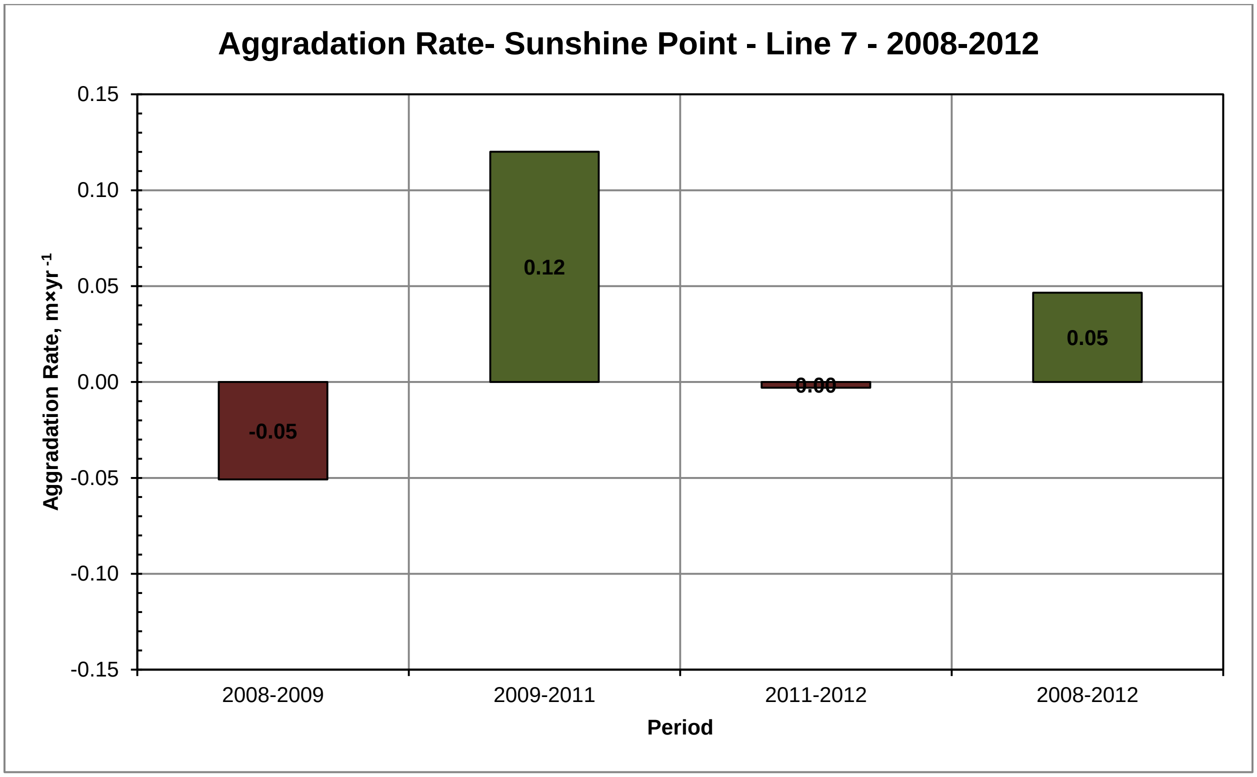
Appendix B.4: Aggradation rates for Sunshine Point, Cross Section 4, 2008-2012.



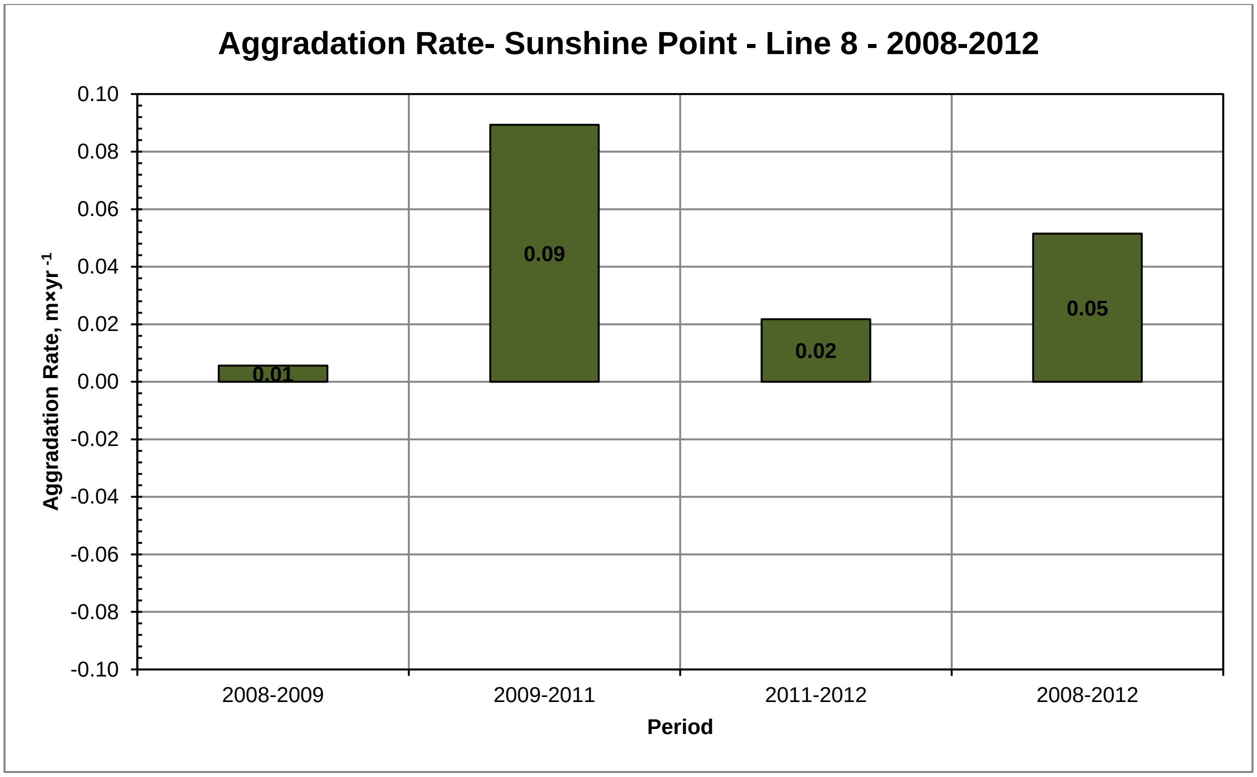
Appendix B.5: Aggradation rates for Sunshine Point, Cross Section 5, 2008-2012.



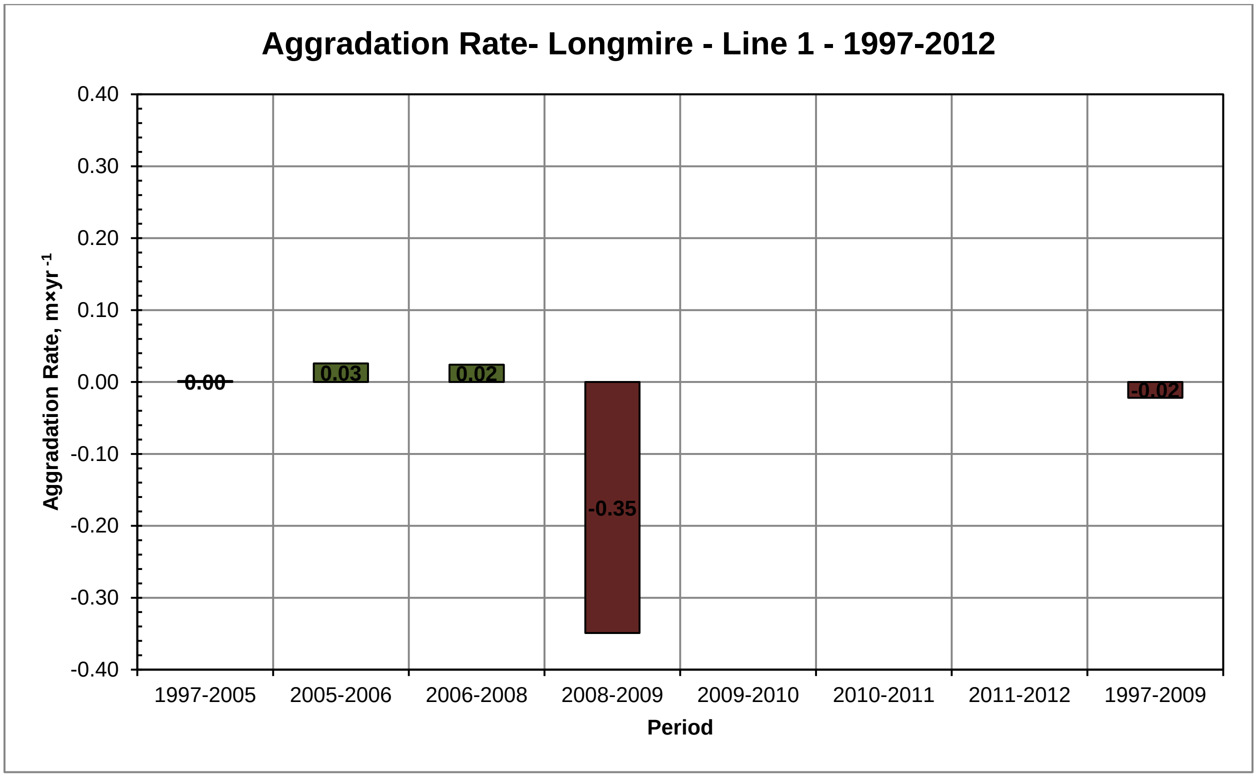
Appendix B.6: Aggradation rates for Sunshine Point, Cross Section 6, 2008-2012.



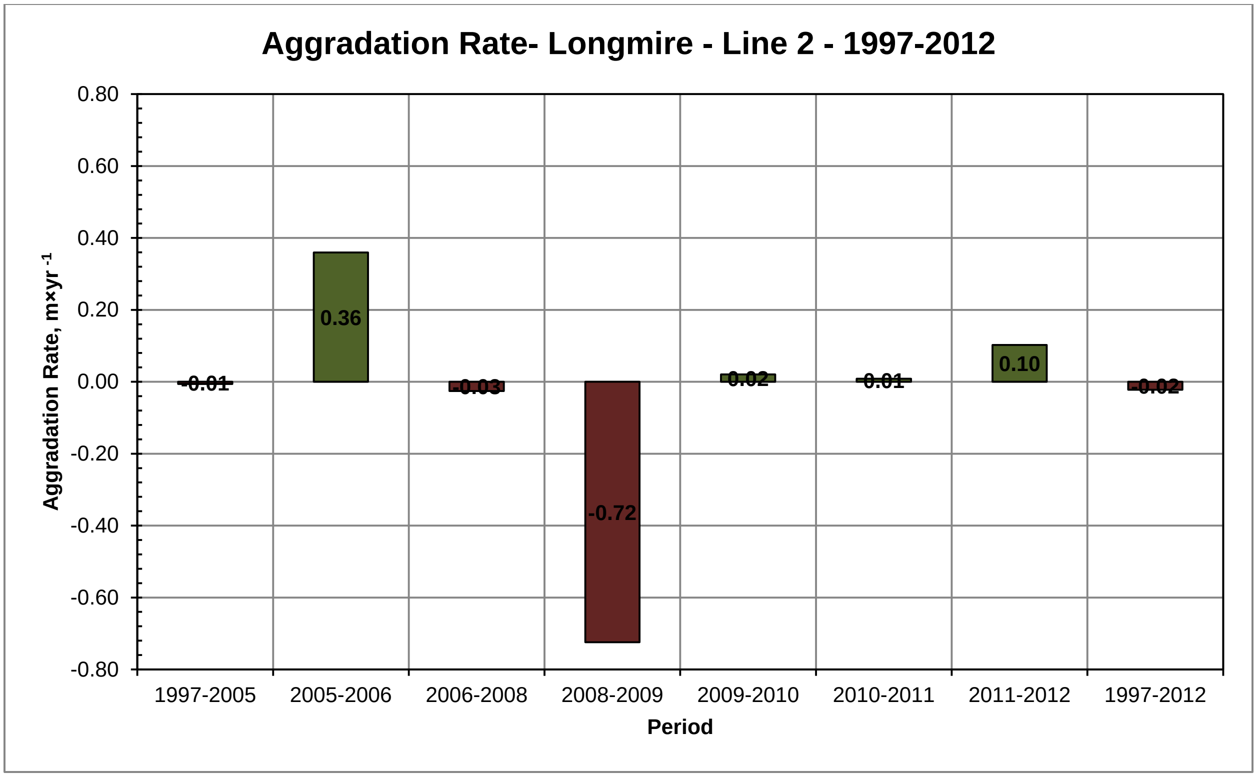
Appendix B.7: Aggradation rates for Sunshine Point, Cross Section 7, 2008-2012.



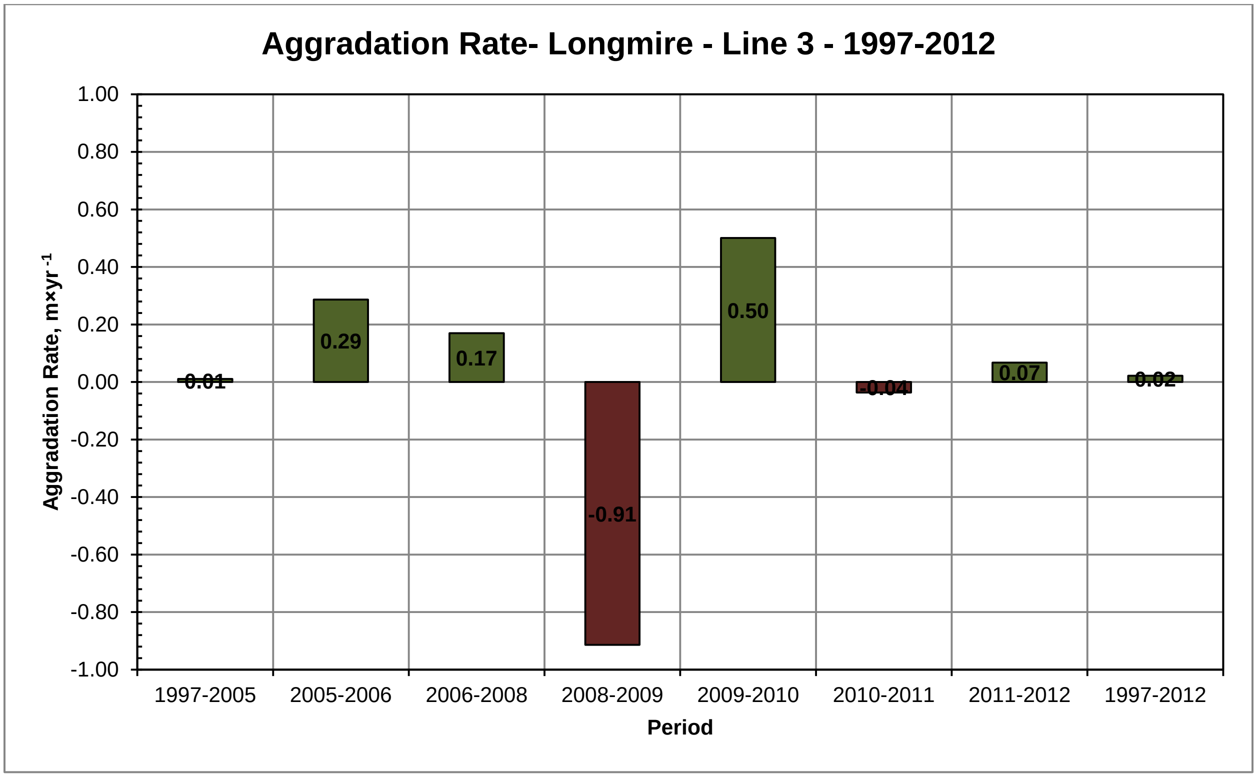
Appendix B.8: Aggradation rates for Sunshine Point, Cross Section 8, 2008-2012.



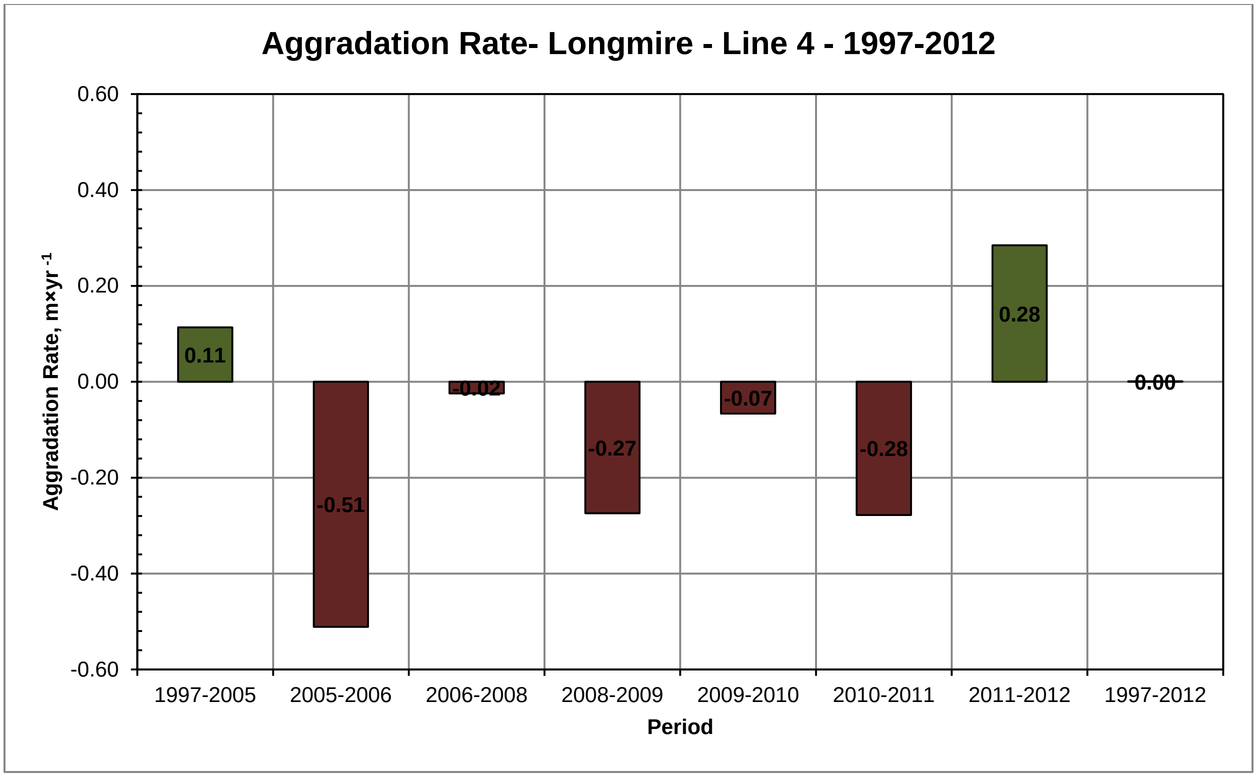
Appendix B.9: Aggradation rates for Longmire, Cross Section 1, 1997-2012.



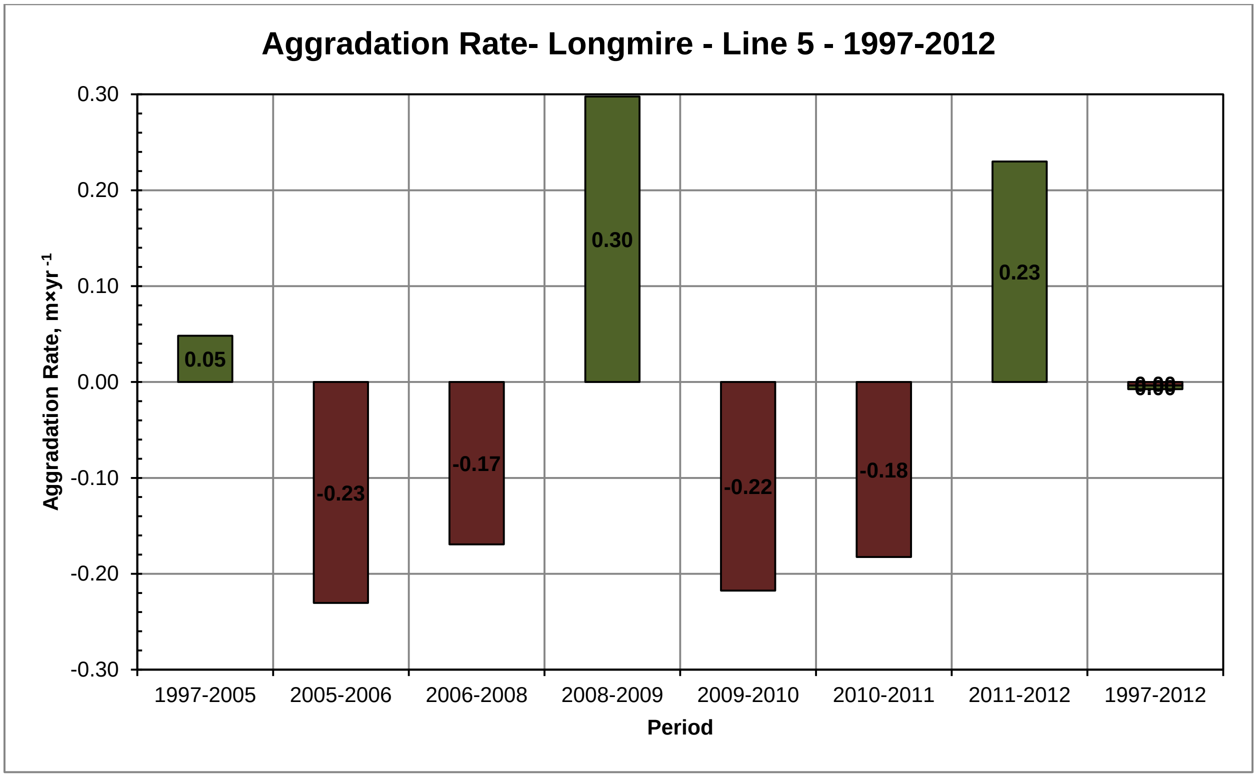
Appendix B.10: Aggradation rates for Longmire, Cross Section 2, 1997-2012.



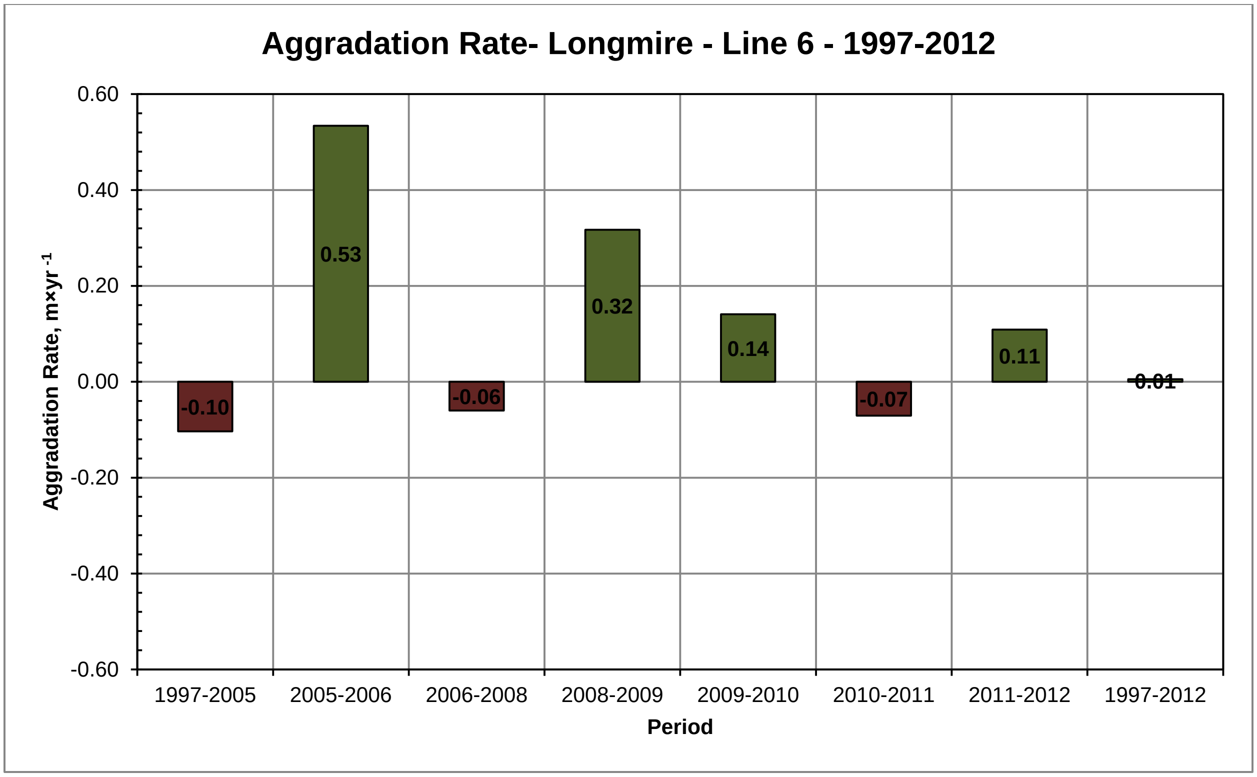
Appendix B.11: Aggradation rates for Longmire, Cross Section 3, 1997-2012.



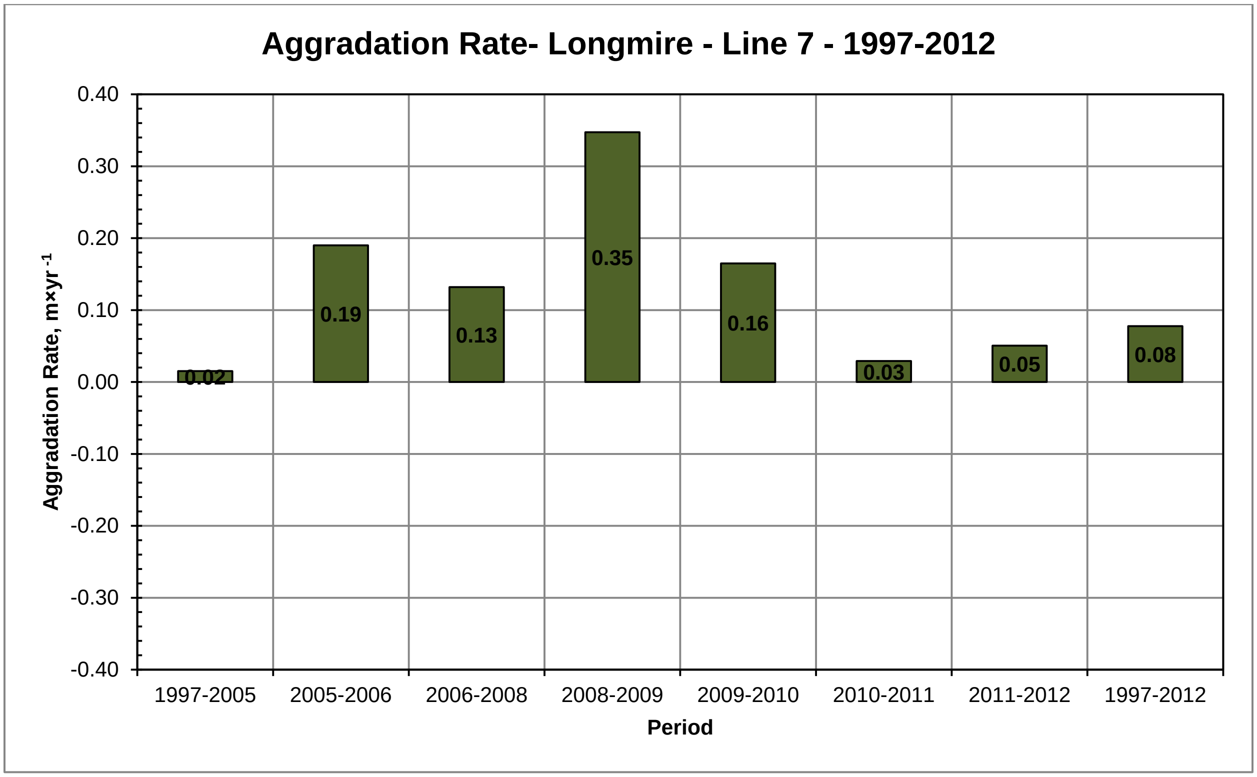
Appendix B.12: Aggradation rates for Longmire, Cross Section 4, 1997-2012.



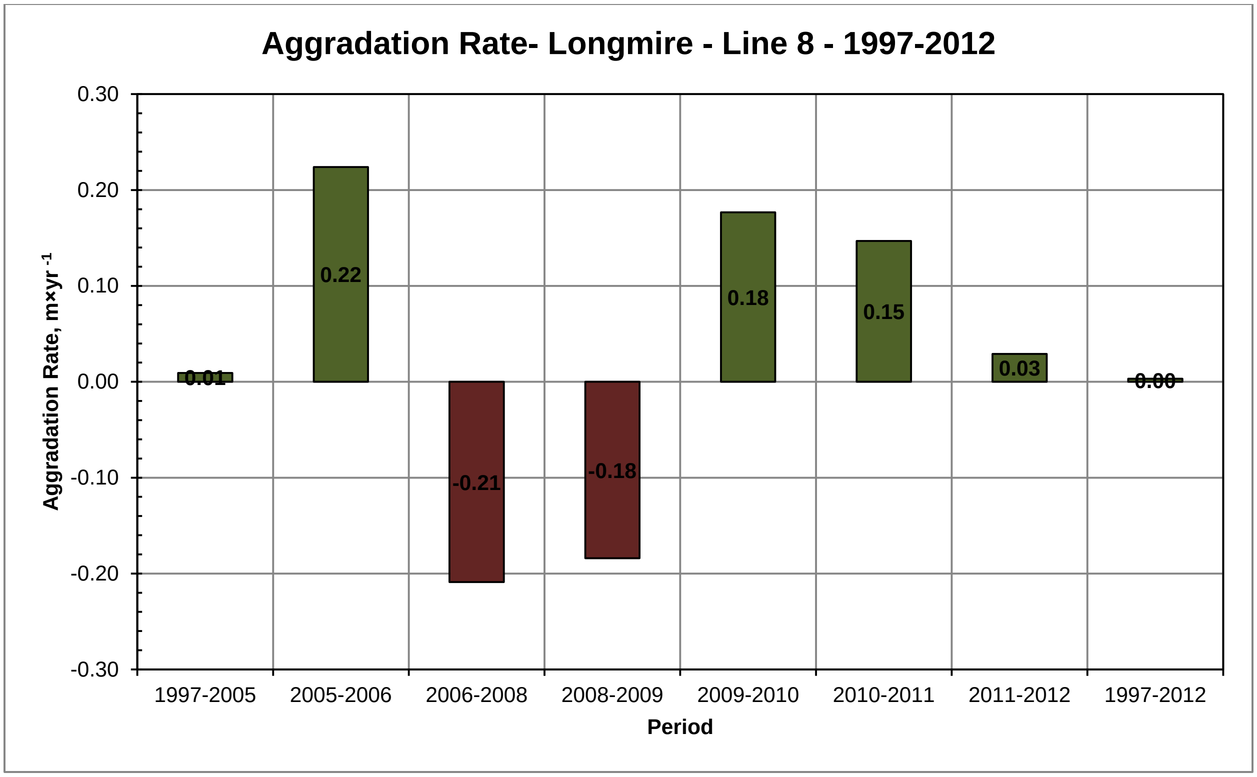
Appendix B.13: Aggradation rates for Longmire, Cross Section 5, 1997-2012.



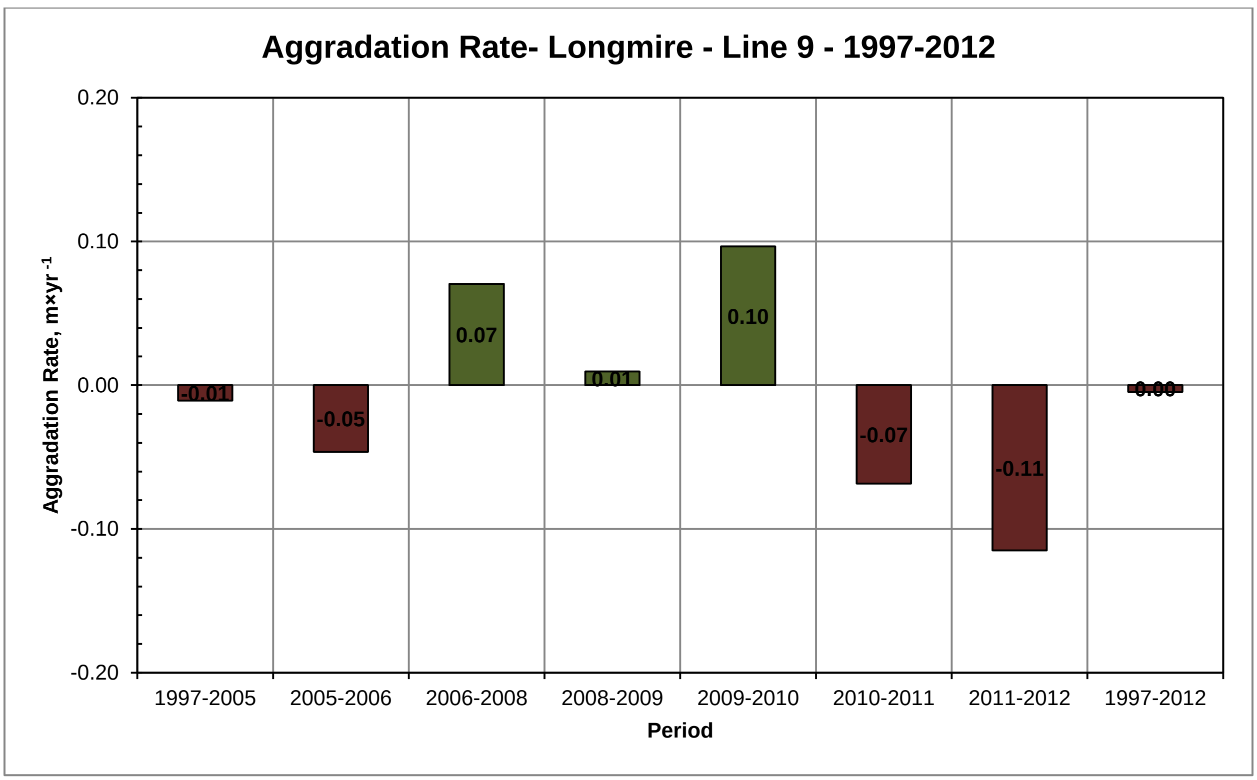
Appendix B.14: Aggradation rates for Longmire, Cross Section 6, 1997-2012.



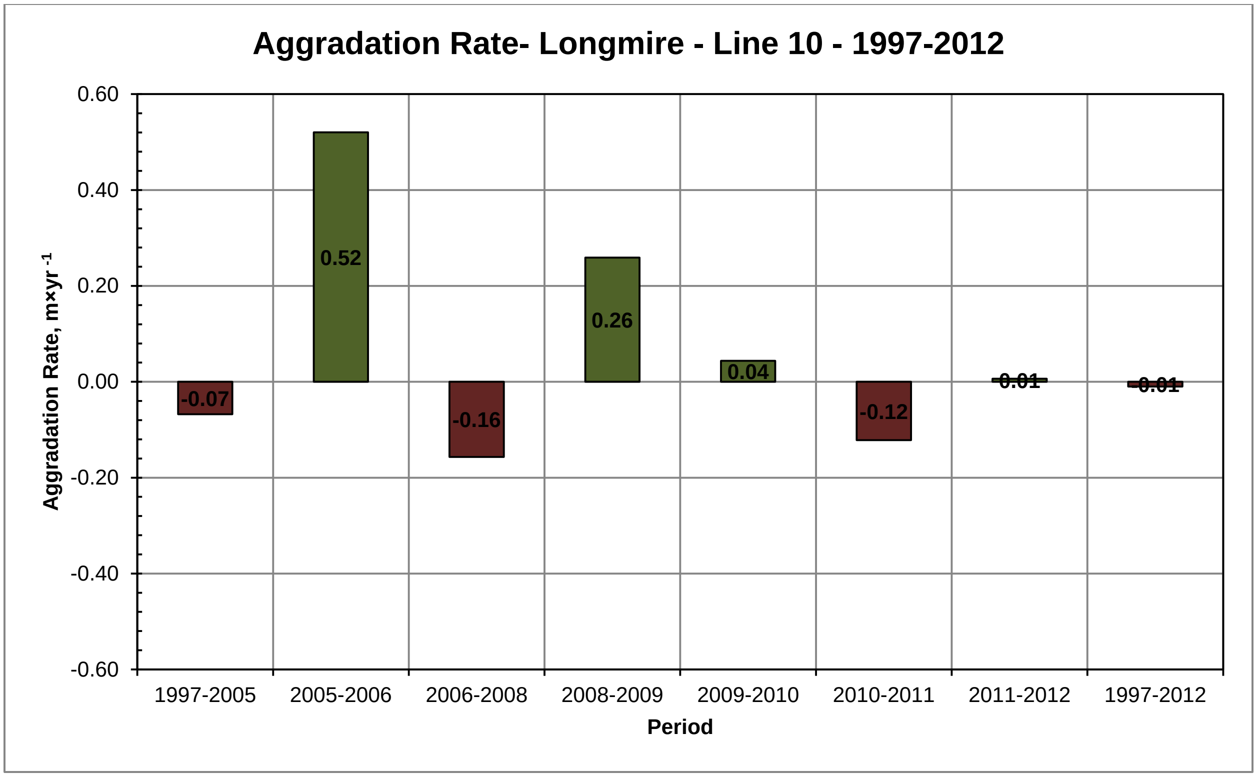
Appendix B.15: Aggradation rates for Longmire, Cross Section 7, 1997-2012.



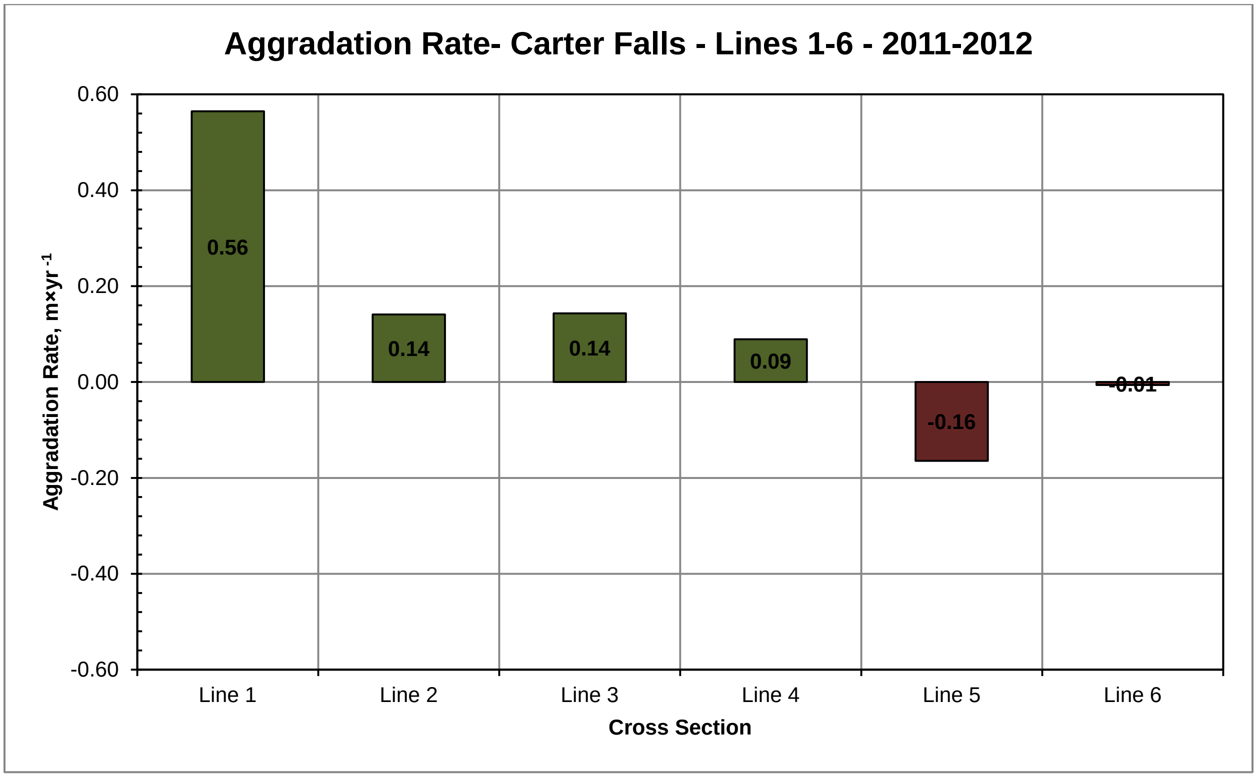
Appendix B.16: Aggradation rates for Longmire, Cross Section 8, 1997-2012.



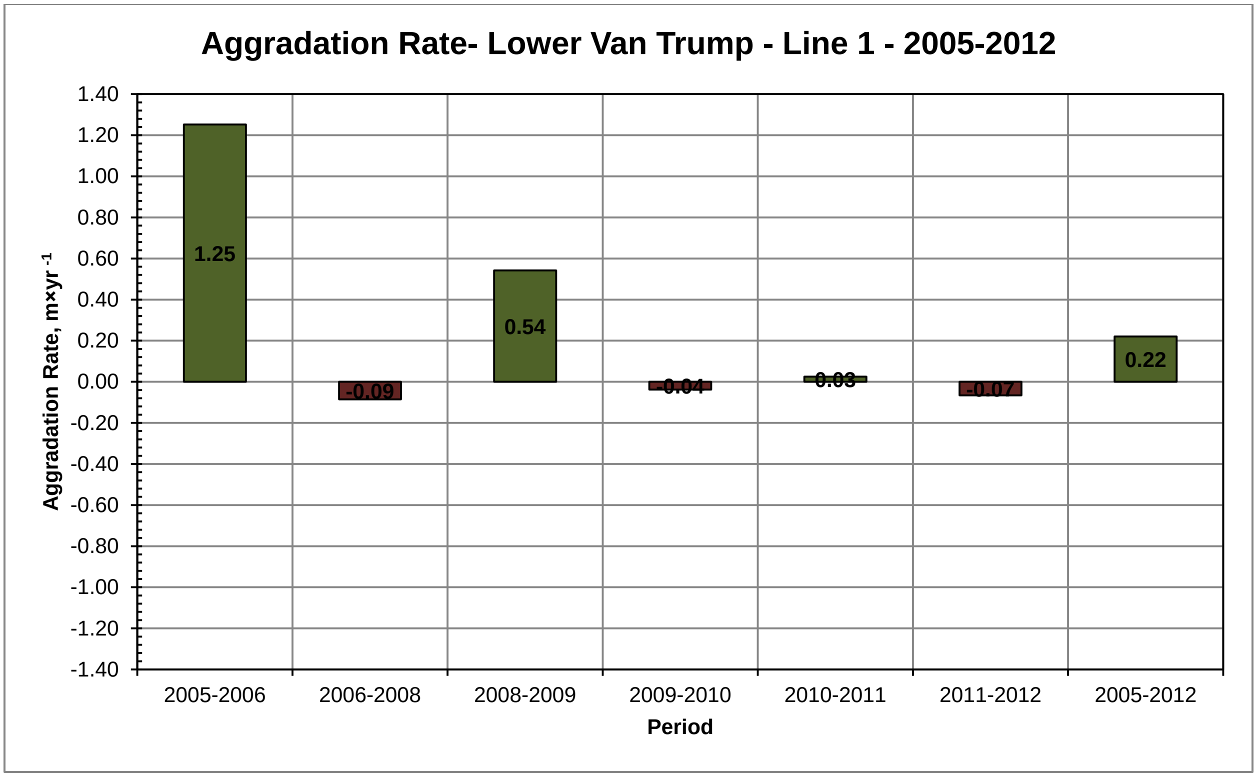
Appendix B.17: Aggradation rates for Longmire, Cross Section 9, 1997-2012.



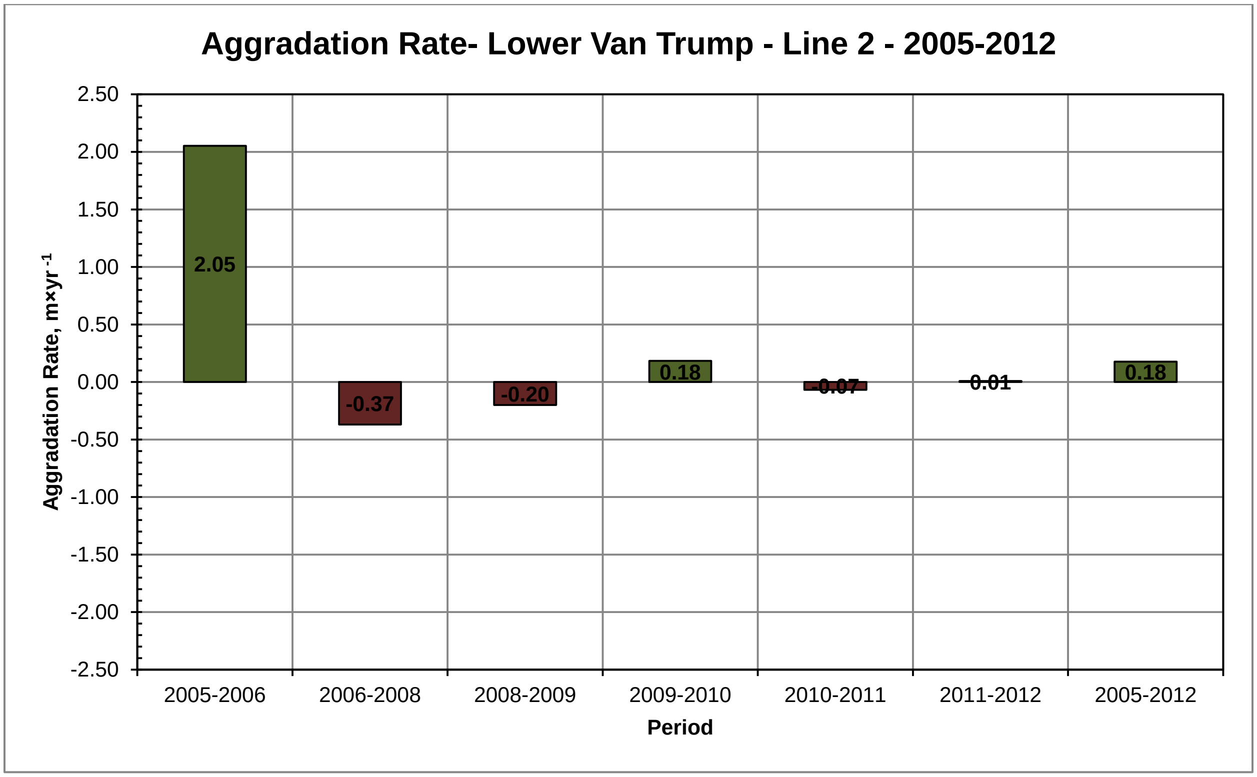
Appendix B.18: Aggradation rates for Longmire, Cross Section 10, 1997-2012.



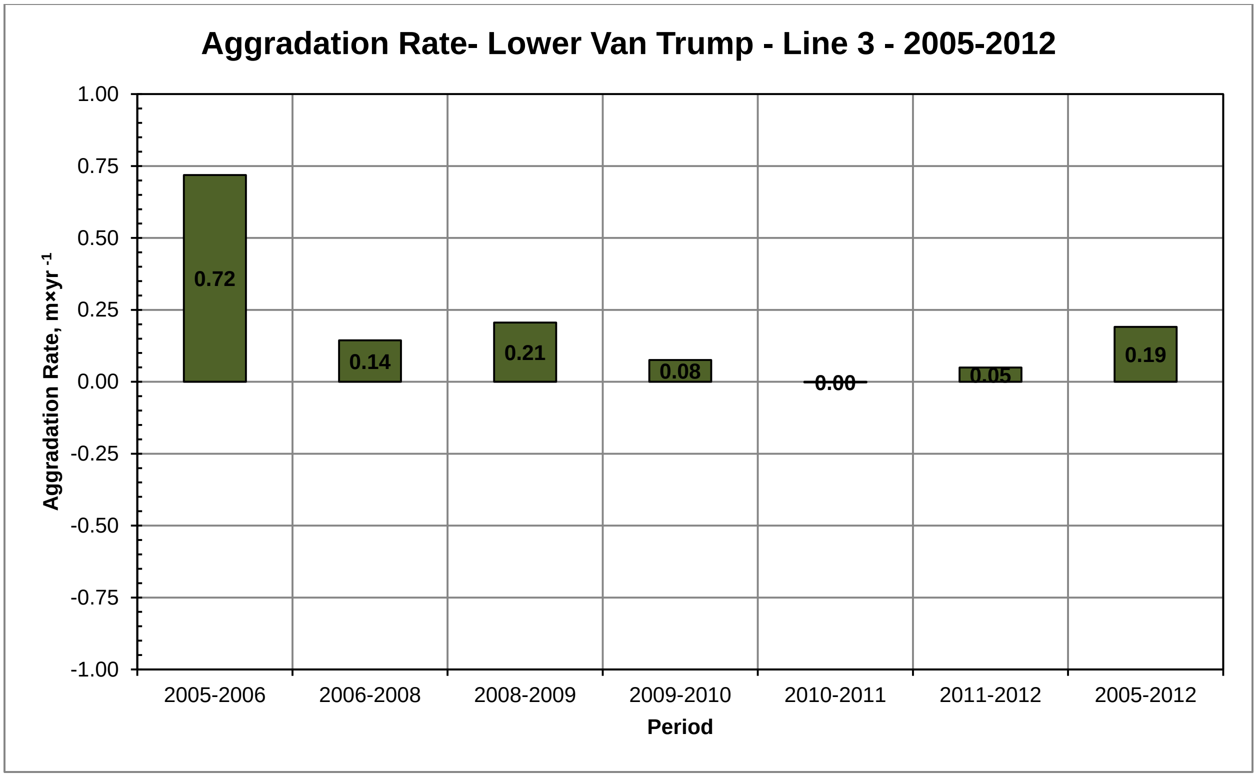
Appendix B.19: Aggradation rates for Carter Falls, Cross Sections 1-6, 2011-2012.



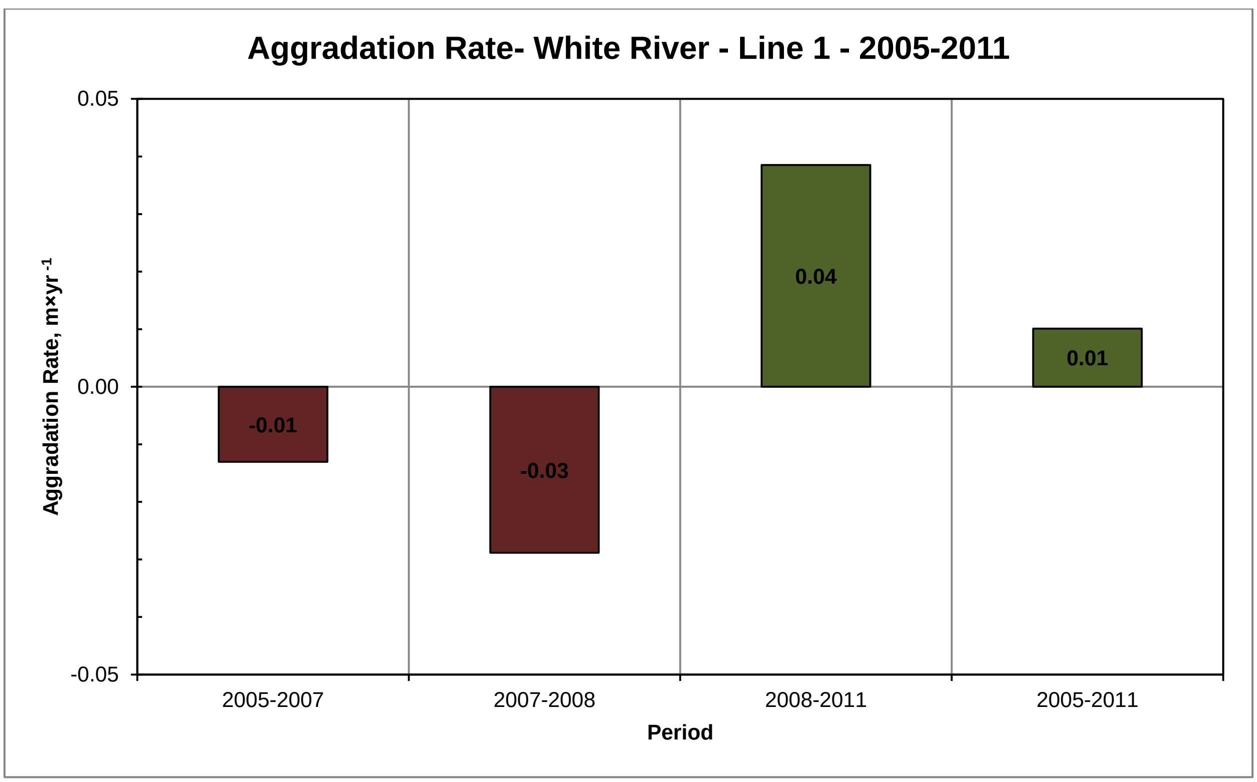
Appendix B.20: Aggradation rates for Lower Van Trump, Cross Section 1, 2005-2012.



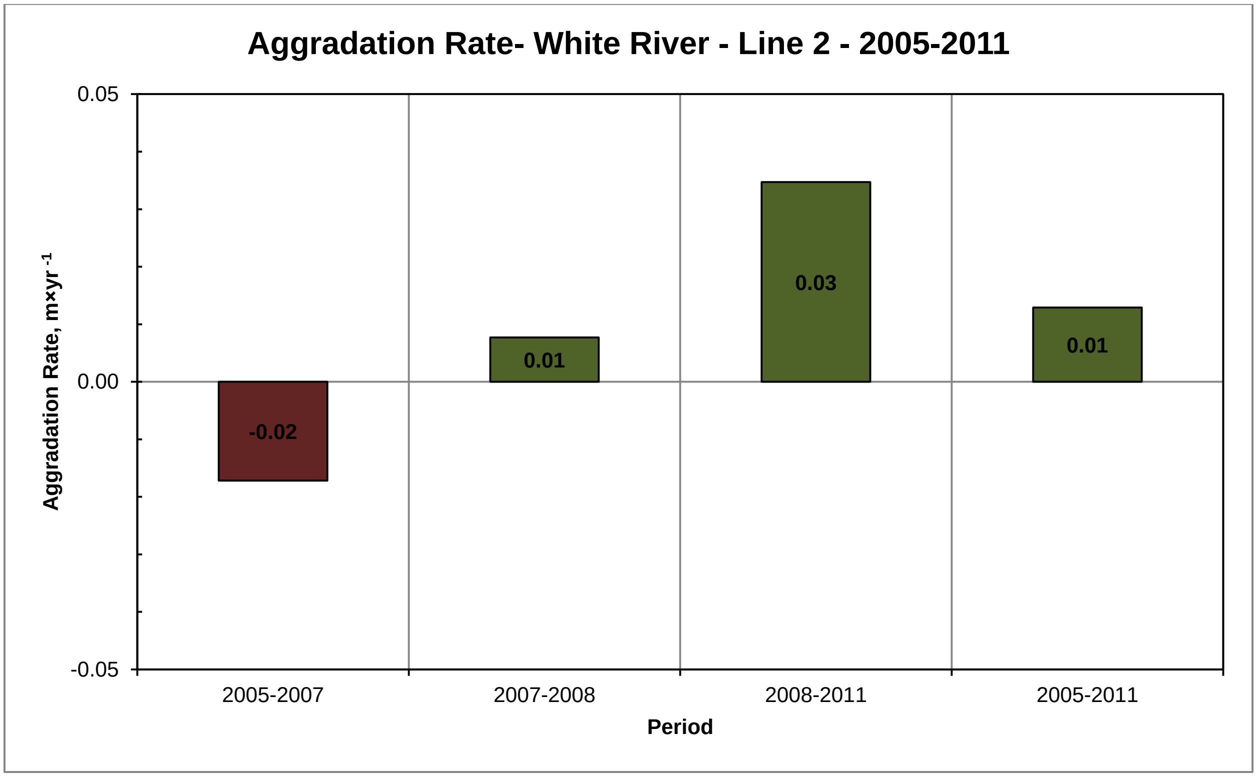
Appendix B.21: Aggradation rates for Lower Van Trump, Cross Section 2, 2005-2012.



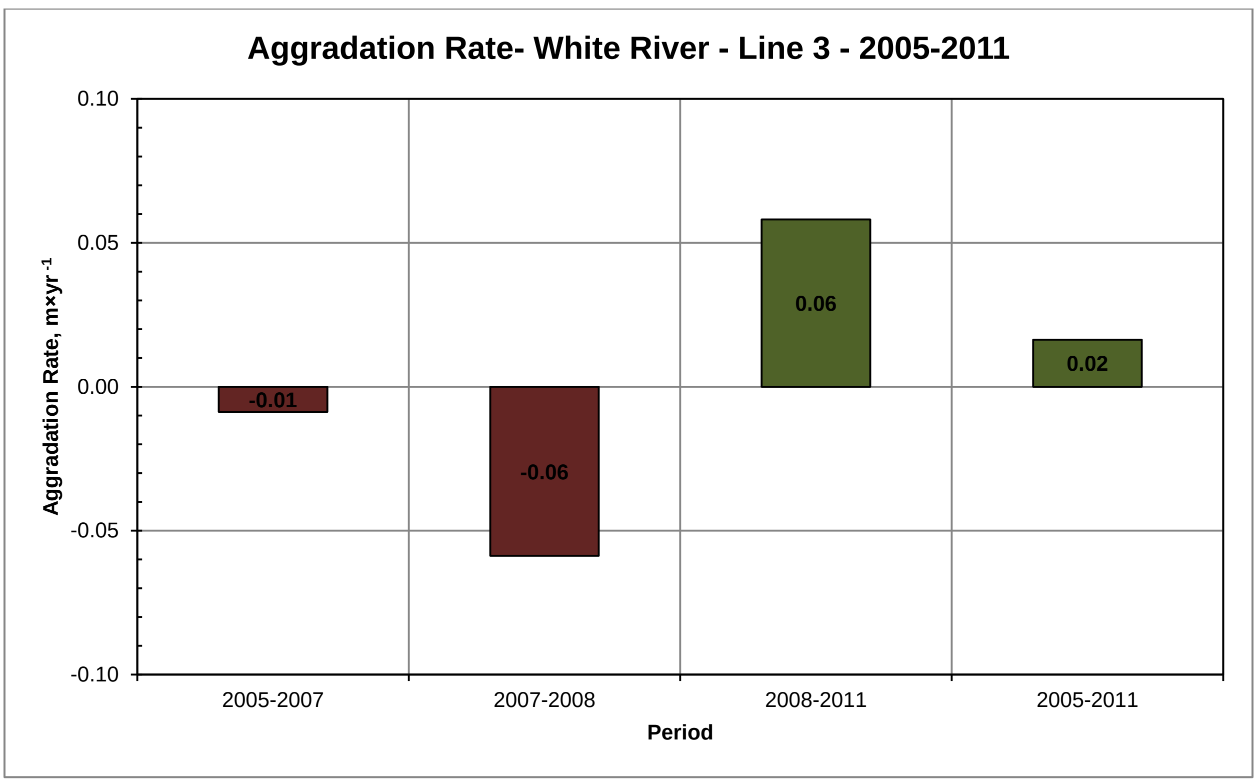
Appendix B.22: Aggradation rates for Lower Van Trump, Cross Section 3, 2005-2012.



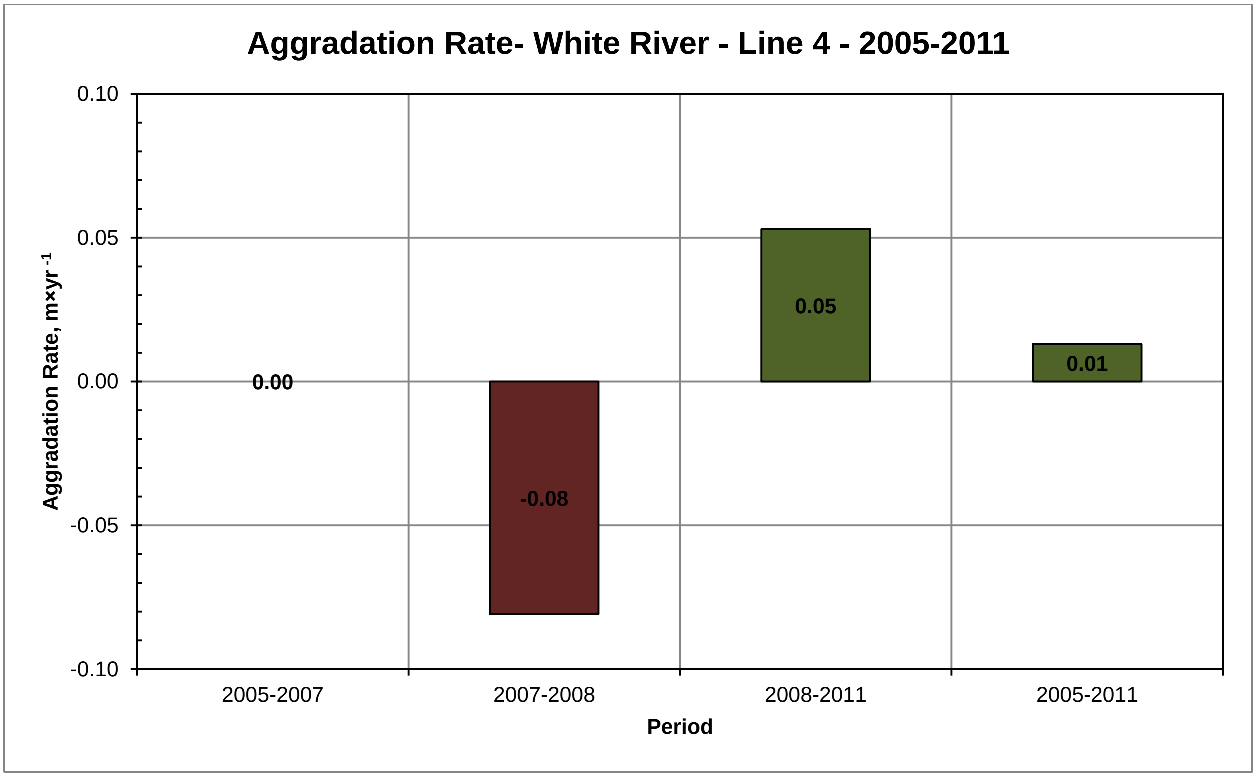
Appendix B.23: Aggradation rates for White River, Cross Section 1, 2005-2011.



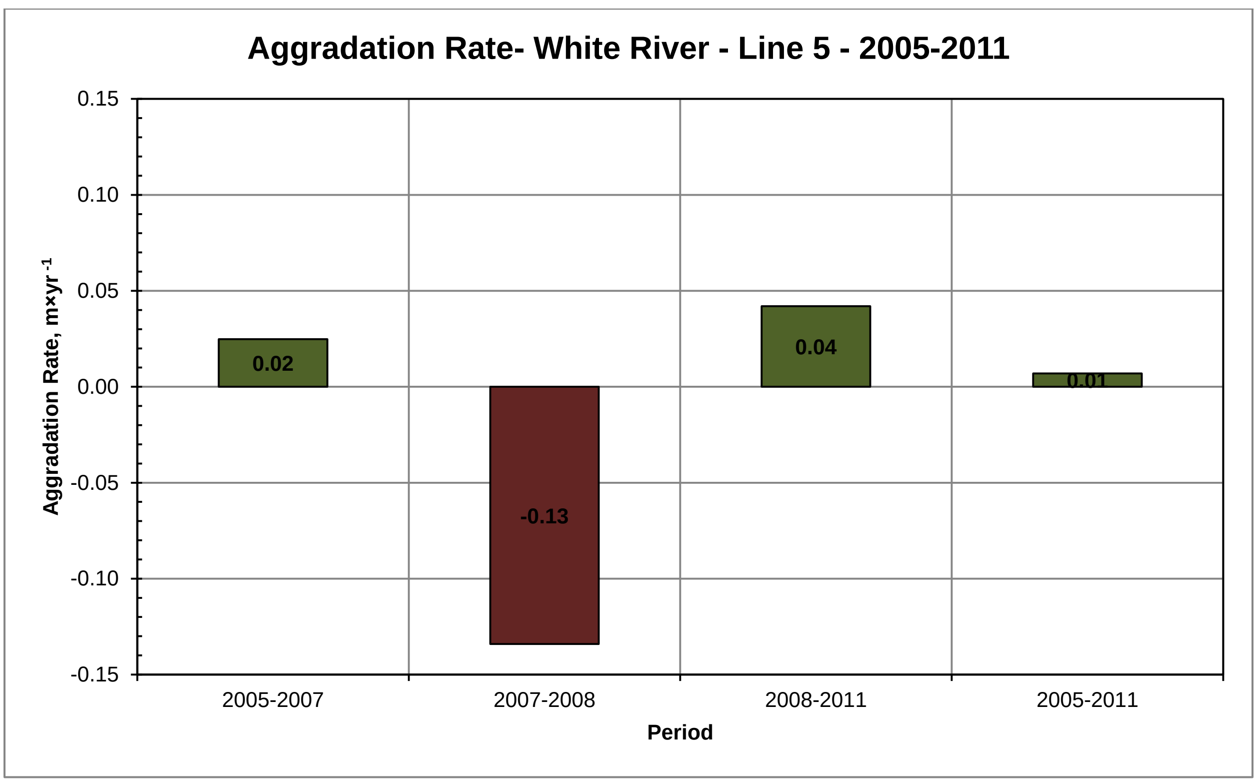
Appendix B.24: Aggradation rates for White River, Cross Section 2, 2005-2011.



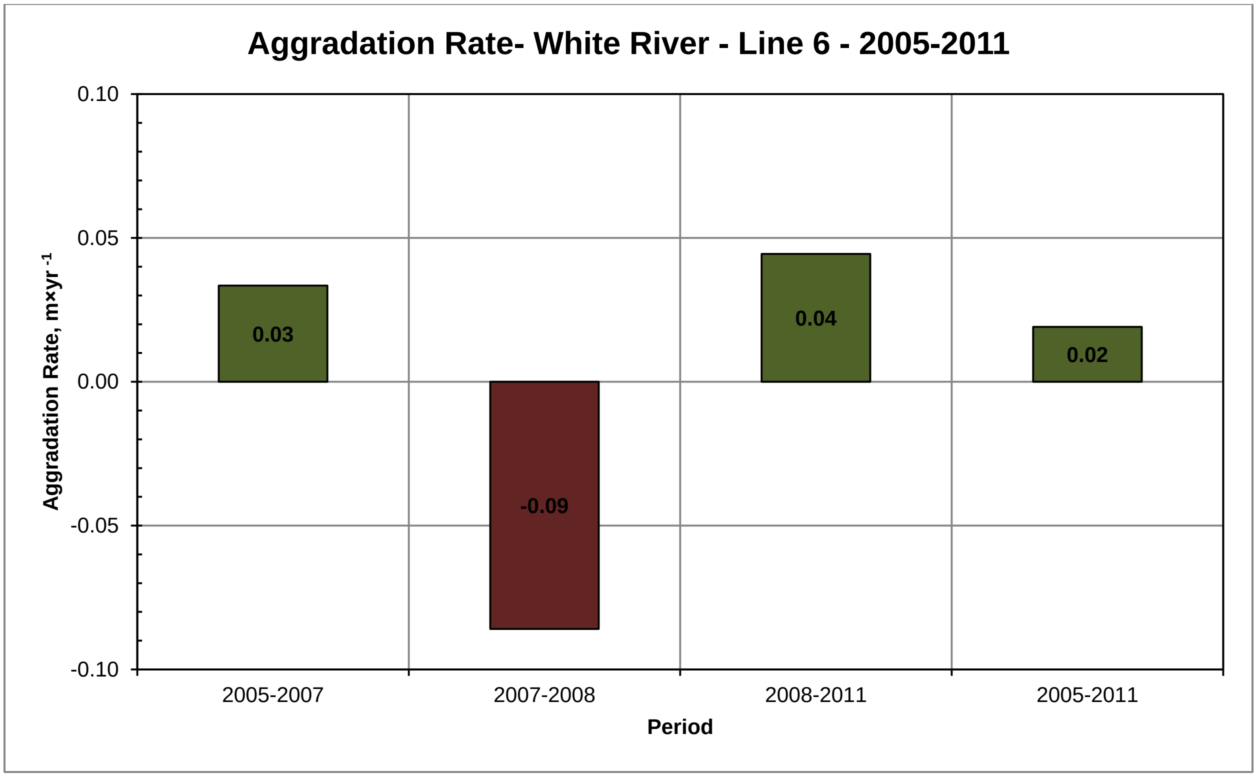
Appendix B.25: Aggradation rates for White River, Cross Section 3, 2005-2011.



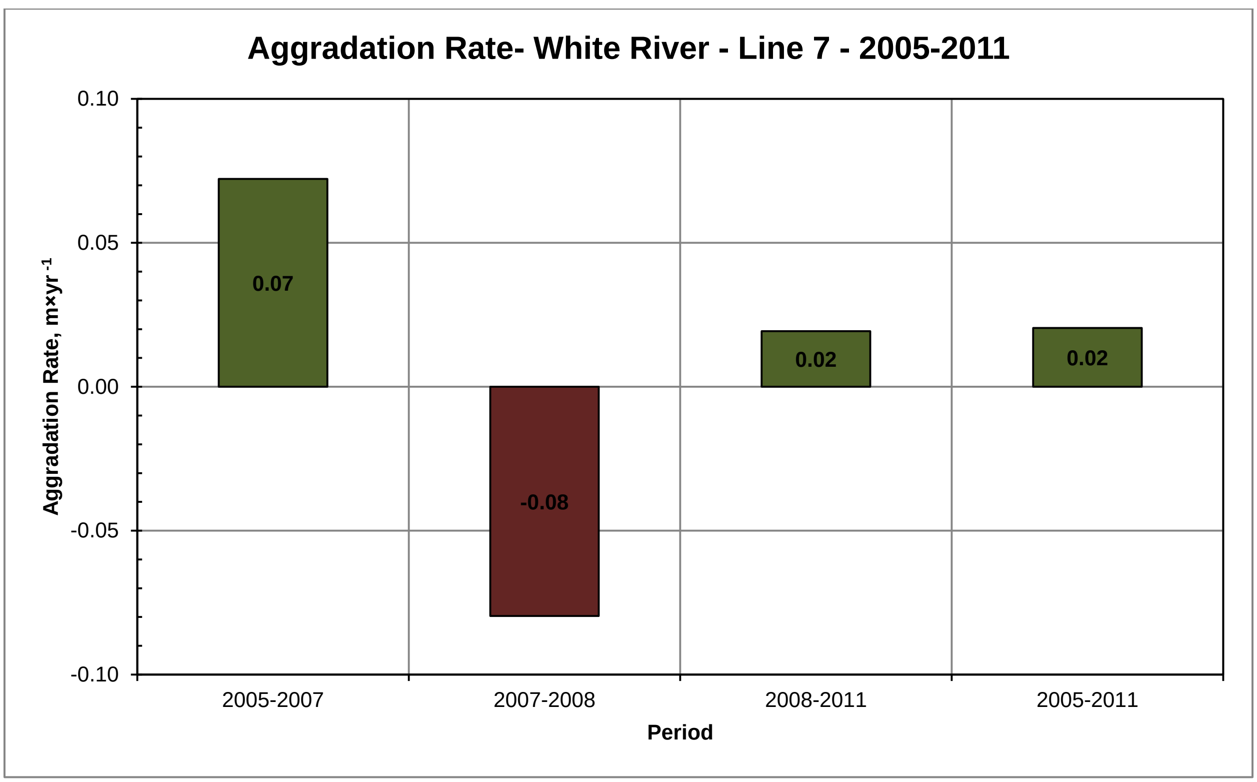
Appendix B.26: Aggradation rates for White River, Cross Section 4, 2005-2011.



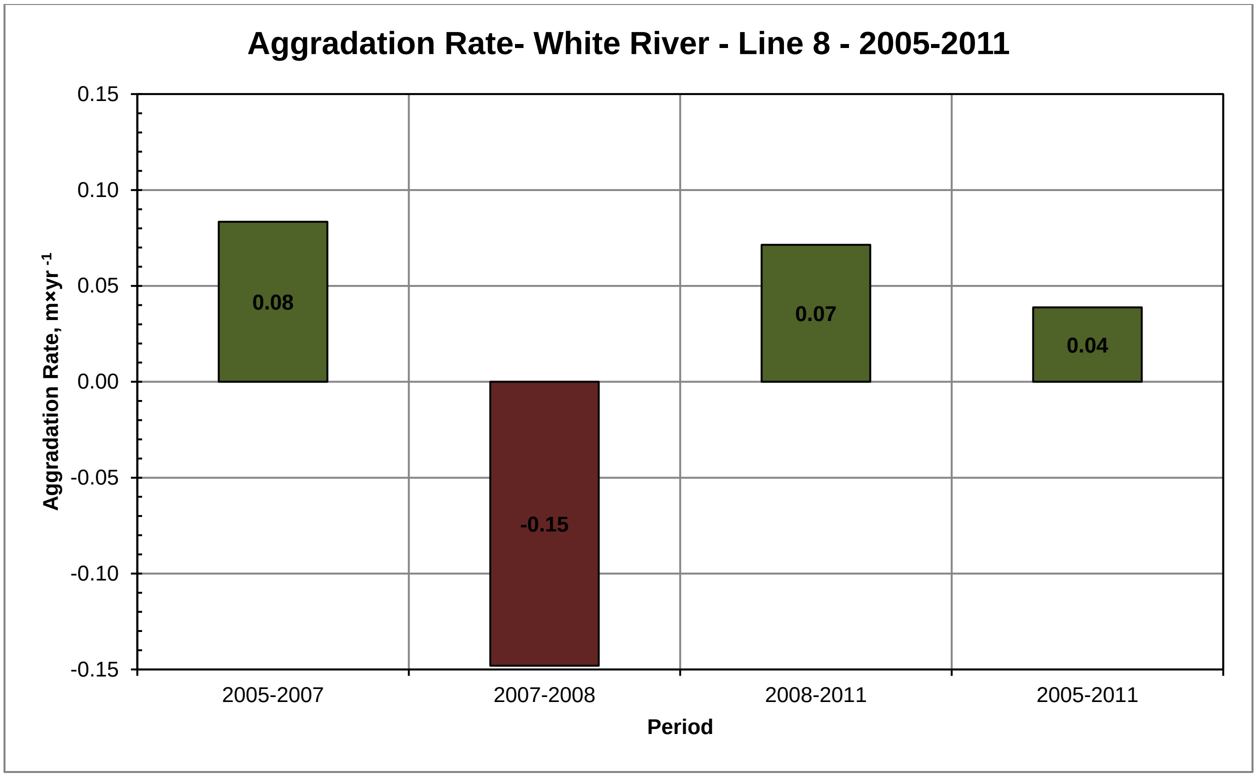
Appendix B.27: Aggradation rates for White River, Cross Section 5, 2005-2011.



Appendix B.28: Aggradation rates for White River, Cross Section 6, 2005-2011.



Appendix B.29: Aggradation rates for White River, Cross Section 7, 2005-2011.



Appendix B.30: Aggradation rates for White River, Cross Section 8, 2005-2011.

Appendix C: Volumetric changes in active channel areas represented by specified cross sections over time. Aggradation rates are from Appendix A and areas are from Tables 14, 16, 18, 20 and 22.

Volume is calculated as Rate × Area represented by cross section for each year.
Net volume is the running total of volume of sediment added or subtracted year-to-year.

Appendix C.1: Volumetric cross sectional changes at Sunshine Point, cross section 1 from 2005-2012. Aggradation rate is from Appendix A.1 and area represented by cross section is from Table 14.

Year	Rate, $m \times yr^{-1}$	Area represented by cross section, m^2	Volume, m^3	Net Volume, m^3
2005	-	-	-	0.00
2006	0.09	2,850.33	252.82	252.82
2007	0.29	11,551.03	3,296.79	3,549.61
2008	0.29	11,551.03	3,296.79	6,846.40
2009	-0.24	11,551.03	-2,803.75	4,042.65
2010	0.12	11,551.03	1,427.87	5,470.53
2011	0.12	11,551.03	1,427.87	6,898.40
2012	0.04	11,551.03	445.26	7,343.66

Appendix C.2: Volumetric cross sectional changes at Sunshine Point, cross section 2 from 2005-2012. Aggradation rate is from Appendix A.2 and area represented by cross section is from Table 14.

Year	Rate, $m \times yr^{-1}$	Area represented by cross section, m^2	Volume, m^3	Net Volume, m^3
2005	-	-	-	0.00
2006	-0.13	1,377.02	-176.28	-176.28
2007	0.47	7,704.06	3,610.77	3,434.49
2008	0.47	7,704.06	3,610.77	7,045.26
2009	-0.24	7,704.06	-1,882.17	5,163.09
2010	0.11	7,704.06	827.40	5,990.49
2011	0.11	7,704.06	827.40	6,817.89
2012	0.00	7,704.06	23.70	6,841.59

Appendix C.3: Volumetric cross sectional changes at Sunshine Point, cross section 3 from 2005-2012. Aggradation rate is from Appendix A.3 and area represented by cross section is from Table 14.

Year	Rate, $m \times yr^{-1}$	Area represented by cross section, m^2	Volume, m^3	Net Volume, m^3
2005	-	-	-	0.00
2006	0.07	1,138.34	79.46	79.46
2007	0.44	7,825.11	3,428.24	3,507.69
2008	0.44	7,825.11	3,428.24	6,935.93
2009	-0.06	7,825.11	-476.60	6,459.33
2010	0.02	7,825.11	136.07	6,595.39
2011	0.02	7,825.11	136.07	6,731.46
2012	-0.01	7,825.11	-61.33	6,670.13

Appendix C.4: Volumetric cross sectional changes at Sunshine Point, cross section 4 from 2008-2012. Aggradation rate is from Appendix A.4 and area represented by cross section is from Table 14.

Year	Rate, $m \times yr^{-1}$	Area represented by cross section, m^2	Volume, m^3	Net Volume, m^3
2008	-	-	-	0.00
2009	-0.51	7,582.16	-3,833.27	-3,833.27
2010	0.13	7,582.16	976.96	-2,856.31
2011	0.13	7,582.16	976.96	-1,879.34
2012	0.06	7,582.16	454.57	-1,424.78

Appendix C.5: Volumetric cross sectional changes at Sunshine Point, cross section 5 from 2008-2012. Aggradation rate is from Appendix A.5 and area represented by cross section is from Table 14.

Year	Rate, $m \times yr^{-1}$	Area represented by cross section, m^2	Volume, m^3	Net Volume, m^3
2008	-	-	-	0.00
2009	-0.52	9,793.86	-5,105.82	-5,105.82
2010	0.18	9,793.86	1,781.23	-3,324.60
2011	0.18	9,793.86	1,781.23	-1,543.37
2012	-0.02	9,793.86	-174.60	-1,717.98

Appendix C.6: Volumetric cross sectional changes at Sunshine Point, cross section 6 from 2008-2012. Aggradation rate is from Appendix A.6 and area represented by cross section is from Table 14.

Year	Rate, $m \times yr^{-1}$	Area represented by cross section, m^2	Volume, m^3	Net Volume, m^3
2008	-	-	-	0.00
2009	0.04	18,581.95	765.33	765.33
2010	0.08	18,581.95	1,440.09	2,205.41
2011	0.08	18,581.95	1,440.09	3,645.50
2012	0.07	18,581.95	1,308.13	4,953.63

Appendix C.7: Volumetric cross sectional changes at Sunshine Point, cross section 7 from 2008-2012. Aggradation rate is from Appendix A.7 and area represented by cross section is from Table 14.

Year	Rate, $m \times yr^{-1}$	Area represented by cross section, m^2	Volume, m^3	Net Volume, m^3
2008	-	-	-	0.00
2009	-0.05	12,126.77	-615.84	-615.84
2010	0.12	12,126.77	1,455.83	839.99
2011	0.12	12,126.77	1,455.83	2,295.82
2012	0.00	12,126.77	-36.18	2,259.64

Appendix C.8: Volumetric cross sectional changes at Sunshine Point, cross section 8 from 2008-2012. Aggradation rate is from Appendix A.8 and area represented by cross section is from Table 14.

Year	Rate, $m \times yr^{-1}$	Area represented by cross section, m^2	Volume, m^3	Net Volume, m^3
2008	-	-	-	0.00
2009	0.01	8,756.80	49.17	49.17
2010	0.09	8,756.80	782.30	831.47
2011	0.09	8,756.80	782.30	1,613.77
2012	0.02	8,756.80	190.68	1,804.45

Appendix C.9: Volumetric cross sectional changes at Longmire, cross section 1 from 1997-2009. Aggradation rate is from Appendix A.9 and area represented by cross section is from Table 16.

Year	Rate, $m \times yr^{-1}$	Area represented by cross section, m^2	Volume, m^3	Net Volume, m^3
1997	-	-	-	0.00
1998	0.00	598.30	0.89	0.89
1999	0.00	598.30	0.89	1.78
2000	0.00	598.30	0.89	2.68
2001	0.00	598.30	0.89	3.57
2002	0.00	598.30	0.89	4.46
2003	0.00	598.30	0.89	5.35
2004	0.00	598.30	0.89	6.24
2005	0.00	598.30	0.89	7.14
2006	0.03	598.30	15.44	22.57
2007	0.02	598.30	14.42	36.99
2008	0.02	598.30	14.42	51.41
2009	-0.35	598.30	-208.80	-157.39

Appendix C.10: Volumetric cross sectional changes at Longmire, cross section 2 from 1997-2012. Aggradation rate is from Appendix A.10 and area represented by cross section is from Table 16.

Year	Rate, $m \times yr^{-1}$	Area represented by cross section, m^2	Volume, m^3	Net Volume, m^3
1997	-	-	-	0.00
1998	-0.01	846.29	-5.26	-5.26
1999	-0.01	846.29	-5.26	-10.52
2000	-0.01	846.29	-5.26	-15.79
2001	-0.01	846.29	-5.26	-21.05
2002	-0.01	846.29	-5.26	-26.31
2003	-0.01	846.29	-5.26	-31.57
2004	-0.01	846.29	-5.26	-36.84
2005	-0.01	846.29	-5.26	-42.10
2006	0.36	846.29	304.37	262.27
2007	-0.03	846.29	-21.66	240.61
2008	-0.03	846.29	-21.66	218.95
2009	-0.72	846.29	-613.06	-394.11
2010	0.02	846.29	17.34	-376.76
2011	0.01	846.29	7.36	-369.40
2012	0.10	846.29	86.56	-282.84

Appendix C.11: Volumetric cross sectional changes at Longmire, cross section 3 from 1997-2012. Aggradation rate is from Appendix A.11 and area represented by cross section is from Table 16.

Year	Rate, $m \times yr^{-1}$	Area represented by cross section, m^2	Volume, m^3	Net Volume, m^3
1997	-	-	-	0.00
1998	0.01	450.22	4.87	4.87
1999	0.01	450.22	4.87	9.74
2000	0.01	450.22	4.87	14.62
2001	0.01	450.22	4.87	19.49
2002	0.01	450.22	4.87	24.36
2003	0.01	450.22	4.87	29.23
2004	0.01	450.22	4.87	34.11
2005	0.01	450.22	4.87	38.98
2006	0.29	450.22	129.11	168.08
2007	0.17	450.22	76.52	244.60
2008	0.17	450.22	76.52	321.12
2009	-0.91	450.22	-411.49	-90.36
2010	0.50	450.22	225.41	135.05
2011	-0.04	450.22	-16.42	118.63
2012	0.07	450.22	30.47	149.10

Appendix C.12: Volumetric cross sectional changes at Longmire, cross section 4 from 1997-2012. Aggradation rate is from Appendix A.12 and area represented by cross section is from Table 16.

Year	**Rate,** $m \times yr^{-1}$	**Area represented by cross section,** m^2	**Volume,** m^3	**Net Volume,** m^3
1997	-	-	-	0.00
1998	0.11	571.68	64.98	64.98
1999	0.11	571.68	64.98	129.97
2000	0.11	571.68	64.98	194.95
2001	0.11	571.68	64.98	259.93
2002	0.11	571.68	64.98	324.92
2003	0.11	571.68	64.98	389.90
2004	0.11	571.68	64.98	454.88
2005	0.11	571.68	64.98	519.87
2006	-0.51	571.68	-292.32	227.55
2007	-0.02	571.68	-13.87	213.68
2008	-0.02	571.68	-13.87	199.81
2009	-0.27	571.68	-156.75	43.06
2010	-0.07	571.68	-37.98	5.08
2011	-0.28	571.68	-158.89	-153.82
2012	0.28	571.68	162.84	9.02

Appendix C.13: Volumetric cross sectional changes at Longmire, cross section 5 from 1997-2012. Aggradation rate is from Appendix A.13 and area represented by cross section is from Table 16.

Year	**Rate,** $m \times yr^{-1}$	**Area represented by cross section,** m^2	**Volume,** m^3	**Net Volume,** m^3
1997	-	-	-	0.00
1998	0.05	1,451.99	70.02	70.02
1999	0.05	1,451.99	70.02	140.04
2000	0.05	1,451.99	70.02	210.06
2001	0.05	1,451.99	70.02	280.07
2002	0.05	1,451.99	70.02	350.09
2003	0.05	1,451.99	70.02	420.11
2004	0.05	1,451.99	70.02	490.13
2005	0.05	1,451.99	70.02	560.15
2006	-0.23	1,451.99	-334.55	225.60
2007	-0.17	1,451.99	-245.85	-20.25
2008	-0.17	1,451.99	-245.85	-266.10
2009	0.30	1,451.99	432.37	166.27
2010	-0.22	1,451.99	-315.78	-149.50
2011	-0.18	1,451.99	-264.89	-414.39
2012	0.23	1,451.99	333.91	-80.49

Appendix C.14: Volumetric cross sectional changes at Longmire, cross section 6 from 1997-2012. Aggradation rate is from Appendix A.14 and area represented by cross section is from Table 16.

Year	**Rate,** $m \times yr^{-1}$	**Area represented by cross section,** m^2	**Volume,** m^3	**Net Volume,** m^3
1997	-	-	-	0.00
1998	-0.10	933.60	-96.51	-96.51
1999	-0.10	933.60	-96.51	-193.02
2000	-0.10	933.60	-96.51	-289.52
2001	-0.10	933.60	-96.51	-386.03
2002	-0.10	933.60	-96.51	-482.54
2003	-0.10	933.60	-96.51	-579.05
2004	-0.10	933.60	-96.51	-675.55
2005	-0.10	933.60	-96.51	-772.06
2006	0.53	933.60	498.48	-273.58
2007	-0.06	933.60	-55.96	-329.54
2008	-0.06	933.60	-55.96	-385.50
2009	0.32	933.60	296.22	-89.28
2010	0.14	933.60	131.59	42.31
2011	-0.07	933.60	-66.03	-23.71
2012	0.11	933.60	101.55	77.83

Appendix C.15: Volumetric cross sectional changes at Longmire, cross section 7 from 1997-2012. Aggradation rate is from Appendix A.15 and area represented by cross section is from Table 16.

Year	**Rate,** $m \times yr^{-1}$	**Area represented by cross section,** m^2	**Volume,** m^3	**Net Volume,** m^3
1997	-	-	-	0.00
1998	0.02	2,288.71	34.56	34.56
1999	0.02	2,288.71	34.56	69.11
2000	0.02	2,288.71	34.56	103.67
2001	0.02	2,288.71	34.56	138.22
2002	0.02	2,288.71	34.56	172.78
2003	0.02	2,288.71	34.56	207.33
2004	0.02	2,288.71	34.56	241.89
2005	0.02	2,288.71	34.56	276.44
2006	0.19	2,288.71	434.98	711.42
2007	0.13	2,288.71	302.10	1,013.52
2008	0.13	2,288.71	302.10	1,315.62
2009	0.35	2,288.71	794.91	2,110.52
2010	0.16	2,288.71	377.62	2,488.15
2011	0.03	2,288.71	66.79	2,554.93
2012	0.05	2,288.71	115.51	2,670.45

Appendix C.16: Volumetric cross sectional changes at Longmire, cross section 8 from 1997-2012. Aggradation rate is from Appendix A.16 and area represented by cross section is from Table 16.

Year	Rate, *m×yr^{-1}*	Area represented by cross section, *m^2*	Volume, *m^3*	Net Volume, *m^3*
1997	-	-	-	0.00
1998	0.01	3,108.27	28.75	28.75
1999	0.01	3,108.27	28.75	57.49
2000	0.01	3,108.27	28.75	86.24
2001	0.01	3,108.27	28.75	114.98
2002	0.01	3,108.27	28.75	143.73
2003	0.01	3,108.27	28.75	172.48
2004	0.01	3,108.27	28.75	201.22
2005	0.01	3,108.27	28.75	229.97
2006	0.22	3,108.27	696.32	926.29
2007	-0.21	3,108.27	-649.38	276.91
2008	-0.21	3,108.27	-649.38	-372.48
2009	-0.18	3,108.27	-572.06	-944.54
2010	0.18	3,108.27	549.35	-395.19
2011	0.15	3,108.27	456.38	61.20
2012	0.03	3,108.27	90.18	151.38

Appendix C.17: Volumetric cross sectional changes at Longmire, cross section 9 from 1997-2012. Aggradation rate is from Appendix A.17 and area represented by cross section is from Table 16.

Year	Rate, *m×yr^{-1}*	Area represented by cross section, *m^2*	Volume, *m^3*	Net Volume, *m^3*
1997	-	-	-	0.00
1998	-0.01	2,543.25	-27.06	-27.06
1999	-0.01	2,543.25	-27.06	-54.13
2000	-0.01	2,543.25	-27.06	-81.19
2001	-0.01	2,543.25	-27.06	-108.26
2002	-0.01	2,543.25	-27.06	-135.32
2003	-0.01	2,543.25	-27.06	-162.39
2004	-0.01	2,543.25	-27.06	-189.45
2005	-0.01	2,543.25	-27.06	-216.52
2006	-0.05	2,543.25	-117.50	-334.02
2007	0.07	2,543.25	179.31	-154.71
2008	0.07	2,543.25	179.31	24.60
2009	0.01	2,543.25	24.46	49.06
2010	0.10	2,543.25	245.59	294.64
2011	-0.07	2,543.25	-174.03	120.62
2012	-0.11	2,543.25	-292.24	-171.62

Appendix C.18: Volumetric cross sectional changes at Longmire, cross section 10 from 1997-2012. Aggradation rate is from Appendix A.18 and area represented by cross section is from Table 16.

Year	Rate, $m \times yr^{-1}$	Area represented by cross section, m^2	Volume, m^3	Net Volume, m^3
1997	-	-	-	0.00
1998	-0.07	1,214.57	-82.39	-82.39
1999	-0.07	1,214.57	-82.39	-164.78
2000	-0.07	1,214.57	-82.39	-247.16
2001	-0.07	1,214.57	-82.39	-329.55
2002	-0.07	1,214.57	-82.39	-411.94
2003	-0.07	1,214.57	-82.39	-494.33
2004	-0.07	1,214.57	-82.39	-576.71
2005	-0.07	1,214.57	-82.39	-659.10
2006	0.52	1,214.57	632.05	-27.05
2007	-0.16	1,214.57	-190.48	-217.53
2008	-0.16	1,214.57	-190.48	-408.00
2009	0.26	1,214.57	314.46	-93.55
2010	0.04	1,214.57	53.12	-40.42
2011	-0.12	1,214.57	-147.88	-188.30
2012	0.01	1,214.57	7.99	-180.32

Appendix C.19: Volumetric cross sectional changes at Carter Falls, cross section 1 from 2011-2012. Aggradation rate is from Appendix A.19 and area represented by cross section is from Table 18.

Year	Rate, $m \times yr^{-1}$	Area represented by cross section, m^2	Volume, m^3	Net Volume, m^3
2011	-	-	-	0.00
2012	0.56	2,788.89	1,574.67	1,574.67

Appendix C.20: Volumetric cross sectional changes at Carter Falls, cross section 2 from 2011-2012. Aggradation rate is from Appendix A.19 and area represented by cross section is from Table 18.

Year	Rate, $m \times yr^{-1}$	Area represented by cross section, m^2	Volume, m^3	Net Volume, m^3
2011	-	-	-	0.00
2012	0.14	5,518.02	776.80	776.80

Appendix C.21: Volumetric cross sectional changes at Carter Falls, cross section 3 from 2011-2012. Aggradation rate is from Appendix A.19 and area represented by cross section is from Table 18.

Year	Rate, $m \times yr^{-1}$	Area represented by cross section, m^2	Volume, m^3	Net Volume, m^3
2011	-	-	-	0.00
2012	0.14	6,124.47	877.97	877.97

Appendix C.22: Volumetric cross sectional changes at Carter Falls, cross section 4 from 2011-2012. Aggradation rate is from Appendix A.19 and area represented by cross section is from Table 18.

Year	Rate, $m \times yr^{-1}$	Area represented by cross section, m^2	Volume, m^3	Net Volume, m^3
2011	-	-	-	000
2012	0.09	5,979.54	533.08	533.08

Appendix C.23: Volumetric cross sectional changes at Carter Falls, cross section 5 from 2011-2012. Aggradation rate is from Appendix A.19 and area represented by cross section is from Table 18.

Year	Rate, $m \times yr^{-1}$	Area represented by cross section, m^2	Volume, m^3	Net Volume, m^3
2011	-	-	-	0.00
2012	-0.16	5,421.16	-891.91	-891.91

Appendix C.24: Volumetric cross sectional changes at Carter Falls, cross section 6 from 2011-2012. Aggradation rate is from Appendix A.19 and area represented by cross section is from Table 18.

Year	Rate, $m \times yr^{-1}$	Area represented by cross section, m^2	Volume, m^3	Net Volume, m^3
2011	-	-	-	0.00
2012	-0.01	3,227.46	-20.17	-20.17

Appendix C.25: Volumetric cross sectional changes at Lower Van Trump, cross section 1 from 2005-2012. Aggradation rate is from Appendix A.20 and area represented by cross section is from Table 20.

Year	Rate, $m \times yr^{-1}$	Area represented by cross section, m^2	Volume, m^3	Net Volume, m^3
2005	-	-	-	0.00
2006	1.25	1,652.39	2,069.47	2,069.47
2007	-0.09	1,652.39	-140.94	1,928.53
2008	-0.09	1,652.39	-140.94	1,787.59
2009	0.54	1,652.39	895.26	2,682.86
2010	-0.04	1,652.39	-62.80	2,620.06
2011	0.03	1,652.39	41.85	2,661.91
2012	-0.07	1,652.39	-109.29	2,552.62

Appendix C.26: Volumetric cross sectional changes at Lower Van Trump, cross section 2 from 2005-2012. Aggradation rate is from Appendix A.21 and area represented by cross section is from Table 20.

Year	Rate, $m \times yr^{-1}$	Area represented by cross section, m^2	Volume, m^3	Net Volume, m^3
2005	-	-	-	0.00
2006	2.05	5,582.97	11,457.64	11,457.64
2007	-0.37	5,582.97	-2,066.76	9,390.89
2008	-0.37	5,582.97	-2,066.76	7,324.13
2009	-0.20	5,582.97	-1,114.99	6,209.14
2010	0.18	5,582.97	1,023.39	7,232.53
2011	-0.07	5,582.97	-378.49	6,854.04
2012	0.01	5,582.97	49.88	6,903.92

Appendix C.27: Volumetric cross sectional changes at Lower Van Trump, cross section 3 from 2005-2012. Aggradation rate is from Appendix A.22 and area represented by cross section is from Table 20.

Year	Rate, $m \times yr^{-1}$	Area represented by cross section, m^2	Volume, m^3	Net Volume, m^3
2005	-	-	-	0.00
2006	0.72	2,748.73	1,976.10	1,976.10
2007	0.14	2,748.73	396.20	2,372.30
2008	0.14	2,748.73	396.20	2,768.51
2009	0.21	2,748.73	565.51	3,334.01
2010	0.08	2,748.73	208.83	3,542.84
2011	0.00	2,748.73	-5.35	3,537.49
2012	0.05	2,748.73	136.42	3,673.91

Appendix C.28: Volumetric cross sectional changes at White River, cross section 1 from 2005-2011. Aggradation rate is from Appendix A.23 and area represented by cross section is from Table 22.

Year	Rate, $m \times yr^{-1}$	Area represented by cross section, m^2	Volume, m^3	Net Volume, m^3
2005	-	-	-	0.00
2006	-0.01	16,659.39	-217.16	-217.16
2007	-0.01	16,659.39	-217.16	-434.32
2008	-0.03	16,659.39	-480.55	-914.87
2009	0.04	16,659.39	641.93	-272.94
2010	0.04	16,659.39	641.93	368.99
2011	0.04	16,659.39	641.93	1,010.92

Appendix C.29: Volumetric cross sectional changes at White River, cross section 2 from 2005-2011. Aggradation rate is from Appendix A.24 and area represented by cross section is from Table 22.

Year	Rate, $m \times yr^{-1}$	Area represented by cross section, m^2	Volume, m^3	Net Volume, m^3
2005	-	-	-	0.00
2006	-0.02	27,116.56	-465.66	-465.66
2007	-0.02	27,116.56	-465.66	-931.32
2008	0.01	27,116.56	208.96	-722.36
2009	0.03	27,116.56	941.12	218.76
2010	0.03	27,116.56	941.12	1,159.88
2011	0.03	27,116.56	941.12	2,101.00

Appendix C.30: Volumetric cross sectional changes at White River, cross section 3 from 2005-2011. Aggradation rate is from Appendix A.25 and area represented by cross section is from Table 22.

Year	Rate, $m \times yr^{-1}$	Area represented by cross section, m^2	Volume, m^3	Net Volume, m^3
2005	-	-	-	0.00
2006	-0.01	64,315.01	-561.58	-561.58
2007	-0.01	64,315.01	-561.58	-1,123.15
2008	-0.06	64,315.01	-3,777.19	-4,900.34
2009	0.06	64,315.01	3,738.89	-1,161.45
2010	0.06	64,315.01	3,738.89	2,577.44
2011	0.06	64,315.01	3,738.89	6,316.33

Appendix C.31: Volumetric cross sectional changes at White River, cross section 4 from 2005-2011. Aggradation rate is from Appendix A.26 and area represented by cross section is from Table 22.

Year	Rate, $m \times yr^{-1}$	Area represented by cross section, m^2	Volume, m^3	Net Volume, m^3
2005	-	-	-	0.00
2006	[1]	101,966.74	[1]	0.00[1]
2007	[1]	101,966.74	[1]	0.00[1]
2008	-0.08	101,966.74	-8,244.22	-8,244.22
2009	0.05	101,966.74	5,404.20	-2,840.02
2010	0.05	101,966.74	5,404.20	2,564.18
2011	0.05	101,966.74	5,404.20	7,968.38

[1] See text for explanation of missing rates and volumes for 2005-2007.

Appendix C.32: Volumetric cross sectional changes at White River, cross section 5 from 2005-2011. Aggradation rate is from Appendix A.27 and area represented by cross section is from Table 22.

Year	Rate, $m \times yr^{-1}$	Area represented by cross section, m^2	Volume, m^3	Net Volume, m^3
2005	-	-	-	0.00
2006	0.02	73,573.56	1,824.38	1,824.38
2007	0.02	73,573.56	1,824.38	3,648.76
2008	-0.13	73,573.56	-9,864.99	-6,216.24
2009	0.04	73,573.56	3,088.20	-3,128.04
2010	0.04	73,573.56	3,088.20	-39.85
2011	0.04	73,573.56	3,088.20	3,048.35

Appendix C.33: Volumetric cross sectional changes at White River, cross section 6 from 2005-2011. Aggradation rate is from Appendix A.28 and area represented by cross section is from Table 22.

Year	Rate, $m \times yr^{-1}$	Area represented by cross section, m^2	Volume, m^3	Net Volume, m^3
2005	-	-	-	0.00
2006	0.03	10,852.52	363.23	363.23
2007	0.03	10,852.52	363.23	726.46
2008	-0.09	10,852.52	-932.28	-205.83
2009	0.04	10,852.52	482.44	276.61
2010	0.04	10,852.52	482.44	759.05
2011	0.04	10,852.52	482.44	1,241.48

Appendix C.34: Volumetric cross sectional changes at White River, cross section 7 from 2005-2011. Aggradation rate is from Appendix A.29 and area represented by cross section is from Table 22.

Year	Rate, $m \times yr^{-1}$	Area represented by cross section, m^2	Volume, m^3	Net Volume, m^3
2005	-	-	-	0.00
2006	0.07	71,620.81	5,169.92	5,169.92
2007	0.07	71,620.81	5,169.92	10,339.83
2008	-0.08	71,620.81	-5,702.43	4,637.40
2009	0.02	71,620.81	1,382.13	6,019.53
2010	0.02	71,620.81	1,382.13	7,401.65
2011	0.02	71,620.81	1,382.13	8,783.78

Appendix C.35: Volumetric cross sectional changes at White River, cross section 8 from 2005-2011. Aggradation rate is from Appendix A.30 and area represented by cross section is from Table 22.

Year	Rate, $m \times yr^{-1}$	Area represented by cross section, m^2	Volume, m^3	Net Volume, m^3
2005	-	-	-	0.00
2006	0.08	103,848.08	8,665.50	8,665.50
2007	0.08	103,848.08	8,665.50	17,331.00
2008	-0.15	103,848.08	-15,381.61	1,949.38
2009	0.07	103,848.08	7,416.66	9,366.05
2010	0.07	103,848.08	7,416.66	16,782.71
2011	0.07	103,848.08	7,416.66	24,199.37

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