Fluvial landscape response to aggradation, debris flows, and landslides: An example from the Nisqually River and Van Trump Creek, Mount Rainier, Washington, USA

BEASON, Scott R., WALKUP, Laura C., and KENNARD, Paul M.
Mount Rainier National Park, 55210 238th Ave E, Ashford, WA, 98304, Scott_Beason@nps.gov

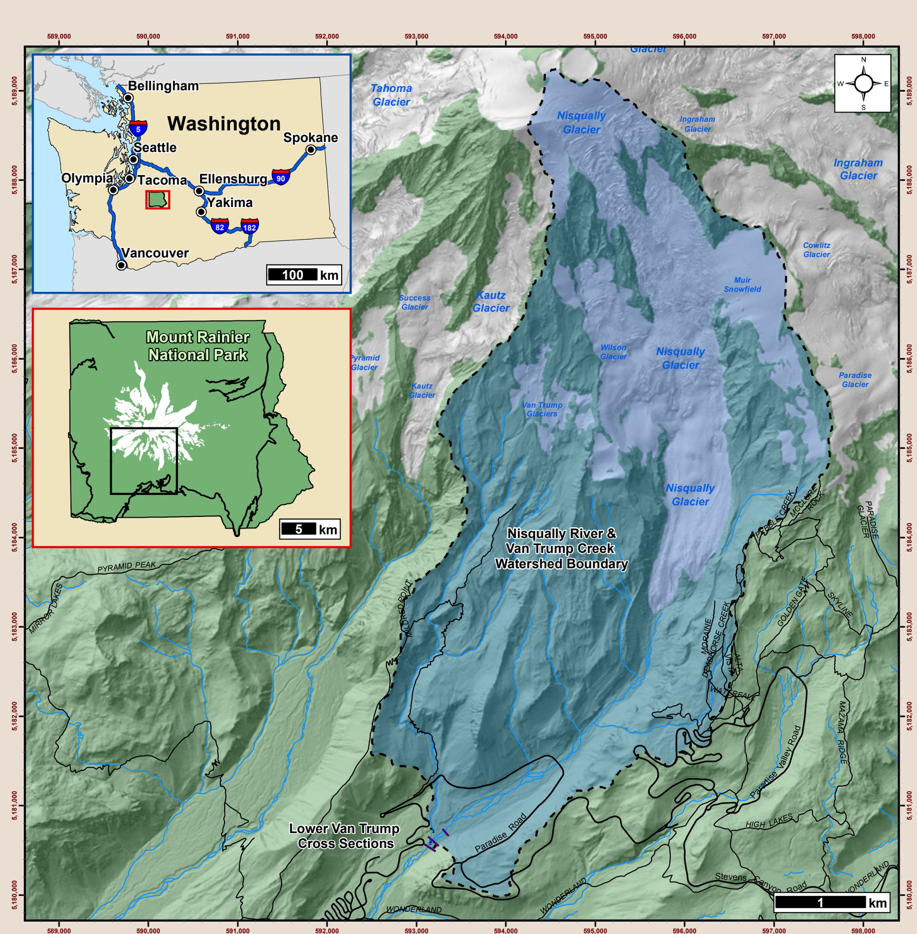
I. Abstract

The form and function of a braided river is driven by sediment inputs balanced with stream flow. Sediment enters braided rivers through a variety of processes at Mount Rainier, including upland erosion, direct delivery by glaciers, rock fall, bank erosion, and landslides. When sediment production overwhelms stream flow, excess sediment aggrades (raises) the river bed, leading to increased floodplain area. Over time, this process enhances flooding and debris flow threats to infrastructure. Given that much of the park infrastructure is built adjacent to glacier-sourced braided rivers, it is critical to understand the complex fluvial landscape in these areas, particularly since increased sediment delivery is a consequence of glacier retreat.

In the past two decades, the Nisqually River at the confluence of Van Trump Creek has seen dramatic changes in channel morphology. The area has been subject to numerous debris flows which deposited ~375,000 m³ of material in the active channel between 2001 and 2006. The debris flow deposit also constricted the river into a narrow channel against the left bank, adjacent to a cliff base. During a ~14 year RI storm in 2008, increased stream flows initiated a landslide that deposited ~18,000 m³ of debris into the river bed. This blocked the active channel for a short time and then concentrated the river into a narrow channel that widened as stream velocities and shear stresses increased. Analysis of repeat LiDAR data shows aggradation zones upstream, incision through the constriction, and aggradation downstream of the debris flow/landslide boundary.

Analysis of landscape response here is important for understanding the complex interactions of braided rivers, debris flows, landslides, and park infrastructure. For example, the 2005 debris flow had the unusual benefit of moving the river away from a primary Park road, decreasing the short-term risk of the road flooding. Incision into the debris flow deposit will increase hazards to the road as sediment is mobilized downstream and the river migrates back toward the road. This research can be used in other locations with similar geomorphic conditions to analyze how rivers route pulse-event sediment downstream, which has important connotations for infrastructure, visitor, and employee safety.

II. Study Area



Mount Rainier is a 4,392 m volcano in southwestern Washington State. The combined Nisqually River/Van Trump Creek basins have an area of 25.7 km² and extend from the summit of Mount Rainier down to approximately 1,030 m. The drainage basin includes the Nisqually, Wilson, and Van Trump Glaciers, as well as the Muir Snowfield. All glaciers at Mount Rainier are thinning and most are actively retreating (Sisson et al., 2011).

III. Background

The confluence of Van Trump Creek and the Nisqually River is located 15.1 km from the park entrance on the Nisqually-Paradise road. Debris flows surged down Van Trump Glaciers and into the study area in 2001, 2003, 2005 and 2006, some impacting the Nisqually-Paradise road (Donovan, 2005, Copeland, 2009). Beason (2007) found that the Nisqually River in the study area aggraded 12 m between 1910-2006. Some of this aggradation can be attributed to the aforementioned debris flows.

Above: Van Trump Creek flooding into the Nisqually River during the 09/29/2005 debris flow. Photo taken during the waning stage of the debris flow.

In order to study the effects of repeated massive sediment deposition, park researchers surveyed in cross sections in 2005. These cross sections were resurveyed in 2006, 2008, 2009, 2010, 2011 and 2012. The 2005 debris flow was directly bracketed by these cross sections. Later, during a storm on 11/12/2008, a steep section of slope above the study area slid and deposited into the area occupied by cross section 1. The study area is upstream of a campground and an administrative and visitor use area.

Left: Boulder levees (left) and battered tree trunks (right) are evidence of the 2005 Van Trump debris flow. Photo taken facing downstream.

IV. Methods

Cross Section Surveys
The majority of the topographic data used in this study was collected using a total station. This includes primarily cross sections, as well as secondary longitudinal profiles. Originally, a Pentax PCS-2 total station was used to survey three cross sections in the study reach. It was used in 2005, 2006, 2008 and 2009. Later, a Topcon GPT-3105W total station (pictured, left) was used in 2010, 2011, 2012 and 2013. All surveys were collected using similar control points and surveyed in the NAD 1983 Washington State Plane Coordinate System.

Above: Geoscientist-in-Park Corrie Floyd uses a Topcon GPT-3105W total station to conduct river surveys.

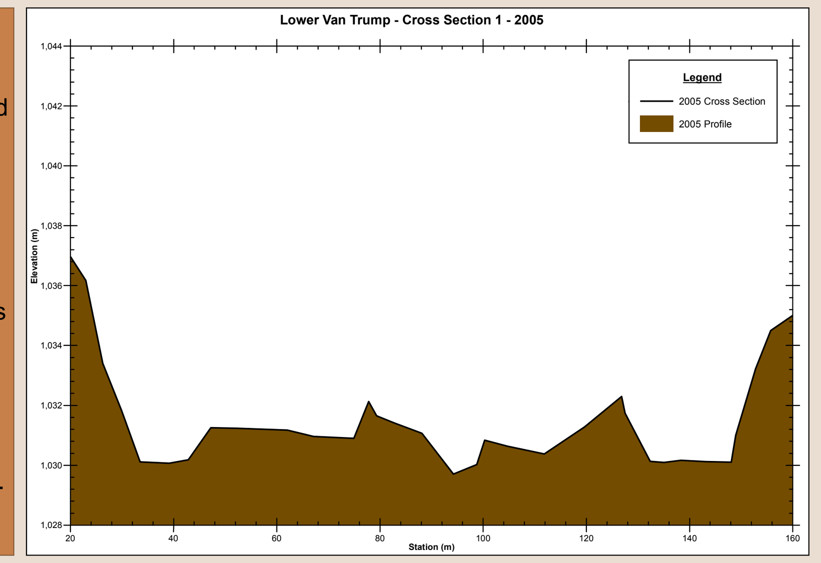
LiDAR Surveys
This study also utilizes two LiDAR data sets. The 2007/2008 LiDAR data set (Watershed Sciences, 2009) was part of a park-wide LiDAR data collection effort with between 7.27 - 5.73 points/m² and average vertical accuracy of 3.7 cm. The 2012 LiDAR was part of a smaller study targeted specifically at the Nisqually and Carbon River valleys (Watershed Sciences, 2012). The average density of this data is 17.28 points/m² and has an average vertical accuracy of 1.4 cm. Both data sets have similar coverage areas in the study area.

Data Analysis
Cross section data were analyzed using a custom-written database-driven cross section analysis tool (described in Beason et al., 2014). LiDAR data were analyzed using ESRI ArcGIS 10.2. Other programs including Microsoft Excel were used in the computation of channel changes.

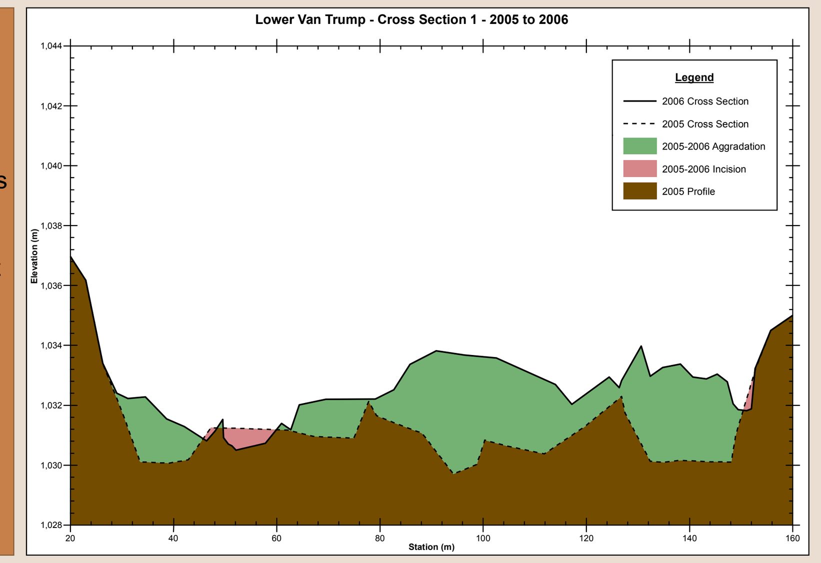
V. Results

Cross Section Results

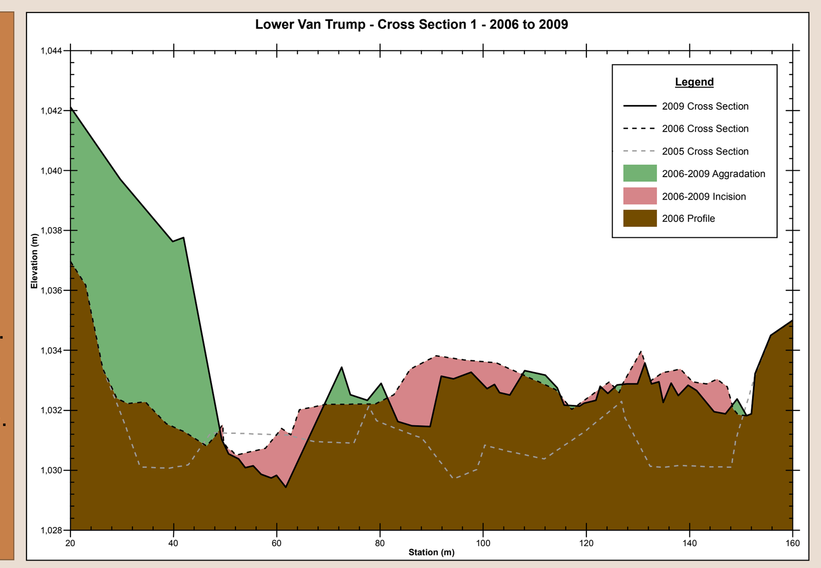
2005: Cross sections at Lower Van Trump were initially surveyed in 2005. The profile to the right is Cross Section 1, the most downstream cross section at Lower Van Trump hairpin. Both of the active channels for the Nisqually River and Van Trump flowed near the Nisqually-Paradise road (right bank), between station 130 - 150 m.



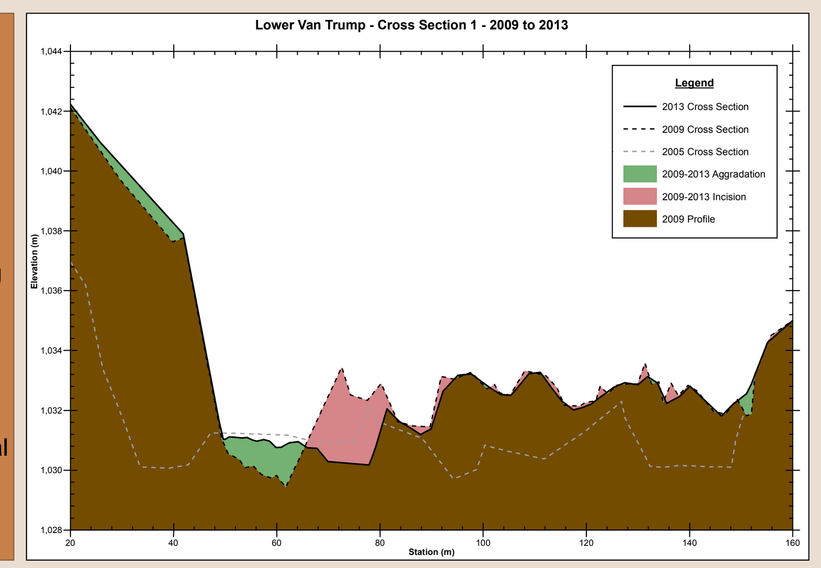
2006: During a September 29, 2005 storm, debris flow deposition occurred in the vicinity of Cross Section 1. The figure to the right shows the influx of sediment from the debris flow (green) and some slight incision (red) that occurred. The Nisqually River was forced toward the left bank (between stations 40-60 m).



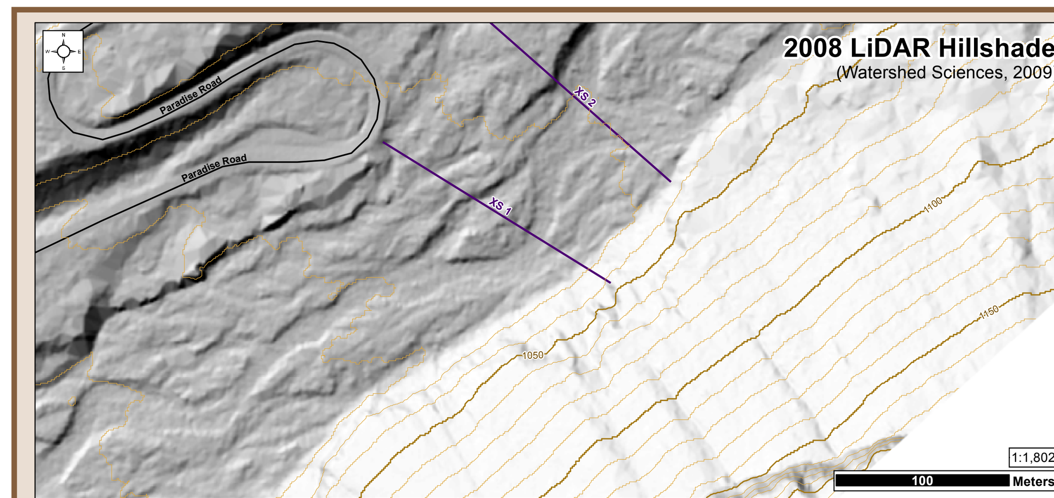
2009: On November 12, 2008, a ~14 year RI storm impacted Mount Rainier and lead to local flooding. During the flood, the Nisqually River incised into the left bank and initiated a landslide through the cross section (green). Significant incision (red) was observed throughout the profile. Incision may be due to overtopping of a temporary landslide dam.

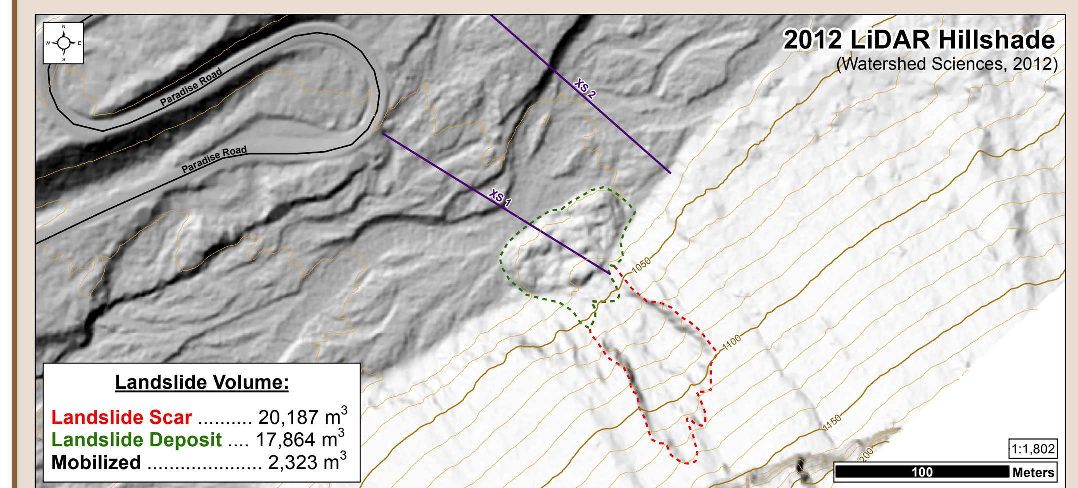


2013: Since 2008, very few floods have impacted the reach. However, the river (the active channel is between station 50 and 80 m) has been widening and eroding into the 2005 debris flow deposit and aggrading vertically. The river also is at a similar elevation compared to the initial cross section profile in 2005.

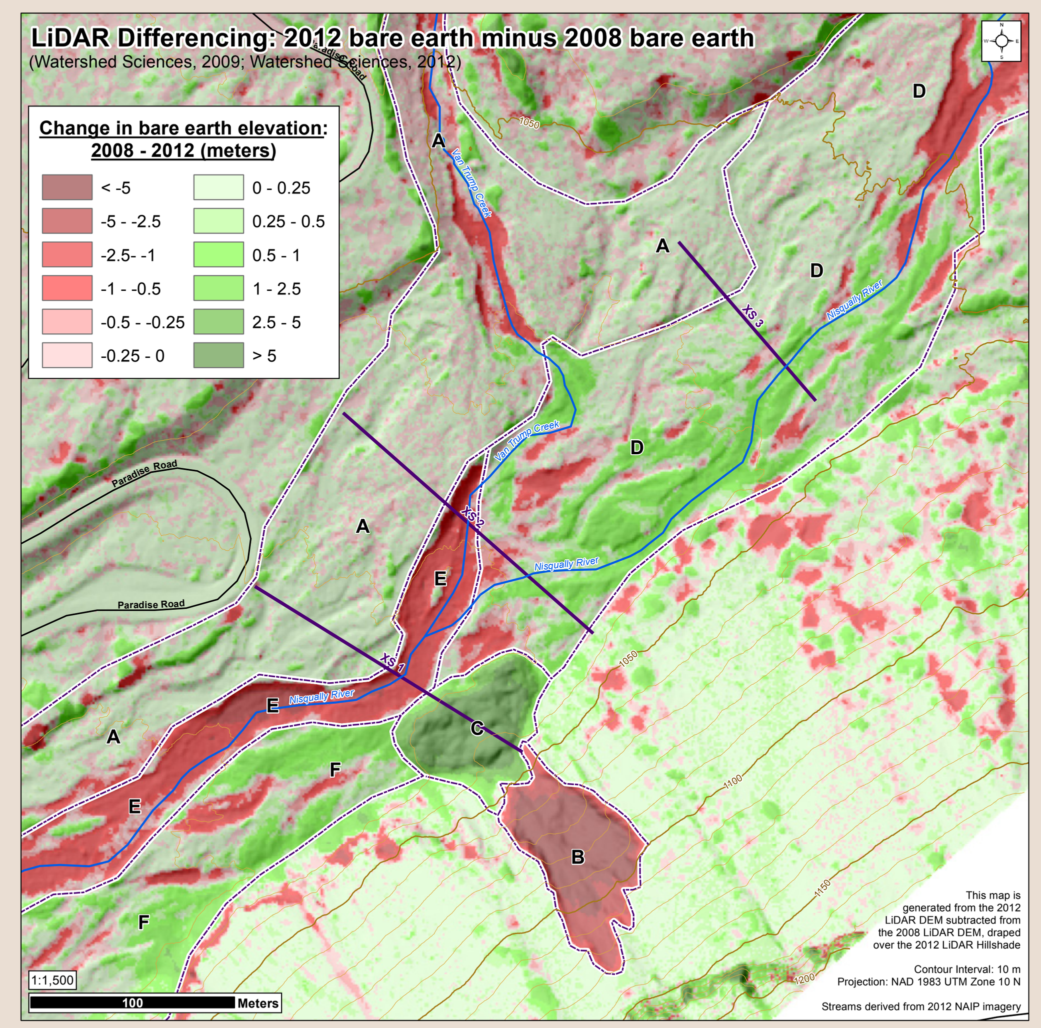


LiDAR Results





Repeated LiDAR flights in 2008 and 2012 showed the 2008 landslide in great detail. Because both LiDAR data sets were of similar resolutions and the volume of the landslide and its corresponding deposit in the channel were calculated from the LiDAR data. Some material was eroded and likely carried downstream.



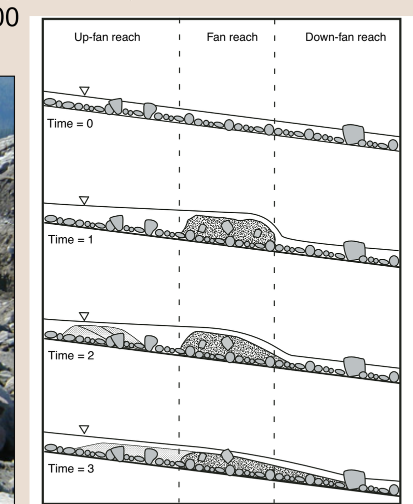
Analysis from subtracting the 2012 LiDAR data set from the 2008 LiDAR data set shows zones of incision and erosion. Zone "A" is the 2001-2005 debris flow fan; Zone "B" is the 2008 landslide scar; Zone "C" is the 2008 landslide deposit; Zone "D" is aggradation upstream of the debris flow blockage; Zone "E" is incision and head-cutting through and downstream of the landslide; and Zone "F" is aggradation of material from the landslide fan and eddying that occurred behind the deposit.

VI. Discussion and Findings

The key findings of this work include:

- The study area has been impacted by numerous debris flows between 2001-2006.
- The study area was impacted by a ~20,000 m³ landslide in 2008.
- Given the character of the source region (see photo, below left), it should be expected that future debris flows will impact the study area.
- The channel response here is unique because of the input of debris flows, landslides, and aggraded fluvial materials.
- This channel response impacts park infrastructure.
- Hoffman and Gabet (2007) described a stream that was impacted by debris flows in Montana and its response over time. Our study area exhibits similar channel response to that described by Hoffman and Gabet (see figure, below right).
- Channel response to sediment inputs has affected all areas in the study reach, including aggradation upstream in response to sediment fans and incision, and mobilization of material as the river attempts to dynamically adjust to sediment input.
- The total input of sediment here is estimated at approximately 395,000 m³, of which, 375,000 m³ is related to debris flows. The other 20,000 m³ is related to the 2008 landslide deposit.

Above: Source area of the 2001-2005 Van Trump debris flows. This area has been recently deglaciated and is over-steepened and meta-stable. Vast stores of sediment will likely source future debris flows.



Above: Figure 12 from Hoffman and Gabet (2007) showing the evolution of an idealized channel profile following sediment input from a debris flow (time units are arbitrary).

VII. Conclusions

This study shows the unique fluvial response of the Nisqually River and Van Trump Creek to repeated debris flows and a landslide. A surfeit of sediment is available in the Van Trump watershed to be provided as future debris flows for the reach. The active channels of the rivers in the study area have shifted from the right bank to the left bank, which has the unusual short-term benefit of protecting a primary park road. However, in doing that, the river incised into the bank of a steep hillslope above and led to the initiation of a landslide during a rain event. This led to the complete blockage of the channel for a very short time. Water pooling up behind the landslide caused aggradation of the river bed. When the pool height finally exceeded the landslide blockage, water flows led to the development of a deeply incised and headcut channel where the Nisqually River currently flows. Subsequent river incision and lateral migration has partially mobilization the 2001-2006 debris flow deposits. All of this sediment is being fluvially reworked and will impact park infrastructure in the next decade to century.

The channel response in this location is extremely dynamic and driven by the massive sediment loads introduced into the reach by debris flows, fluvial aggradation, and landslides. The channel response here is similar to debris flow deposition and fluvial reworking in Montana (Hoffman and Gabet, 2007). Given current glacier recession and forecasted climate impacts in the next century, this reach is likely to be impacted by sediment coming on line in the upper basin and moving downstream in pulse events.

Left: Aerial view of the study area from a helicopter-mounted GoPro camera in 2014, view facing downstream. The Nisqually River flows from bottom to top; Van Trump Creek enters from the right to the confluence with the Nisqually River. Both the debris flow fan and landslide deposits are noted.

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