Tahoma Creek: Aggradation and Resource Management

Scott Anderson

August 7, 2013

Contents

List of Figures

List of Tables

Chapter 1

Summary

Aggradation directly beneath the Tahoma Creek Bridge has required repeated dredging to maintain adequate freeboard. Given that this span is an integral part of the Parks main access route, damage to or destruction of this structure would be a major disruption to Park functioning. This research was initiated with a goal of documenting and understanding the aggradation within Tahoma Creek, with the hope that such information would provide a better sense of how such hazards may evolve in the future and how best to manage these hazards. Specifically, the research attempts to a) document the rates of vertical channel change along the length of Tahoma Creek, b) determine, if aggradation is observed, whether this represents a systemic or transient disturbance, and c) discuss the potential options for mitigating these hazards.

Using LiDAR surveys flown in 2002, 2008 and 2012 to directly measure aggradation and incision over the entirety of the basin, I find that the lower reaches of Tahoma Creek, as a whole, have not aggraded over this period of record. While over 10^6 m^3 of sediment was transported through the lower five kilometers of the creek, the net change in storage within these reaches was about $-5x10^4$ m^3. Averaged over this area, this represents around 10cm of incision. Local exceptions exist, including a zone of net aggradation between the bridge and the Nisqually confluence for the 2008-2012 period.

Alder stands growing on the bare-gravel surfaces within the channel were observed to have established primarily in the years immediately following the debris flows of the early '90s, indicating that the lower channel does respond to such upstream sediment loading. However, the vertical position of these stands within the channel places a low upper limit on the extent of aggradation that may have occurred during these years, and further in-

dicate that the modern channel has not risen above the high-stand position obtained in the mid-'90s. Taken together, it appears that debris flows do cause increased channel activity in the lower reaches, but that this activity largely manifests as increased lateral mobility and sediment transport rates, with only minor associated aggradation. The increased activity appears to subside within several years of the end of significant upstream sediment loading.

A variety of sources were used to investigate channel activity over the past 100 years. The methods are not exact, but broadly suggest that the channel has seen several intervals of increased activity or aggradation over this period, while maintaining a long-term stability.

Tree-ring records were used to reconstruct debris flows over the past 500 years. This records shows that there was a suite of events, similar in extent to the modern debris flows, in the mid-19th century. This coincides with the onset of glacial retreat out of the Little Ice Age (LIA). This suite of debris flows, along with several other isolated events that occurred during earlier periods of retreat, suggest a connection between negative glacial mass balance and debris flow frequency. However, the exact mechanisms of this connection are unclear, making it difficult to predict how this frequency will evolve in the coming decades. Regardless, these records show that the modern debris flows are not without precedent, increasing the odds that Tahoma Creek is already in an equilibrium defined by semi-regular intervals of such elevated sediment loading. That being said, the extent of forest mortality in the upper basin, and particularly above the old campground site, does appear to be unprecedented since the forests were last cleared by the Tahoma lahar c. A.D. 1500.

Taken together, these findings indicate that the lower channel has been dynamically stable over the period of record, and the recent debris flows do not appear to be significantly more frequent or intense than those of the past 500 years. The aggradation at the bridge appears to be a function of unique local conditions, which may include a) the narrowness of the bridge opening relative; b) a dynamic overshoot of aggradation as the stream infills the dredged reach; c) augmented local sediment influxes from dredging spoils placed on local gravel bars; or d) an increased local base-level caused by aggradation at the Nisqually-Tahoma Creek confluence. All four options are plausible readings of the available data, nor are they mutually exclusive.

While uncertainty remains, it is my belief that dredging provides little benefit to the long-term maintenance of the Tahoma Creek Bridge, and likely plays a role in the persistence of the local aggradation. Near the bridge, Tahoma Creek transports an average of 45,000 m^3/yr of bed-material, and may transport an order of magnitude more than this during a single large flood. In contrast, dredging efforts generally reposition between 2,000 and 25,000 m^3 of material. As such, even if the dredged material was removed from the channel, the channel transports enough material to re-obtain the pre-dredging profile in, at most, several years. The lower local channel slope created by dredging causes material to preferentially deposit in this reach, and may cause transient aggradation above the equilibrium profile as the channel attempts to dynamically re-obtain balance. This situation is exacerbated by the practice of placing dredging spoils on top of gravel bars within the active channel. This sediment is readily re-entrained by the river, creating a lateral sediment influx of a magnitude that greatly exceed the natural lateral inputs that are derived from the erosion of vegetated floodplain banks.

These results put the fate of the bridge in something of a grey area. While there is no evidence to suggest that the recent aggradation will continue unabated, it is very likely that periodic, local conditions will reduce the freeboard of the bridge below acceptable margins of safety with some regularity. This is simply the nature of dynamic, mountain streams. Given the regularity with which channel maintenance has been performed near the bridge reach, and the very short-term nature of the improvements, it still seems reasonable to consider an investment in a longer-term solution that will reduce the need for emergency operations.

There exists a suite of techniques designed to increase local sediment transport rates, which theoretically could reduce the potential for aggradation at the bridge. However, none of these methods are likely to be effective in Tahoma Creek, given the high energy of the stream and coarse sediment being transported. Modifying the bridge to accommodate the creek is a more reasonable solution, and seems most inline with the mission of a National Park. While the entire Park is classified as a National Historical Landmark District, the Tahoma Creek Bridge itself is considered a non-contributing structure, reducing the bureaucratic overhead needed to modify it. The major drawback to this solution is the cost involved. This cost must be weighed against that of repeated dredging, which provides only marginal benefits in the short-term and may actually exacerbate the situation in the long run. Regardless of which mitigation strategy is used, simple long profile surveys of the low-flow wetted channel, taken annually between the Nisqually-Tahoma confluence and a point somewhat upstream of the bridge, would provide valuable insight into the processes at play. Such surveys could be easily obtained within the parks current framework of resource management.

Chapter 2

Research Findings

The concerns regarding aggradation within Tahoma Creek are founded on the readily visible impacts the river has had on Park infrastructure over the past decades. In the upper reaches, repeated debris flows and associated sedimentation have restricted or closed access to much of the western margin of the Park (figure 2.1). Aggradation and channel widening have repeatedly threatened the Tahoma Creek Bridge, requiring regular attention to maintain an adequate margin of safety. The purpose of this research was to gain a clearer understanding of the processes that drive these geomorphic changes, with the hope that this information could help predict the severity and persistence of such hazards in the coming years. This report will focus primarily on the bridge, given its importance in maintaining access to the most visited Park locations, but includes discussions of processes throughout the basin, including a historical perspective that spans the last five hundred years. Such a broad spatial and temporal perspective is a necessary component of understanding river system processes, as the activity at a given location is the product of both upstream and downstream forcings, all conditioned by the form of the valley floor built up over the past millennia.

2.1 Background information

Alluvial rivers, such as Tahoma Creek, flow through self-formed beds composed of the same material they transport. The stability of an alluvial river is dependent on a dynamic equilibrium between the rate that sediment is introduced into the river and the ability of the river to transport that sediment. If either aspect is substantially altered, the river will no

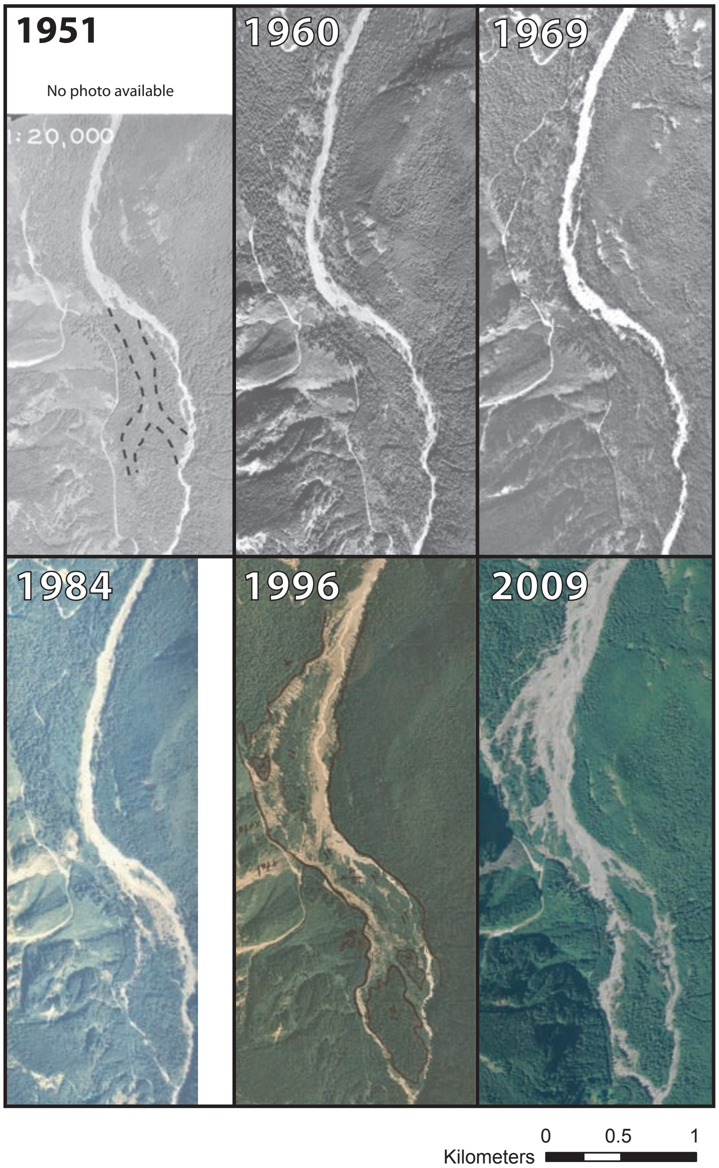

Figure 2.1: Aerial photographs showing Tahoma Creek between RK 3.5 and 8, the zone of primary debris flow deposition. 2009 photographs were provided as digital georeferenced images, while all others were scanned from hard-copy images stored on-site at Mt. Rainier NP, GIS building

longer be in equilibrium, and so will begin to adjust to re-obtain that state. These adjustments include changes in both the geometry of the river (aggrading/incising, widening/narrowing) and in the caliber of the sediment it carries (coarsening/fining).

There is reason to suspect that Tahoma Creek may be in disequilibrium. The South Tahoma Glacier, from which the stream is sourced, has retreated over two miles since its Little Ice Age (LIA) maximum in in the 1840s, accelerating such that over a mile of that retreat has occurred since 1950. This retreat has left behind massive volumes of unconsolidated glacial sediments, which constitute the primary sediment source for the numerous debris flows that have swept down the valley. The exposure of these deposits has the potential to increase the rate at which sediment enters the fluvial system.

The frequency and intensity of floods moving down Tahoma Creek is linked to the regional hydroclimatology, influenced by both cyclic processes such as the El-Nino/Southern Oscillation (ENSO) and the Pacific Decadal Oscillation (PDO), and possibly by the modern climate-warming trends. Recent research has noted an increase in the size of floods in western Washington, though the trend is not strong nor particularly obvious. Locally, flood records for the upper Nisqually show a strong linear increase in the size of the largest floods since the 1960s, exemplified by the massive 2006 event. However, the relatively short period of record (1943-present) makes it difficult to determine if this represents a true trend or simply the rising arm of a cyclic process.

Both of these processes have the potential to drive geomorphic change in Tahoma Creek, if the magnitude of the recent change is sufficiently large.

2.2 Analysis of Recent Change

Over the past 30 years, Tahoma Creek has experienced significant geomorphic activity. Dozens of debris flows have caused significant change to the upper basin, while the 2006 flood moved immense volumes of sediment downstream. Documenting and understanding the dynamics of the channel in the face of these events is the first-order goal of this study.

2.2.1 Repeat Aerial LiDAR

Tahoma Creek has been surveyed several times over the past decade, using an airborne laser-mapping system known as LiDAR. These surveys, flown in 2002, 2008 and 2012, produce extremely accurate representations of the basin topography, with vertical accuracies on the order of several centimeters

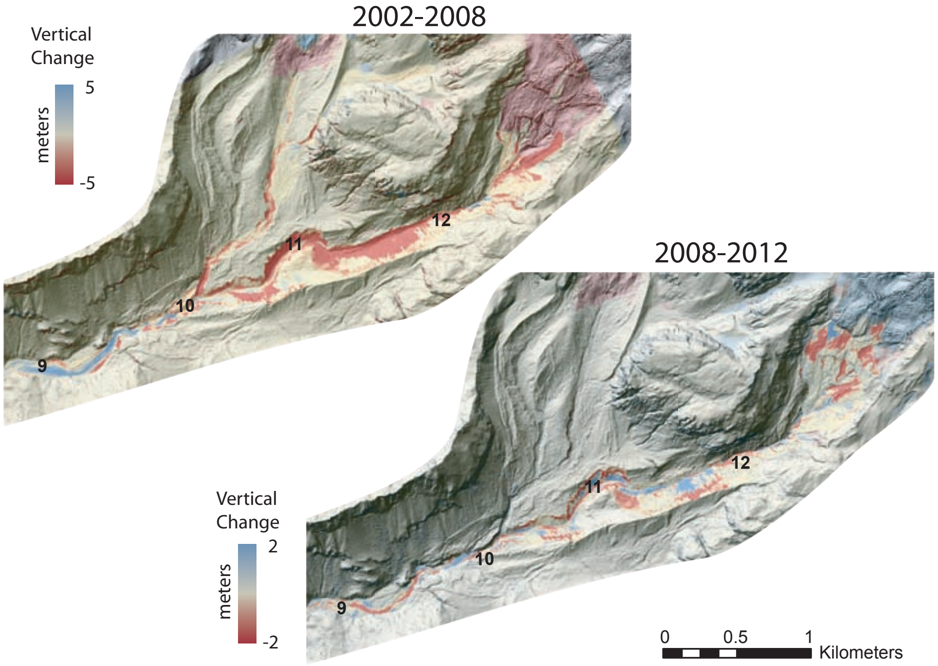

Figure 2.2: 1-m DEMs of change in the upper reaches of Tahoma Creek, as derived from repeat LiDAR surveys. Red colors indicate incision over the time period noted, while blue colors represent aggradation. The color ramp of the two time periods are scaled differently, reflecting the significantly higher activity levels of the earlier period. Numbers indicate river kilometers upstream from the Tahoma Creek Bridge

and a resolution one to four xyz points per square meter. By repeating these surveys, we are then able to take the difference of two sequential surveys, producing a highly resolved map of aggradation and incision over the entire extent of Tahoma Creek. With the available data, we are able to produce two such maps; one encompassing change from 2002 to 2008, and the other change from 2008 to 2012 (figures 2.2, 2.3). These figures also show the linear referencing system used in this report - locations in the river are noted as the number of river kilometers (RK) upstream of the bridge. Distance is measured alone the valley centerline. With this information, we are also able to estimate the volume of sediment that has been transported past any given point in the river over the time-period between surveys. We are able to extract this information because the surveys encompass the entirety of the basin, including all sources of coarse sediment. As sediment can only

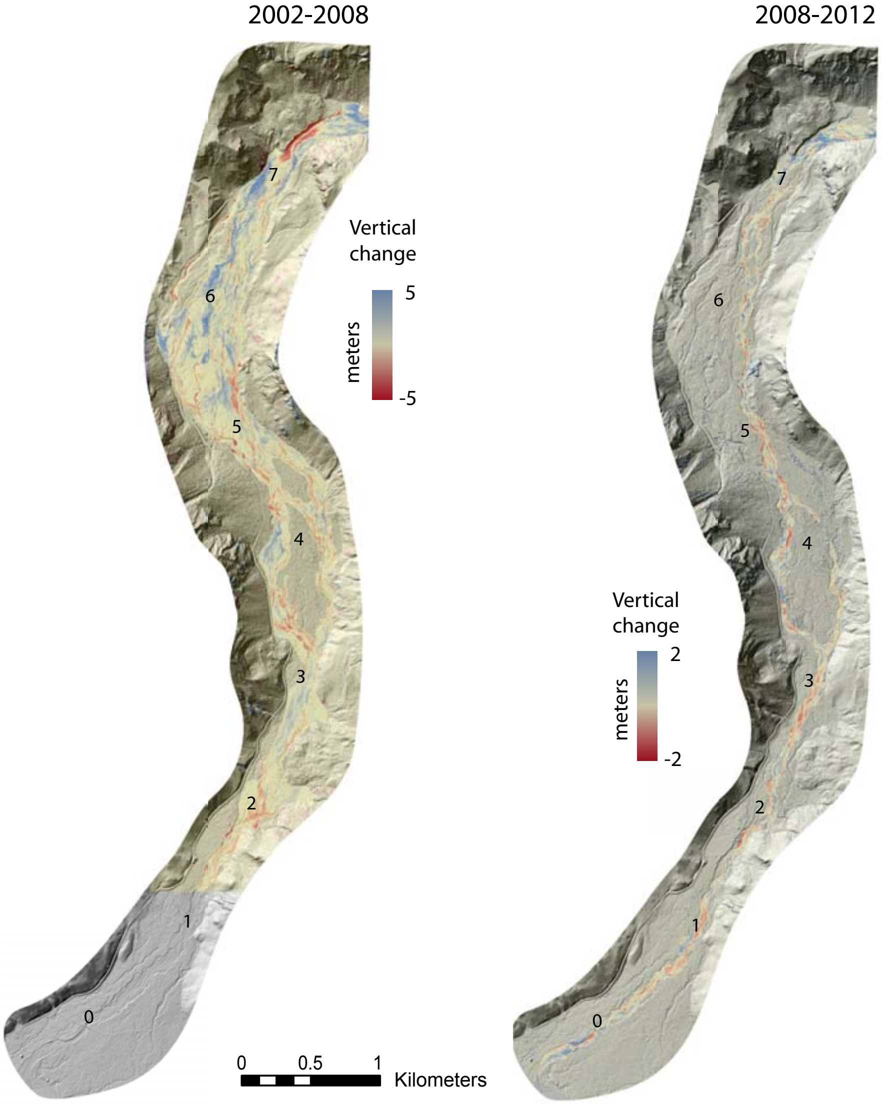

Figure 2.3: 1-m DEMs of change in the lower reaches of Tahoma Creek, as derived from repeat LiDAR surveys. Red colors indicate incision over the time period noted, while blue colors represent aggradation. The color ramp of the two time periods are scaled differently, reflecting the significantly higher activity levels of the earlier period. Numbers indicate river kilometers upstream from the Tahoma Creek Bridge

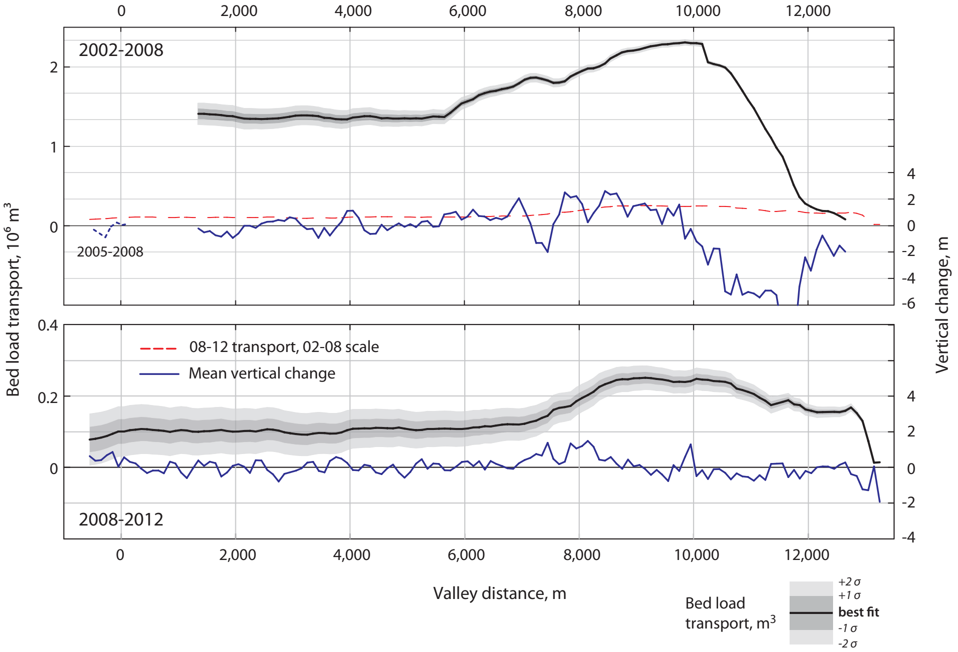

Figure 2.4: Mean vertical change (blue lines) and sediment transport (black lines) down the long profile of Tahoma Creek for 2002-2008 and 2008-2012, as derived from repeat LiDAR. Both measurements are marked at 100m intervals, as measured down the valley centerline. The shading around measurements of sediment transport represent the uncertainty associated with ±2.5 cm and ±5 cm of survey alignment uncertainty.

leave the basin through downstream transport, we simply assume that the volumetric sum of change upstream of a point is equal to transport past that point. By analogy, this is like measuring the changing height of water in pool that is draining out a hose in the bottom - the change in the height of the water, translated into a volume, gives you the total volume of water that has flowed through the hose. The results of this analysis can be seen in figure 2.4. The blue lines represent vertical change in the stream bed, averaged over sequential 100m sections. The black lines represent our estimates of total transport past a given point. Vertical change and transport rates showed similar spatial trends for the two time periods. Sediment has been largely sourced from upper glacial sediments, moving as debris flows until they reach the widening reaches of the valley near RK 7. Below this point, material generally begins depositing, splaying sediment over much of the width of the valley. By RK 5, most debris flows slow to a stop, and transport below these points occurs through conventional fluvial transport. For both time periods, roughly 50% of the initially mobilized material was deposited above these fluvial reaches, while the remaining material was routed through these reaches, exiting into the Nisqually River. Transport rates through these lower reaches were very consistent, and so, by extension, there was minimal vertical change along these reaches.

These similarities exist despite the order of magnitude difference in absolute transport rates observed between the two time periods. This difference is entirely a function of the 2006 flood, which moved an immense amount of material throughout the entire system. 2,300,000 m^3 of sediment was mobilized from the upper glacial sediment between 2002 and 2008; in contrast, only 250,000 m^3 of material was mobilized between 2008 and 2012. In the earlier time period, 1,200,000 m^3 of material transited the lower fluvial reaches; from 2008 to 2012, only 100,000 m^3. Additionally, the specific location from which sediment was mobilized within the upper kilometers differed between the two time periods. In the earlier period, sediment was predominately sourced from broad slope failures along the entire extent of recently exposed lateral moraines, dramatically widening and deepening the pro-glacial gully. In the latter period, these same moraines moved material downslope, but little, if any, of this material was entrained further downstream. Sediment in these latter years was sourced from discrete slumps of material mantling a steep bedrock step just below the 2012 terminus.

2.2.2 Alder Stands

Direct measurements of the basin topography are not available before 2002, and so indirect methods were used to gain some sense of change in the decades before this. This was primarily done through the analysis of the age structure and locations of alder stands growing within the active channel. These stands were common features along the lower channel. These stands establish on surfaces that remain stable for sufficiently long such that alder seeds can germinate, and the seedlings grow to a point where they can act to lock the surface in place. They will, in turn, be removed by significant floods or aggradation that kill trees through either direct impact injuries or burial. As such, the age and vertical position of these stands should give a rough indication of channel activity, and particularly, when surfaces within the active channel stabilized. There are two primary mechanisms that would cause active gravel surfaces to become inactive - the clearing of surfaces by exceptional floods, or the onset of incision that leave gravel surfaces stranded above the level of regular inundation. In both cases, the vertical position provides additional information; for the first case, it indicates a minimum inundation level for the flood, while for the second, it places a rough bound on the high stand elevation of the channel before incision.

In total, 63 trees from 21 distinct stands were cored for age, with two cores taken from each tree. Cores were dried, mounted and sanded, and rings counted. If the pith was not cored, the number of missing rings to the pith was estimated. However, given the small diameters of the trees, most included at least one core containing pith. To explore the vertical position, distinct stands were digitized using the 2008 LiDAR and the 2009 aerial photography. Elevations were taken from the 2008 LiDAR, and expressed as a height above the adjacent active channel. Most trees within distinct stands were of a similar age, usually clustering within a three year spread. The age of a stand was taken as the age of the oldest individual found. The ecesis interval, representing the lag between the date of the surface stabilizing and the germination of alder seeds, was taken to be a single year, based on the rapid recolonization of surfaces created by the 2006 flood. The age of a surface was thus taken as the age of the oldest individual growing on it, plus one year.

All trees cored established after 1960, with the majority establishing after 1980 (figure 2.5). The most notable feature of the data is the spike of establishments occurring between 1989 and 1995, with peaks in 1993 and 1994. These dates match the period of debris flow activity observed between 1986 and 1992 with a three-year lag, with the peak occurring in the years immediately following the end of the major debris flow activity. The strong signal of alder establishment immediately following the cessation of debris flow activity has several implications. First, it clearly demonstrates that debris flows in the upper basin do have notable impacts on the lower channel morphology. Second, the fact that alder establishment occurs in the immediate aftermath of the debris flows places a low limit on the duration of those impacts once active sediment loading ceases. Elevated downstream channel activity does not appear to last for more than three to five years following major debris flow activity, though this time span is very likely sensitive to the flood hydrology during those years. In the case of the 2006 flood, field evidence suggests that much of the newly mobilized material was transported through the entire system within the three days of the event, and as such, there may not have been much a morphologic response in the following years beyond normal post-flood readjustments.

Lastly, the elevation of these alder stands above the modern active channel places a rough upper limit on the high-stand vertical position the channel

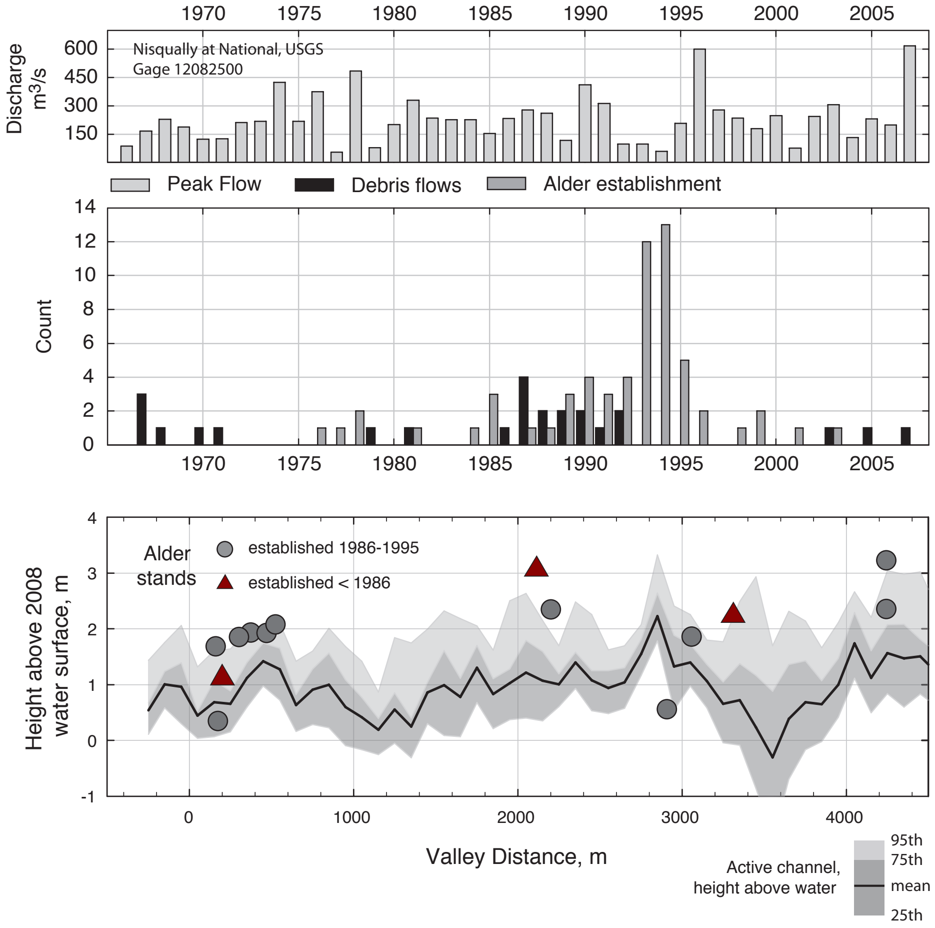

Figure 2.5: Center subfigure shows the distribution of establishment dates for individual alder trees cored in Tahoma Creek in grey, compared with the historical records of debris flows currently available shown in black. Subfigure above shows peak flow records at the National gage on the Nisqually River, demonstrating the potentially confounding factor of low flows associated with the '93-'94 alder establishment peaks. Lower subfigure shows the elevation of individual alder stands in comparison to the 2008 active channel, as measured from 2008 LiDAR. Alder stands are grouped into those occurring in the years after debris flows in '86, and those occurring before.

obtained in the wake of the last debris flows of the early ’90s, and provide a point of context for the modern channel. While there is no way of determining what elevations the channel was at in the years prior to the debris flows of the late ’80s/early ’90s, the presence of alder stands pre-dating these events and a rough analysis of aerial photographs suggest that aggradation during these events did not exceed two meters, and was unlikely to exceed one meter in many locations. Further, the modern channel, as documented in LiDAR since 2002, does not appear to have exceeded this high-stand elevation.

2.2.3 Synthesis of Modern Change

Both the LiDAR analysis and the structure of alder stands suggest that the lower fluvial reaches of Tahoma Creek have remained largely stable over the past three decades. Detailed measurements of vertical change since 2002, recorded in repeat LiDAR datasets, show a remarkable stability in the face of multiple debris flows and a catastrophic flood. The pulse of alder establishments in the wake of the debris flows of the late ’90s demonstrates that these events do have a measurable impact on the lower channel, but these same alders also place a relatively low limit on the extent of aggradation that occurred during this period. Given this evidence, it is most probable that Tahoma Creek is sufficiently steep and has sufficient flow to process the elevated sediment loads introduced by debris flows in an efficient manner. While total sediment loads are likely to increase during these times of disturbance, this increase is likely accommodated by increased transport efficiency accomplished through changes in surface sediment textures and a smoothing of channel forms.

2.3 Analysis of historical records

The following section covers a number of scattershot efforts to determine if the channel of Tahoma Creek has undergone any systematic change over the past century. This time period covers much of the recent warming and associated glacial retreat, and provides a longer baseline over which to measure change associated with these climatic processes. The methods used are variable, and much of the final analysis is somewhat speculative. Regardless, the longer time-scale of analysis improves the odds that change could be detected, and provides a stronger contextual grounding for the analysis of the more recent change documented above.

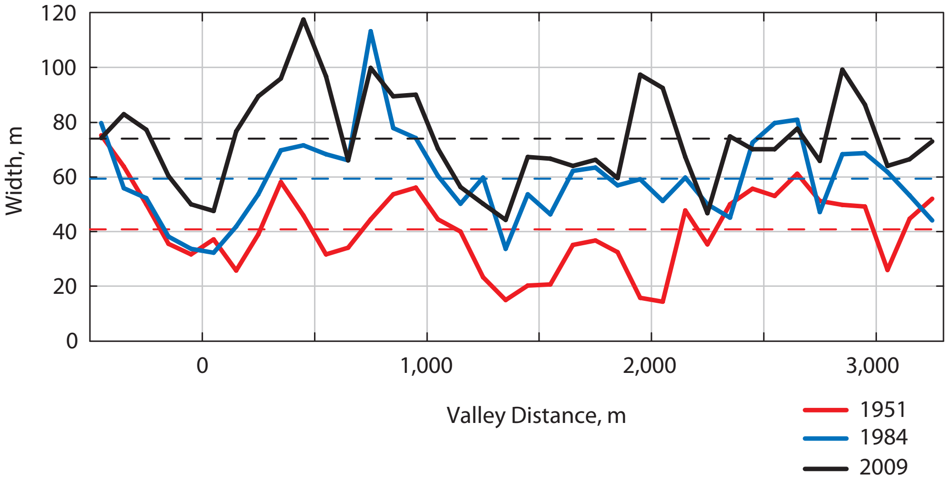

Figure 2.6: Channel width of the lower three river kilometers of Tahoma Creek in 1951, 1984 and 2009.

2.3.1 Channel Width

The width of an alluvial channel is one of the central variables by which these systems respond to changing boundary conditions. Generally, increasing sediment fluxes are associated with widening, while decreasing sediment fluxes are associated with narrowing. Aerial photographs stored at the Longmire GIS building were scanned, georectified, and the active channel digitized to provide a continuous measure of width. The active channel is idealized as the surfaces that are inundated by high flows at least every other year. In practice, this surface was defined in the aerial photographs as those covered with bare gravel or light riparian vegetation, and was generally very distinct from the bounding conifer forests. Dense stands of alder are a bit ambiguous, as it is difficult to determine if these stands are regularly inundated from photographs. Generally, stands dense enough to create a closed canopy of dark foliage were considered outside of the active channel, while young, lighter stands with lower densities were considered within the active channel. This is an important point, as the establishment and removal of alder is one of the primary modes by which the channel expands or contracts, given that these trees rapidly colonize bare gravel surfaces.

Widths of the lower three kilometers of the channel were digitized using photos from 1951, 1984 and 2009. These dates represent the earliest available aerial photographs, the channel state just before the highly active period from 1986-92, and the most recently available photos, respectively.

The mean active channel width has steadily increased since 1951, from 40m to 60m in 1984 and to 75m in 2009(figure 2.6). This near doubling in mean width was achieved in two distinct ways - the increase over the earlier period, '51-'84, consisted of relatively uniform widening over the entire analyzed reach, while the increase over the latter period, '84-'09, was largely driven by localized zones of extensive widening, such as near RK 0.5 and RK 2. In the earlier period, much of change is driven by the removal of what appear to be dense alder stands, while in the latter period, the localized width increases are associated with scalloped bites into the adjacent floodplain surface, primarily during the 2006 flood.

On the face of it, the presence of such significant widening over the past 60 years would suggest disequilibrium and a significant response to recent sediment loading and/or a changing flood hydrology. However, in looking at the specific changes mentioned in the above paragraph, I do not believe that the data points to a long-term and continuous trend. To my eye, the most convincing argument in this regard is, ironically, the significant widening that occurred, valley-wide, between 1951 and 1984. That the latter period did not show similar widening trends, even with the combined effects of all the debris flows and the massive floods of 1990, 1996 and 2006, suggests to me that the earlier widening was unlikely to have expanded the active channel significantly, but instead simply cleared the historical active channel of recently established alder. In this reading, the widening is more an indication of the relative mildness of the years before 1951, and less of the intensity of the years following. In looking at the latter period, a significant percentage of the widening has occurred in the reaches immediately upstream of the bridge - as will be discussed below, this may be related to ponding effects caused by the bridge itself, and not indicative of a naturally forced widening.

2.3.2 Relict Surfaces

Field examinations of Tahoma Creek, along with aerial photo analysis, uncovered several surfaces that had been active in the relatively recent past, but had since vegetated over. The age of vegetation growing on these surface provides a way of dating when the surfaces were last active, while the elevation of the surfaces provide some clues as to the vertical position of the channel during that period.

The most recently abandoned surface, as well as the most dynamic, was identified in both the field and in aerial photographs near RK 2 (figure 2.7).

At this point, the channel has recently flowed to both the west and east of a small forested island of conifers. In 1951, the main thread of flow was to the west of the island, though fingers of bare gravel surfaces can be seen along the eastern side of the channel. By 1960, the western channel had begun to vegetate over, while the eastern channel had continued to expand. This trend was reversed by 1969, with both east and west channels appear bare, indicating the removal of a significant amount of vegetation from the western path. Both channels remained active until sometime between 1989 and 1996, at which point the western channel again revegetated, and remained so even following the 2006 flood. These dates overlap well with the observed increase in channel width from 1951 and 1984, in that they suggest an increase in activity sometime between 1961 and 1969 that persisted until sometime between 1990 and 1996.

The elevation of this surface constrains the vertical position the channel over the last 60 years (figure 2.8). The mean elevation of this surface is on the order of two meters higher than the adjacent 2008 active channel surface. Terraces along the eastern margin of the valley sit at similar elevations, suggesting that the elevation was widespread during the high stand. Between 0.5 and 1 meter of the apparent incision since then was accomplished between 2003 and 2008, presumably during the 2006 flood. This leaves roughly one meter of net incision since the presumed high point sometime between 1989 and 2003. Both the primary surface and analogous surfaces to the east support alder stands that established in the years just prior to 1991, placing a tight constraint on the likely high-stand date. This date corresponds roughly to the end of debris flow activity in the upper basin, as well as with a significant flood recorded at the national gage in 1990. Given that the large flood of 2006 incised this reach, it is plausible that similar incision occurred during the 1990 flood.

Just upstream, an older surface was discovered, sitting at a similar elevation above the 2008 active channel. Conifers growing on this surface indicate that it was abandoned in the years prior to 1929. This surface indicates that the aggradation of the early ’90s has historical precedents. The fact that the channel was abandoned also suggests that, for some period of time between 1929 and c. 1960, the channel incised and flowed at a lower elevation.

Below this reach, three surfaces with two distinct abandonment dates were identified (figure 2.9). One, near RK 0.8, was abandoned in the years before 1910, while two surface on either side of the channel just upstream of the bridge were abandoned in the years before 1948. Given the location of these surfaces, it is likely that they were not truly ”abandoned,” in the sense of an active channel that becomes inactive, but rather cleared during

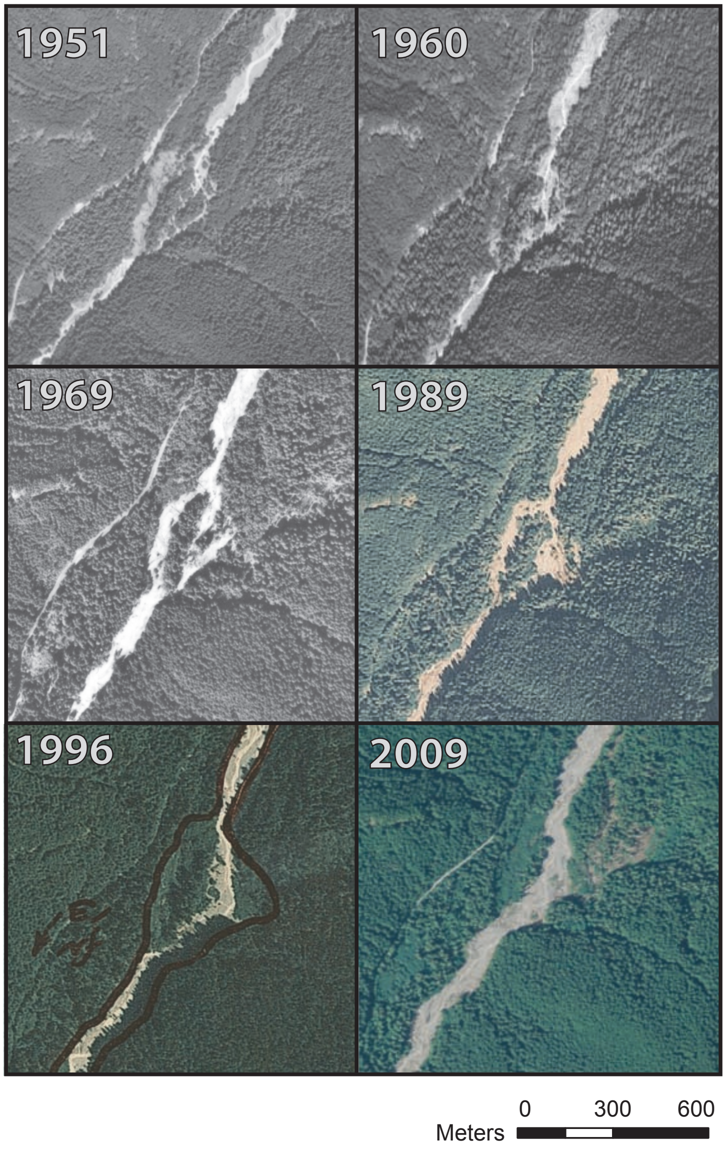

Figure 2.7: Repeat aerial photography showing channel dynamics near RK 2.

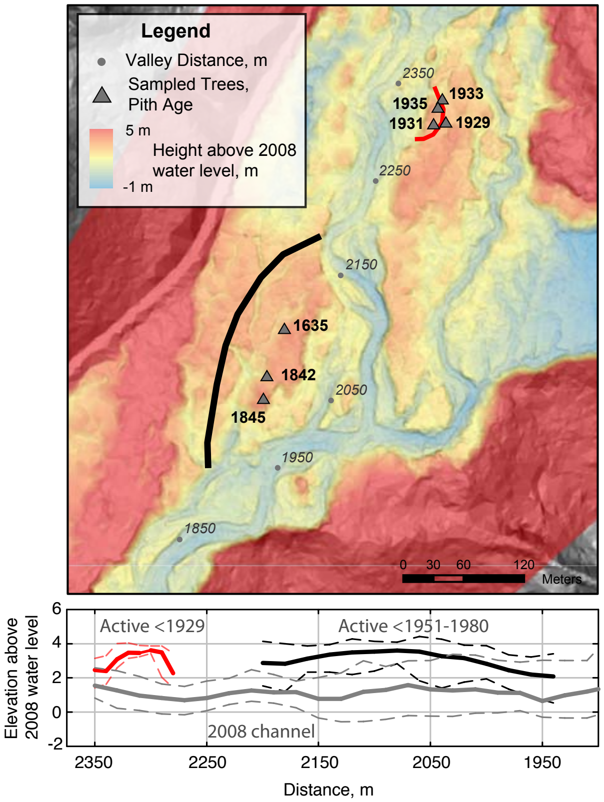

Figure 2.8: LiDAR imagery showing elevations of relict surfaces around RK 2, and their elevations above the 2008 water surface. The recently abandoned channel featured in figure 2.7 is noted with the black line, while an older surface upstream is noted in red. Long-profiles of these surfaces, compared against the 2008 active channel, are shown in the subfigure. Triangle markers with dates note the position and pith age of conifers used to establish a rough date of abandonment for the older surface. Numbers in italics represent river kilometers.

either a single large flood or a period of sequential floods and revegetated in the years following. The pre-1910 surface has seen mild inundation in the recent years, with no obvious stand mortality. The pre-1948 surfaces have seen substantial inundation in the recent years, and a sizable percentage of the trees within these stands were dead as of 2011.

Taken together, the relict surfaces found in the lower reaches of Tahoma Creek suggest there were particularly active periods in the years just before 1910, 1948 and between 1969 and 1991. These surfaces place some upper bounds on the degree of aggradation that occurred in the past - generally less than two meters and more commonly around one meter. That they have remained largely intact since the establishment of significant vegetation also suggests that the channel has not aggraded beyond its historically observed range in the recent years, with the exception of the surfaces immediately upstream of the bridge.

2.3.3 The Bridge

Photographs of the bridge provide a glimpse of the channel in the earlier years of the last century (figure 2.10). The concrete span, photographed at the completion of its construction in 1915, was quickly washed out in 1917, to be replaced by the wooden stringer bridge seen in 1918. This remained in place until it was replaced by the modern concrete structure in 1968. The photographs do not provide much vertical reference that would allow for easy comparisons with the modern channel. However, comparing the level of the wetted channel with that of the adjacent floodplain, it is clear that the 2011 state is not radically different than that of the early photos. This is all the more notable, since the 2011 photos represent the highest elevation the channel has obtained in recent memory. Anecdotally, researchers working on Tahoma Creek during the late '80s and early '90s commented that the 2011 photo showed significantly more aggradation than their recollections of the bridge during that period.

2.3.4 Synthesis of Historical Records

Taken together, the three analyzes indicate that Tahoma Creek has show periods of increased channel activity relatively frequently over the past century, and that, at least locally, that activity drove aggradation beyond what is observed at present. Changes in channel width suggest decadal-long trends of higher and lower activity, but do not, to my eye, show a clear indication of a trend that would suggest persistent disequilibrium. There is little evidence

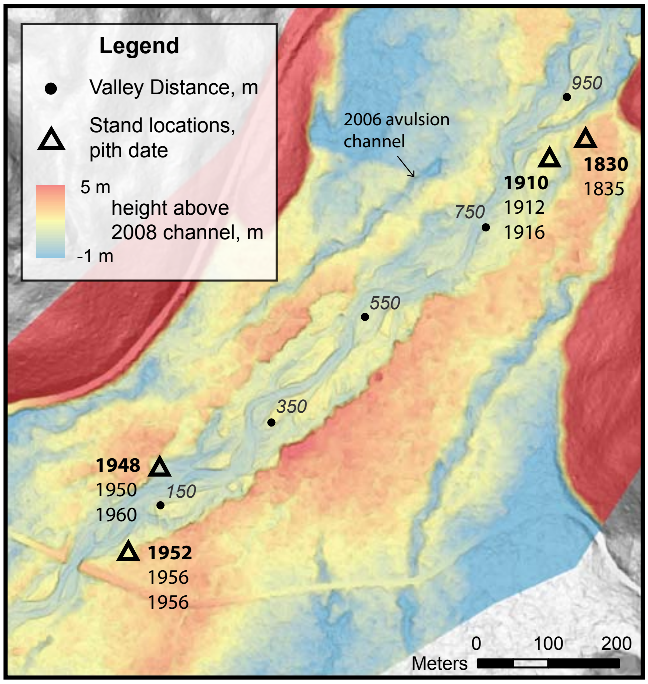

Figure 2.9: LiDAR imagery noting the position of several young surfaces supporting conifers in the lower reaches of Tahoma Creek. Triangles present distinct stands, with the associated dates indicating the pith age of the trees comprising the stand. The oldest individual in the stand, and so the limiting age of the surface, is marked in bold.

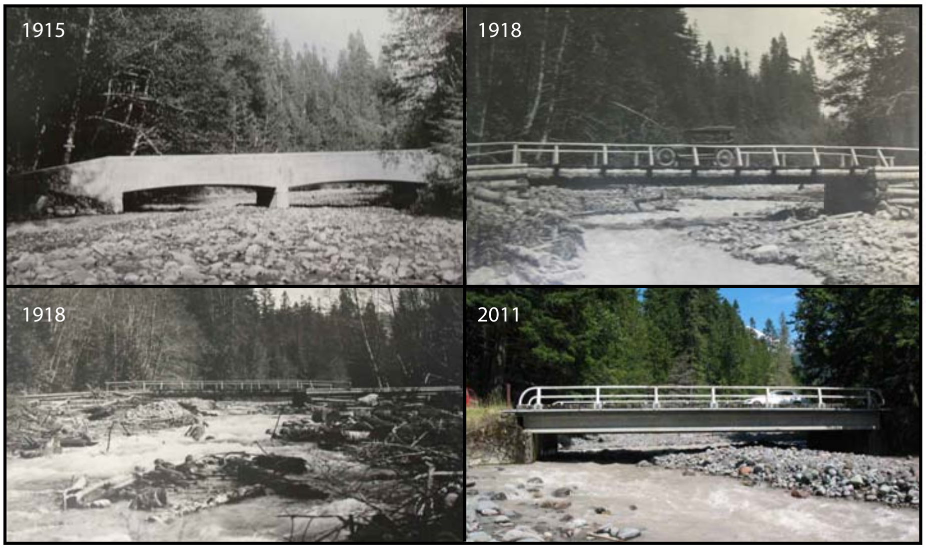

Figure 2.10: Repeat photography of the Tahoma Creek Bridge. Photo from 2011 taken by author, all others obtained from Mount Rainier NP archives located at the Tahoma Woods records archive.

to suggest that the modern channel is markedly disturbed when compared against activity of the past century.

2.4 Dendrochronologic Record of Debris flows

Much of the interest in Tahoma Creek in recent decades has been driven by the high frequency of debris flows moving within the basin. These events have had a very visual impact on the valley morphology, and have moved an immense volume of sediment down valley. A change in debris flow frequency or intensity is a reasonable mechanism by which a changing climate would impact the valley, and such a trend surely feels plausible. However, the historical record of debris flows is incredibly incomplete, and given the return interval of debris flow events, insufficiently long to illustrate any clear trends. Below I present an attempt to extend this record through dendrogeomorphological analysis, placing the recent events within a broader context and providing some suggestions as to what climatic factors influence debris flow frequency.

The valley floor of Tahoma Creek is covered with conifers growing on alluvial surfaces, many of which are well over 500 years old. Many of these conifers sit within the path of large debris flows or floods, as the past decades have made abundantly clear. The annual growth records of these trees then have the potential to record such events, manifesting as various growth disturbances that can be visually identified in cores taken with an increment borer (figure 2.11). Years in which an abnormally high number of growth disturbances occur can be attributed to some sort of geomorphic flow, with annual resolution. Previous records of fire and climate provide a means of excluding other possible causes for disturbance. Stands of conifers with a uniform age growing on sediment deposits may also be used to infer debris flow activity, by placing a bounding age on the deposition of the surface on which they grow. Such records are less exact in terms of dating, but also less ambiguous in interpretation. Both such records are used here to reconstruct debris flow activity for Tahoma Creek over the past 500 years. In total, 158 trees were cored in this effort, with two cores taken per tree. Sampling extended between the bridge and RK 8, with a focus on the depositional zone above RK 3.5 where debris flow damage would be most likely to occur. Tree sampled were primarily Douglas Fir and Western Hemlock, supplemented by occasional Silver Fir and Western Red Cedar. Once sampled, the tree cores were dried, mounted and sanded to clearly expose the rings. These cores were then digitally scanned, and a semi-automated image analysis pro-

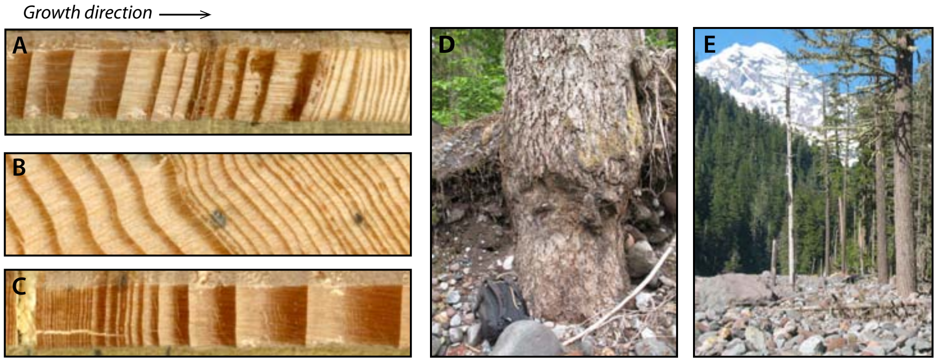

Figure 2.11: Left images show examples of growth disturbances found on cores taken from Tahoma Creek. Top and middle images show traumatic resin ducts and abrupt suppression, or narrowing, of annual rings. Lower image shows abrupt release, or widening, of annual rings as competition from surrounding trees is removed. The left of the two field photographs shows a western hemlock that was buried by a mid-19th century debris flows, continued to normally above the burial line, and was then later killed by a recent debris flow, likely 2006. The right image shows significant burial by debris flow material of stands near RK 8.

gram (WinDendro) was used to both count and measure the annual growth rings. The ring width records are used to cross-date the cores, reducing the chance that counting errors or missing rings clutter the final analysis. Once cross-dated, both the ring widths and visual markers on the cores are used to identify growth disturbances within a tree. The spatial and temporal patterns of growth disturbances are then used to identify past geomorphic flows. These flows were identified as debris flows, floods, or both, based on the relative proportion of disturbances high and low in the valley. They were also given a binary classification of high- and low-confidence events.

The resulting record is necessarily incomplete. This arises primarily from the fact that only debris flows large enough to significantly impact surrounding forests have the potential to be recorded, and even some large events may not be captured in the relatively small number of cores obtained. There is also a bias towards more recent events, as debris flows have caused significant mortality within the valley forests, erasing records of earlier events.

The most notable feature of the reconstructed record is the suite of debris flows that occurred between 1820 and 1900, with a particular clustering between 1840 and 1860 (table 2.1, figure 2.12). These specific dates are well matched by extensive stands of conifers that colonized bare gravel surfaces between 1860 and 1890 (figure 2.13). The spatial distribution of these stands suggests that these mid-19th century debris flows destroyed valley-floor forests over an area similar in extent to that of the more recent debris flows. However, the wholesale deforestation of the valley near the West Side Road closure has removed any record of the lateral extent of these flows within the reach, leaving it unclear if past events opened up a similarly wide bare-gravel channel.

The debris flows since the late '60s have change the course of the main thread of flow near Rkm 4.5, sending Tahoma Creek down the western margin of the valley. Prior to this, this area was entirely forested. However, many of the stands that are now directly adjacent to or within this new channel are part of the group that established directly after 1860, showing that the channel has taken a similar route in the relatively recent past.

The timing of these debris flows line up very well with the end of the Little Ice Age, occurring between 1830 and 1870 (figure 2.14). Dated moraines indicate that, during these decades, many of Mt. Rainier's glaciers were at their downstream-most extent since the Last Glacial Maximum around 12,000 years ago. Since the Little Ice Age, these glaciers have generally retreated at increasing rates, though periods of stand-stills or slight re-advancements have punctuated this retreat.

Expanding on this correlation between debris flows and the onset of glacial retreat, the four debris flows identified before 1820 all sit within a decade of clusters of moraine ages identified around Mt. Rainier by previous researchers. This correlation is interesting, but unfortunately, the mechanism underlying it remains obscure. Both the increasing sediment availability associated with glacial down-wasting or the frequency of triggering events, primarily glacial outburst floods, could plausibly be at work. However, the current data does not provide any compelling reason to suspect one over the other.

Regardless of the exact mechanisms controlling debris flow frequency, this record clearly demonstrates that the recent debris flows are not new phenomenon, and there is no clear trend of increasing frequency or intensity when compared to events over the past ∼250 years. This does not mean that such increases are definitively not occurring - simply that, in this coarse analysis, no such trends could be detected. However, this result is potentially significant when considering the geomorphology of an alluvial river. If the recent events are simply part of a semi-regular pattern of increased sediment delivery to the upper channel, it is more likely that the channel is adapted to these events, and so decreases the likelihood of the channel undergoing significant adjustments in response.

Year	*Event Type*	*disturbances recorded*	*Sample depth*	*Percent affected*	*Establishments*
1508	Tahoma Lahar?	**3**	**9**	**33%**	*na*
1530-1563	Establishment	*na*	*na*	*na*	**12**
1611	*Debris flow*	*2*	*33*	*6%*	*na*
1643	Landslide	**4**	**38**	**11%**	*na*
1649	Debris flow	**5**	**38**	**13%**	*na*
1685	Flood	**4**	**44**	**9%**	*na*
1697	Debris flow	**6**	**45**	**13%**	*na*
1730	Flood	**5**	**51**	**10%**	*na*
1753	*Debris flow*	*5*	*55*	*9%*	*na*
1791	*Flood*	*4*	*66*	*6%*	*na*
1826	Flood	**7**	**73**	**10%**	*na*
1831	*Debris flow*	*4*	*73*	*5%*	*na*
1840	*Debris flow*	*5*	*81*	*6%*	*na*
1847	Debris flow, flood	**7**	**84**	**8%**	*na*
1853	Debris flow	**7**	**87**	**8%**	*na*
1855	Flood, debris flow?	**7**	**87**	**8%**	*na*
1877	*Flood*	*4*	*98*	*4%*	*na*
1880	Debris flow	**7**	**101**	**7%**	*na*
1890	*Flood*	*4*	*120*	*3%*	*na*
1895	Debris flow, flood	**12**	**129**	**9%**	*na*
1870-1896	Establishment	*na*	*na*	*na*	**38**
1905-8	*Floods, debris flows?*	*11*	*135*	*8%*	*na*
1911-12	*Debris flow, flood*	*5*	*136*	*4%*	*na*
1925-6	Flood	**11**	**144**	**8%**	*na*
1936	Flood	**9**	**148**	**6%**	*na*
1959-60	Flood, debris flow?	**16**	**155**	**10%**	*na*
1966-1968	Outburst floods?	**16**	**158**	**10%**	*na*
1988	Flood, debris flow?	**8**	**158**	**5%**	*na*
1991	Debris flow	**20**	**158**	**13%**	*na*
1993-1995	Debris flows	**19**	**158**	**12%**	*na*
2007	Flood, debris flow	**14**	**151**	**9%**	*na*
2008-2009	Floods	**13**	**151**	**9%**	*na*

Table 2.1: A list of events identified though dendrochronological analysis. The nature of the event was identified by the spatial distribution of the impacted trees. High confidence events are in bold, while low-confidence events are in italics. Several periods that experienced above-average rates of establishment are also noted.

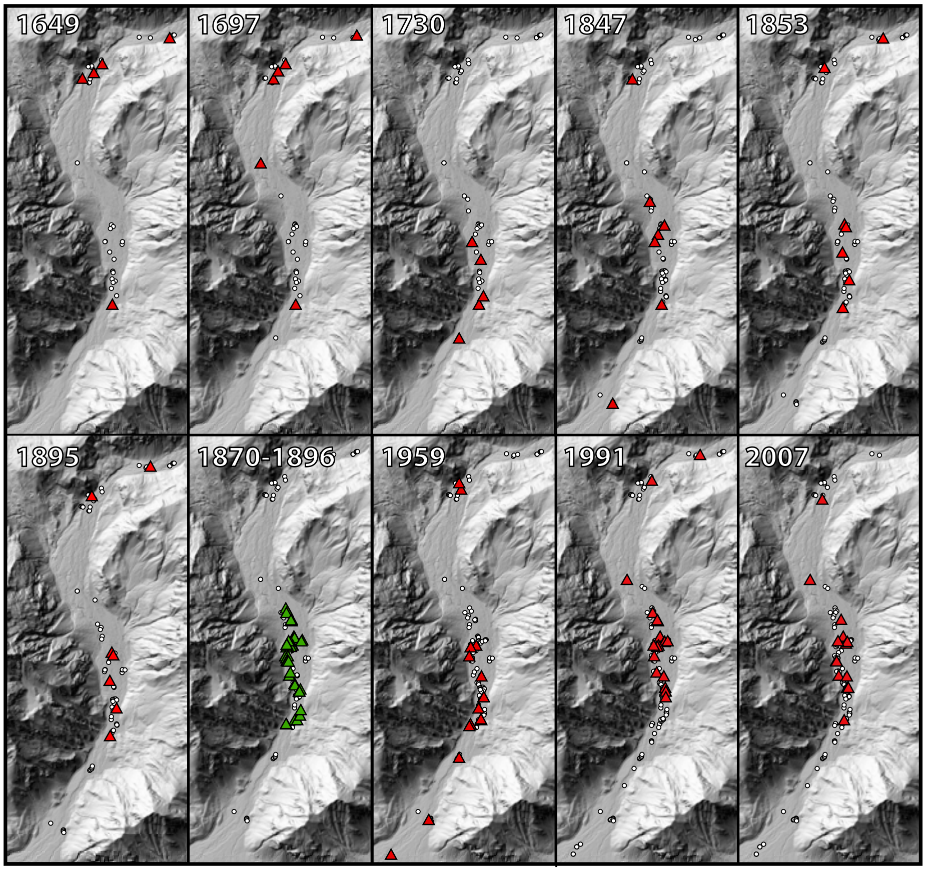

Figure 2.12: Maps showing the spatial distribution of trees defining selected events identified in the dendrochronological analysis. Trees showing growth disturbances for a given event are shown in red triangles, trees establishing during a given period are shown as green triangles, and all other trees with a ring record encompassing the indicated date are shown as white dots.

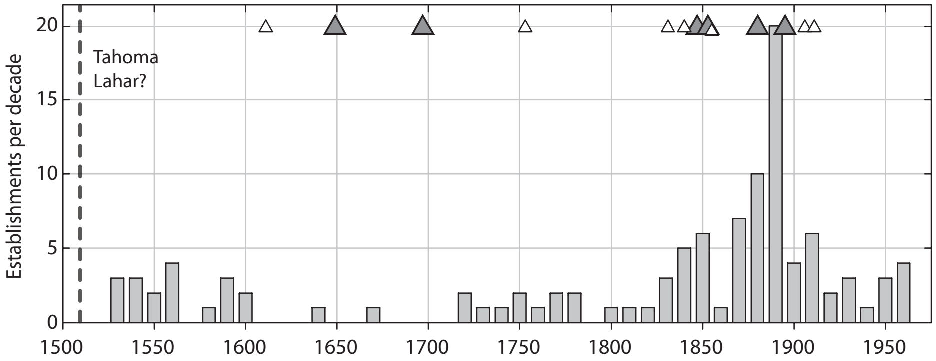

Figure 2.13: The distribution of pith ages of conifers cored in Tahoma Creek, grouped by decade. Debris flow events identified by this analysis are indicated along the top of the figure, with high- and low-confidence events shown as dark and white triangles, respectively.

It is worth noting that there are some hints that the recent debris flows have had an unprecedented impact on the upper basin, when compared against the past 500 years. The conifer stands growing along the valley margins within the confined reaches upstream of RK 7 established between A.D. 1530 and A.D. 1560, following the passage of the Tahoma Lahar early in the 16th century. Tree ring records indicate that they were largely undisturbed by the passage of debris flows in the following centuries. However, the majority of these trees, sampled in 2012, were dead or dying as a result of significant impact injuries or burial during the 2006 flood. This could reflect the singularly intense nature of that flood, or the combined dynamics of the flood and the deposition of the debris flows over the past decades.

2.5 Synthesis of Results

Three broad sections of analyzes were conducted, covering change and processes over the past 30, 100 and 500 years respectively. While the analyses don't directly overlap, they can be combined to create a relatively coherent view of processes within Tahoma Creek, and particularly in regards to aggradation in the lower channel.

Vertical change in the lower channel, viewed in direct detail since 2002 and inferred to varying degrees of precision back to 1910, seems to be constrained to less than roughly one meter above the modern channel and

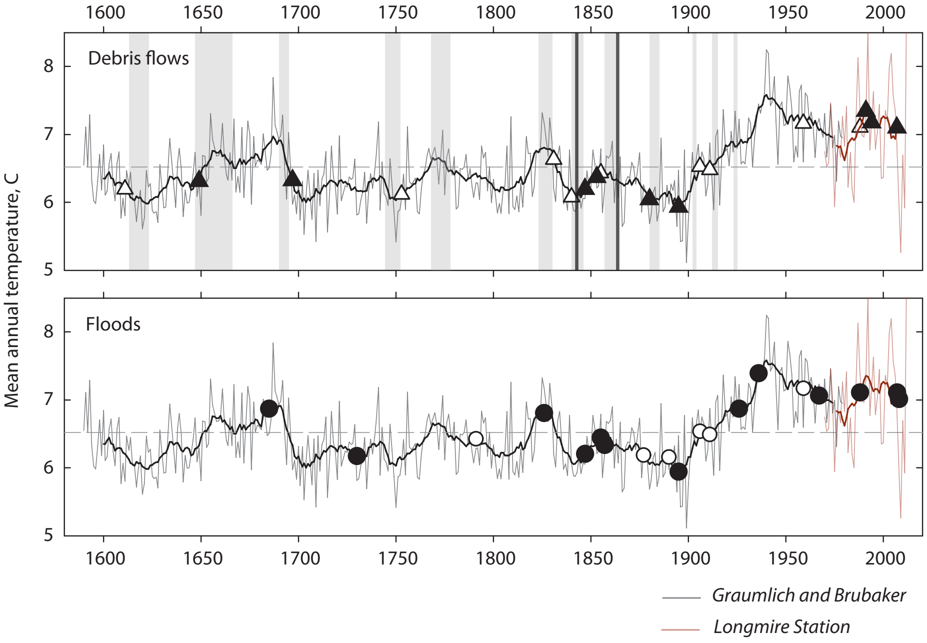

Figure 2.14: This figure depicts the correlation between debris flow events and periods of moraine stabilization, dated by previous researchers. High- and low-confidence debris flow events are noted as dark and light triangles, respectively. The black line represents an 11-year running mean of annual temperature, reconstructed from tree-ring records for Longmire, WA. Debris flow events are plotted on a y-position corresponding to the 11-year running mean temperature at the date of the event. Vertical grey bars indicate periods of moraine establishment occurring in rough synchrony around Mt. Rainier, while vertical black lines indicate stabilization dates for moraines within the Tahoma Creek valley.

largely transient in nature. The debris flows of the '90s appear to have caused mild aggradation throughout the lower channel, and the more recent debris flows and floods do not appear to have driven aggradation above the level obtained then. This level, in turn, does not appear to be significantly higher, if indeed higher at all, than levels obtained at various points over the past century.

The mildness of the the aggradational response to such significant sediment loading in the upper basin may partially be explained through the results of the tree-ring reconstruction of debris flows, which indicate that the suite of modern debris flows have at least one historical analog in the recent record, and likely more that remain undetected. If this is the case, the channel of Tahoma Creek is likely to be in a rough equilibrium with such periodic increases in sediment loading. Given the steep nature of the stream and high background rates of sediment delivery, the channel may have sufficient energy to accommodate these increased loads through adjustments in sediment caliber and/or changes to the topography of the current active channel, with little associated aggradation or widening.

While the recent aggradation at the bridge has been persistent and has risen to levels that appear to exceed those of the past decades, the results here suggest that this is a largely local phenomenon, and not representative of the broader condition of Tahoma Creek. The chapter below will address potential causes of this localized aggradation.

Chapter 3

Aggradation at the Bridge

3.1 Plausible Causes

Several plausible explanations exist as to why the reach immediately around the bridge would experience aggradation to a greater degree than the rest of the channel. These different explanations are not mutually exclusive, and it is likely that several may be working in concert to create the sedimentation hazard observed.

Most directly, the bridge opening may be overly narrow to accommodate the full range of dynamic motion Tahoma Creek would normally undergo. The bridge opening is roughly 20 meters in width - even in 1951, the narrowest period recorded in this analysis, the mean channel width below RK 3 was 40 meters. The mean channel width of 1984, 60 meters, is likely more representative of a "mean" state for the stream. By creating a pinch point, the stream becomes ponded, preferentially depositing sediment in the reaches just upstream of the bridge. This may also explain the dramatic increase in width seen in the reaches above the bridge (figure 2.6)

The dredging practices used may further exacerbate the aggradation seen at the bridge. This could act through two mechanisms. First, and most directly, the practice of piling the dredging spoils atop the gravel bars directly up- and downstream of the bridge provides a ready source of sediment that would otherwise be unavailable to the reach. NPS employees has readily observed first-hand how quickly this material is eroded during even mild flooding. Even placed downstream of the bridge, this material creates a localized spike in the sediment influx rates, which in turn can create localized aggradation that extends upstream. Second, the dredging creates an artificial low point in the long profile of the stream, a location which will

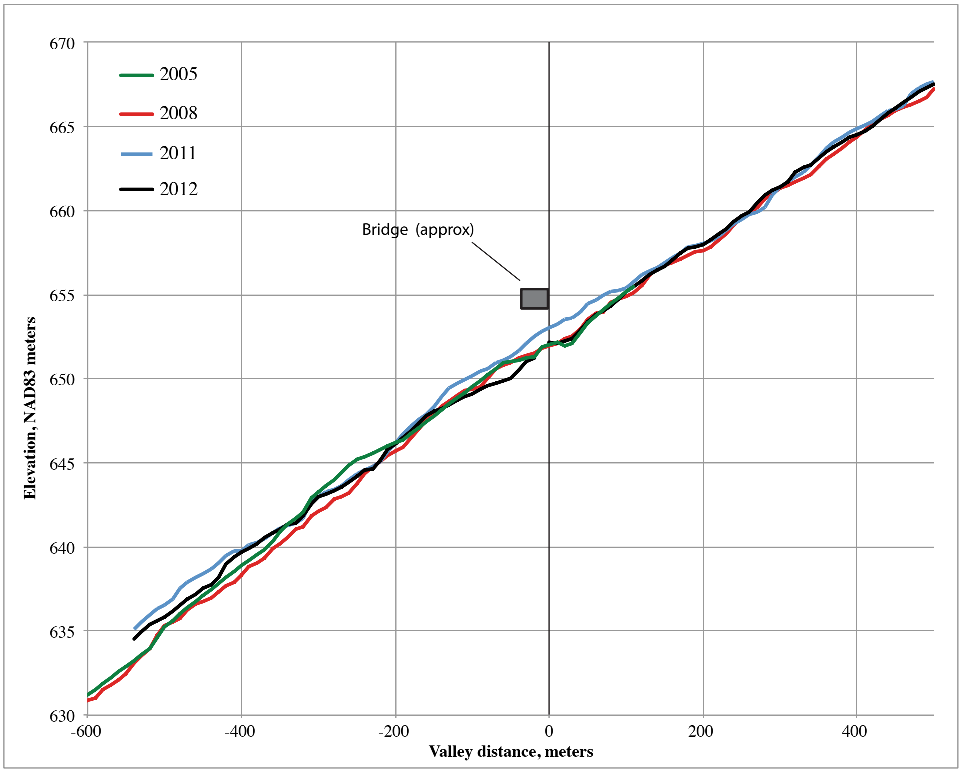

Figure 3.1: Long profiles of the low-flow water surface in the reaches immediately near the bridge. 2005 data was taken from a total station survey performed by Rimrock Surveyors; 2008 and 2012 data was derived from aerial LiDAR, while 2011 data is from total station surveying. Distances are noted as meters upstream of the bridge.

be preferentially infilled by sediment transported through the reach. However, the stream does not simply infill to the original equilibrium point and stop - it often overshoots this point, aggrading above the pre-dredge profile before obtaining a balance. Conceptually, this is analogous to the way in which a stretched string does not return straight to its relaxed position when released, but instead oscillates around this point for a period of time.

The best support for these ideas comes from looking at long profiles of the low-flow water surface near the bridge (figures 3.1, 3.2). From 2008 to 2011, there is localized aggradation occurring between a point 200 meters downstream of the bridge and 100 meters upstream of the bridge. Using a simple linear regression to provide a de-trended look at the 2011 channel, it's

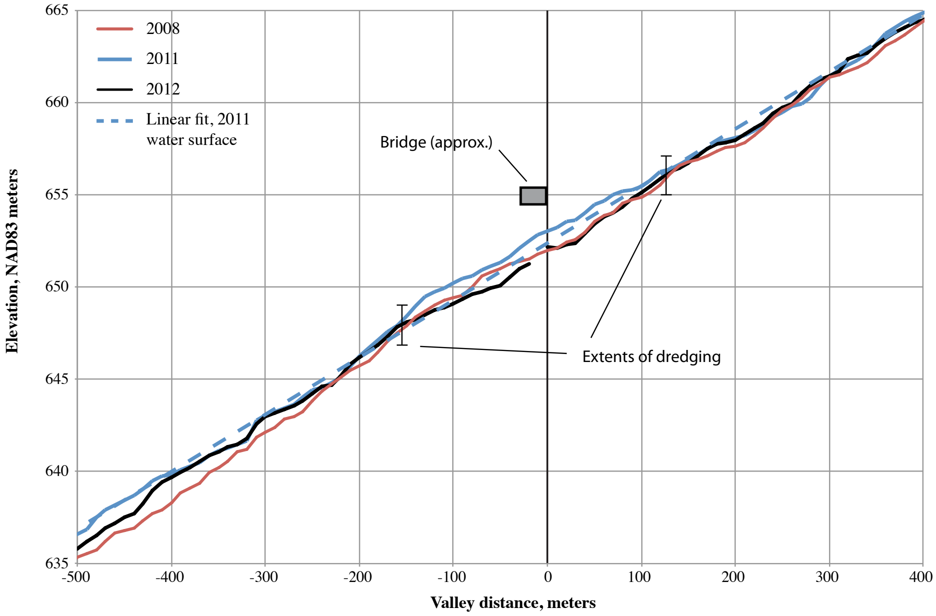

Figure 3.2: Long profiles of the low-flow water surface in the reaches immediately near the bridge. 2008 and 2012 data was derived from aerial LiDAR, while 2011 data is from total station surveying. The dashed line is a simple linear fit to the 2011 profile over the reach indicated, and is presented to illustrate the bulge near the bridge. Distances are noted as meters upstream of the bridge.

clear this this small reach sits high above this idealized channel profile. In the winter of 2011, just prior to the 2012 survey, the channel was again dredged. Looking at the 2012 profile, this zone of elevated channel exactly matches the extents of the dredging efforts, and the channel now sits relatively low, beneath the idealized profile. That this aggradation would

It is worth noting that, on average, ∼45,000 m^3 of coarse sediment is transported past the bridge each year, though interannual variability is huge. Low-flow years may see as little as several thousand cubic meters transported, while a single large flood may move closer to 500,000 m^3. In contrast, the dredging efforts generally reposition between 2,000 and 20,000 m^3 of material. It is clear that the channel moves more than enough sediment to infill the low-point created by the dredging in a very short period of time, as has been clearly demonstrated by the nearly annual dredging efforts required in recent years.

Lastly, the aggradation may be related to the interplay of Tahoma Creek and the Nisqually River, and specifically, the potential for aggradation of the latter to raise the local base level of the former, creating a wedge of aggradation. Such a wedge is observed in the 2008-2012 change profile. Unfortunately, the 2002 LiDAR does not extent below RK 1.3, so it is not possible to say if a similar wedge was observed in the earlier period. A relatively small total station survey of the channel immediately surrounding the bridge was completed in 2005, and differencing of that survey with the 2008 LiDAR shows net incision, though the volume of material removed is on the order of the uncertainty of the data.

3.2 Recommendations

These results would suggest that the aggradation at the bridge is a transient response to recent debris flows, and does not reflect a systemic change in upstream sediment loading. The lack of a basin-wide aggradational response, paired with the readily apparent aggradation at the bridge, further suggests that the issue is likely related to the bridge design and may be exacerbated by the current dredging practices. These results, viewed from a park-wide perspective, are positive, in that they decrease the probability that aggradation will pose a pervasive and long-term threat to the park. However, they do not provide an obvious pathway for sediment management at the bridge itself. Given the extremely dynamic nature of the stream and the large volumes of sediment it carries, methods which act to decrease the sediment deposition at the bridge reach (upstream sediment traps, channelization) are not feasible. This leaves two possible solutions; continue dredging as need arises, or restructure the bridge. In theory, the transient nature of the aggradation would point towards the former solution, since there is no indication that the aggradation will continue unabated. However, the small volume of material that can be reasonably dredged out of the river, relative to annual transport rates, combined with evidence that suggests that dredging practices may actually make local conditions worse, both argue against this course of action. Further, Tahoma Creek has shown itself capable of aggrading the bridge reach rapidly during even small events. While the bridge has withstood some significant floods, there is no guarantee that some future combination of sediment loading and flood hydrology won't create a significant hazard.

My recommendation would be to fully consider the feasibility of restructuring the bridge to create a larger opening, both slightly taller and with a width closer to that of the active channel of the surrounding reaches. While increasing the height without a change in the abutment positions would be less involved, I believe that the narrowness of the bridge is one of the primary factors driving local aggradation. Increasing the width would decrease ponding, and so decrease the odds of the channel avulsing in the reaches just upstream of the bridge, as occurred briefly during the 2006 flood. This would also likely help reduce the frequency with which the rip-rap currently armoring the channels up- and downstream of the bridge would require repair.

While the Park is considered a National Historic Landmark District (NHLD), placing a level of protection against changing the design of much of the current infrastructure, the Tahoma Creek Bridge is designated a non-contributing structure. This reduces, though does not eliminate, the bureaucratic overhead that would be associated with that change in design.

Given the current economic climate, particularly for federal organizations, the cost of this project may be prohibitive. However, this cost must be weighed against the cost of the future repair and dredging efforts that will likely be needed from time to time. Recent records show that dredging or rip-rap repair has occurred at least ten times since 1988, including every other year since 2006.

Regardless of what mitigation efforts are taken, I would strongly encourage the park to continue monitoring the long profile of the wetted channel using total station surveys, extending from RK 0.5 downstream to just above the confluence with the Nisqually River. Various monuments installed on the bridge provide good vertical control for these surveys, and they could reasonably be completed by two operators in one full day. This data would help illuminate the local processes of channel change occurring near the bridge, and provide a means of assessing the effectiveness of any future dredging efforts.

Chapter 4

Additional Data Collected

The data presented above has been streamlined to provide the clearest possible understanding of processes within Tahoma Creek in regards to aggradation at the bridge. However, there are additional results and data sources that deserve to be mentioned, as they add to the broader history and knowledge of the valley.

4.1 The Tahoma Lahar

The Tahoma Lahar is one of the younger lahars documented on Mt. Rainier. Previous research has indicated that this event initiated as a debris avalanche within the Sunset Amphitheater, transforming into a lahar lower in the valley. The deposits overlay the W-layer of ash, which have been dated to A.D. 1480. The oldest tree growing on the deposits had established by A.D. 1535, placing a relatively tight bound on the age of this event. In the dendrochronological analysis, several dozen of the tree-ring records included this entire plausible range of dates. Based on growth disturbances seen in those records, I'm tentatively proposing a date of A.D. 1508 for the Tahoma Lahar. However, the observed growth disturbances were not particularly notable, nor extensive. Based on my understanding of the depth and extents of the deposits identified in the field, this lack of a strong signal is somewhat puzzling. At present, I have no explanation to offer.

Additionally, the decadal-rate of conifer establishments shown in figure 2.13 show a notable cluster between 1525 and 1565. Spatially, nearly all the cored trees that established during this period were located within stands above RK 7, within the relatively confined reach upstream of the depositional zone. The flow depths of the Tahoma Lahar were presumably quite deep through this reach, and likely cleared any conifers growing on the valley floor. This cluster of establishments then likely represents the recolonization of the valley floor following this event.

4.2 Carbon-14 Dates

Subfossil stumps were a common feature along Tahoma Creek, exposed through lateral motion of the river and sitting near the elevation of wetted channel (figure 4.1). These stumps are relicts of forests that once grew within the Tahoma Creek valley, and were presumably buried by some action of the river. Lahars provide the most probable method of quickly burying such trees, though relatively rapid aggradation could also accomplish the same. Five samples from the outer rings of such stumps were submitted for carbon-14 dating analysis. In living trees, the outer-most ring is the only living wood actively exchanging carbon with the atmosphere. This ring then becomes structural wood the following year, preserving the carbon record of when it was alive. This means that the carbon date of a piece of wood does not necessarily indicate when the tree as a whole died, but only the date in which the ring (or rings) were actively put on. Given that most of the stumps sampled have lost an unknown number of outer rings to rot and abrasion by the river, the dates obtained from these samples represent the latest date in which the tree was definitely alive, but underestimates the date of burial. This underestimate could plausibly be between ten and 200 years.

The five samples where taken from three distinct sample sites. At two of the sites, two different samples were taken from stumps that sat at nearly identical locations and elevations. This was done as something of a check, to ensure that stumps that were overwhelmingly likely to have been killed by the same event dated to the same time period. These three sites represent a small percentage of the total number of sites found during field work, and were chosen for having stumps that remained unambiguously in growth position, having more than one stump with in a localized area, and containing stumps that were relatively well-preserved.

Carbon dating is based on the regular rate at which C-14 decays into C-12. While this rate is basically constant, the ratio of C-14 to C-12 in the atmosphere has varied over time. To convert a C-14 date into a calendar date then requires the use of a calibration curve, which takes into account this historical variation. It is this conversion to produces irregular or double-humped probability distributions of calendar dates seen in the results below.

Figure 4.1: Example of subfossil stump found in the lower valley of Tahoma Creek. A sample taken off this particular stump was dated to around A.D. 500.

Two directly adjacent stumps situated just upstream of the bridge were dated to either A.D. 1300 or A.D. 1370, with nearly identical probability distributions (figure 4.2). A single stump taken near RK 1.5 was dated to A.D. 500. The final two adjacent stumps included overlapping probability distributions, but one was centered around A.D. 800 and the other around A.D. 950.

When considering the possible underestimate of the actual date of burial associated with these ages, the youngest two stumps could possibly be related to the Tahoma Lahar, dated here to A.D. 1508. However, one of the samples was taken from an exposed root that was unlikely to have been significantly eroded, and the overall appearance does not suggest over 100 years of growth having been removed. Further, these stumps sit downstream of the inferred extent of the Tahoma Lahar, though this extent is not well

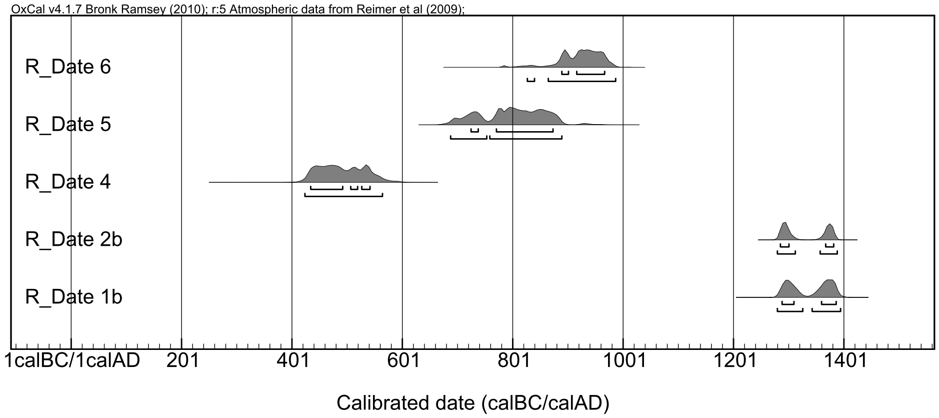

Figure 4.2: Results of carbon-14 dating on subfossil stumps. Samples 1 and 2 were taken just upstream of the bridge, sample 4 was taken at RK 1.5, and samples 5 and 6 were taken at RK 1.8. Radiocarbon dates converted to calendar dates using OxCal online interface.

constrained. This suggests that these stumps may have been buried by an event predating the Tahoma Lahar. The two samples dated to just before A.D 1000 may be related to the appropriately named 1000-year-old lahar mentioned by Crandall. The younger of the two samples was taken directly adjacent to remnant bark, indicating that essentially no exterior rings had been lost to erosion. As such, the age of this tree provides a decently well-constrained date for burial.

The single sample dated to around A.D. 500 does not correlate with any previously dated lahars in the valley.

The elevation of these samples, along with many other similar stumps not sampled, was consistently at or slightly above the adjacent river level. This is primarily a function of sampling bias - if they were lower, they would remain hidden, and if they were significantly higher, they would likely have been undercut and washed away while being exposed. However, the fact that so many stumps do sit at this level, spanning at least 1000 years of growth punctuated by multiple burial events, does seem significant. It suggests a fairly small change in the vertical position of the channel over the past millennia, even in face of significant climate events and multiple lahars. However, it also presents something of a conundrum - why were there so many forested surfaces sitting roughly two meters below the current floodplain? On the face of it, this suggests valley-wide aggradation, involving a massive volume of sediment. However, the modern floodplain forests contain individuals significantly older than the youngest of the dated stumps. For this to make sense, the aggradation would have to have been localized within a relatively narrow width of the valley, at least in the reach near the bridge. I don't have sufficient knowledge of the forest ages and their distribution to say that this implausible, nor does the floodplain topography invalidate this idea.

As an alternative, it is possible that the relict stumps originally grew on abandoned active channel surfaces following lateral migration, avulsion, or narrowing during quiescent periods. In this interpretation, their position within the active channel would suggest negligible aggradation over the period of record.

Regardless of their initial position within the valley, lahars present the most obvious means of rapidly burying and preserving these stumps. However, only a small number of cut-banks examined contained any obvious lahar deposits. The majority of sediment appeared to be normal fluvial material, grey in color and consisting of a sediment distribution similar to the active channel. Massive deposits of fine sand that seemed likely to have been hyper-concentrated flows were also common.

I am not an expert in identifying deposits based on sedimentology, but it does seem to me that the combination of relict forests and sediment deposits open up the possibility that Tahoma Creek has experienced some significant disturbance not explained by the lahar history. Identifying and understanding such dynamics would provide a very interesting comparison to modern processes. This would involve a careful examination of floodplain and cut-bank deposits coupled with additional C-14 dates from exposed stumps.

4.3 Forest Succession Dynamics

The classic model of succession in pacific northwest forests involves initial colonization of surfaces by Douglas Fir, succeeded by more shade tolerant Western Hemlock and Silver Fir. Climax communities general consist of a canopy dominated by the latter two species, dotted with the occasional old, massive Douglas Fir. In this case, the majority of the initial colonizers have died off, and so the age of a surface is presumed to be significantly older than the majority of the trees. However, it was observed that, on alluvial surfaces, this sequence was slightly altered by the presence of dense alder stands. These stands colonized fresh alluvial surfaces very rapidly, and created a dense canopy within as little as a decade. Under this shady canopy, the majority of established seedlings were noted to be Western Hemlock. Similarly, the young stands of conifers found growing on the mid-19th century debris flow surfaces consisted almost entirely of Western Hemlock.

This shortcutting of the successional sequence has implications for the age of surfaces hosting what appear to be climax communities, as was the case for much of the lower Tahoma Creek floodplain. While the presence of very old Douglas Firs still provides undeniable evidence of age, it is possible that swaths of these forests sit on younger surfaces, but are difficult to differentiate because the colonizing forests appear largely similar to adjacent climax communities.

Such shortcutting appears to occur most commonly in situations where relatively discrete surfaces are created next to surviving forests. In contrast, the forests sitting of the surfaces created in the aftermath of the Tahoma Lahar were predominately Douglas Fir. This event would have likely leveled the majority of the forests in the upper valley, leaving the Douglas Firs growing on hillslopes as the primary seed source.