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Tahoma Creek Bridge Focused Condition Assessment

The north side of the Tahoma Creek Bridge, facing south on August 6th, 2019, during a period of increased water stage and sediment transport from an upstream debris flow.

NPS / TAYLOR KENYON

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Science Report NPS/SR—2024/103

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Abstract

The Tahoma Creek Bridge on the southwest side of Mount Rainier is an essential crossing for year-round vehicular access to Mount Rainier National Park (MORA). This site is also exposed to significant hydrologic variability, which the current structure was not designed to withstand. Locally enhanced vertical increases to the riverbed elevation, known as aggradation, threaten the structure's long-term viability. The purpose of this report is to (1) clarify the details of channel maintenance operations related to the bridge; (2) synthesize the natural and human influences of sediment deposition in the lower watershed; and (3) discuss the potential solutions for sustainable bridge maintenance. Information was collected through prior structural inspection reports, raw hydrologic data stored by the National Park Service, and both published and unpublished reports focused on Tahoma Creek. It was found that the height and width of the Tahoma Creek Bridge are severely underfit for relatively common flooding events on Tahoma Creek. Additionally, dredging and sediment storage practices employed to maintain the bridge are ineffective and even enhance aggradation in nominal flow conditions. Further research in the Tahoma Creek Watershed suggests the river is generally efficient at exporting produced sediments and maintains a relatively stable vertical profile in its lower reaches, where the bridge is located. The singular variation from this stable vertical trend at the bridge site suggests locally enhanced aggradation at the bridge is entirely due to the presence of the bridge itself and the channel modification actions taken to support the structure. All told, neither the overall size of the Tahoma Creek Bridge nor the channel modification actions taken to maintain the crossing, are viable for long-term access into MORA. With no changes to the existing bridge profile, the status-quo for operations to manage the Tahoma Creek Bridge will eventually fail to maintain access.

Acknowledgments

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Introduction

The Tahoma Creek Bridge is located 1.92 km (1.19 mi) east of the Nisqually entrance in the southwest corner of Mount Rainier National Park (MORA) (Figures 1 and 2). The bridge serves as a crossing over the glacially fed channel of Tahoma Creek along the Nisqually-Paradise Highway, which is the only year-round maintained thoroughfare in the park. During flood events, sediment is deposited under the bridge, which increases the elevation of the stream bed and thus reduces the hydraulic capacity, which is defined as the amount of open space available for water and debris to pass under the bridge. This promotes lateral movement of the wetted channel toward the banks, causing erosion, channel widening, and further deposition of sediment. The rate of deposition during the 1990s was estimated to be 10 cm (4 in) annually over 12 years (USFHA 2004), totaling 1.2 m (4 ft) of material. Since 1975, the U.S. Federal Highway Administration (USFHA) has consistently recommended that sediment be excavated from the stream bed around the bridge to consolidate the active channel in the center of the bridge span and that riprap be placed along the banks and abutment footings upstream and downstream of the bridge.

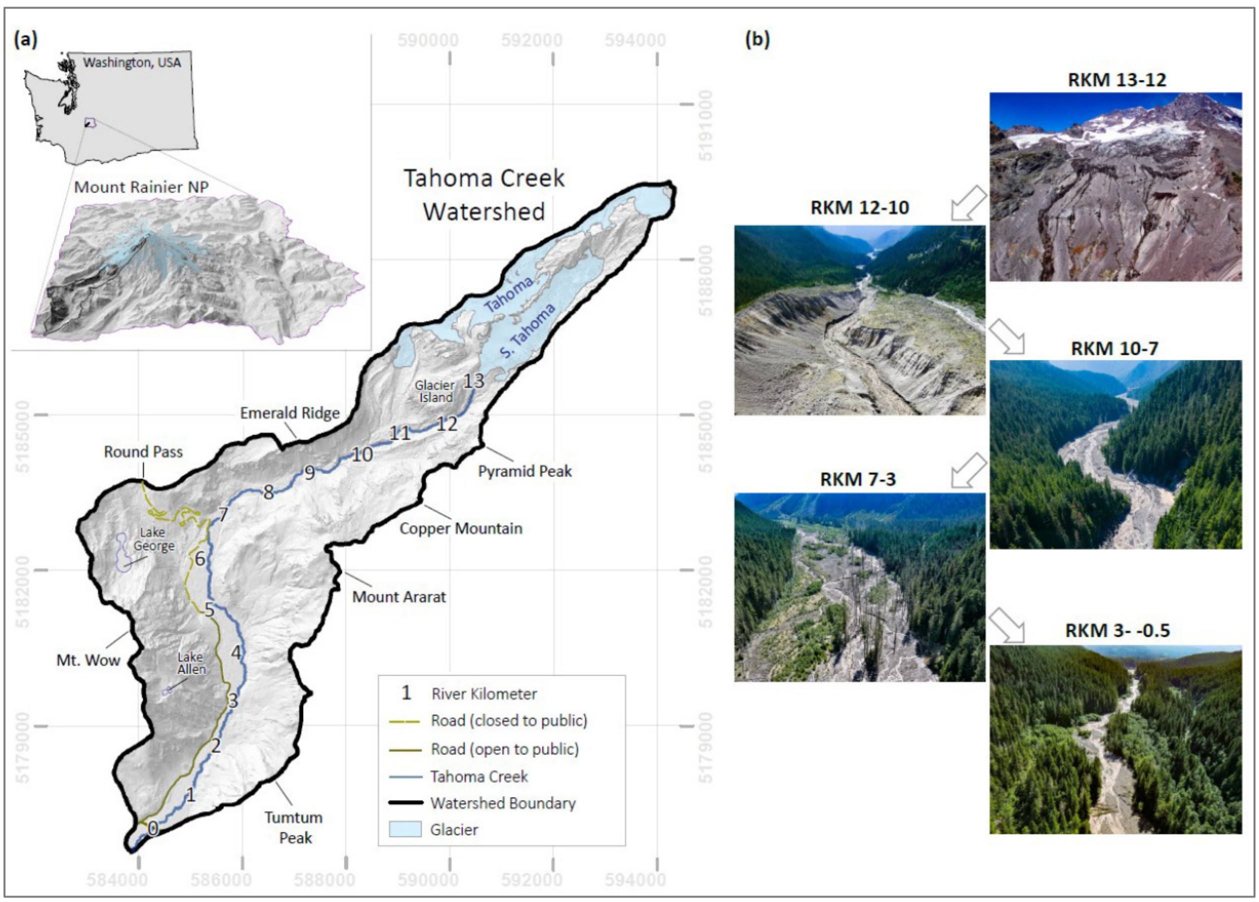

Figure 1. Map of the Tahoma Creek Watershed, including (a) location map with selected place names, and (b) photos chosen to represent the defined reaches of the river (Modified from Figure 2 in Turley [2020]). River kilometers (RKM) are measured as distances upstream from the Tahoma Creek Bridge.

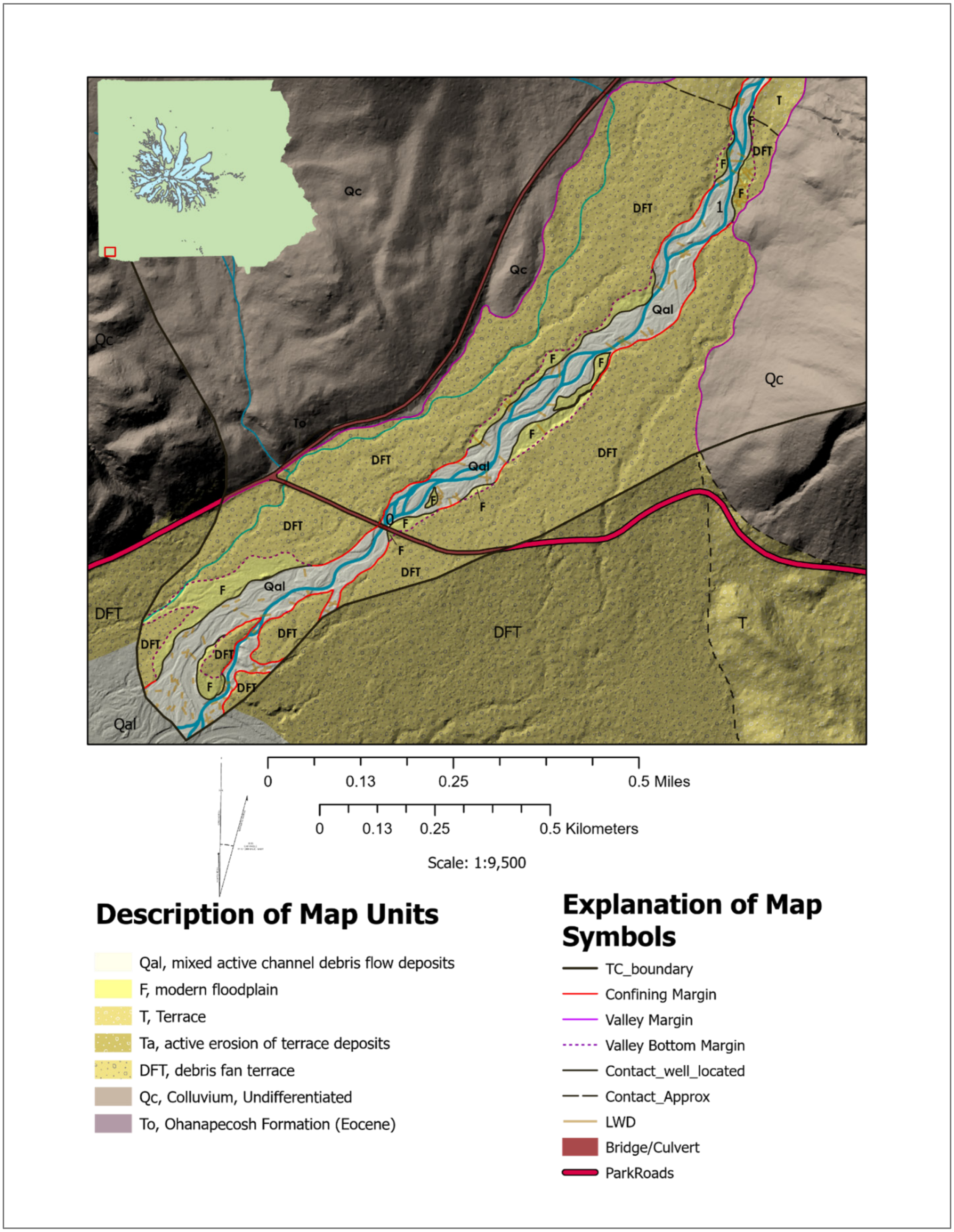

Figure 2. Surficial geologic map and study area for the Tahoma Creek Bridge reach (Modified from Figure 3 in Turley [2020]).

The floods that impact the bridge are produced by heavy precipitation in the autumn and winter months. Streamflow data from the Nisqually River is used as proxy to infer hydrologic activity in the un-gaged Tahoma Creek Watershed. The Nisqually River at National gage (USGS gage 12082500) is located about 27 km (16.7 mi) downstream from the mouth of Tahoma Creek at National, Washington (Anderson 2013a). Analysis of streamflow data from this gage indicates that annual peak-flows increased between 1942 and 2011 (Czuba et al. 2012). The 1990s and early 2000s were especially active, with above-normal streamflow and several large floods impacting the park. Channel modification operations recounted in this report were completed primarily in response to damages incurred during these flooding events.

Vehicles entering MORA through the southwestern Nisqually entrance have no choice but to use the Tahoma Creek Bridge when continuing into the park. With as much as 60% of annual visitation coming in through the Nisqually entrance and a host of critical National Park Service (NPS) functions being run in this district of the park, it is imperative for the NPS to maintain functional use of the bridge (Catton 1996; Thomas and Koontz 2021). However, channel alignment operations have negative impacts on the surrounding ecosystem and seem to produce limited results. These challenges have prompted discussions of building a structure that spans more of the valley bottom and would be less susceptible to the issues facing the current bridge.

Study Area

Locations in the watershed are referenced relative to the longitudinal distance along the channel with the Tahoma Creek Bridge at river kilometer (RKM) 0 in Figures 1 and 2. The 38 km^2 (14.7 mi^2) watershed is fed primarily by the South Tahoma Glacier and receives additional runoff from a small offshoot of the Tahoma Glacier (which primarily feeds the South Puyallup River). The South Tahoma Glacier has retreated more than 3 km (1.9 mi) since 1840 (Sigafoos and Hendricks 1972; Beason et al. 2023). This retreat has exposed moraines mantled on the bedrock flanks of the volcano (RKM 7–13). Sediment is recruited from these moraines and delivered to the channel network as debris flows (Anderson 2013a).

Between RKM 5 and 7, the valley bottom widens into a braided floodplain flanked by forested terraces. The floodplain contains active and inactive channels that meander through sections of dead standing trees killed by recurrent debris flow deposition. Fluvial processes dominate from RKM 5 down to the confluence with the Nisqually River (RKM 0). Below RKM 5, sediment is primarily mobilized during floods. Most of the sediment in fluvial transport that reaches RKM 5 is exported from the watershed, with isolated areas of deposition or incision noted by changes to the riverbed elevation.

The active channel is defined as the bare gravel surface that supports riparian vegetation communities including red alder (*Alnus rubra*) and willow and is bounded by mature conifer forests growing on floodplain terraces elevated 2–3 m (6–10 ft) above it (Anderson 2013a). The planform of Tahoma Creek's wetted channel oscillates between a multi-threaded meandering pattern during low-flow periods and a straightened braided pattern during higher flows (Figures 1 and 3). This system's compound nature is the product of high annual runoff variability, steep gradient, and sediment supply within the watershed.

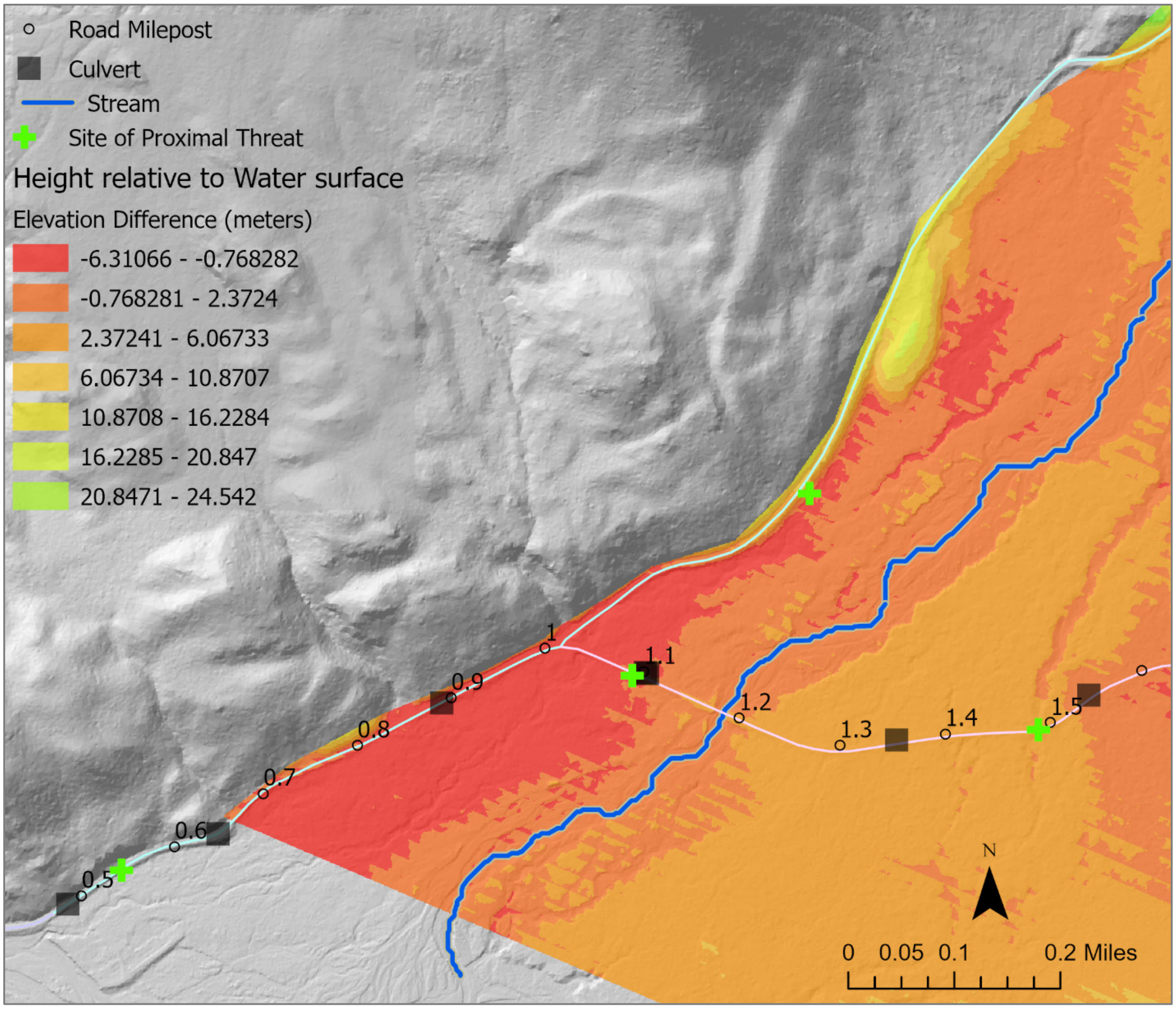

Figure 3. Elevation of the valley bottom relative to the Tahoma Creek active channel denoted as a blue line. Green crosses are locations where the road may become susceptible to inundation during major flooding events.

The study area encompasses the debris fan terrace (DFT) that has formed where Tahoma Creek begins to merge with the Nisqually River (Figure 2). The Nisqually-to-Paradise Highway traverses the full width of this convex landform, with the bridge located near the fan apex. Vehicles traveling along the road must climb the western limb of the fan to reach the bridge, and the western margin of the fan is as much as 6.3 m (20.7 ft) lower in elevation relative to the active channel (Figure 3).

Purpose and Need

The bridge over Tahoma Creek is the primary access to MORA and the only access from the southwest corner. Many necessary park activities rely on the bridge for access, and it follows that both visitor access and normal operation of the park are closely tied to geomorphic processes controlling the Tahoma Creek Watershed. With more than half of the visitors to MORA traveling over the Tahoma Creek Bridge annually, any impairment of this structure would be a major disruption to park revenue, total economic output, and the visitor experience (IRMA 2021; Thomas and Koontz 2021). The goals of this study are to (1) clarify the details of channel maintenance operations related to the bridge; (2) synthesize the natural and human influences of sediment deposition in the lower watershed; and (3) discuss the potential solutions for sustainable bridge maintenance.

History Synthesis

This section details the relevant history of human actions at the location of the Tahoma Creek Bridge. A brief overview is presented, which describes the structures that have stood in this location over time. Additional information is presented regarding the floodplain modifications and dredging done over time to support current and past iterations of the bridge.

Bridge History

The Nisqually-Paradise Road has crossed Tahoma Creek in its current location since 1909. A concrete bridge was originally constructed in 1915. However, this structure was washed away during a flood in 1917 and was replaced with a wooden stringer bridge in 1918 (Catton 1996; Anderson 2013a). The current Tahoma Creek Bridge is a single-span concrete structure that was built in 1969 atop pre-existing foundations (USFHA 1975).

The deck spans 20 m (66 ft) over the floodplain, is 10 m (33 ft) wide, and runs at a grade of +0.88% from west to east (Figure 4). The abutments are 3.2 m (10.5 ft) tall, with shallow, concrete spread footings resting on the unconsolidated alluvium. The structure has roughly 0.3-m-thick (1 ft) concrete foundation “wings.” These wings project 45 degrees away from each corner of the bridge into the floodplain for 3.6 to 5 m (11.8 to 16 ft), creating a conic opening larger than the bridge span. Riprap lining the upstream banks was included in the 1966 design. The riprap structures are necessary to prevent erosion of the wingwalls and to maintain the alignment of the active channel.

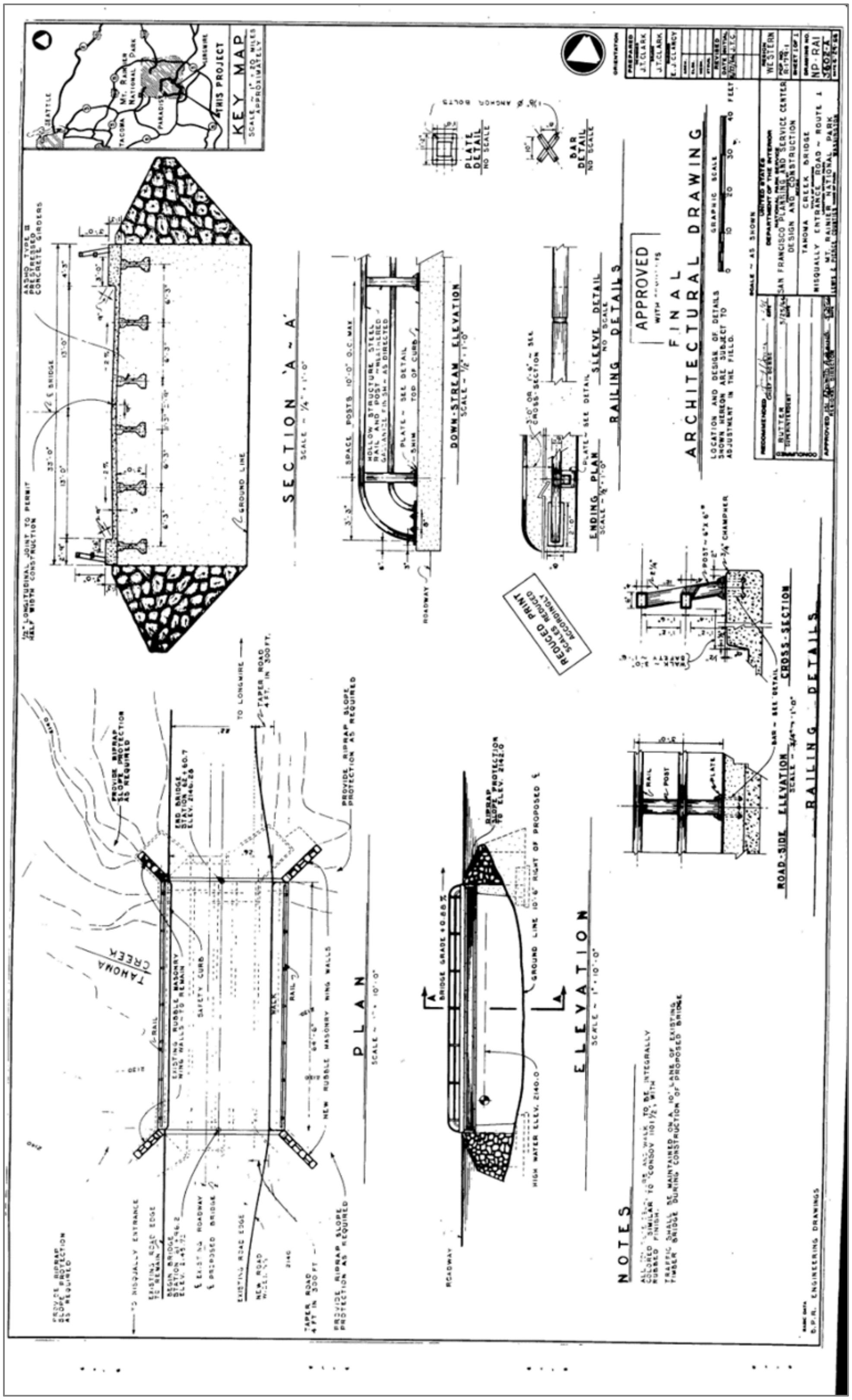

Figure 4. Final architectural designs from 1966, which the existing bridge is based on. The deck spans 20 m (66 ft) over the floodplain, is 10 m (33 ft) wide, and runs at a grade of +0.88% from west to east (Modified from Clark 1966).

Channel Modification History

The historical record of channel maintenance activities throughout the 1980s and 1990s was compiled from bridge inspection reports. Activities in the 2000s are sourced from internal NPS documents and interviews with current maintenance employees. This record only accounts for activities related to the current bridge, as little information was found predating 1969.

Bridge inspection reports confirm that channel alignment was completed by the NPS in 1980, 1982, and 1985 (USFHA 1986). A few unspecific accounts are provided by the United States Geological Survey (USGS) that "dredging" took place during the late 1980s and early 1990s (Walder and Driedger 1994). Channel alignment was recommended to direct the stream flow to the middle of the bridge, away from the abutment footings. Scour along the channel was the primary concern noted during inspections from 1975 through the early 2000s. The accumulation of sediment under the bridge is not mentioned until the 1998 report (USFHA 1998).

The inspection reports are inconsistent when describing work done between visits. Channel work is inferred from photos where the wetted channel appears to have a concave cross-sectional profile rather than a planar profile that is more typical for the study area. Inspection visits take place in even years, so changes in the stream channel between inspections can be constrained to having occurred within two years. The channel appears planar in the 1990 report and concave in both the 1992 and 1994 reports (USFHA 1990, 1992, 1994).

The park experienced the largest flood on record in November 2006, and in response, the USFHA recommended that the active channel be consolidated into a trough 18 m (59 ft) wide with approximately 2–3 m (7–10 ft) of clearance between the bottom deck of the bridge and the streambed. This operation took place in the fall of 2007, with excavation beginning 30 m (100 ft) upstream of the bridge and extending 94 m (310 ft) downstream, maintaining a longitudinal slope of 2%. This slope was estimated to be steep enough to transport sediment in the channel. The profile was tapered to match the elevation of the existing streambed as it approached the distal boundaries of the permitted construction area (Figure 5).

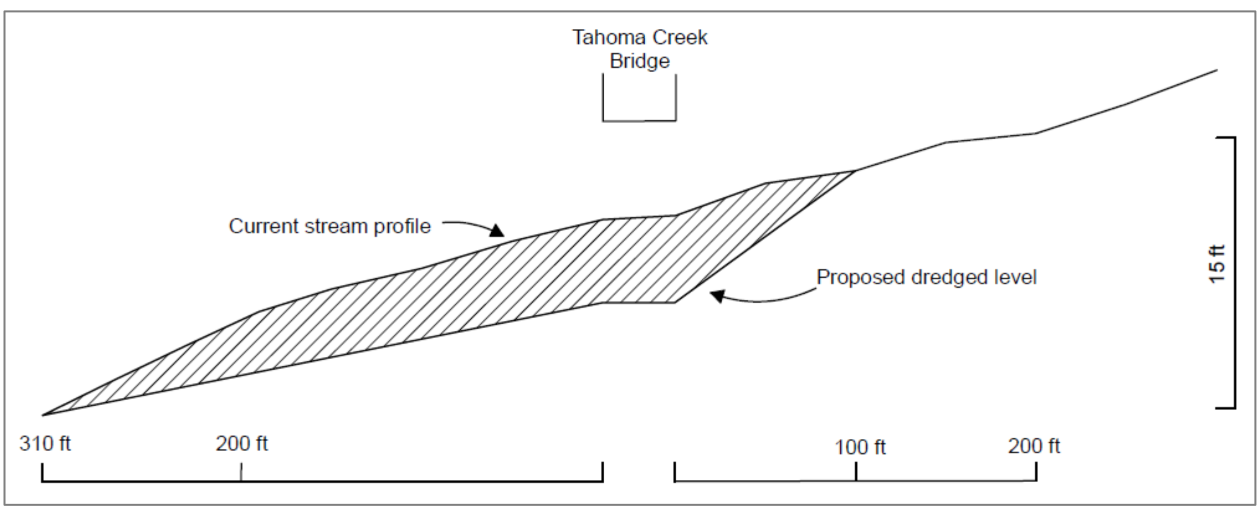

Figure 5. Profile view schematic of the channel modification that took place in fall 2007 (MORA 2007b).

The park faced a dilemma regarding the placement of spoils during this operation and considered the following three alternatives in its Joint Aquatic Resources Permit Application (JARPA) (MORA, 2007a, Page 3):

1) *Hauling the dredged material out by truck to a local quarry. This alternative was considered financially impracticable and environmentally less desirable based on hauling/new access road construction costs and substantial environmental impacts. For the anticipated 2,400 cubic yards of debris material at an estimated one truck per 10 cubic yards of fill, hauling cost[s] are expected to be in the range of $30,000 to $40,000. In addition, a new access road to get the haul trucks into the construction area would be expected to cost another $10,000-$15,000. The new access road construction would have to go through jurisdictional wetlands and old growth riparian forest.*
2) *Pushing the dredged material out into the wooded areas outside the two-year high-water mark. This alternative would result in impacts to old growth mature forest trees, jurisdictional wetlands, and sensitive species (e.g., amphibians) habitat. This alternative was considered less desirable based on likely and potential environmental impacts.*
3) *Another alternative considered was to place the dredged material on a gravel bar above the OHW [ordinary high water] line and still within the treeless stream corridor. The gravel bars start approximately 50 feet downstream from the bridge and extends [sic] to approximately 350 feet downstream from the bridge.*

Alternative three was ultimately chosen as the preferred alternative, which eliminated the additional costs of hauling the excavated sediment to an offsite location. Subsequent operations followed these same specifications despite observations by NPS staff that the banks of the modified channel would begin to erode immediately after the work was completed.

Channel modification was done five times between 2007 and 2011. Notably, two operations took place within two months, first in November 2008 and again in January 2009. The most recent confirmed dredging operation took place in 2016. In addition to channel alignment, riprap installation has been routinely carried out based on recommendations from the USFHA. Channel alignment and riprap installation appear to be the primary strategies for maintaining conveyance capacity under the bridge.

MORA employees state anecdotally that operations took place annually from 2005 to 2014; however, no documentation could be found for channel excavations in 2006, 2012, 2013, and 2014 (Ray and Mettler, personal communication, 2021). Furthermore, woody debris located on the river right bank remained in place from 2011 to 2014, suggesting the channel was not modified during that period. This debris is no longer visible in the photo because the bank was eroded. The absence of dredging is also supported by the elevation profile comparisons presented in the next section.

Aggradation and Sediment

While the dramatic sediment loading in the upper watershed has affected the downstream reaches, the primary source of sediment deposited in the study area is the spoils placed on gravel bars in the active channel. This section begins by interpreting changes in longitudinal profiles surveyed between 2005 and 2020, with a focus on the areas of the profile that are repeatedly dredged. The second subsection describes changes throughout the watershed that have been observed over longer time scales.

Observed Trends in Elevation and Interaction with Channel Modification

Channel alignment operations influence aggradation by creating artificial slope inflection along the streambed. Areas around these points are subsequently filled in with sediment that has been piled along the banks of the active channel. This process is evident when comparing longitudinal profiles (Appendix A) and photographs. The 2005 through 2012 channel profiles were surveyed when operations were the most frequent and invasive, often extending a full kilometer down to the Nisqually River confluence.

Figure 6 shows the mean elevation of the low-flow water surface of points surveyed along a 200 m (660 ft) channel segment centered around the bridge based on profile data shown in Appendix A. The profile with the highest overall elevation is from 2011 and was surveyed immediately prior to channel modification that led to the sudden decrease in the 2012 datapoint. A steady elevation increase is observed between 2012 and 2014, when no channel modifications took place, followed by a lowering of the mean elevation between 2016 and 2020, when only one operation took place.

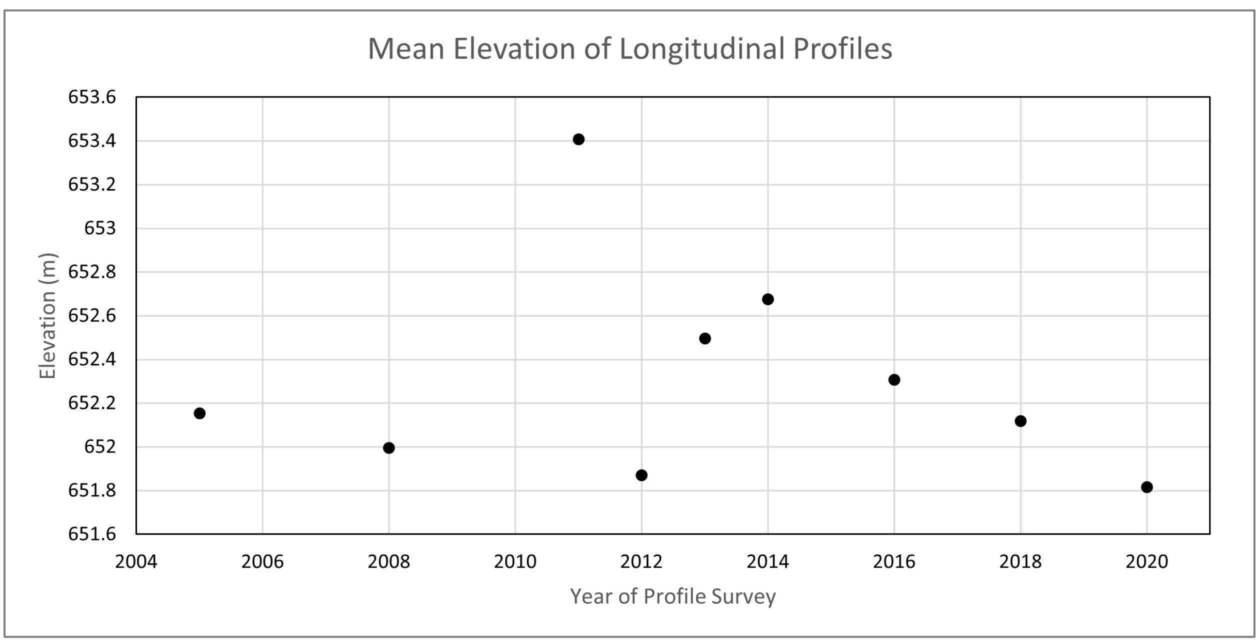

Figure 6. Mean elevation of the low-flow water surface for points surveyed 100 meters downstream and 100 meters upstream from the bridge.

Figure 7 shows the evolution of the channel below the bridge. Figure 7(a) depicts the modified channel in the days following the 2011 alignment operation. The channel widens and begins to braid as the banks get eroded (Figures 7[b] and 7[c]). There is an abundance of sand in the bank material that is capable of being transported even during the low-flow conditions present in Figures 7(a), 7(b), and 7(c). Selective entrainment of sand causes bank failure, delivering pulses of sediment to the channel bed. While the sand may continue to travel downstream, the larger particles remain close to the point of failure until a higher flow occurs, reducing overall conveyance through the bridge. This channel achieves a conditional level of stability by arranging particles into hydraulically smooth bedforms.

Figure 7. Evolution of the modified channel over three years. Panels (a) through (f) are looking downstream from the bridge deck. The stream flow in (a) through (d) is representative of low-flow conditions. Flow in panel (e) is typical of summer runoff. Panel (f) is near bankfull runoff during a precipitation induced flood (Photos: NPS and US Federal Highways Administration).

Watershed Context and Upstream Factors Potentially Impacting the Bridge

The upper Tahoma Creek Watershed has been experiencing dramatic geomorphic change since at least the 1960s. Over 33 debris flows have deposited vast amounts of sediment in the middle portions of the watershed (Beason et al. 2021), and significant floods have transported these stockpiles downstream (Walder and Driedger 1994). This section describes the geomorphic connectivity in the Tahoma Creek Watershed.

The USGS gaging station on the Nisqually River at National, Washington is used as a proxy for streamflow trends in the un-gaged Tahoma Creek Watershed. Streamflow was below normal between 1978 and 1994, and few peak-flow events occurred (Czuba et al. 2012). This same period is when debris flow activity was most frequent. Hydrologic activity increased in the 1990s, resulting in large peak-flows within the park.

Anderson (2013a) identified sediment source areas using repeat LiDAR (collected in 2002, 2008, and 2012) and estimated sediment flux during a period that contained the park flood-of-record in 2006 (2002–2008), and one period that covered more typical geomorphic processes (2008–2012). During the 2002–2008 period, an estimated 1.2 million cubic meters (1.6 million cubic yards) of sediment was transported through the lower watershed, while an estimated 100,000 cubic meters (130,000 cubic yards) of sediment was transported between 2008 and 2012. Bedload transport volumes peak between RKM 8 and 10, indicating the moraines near the South Tahoma Glacier terminus are the main source of sediment. Sediment recruitment is highest in the upper reaches of the watershed due to steep, unvegetated slopes that lead directly into the active channel (Turley 2020).

Debris flow deposition takes place between RKM 4 and 7, where the valley bottom widens and the channel slope decreases. Across both time periods, roughly 50% of the material recruited in the upper basin was deposited above RKM 4.5 (Anderson 2013a). The remainder was transported through the lower reaches of the watershed and into the Nisqually River. Elevation profiles show that below RKM ~5, there is very little difference in vertical change between the high-transport (2002–2008) and low-transport (2008–2012) time periods. Yet, even with most sediment passing through the system this far down in the watershed, the bridge is observed to be the only site with enhanced vertical storage of sediment coupled with sharp increases in channel width. This observation lends support to the theory that the local channel geometry exerted by the bridge influences sediment deposition.

The age and distribution of red alder stands (*Alnus rubra*) growing on surfaces adjacent to the active channel can provide insights into geomorphic activity over long timescales (Anderson 2013a). The age of the oldest tree cored in a stand was taken to be the age of the surface plus a three-year lag. There were spikes in red alder establishment between 1989 and 1995, with peaks in 1993 and 1994. The dates of red alder establishment coincide with the end of frequent debris flows in the upper watershed and suggest that these events were large enough to disturb the lower channel network. Anderson (2013a) goes on to indicate that aggradation in the channel network subsides in three to five years after debris flow activity.

Estimates of vertical change from sequential LiDAR datasets, combined with volumetric bedload transport remaining consistent below RKM 6, suggest that the impact of geomorphic processes in the upper basin largely attenuates before reaching the bridge. Tahoma Creek does appear to be steep enough to transport the bulk of sediment entrained out of the watershed, even under the influence of increased sediment loading (Anderson 2013a, 2013b). This implies that the bed elevation of Tahoma Creek below RK 5 has generally remained stable across the historic record and that sediment transfer between large areas of the watershed is only being connected during higher-magnitude flooding or debris flow events (Turley et al. 2021). The locations of aggradation and incision are largely determined by channel geometry and the presence of flow obstructions such as large woody debris (LWD).

Federal Highways Modeling Results

The USFHA was contracted by the NPS to model hydraulic behavior in the study area. The assessment utilized the 2008 LiDAR data (Watershed Sciences 2009) to construct a two-dimensional unsteady flow model. Figure 8 depicts a modeled flow of 3,000 cubic feet per second (85 cubic meters per second) of a 100-year flow event in the unmodified channel. This figure demonstrates the contraction of the active channel above and below the bridge. The spacing between the contours immediately above the bridge along the modified channel length is greater than the contours outside the modified area. The spacing between contours represents the longitudinal elevation drop of the river channel, where wider spacing results in less of a slope and a decrease in the potential energy of water flowing across the elevation change. The same pattern is observed in Figure 8, which depicts the same flow interacting with a simulated blockage of the bridge. In both scenarios, the rapid change in the channel slope directly affects the transport capacity of the flow and is the primary driver of persistent sediment deposition around the bridge.

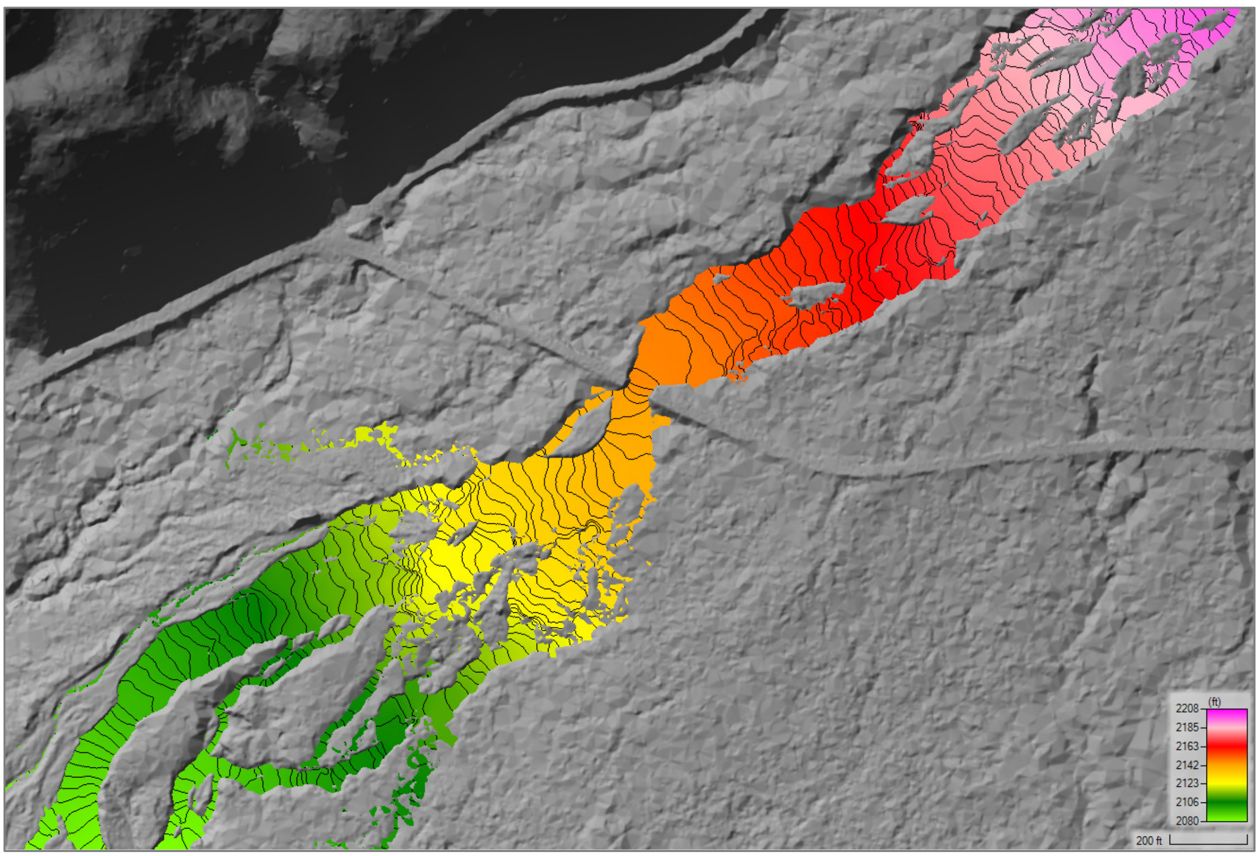

Figure 8. Water surface elevation of modeled 100-year flow event in the unmodified channel. Contour interval is 1 ft (0.3 m). Colors represent elevations above mean sea level in feet (Modified from Figure 9A in Leon [2020]).

The result depicted in Figure 9 is an overtopping and lateral migration of the Tahoma Creek active channel, causing spill-over locations on the road to appear across roughly 274 m (900 ft) of the active floodplain (Leon 2020). Most of the flow, visually estimated to be roughly two-thirds or more of the modeled discharge, heads west and flows parallel to the roadway, spilling across most of it. Several potential head cuts are visible along the 152 m (500 ft) of road west of the bridge, with the Westside Road junction being inundated by up to 0.6 m (2 ft) of water.

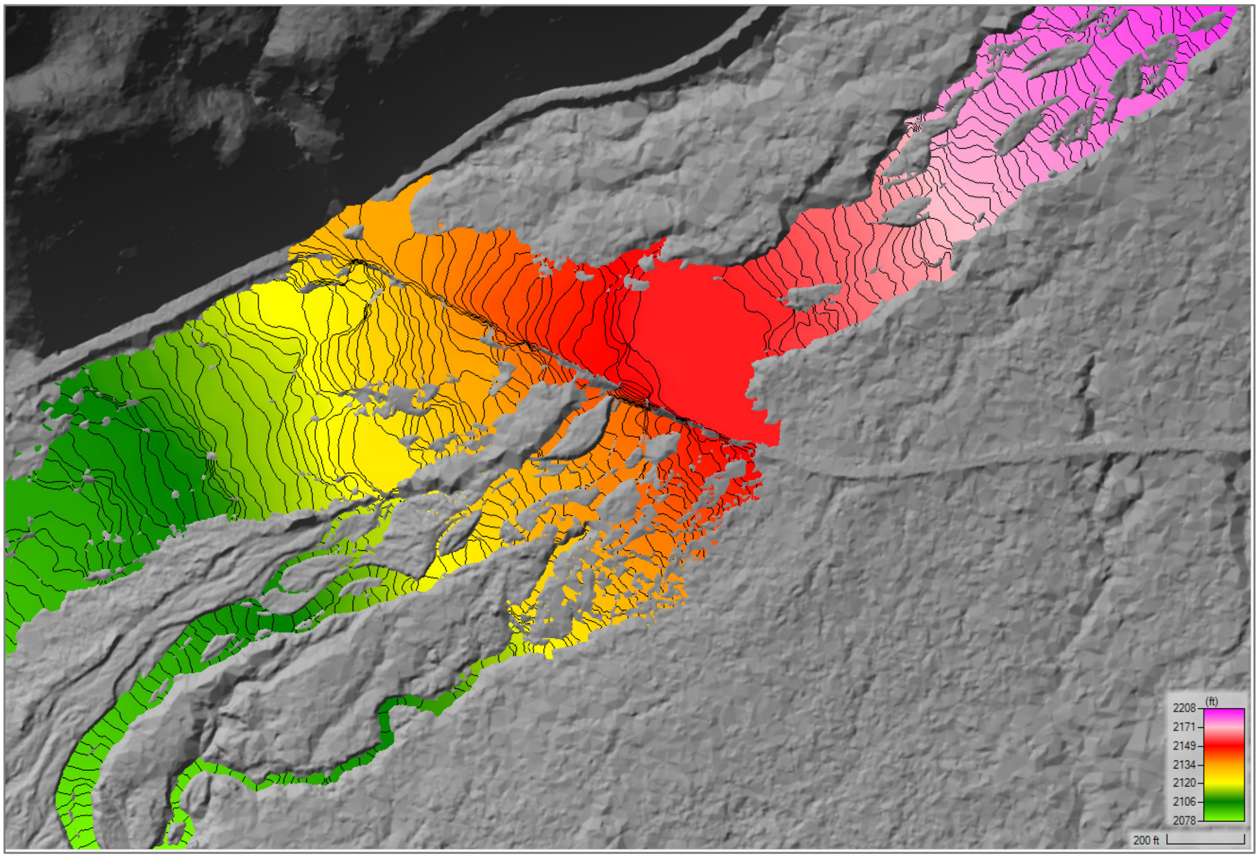

Figure 9. Water surface elevations of modeled 100-year flow event interacting with a debris plug at the upstream face of the bridge. Contour interval is 1 ft (0.3 m). Colors represent elevations above mean sea level in feet (Modified from Figure 9A in Leon [2020]).

Figure 10 depicts the flow velocities of a 2-year flow in the modified channel. High velocity values are sustained through the length of the dredged channel and suggest that this design is sufficient to facilitate sediment transport. The upstream end of the modified channel shows a velocity increase associated with the sudden change in slope where the modified channel tapers to meet the natural channel profile.

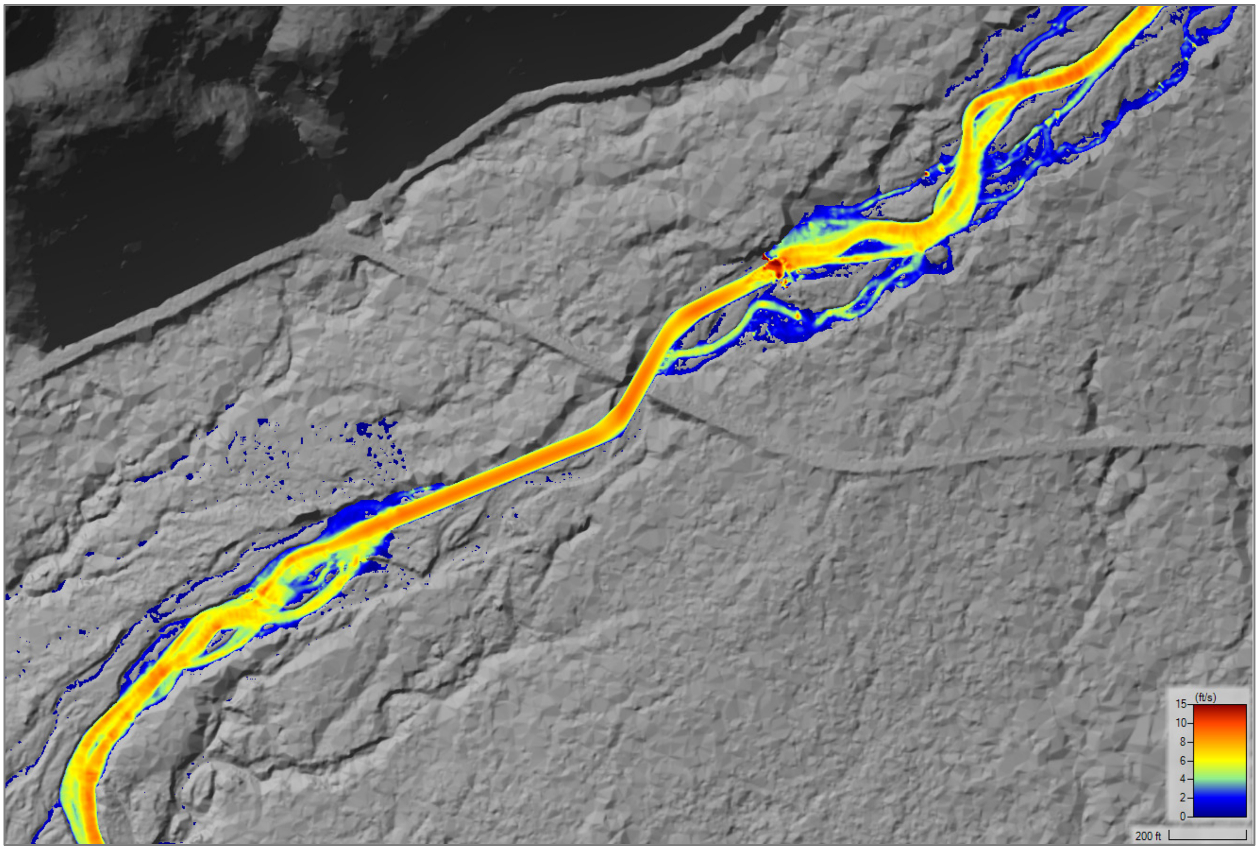

Figure 10. Velocity of a 2-year flow in the modified channel. The warmer colors represent higher velocity values of up to 15 ft/s (4.6 m/s) where entrainment of sediment is likely, while cool colors represent areas of lower velocity where deposition is expected. The highest velocity values are located at the upstream end of the modified channel (Modified from Figure 7D in Leon [2020]).

Integrated Discussion

The channel geometry along the study area encourages sediment deposition due to decreases in both channel slope and width over a short distance upstream from the bridge. Delivery of sediment downstream to the bridge is accomplished through flooding or debris flows and is enhanced by the narrowing of the river imposed by the bridge profile. The delivery of woody debris ultimately poses the greatest short-term risk to the bridge by possibly blocking the flow and causing lateral river migration until bridge abandonment occurs.

Several lines of evidence suggest that the lower portions of the Tahoma Creek channel network are in dynamic equilibrium. Repeat LiDAR data differencing shows localized segments of sediment erosion and deposition, but the cumulative volume of sediment exported from the watershed is negative. Estimates of channel width since 1951 show an increase in the average channel width across the entire watershed. Width increases between 1984 and 2009 only occurred along discrete segments, but the greatest increases were immediately upstream from the bridge. Finally, the age distribution of alder stands in the active channel indicates that the bed elevation of these channels is stable over decadal timescales.

Anderson (2013a) found that Tahoma Creek is a net exporter of sediment. This strongly suggests aggradation in the channel network occurs along segments where changes in slope and width directly alter the transport capacity of the flow. The bridge creates such a pinch point, where the channel contracts and expands over a short distance. The upstream contraction, coupled with a reduction in slope, reduces the water surface gradient (Figures 8 and 9) during high flows, and sediment is deposited along the channel margins. Narrowing of the flow through this constriction causes it to deepen and often focus against the banks, leading to enhanced erosion. In the study area, the most readily mobile sediment grains are the spoils piled below the ordinary high-water mark (OHWM). The spoils are poorly sorted, and their matrix consists of grains small enough to remain mobile under low-flow conditions (Figure 7).

During channel alignment operations, sediment is excavated from the center of the active channel and placed along the channel margins. These operations are referred to as dredging; however, the term dredging implies that the excavated sediment is moved to a location above the OHWM of the site. While the placement of spoils below the OHWM is permissible in the regulatory framework the NPS operates within, this decision may lead to greater aggradation during periods of frequent flooding and shows little benefit under normal streamflow conditions. The longevity of the freshly modified channel form is dependent on the arrival of the next high-water event, after which the channel typically reorganizes and experiences short-term aggradation.

Summary of Management Options

Leon (2020) presented the following four alternatives to maintain the current level of access in the study area: (1) maintain the existing road and bridge; (2) construct a new 122 m (400 ft) bridge with greater clearance; (3) construct two new 122 m (400 ft) bridges with greater clearance connected by a raised roadway; and (4) construct a new 305 m (1,000 ft) pier-supported bridge with greater clearance to span the active fan surface. All proposed designs recommend raising the clearance of the structures by up to 1.8 m (6 ft). These structures have projected 100-year service-life costs of approximately $3.1 million, $6.6 million, $12.8 million, and $13.6 million, respectively. The ongoing costs of dredging increase proportionally with the first two alternatives, but the cost of dredging for the 305 m (1,000 ft) bridge is less than half that of the single 122 m (400 ft) bridge, due to the expected ability to allow for normal floodplain processes.

The greatest weakness of the bridge is the 20 m (66 ft) span available to convey water, sediment, and wood. During floods, this narrow passage forces sediment deposition upstream of the bridge and is susceptible to obstruction by woody debris during the same events. Another serious concern is erosion of the banks above the bridge, which could lead to a channel avulsion. This occurred during the 2006 storm and caused extensive damage to the adjacent road. It is in the park’s best interest to consider a bridge that spans from the western valley margin to the apex of the debris fan. Extending the bridge would eliminate the need to keep the active channel in a specific alignment. Abandoning channel modification operations as much as possible will benefit local ecology, reduce costs to operate, reduce time-strain on park operations during unplanned events, and eliminate a source of local aggradation around the bridge.

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Appendix A: Tahoma Creek Longitudinal Profiles

This appendix shows longitudinal profiles of Tahoma Creek in 2005, 2008, 2011, 2012, 2013, 2014, 2016, 2018, and 2020 (Figures 11 through 18). During this period, the profile elevation is lowered through dredging, and by the next time-step, the profile is at or above the previous elevation. Furthermore, the change in profiles in Figures 16 and 17 were surveyed during a time when only one dredging operation took place (2016) and show less variability in elevation changes. It is especially interesting to note that the profile difference between 2018 and 2020 (Figure 18) is net negative. The profiles surveyed during time periods with frequent dredging have a more widespread aggradation signal along the profile. In contrast, aggradation appears more isolated during periods of less frequent dredging, and incision can be observed.

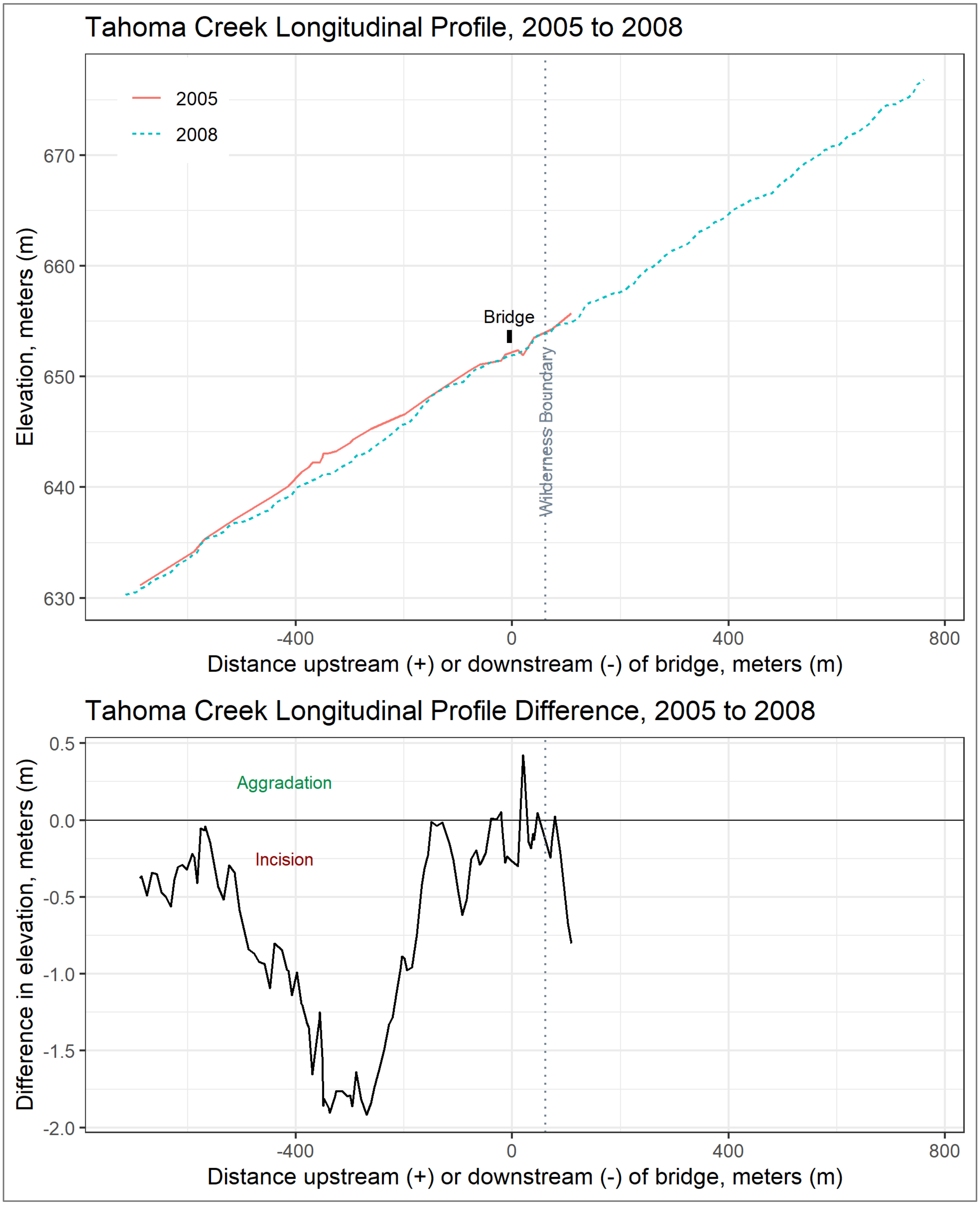

Figure 11. Longitudinal profiles of Tahoma Creek surveyed in 2005 and 2008 (top), and elevation difference between the two profiles (bottom). Elevation difference is calculated as the elevation of the more recent profile minus the elevation of the older profile, along the longitudinal distance of the profile. Vertical exaggeration: ~20.5x (top); ~285x (bottom).

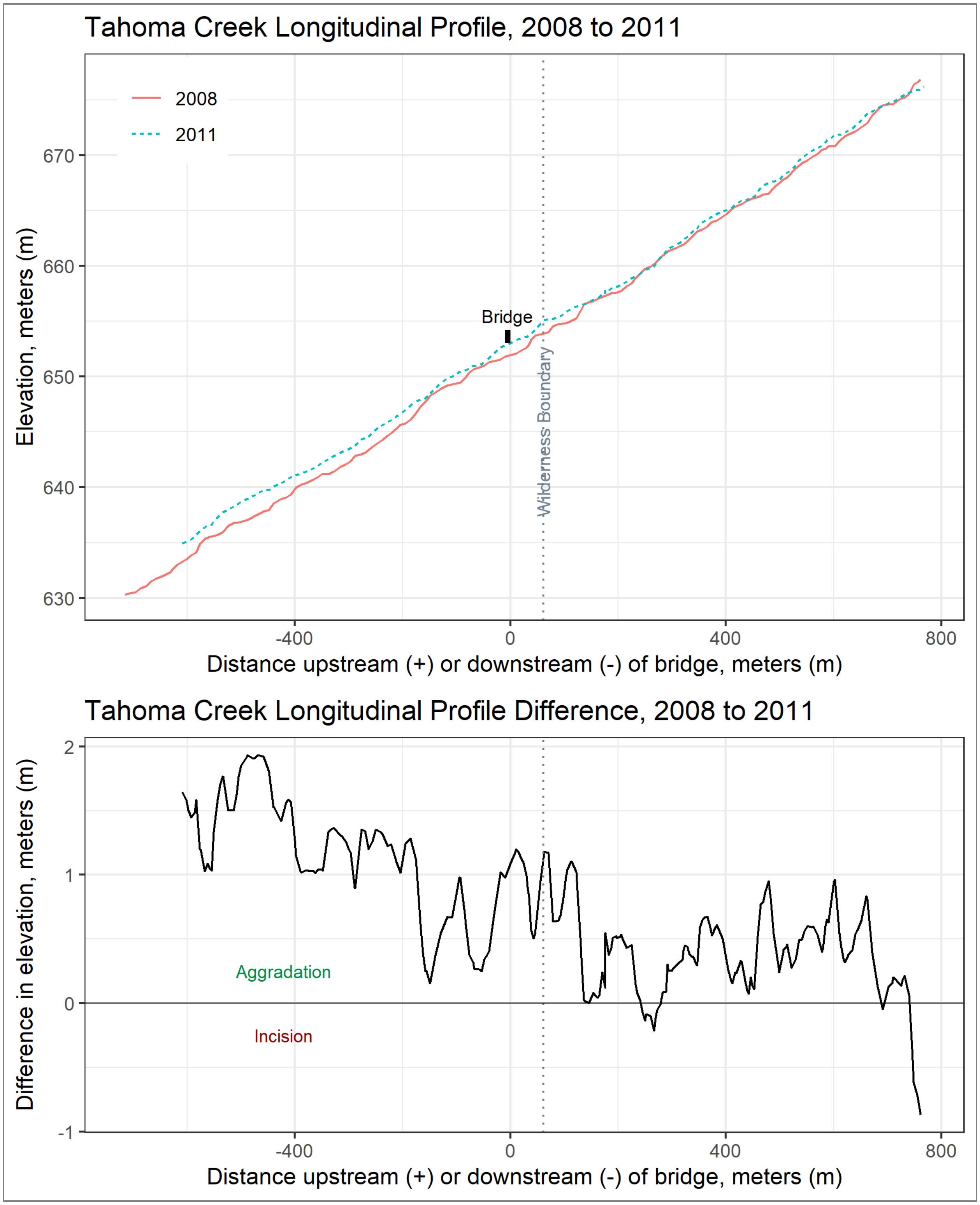

Figure 12. Longitudinal profiles of Tahoma Creek surveyed in 2008 and 2011 (top), and elevation difference between the two profiles (bottom). Elevation difference is calculated as the elevation of the more recent profile minus the elevation of the older profile, along the longitudinal distance of the profile. Vertical exaggeration: ~20.6x (top); ~239x (bottom).

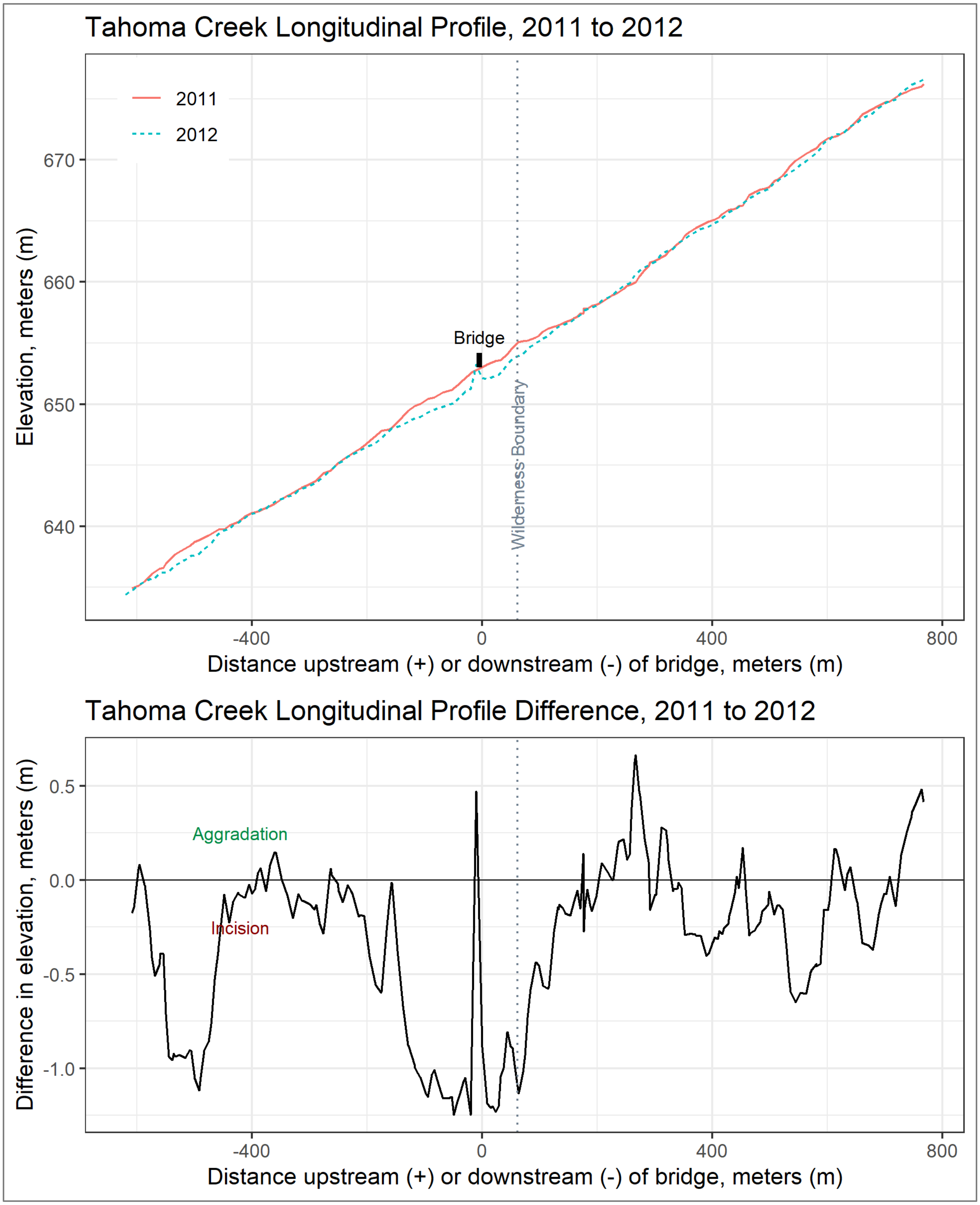

Figure 13. Longitudinal profiles of Tahoma Creek surveyed in 2011 and 2012 (top), and elevation difference between the two profiles (bottom). Elevation difference is calculated as the elevation of the more recent profile minus the elevation of the older profile, along the longitudinal distance of the profile. Vertical exaggeration: ~21.2x (top); ~328x (bottom).

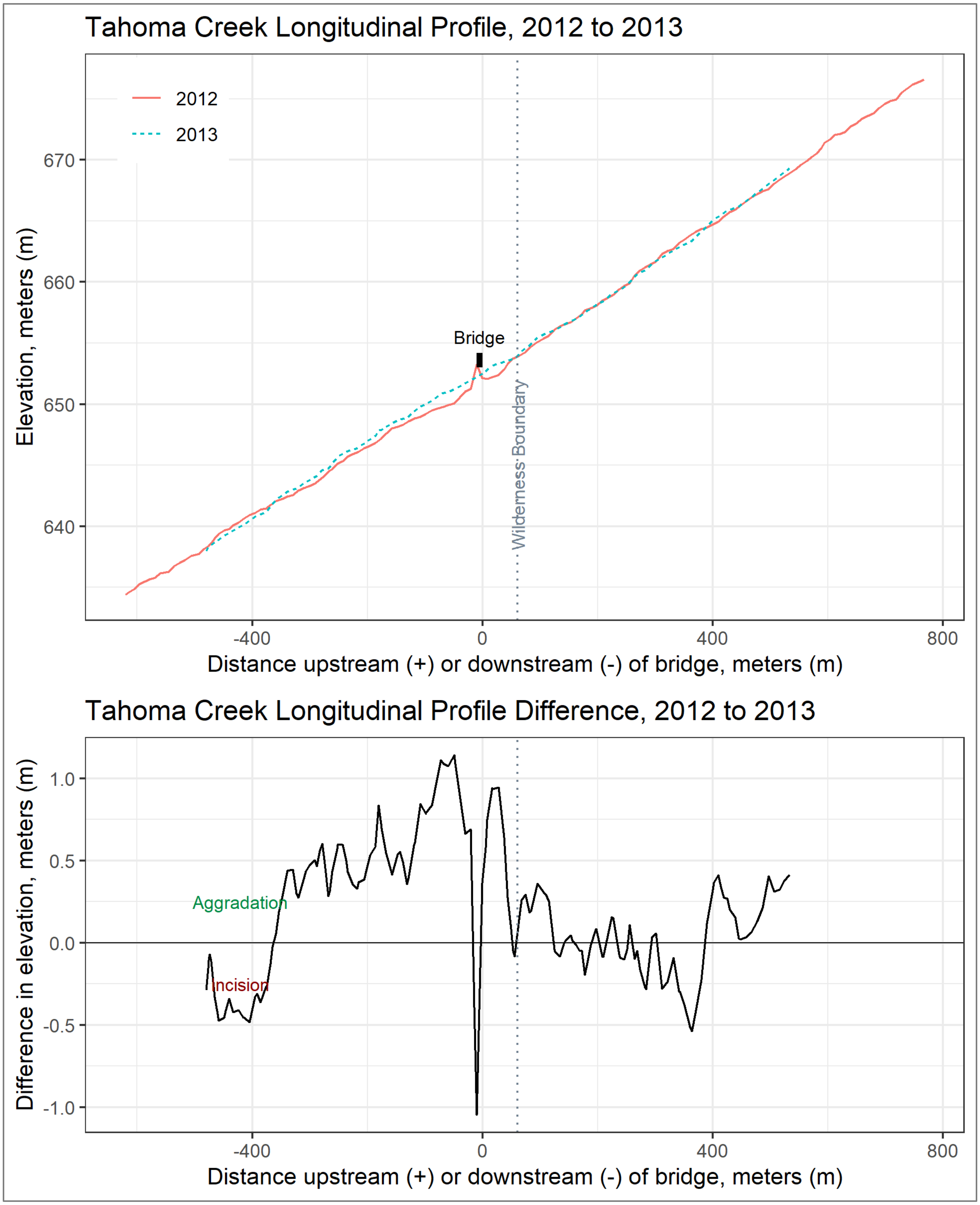

Figure 14. Longitudinal profiles of Tahoma Creek surveyed in 2012 and 2013 (top), and elevation difference between the two profiles (bottom). Elevation difference is calculated as the elevation of the more recent profile minus the elevation of the older profile, along the longitudinal distance of the profile. Vertical exaggeration: ~21.2x (top); ~286x (bottom).

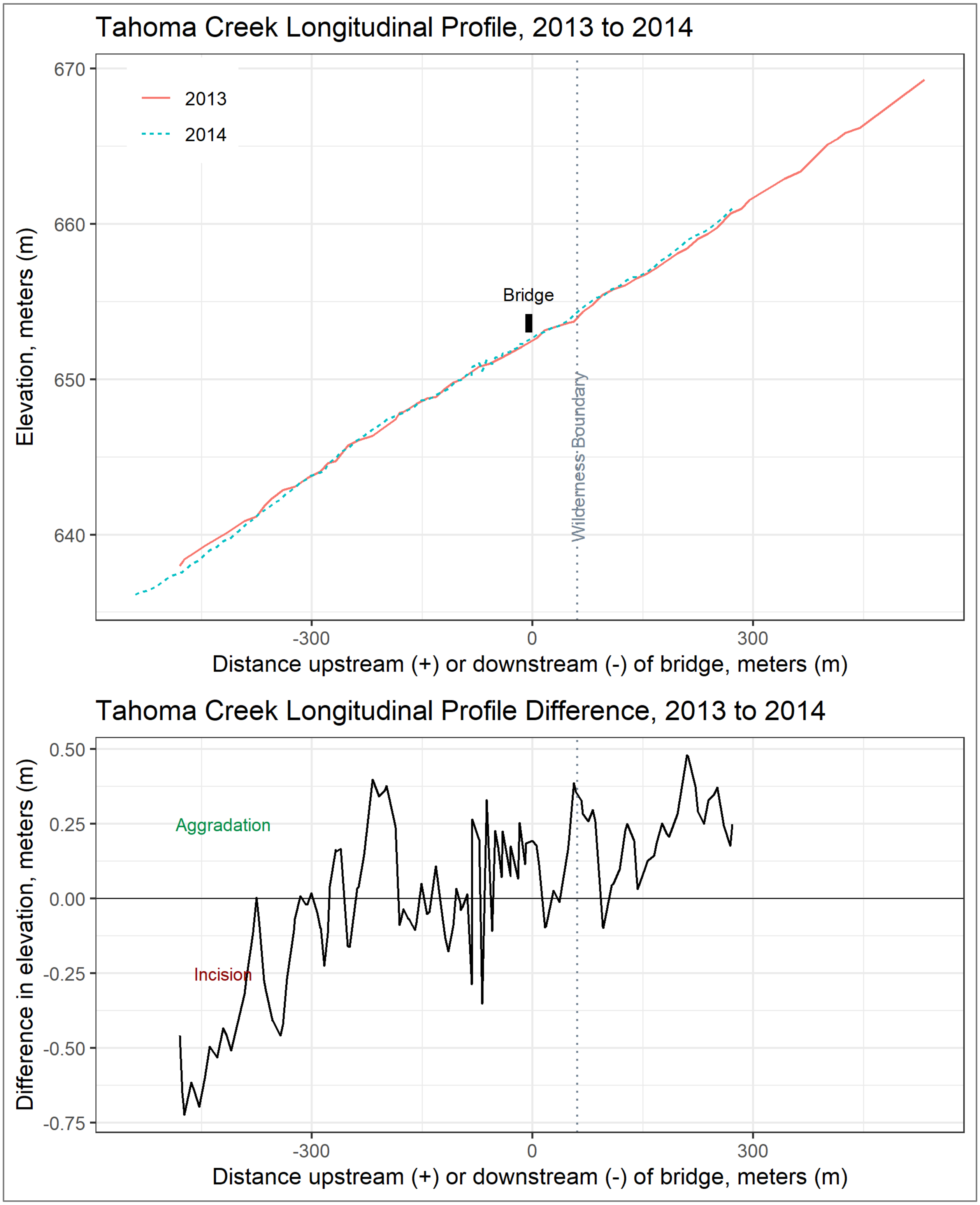

Figure 15. Longitudinal profiles of Tahoma Creek surveyed in 2013 and 2014 (top), and elevation difference between the two profiles (bottom). Elevation difference is calculated as the elevation of the more recent profile minus the elevation of the older profile, along the longitudinal distance of the profile. Vertical exaggeration: ~21.1x (top); ~406x (bottom).

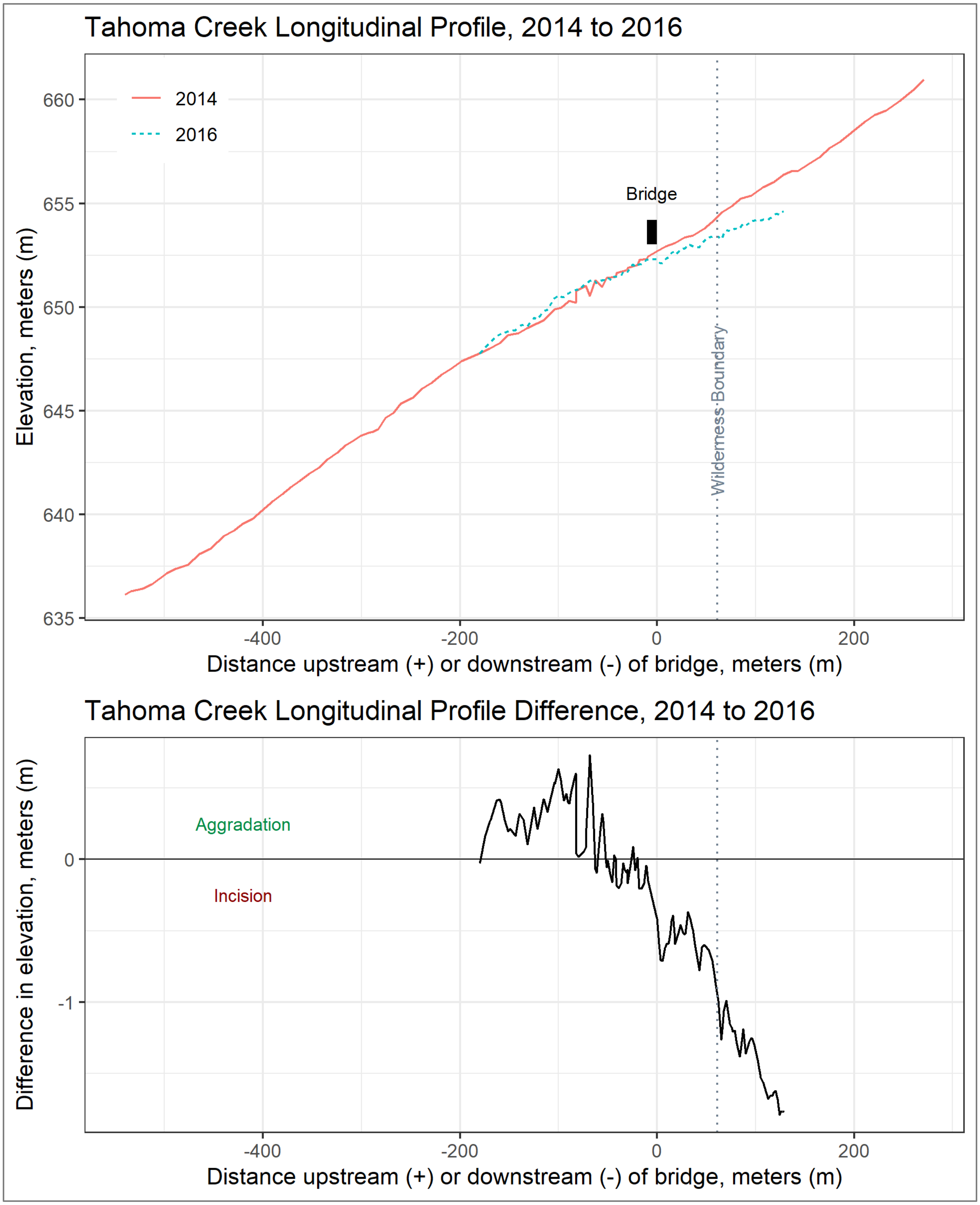

Figure 16. Longitudinal profiles of Tahoma Creek surveyed in 2014 and 2016 (top), and elevation difference between the two profiles (bottom). Elevation difference is calculated as the elevation of the more recent profile minus the elevation of the older profile, along the longitudinal distance of the profile. Vertical exaggeration: ~21.0x (top); ~145x (bottom).

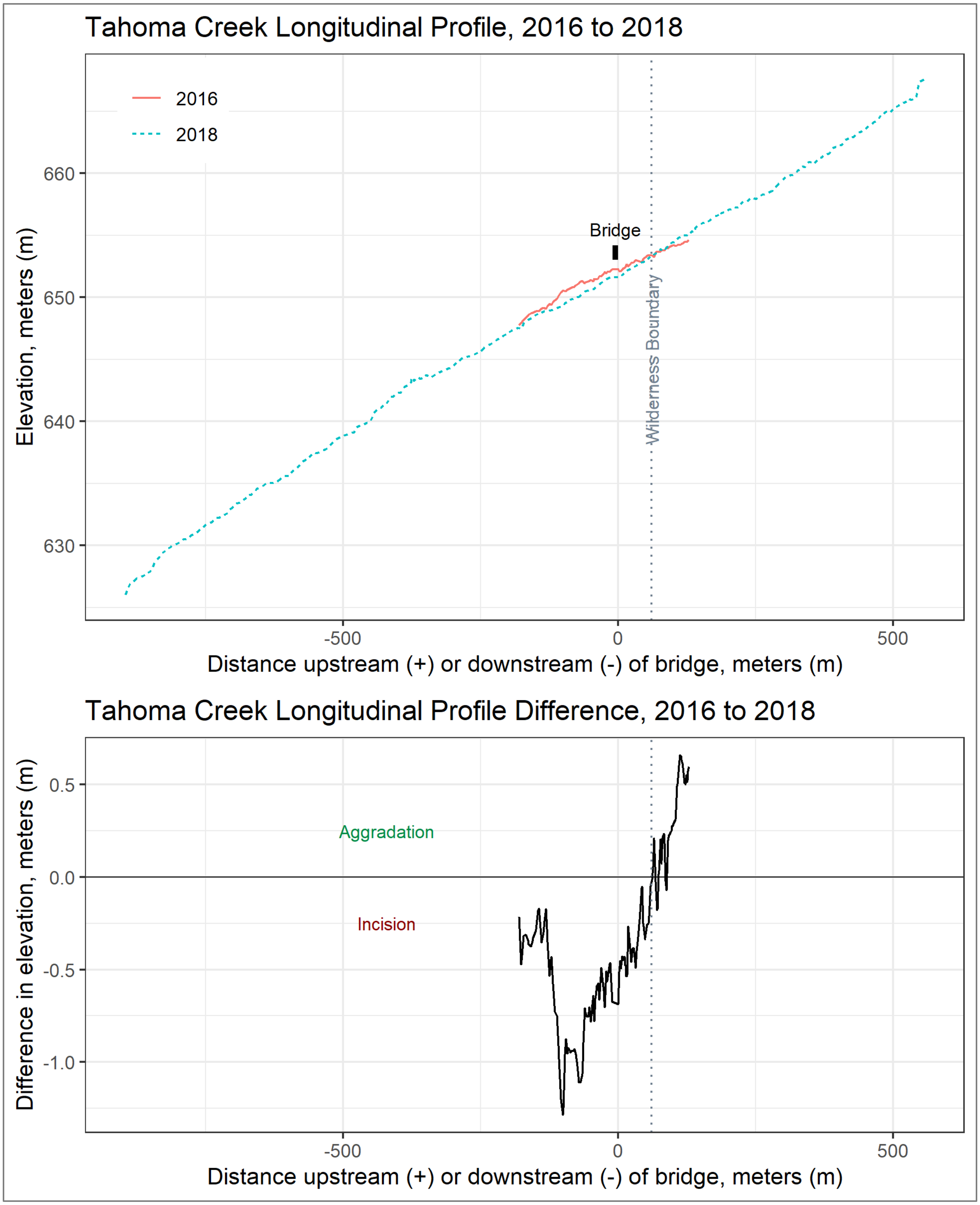

Figure 17. Longitudinal profiles of Tahoma Creek surveyed in 2016 and 2018 (top), and elevation difference between the two profiles (bottom). Elevation difference is calculated as the elevation of the more recent profile minus the elevation of the older profile, along the longitudinal distance of the profile. Vertical exaggeration: ~22.6x (top); ~336x (bottom).

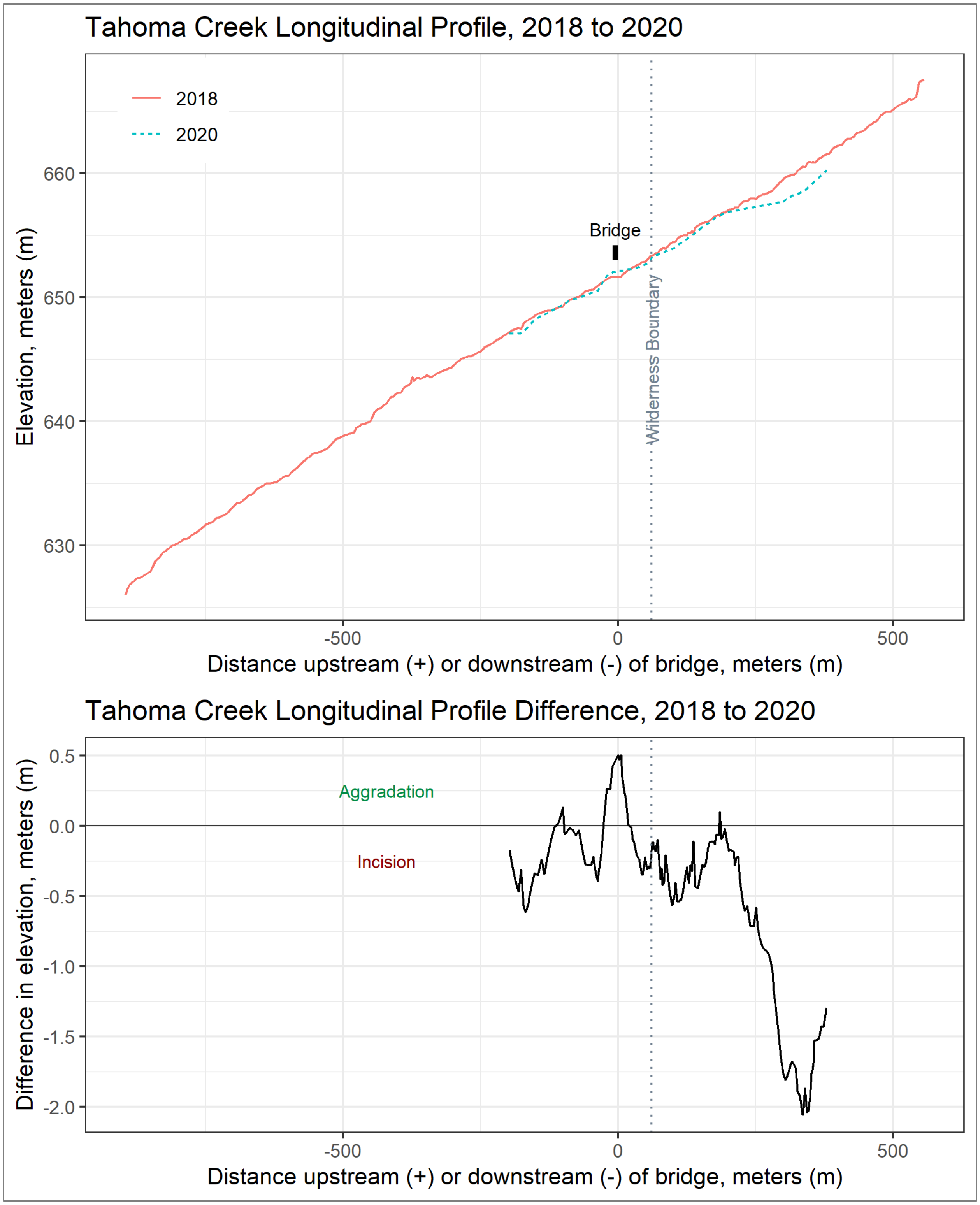

Figure 18. Longitudinal profiles of Tahoma Creek surveyed in 2018 and 2020 (top), and elevation difference between the two profiles (bottom). Elevation difference is calculated as the elevation of the more recent profile minus the elevation of the older profile, along the longitudinal distance of the profile. Vertical exaggeration: ~22.5x (top); ~256x (bottom).

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