Title
Assessment of Channel Changes Three Years after Implementation of the Salmon Habitat Enhancement, Phase 1 on Redwood Creek at Muir Woods

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Publication Date
2022-10-01

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Prepared for:
Kondolf, Landscape Architecture 227
University of California, Berkeley
Fall 2022

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Abstract

In 2019, the National Park Service (NPS) began restoration efforts on sections of Redwood Creek in Muir Woods to improve habitat for endangered coho salmon (*Oncorhynchus kisutch*) and threatened steelhead trout (*O. mykiss*). The restoration consisted of riprap removal and large woody debris (LWD) placement. This project aimed to assess the impacts of the restoration efforts by comparing the current condition with pre-project and as-built conditions, three years after the work and after a peak flow event with a recurrence interval of 2 to 5 years. In May 2022, the NPS collected longitudinal and cross section profile survey data. We analyzed this data to detect riverbed changes along the creek and investigate the relationships between these changes and LWD presence and riprap removal. Additionally, we performed facies mapping and geomorphic mapping within a subreach of the creek and compared with previous data. The riverbed elevation analysis showed that in some portions the banks were undercut, and that some of the constructed pools were filled in while other pools were scoured. Documented LWD displacement in some locations appeared to be the cause of filling and/or scouring of pools. Comparing the facies mapping conducted on the pre-project condition and 2022 post-project conditions, the surficial bed material in the subreach has become noticeably finer and more heterogeneous. A qualitative comparison of geomorphic mapping from the 2019 pre-project and 2022 post-project conditions show that the stream has created new valuable habitat for the target species since the restoration efforts. Overall, the topographical, facies, and geomorphic analyses found that the 2019 restoration improved Redwood Creek's stream channel complexity, thus benefiting coho salmon and steelhead trout.

Introduction

Flowing through the old-growth redwoods of Muir Woods, Redwood Creek has had a long history of anthropogenic alterations. In the 1930s, the Civilian Conservation Corps (CCC) installed rock armoring (riprap) along the creek's banks to improve bank stabilization (NPS

2018). Until the 1980s, park managers would routinely remove large woody debris (LWD), such as fallen logs, from the creek's channel to improve hydraulic efficiency (NPS 2018). Unfortunately, both of these alterations harmed the creek's natural processes. The riprap prevented bank erosion, thus blocking lateral mobility. Limited mobility and flow resistance then induced the incision of the riverbed and disconnection with the floodplain. Similarly, the removal of fallen logs prevented sediment from being trapped and deposited, reduced flow resistance, and inhibited the formation of pools. The combination of these two pressures resulted in a hyper-simplified straight channel with limited habitat availability (NPS 2018).

In 2019, the National Park Service (NPS) conducted restoration work in Redwood Creek within the upstream half of Muir Woods in an attempt to undo the previous creek alterations to improve habitats that support endangered coho salmon (*O. kisutch*) and threatened steelhead trout (*O. mykiss*), and improve the overall riverine and forest ecology. Redwood Creek supports a population of coho salmon but the survival of juveniles in the reach is low (NPS 2018). The main limiting factor on salmonid populations in Redwood Creek has been identified as poor juvenile summer and winter rearing habitat. The objective of the Phase 1 restoration project was to improve habitat availability by increasing geomorphological complexity and generating deep and covered pools as well as areas with lower velocities for winter refugia. For the 2019 restoration work, the NPS removed riprap, conducted bank revegetation, and added large and small woody debris. The NPS also graded a high-flow channel and excavated new pools at locations where wood was added (NPS 2018).

The removal of riprap and bank revegetation were performed to increase bank roughness (velocity refugia), stream cover and pool scour for summer habitat, and allow natural channel migration with undercut banks creating new winter and summer habitats (Kimbal and Kondolf, 2002; NPS 2018). Similarly, the addition of large and small woody debris was expected to reduce water velocity and create obstructions that would force pool scouring and increase sediment storage, thus expanding summer pool habitat and regions for high-flow refugia (Montgomery et al. 1995; NPS 2018). The increase of flow resistance may also prevent further channel incision by slowing down strong flows.

Kimbal and Kondolf (2002) observed that before the restoration in Redwood Creek, pool-to-length ratios were higher in the reaches without riprap (downstream: 1 pool per 92 ft of stream length, upstream: 1 pool per 130 ft) than in the reach through Muir Woods with riprap (1 pool per 169 ft of stream length). By comparing riprap reaches to natural bank reaches, they also found that the latter had both higher aquatic insect diversity and higher numbers of individuals.

The effect of LWD on channel morphology and especially on the presence of the pools has been investigated in literature. For example, Montgomery et al. (1995) described that pools can be free-formed or forced, with forced pools created by the interaction of flows with obstructions like LWD, bank projections (e.g. tree roots), boulders, and bedrock outcrops. They found that pool spacing was controlled by LWD loading, channel type, slope and width. The effect of large woody debris on pool formation is greatest when logs are oriented oblique or perpendicular to flow.

In the design of LWD installation, one can opt to lock the logs in fixed positions or leave them unpinned. In the case of non-locked logs, the flow can eventually move the logs downstream. Gurnell et al. (2002) investigated the effect of log size and weight on mobility and river form. They investigated the wood and how the eventual displacement of the logs downstream impacted pool creation. The NPS was aware of the potential mobility of some of the placed logs. Assessment should be conducted to determine if pool formation processes occur even after log displacement or a return to pre-project pool conditions.

Redwood Creek drains from the slopes of Mount Tamalpais in Marin County, California releasing into the Pacific Ocean at Muir Beach. Phase 1 of the restoration work involved a reach of Redwood Creek (which we refer to as the Phase 1 reach) that flows within Muir Woods National Monument (MWNM) between bridge four and three (Figure 1) with a project area of 3.65 square miles. In this reach, the channel has a width between 25-40 ft (8-12 m) and an average slope of 1.3%. Figure 1 shows the position and labels of the removed riprap segments and the location of the placed LWD. We introduced a notation to identify some of the LWD that we refer to in the following paragraphs.

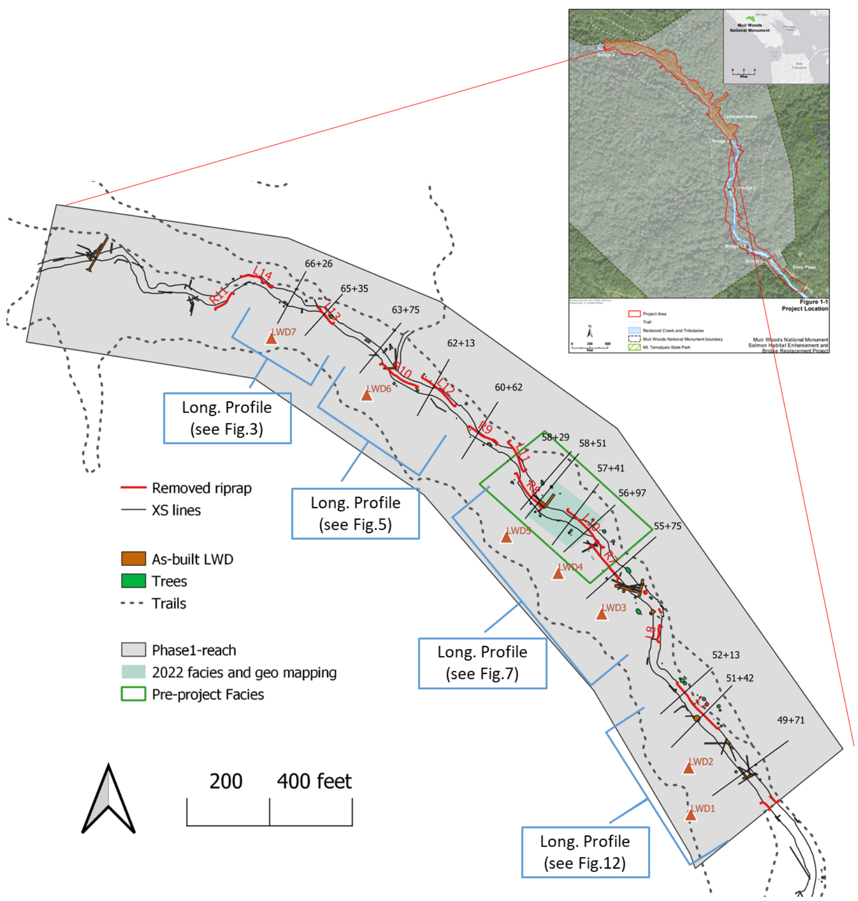


Figure 1. Map of the river restoration work area (phase 1). The blue brackets identify the subreaches where the longitudinal profiles were surveyed in 2018 (pre-project), 2019 (as-built) and 2022.The black “XS lines” identify the sections that were surveyed in 2018, 2019 and 2022.

In 2014 and 2015, students at UC Berkeley (UCB) conducted research along sections of Redwood Creek. The students in 2014 compared sections of the reach where riprap had been installed in the 1930s and sections that had not received riprap. The students found that the un-riprapped channel had significantly more habitat heterogeneity with more pools, riffles, and LWD (Edwards et al. 2014). In 2015, student Allison Jacobson mapped the geomorphic features in all of the Phase 1 reach (Figure 1). Facies mapping was performed in subreaches in the pre-project condition in 2019 (Shoulders and Adams, 2020).

Redwood Creek did not experience a geomorphically competent flow after the riprap removal until 2019 when an intense rain occurred on the 24th of October 2021 (Water Year 2022), producing a peak flow of 786 cubic feet per second (cfs) at bridge 3 in MWNM.

The gauging station at the Highway 1 bridge, about 5 km downstream from the study reach, had a peak flow of 995 cfs during the event. Based on the recorded data from the Highway 1 gauge, flood frequency analyses indicated the October rain event had a return period between 2 and 5 years (NHE, 2010). Months after the rain event, the NPS resurveyed monumented cross sections and a long profile of the restored reach, as shown in Figure 1.

The objective of this report is to analyze the NPS's cross section and long profile data while supporting the analysis with facies and geomorphic mapping collected by our team. From the data analysis, this report will assess the overall changes in Redwood Creek's morphology subsequent to the October 2021 rain event. We will also analyze the impact of LWD loading and its effect on pool formation. Figure 2 below shows a timeline of the relevant events for this project's analysis.

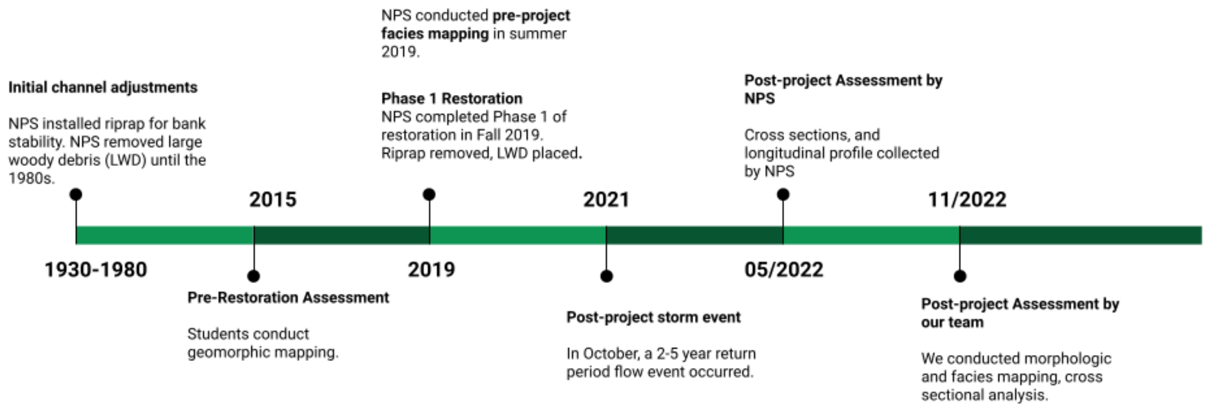


Figure 2. Redwood Creek context timeline

Methods

Carolyn Shoulders, the Project Manager for the Redwood Creek restoration project and the UCB contact for our work, provided our team with cross section and longitudinal profiles, facies mapping, and geomorphic mapping from previous studies. We used these data and collected new ones to perform analysis of riverbed elevation, sediment size changes and morphological changes over time.

Analysis of riverbed elevation changes in time

The NPS surveyed cross section and longitudinal profiles in 2018 to document the pre-project conditions, in 2019 to document as-built conditions, and three years after the restoration in May of 2022. The 2022 longitudinal profile was surveyed in subreaches of the phase 1 reach. The surveyed subreaches are shown in Figure 1. We plotted the three years of cross section and longitudinal data in Excel, overlaying them to detect changes. We compared elevations in the as-built and 2022 cross sections to document the impact of the October 2021 peak flow event. We made specific field observations of the phase 1 subreach at each cross section with available topographic data. We laid out a tape transversely using permanent benchmarks as endpoints to observe the cross section locations. Then, we took photos and noted the morphological features, the location of the LWD, the presence of pools, and the possible erosion or undercut of the banks. We performed pebble counts at locations where the profile data showed aggradation of the channel bed of at least one foot from 2019 to 2022. At these locations, we dug down at least a foot into the deposit and took a picture. This was done to show the underlying sediment composition. This information was added to the cross section fact sheets located in Appendix A for cross sections with deposition. Since sediment scouring cannot be assessed by the same method as deposition, we did not include photos of scoured areas in the fact sheets.

Analysis of sediment size changes in time

We performed facies mapping in a subreach of the river (the green area in Figure 1) within cross sections XS 58+29 and XS 56+97 and compared our maps with one of the two reaches in which the NPS conducted pre-project facies mapping in 2019, specifically reach A of Shoulders and Adams (area in the green frame of Figure 1). We followed the procedure outlined in Laurel Collins (1988) and Edwards et al (2014) to model the grain size distribution spatially. We first identified and mapped different facies in the selected river stretch. The facies consisted of patches of the riverbed where the grain size appeared to be homogenous. We laid out measuring tapes longitudinally and transversely to the channel, using the ground-based endpoints of the cross sections for reference to draw the facies mapping. Then we drew the facies on a printout of the project base map of the channel at a scale of 1"=10'.   We conducted a modified Wolman pebble count from Jacobson et al. (2014) on each identified patch unless it consisted of fine sand. If this was the case, the patches were described by their texture alone.

After the fieldwork, we scanned the field drawings, geo-referenced and digitized the drawings in AutoCAD and converted them into GIS shape files. We then created grain size distribution curves for each patch and calculated the D_{50}, which is the diameter of the sieve through which 50% of the grains pass. The D_{50} was used to classify the facies. The facies characterized by the same D_{50} were grouped together. We compared this map to the pre-project one to detect changes in sediment size and to assess whether the new configuration had a higher number of distinct sediment patches.

Analysis of morphological units changes in time

We performed geomorphic mapping in the same subreach as the facies mapping (the green area in Figure 1) within XS 58+51 and XS 56+97. We followed the same methods protocol as the student, Allison Jacobson, who mapped the reach in 2015. Using a scale of 1" = 10', we drew morphological features including pools, gravel bars, LWD, and the active water channel on a basemap. For reference, we utilized the same measuring tapes laid out for the facies mapping, drew on the same base map and digitalized the map as described in the facies mapping methods section to obtain GIS shape files.

The NPS provided the GIS shape files of the pre-project morphological map from 2015. We compared the morphological unit of 2022 to the pre-project ones through visual analysis and identified changes.

Results

In this section, we present the results of our study. In Appendix A, "Cross section fact sheet" graphs are shown for each surveyed section with the profile measured in 2018 (before work), in 2019 (as-built condition), and in 2022 (post-peak flow event). Appendix A also includes photographs taken during the October and November 2022 surveys. Appendix B displays graphs of sediment grain sizes, and Appendix C contains the geomorphic maps from 2015 and 2022.

Riverbed elevation changes in time

In the following graphs, we report the elevation changes of the longitudinal profile for the sub-sections in the phase 1 reach. We also include graphs of the cross section profiles (see

Figure 1 for the localization of profile subreaches and cross sections). The 2022 surveys overlain on the 2019 as-built surveys indicate that the riverbed has aggraded in some sections and lowered in others, increasing the complexity of the profile.

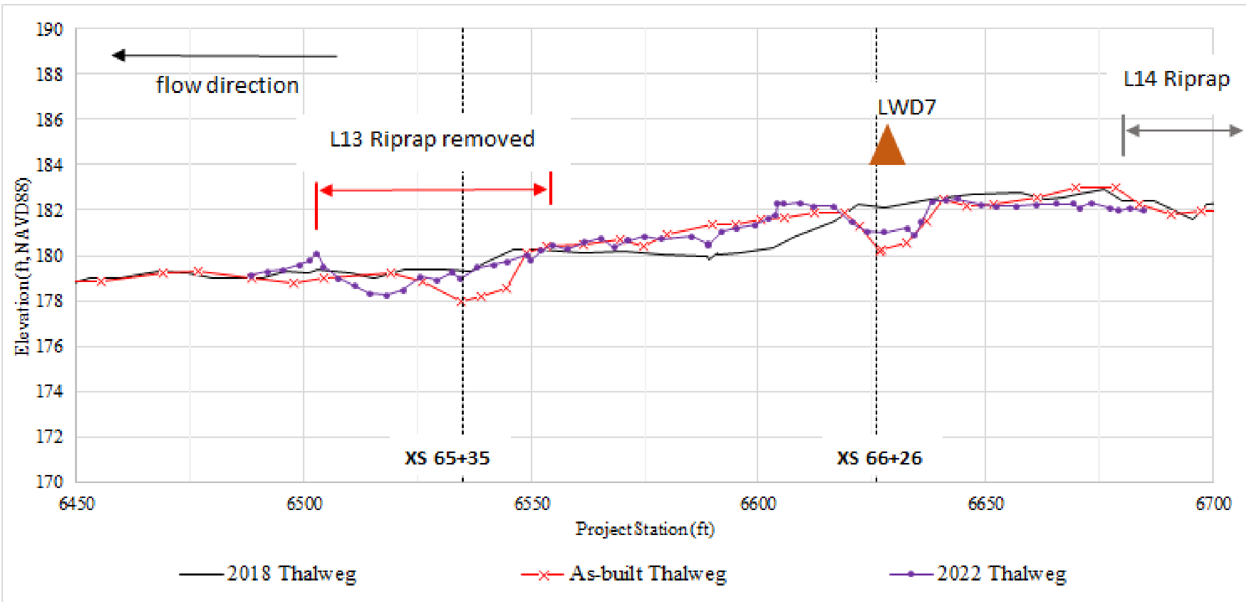
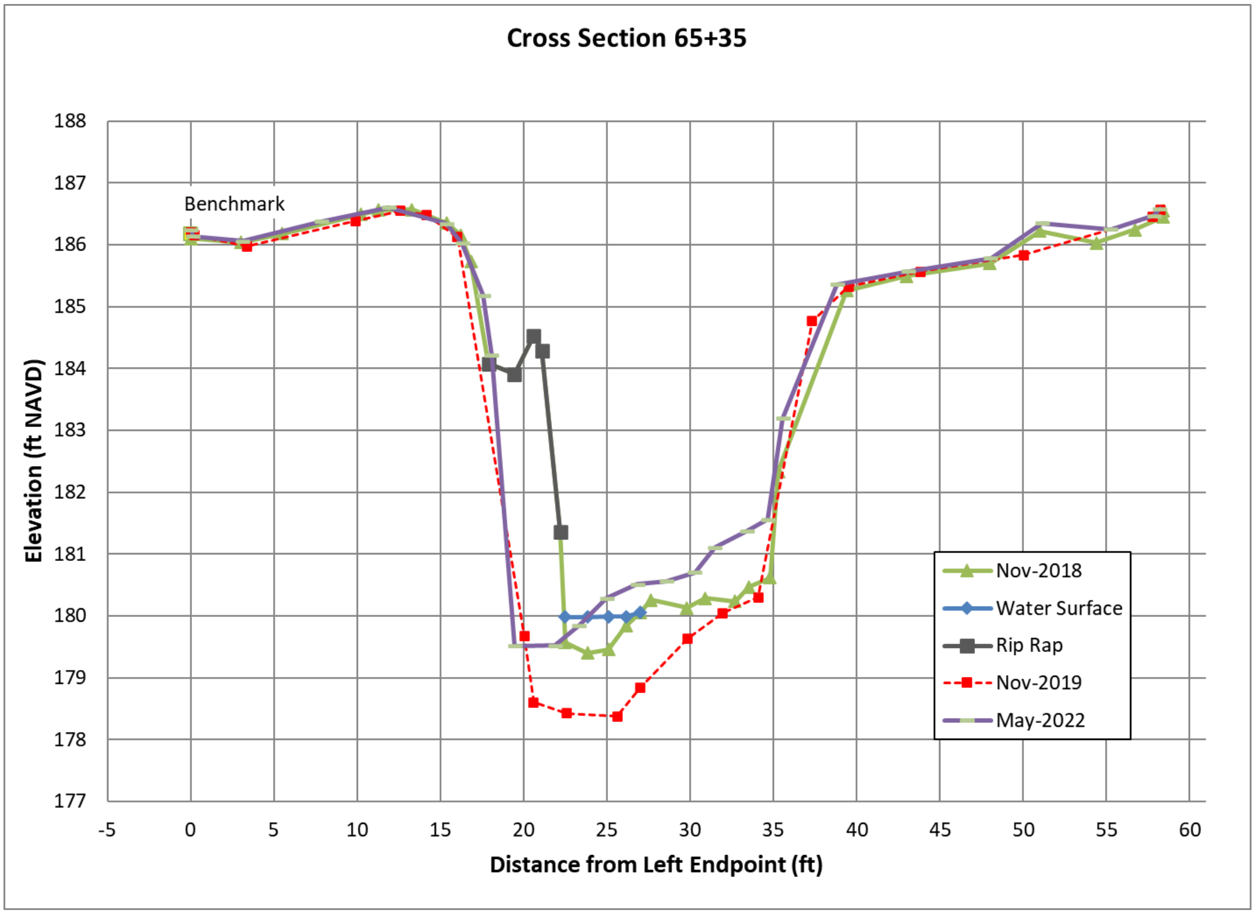
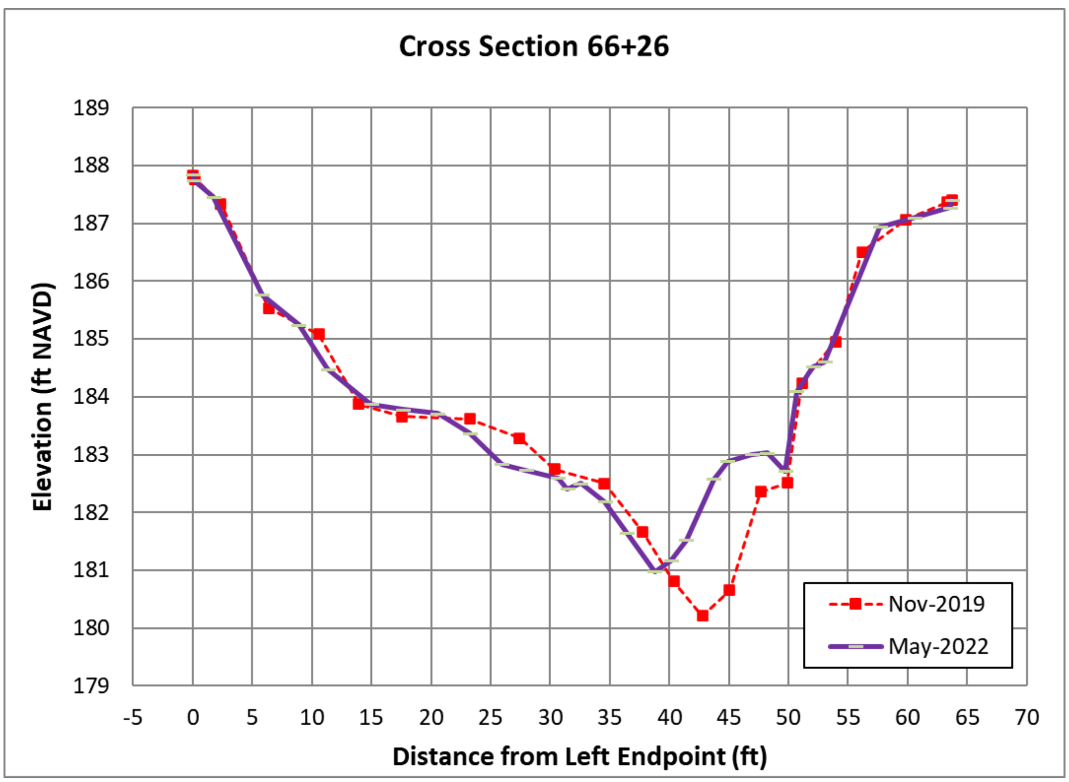


Figure 3. Thalweg profile through cross sections (XS) 65+35 and 66+26



Cross Section 65+35
Benchmark
Elevation (ft NAVD)
Distance from Left Endpoint (ft)
188
187
186
185
184
183
182
181
180
179
178
177
-5
0
5
10
15
20
25
30
35
40
45
50
55
60
Nov-2018
Water Surface
Rip Rap
Nov-2019
May-2022



Cross Section 66+26
Elevation (ft NAVD)
Distance from Left Endpoint (ft)
189
188
187
186
185
184
183
182
181
180
179
-5
0
5
10
15
20
25
30
35
40
45
50
55
60
65
70
Nov-2019
May-2022

Figure 4. Cross section data for XS 66+26 (top) and 65+35 (bottom). Bottom left, picture of the pools downstream reach 65+35 (downstream view). Bottom right, LWD upstream XS 66+26 (downstream view).

The LWD7 (Figure 3) consists of placed large and small wood adjacent to the right bank. A pool excavated 2-feet deep in 2019 downstream of LWD7 has been partly filled by about one foot, as shown in XS 66+26. In the right side of XS 66+26 there is a deposit lens with maximum thickness of around 2 ft; we observed that this deposit is made up of very fine sandy sediments. Between project stations 6500-6550 ft, where riprap L13 was removed, a pool or lowered thalweg graded in 2019 is almost completely filled in, but a new pool has formed a little further downstream. Deposition has occurred on the right bank of XS 65+35 such that the channel bed on the right aggraded more than a foot compared to the pre-project condition (Figure 4). We observed at XS 65+35 that the wet channel is in contact with the left bank, which is undercut. Downstream there is a pool about 12 ft long and 7 ft wide, a little further downstream the wet channel is in contact with the right bank and has undercut the bank there as well (Figure 4). After riprap removal the wet channel tends to undercut the banks alternately in the right and left banks. This could be interpreted as a trend to recreate a more sinuous course over time.

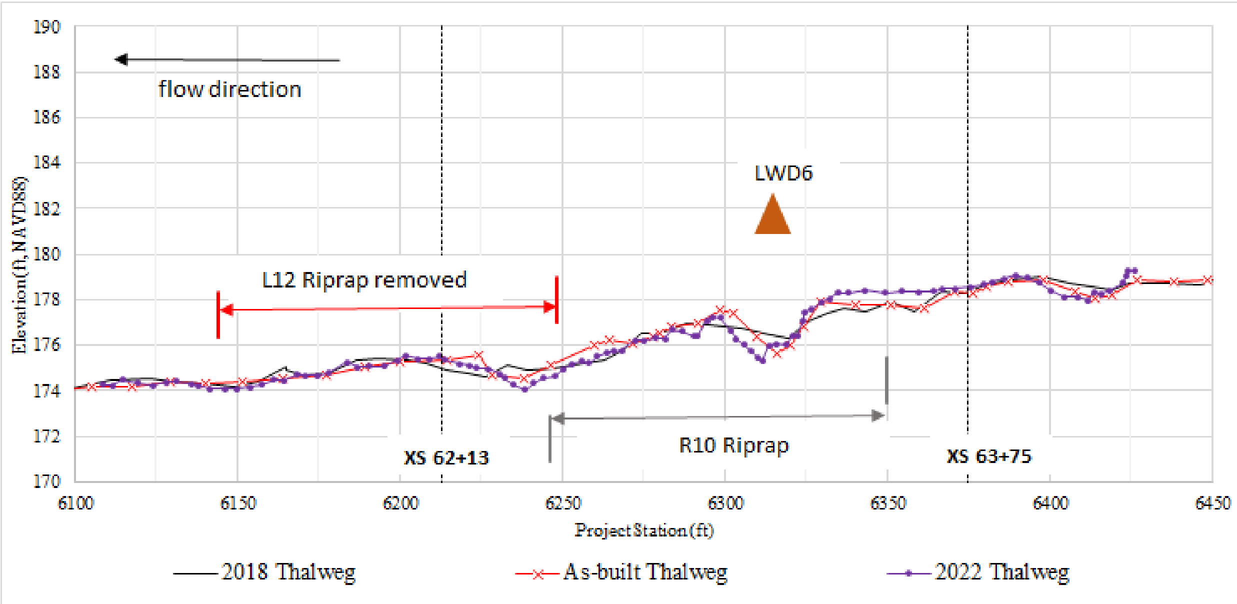
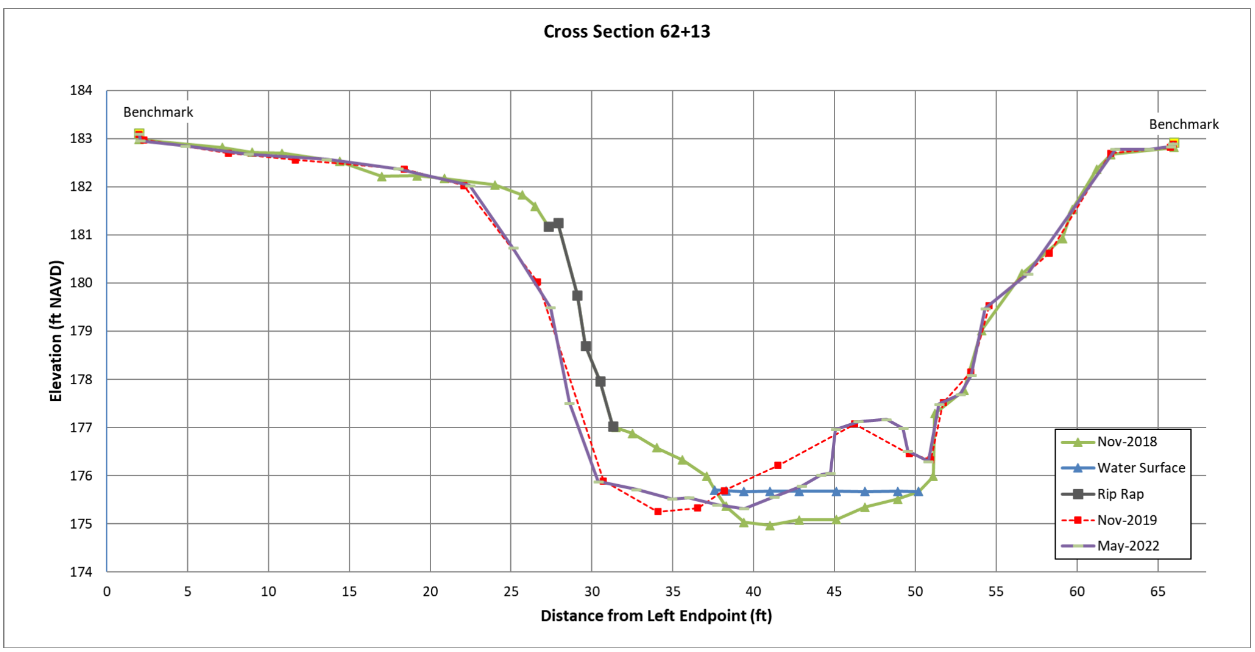


Figure 5. Thalweg profile through XS 62+13 and 63+75



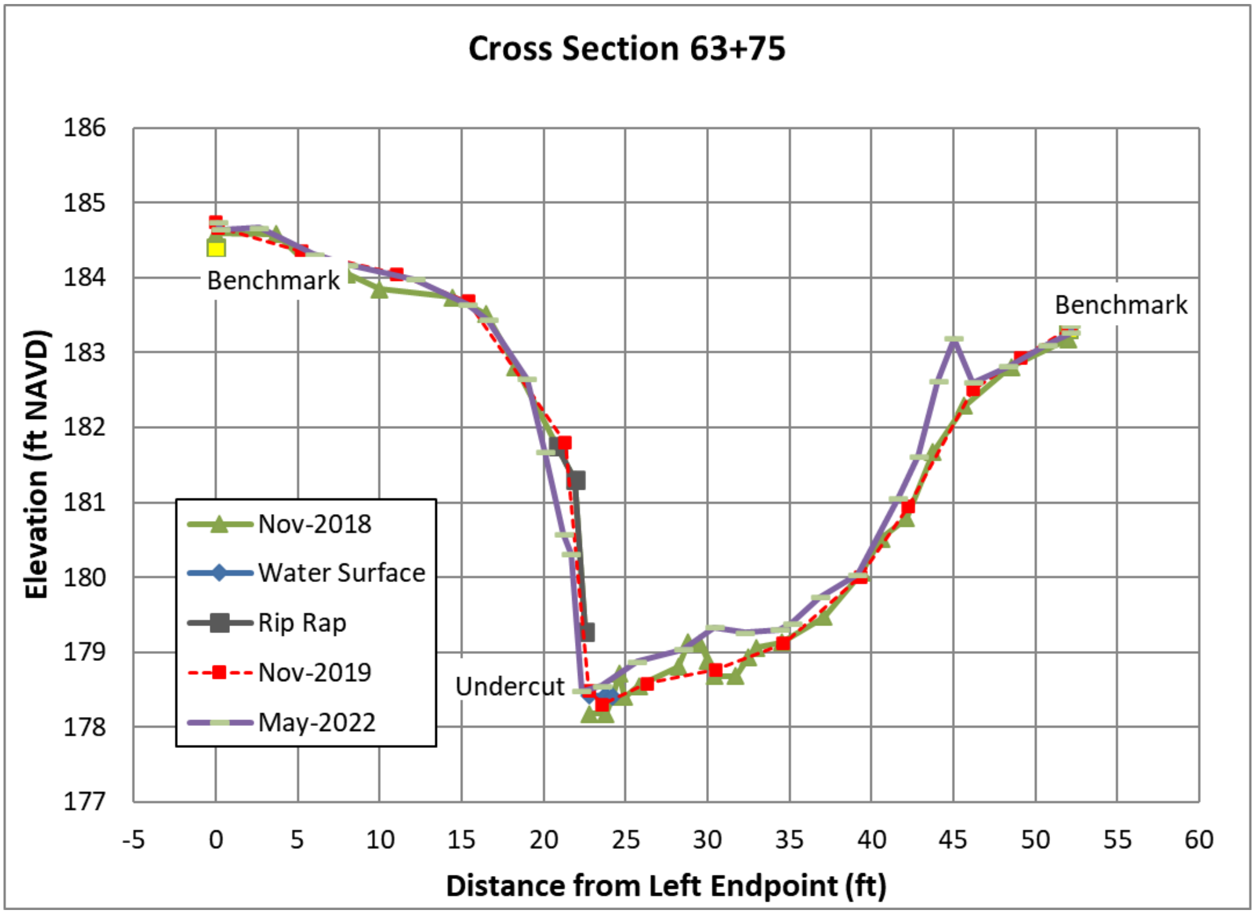


Figure 6. Cross section data for XS 62+13 (top) and XS 63+75 (bottom)

The thalweg profile of project stations 6100-6450 ft (Figure 5) shows little change between the 2019 as-built channel bed elevations and the current condition. The left bank is undercut in the area of XS 63+75. Some of the logs of LWD6 are held in place by vertical pin logs. Sediment deposition occurred at project station 6350 ft, whereas the pool deepened and lengthened downstream LDW6 where there is also a tributary confluence with Fern Creek (Figure A4 in Appendix). The left bank eroded in this area since 2019. However, further downstream the left bank where the L12 riprap was removed is protected by an unaffected erosion control fabric. Interestingly, unlike the section where L13 was removed (Figure 3), the NPS did not excavate a pool or place LWD at L12 during the project work. In this case, the process of alternating right and left bank under-excavation did not occur.

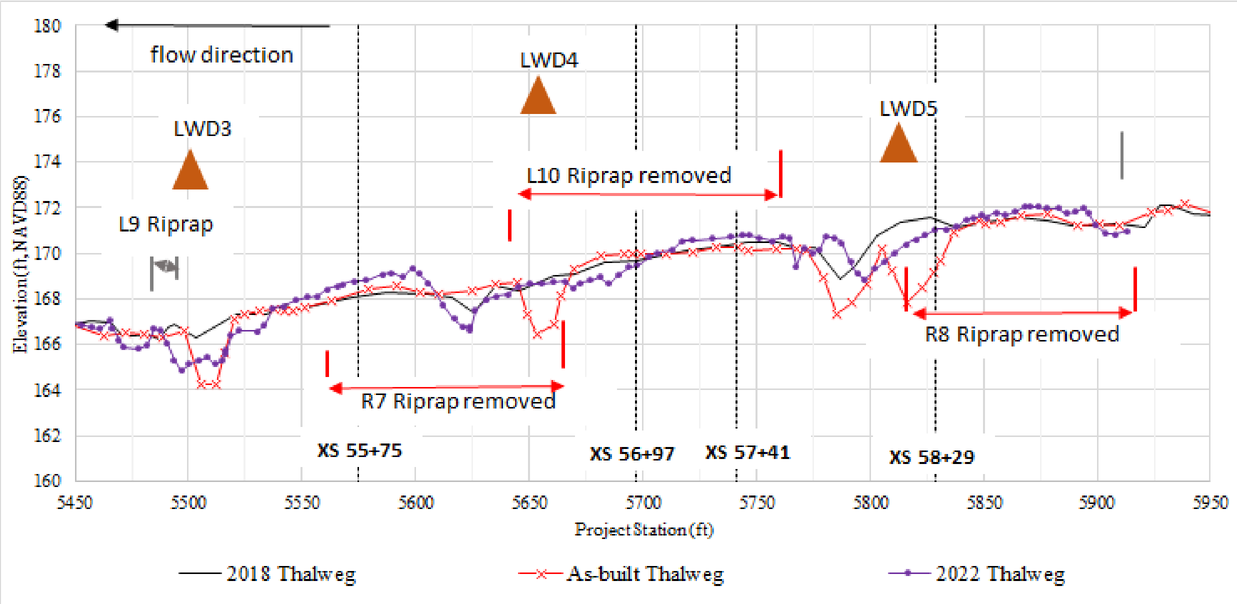
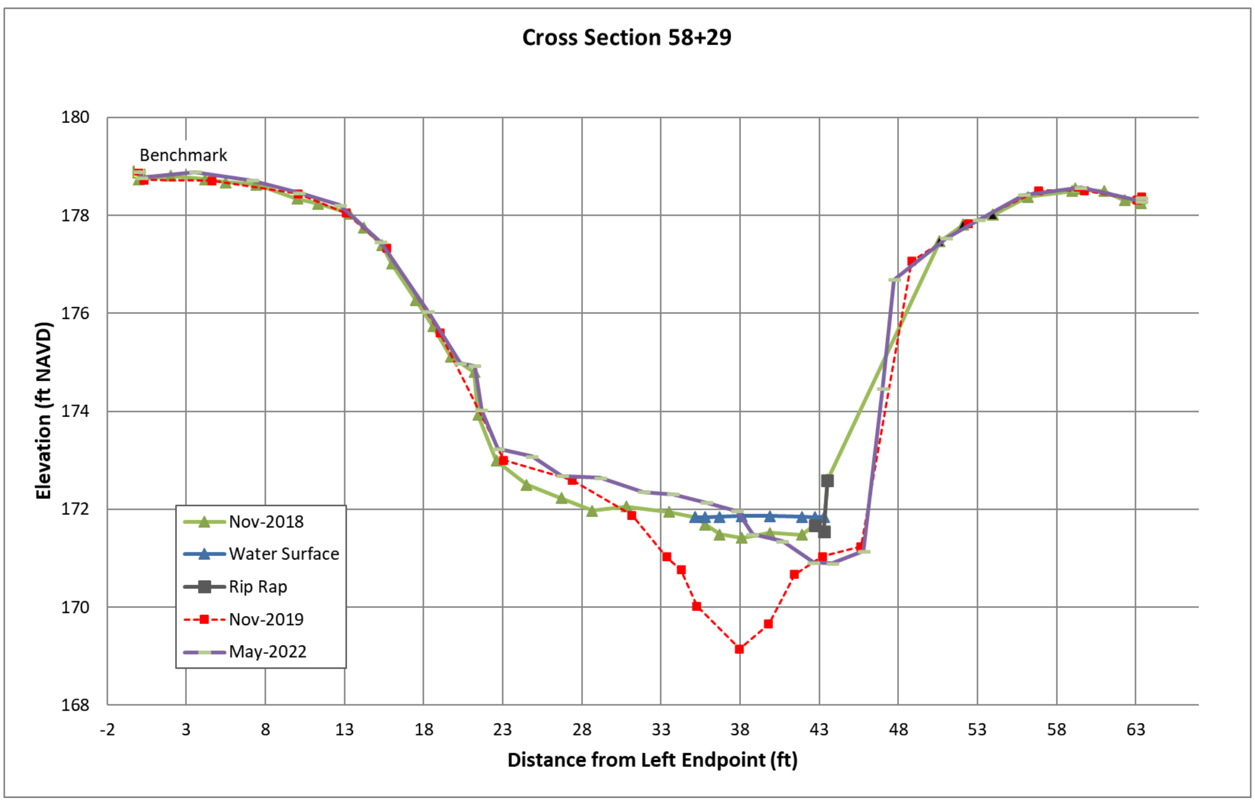


Figure 7. Thalweg profile through XS 55+75 and 58+29



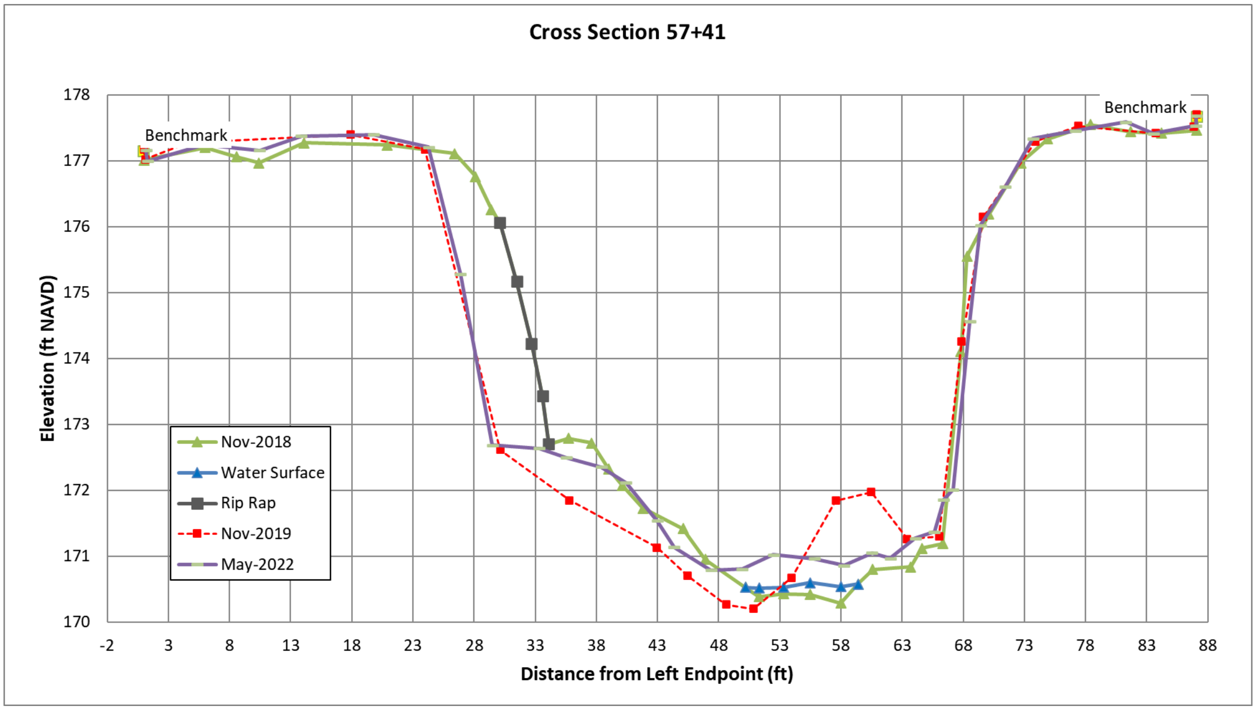
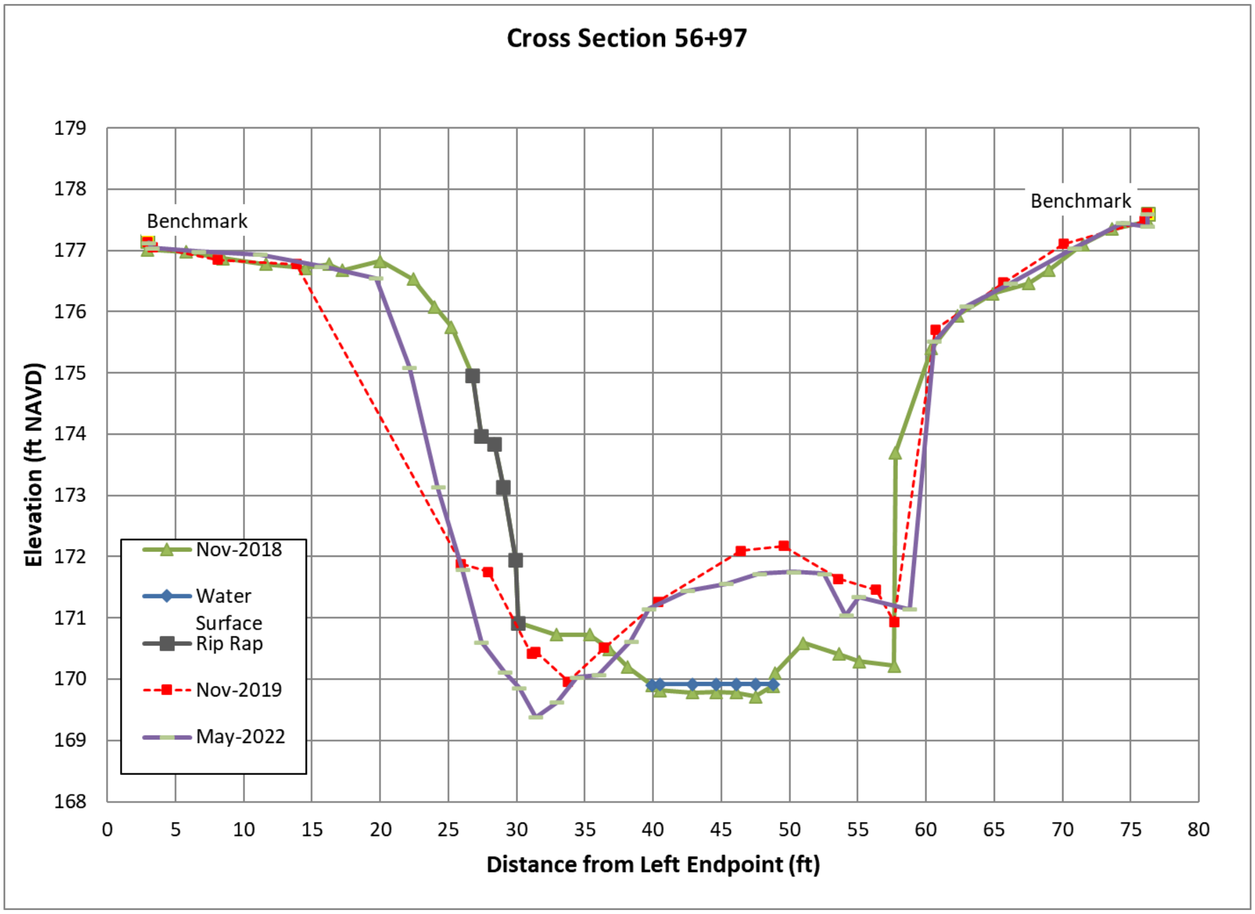


Figure 8. Cross section data for XS 58+29 (top) and 57+41 (bottom)


Cross Section 56+97
Benchmark
Benchmark
Elevation (ft NAVD)
Distance from Left Endpoint (ft)
Nov-2018
Water Surface
Rip Rap
Nov-2019
May-2022
179
178
177
176
175
174
173
172
171
170
169
168
0
5
10
15
20
25
30
35
40
45
50
55
60
65
70
75
80

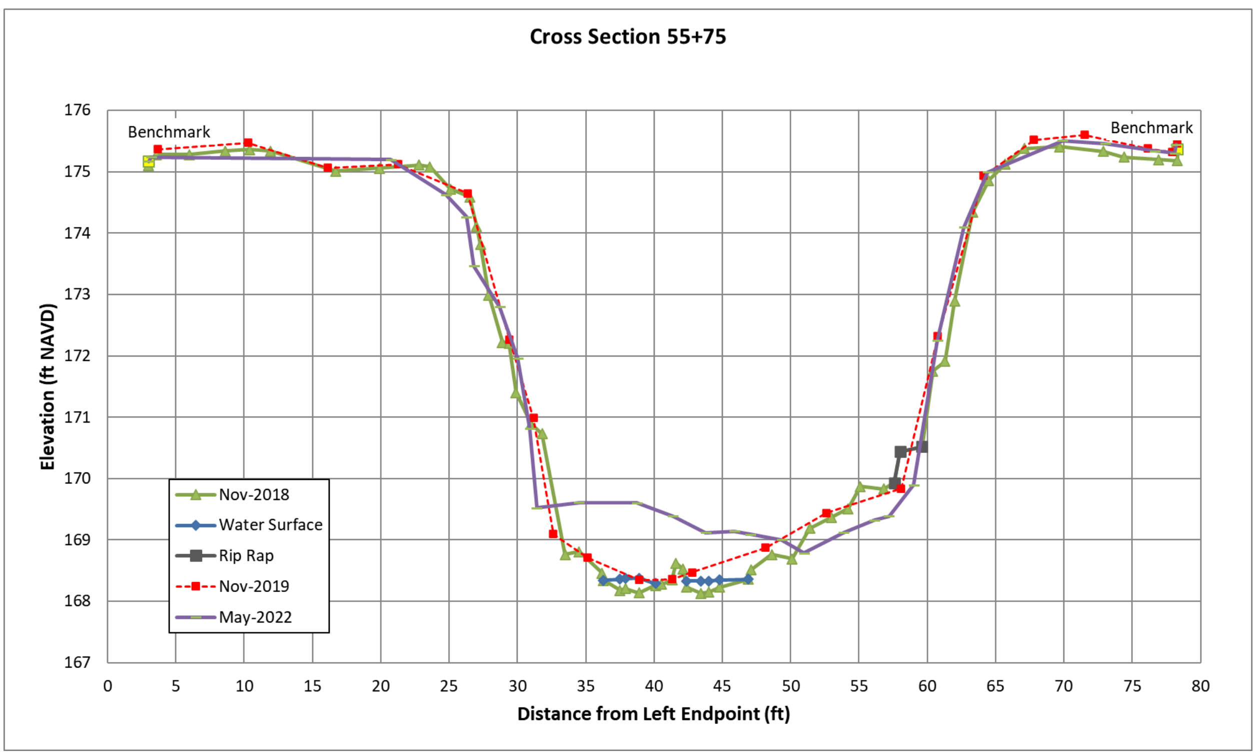

Cross Section 55+75
Benchmark
Benchmark
Elevation (ft NAVD)
Distance from Left Endpoint (ft)
Nov-2018
Water Surface
Rip Rap
Nov-2019
May-2022
176
175
174
173
172
171
170
169
168
167
0
5
10
15
20
25
30
35
40
45
50
55
60
65
70
75
80

Figure 9. Cross section data for XS 56+97 (top) and 55+75 (bottom)

In Figure 7, the right bank from which riprap R8 was removed (between stations 5900 and 5850 ft) has maintained the same shape since 2019, but it is now undercut. Only two of the four placed logs in the LWD5 constructed log jam remain. The two remaining logs are oriented in the flow direction and the cross section no longer has logs that span the channel (Figure A22 in Appendix A). The 2019 excavation at approximately station 5800 ft filled in and the bed of XS 58+29 reaggraded to 2018 elevations, except along the toe of the right bank, where a lateral pool occurs (Figure 8). With XS 57+41 showing deposition on the left and erosion of the upstream end of a constructed bar on the right, the bed at this location has returned to conditions similar to pre-intervention conditions. The left bank where the L10 riprap was removed is protected by the erosion control fabric, with a portion of the left bank cut at the toe (Figure A23). However, further downstream at XS 56+97, erosion of about 1 ft has occurred at the toe of the left bank where the erosion control fabric is also torn (Figure 9). The top of the bar (downstream of station 5700 ft) has also lowered by about 0.3 ft. The LWD4 is maintained in place by vertical pin logs. The longitudinal profile shows that the pool excavated in 2019 (station 5650 ft) at LWD4 filled up, but a new one has formed downstream (approx. station 5625 ft) along the toe of the left bank. This pool formed at the endpoint of the LWD4 logs and includes an undercut left bank (Figure 10).

Figure 10. Downstream view of the river approximately at station 5650 ft with LWD4 on the right and undercut bank on the left in the place where riprap L10 was removed.

At XS 55+75 (Figure 9), sediment deposition occurred from the left bank’s toe to 20 feet into the channel; then half a foot of erosion occurred near the toe of the right bank, where riprap R7 was removed. Some logs of the LWD3 were washed downstream, with one particularly long log remaining crosswise, likely stuck due to its length and the presence of a bend in the river (Figure 11). Here the pool dug in 2019 has expanded (station 5500 ft) and a second one formed further downstream (approx. station 5475 ft).

Figure 11. Downstream view approximately at station 5500 ft with one of the logs of LWD3 stuck against the left bank.

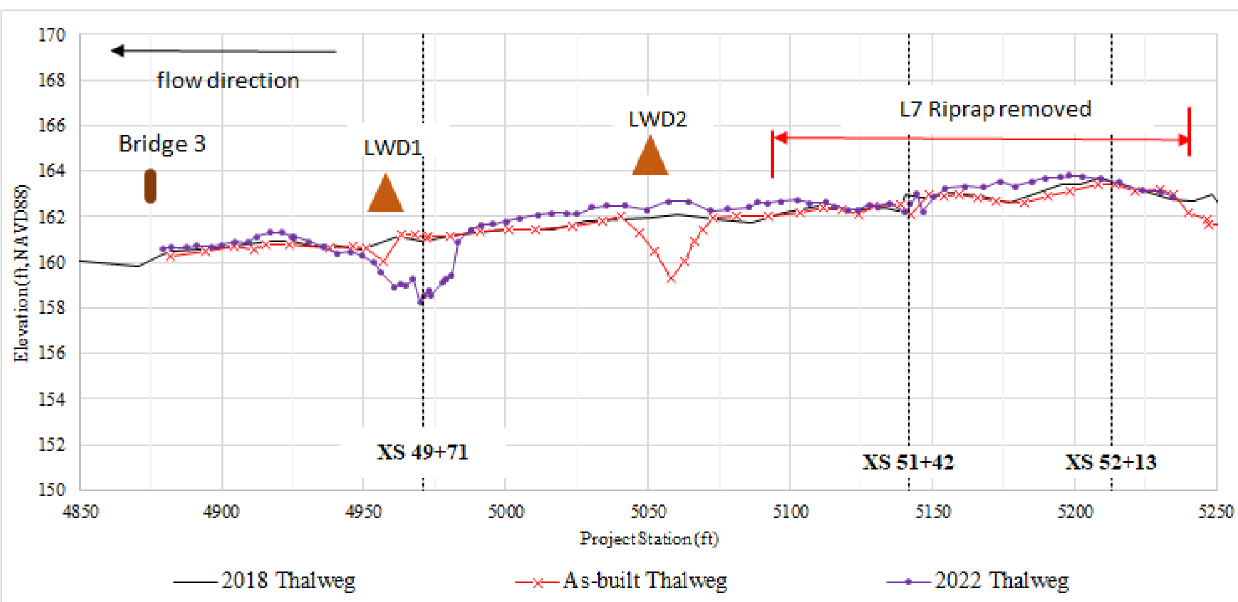
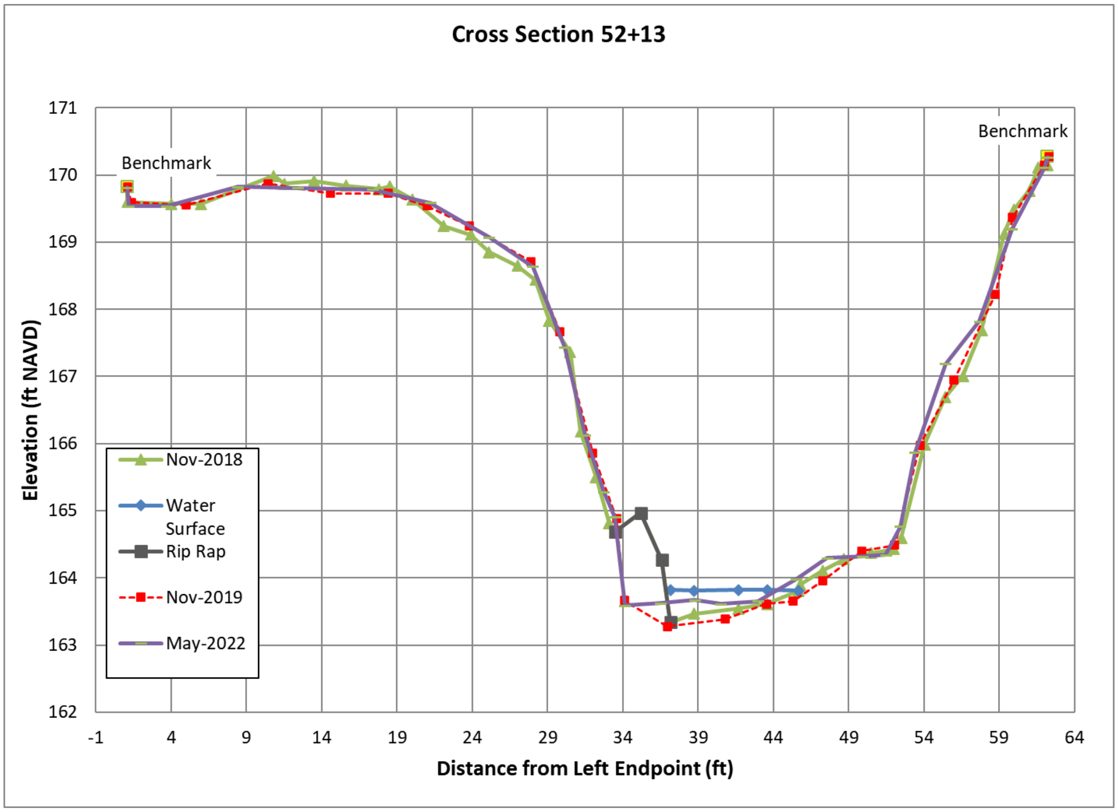


Figure 12. Thalweg profile through XS 49+71 and 52+13



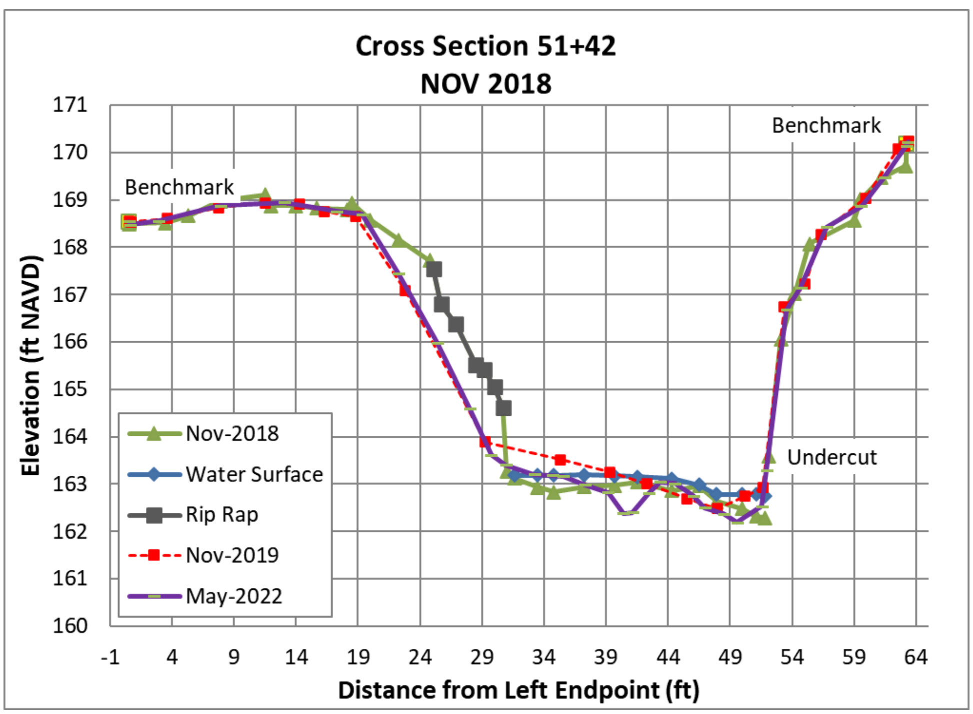


Figure 13. Cross section data for XS 52+13 (top) and 51+42 (bottom)

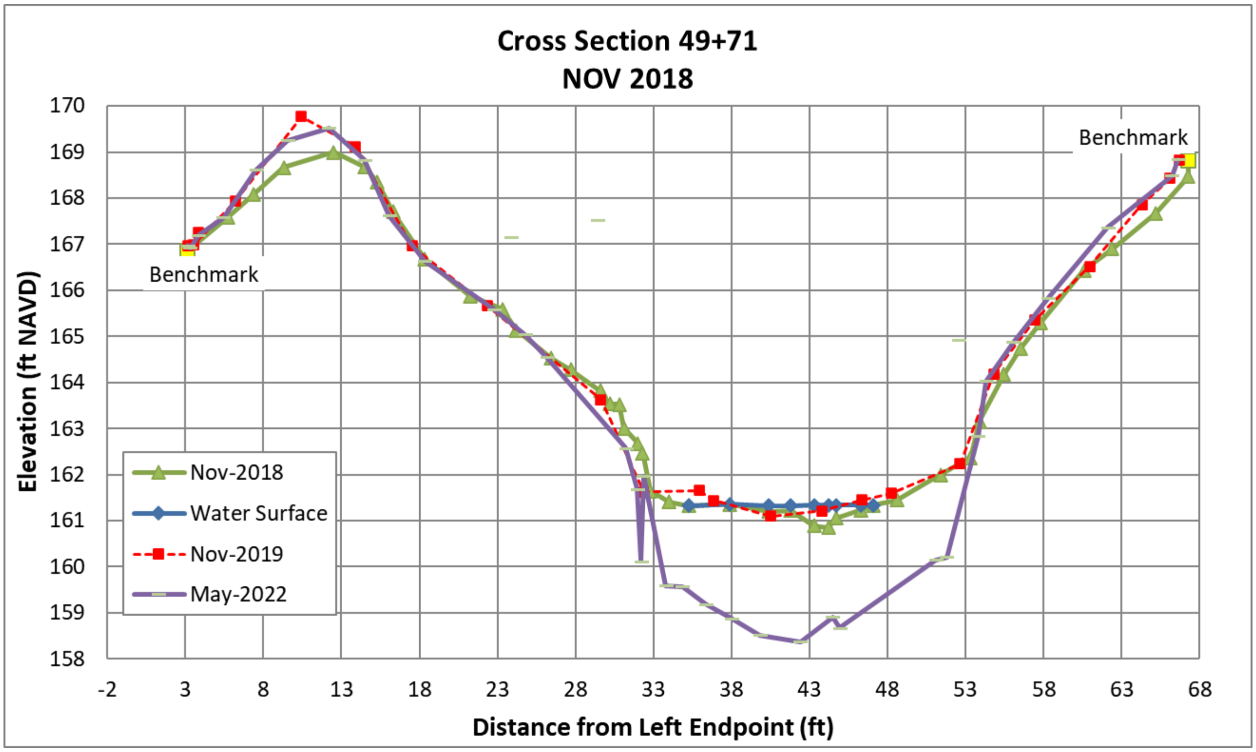


Figure 14. Cross section data for XS 49+71

In Figure 12, the section in the Cathedral Grove reach where the riprap L7 was removed (between project stations 5250 and 5100 ft) has slight bed aggradation. However, an area of minor bed scour is observed in the central part of XS 51+42. The logs in LWD2, which were not secured in place with pin logs, have either washed downstream or washed to the toe of the left bank. At station 5050 ft, a sediment deposit has filled the pool that was constructed under the logs of LWD2 in 2019. There is a little aggradation of the riverbed between stations 5050 and 5000 ft. The LWD1 log jam remained in place, due to a long redwood log that spans the channel. Its ability to trap wood had been augmented by some placed pieces under the spanner in 2019; many of those places moved but are still part of a log jam at that location. Some of the dislodged upstream logs accumulated in this section. This large log jam also retained many small branches (small woody debris). At approximately station 4975 upstream of LWD1, a small pool constructed in 2019 has deepened, widened and expanded laterally upstream. The XS

49+71 in Figure 14 shows erosion along the entire cross section with maximum depth of scour in the center of about 2.5 ft. (Pools would be deeper when water surface elevation is included). Downstream of the log jam, where no project actions were conducted, the riverbed retains the simplified channel bed of the pre-project conditions.

Riverbed sediment size changes in time

Figure 7 shows the longitudinal profile in this area, Figure 8 shows the XS 58+29 profile and Figure 9 shows XS 56+97. The facies map (Figure 16) shows patches 1, 5, and 8 are within the wetted channel. The pre-project configuration is reported in Figure 16. We identified a higher number of patches with a unique assemblage of grain sizes in the recent survey than in the pre-project condition. This reflects a higher complexity of the riverbed morphology and more diverse array of grain sizes.

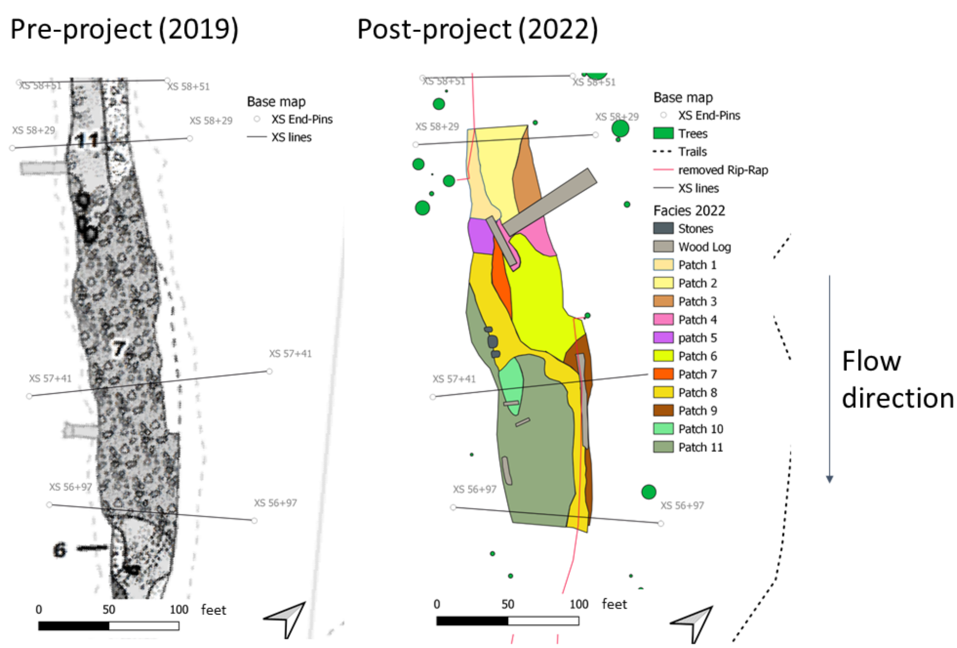


Figure 15. Pre-project facies map between XS 58+29 and XS 56+97 from the 2019 survey, from the NPS (2020), on the left, with annotations. Facies map from the 2022 survey, on the right.

On the map of Figure 16, the patches with the same D_{50} were grouped into a single unit. We used the same classes of D_{50} used in the pre-project analysis: sand (< 2 mm), very fine gravel (2-4 mm), fine gravel (4-8 mm), medium gravel (8-16 mm), coarse gravel (16-32 mm), and very coarse gravel (32-64 mm). Patches 4 and 5 had grain sizes that were too small to perform pebble counts, so we mapped these patches as sand.

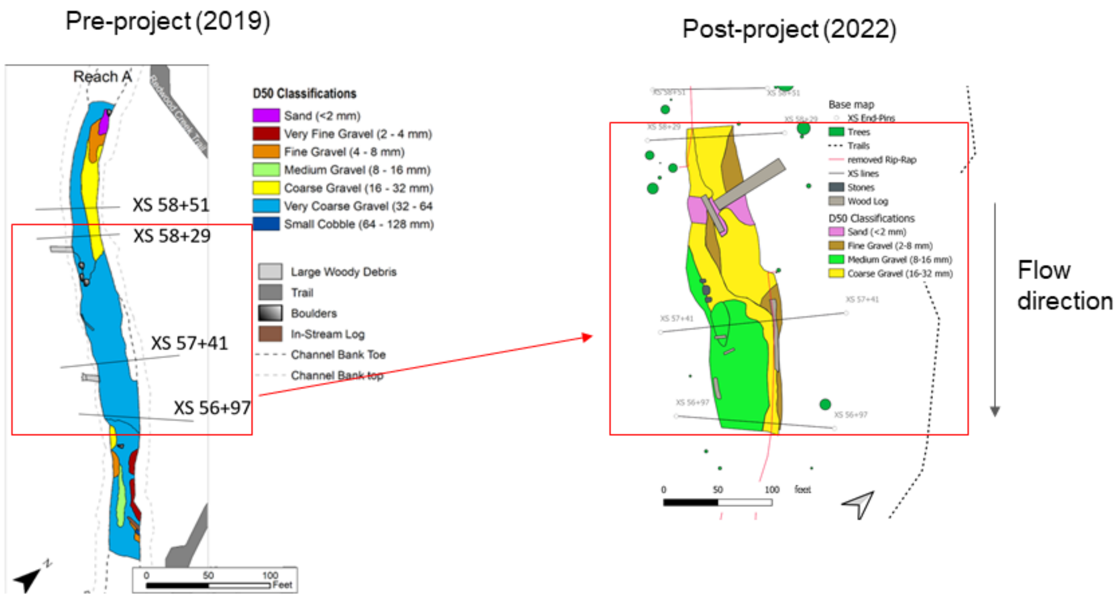


Figure 16. Comparison between D_{50} grain size map of the 2022 survey we completed and of the previous 2019 survey, adapted from Shoulders and Adams (2020)

We mapped four classes of D_{50} in the subreach we surveyed. In the pre-project condition, there were only two classes and the sediments were generally coarser than the pre-project patches. In particular, we can see the onset of areas of sand and fine gravel close to the LWD. Areas formerly with very coarse class sediments now have finer sediments, and the very coarse class is no longer present.

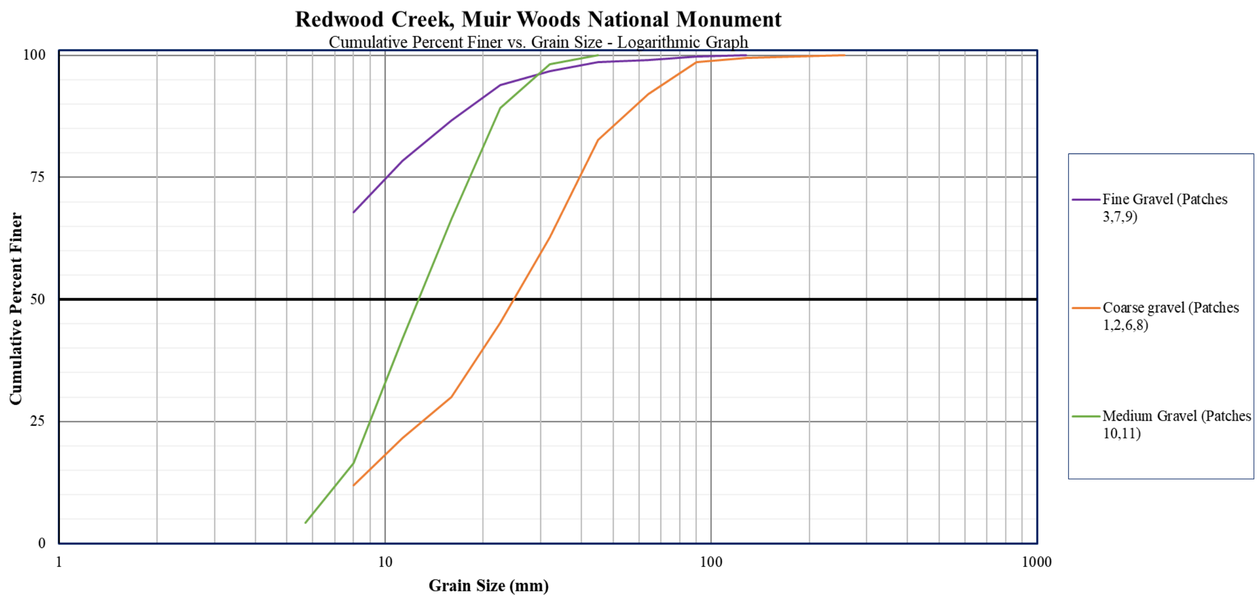


Figure 17. Sediment Size Distribution in 2022 subreach

On Figure 17, we report the grain size distribution curves obtained by pebble counts. We combined the patches with the same D50 classification and assumed they belonged to the same patch. Pebble counts conducted on all patches except for 10 and 11 do not measure sediments below 8 mm due to the limitations of our equipment. The orange line indicates that the D_{50} class corresponds to coarse gravel, the green lines indicate a D_{50} sediment class of medium gravel, and the purple lines indicate a D_{50} sediment class of fine gravel.

Changes of riverbed geomorphic features in time

Figure 18 illustrates the geomorphic map of Redwood Creek from XS 58+51 to XS 56+97. The 2022 geomorphic map of the reach contains two shallow pools, several logs, significant undercut banks on the right downstream side, large gravel beds, some small woody debris and a low flow channel meandering from the right bank to the left. At some points, the undercut bank reached more than 30 cm deep, and provided protected habitat with the shallow pool beneath it. The small woody debris (SWD) downstream of the logs also creates a shallow pool habitat. The position of the LWD compared to as-builts of the LWD shows the creek flows pushed the logs downstream.

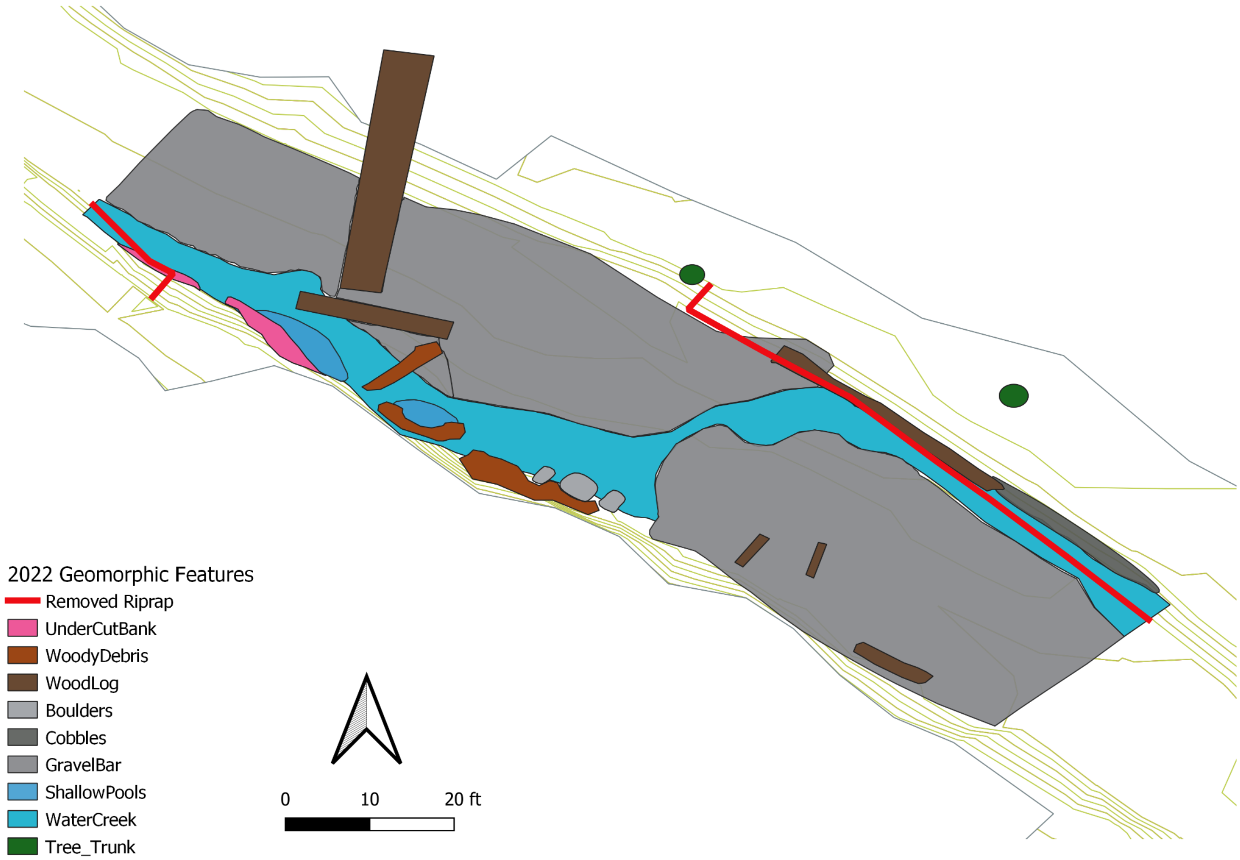


Figure 18. 2022 Geomorphic Features

The 2015 geomorphic map in Figure 19 contains two long shallow pools, some LWD, a small undercut bank on the right downstream side, smaller gravel beds, some small woody debris and a low flow channel hugging the right bank, without a meander.

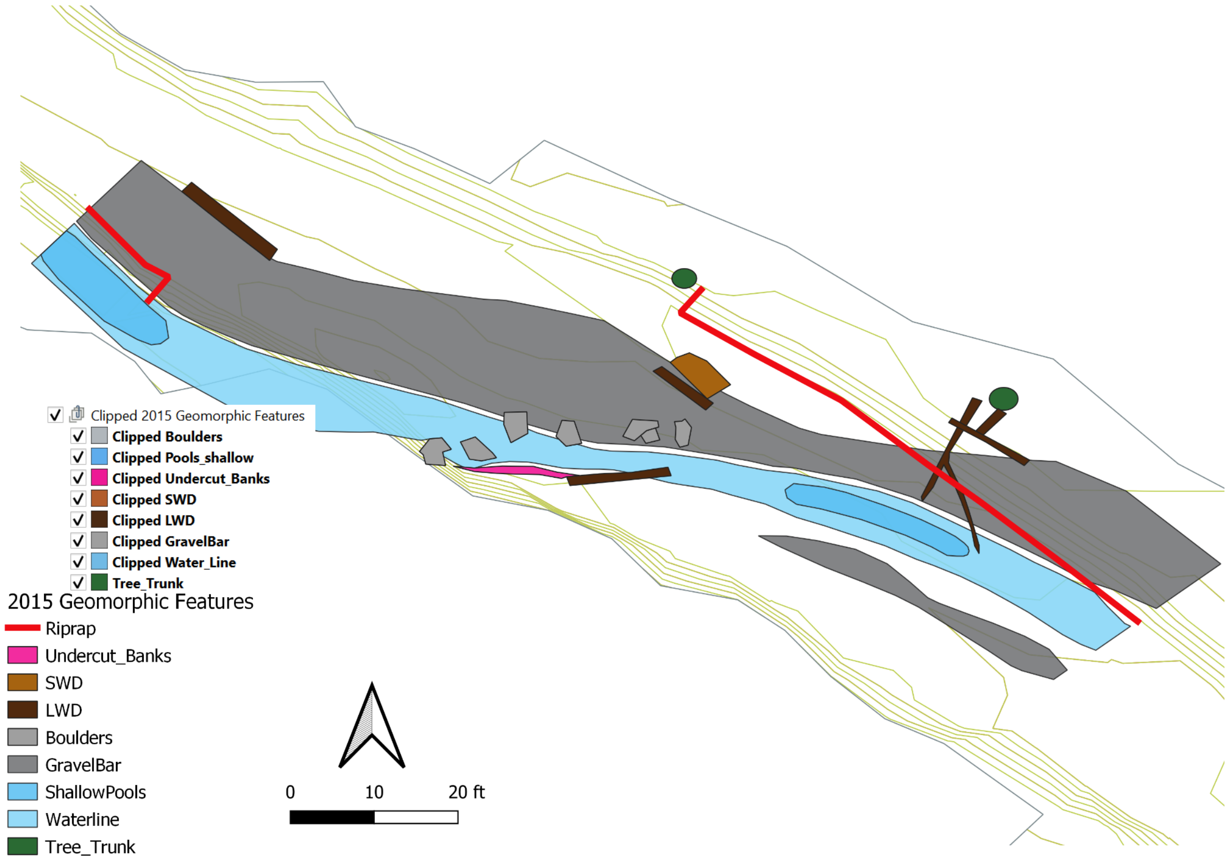


Figure 19. 2015 Geomorphic Features (Allison 2015)

To compare the geomorphic changes since 2015, Table 1 below shows a qualitative comparison of several important features for river complexity. Indicators of a more complex river reach include deposits of gravel bars, larger pools and undercut banks for habitat creation, and significant LWD and SWD. In almost every geomorphic feature category, the feature area from the 2022 map was larger than the 2015 map area. However, in 2022 the river reach had smaller areal extent of pools than in 2015. Despite having smaller areas, the newly formed pools observed in 2022 were slightly deeper than pre-project pools shown in the 2018 thalweg profile (Figure 7). Moreover, this pool extends below the undercut bank, a feature that makes the habitat particularly favorable.

Table 1. Geomorphic Features Comparison

Geomorphic Feature	2015	2022
Gravel Bars	Less gravel accumulation near left bank, but it could not be fully mapped	More gravel area on either side of the channel, but this may be due to overall channel widening
Shallow Pools	Longer pools	Shorter pools formed recently by LWD and SWD
LWD	A few logs of similar size, one located within the water channel	Several logs of various sizes, two located within the water channel
SWD	One region of small woody debris, far from the water channel	Significant small woody debris near pools in water channel
Undercut Banks	Minimal undercut bank on the right bank	Increased undercut right bank connected to pool

Discussion

Riverbed elevation analysis

The surveys performed in October and November 2022 found that nearly all existing LWD structures have pools in close proximity that form suitable habitat for the target species (Figure A19). Generally the pools are below the logs if they span the entire channel, or downstream of one end of the log for those not crossing the entire channel. Pools formed below logs (e.g. LWD6 and LWD1) have the advantage of being covered and thus can be particularly useful as refuge habitat. Several logs placed as LWD installed in 2019 which were not pinned in place at the time have been relocated by the peak flow that occurred in 2021. Of the seven LWD structures analyzed, two were secured in place by vertical pin logs, and they remained in place albeit losing a few pieces (LWD6 in Figure A21 and LWD7 in Figure A20). In contrast, two unpinned LWD structures lost several pieces that drifted slightly downstream (LWD5 in Figure A22 and LWD4 in Figure A23). In one case a particularly long log got stuck against a bank

(LWD3 in Figure A24), while another case saw all the logs dragged away (LWD2 in Figure A25). Finally, just upstream of Bridge 3, where a naturally occurring redwood log spans the channel from bank top to bank top but does not touch the channel bed, wood had been added in 2019 to increase the trapping ability of the log structure. In the October 2021 event, this structure (LWD1 in Figure A26) trapped both large and small diameter logs that had been placed upstream, forming a mechanism for bed scour with substantial cover. The last case is probably a natural condition for rivers flowing through redwood forests under undisturbed conditions as observed, for example, in some sections of Redwood National Park. The observed log mobility seems to align with the findings from Gurnell at Al. (2002). The displacement of the LWD logs raises the question of the durability of the project. In the case of LWD being completely removed (e.g. LDW2), the pool was filled up and the bed had regained its pre-project shape. In the case of log rearrangement, the pools migrated downstream with the log end points (e.g. LWD5 and LDW4). Therefore, local shifts are not a problem while complete removal may result in reduced effectiveness of the restoration in a particular subreach. However, the mobilized woody debris may improve channel conditions in a new location downstream, thus still meeting the NPS goal of increasing overall channel complexity.

Riprap removal has also improved the morphological quality of the stream. Some of the banks where NPS removed riprap now have covered pools at the toe of their undercut banks. The best results occurred where LWD was on one side of the cross section and riprap was removed on the opposite side. In this configuration, the flow eroded on the side opposite the LWD, creating a pool and undercutting the bank. The geomorphic map in Figure 12 offers an example of this configuration. We found that it is particularly effective to carry out LWD creation and riprap removal in the same reach. Thus, we recommend for the NPS to continue these practices in the next phases of the restoration project where possible. However, we understand the limitations of available logs and accessible equipment in Muir Woods. With the small, narrow, and steep sides of Muir Woods surrounding Redwood Creek, the NPS can not move logs easily to any design location in the Phase 1 reach, therefore the placement of LWD and riprap removal may not always occur in the same subreach.

The 2019 work also included a regrading of the riverbed with the excavation of some pools. Since then, some of the pools have been partially or completely filled (Figures 3, 5, 7 and 12). In several cases immediately downstream, new pools were scoured by high flows. In one case of riprap removal without pool excavation, the riverbed did not change significantly (e.g. L12 and L7), whereas in the case of riprap removal with associated pool excavation a process of morphological change was triggered, with pool filling, pool excavation further downstream, and alternate undercut banks in the right and left (e.g. L13, L10 and R7). This could lead over time to a more sinuous planform.

When we spoke to the NPS, they explained that they knew the pools excavated in 2019 would be altered by the flow but needed to provide short-term habitat for juvenile coho habitat until the next large storm event after restoration. Since this type of larger storm took place two years after implementation, the NPS were able to provide sufficient habitat for at least two cohorts of juvenile coho salmon. Therefore, while excavating pools below LWD placements may seem unnecessary in aiding the long term goal of pool formation from high flow events, the short term benefits of such excavations still have merit.

Sediment size analysis

We found that the average sediment size of the recently surveyed patches ranged from very fine gravel to medium gravel. Before the project, the most common average sediment size for the patches in the same area was very coarse gravel. When the sediment deposit at XS 57+41 was shoveled, the sediment under the fine gravel was substantially coarser (Figure A7), which means that the finer sediment likely deposited on top of the original coarse sediment. Additionally, we observed that sandy patches formed in the subreach close to the LWD. We can deduce that LWD setting and riprap removal increased the flow resistance and resulted in the deposition of finer sediment fractions and increased complexity of the sediment size variation. Increasing the complexity of sediments in the channel creates suitable conditions for habitat creation of the target species. Sediment variation was not an intended objective for the original project, however, the variation was induced by natural processes, which was a restoration objective. The observed deposition would suggest that channel aggradation will potentially continue, which would be a beneficial outcome for an incised channel.

Geomorphic habitat creation analysis

The comparison between geomorphic features of a short subreach in 2015 (pre-project condition) and 2022 (post-project condition) showed an increase in river complexity. Since 2015, the undercut banks have grown, the woody debris has provided new habitat pools, the water shows a more sinuous shape, and gravel bars are wider. The slightly deeper pools connected to significantly undercut banks creates useful covered refugia habitat for juvenile coho. This increased morphological complexity in the short subreach suggests that NPS restoration efforts may have successfully improved Redwood Creek’s coho salmon habitat. We recommend for the NPS to extend the geomorphic mapping over the whole phase 1 reach for a complete comparison.

Conclusion

The NPS surveys and our field mapping shows that the complexity of the riverbed has increased after the 2019 river restoration intervention. The restoration led to new pools forming and some previous pools to grow deeper, which improved the availability of refuge habitat during summer droughts and winter floods. Moreover, many of the banks are undercut, thus offering suitable covered habitat. In many stretches a newly defined low flow channel flows close to the toe of the bank alternating right and left turns, showing a possible tendency to create a more sinuous layout. The representative sediment size on the sampled subreach changed from very coarse gravel to a combination of sand and medium gravel. This indicates an improvement in channel sediment deposition, a beneficial outcome in an incised reach. With greater morphological variation, fine sediments are no longer washed out of the reach. From the observed results, the 2019 Phase 1 restoration of Redwood Creek has successfully improved habitat for coho populations and increased river complexity thus far. In particular, we observed that the combination of riprap removal and addition of LWD in the same section yielded the best results. Regarding the possible displacement of logs by the flow, an attempt could be made to identify the ideal size of logs that become embedded in the river allowing their longer-lasting presence in the restored stretch.

Acknowledgements

Thank you to Carolyn Shoulders and the National Park Service for providing our team with all the necessary reports, data, maps, and resources to conduct our Redwood Creek analysis. We would also like to thank Hozefa Haidery for not only assisting in pebble counts and in-field geomorphic mapping, but also for drawing the geomorphic features in AutoCAD so that they could be mapped in QGIS. Finally, thank you to Kirstin Weeks for joining our team in the field to collect pebble count data and map geomorphic features along Redwood Creek.

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Appendix A - Cross Section Fact Sheets

Fact sheet – cross section 66+26

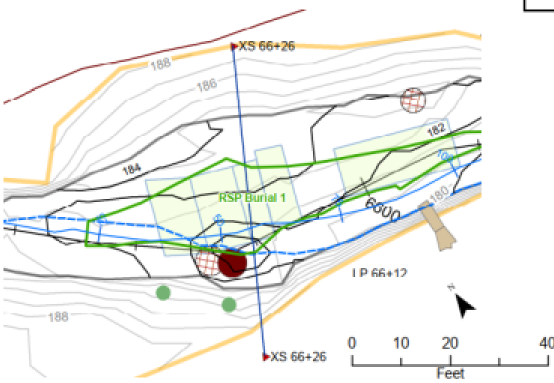

Fig. A1.1: Excerpt from the Northern Hydrology and Engineering (NHE) project plan (2019)

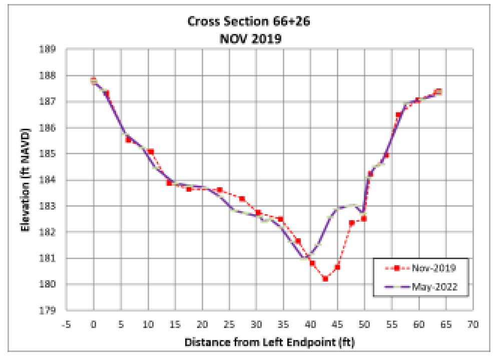

Fig. A1.2: Cross section profile

Fig. A1.3: View downstream, post-project

Fig. A1.4: Deposit's surface

Fig. A1.5: Underlying deposit

NOTES: there is a woody sediment stack in the hydraulic right immediately upstream of the section. Behind the stack is a lens of deposit with a maximum thickness of about 2 ft. The deposit has very fine sediments at the surface D50 < 2 mm (Figure A1.4). The sediments of the underlying layers (Fig. A1.5) show fine clay particles and decaying woody debris.

Figure A1. A collection of figures and graphs for cross section 66+26 with the profile measured in 2018 (before work), in 2019 (as-built condition), and in 2022 (post-event conditions)

Fact sheet – cross section 65+35

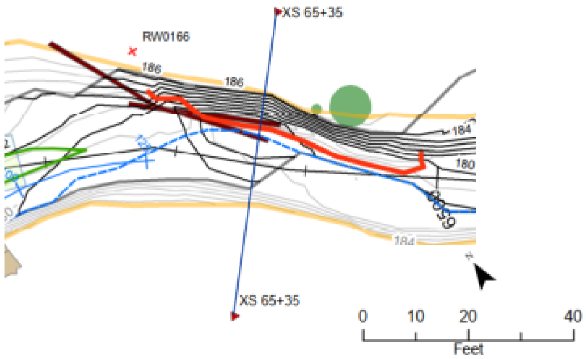

Fig. A2.1: Excerpt from the NHE project plan (2019)

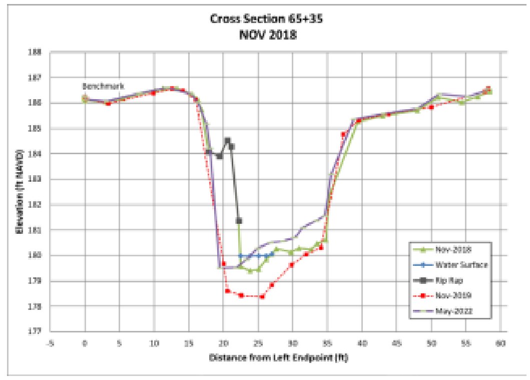

Fig. A2.2: Cross section profile

Fig. A2.3: View downstream, pre-project, National Park Service (NPS 2018)

Fig. A2.4: View downstream, post-project

Fig. A2.5: Deposit's surface

Fig. A2.6: Underlying deposit

NOTES: Rip-rap has been removed on the left in this section. The profile of the banks has not changed. A deposit about 1 foot thick has formed. Just upstream of the section, on the left, there is a small pile of branches and logs. It can be seen from the longitudinal profile that further downstream the bed elevation has lowered. In that area, there is a pool about 12 feet long and 7 feet wide. At the pool, the bank is undercut.

Figure A2. A collection of figures and graphs for cross section 65+35 with the profile measured in 2018 (before work), in 2019 (as-built condition), and in 2022 (post-event conditions)

Fact sheet – cross section 63+75

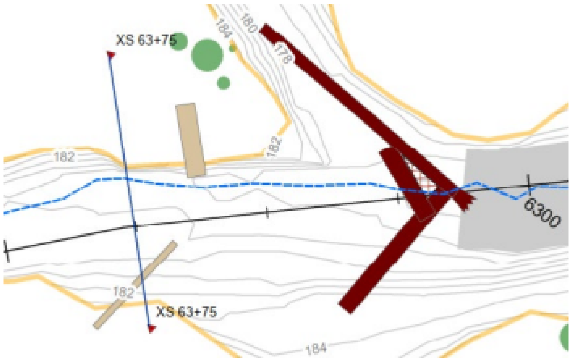

Fig. A3.1: Excerpt from the NHE project plan (2019)

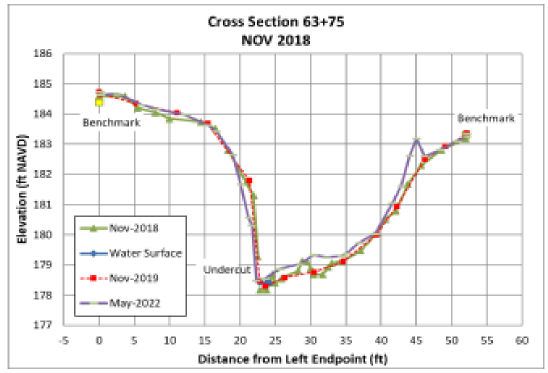

Fig. A3.2: Cross section profile

Fig. A3.3: View downstream, pre-project (NPS 2018)

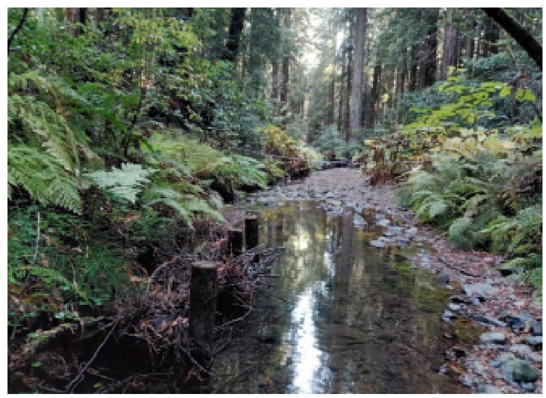

Fig. A3.4: View downstream, post-project

Fig. A3.5: Deposit's surface

NOTES: About 30 ft upstream of the section, on the left, a structure was created in 2019 to retain branches. The structure is stuck in the riverbed. The left bank is undercut from the structure to the section (Fig. A3.2). About 50 ft downstream there is a log jam (Fig. A4.3). In the section, there is a thin deposit of about 0.3 ft.

Figure A3. A collection of figures and graphs for cross section 63+75 with the profile measured in 2018 (before work), in 2019 (as-built condition), and in 2022 (post-event conditions)

Reach between cross sections 63+75 and 62+13

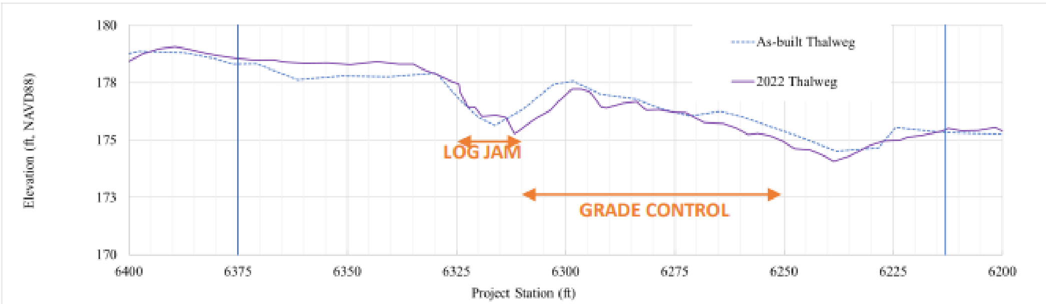

Fig. A4.1: Longitudinal profile

Fig. A4.2: Undercut bank (left side)

Fig. A4.3: Downstream view

Fig. A4.4: Log jam

Fig. A4.5: Bank erosion and pool (left side)

NOTES: At the log jam there is the junction of a tributary on the left. Immediately upstream of the log jam, there is a central bar with a lobe of sediment deposits (Fig A4.3). Of the three logs arranged in 2019, the middle one is missing. The logs are blocked by poles and retain branches. On the left downstream of the log there is bank erosion and a deep pool (Fig A4.4 and Fig. A4.5). Downstream there is a grade control structure at the end of which there is a large pool about 1.4 ft deep.

Figure A4. A collection of figures and graphs for the reach between cross sections 63+75 and 62+13 with the profile measured in 2018 (before work), in 2019 (as-built condition), and in 2022 (post-event conditions)

Fact sheet – cross section 62+13

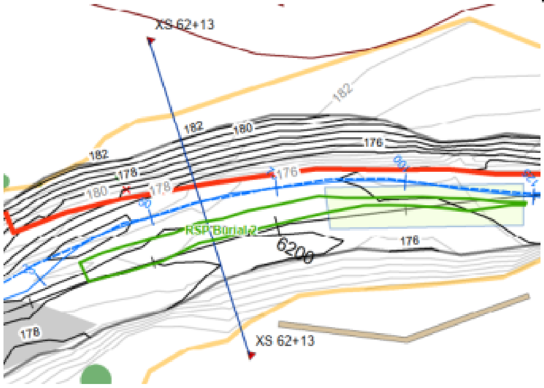

Fig. A5.1: Excerpt from the NHE project plan (2019)

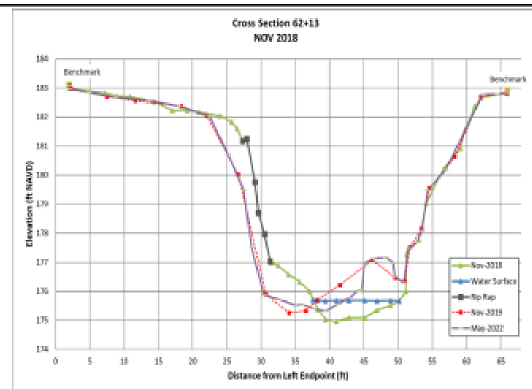

Fig. A5.2: Cross section profile

Fig. A5.3: View upstream, pre-project (NPS 2018)

Fig. A5.4: View upstream, post-project

Fig. A5.5: Deposit's surface

NOTES: Rip-rap has been removed on the left in this section. The bank has maintained its shape since 2019. The section has had erosion in the central part. The bar laterally to the right has widened. An incision remains in contact with the right bank.

Figure A5. A collection of figures and graphs for cross section 62+13 with the profile measured in 2018 (before work), in 2019 (as-built condition), and in 2022 (post-event conditions)

Fact sheet – cross section 58+29

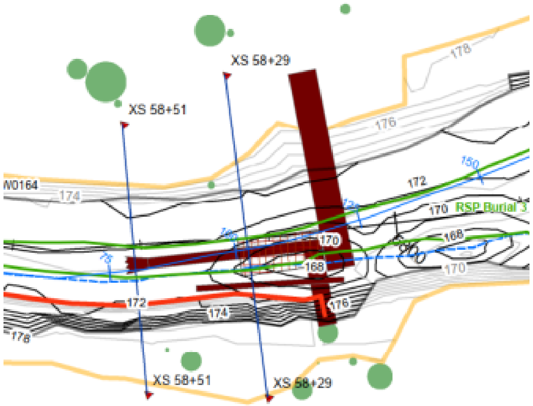

Fig. A6.1: Excerpt from the NHE project plan (2019)

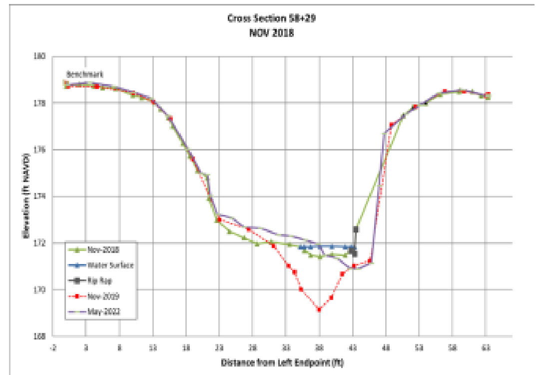

Fig. A6.2: Cross section profile


Fig. A6.3: View downstream, pre-project (NPS 2018)


Fig. A6.4: View downstream, post-project

Fig. A6.5: Deposit's surface

Fig. A6.6: Underlying deposit

NOTES: The log jam arranged in 2019 was displaced, the remaining logs are oriented in the flow direction. The 2019 excavation was filled in and the section resumed shape like 2018 except for a lower elevation portion at the right bank. In the right the rip-rap was removed, and the bank has kept the shape given in 2019. The right bank is undercut.

Figure A6. A collection of figures and graphs for cross section 58+29 with the profile measured in 2018 (before work), in 2019 (as-built condition), and in 2022 (post-event conditions)

Fact sheet – cross section 57+41

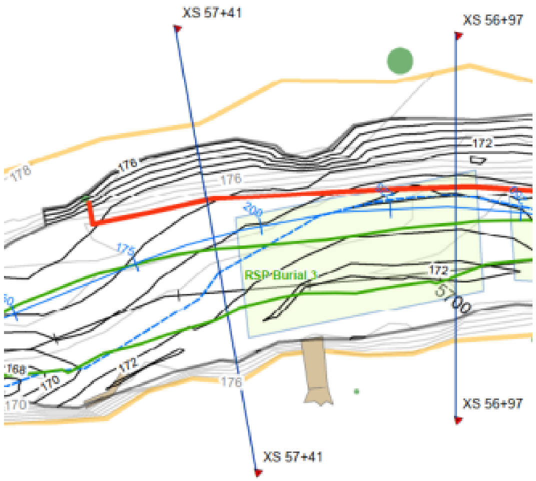

Fig. A7.1: Excerpt from the NHE project plan (2019)

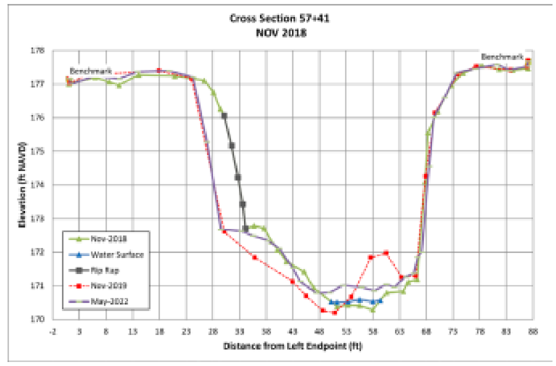

Fig. A7.2: Cross section profile

Fig. A7.3: View toward the left bank, pre-project (NPS 2018)

Fig. A7.4: View toward the left bank, post-project

Fig. A7.5: Deposit's surface on the left close to the log

Fig. A7.6: Underlying deposit on the bar

NOTES: Rip-rap was removed on the left. The bank has the same shape given in 2009. On the riverbed there is deposition on the left and erosion on the right, it seems the shape has returned to something like the pre-intervention situation (2008, see Fig. A7.4). The deposit has finer sediments at the surface on the left and coarser sediments on the right.

Figure A7. A collection of figures and graphs for cross section 57+41 with the profile measured in 2018 (before work), in 2019 (as-built condition), and in 2022 (post-event conditions)

Fact sheet – cross section 56+97

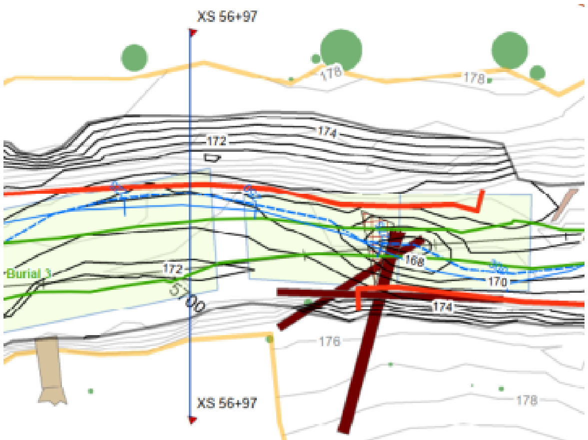

Fig. A8.1: Excerpt from the NHE project plan (2019)

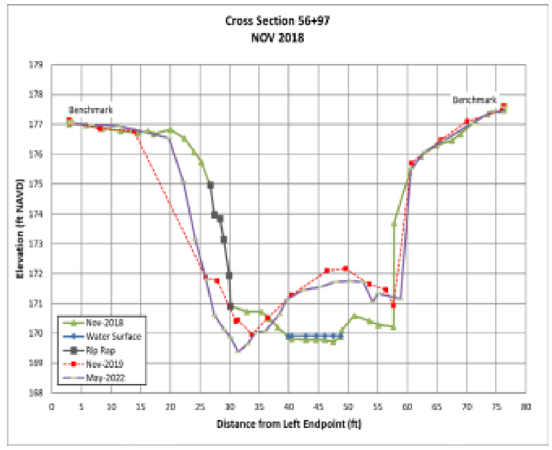

Fig. A8.2: Cross section profile

Fig. A8.3: View downstream, pre-project (NPS 2018)

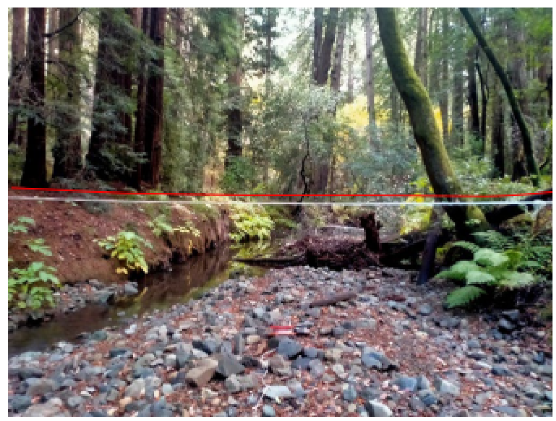

Fig. A8.4: View downstream, post-project

NOTES: The rip-rap was removed on the left and the bank was reshaped. The 2019 and 2022 left bank profiles do not match, probably this is because fewer points were surveyed in 2019. Erosion of about 1 ft has occurred at the toe of the left bank, the erosion control fabric is cut. The top of the bar has also lowered by about 0.3 ft.

Figure A8. A collection of figures and graphs for cross section 56+97 with the profile measured in 2018 (before work), in 2019 (as-built condition), and in 2022 (post-event conditions)

Reach between cross sections 56+97 and 55+75

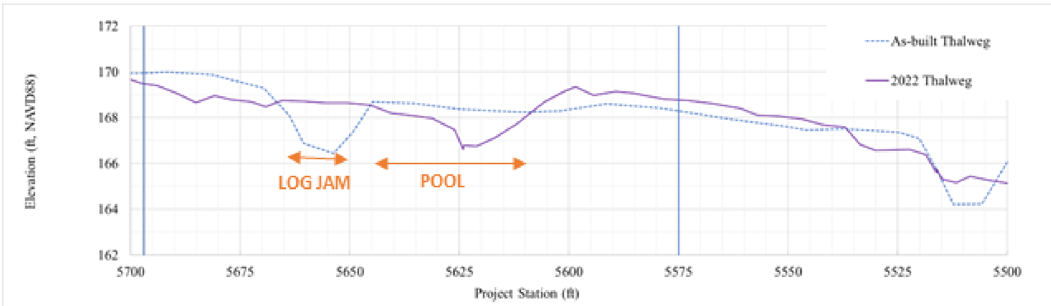

Fig. A9.1: Longitudinal profile

Fig. A9.2: Log jam (downstream view)

Fig. A9.3: Deep pool and bank erosion

Fig. A9.4: Log jam (downstream view)

NOTES: The log jam has been modified; some logs are absent. Branches have been retained. A pool occupies the left half of the riverbed for a length of about 30 ft. The maximum depth in the central part is about 2 ft.

Figure A9. A collection of figures and graphs for the reach between cross sections 56+97 and 55+75 with the profile measured in 2018 (before work), in 2019 (as-built condition), and in 2022 (post-event conditions)

Fact sheet – cross section 55+75

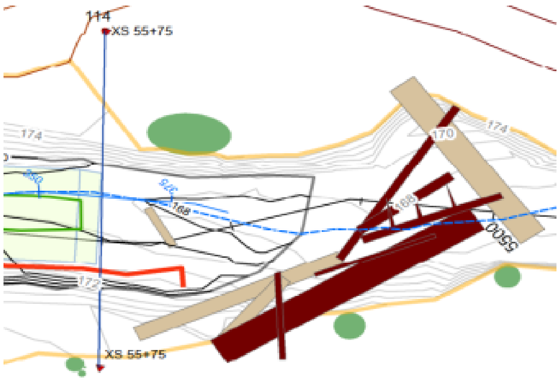

Fig. A10.1: Excerpt from the NHE project plan (2019)

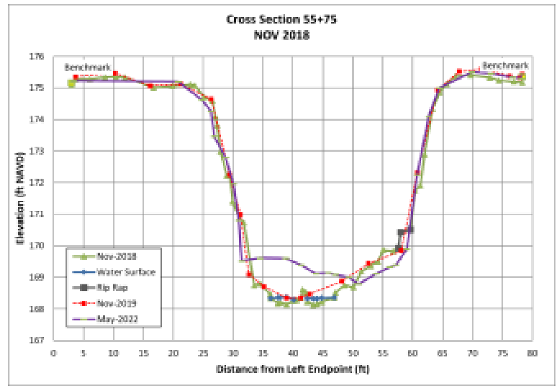

Fig. A10.2: Cross section profile

Fig. A10.3: View downstream, pre-project (NPS 2018)

Fig. A10.4: View downstream, post-project

Fig. A10.5: Deposit's surface

Fig. A10.6: Underlying deposit

NOTES: The cross-section has formed a deposit of about 1 ft. In the middle and left part of the section and erosion about 0.5 ft. at the foot of the right bank.

Figure A10. A collection of figures and graphs for cross section 55+75 with the profile measured in 2018 (before work), in 2019 (as-built condition), and in 2022 (post-event conditions)

Reach between cross sections 55+75 and 52+13

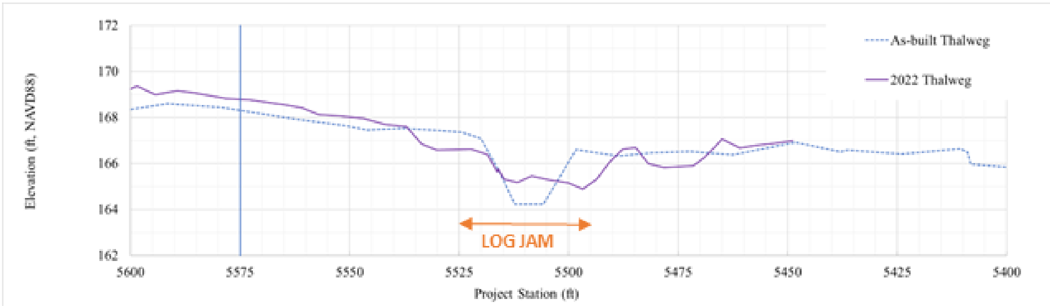

Fig. A11.1: Longitudinal profile

Fig. A11.2: Log jam (downstream view)

Fig. A11.3: Log jam (view toward the right bank)

Fig. A11.4: Pool and undercut bank (view toward the right bank)

NOTES: Logs have been moved and oriented in the direction of the flow. Some logs are missing. A pool has formed at the log jam and another further downstream. The right bank is undercut for a long stretch.

Figure A11. A collection of figures and graphs for the reach between cross sections 55+75 and 52+13 with the profile measured in 2018 (before work), in 2019 (as-built condition), and in 2022 (post-event conditions)

Fact sheet – cross section 52+13

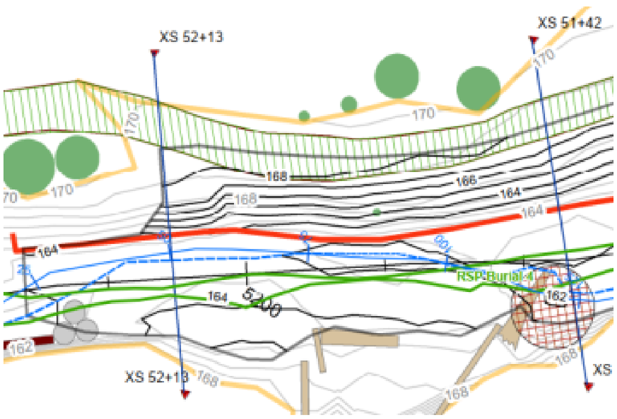

Fig. A12.1: Excerpt from the NHE project plan (2019)

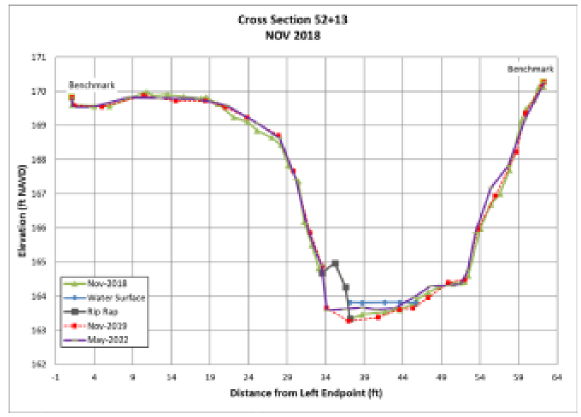

Fig. A12.2: Cross section profile

Fig. A12.3: View downstream, pre-project (NPS 2018)

Fig. A12.4: View downstream, post-project

NOTES: There appear to be no significant changes from 2019, other than placement of large woody debris.

Figure A12. A collection of figures and graphs for cross section 52+13 with the profile measured in 2018 (before work), in 2019 (as-built condition), and in 2022 (post-event conditions)

Fact sheet – cross section 51+42

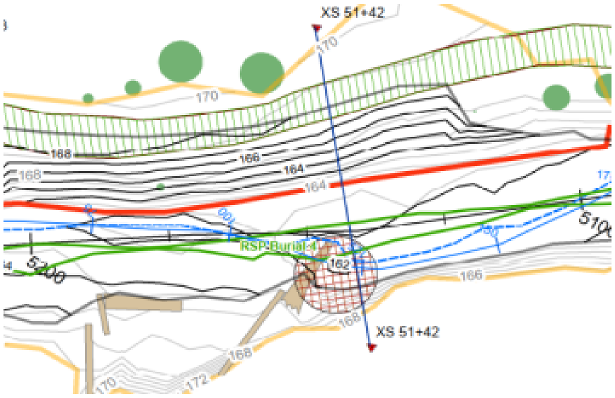

Fig. A13.1: Excerpt from the NHE project plan (2019)

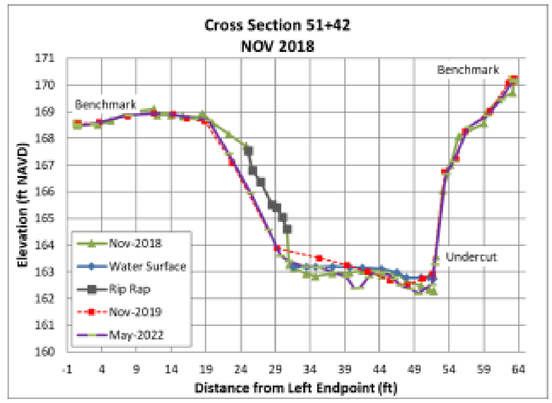

Fig. A13.2: Cross section profile

Fig. A13.3: View downstream, pre-project (NPS 2018)

Fig. A13.4: View downstream, post-project

NOTES: The banks have not changed from 2019. The riverbed has slightly lowered (about 0.5 ft). Erosion is more pronounced in the center and on the right side. The right bank is undercut.

Figure A13. A collection of figures and graphs for cross section 51+42 with the profile measured in 2018 (before work), in 2019 (as-built condition), and in 2022 (post-event conditions)

Reach between cross sections 51+42 and 49+71

Fig. A14.1: Longitudinal profile

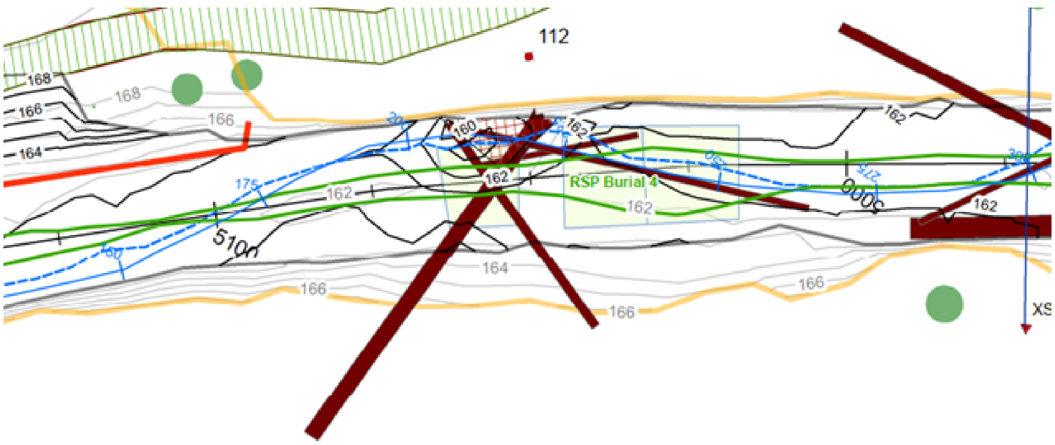

Fig. A14.2: Excerpt from the NHE project plan (2019)

NOTES: Logs have been removed, only one log is left sitting on the toe of the bank. A sediment deposit filled the hole that in 2019 was under the logs

Figure A14. A collection of figures and graphs for the reach between cross sections 51+42 and 49+71 with the profile measured in 2018 (before work), in 2019 (as-built condition), and in 2022 (post-event conditions)

Fact sheet – cross section 49+71

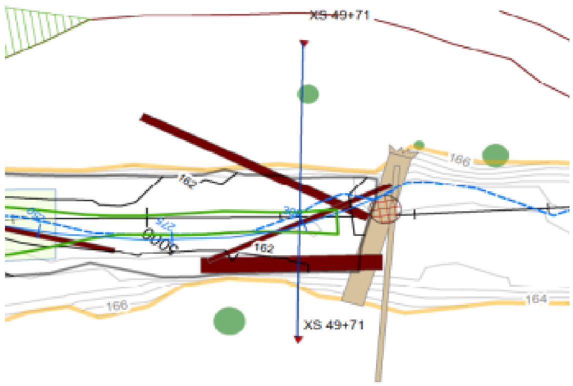

Fig. A15.1: Excerpt from the NHE project plan (2019)

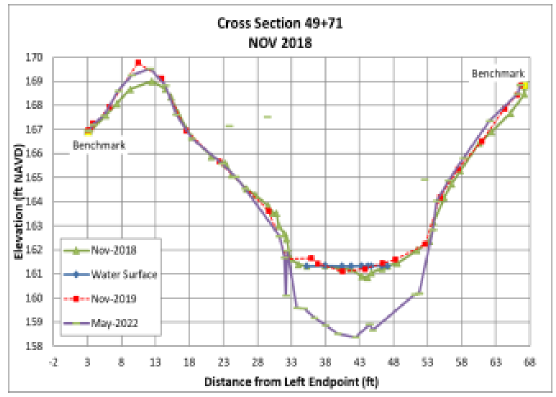

Fig. A15.2: Cross section profile

Fig. A15.3: View downstream, pre-project (NPS 2018)

Fig. A15.4: View downstream, post-project

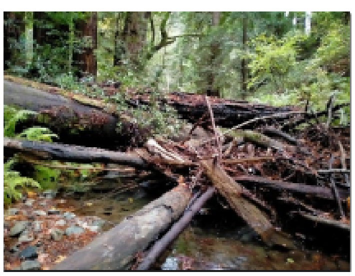

Fig. A15.5: Log jam

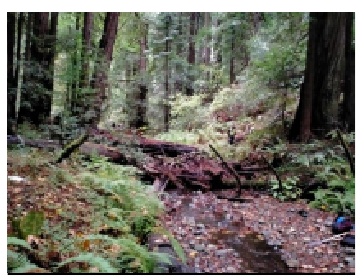

Fig. A15.6: Log jam

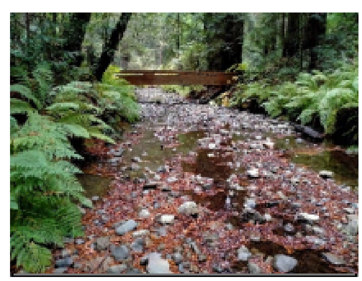

Fig. A15.7: Downstream reach of the log jam and bridge 3

NOTES: Some of the logs washed out from upstream have accumulated in this section. The log jam also retained many branches. There is erosion along the entire cross-section width with maximum thickness in the center being about 2.5 ft. Downstream of the log jam the riverbed has a simplified shape.

Figure A15. A collection of figures and graphs for cross section 49+71 with the profile measured in 2018 (before work), in 2019 (as-built condition), and in 2022 (post-event conditions)

Figure A16. XS 58+29

Figure A17. Downstream of XS 58+29 logs

Figure A18. Boulders by XS 57+44

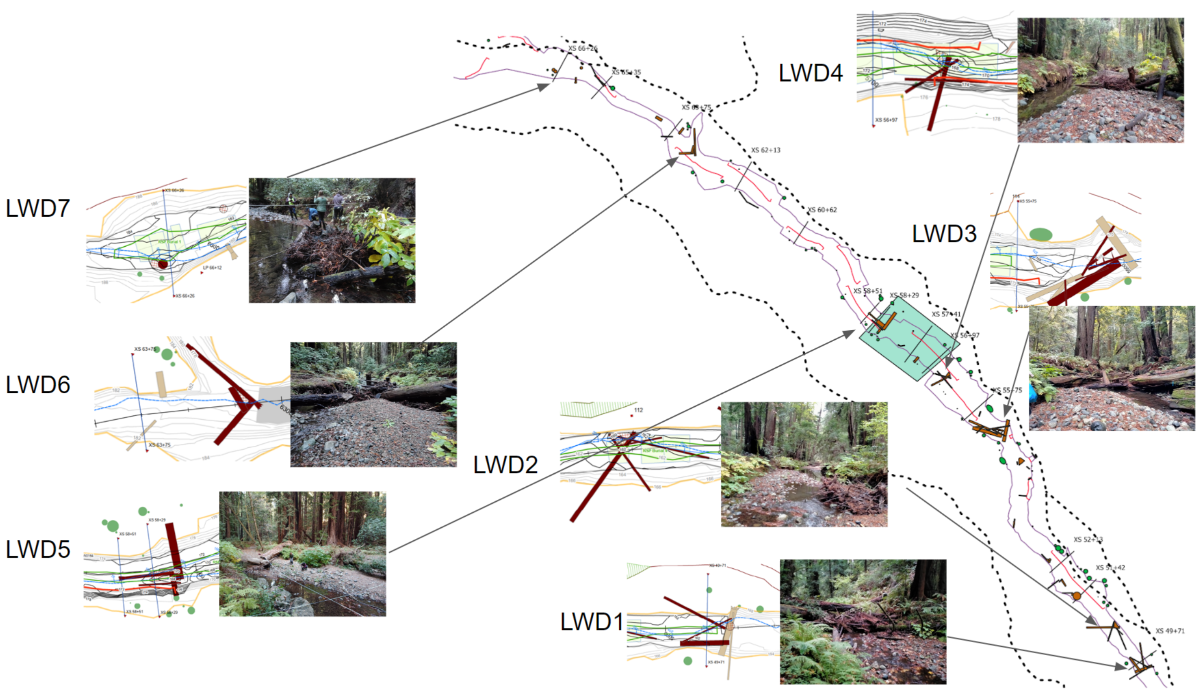

Figure A19. Large Woody Debris Placements

Figure A20. LWD7 as-built (Northern Hydrology and Engineering 2019) vs 2022 photo

Figure A21. LWD6 as-built (NHE 2019) vs 2022 photo

Figure A22. LWD5 as-built (NHE 2019) vs 2022 photo

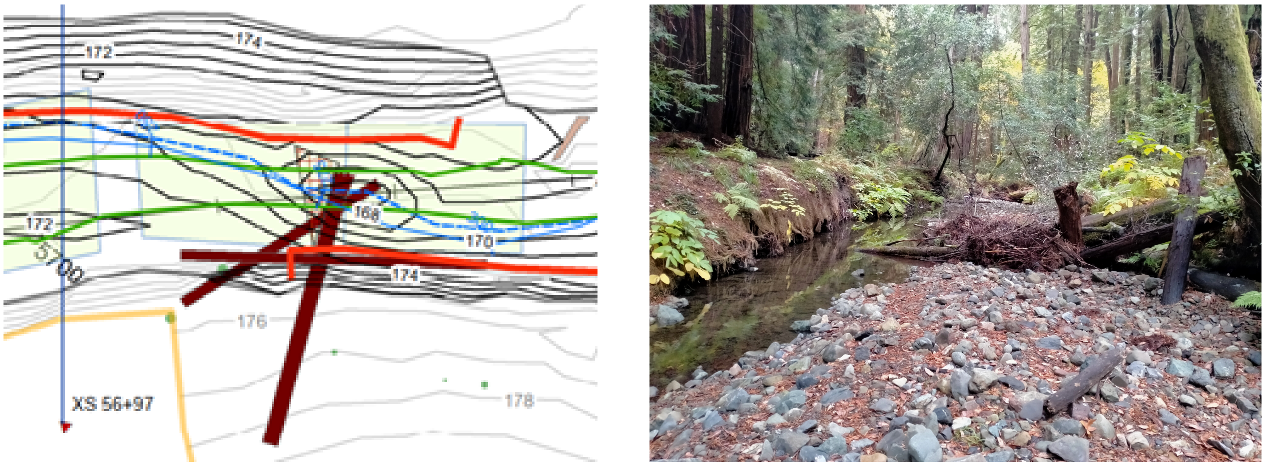

Figure A23. LWD4 as-built (NHE 2019) vs 2022 photo

Figure A24. LWD3 as-built (NHE 2019) vs 2022 photo

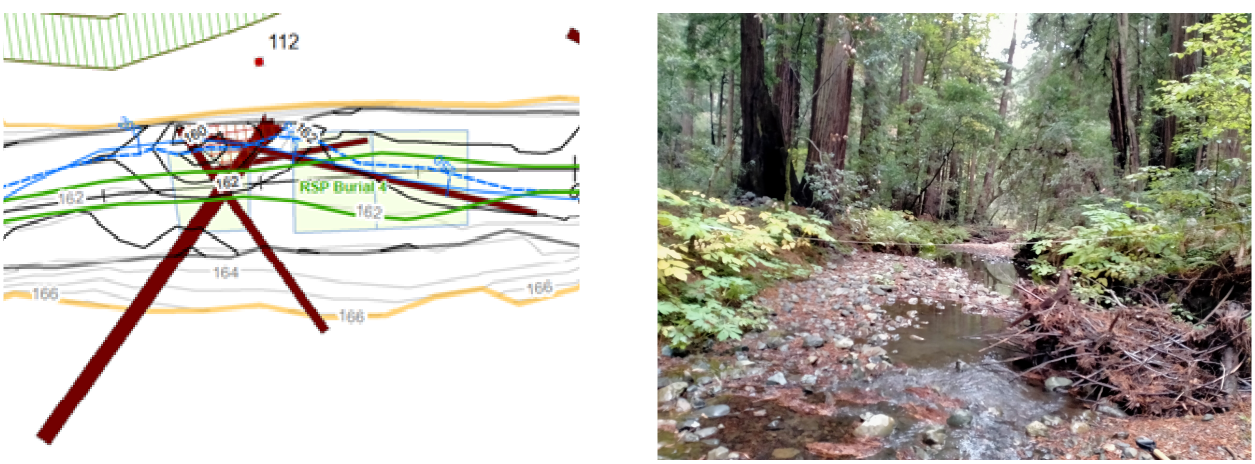

Figure A25. LWD2 as-built (NHE 2019) vs 2022 photo

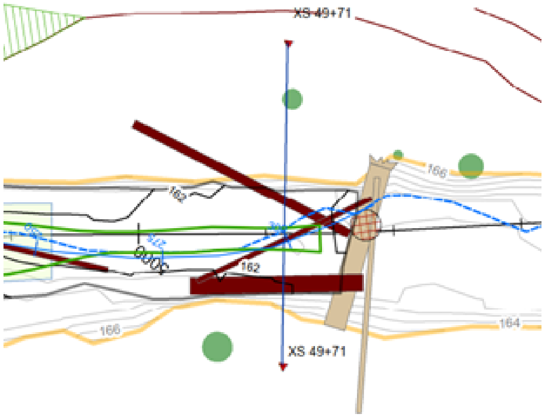

Figure A26. LWD1 as-built (NHE 2019) vs 2022 photo

Appendix B - Sediment Grain Size Graphs

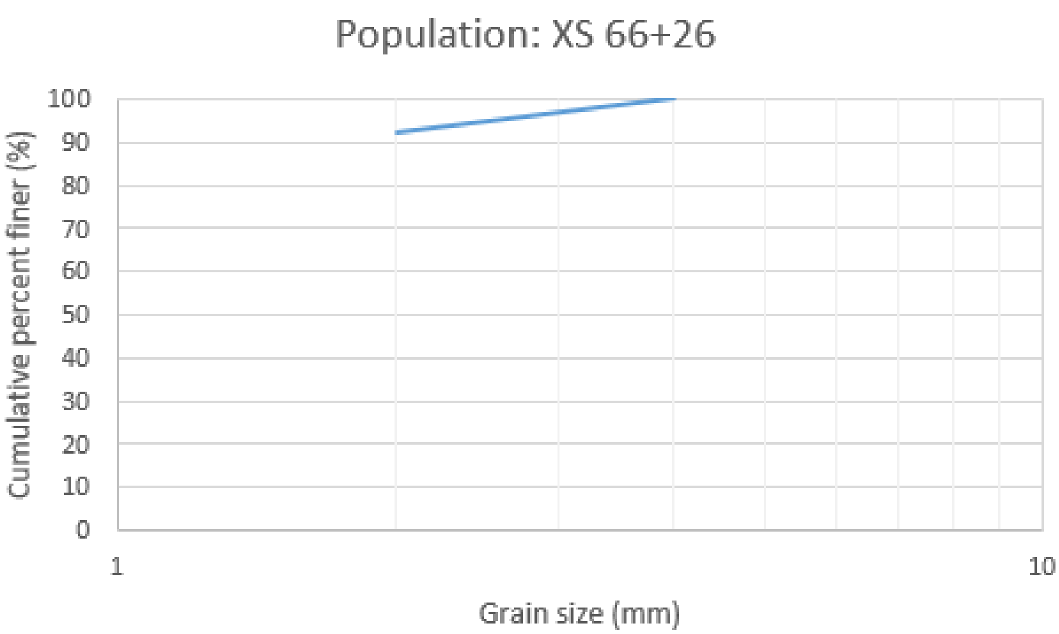

Figure B1. Grain size distribution curve for cross section 66+26

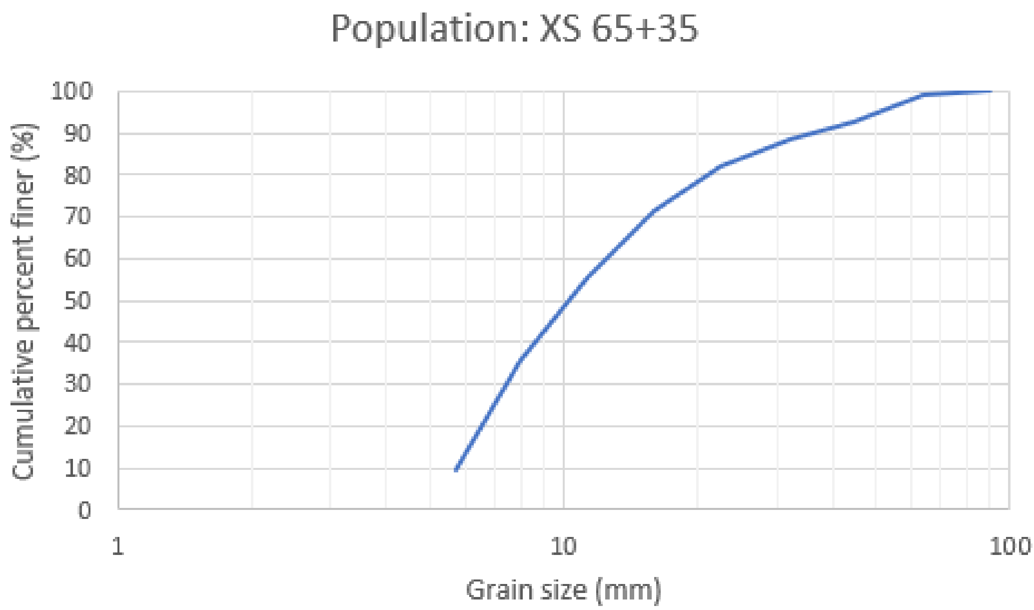

Figure B2. Grain size distribution curve for cross section 65+35

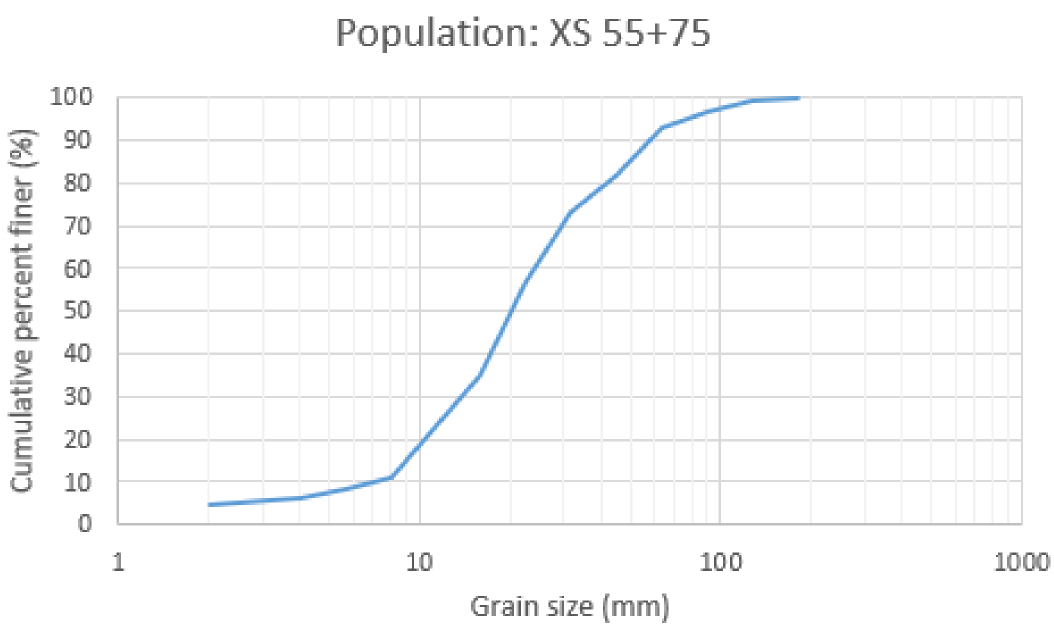

Figure B3. Grain size distribution curve for cross section 55+75

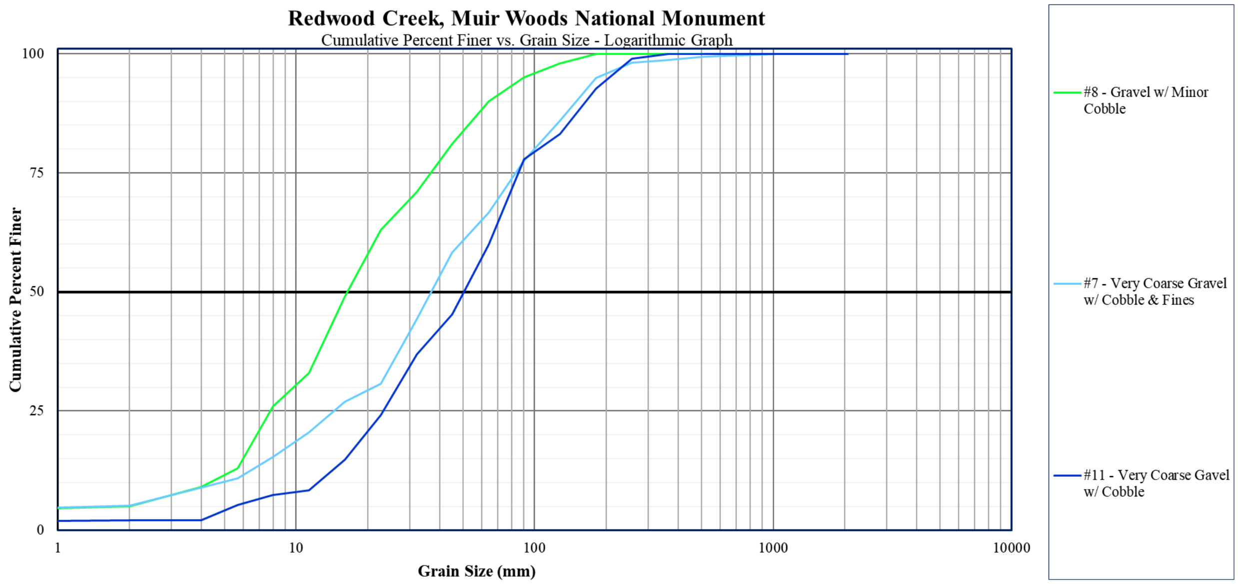

Figure B4. The graph above shows the sediment size distribution of each patch for the pebble counts collected by Shoulders et al (2020). Each patch is classified by its D_{50} Class name: green for medium gravel and blue for very coarse gravel.

Appendix C - Geomorphic Maps from 2015 and 2022

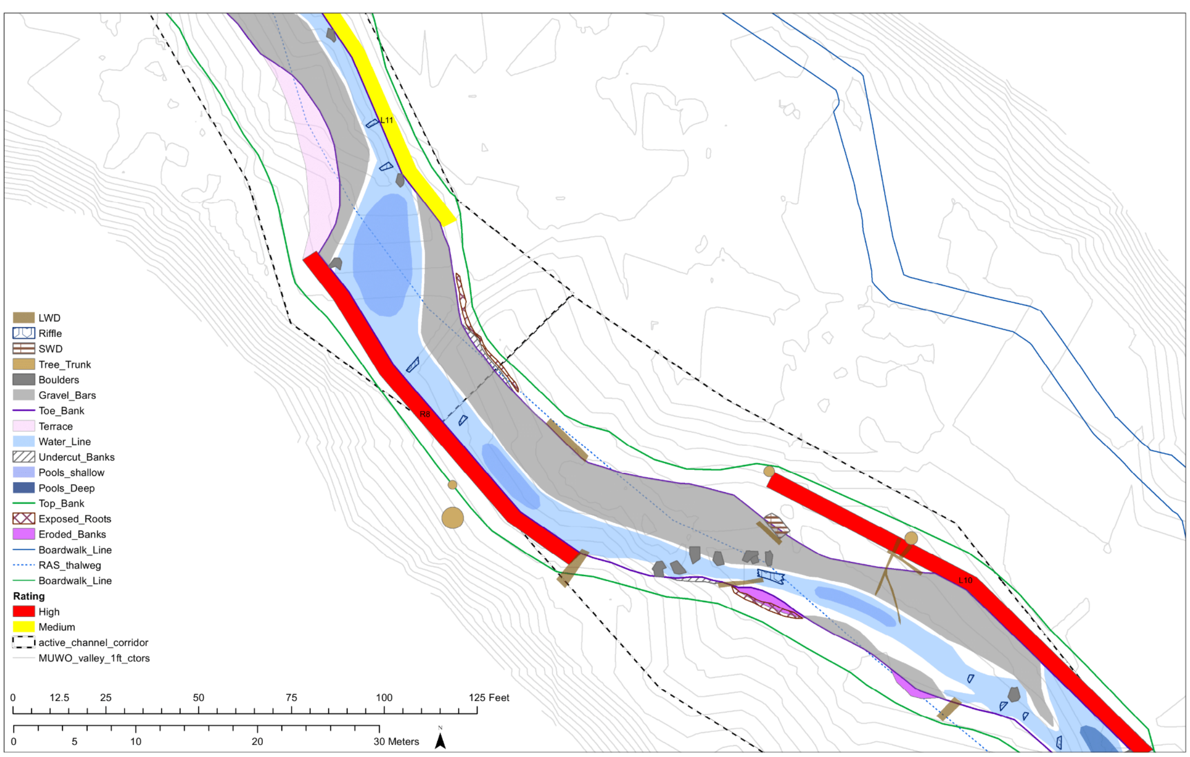

Figure C1. Geomorphic 2015 digitized map of cross sections 58+51 to 56+97 (NPS 2015)

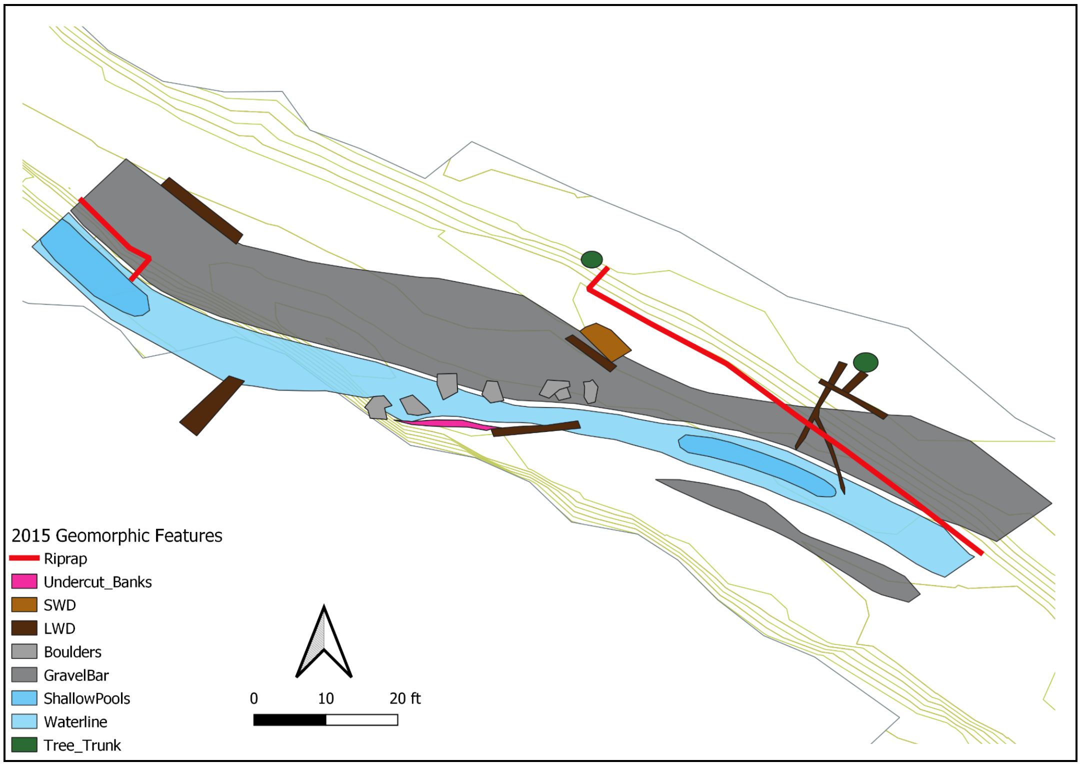

Figure C2. Geomorphic 2015 map of cross sections 58+51 to 56+97 (Allison 2015)

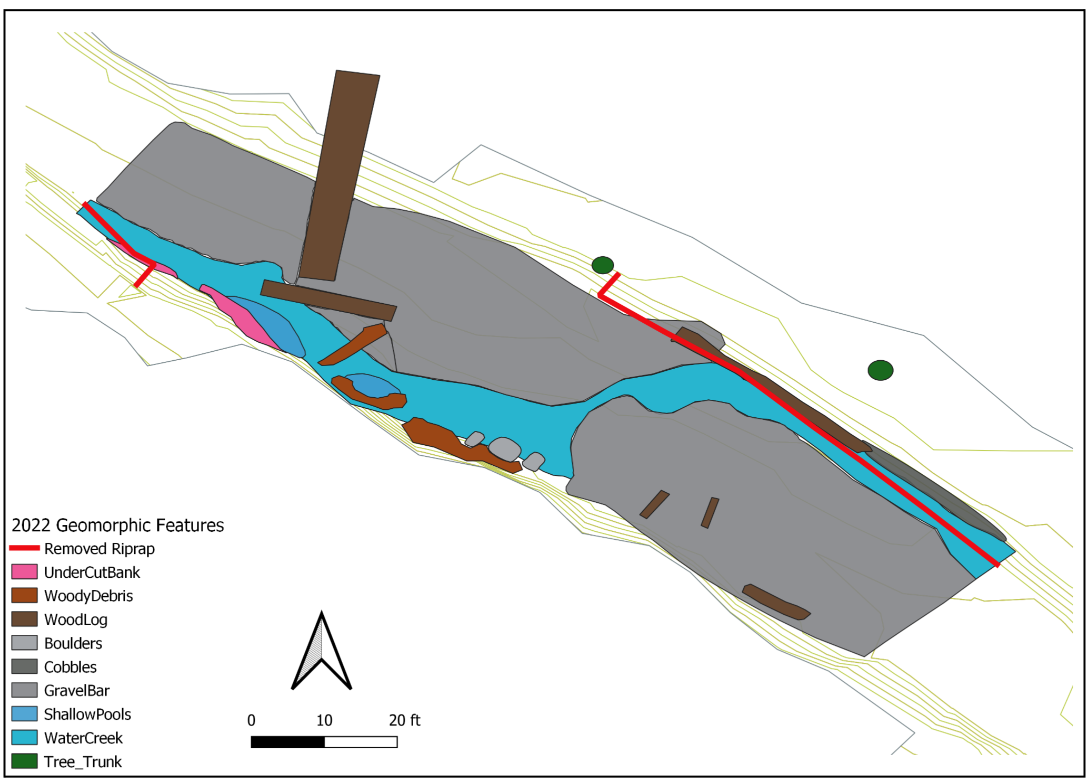

Figure C3. Geomorphic 2022 map of cross sections 58+51 to 56+97