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Engineering – Hydrology – Stream Restoration – Water Resources

# TECHNICAL MEMORANDUM

Date: 05 June 2015

To: Caroline Christman
Project Manager

Golden Gate National Parks Conservancy
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From: Bonnie Pryor and Jeffrey K. Anderson, P.E. (C50713)

**Re: 50% Culvert #2 Design for Redwood Creek Trails Project**

## Introduction

The project site is a located on a tributary to Redwood Creek within the Mount Tamalpais State Park in Marin County, California, approximately 15 miles north of San Francisco (Figure 1). The project consists of removing a plugged and perched culvert at the stream crossing and restoring the geomorphic and ecologic function of the channel by removing all components of the disturbance created by the crossing. The project site will no longer be maintained as a trail crossing. This report summarizes the existing condition and analysis used to develop the 50% channel design. Supporting information is also provided in the 50% design plans (Plans) and draft specifications.

## Geomorphic Setting

The crossing is located on a small, steep tributary to Redwood Creek, in the Upper Frank Valley subwatershed delineated by Stillwater (2004). The watershed area above the project site is 0.15 square miles. The geomorphic history of the Redwood Creek watershed is described in Stillwater (2004) and portions relevant to the project site are summarized here.

Prior to European settlement (1840), small tributaries in this portion of the watershed were thought to deliver water and sediment load into alluvial fan complexes that extended into the wide valley bottom, referred to as Frank Valley. The mainstem of Redwood Creek is assumed to have been poorly defined in this area due to frequent overbank flooding and channel depositional processes during this period. Sediment from the tributaries was generally not delivered directly to the mainstem; rather, sediment was deposited on the valley floor. Water from tributaries spread across the valley floor and infiltrated into the subsurface.

This condition changed following settlement as dramatic shifts in land use and vegetation cover accelerated erosion of tributaries and the mainstem. Vegetation and land use changes caused the headward extension of tributaries, and incrementally increased the surface runoff through the tributaries. Road and trail building also altered flow paths, delivering higher volumes of surface runoff to tributaries. This increased surface runoff, coupled with the loss of deeply rooted vegetation, led to accelerated incision of the tributaries. Along the valley floor, channel (tributary and mainstem) confinement increased as land was developed. Increased runoff and flow concentration promoted downcutting of the channels through the broad alluvial floodplain.

The downcutting of tributaries and flow confinement led to more persistent surface water connnections between the mainstem and tributary. These surface connections linked the base level of tributaries to the mainstem, such that accelerated erosion/downcutting in the mainstem resulted in additional erosion/headcuts moving up through the channel network. Sediment loads, which were formally deposited on alluvial fans as water infiltrated into the subsurface, were then delivered directly to Redwood Creek.

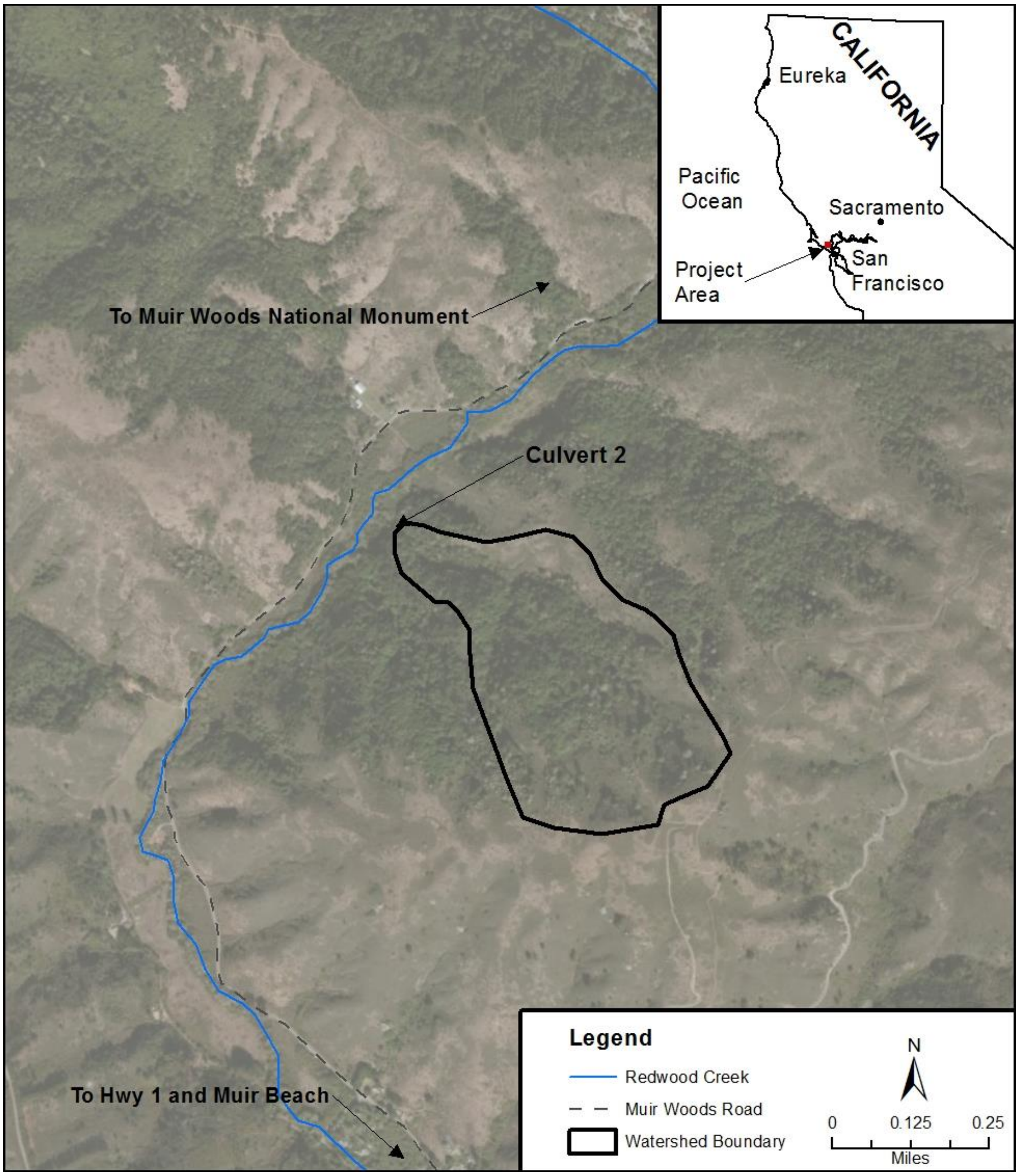


**Figure 1. Location map of project area.**

## Existing Conditions

The existing tributary channel flows into the mainstem of Redwood Creek approximately 200 feet downstream of the culvert crossing. Bedrock is exposed in the channel bottom approximately 185 feet upstream of the crossing. Between the bedrock and the confluence with Redwood Creek, the channel is incised in alluvial deposits with steep, erodible banks. The channel banks are predominately fine grained material with intermixed gravels, cobbles and an increasing frequency of boulders as the channel steepens to the bedrock reach. Active erosion of the banks is apparent throughout the tributary, but banks tend to be more stable where mature vegetation is deeply rooted and/or cobbles and boulders have stabilized the toe of the banks. The section of channel with the most accelerated erosion is immediately downstream of the existing trail crossing where water flows over the top of a plugged, 2 foot diameter culvert, through a constructed swale in the trail (Figure 2), and drops 8.25 feet to the channel bed. In this area, the left bank is vertical and/or undercut and devoid of vegetation with the exception of roots that overhang the bank.


**Figure 2. Tributary crossing showing the channel flowing over the top of the plugged culvert (A). Water falls over a vertical drop 8.25 feet and the left bank is actively eroding (B).**

In addition to the accelerated erosion on the left bank, the material beneath the culvert is also actively eroding, undercutting the downstream end of the culvert. The material exposed below the culvert is predominantly fine grained with discrete chunks of concrete in the upper portion. Additional concrete (appears to be a stem wall) is exposed, roughly parallel to the longitudinal axis of the trail along river left, approximately 6 feet from the left bank. The concrete stem wall and concrete debris found in the vicinity of the crossing do not appear to be structurally related to the existing culvert and are assumed to be remnants of structures that were built prior to Park ownership. Water pipes were found in the subsurface, upstream of the crossing, and may cross the work area.

The upstream side of the culvert is buried with sediment and is not exposed at the crossing. The length of the culvert is estimated to be 14 feet by California State Parks staff (personal communication, Caroline Christman) and the culvert outlet invert is perched approximately 6.25 feet above the channel bed. There is no information available regarding the channel condition at the time the culvert was placed. One possibility is that the culvert was placed at grade (~1960's) and 6.25 feet of incision occurred since that time. Alternatively, the culvert may have been set atop a former crossing and perched at the time of placement. Under this scenario, some vertical erosion may still may have occurred following placement of the culvert that further increased the height of the drop. The plugged culvert would have also increased the height of the drop and broadened the area subject to direct hydraulic erosion. In either case, stabilization of the existing 8.25 vertical drop is necessary to remove the current chronic sediment delivery from this source, as well as avoid a rapid delivery of sediment stored in the crossing and immediately upstream to Redwood Creek.

A longitudinal profile of the tributary was surveyed from the confluence with Redwood Creek (0 feet), through the crossing (~200 feet) to the bedrock controlled reach (~385 feet) (Figure 3). A detailed topographic survey was conducted over 165 feet. The channel gradient from the culvert downstream to the confluence with Redwood Creek is 9%. The channel is dominated by coarse gravel substrate and wood drops with roughness dominated by irregular bed and banks, and woody and herbaceous vegetation. The stream banks are typically 1H:1V or steeper and are partially covered by herbaceous vegetation and roots from adjacent trees. A large buckeye is located on river right, immediately upstream of the crossing (Figure 1).

Upstream of the culvert, the slope flattens to 2% over 45 feet and is predominately gravel bedded. These changes in slope and channel dimensions are a direct result of the existing crossing. The depth of the channel is approximately 2 feet, bottom width is 3 feet and top width is 10 feet. The channel begins to steepen dramatically upstream of this sediment plug and the channel bed coarsens to cobble, boulder, and finally a boulder/bedrock channel. The slope increases to 8% in the cobble reach, 11% in the boulder reach and 17% in the boulder/bedrock reach. The channel size varies from a bottom width of 10 feet and top width of 20 feet at the widest location, to a bottom width in the boulder reach of approximately 4.5 feet, top width 10 feet and channel depth 5 feet.

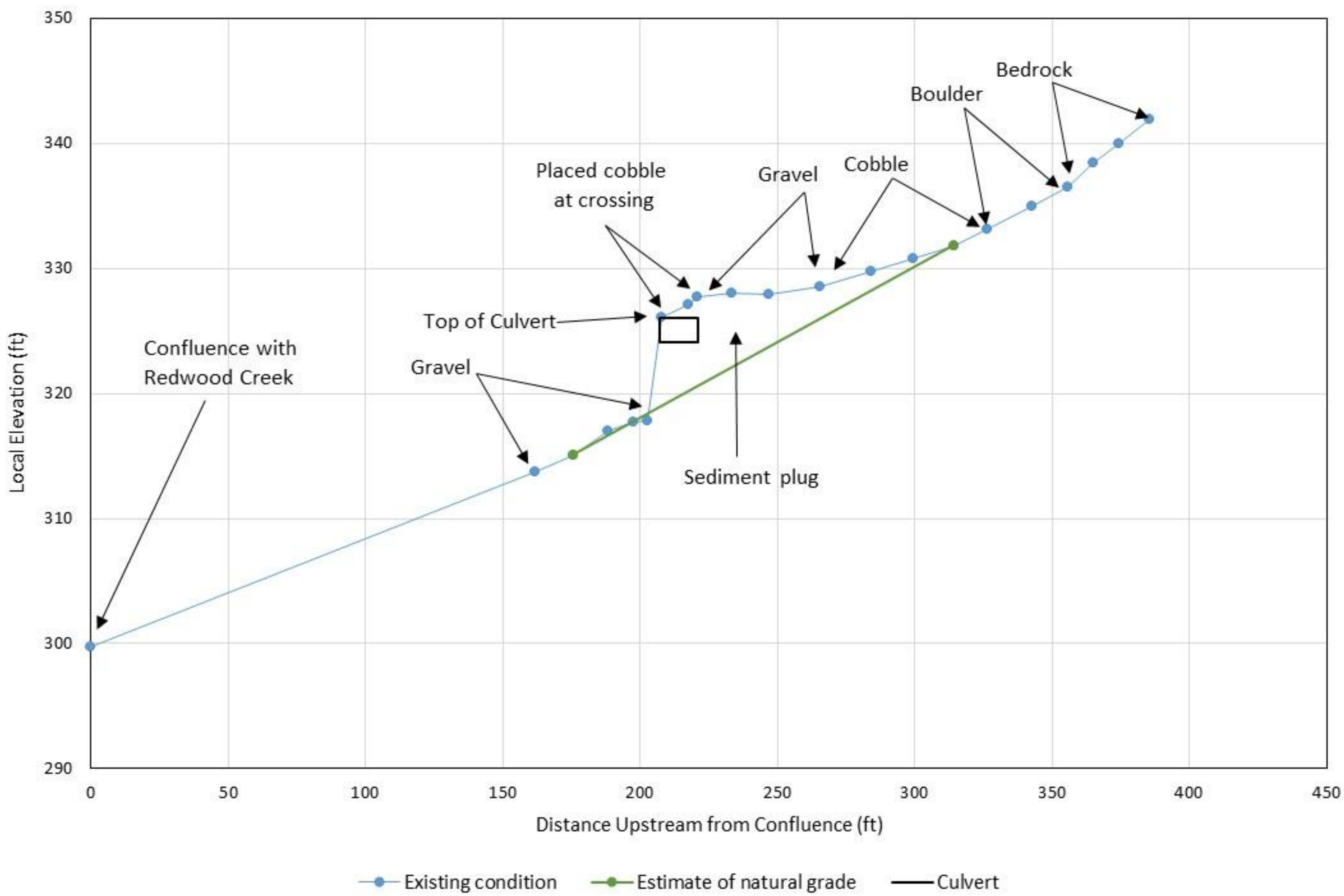


**Figure 3. Longitudinal profile, substrate, and estimate of natural grade in the vicinity of the crossing.**

## Design

The purpose of the design is to: (1) reduce sediment delivery to Redwood Creek by reducing the current erosion occurring in the vicinity of the culvert outlet, (2) reduce the potential for future sediment delivery of the sediment stored immediately upstream of the plugged culvert (referred to as sediment plug in Figure 3), (3) improve the ability of species (e.g. tree frogs, salamander) to move upstream by removing the current 8.25 foot drop, and (4) improve the overall hydrologic, geomorphic and ecological connectivity through the project area by returning the channel to the natural grade and channel morphology.

The components of the former crossing that will be removed include: the 2'x 14'culvert, the associated fill below the culvert, the sediment plug that has formed upstream of the culvert, the concrete stem wall (~4-6" x 17.5'), and miscellaneous concrete rubble from the scour hole at the culvert outlet (Figure 3, Plans - Sheet C1). The restoration components include: reducing excessive bank erosion occurring downstream of the culvert outlet and returning the channel to a natural grade, channel geometry, grain size and channel morphology. These modifications are intended to restore hydrologic and geomorphic processes, and ecological function.

Design channel grading will extend the full length of the sediment plug, (105 feet upstream of the existing culvert outlet, Figure 3). Downstream, channel bed grading will occur in the vicinity of scour hole created by the culvert (12 feet) and along the left channel bank where excessive bank erosion has occurred (60 feet downstream of the culvert). The right bank downstream of the outlet is more stable, is partially vegetated and will not be graded. Channel bank slopes are designed at 1H:1V up to the 100-yr peak flow water surface elevation and sloped to 1.5H:1V above the 100-yr peak flow water surface elevation. The bed is 4.5 feet wide. Design cross-sections are shown in Sheet C2 of the Plans. The design channel alignment follows the existing alignment. The top of the right bank is generally preserved with the majority of the grading occurring in the channel and along the left bank (Plans - Sheet C1). This configuration was selected to preserve riparian vegetation on the right bank, including a large buckeye tree located on the right bank immediately upstream of the crossing, and treat the most actively eroding bank (left bank) downstream of the culvert. Due to close proximity of the left valley wall to the design channel, further reducing the bank slopes would require shifting the channel alignment toward river right and removing the large buckeye tree as well additional trees along the right bank.

Channels within the measured slope range typically have cascade channel morphology (Montgomery and Buffington, 1997) (Figure 4). Cascade channels have disorganized, immobile rocks, that create flow divergence and convergence flow paths that form small, irregularly spaced pools and steps (Figure 5 and Figure 6). Smaller cobbles, gravels and fine sediment are mobile and transported around the larger immobile rocks. The channel upstream of the culvert within this slope range has a boulder dominated bed and cascade morphology (Figure 7). Based on the estimated natural grade of the channel in the vicinity of the culvert and upstream observations of typical channel morphologies at similar slopes, a cascade channel morphology was selected for the channel. The coarse bed material proposed in this design is meant to mimic the natural channel. A typical layout of the coarse bed material is shown in Plans -Sheet C3. It is likely that this same material type will be intercepted at depth and can be utilized in the design channel, reducing the need for imported rock.

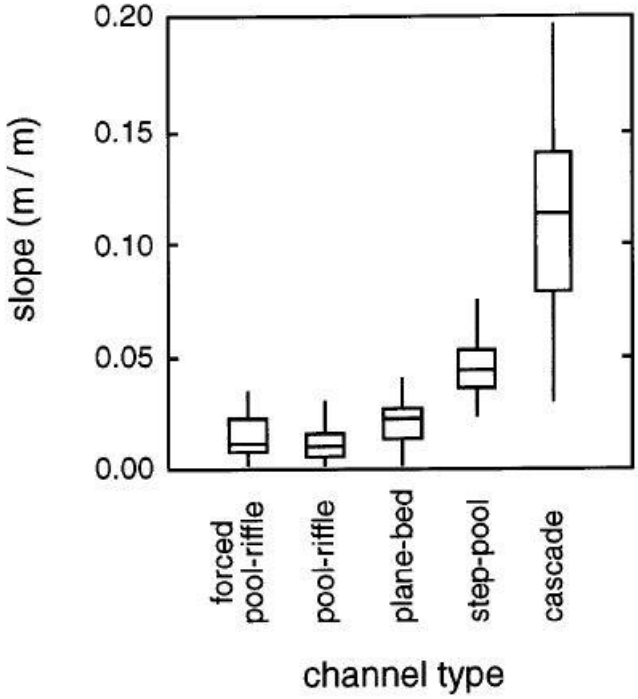


**Figure 4. Composite slope distributions for channel reaches surveyed in Montgomery and Buffington (1997) and related studies (Buffington, 1995; Montgomery et al., 1995); boxes represent inner and outer quartiles; vertical lines represent inner and outer tenths. Figure reproduced from Montgomery and Buffington (1997).**

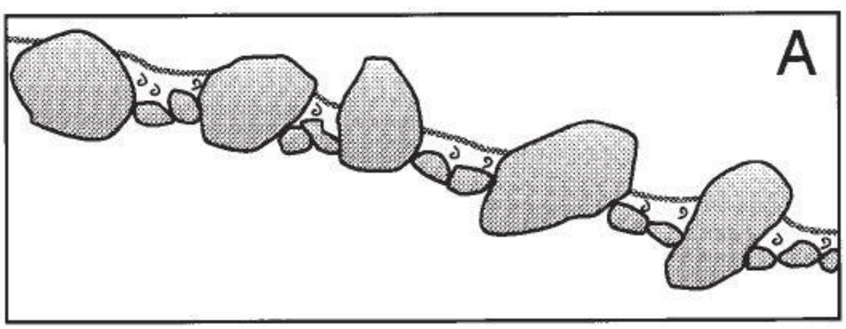


**Figure 5. Schematic of longitudinal profiles of a cascade channel morphology at low flow. Figure reproduced from Montgomery and Buffington (1997).**

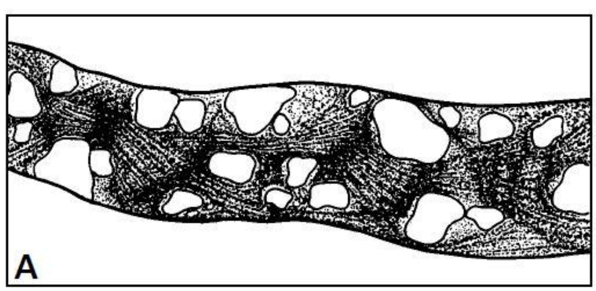


**Figure 6. Schematic planform of a cascade channel morphology shown at low flow. Figure reproduced from Montgomery and Buffington (1997).**

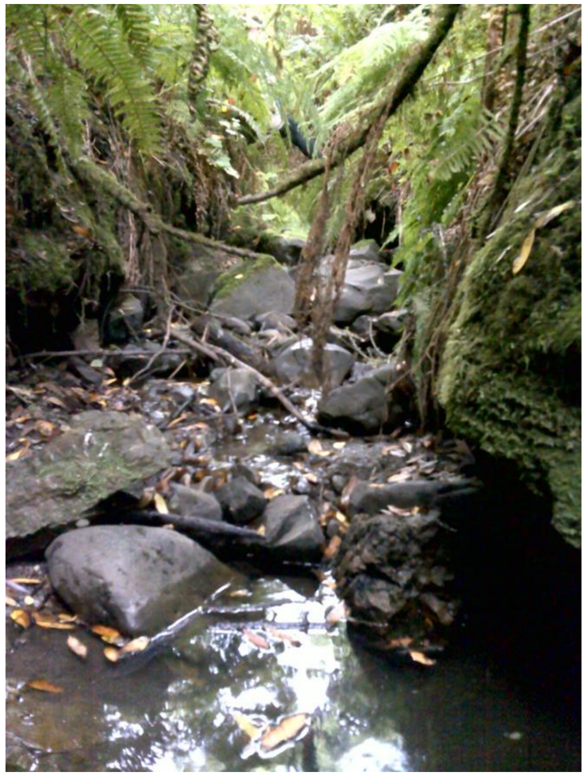

**Figure 7. Channel bed dominated by boulders.**

## Design Flow

The design flow used to compute the rock size required for channel stability is the 100-yr peak flow. The 100-yr peak flow was estimated using the USGS California regional equations (Gotvald et. al., 2012). The equations require input parameters of watershed area and mean annual precipitation. Watershed area was delineated from LiDAR data provided by the National Park Service, and mean annual precipitation was determined using the USGS online StreamStats software (water.usgs.gov/osw/streamstats). The watershed area above the project site is 0.15 square miles and the mean annual precipitation was determined to be 35.3 inches. The 100-yr peak flow was calculated to be 68 cubic feet per second (cfs).

## Hydraulics

The purpose of the hydraulic analysis is to estimate the water surface elevations and flow depth for the proposed design channel for the 100-yr peak flow. Hydraulic parameters were estimated using the U.S. Army Corp of Engineers (COE) River Modeling System, HEC-RAS V4.1 (COE, 2010). HEC-RAS calculates one-dimensional water surface profiles and average channel velocities for both steady gradually varied flow, and unsteady flow through a network of channels. For this analysis, steady-state modeling was used to predict water surface elevation and depth within the project area.

Model inputs include channel geometry and roughness, downstream water surface elevation, and discharge. Manning' roughness coefficients (*n*) were estimated based on the Jarrett Equation (Jarrett, 1984):

$$n = 0.32S^{0.38}R^{-0.16} \qquad \text{(Eq. 1)}$$

where *S* is slope and *R* is hydraulic radius. The equation was derived from cobble and boulder bedded streams with slopes ranging from 0.2-4%. The design channel manning *n* value was estimated to be 0.16 for the 100-yr peak flow.

For steady-state modeling, upstream and downstream boundary conditions are necessary for the hydraulic models. Normal depth was assumed for both the upstream and downstream boundary conditions using the design slope of 12%.

The HEC-RAS model predicts an average water depth of 2.6 feet depth in the design channel at the 100-yr peak flow.

### Channel Bed and Bank Materials

The US Army Corps of Engineers steep slope riprap design equation (COE, 1994) was used to design the stable rock size for the 100-yr peak flow (Eq 2). This rock lines the bed (channel base rock) and banks (bank rock) of the channel up to the 100-yr peak flow water surface elevation and is designed to provide a stable foundation and reduce the potential of water to outflank the constructed channel (Plans - Sheet C3). The equation estimates the intermediate axis of the 30th percentile in the sediment distribution.

$$D_{30} = \frac{1.95S^{0.555}1.25q^{2/3}}{g^{1/3}} \qquad \text{(Eq. 2)}$$

Where *S* is slope, *q* is the unit discharge and *g* is the gravitational constant.

The $D_{30}$ is estimated to be 0.90 feet. 1/4 Ton rock is specified to achieve the desired stability for both the Channel Base Rock and Bank Rock. The gradation of the 1/4 Ton rock and description of methods to seal the base rock are provided in the draft specifications.

The bed material in the channel that mimics the cascade morphology is referred to as the "coarse bed material". Coarse bed material gradation was based on the Bathurst (1987) unit discharge method to estimate the diameter of the $D_{84}$ (84% of the material is finer than this size) (Eq 3). This method is recommended for slopes greater than 4%. The equation estimates the $D_{84}$ that will be near the threshold of mobility. The median grain size ($D_{50}$) is computed following Love and Bates (2009) (Eq 4).

$$D_{84} = \frac{3.54S^{0.747}1.25q^{2/3}}{g^{1/3}} \qquad \text{(Eq. 3)}$$

$$D_{50} = 0.4 * D_{84} \qquad \text{(Eq. 4)}$$

The finest 30% of the coarse bed material gradation is based on the Washington State Department of Transportation specifications for aggregate materials to be used in stream and culvert projects to ensure adequate sealing of the coarse bed material.

The coarse material is not expected to be rigid at the 100-yr peak flow. Material within the bed is expected to exchange with sediment delivered from upstream sediment sources during large floods similar to natural stream channels. The bed may coarsen or fine over time depending on upstream sediment deliveries.

Rock gradations for the channel base rock, bank rock and channel material are provided in the draft specifications.

## Bank Protection

The goal of the bank protection is to limit large scale bank erosion when the project is most vulnerable, following construction. After vegetation is established, the intrinsic stability of the banks will increase from root strength and additional roughness created by dense vegetation will reduce erosion potential. The current design to protect the bank includes a coarse rock bank up to the 100-yr peak water surface elevation, erosion control fabric from the top of the constructed bank to the base of the coarse bank rock, and re-vegetation of the bank (Plans - Sheet C3). The coarse bank rock is not designed as rock slope protection, which requires two layers of rock rather than a single layer. The rock in the bank is intended to mimic a cascade channel where large rock provides stability to the banks, but does not limit long-term channel adjustments. Over the long-term the channel and banks may adjust in response to large wood recruitment and upstream sediment supply. Erosion control fabric is used to reduce bank erosion on the channel banks in the event that water levels exceed the estimates of the 100-yr peak flow which may occur due to woody debris recruitment, upstream sediment loads and uncertainties in hydraulic predictions. The combination of rock and erosion control fabric will also help maintain stability of the steep banks that are necessary to conform to the upstream and downstream channel geometry.

## Woody Debris

The project is located within a forested watershed where natural wood recruitment to the project is expected. Woody debris will also be generated on-site as a result of channel grading. In channel woody debris provides many ecological benefits and may be retained on the floodplain with no risk to the project. The addition of woody debris to the channel, whether naturally recruited immediately following the project or placed during construction carries some risk to the project. The addition of woody debris will locally increase water surface elevations due to increased roughness and physical obstruction. The erosion control fabric will reduce the erosion potential due to higher water surface elevations, but can be damaged by woody debris. The fabric is critical to reduce potential for excessive bank erosion in large floods until native vegetation is established and banks gain more intrinsic stability from the associated root systems and added roughness on the banks. If the erosion control fabric is damaged, excessive bank erosion may occur and repairs will be necessary until native vegetation is established.

The addition of the woody debris to the floodplain and channel will be guided in the field by the Project Team. These general guidelines are recommended:

- Wood added to the channel should be placed on top of the coarse bed material with limited embedment into the coarse bed material. Widespread incorporation of the wood into the bed material may affect the sealing of the bed material.
- The density of wood added into the channel should be low to limit widespread increases in water surface elevation and limit the potential for the wood to form a jam within the project area in the near term (e.g. until vegetation has established on the banks).

- The diameter of the wood placed in the channel should not exceed 1 foot in diameter and should not reduce the cross-sectional area by more than 5%.
- Wood should be placed stream parallel to limit flow deflection into the banks.
- Woody material should not be placed on the erosion control fabric to limit damage to the fabric.

### Headcut Potential

The project has a low risk of major headcut delivering significant quantities of sediment to Redwood Creek. Upstream of the project, the channel quickly transitions to a bedrock dominated channel that limits the potential for a headcut to propagate upstream through the drainage network. There is a potential for a headcut to form downstream of the project area and migrate into the project area. A headcut could undermine the bank rock on river left. This risk is substantially reduced by keying in the bank rock approximately 3 feet in depth below the channel bed (Plans - Sheet C3). Similarly, a headcut moving upstream will be limited by the channel base rock which extends approximately 3 feet below the channel bed (Sheet C3). In the event that incision is deeper than 3 feet, the channel base rock will become a source of large rock that will stabilize the propagating headcut.

### Material Volumes

The design requires excavation of approximately 500 cubic yards (CY) of material and placement of 520 square yards of erosion control fabric. Approximately 32 CY of this material will be re-used in the project to backfill void spaces in the channel base rock and 468 CY would be off-hauled. The import rock totals approximately 254 CY (Table 1).

These volumes assume:

- Materials excavated are not suitable for re-use in the channel design except for backfill of voids of channel base rock.
- Bedrock is not intercepted above the subgrade.

If the excavated materials are suitable for re-use (e.g. boulders and coarser gravels) or bedrock is encountered at a shallower depth, the volumes required for import may be substantially smaller. The re-use of existing native materials are preferred over imported materials.

Table 1. Material quantities

| MATERIAL TYPE | TOTAL (CY) | TOTAL (TON)* | PROJECT ELEMENT |
|---|---|---|---|
| **Total Imported Rock** | 254 | 396 | |
| 1/4 Ton Rock | 203 | 317 | Channel Base Rock and Bank Rock |
| Coarse Bed Material | 22 | 34 | Coarse Bed Material |
| Stream Bed Material | 29 | 45 | Backfill Voids in Bank Rock |
| **Total Native Material** | 32 | | Backfill Voids in Channel Base Rock |
| **Total Off-Haul** | 468 | | |

*Assume 30% voice space and specific weight of rock = 4,455 lb/cy

## Monitoring

The project will be monitored for a minimum of 5-years by a qualified fluvial geomorphologist or engineer to ensure the project functions as desired. This monitoring will include photo points that include the right and left bank and channel at the upstream and downstream project boundaries and from a mid-point within the channel. Project performance does not depend on maintaining this particular channel alignment or bed elevation in the long-term. The channel is expected to respond to flow and sediment deliveries. In the short-term, some channel stability is required to allow vegetation to establish and provide additional cohesion to the soil. The stability is provided by the channel base rock, bank rock and erosion control fabric.

The performance criteria for geomorphic and hydrologic function shall be the following:

- No signs of excessive movement of the bank rock and base rock. Excessive movement of bank or base rock would result in large swaths of soil bed or banks exposed that may results in excessive erosion. Some movement of bank and channel rock is acceptable as long as the erosion control fabric is intact and the area is either filled with sediments from upstream or vegetated.
- No signs of excessive wear and tear to the erosion control fabric. The erosion control fabric is expected to break down naturally over time. Excessive wear and tear identified by large swaths of the soil exposed prior to vegetation establishment.
- No signs of excessive erosion at the upstream and downstream project boundaries of the bank or bed.
- No signs of sediment aggradation that would lead to channel avulsion.

If these performance criteria are not achieved, the cause will be identified and corrective measures will be taken. Any action taken will identified and implemented in consultation with the appropriate agencies.

## References


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