Northern Hydrology & Engineering

P.O. Box 2515, McKinleyville, CA 95519
Telephone: (707) 839-2195; email: nhe@northernhydrology.com

Engineering – Hydrology – Stream Restoration – Water Resources

TECHNICAL MEMORANDUM

Date: 31 July 2015

To: Caroline Christman
Project Manager

Golden Gate National Parks Conservancy
Building 201 Fort Mason, 3rd Floor
San Francisco, CA 94123

From: Corin Pilkington, Bonnie Pryor and Jeffrey K. Anderson, P.E.

Re: Recommendations for Trail Crossings and Erosion Sites for Redwood Creek Trail Project

Introduction

The trail crossings and erosion sites are a located on the Redwood Creek Trail in Marin County, California, approximately 15 miles north of San Francisco (Figure 1). The trail crossings and erosion sites assessed in this memo include three crib walls (Bridge 10, 11, and 12), three culverts (Culvert 1, 3, and 4), two spur trail crossings (Trail Crossing 1 and 2), and two erosions sites (Erosion Site 1 and 2). The erosion sites are adjacent to, and down slope of the Redwood Creek trail, but do not have crossing structure associated with them (Figure 1). Culvert 4 is located within Golden Gate National Recreation Area, all the other sites are located within Mount Tamalpais State Park.

Geomorphic Setting

The trail crossings are located on a small, steep tributaries to Redwood Creek, in the Upper Frank Valley subwatershed (Culverts 1 and 3, Trail crossing 1, and Erosion sites 1 and 2) and Lower Frank Valley subwatershed (Culvert 4, Trail crossing 2, Bridge 10, 11 and 12). Subwatersheds were delineated by Stillwater (2004). 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 be a 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 development. Increased runoff and flow concentration promoted downcutting of channels through the broad alluvial floodplain. The downcutting of tributaries and flow confinement led to more persistent surface water connections 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.

Tributaries in the Upper Frank Valley subwatershed are still incising in response to based level and hillslope influences, while tributaries in the Lower Frank Valley are incising at a slower rate, or may have stopped incising (Stillwater, 2004). The tributaries in the Lower Frank Valley subwatershed have stable base level controls at Muir Wood Road. However, active erosion is still apparent throughout the tributary, likely related to a combination of hillslope, vegetation and trail influences.

Recommendation Summary

The larger scale drivers identified by Stillwater Sciences (2004), such as base level changes, vegetation conversions and extension of the channel network are not treated as part of this project, but are considered within a site specific context. The intent of the designs is to treat localized erosion that is occurring due to existing infrastructure and trail design. In all cases, the trail should be outsloped to avoid concentration of flows. Portions of trails that are deeply rutted may require fill to bring the trail back to grade and achieve and proper grades. Decommissioned trails should be vegetated to avoid re-occupation of these established flow paths. Treatment of the trails in conjunction with the crossing is expected to substantially reduce localized erosion at the crossing. There is also likely to be network wide reduction in erosion as flow concentrated by the trail is reduced through proper outsloping and implementation of properly spaced water bars (design by others). These treatments will not prevent headcuts from migrating through the channel network. Treatment of incision that is tied to lowering base levels would need to begin at the distal end of the channel network and work systematically upstream, stabilizing the channel network.

Recommendations for crossing include:

- Trail Crossing 1: The trail and crossing will be decommissioned.
  - No additional site work is recommended due to lack of infrastructure found at the wet crossing (no culvert, crib walls, etc.) and presence of dense vegetation downstream of crossing.

- Culvert 1 and 3 Action: The trail and crossing will be decommissioned.
  - Decommissioned crossings will be restored. This action includes:
    - Removal of the culvert and all associated structures including, but not limited to, rock walls, wood retaining walls, etc.
    - Constructed bank slopes, bed width and top width transition to conform to existing bed width and bank slopes at the upstream and downstream tie-in. The channel slope will transition from the upstream channel grade to the downstream channel grade.
    - Bed material added to the channel is typical for natural streams with similar discharge and stream gradient.
    - Erosion control fabric is used to limit erosion until vegetation is adequately established to provide bank stability.
  - Larger rock may be substituted at these locations to slow further downcutting at these sites in response to base level changes. The tributary network upstream of Culvert 3 is not at risk because Muir Wood Road intersects the drainage and controls the base level.

However, the migration of a headcut upstream of Culvert 3 could further undermine Muir Woods Road. An existing erosion problem already exists at this location. There is no infrastructure in the vicinity of Culvert 1 that would limit the upstream migration of a headcut.

- Culvert 4 Action: Maintain and upgrade trail crossing from a culvert to a bridge.
  - Remove the culvert and all associated structure including, but not limited to, rock walls, wood retaining walls, etc. Bank slopes, bed width and top width transition to conform to existing bed width and bank slopes at the upstream and downstream tie-in. The channel slope will transition from the upstream channel grade to the downstream channel grade.
  - Maintained crossings have a conservative rock size. The channel and bank slopes up to the 100-year flood are lined with rock. The rock will not eliminate the potential for a headcut that originates downstream of the crossing to migrate through the trail crossing.

- Bridge 10, 11, 12 Action: Maintain and upgrade trail crossing from existing crib wall crossings to bridges.
  - Removal of the crib walls are recommended, rather than building the rock drop and energy dissipater over the top of the crib wall. The wood materials that form the crib have begun to decay and will continue to do so. As the wall decays, slumps into voids, water piping, etc. will increase erosion risk.
  - The channel will be lined with rock. The rock will stabilize the sediment plug upstream of the crib wall, preventing a headcut from originating at the sediment plug and migrating upstream, and dissipate hydraulic energy from the drop to reduce downstream erosion of the bed and banks.
  - The design channel will conform to existing bed slope and bank grade at the upstream and downstream tie-ins. All disturbed areas will be covered with erosion control fabric and re-vegetated.
  - Maintained crossings have a conservative rock size. The channel and bank slopes up to the 100-year flood are lined with rock. The rock will not eliminate the potential, for a headcut that originates downstream of the crossing to migrate through the trail crossing.

- Trail Crossing 2 Action: Maintain wet trail crossing and reduce excessive erosion with rock structure.
  - CDPR Trails staff determined that upgrading the trail crossing to a bridge, similar to other sites would require substantial changes to the trail and placement of additional infrastructure.
  - CDPR design includes:
    - Grading of downstream channel bank, construction of an armored wet crossing, rock wall to protect the trail and a rock energy dissipater. Rock will be extended downstream in the channel and along the left and right banks to control erosion.

- Erosion Sites 1 and 2 Action: Decommission trail and stabilize headcut.
  - Apply erosion control fabric over re-contoured trail to ensure that re-channelization does not occur.
  - Fill headcut(s) at a maximum slope of 2H:1V with native soil, cover disturbed areas with erosion control fabric, and re-vegetate.
  - Do not disturb existing woody vegetation
  - Erosion Site 2: exposed portions of the channel between root masses may be carefully backfilled with logs and small woody debris to increase roughness, reduce erosion and promote trapping of fine sediments.

Existing Conditions

The trail crossings and erosion sites were assessed in the field by Golden Gate National Parks Conservancy (GGNPC) and Northern Hydrology and Engineering staff. GGNPC staff measured key site components including structure dimensions, channel geometry and slope, sedimentation and erosion patterns, and vegetation characteristics. Channel geometry was measured with an auto level and tape measure and slope was measured with a clinometer. The site descriptions provided below are based on field measurements and descriptions provided by GGNPC.

Bridge 10

A crib wall (2.2 ft high, 5 ft wide, and 8.1 ft long) is installed across the drainage at Bridge 10 (Figure 1, Figure 2). Bridge 10 will be replaced by a spanning bridge (design by others). The channel in the vicinity of the crib wall is densely vegetated upstream with shrubs and vines, downstream is relatively open with some grasses, poison oak and blackberry. Upstream of Bridge 10, a sediment plug has filled the channel creating a relatively flat grade. The sediment plug is approximately 30 feet long and has a small incised channel running through it. The onsite sediment is mostly soil with sparse 2 - 4 inch rock. Downstream of the crossing, the channel has an approximate grade of 23%, the width of the channel bed varies around 1.2 ft, while the top width is around 4.5 feet.

Trail Crossing 2

Trail Crossing 2 is located on a Redwood Creek Spur Trail which connects from Muir Wood Road, across the street from the volleyball court, to Redwood Creek Trail via two switchbacks (Figure 1). Between the first and second switchback, the trail crosses the channel. The channel is shallow upstream of the trail and at grade with the trail. Downstream of the trail, the channel has ~7 foot vertical drop into a substantially larger, actively eroding channel (Figure 3). The length of channel between the crossing and Muir Wood Road is approximately 63 feet. The trail crossing is on the same channel as Redwood Creek Trail Bridge 10, and is approximately 64 feet downstream of Bridge 10.

There are no erosion control features at the crossing to protect the trail tread during storm events. A loose pile of large rock has been placed in the channel below the spur trail to slow erosion, but the rock is being actively undercut and new failures are occurring adjacent to the large rock.

Bridge 11

A crib wall (3.2 ft high, 5 ft wide, and 7.6 ft long) is installed across the drainage at Bridge 11 (Figure 1, Figure 4). The trail is cut into the hillslope on the north and south sides of the crib wall. Bedrock is exposed on the north side of the crossing and on the south side of the channel. The channel flows over the top of trail/crib wall. A split rail fence borders the trail crossing on the down slope side. Bridge 11 will be replaced by a spanning bridge (design by others). The channel in the vicinity of the crib wall is densely vegetated with shrubs, vines and small trees. Downstream of the crossing, the channel has an approximate grade of 7%, the width of the channel bed varies around 2 ft, while the total channel width is around 5 feet. Upstream of Bridge 11, a sediment plug has filled the channel creating a relatively flat grade. The sediment plug is approximately 26 feet long and has a small incised channel running through it. The onsite sediment is primarily soil, but there is a significant component of 2 - 12 inch rock.

Bridge 12

A crib wall (3.2 ft high, 4.7 ft wide, and 5.8 ft long) is installed across the drainage at Bridge 12 (Figure 1, Figure 5). On top of the crib wall parallel to the banks of the channel, wood beams and rock serve as bridge abutments. A wooden bridge rests on these abutments spanning the crib wall and allowing water to pass under the bridge and over the crib wall (Figure 5). Bridge 12 (crib wall and existing bridge) is scheduled to be replaced by a spanning bridge (design by others). The channel in the vicinity of the crib wall is densely vegetated with shrubs, vines and small trees. Downstream of the crossing, there is a small channel within a gully that has an approximate grade of 14%, the width of the smaller channel bed varies around 1 ft, while the total small channel width is around 4 feet. Upstream of Bridge 12, a sediment plug exists although the dense vegetation obscures reasonable vantage to determine its extent. The onsite sediment is primarily soil, but there is a significant component of 2 - 8 inch rock.

Culvert 1

Culvert 1 (4 ft diameter, 14 ft long) is a metal culvert (Figure 1, Figure 6 and Figure 7). The trail in the area of Culvert 1 is scheduled to be decommissioned. The culvert appears to have been placed near channel grade, but at the outlet there is a ~18 inch deep scour hole. The culvert has a minimal fill prism with a soil cap (<0.5ft) that creates the trail crossing. Upstream, both banks are lined with manmade rock walls that are approximately 10 feet long and ~5 feet tall. Downstream, on the right bank, a two terrace rock walls line the bank and are approximately 8 feet long and ~5 feet tall. The culvert bedding material and the extent the rock walls protrude into the banks is unknown. The channel is fairly open in the vicinity of Culvert 1 and the over bank areas are well vegetated. The channel bed is a gravel/cobble mix (1/2 to 7 inch). The banks beyond the rock walls are primarily soil. The channel slopes are 7% upstream and 1-2% downstream. The culvert grade is estimated at 2.6%.

Trail Crossing 1

Trail Crossing 1 is a wet crossing on the Miwok Trail (a spur trail off of Redwood Creek Trail) approximately 90 feet upstream of Culvert 1 (Figure 1). The trail in the area of the wet crossing is scheduled to be decommissioned. The channel shallows and widens in the downstream direction as the channel approaches the trail, typical of a sediment wedge. Downstream of the trail, there is thick vegetation overlying woody debris where layers of intertwined woody material ranging from 2 to 6 inches diameter. While there was an obvious drop downstream of the woody material, the channel bed and banks were too obscured with vegetation to assess whether there is active erosion occurring in the vicinity of the crossing. There is no visible infrastructure associated with the trail crossing, no subsurface structures were discovered during investigative digging (Figure 8). Given the lack of infrastructure and established vegetation, no additional site work beyond the general recommendations for trail decommissioning is recommended.

Culvert 3

Culvert 3 (4 ft diameter, 20 ft long) is a metal culvert (Figure 1, Figure 9). The trail in the area of Culvert 3 is scheduled to be decommissioned. The culvert appears to be at grade with the channel bed but the bottom of the culvert has rusted away and this has created scour pockets under the culvert. The culvert has a fill prism of unknown material that creates the trail crossing, the fill is contained from the channel bed to the trail (~7 feet) by a wood beam retaining wall on both ends of the culvert. The extent the wood retaining walls extend into the banks is unknown. The culvert bottom has rusted away in some areas and it appears the culvert bedding may be native material. The channel in the vicinity of Culvert 3 is fairly open, but the banks and over bank are densely vegetated. The channel bed upstream is finer grain material, than the channel downstream, which and has coarse material (4-6 inch) that lines the channel bed. The banks are primarily soil.

Serving the same channel as Culvert 3, but upstream (~100 feet) there is another culvert that crosses under Muir Woods Road (County Road). This culvert provides base level control for the upstream channel network. The culvert is in disrepair. The downstream end of the culvert has a section that has rusted and broken off, this has created a free drop from the remaining culvert end and a large scour hole has developed. The broken off section of culvert has also resulted in the erosion of the edge of the road. At the inlet of the culvert, there is wooden intake wing wall that appears intact, but the culvert itself is severely corroded.

Culvert 4

Culvert 4 (4 ft diameter, 8 ft long) is a metal culvert that intersects Redwood Creek Trail (Figure 1, Figure 10). The culvert is to be replaced by a spanning bridge (design by others). The culvert has a natural layer (~4 inches) of deposited bed material lining its bottom, and sits at grade with the channel bed. The culvert has a minimal fill prism of unknown material that creates the trail crossing and is retained with a combination of rock and wood beams, including wood wing walls. The culvert bedding material and the extent the wood and rock retaining material extend into the banks is unknown. There are wood controls in the channel bed upstream and downstream of the culvert. The channel in the vicinity of Culvert 4 is fairly open, but the banks and over bank are fairly vegetated. The channel bed is primarily soil with some scattered rock (1/2 to 6 inch diameter). The banks are primarily soil. No significant erosion exists in the vicinity of the culvert.

Erosion Site 1

Erosion Site 1 is a small headcut that has developed immediately adjacent and downslope of Redwood Creek Trail, about 75 feet northeast of Erosion Site 2 (Figure 1, Figure 11). The headcut is currently at the edge of the trail and has begun to cut underneath it. Downslope of the headcut, there appears to be a broader swale that extends to the Redwood Creek channel. This broader swale may be a former trail alignment or cattle access point. The active portion of the headcut appears to have formed at a low point in the trail grade as the trail traverses a hillslope. Flow concentrated along the trail enters the head of the channel (Figure 11). Upslope, there is not defined channel or erosional features. The trail in the area of Erosion Site 1 is scheduled to be decommissioned.

Erosion Site 2

Erosion Site 2 is a small headcut that has developed immediately adjacent and downslope of Redwood Creek Trail (Figure 1, Figure 12). The trail in the area of Erosion Site 2 is scheduled to be decommissioned. The headcut has formed at a low point in the trail grade. Upslope of the erosion area (~300 feet) a well-defined larger swale is evident, nearer the trail (~ 25 feet) a shallow channel (4 inches deep) is evident but ceases to be defined at the trail. The headcut adjacent to the trail is associated with water that flows directly down the swale, but also receives significant water flowing down the channelized trail grade (Figure 12). The headcut is currently at the edge of the trail and has begun to cut underneath it.

Below the trail and headcut the channel is defined (roughly 1 foot wide by 1.5 feet deep) and deepens toward Redwood Creek. Large tree roots cross the channel and form a ceiling over portions of the channel composed of roots and soil. Dense vegetation obscures much of the channel. From a vantage point below the trail, looking up the channel, it appears that another headcut is working its way upslope adjacent (north) to the aforementioned headcut. This headcut is likely forming due to concentrated trail runoff. The extent of additional erosion was obscured by vegetation.

Methods

NHE used data provided by GGPC to develop typical designs that include bed width, bank slope and bed and bank material rock size.

100-year Peak Flow Estimate

The 100-year peak flow was selected as the design flow used to compute the rock size required for channel stability. The peak flow estimates were determined for the sites: Bridge 10, 11, and 12 and Culvert 1, 3, and 4 (Figure 1). These estimates are used to calculate flow depths and velocities, and subsequently determine the necessary rock size for channel base rock and bank protection rock.

U.S. Army Corp of Engineers (COE) Hydrologic Modeling System, HEC-HMS V4.0 (COE, 2013) was used to estimate 100-year peak flow at all sites. The U.S. Geological Survey (USGS) regional flood frequency relations for California (Gotvald, 2012) was also used to compare peak flow for sites with watershed areas greater than 0.13 square miles.

HEC-HMS simulates the rainfall-runoff and routing processes for both natural and anthropogenic-controlled environments, which can be used for event or continuous modeling. HEC-HMS contains a variety of internal models for simulating water losses, runoff transformations, open-channel routing, and methods for analysis and generation of meteorological input data. For this analysis, the following models/methods contained in HEC-HMS are used: (1) infiltrative losses were modeled using the Natural Resource Conservation Service (NRCS, 1986) (formally Soil Conservation Service (SCS)) curve number method, (2) NRCS unit hydrograph method using default settings was used to transform excess rainfall into surface runoff, and (3) basin wide precipitation is estimated using the NRCS (SCS) 24-hour hypothetical design storms, and 24-hour precipitation depths specified in the NOAA Atlas 14 for the Western U.S. Channel routing lag is not used in this analysis, but is incorporated into the time of concentration estimate.

Time of concentration (t_c) is estimated using the method described in the NRCS TR-55 manual (NRCS, 1986). The lag time (t_{lag}) parameter used in the NRCS method is estimated from the calculated t_c using the suggested NRCS default ($t_{lag} = 0.6t_c$). An assumed winter base flow of 0 cfs is included in the flood analysis. Basin-wide precipitation input for HEC-HMS consisted of the NRCS 24-hour Type 1A synthetic storm for the Pacific Northwest Region. Precipitation depths were determined from the NOAA Atlas 14 for each Erosion Site watershed.

NHE estimated watershed area, stream length, and stream slope from the 2010 LiDAR digital elevation model provided by National Park Service. Soil conditions were determined using a NRCS Web Soil Survey Database, and land cover classifications were based on the 2003 National Park Service Plant Community Classification and Mapping Project. A composite curve number (CN) was determined from area-weighted land use curve numbers defined by the underlying soil drainage quality (NRCS, 1986). HEC-HMS input parameters are summarized in (Table 1).

The 100-year peak flow water depth is used to determine bank protection rock height for sites that will be maintained as trail crossings (Bridge 10, 11, 12 and Culvert 4). The depth was estimated using the Hydraulic Design Uniform Flow tool in the U.S. Army Corp of Engineers (COE) River Modeling System, HEC-RAS V4.1 (COE, 2010). The Hydraulic Design tool requires input parameters of discharge, cross-section geometry, channel roughness and channel slope to estimate water depth. The tool assumes steady state flow, uniform channel dimensions with no abrupt contractions or expansions and an energy slope equal to the channel bed slope.

A range of channel slopes were measured in the field. For the bridges, the maximum water depth (h_{max}), was estimated using the minimum measured slope of 7% (measured in the field) and a conservative Manning' roughness coefficient (n) of 0.08. Minimum depth (h_{min}), was estimated using the maximum slope of 33%, corresponding to the design slope through the drop, and a low Manning' roughness coefficient of 0.035 are used. For the bridges, the Bridge 11 100-year peak flow was selected for the model discharge (Table 2). The Bridge 11 existing measured cross-section was selected for the model geometry, which was the most constrictive of the measured bridge cross-sections (bed width 1.3 ft, bank slopes ~1H:1V).

For Culvert 4, the 100-year flow water depth was estimated using the minimum measured slope of 1.75% (measured in the field) and a conservative Manning' n of 0.09. The Culvert 4 100-year peak flow and the design geometry was input in to the model.

Table 1. HEC-HMS input parameters.

Parameters	Unit	Bridge 10	Bridge 11	Bridge 12	Culvert 1	Culvert 3	Culvert 4
Watershed Area	(mi^2)	0.009	0.016	0.013	0.221	0.063	0.022
CN (Weighted)		68.97	66.39	65.68	68.62	68.91	65.56
Percent Impervious (assumed)	(%)	0	0	0	0	0	0
Initial Abstraction	(in)	0.90	1.01	1.05	0.91	0.90	1.05
Time of Concentration (T_c)	(min)	17.3	18.8	22.1	45.8	27.2	21.6
Hydrograph Lag Time (T_{lag})	(min)	10.4	11.3	13.2	27.5	16.3	13.0
Winter Baseflow (assumed)	(cfs)	0	0	0	0	0	0
100-year 24hr Precipitation Depth[1]	(in)	7.60	7.60	7.75	8.13	8.25	7.39

1) Precipitation depth from NOAA Atlas 14.

Channel Bed and Bank Materials for Maintained Channel Crossings

Bridge sites had similar watershed areas and channel slopes. The bridge site with the largest 100-year peak flow was used to design the channel bed and bank material for all bridge sites. Culverts 4 has a larger watershed area and lower slope, thus, bed and bank material size gradations were computing using site specific parameters.

The US Army Corps of Engineers steep slope riprap design equation (COE, 1994) was used to design the stable rock size during the 100-year flood (Eq. 1). This rock will line the bed and the bed and banks of the channel at the Bridge sites and Culvert 4 up to the 100-year water surface elevation. The rock is designed to provide a stable foundation and reduce the potential of water to outflank the constructed channel (Appendix I). The equation estimates the intermediate axis of the 30th percentile in the sediment distribution.

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

Where:

D_{30} = rock diameter of which 30 percent of the rock gradation is finer than by weight (ft),
S = slope of channel bed,
q = unit discharge (ft/s), and
g = gravitational constant (ft/s^2).

Unit discharge is multiplied by a safety factor (S_f) and calculated by equation:

$$q=Q/b \tag{Eq. 2}$$

where:

Q = discharge (ft^3/s) and
b = bottom width of the channel (ft).

Assuming a spherical rock with a specific gravity (γ) of 165 pounds per cubic foot, the weight (W_{30}) of the D_{30} rock can be calculated with the equation:

$$W_{30} = \frac{D_{30}{}^{3}\pi\gamma}{6} \tag{Eq. 3}$$

The W_{30} represents the minimum stable rock size that resists forces applied to it by moving water in the estimated design conditions. This rock size is used to determine the design channel rock gradation, following the procedures outlined in the California Department of Transportation (Caltrans) Guide to Determining RSP-Class (Caltrans, 2000).

Channel Bed Material for Decommissioned Channel Crossings

The bed material size gradation at crossings that will be decommissioned (Culvert 1 and 3) is based on the Bathurst (1987) unit discharge method to estimate the diameter of the D84 (84% of the material is finer than this size) (Eq 4). This method is recommended for slopes greater than 4%. The equation estimates the D84 that will be near the threshold of mobility. The median grain size (D50) is computed following Love and Bates (2009) (Eq 5).

$$D_{84} = \frac{3.54S^{0.747}1.25q^{2/3}}{g^{1/3}} \tag{Eq. 4}$$

$$D_{50} = 0.4 * D_{84} \tag{Eq. 5}$$

The finest 30% of the 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 bed material.

The bed 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.

Results and Recommendations

Peak Flow Estimates

The 100-year peak flow estimates for the bridge sites are under 10 cfs, while the culvert sites have estimates ranging from approximately 10 to 110 cfs (Table 2). Culvert 1 100-year peak flow estimate calculated using the USGS regional equation is 96.5 cfs. The HEC-HMS estimate of 109.1 cfs is approximately 12% higher than the regional estimate for the 100-year peak flow. Based on this comparison, the HEC-HMS peak flood estimates are considered conservative.

Table 2. HEC-HMS 100-year peak flow estimates.

Event	Bridge 10 (cfs)	Bridge 11 (cfs)	Bridge 12 (cfs)	Culvert 1 (cfs)	Culvert 3 (cfs)	Culvert 4 (cfs)
100-year	4.4	8.1	6.8	109.1	37.3	10.3

Bridge 10, 11, 12 Results and Recommendations

The 100-year peak flow estimated for Bridge 10, 11 and 12 can be found in Table 2, specifications are listed in Appendix II and material quantities are listed in Appendix III.

The recommendations for Bridges 10, 11 and 12 are to remove the crib wall and construct a rock lined channel in its place (See Appendix I, Sheet C1). The design rock channel will stabilize the upstream sediment plug and dissipate hydraulic energy from the drop. The design channel will conform to existing bed slope and bank grade at the upstream and downstream tie-ins. All disturbed areas will be covered with erosion control fabric and re-vegetated (See Appendix I, Sheet C1 and Appendix II).

The design rock channel is trapezoidal with a 2 foot wide bed and target bank slopes of >1.5H:1V. Typical design cross-sections are shown in Sheet C1 of the Plans (Appendix I). The design rock channel consists of three main components: the upstream tie in component that is approximately 5 feet long and conforms to existing channel bed slope, a variable length (See Appendix I, Sheet C1) drop component that has a slope 3H:1V, and a 20 foot long dissipation component that conforms to existing channel bed slope and dissipates the hydraulic energy created by the unstable flow through the design drop (See Appendix I, Sheet C1).

Input parameters and computed rock sizes are provided in Table 3. The larger estimate of the D_{30} and W_{30} rock are calculated to be 0.98 feet and 81 pounds, respectively. This larger size rock gradation was selected for the design rock slope protection (RSP) and is approximately equivalent to Backing No. 1 RSP (Caltrans, 2000). The maximum depth anticipated in the design conditions is 1 foot, consequently two layers of Backing No. 1 RSP is necessary to provide protection during a 100-year peak flow.

Table 3. Depth and rock size estimated for Bridge 10, 11, and 12.

	Slope 7%	Slope 33%
q (ft^2/s)	4.05	4.05
b(ft)	2	2
S	1.25	1.25
h_{max}(ft)	1	0.69
h_{min}(ft)	0.67	0.43
D_{30} (ft)	0.41	0.98
W_{30} (lb)	6	81

Culvert Sites 1, 3 and 4

The general recommendation for culvert sites is to remove the culvert and all associated structure including, but not limited to, rock walls, wood retaining walls, etc. The design channel geometry for the culvert sites is based on the measured channel bottom width upstream and downstream of the crossing and a target bank side slope of >1.5H:1V. Bank slopes, bed width and top width transition to conform to existing bed width and bank slopes at the upstream and downstream tie-in. The channel slope will transition from the upstream channel grade to the downstream channel grade.

The coarse bed material is sized based on whether the crossing will be maintained. Maintained crossings (Culvert 4) has a more conservative rock size and bank slopes up to the 100-year flood are lined with rock to increase stability at the crossing and are equivalent to Bridge sites (Table 3). Decommissioned crossings (Culverts 1 and 3) are returned to a natural bed material size and gradation, and banks are lined with erosion control fabric only. Site specific coarse bed material grain sizes for Culverts 1 and 3 (Table 4) are similar to the coarse bed material gradation proposed for Culvert 2 (NHE, 2015), thus one coarse bed material gradation is recommended for Culverts 1, 2, and 3 (See Appendix II).

Typical design cross-sections are shown in Sheet C2 – C4 of the Plans (Appendix I), specifications are provided in Appendix II, and material quantities are provided in Appendix III.

Table 4. Depth and rock, and coarse bed material gradation estimated for Culvert 1, 3, and 4.

	Culvert 1	Culvert 3	Culvert 4
q (ft^2/s)	24.2	9.3	3.4
Slope	0.04	0.07	0.25
b(ft)	4.5	4	3
S_F	1.25	1.25	1.25
h (ft)	3.18	1.81	1.16
D_{30} (ft)	NA	NA	1.12
W_{30} *(lb)*	NA	NA	36.6
D_{84}	1.05	0.85	NA
D_{50}	0.42	0.34	NA

Erosion Sites

Erosion sites 1 and 2 are active headcuts that receive excess water from the channelized trail. The treatment of both erosion sites requires excess water that is concentrating in the existing trail and entering the headcut to be diverted away from the active headcuts. The decommissioned trail must be outsloped so excess water will not concentrate on the trail and into small swales, channels, or headcuts and include properly spaced water bars and drainage dips (Figure 13). The decommissioned trail should be covered with erosion control fabric to ensure that it is not re-channelized prior to vegetation establishment.

Erosion Site 1 Recommendation

The recommendation for Erosion Site 1 is to demolish the trail, fill the headcut with soil and cover with erosion control fabric and re-vegetate (See Appendix I, Sheet C7). The headcut will be filled with native soil, covered with erosion control fabric, and re-vegetated (See Appendix II).

Erosion Site 2 Recommendation

The primary headcut (Headcut 1) at the edge of the trail will be filled with native soil and covered to a maximum slope of 2H:1V (See Appendix I, Sheet C6). The banks in the vicinity of the headcut will be graded to a maximum of 1.5H:1V. Soil is expected to be generated from off-haul at other crossing sites. The soil and any disturbed areas will be covered with erosion control fabric and re-vegetated. Downslope of the headcut, large tree roots cross the channel and hold soil. These areas should not be disturbed. Exposed portions of the channel between roots can be carefully backfilled with logs and small woody debris to increase roughness, reduce erosion and promote trapping of fine sediments.

Headcut 2 is obscured by vegetation. Non-woody vegetation should be cleared and the headcut should be filled with soil, similar to Headcut 3, covered with erosion control fabric and re-vegetated.

Trail Crossing 2

Designs for the channel crossing at the spur trail were not included as part of this scope of work. At the request of GGNPC, a general recommendations for treatment is included, but specific site designs were not developed by NHE. NHE provided an initial recommendation that a bridge should be installed at the crossing, similar to the proposed bridge at site Bridge 10, located 64 feet upstream.

Mike Nelson of CDPR Trails assessed this area and determined that building a bridge at this location would require significant changes to the trail. Due to the existing grade of the trail, installing a bridge would require either building a long ramp with a retaining wall to the bridge on the lower portion of the trail, or cutting the trail down on the higher portion of the trail and re-grading the connection to Redwood Creek Trail.

An alternative option was proposed by Mike Nelson that does not require substantial trail work. This option maintains the wet crossing in the existing location. CDPR plans to install a rock armored crossing on the tread and a rock wall in the channel to protect the portion of trail that is being undercut. The channel banks on the downstream side of the trail will be re-graded to facilitate the construction of a rock wall and rock slope protection that will stabilize the toe of the trail and dissipate energy. The total amount of soil to be removed is estimated to be roughly 10 CY.

The rock wall will be hand-constructed with ¼ ton rock, using small rock to backfill voids. The rock will be keyed into the base of the channel and into the slope. The wall will wrap around, so that it covers both the area parallel to the trail and the left and right banks of the channel downstream of the trail crossing to ensure bank stability in the vicinity of the crossing. The footing for the rock wall, installed below the surface grade of the channel, will be approximately 3' deep x 3'high x 13' wide. The rock wall placed atop this footing will be approximately 7' high x 13' wide. The face of the wall will be at an approximate 70% grade, extending approximately 10' downstream at the base and will act as a flow dissipater with irregular protruding rocks and small pockets to slow water velocity as it cascades down the channel.

NHE has not reviewed site specific dimensions for the proposed approach, but concurs that this approach is suitable for the location, given the site constraints.

Monitoring

Specific post-project monitoring recommendations vary depending on the site; however, the following procedures apply to all sites.

- The first survey and inspection should be conducted following site construction to document the as-built condition. Subsequent surveys and inspections should be conducted annually for the first 3 years. Following the initial 3-year monitoring period, photo monitoring should occur following large floods (~2-5 year recurrence interval).
- A sketch map of the site should be included with the initial survey to aid in locating end pins during future surveys. The sketch map should have distances from a minimum of three stable, easily identifiable features (e.g. bridge, large trees, etc.) such that the location can be triangulated using tapes.
- The cross-sections and longitudinal profile should be tied into a common datum that is in a stable location, outside the areas of the trail that may require future maintenance and out of sight to minimize vandalism. Cross-sections and longitudinal profiles should be surveyed with an engineer's auto-level or equivalent survey equipment.
- Photos points that document the upstream and downstream channel tie-in and constructed channel conditions should be established. Vegetation should not be cut to maintain a line of sight. Areas that are not visible in the photo should be documented with a descriptive narrative of the channel and bank condition and new photos points established as needed.

Site specific recommendations are provided in the following sections.

Sites that are maintained as Trail Crossings

Post project monitoring should be conducted to assess the stability of the bed and banks in the vicinity of the crossings at Bridge 10, 11, 12, Culvert 4 and Trail Crossing 2. The sites that will be maintained at trail crossings are expected to be generally stable. A headcut is not expected to originate at the project site. However, the constructed crossings will not prevent a headcut from moving upstream that originates downstream of the project site. Where possible, headcuts should be stabilized prior to reaching the project site.

Establish four permanent monitoring cross-sections and a longitudinal profile per site. Channel cross-sections can be used to identify bank erosion and channel incision or aggradation. The longitudinal profile can be used to identify the extent of channel change between the cross-section and the stability of the drop. Cross-sections should be monumented with rebar with plastic caps (end pins).

- Cross-section 1 should be located approximately 3-5 channel widths downstream of the construction area.
- Cross-section 2 should be located downstream of the drop.
- Cross-section 3 should be located immediately upstream of the drop.
- Cross-section 4 should be located 3-5 channel widths upstream of the construction area.

A longitudinal profile between cross-section 1 and 4 should be established. The longitudinal profile will help identify the extent channel changes between cross-sections.

The interface between the rock and the soil and/or erosion fabric should be inspected for erosion. The rock should be inspected for large gaps and filled as needed. If the gap in the rock occurs such the at the rock slope protection fabric is exposed, the fabric should be inspected for tears and repaired as needed.

Decommissioned Trail Crossings

These sites are designed to return the channel to a typical stream condition. Channel adjustments at these sites are expected within the range of the adjustments occurring upstream and downstream. These sites are not designed to halt, or slow incision that is occurring throughout the tributary network.

Post project monitoring should be conducted to ensure that vegetation is re-established on constructed banks to provide necessary root-strength to avoid excessive erosion and that bed material is not exported from the project site at a rate faster than it is being replaced by the upstream sediment supply. This condition would be identified through the exposure of bare soil in the stream bed, or a headcut moving upstream from the project site.

Three monitoring cross-sections should be established at each site. In order from downstream to upstream:

- Cross-section 1 is located 3-5 channel widths downstream of the construction area.
- Cross-section 2 is located at the existing channel crossing.
- Cross-section 3 is located 3-5 channel widths upstream of the construction area.

A longitudinal profile should be measured upstream between cross-sections 1 and 3.

Erosion Sites 1 and 2

These sites should be monitored to ensure the existing headcuts do not migrate upstream. The keys to stabilization at these sites are outsloping the trail, adding water bars as needed, vegetating the decommissioned trail to avoid excess water from entering the headcut, stabilizing the active portion of the headcut through re-grading, erosion control fabric and re-vegetation. Site visits should occur when there is runoff to ensure excessive water is not concentrating at the headcut locations. A longitudinal profile should be surveyed from Redwood Creek to the former trail (upslope of the headcut) to ensure the headcut does not re-establish and migrate upstream. The starting point of the profile should be marked with rebar with a plastic cap.

References

California Department of Transportation, (2000). California Bank and Shore Rock Slope Protection Design – Practitioner's Guide and Field Evaluations of Riprap Methods, California Department of Transportation, Caltrans Engineering Service Center, Sacramento, California, FHWA-CA-TL-95-10.

Natural Resource Conservation Service (formally Soil Conservation Service), 1986. Urban Hydrology for Small Watersheds, Technical Release 55. United States Department of Agriculture, Soil Conservation Service.

Northern Hydrology and Engineering (NHE), 2015. 50% Culvert #2 Design for Redwood Creek Trails Project. Prepared for Golden Gate National Parks Conservancy, 15 April 2015. Building 201 Fort Mason, 3rd Floor, San Francisco, CA 94123.

Stillwater Sciences, 2004. Sediment Budget for Redwood Creek Watershed, Marin County, California. Prepared for Golden Gate National Recreation Area, Building 201, Fort Mason, San Francisco, CA, 94123.

U.S. Army Corps of Engineers (COE), Hydraulic Engineering Center, 2013. Hydrologic Modeling System, HEC-HMS Version 4.0, User's Manual and Technical Reference Manual. U.S. Army Corps of Engineers Hydraulic Engineering Center, Davis, California, CPD-74A and CPD-74B.

U.S. States Army Corps of Engineers (COE), 2010. HEC-RAS, River Analysis System – User's Manual and Hydraulic Reference Manual. U.S. Army Corps of Engineers, Institute of Water Resources, Hydraulic Engineering Center, Davis, California, CPD-68 and CPD-69.

U.S. States Army Corps of Engineers (1994). Hydraulic Design of Flood Control Channels,

U.S. Army Corps of Engineers Hydraulic, Washington, DC, EM 1110-2-1601.

Gotvald, A.J., Barth, N.A., Veilleux, A.G., and Parrett, Charles, 2012, Methods for determining magnitude and frequency of floods in California, based on data through water year 2006: U.S. Geological Survey Scientific Investigations Report 2012–5113, 38 p., 1 pl., available online only at http://pubs.usgs.gov/sir/2012/5113/.

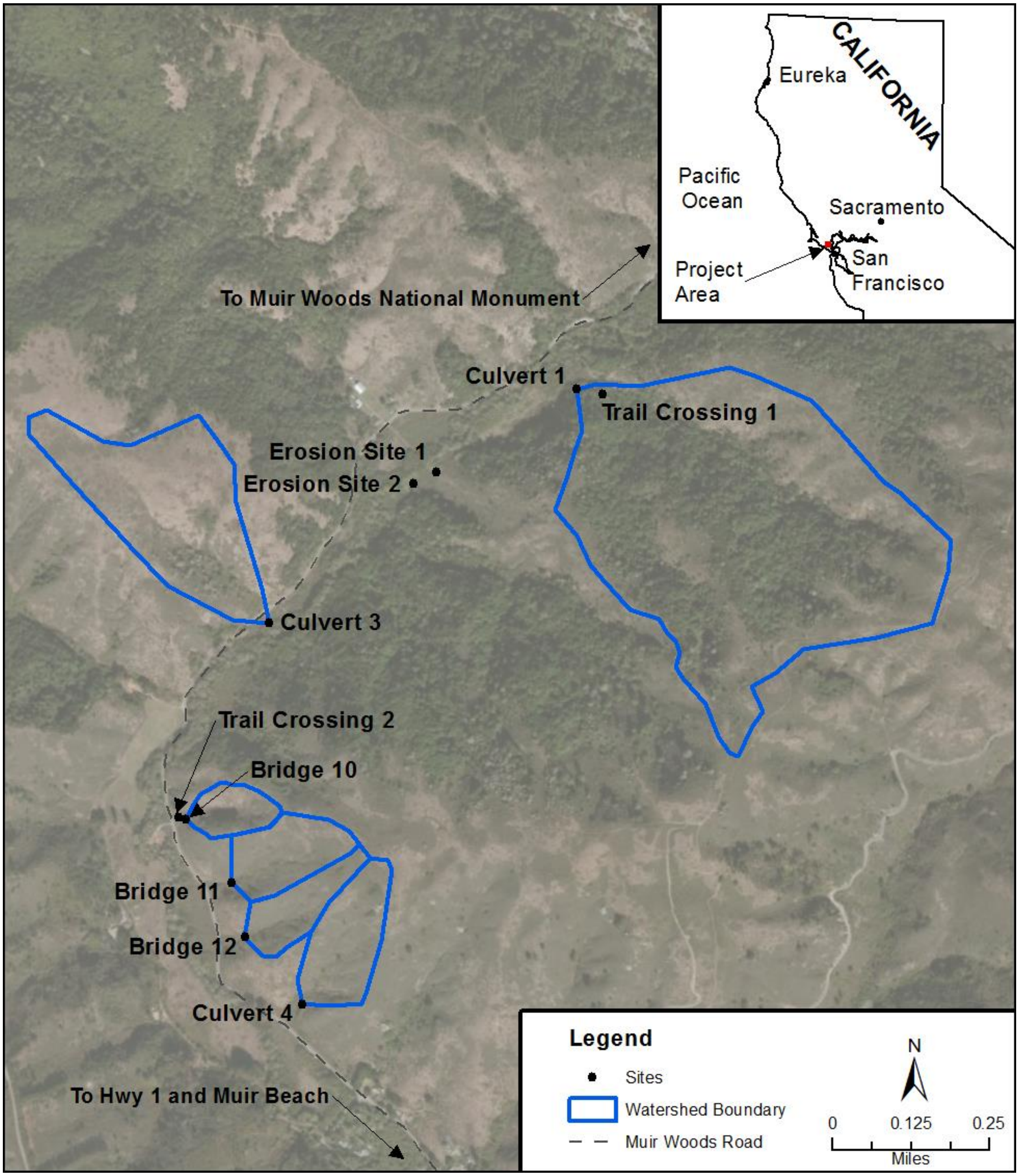

Figure 1. The sites are a located on the Redwood Creek Trail network in Marin County, California, approximately 15 miles north of San Francisco.

Figure 2. Crib wall at Bridge 10. Photo credit: GGNPC

Figure 3. Trail Crossing 2, looking downstream at actively eroding channel.

Figure 4. Crib wall at Bridge 11. Photo credit: GGNPC

Figure 5. Crib wall at Bridge 12. A wood bridge spans the crib wall. Photo credit: GGNPC

Figure 6. Culvert 1, looking upstream through culvert. Photo credit: GGNPC

Figure 7. Culvert 1, looking downstream. Photo credit: GGNPC

Figure 8. Trail Crossing 1, a stream crossing on Miwok Trail. Displayed in the photo are the investigative digging locations (round posts sticking out of the ground): the trail hole where the digging bar is pointing (photo center), the upstream hole where the post hole digger is pointing, and the downstream hole where the handle end of the digging bar is pointing (far right in the photo). Photo credit: GGNPC

Figure 9. Culvert 3. Photo credit: GGNPC

Figure 10. Culvert 4. Photo credit: GGNPC

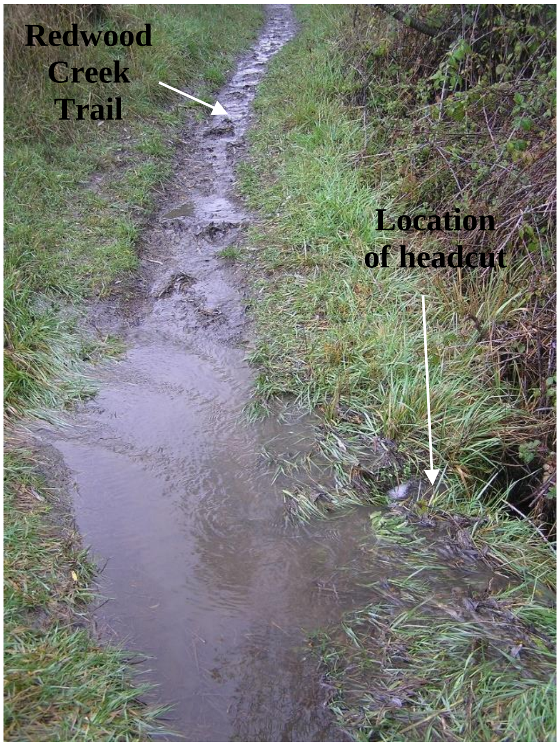

Figure 11. Erosion Site 1 is a small headcut that has developed immediately adjacent and downslope of Redwood Creek Trail (in the picture, the headcut is at bottom right where water is flowing off the trail). Photo credit: GGNPC

Figure 12. Erosion Site 2 following high rainfall. Water is flowing along Redwood Creek Trail into headcut. Photo credit: GGNPC

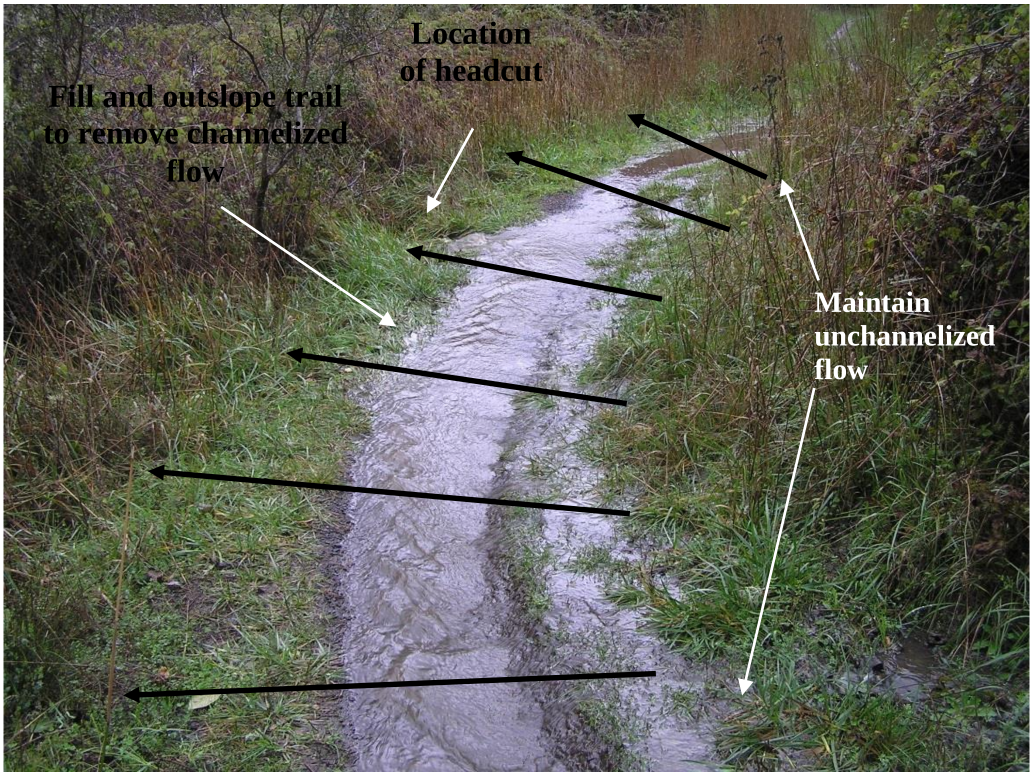

Figure 13. Erosion Site 2 following high rainfall with target flow paths that maintain unchannelized flow. Photo credit: GGNPC