Swale Creek Tributaries

Basis of Design Report

Klickitat, WA, 98628

LCE Project No. 3120

Prepared for:

Yakama Nation/Klickitat Fisheries Project
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Acronyms

Cubic Feet Per Second (CFS)
Hydrologic Engineering Center's-River Analysis System (HEC-RAS)
Light Detection and Ranging (LiDAR)
National Marine Fisheries Service (NMFS)
US Dept. of Agriculture (USDA)
Washing Dept. of Fish and Wildlife (WDFW)
Wolf Water Resources (WWR)
Yakama Nation (YN)

Preface

Project Description

In 2019 Wolf Water Resources (WWR) conducted a study for the Yakama Nation (YN) in order to support a strategic plan for Swale Creek watershed and trail enhancements. Some of the identified enhancements within the report are tributary drainage and sediment transport, reconnection of side channels, and conceptual designs to improve Swale Creek Bridge crossings. Through the study conducted by WWR, specific tributaries were identified that would bring a higher net benefit through enhancement projects than others. Rattlesnake Gulch Creek (unofficial local name) was identified as one of the higher priority tributaries for an enhancement project. According to information from the YN, watershed analysis of drainage area and slope found that Rattlesnake Gulch has the largest drainage area and sediment contribution potential of 18 tributaries evaluated in Swale Canyon. The conceptual designs in this project focus on increasing fish passage, increase of habitat quality, and increasing access to reaches further up the watershed.

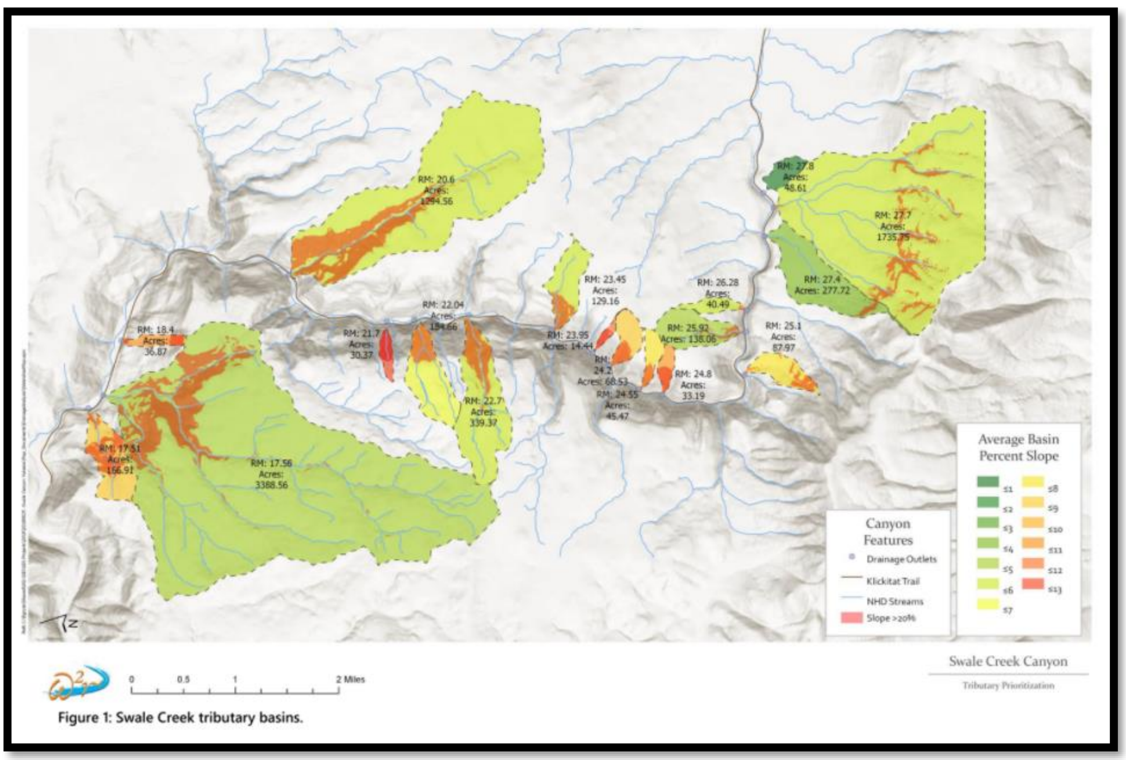
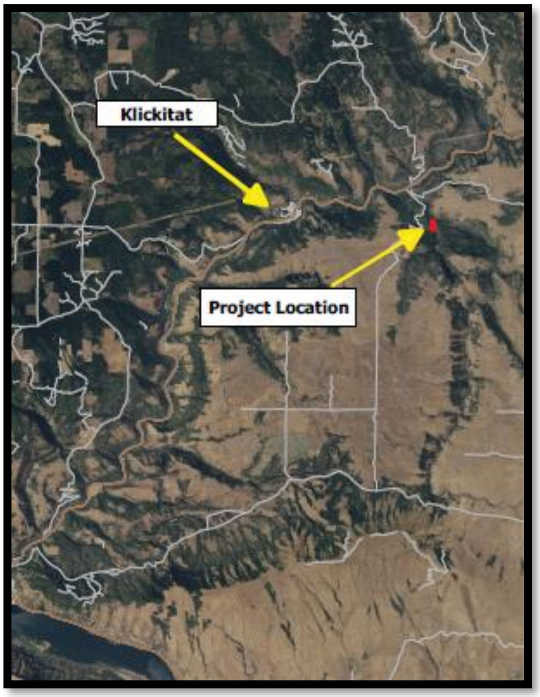


Figure 1. Swale Creek Tributary Basin (WWR Report 2019)

Project Reach Description

The location for this specific enhancement project is approximately 1000 feet upstream from the confluence of Swale Creek and the Rattlesnake Gulch tributary. The Rattlesnake Gulch tributary is comprised of two tributaries which converge approximately 800 feet from the Swale Creek confluence. Upstream from their confluence both tributaries pass under Lovers Lane Road at separate locations through culverts which are currently fish passage barriers. This project aims to remove those fish passage barriers and enhance the habitat around the crossings.



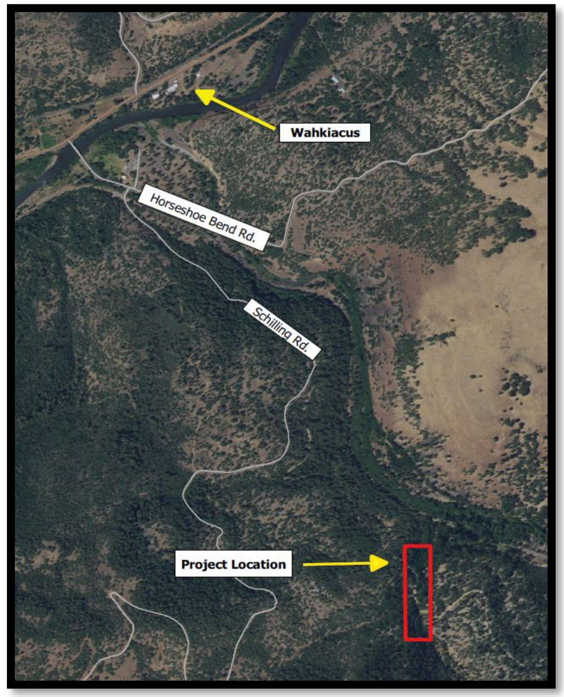


Figure 2. Project Location

Project Background

1) Name and titles of sponsor, firms and individuals responsible for design.

This project is sponsored by Yakama Nation. LC Eco *a division of Lower Columbia Engineering* is providing the engineering and design services for the project. Andrew Niemi (PE) is the licensed engineer of record for this project.

2) List of project elements that have been designed by a licensed Professional Engineer.

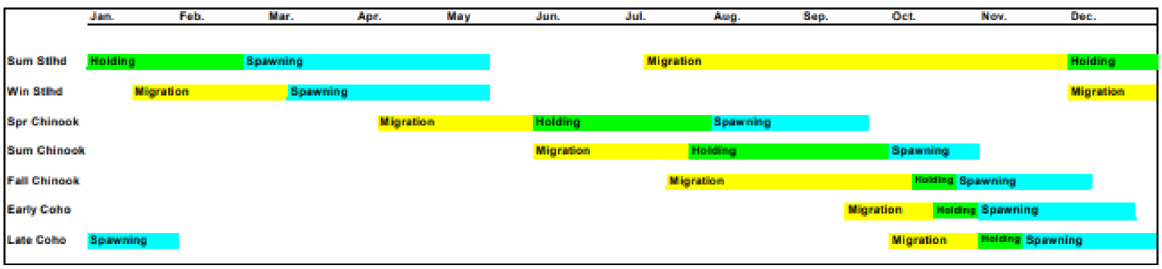
Andrew Niemi (PE) has personally performed a site assessment and the LC Eco team has evaluated several design alternatives. The following chart shows the selected project elements and the BPA HIP activity and risk category:

Description of Proposed Enhancement	Work Element	HIP Category	HIP Risk Level
Culvert Removal and Bridge Installation	Bridge and Culvert Removal or Replacement	1F	Medium
Log Structure to improve channel habitat suitability and stability	Install Habitat-Forming Instream Structures	2D	Medium
Replace creek bed when culvert is removed with fluvial material. Installation of shadow rocks.	Install Habitat-Forming Materials	2G	Low-Medium
Revegetation of all disturbed surfaces	Riparian vegetation planting	2E	Low

3) Explanation and background on fisheries use (by life stage - period) and limiting factors addressed by project.

The primary focus of this project is improving off-channel habitat for Swale Creek through fish passage barrier removal and habitat enhancement in two tributaries of Swale Creek. The species that are known to utilize the project area and will be directly impacted by the project are Steelhead and Rainbow Trout (*O. mykiss)*. Even though the project is focused on increasing access and habitat for steelhead and rainbow trout there is a likely chance it will benefit other ESA listed fish species as well as non-listed species. According to the WDFW Priority Habitats and Species website, within Swale Creek there have been occurrences of Fall Chinook, Coho, Spring Chinook, Winter and Summer Steelhead, as well as resident trout species (WDFW PHS Website 2021). The Klickitat Basin is a vast network of tributaries that provide spawning, rearing, and refugia habitat for multiple anadromous species as well as resident species. This project falls within the Klickitat Basin and will hopefully provide better passage and habitat enhancement for those species. Below is a table depicting the timing and activity of use within the Klickitat Basin by different species.

Table 1. Klickitat Basin Timing and Use by Species.



Source: YN Fisheries and WDFW 2000

Steelhead

The Klickitat River basin supports two runs of steelhead, winter and summer. Both are native to the system. The winter run is one of only two populations of inland winter steelhead in the United States (NMFS 1999) (the other is in Fifteenmile Creek). Both runs of Klickitat River steelhead are part of the Mid-Columbia Evolutionarily Significant Unit (ESU) and were listed as Threatened under the ESA in March of 1999 (NMFS 1999). Mainstem spawning distribution of steelhead is concentrated between RM 5 and RM 50, with occasional spawning above Castile Falls (RM 64, Figure 4). Tributary spawning occurs in Swale, Summit, and White creeks, the lower (and occasionally upper) Little Klickitat River, and other smaller tributaries (Yakama Nation 2004).

Rainbow Trout

Resident rainbow trout are found throughout the Klickitat basin. Naturally reproducing populations exist within the mainstem from RM 85 to the Columbia River confluence and in virtually all tributaries. (Yakama Nation 2004).

4) List of primary project features including constructed or natural elements.

The key components of this project are (1) to provide engineering designs services for replacing two road crossings to eliminate fish passage barriers, and (2) within the designs, provide habitat enhancement elements to improve longitudinal movement of flood flows, wood, and sediment within the tributaries.

Designing for Road Crossings

Currently there are two road crossings within the project area that are creating passage barriers through elevated culverts. The primary project features consist of replacing the culverts with two single span bridges that will create an open bottom, natural crossing for the tributaries.

Habitat enhancement

Currently the project area is lacking in large wood structures and lateral floodplain activation. In order to address these issues, the designs incorporate large wood placement, potential for floodplain/alluvial habitat enhancement, and plantings of native vegetation for bank stabilization as well as erosion and sediment control measures.

5) Description of performance / sustainability criteria for project elements and assessment of risk of failure to perform, risk to infrastructure, potential consequences and compensating analysis to reduce uncertainty.

Infrastructure and flood risk

The project is located on private property that has been made available by the landowner for the enhancement project. The roadway (Lovers Lane Rd) that is within the project area provides year around access to a permanent residence and multiple other pieces of private property. The current crossings in place over the tributaries are creating a bottleneck for flow and confines while crossing under the roadway increasing outflow velocities. The proposed bridges will decrease the current potential for flood risk to the roadway.

Design criteria

Heavy equipment will be used in the installation of the bridges, large wood placement, and boulder placement. Large wood structures will be stabilized to maintain position and function during high flow by partial burial of wood logs and bracing to timber piles and ballast boulders. Planting of native riparian vegetation will be conducted for bank stabilization and erosion control measures.

Risk of failure to perform

The site will benefit greatly from the removal of the old culverts beneath the crossings. By replacing the culverts with the single span bridges there will be a decreased potential for debris build up behind the road crossing which currently could lead to failure or the road being overtopped by the tributaries. Removal of the current culverts may cause a change to the flow rates on the downstream side of the crossing however, this can be managed through modeling the effects and reduced by large wood placement. All aspects of the project will be designed to reduce and/or eliminate risk of failure.

6) Description of disturbance including timing and areal extent and potential impacts associated with implementation of each element.

All areas of disturbance are depicted in the designs attached to this document. Disturbance will be limited to the access routes, work areas for bridge installation, and extents of large wood placement locations. Impacts will be minimized and avoided wherever possible to achieve as little impact as possible. Where areas of impact occur, the impacts will be offset after construction via plantings and seeding of native vegetation.

Resource Inventory and Evaluation

1) Description of past and present impacts on channel, riparian and floodplain conditions.

Within the project area there is apparent historical impacts to the channel of the tributaries. It appears that in the past that both tributaries have been channelized with machinery which appears to be why the floodplain is now cut off from the tributaries. It also is evident that after the confluence of the two tributaries there has been impact to the east bank in the form of a berm of soil between the creek bank and the assumed historic floodplain.

2) Instream flow management and constraints in the project reach.

The two crossings under Lovers Lane Rd. are currently constraints for instream flow. Located below the confluence of the tributaries there is a manmade pour over dam that was installed to create a soaking pool.

3) Description of existing geomorphic conditions and constraints on physical processes.

The project site falls within the southern portion of the Yakima fold-and-thrust belt. This is an area of topographical folds raised by tectonic compressions comprising a highly faulted zone. Basal geology is basaltic and associated with several different units of the Columbia River Basalt Group (WDNR 2013).

Our study area focused on a tributary entering Swale Creek at RM .5, that is unofficially referred to as "Rattlesnake Gulch Creek". This tributary splits into two forks just below Lovers Lane, approximately 600 Feet Southwest of the confluence with Swale Creek. Both forks generally flow to the Northeast. Elevations for the study area range from approximately 610 feet at Swale Creek to over 1,700 feet at the headwaters.

The primary area of focus, from approximately 200 feet below Lovers Lane, to .5 miles upstream (along both forks) included a heavily modified and disconnected floodplain. Native material throughout the floodplain has been pushed into berms with heavy equipment years ago. Based on visual observations, this material includes a primary mix of: gravels, cobble and boulders up to 4 feet in diameter. Bedrock was exposed in some areas in the upper portions of the reach. In general, embankments appear to be relatively stable with ample opportunity for floodplain reconnection with little risk to loss of vegetation or habitat. There was an observed lack of large woody debris within this reach, especially given the fact that the upper reach of the system is heavily forested before breaking out into the upper, more open plateau.

4) Description of existing riparian condition and historical riparian impacts.

Riparian vegetation is in moderate condition adjacent to the channel within the project reach and would benefit from more age class and species diversity. The majority of the riparian vegetation is "old growth" willow in thick patches located between the upper stream bank and the low flow edge of water. The upper banks of the reach primarily consist of pine and oak trees. The project area would greatly benefit from beaver activity.

5) Description of lateral connectivity to floodplain and historical floodplain impacts.

Due to the historic channel modifications the tributaries access to the adjacent floodplain is extremely limited. The channelization and berms have caused the tributaries to become incised, allowing for very little connectivity to adjacent floodplains.

6) Tidal influence in project reach and influence of structural controls (dikes or gates).

Not applicable to this project.

Technical Data

1) Incorporation of HIP specific Activity Conservation Measures for all included project elements.

HIP conservation measures will be met through the project design and requests for variances will be submitted for any conservation measures that cannot be met.

2) Summary of site information and measurements (survey, bed material, etc.) used to support assessment and design.

Elevation Data

The project location was surveyed in 2020 by LC Eco staff to collect cross sections, topographical data, and the existing infrastructure. Control points were established outside of the construction area for use in the next phases of the project. USGS monuments on the property corners were located and surveyed to assist in the geolocating of the project area.

Fish Use

Fish presence and life-stage timing data were taken from the 2000 Genetic Analysis of Chinook Populations in the Klickitat River (Yakama Nation 2000), the 1999a Endangered and Threatened Species: Threatened Status for Two ESUs of Steelhead in Washington and Oregon (NMFS 1999), and the 2004 Klickitat Subbasin Anadromous Fishery Master Plan (Yakama Nation 2004).

Aerial images

Historic aerial photos were viewed to assess historic impact. Photos were found dating back to 1996 and no obvious impact was apparent in the photos viewed from 1996 through 2020.

3) Summary of hydrologic analyses conducted, including data sources and period of record including a list of design discharge (Q) and return interval (RI) for each design element.

The flowrate for the design was a 100-year storm of 388 cubic feet per second (cfs) for Rattlesnake Gulch Tributary A and 104 cfs for the Rattlesnake Gulch Tributary B. The flow data was obtained from USGS Stream Stats and precipitation data from Applied Climate Information System.

Table 2: Peak discharge 88 feet upstream from stream crossing

Rattle Snake Gulch Tributary A						
Recurrence flow	2-YR	5-YR	10-YR	25-YR	50-YR	100-YR
Discharge (cfs)	73.1	158	187	261	322	388

Table 3: Peak discharge 55 feet upstream from tributary stream crossing.

Rattle Snake Gulch Tributary B						
Recurrence flow	2-YR	5-YR	10-YR	25-YR	50-YR	100-YR
Discharge (cfs)	23.9	44	60.6	84.1	103	124

4) Summary of sediment supply and transport analyses conducted, including data sources including sediment size gradation used in streambed design.

Not included in the scope of these conceptual designs. Will be addressed in later design phases.

5) Summary of hydraulic modeling or analyses conducted and outcomes – implications relative to proposed design.

A two-dimension (2D) model was created using the U.S. Army Corps of Engineers Hydraulic Engineering Center River Analysis System (HEC-RAS) in order to simulate the existing and proposed channel. The purpose of this model was to analyze changes in flow patterns and depth around the existing structures and proposed structures.

The existing conditions HEC-RAS model was developed using LC Eco survey data from 2020. The model extents are approximately 50 feet or more upstream of each project area and a couple hundred feet downstream of the structures in order to allow for minimal influence from model boundaries. The proposed conditions HEC-RAS model used LC Eco survey data that had been altered to reflect the removal of the culverts and the implementation of the new bridges. The terrain was the only alteration to the proposed conditions model.

The 2-D model geometry was developed with a mesh computational grid with a cell size of 6 feet. Break lines were applied to realign cell faces and add finer mesh detail with smaller cell sizes on the range of 1 to 2 feet. The higher detail allowed for higher computational accuracy with the more hydraulically complex areas of the model such as structures and the delta where the tributaries intersect. A spatially varying roughness (Manning's n) layer was created by hand-digitizing regions with similar land cover. In general, roughness coefficients were applied to these regions based on field observations, aerial photos, and professional judgement. The model applies only two Manning's n values; 0.05 for the main channel and floodplain and 0.02 for the existing culverts.

The model results show a decrease in velocity for both crossings after project implementation. A decrease in velocity supports the need for replacing the structures by creating more ideal conditions for fish habitat during high flow events. Sediment movement would decrease with lower velocities therefore decreasing risk of stream incision and erosion. This model does not include an analysis of habitat features.

6) Stability analyses and computations for project elements, and comprehensive project plan.

The habitat aspects of this project include log jams and shallow rock structures. The stability of the log structures was assessed using the USDA's Large Wood Structure Stability Analysis Spreadsheet (Rafferty, 2016). At this stage of design two representative log calculations were completed to show feasibility for the large wood placement.

The first set of logs are downstream of the delta between the two tributaries. The log set includes a root wad, a boulder for vertical ballast, and a piling to prevent rotational movement. The calculations were completed using the 100-year flowrate in order to represent the watersheds flashier hydrographs. The HEC-RAS existing conditions model outputs were applied for velocity and depth. The results show that the log stays in place during a 100-year flow with a factor of safety for buoyancy of 1.89, a factor of safety for horizontal forces of 13.27, and a factor of safety for moment forces of 3.54. Overall representing a low likelihood of movement.

The second set of logs are downstream of crossing B on the right bank. This log set includes a root wad but does not require any form of ballasting. The calculations were completed using variables as discussed for the first log. The results show that the log stays in place during a 100-year flow with a factor of safety for buoyancy of 2.8, a factor of safety for horizontal forces of 5.33, and a factor of safety for moment forces of 2.95. Overall representing a low likelihood of movement.

7) Description of how preceding technical analysis has been incorporated into and integrated with the construction– contract documentation.

The proceeding analysis was used as a basis for the conceptual designs.

8) For projects that address profile discontinuities (grade stabilization, small dam and structure removals): A longitudinal profile of the stream channel thalweg for 10 channel widths upstream and 10 channel widths downstream of the structure shall be used to determine the potential for channel degradation.

The longitudinal profiles of the stream thalwegs are provided in the conceptual designs.

9) For projects that address profile discontinuities (grade stabilization, small dam and structure removals): A minimum of three cross-sections – one downstream of the structure, one through the reservoir area upstream of the structure, and one upstream of the reservoir area outside of the influence of the structure to characterize the channel morphology and quantify the stored sediment.

Cross sections were taken at the inlet and outflow of the culverts to be replaced as well as up and down stream from each crossing. The channel morphology and stored sediment will be addressed in the conceptual designs.

Construction – Contract Documentation

1) Incorporation of HIP General and Construction Conservation Measures

Later design phases will include standard conservation measures in the drawings.

2) Design – construction plan set including but not limited to plan, profile, section and detail sheets that identify all project elements and construction activities of sufficient detail to govern competent execution of project bidding and implementation.

Proposed conditions drawings can be viewed in the drawing set. Design drawings will provide greater detail.

3) List of all proposed project materials and quantities.

Two bridges, pre-cast cement footings, fill aggregate, boulder armoring, and large wood/trees are proposed materials for the project. Quantities will be provided during later design phases.

4) Description of best management practices that will be implemented and implementation resource plans including:

Later phases of design will include the following:

- Site access staging and sequencing plan
- Work area isolation and dewatering plan
- Erosion and pollution control plan
- Site reclamation and restoration plan
- List of proposed equipment and fuels management plan

5) Calendar schedule for construction/implementation procedures.

A construction timeframe has not been established yet.

6) Site or project specific monitoring to support pollution prevention and/or abatement.

To be completed during later design phases.

Appendix A: References

Marshall, A.R. 2000. Genetic Analysis of Chinook Populations in the Klickitat River. WDFW unpublished draft Report to Yakama Klickitat Fisheries Project. WDFW Genetics Unit, Olympia, WA. 26 pp

NMFS. 1999a. Endangered and Threatened Species: Threatened Status for Two ESUs of Steelhead in Washington and Oregon. Department of Commerce, National Oceanic and Atmospheric Administration. Federal Register, Vol. 64, No. 57. March 25, 1999.

NMFS. 1999b. Biological Opinion on Artificial Propagation in the Columbia River Basin. Incidental Take of Listed Salmon and Steelhead from Federal and Non-Federal Hatchery Programs that Collect, Rear and Release Unlisted Fish Species. March 29, 1999. NMFS, Portland, OR. 175 pp. plus appendices.

Rafferty, M. 2016. Computational Design Tool for Evaluating the Stability of Large Wood Structures. Technical Note TN-103.1. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, National Stream & Aquatic Ecology Center. 27 p.

WDFW. Priority Habitat and Species Web map. https://geodataservices.wdfw.wa.gov/hp/phs/ Accessed 3/28/2021

Wolf Water Resources. 2019. Swale Creek Watershed and Trail Enhancement Prioritization Scheme.

Yakama Nation/WDFW. 2004. Klickitat Subbasin Anadromous Fishery Master Plan. Northwest Power Planning and Conservation Council. 173p.

Appendix B: HEC-RAS Results

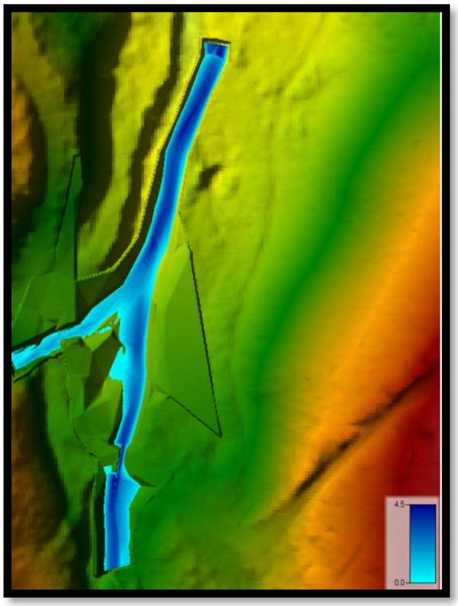


Figure 1: Existing conditions model at maximum depth for a 100 year flow

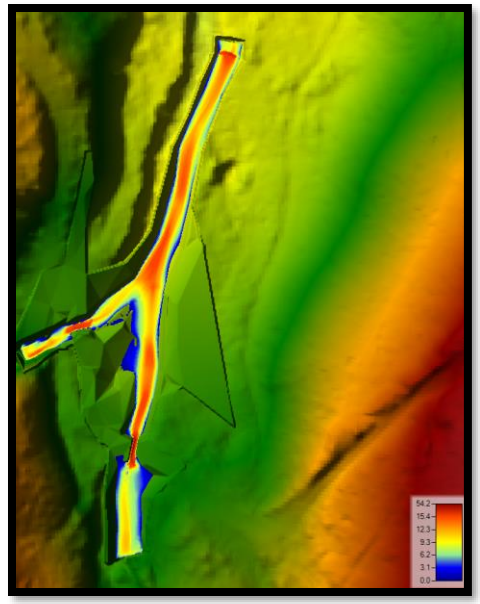


Figure 2: Existing conditions model at maximum velocity during a 100-year flow event.

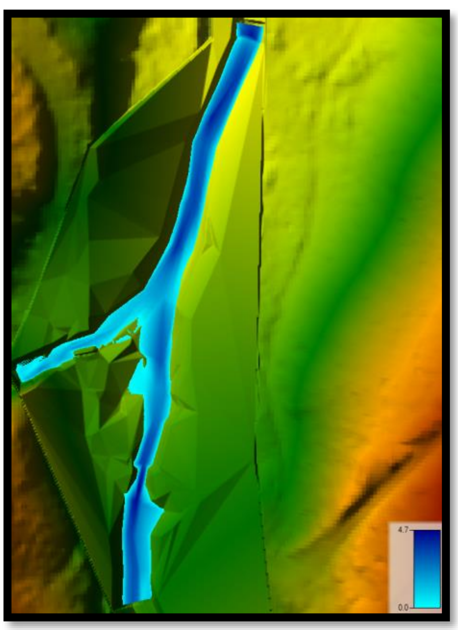
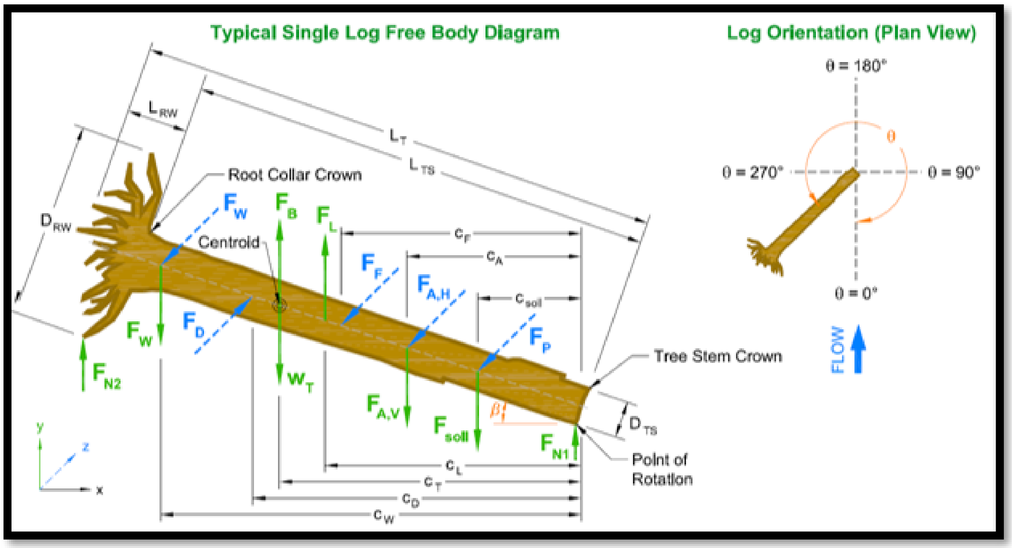


Figure 3: Proposed conditions model at maximum depth during a 100-year flow event.

Figure 4: Proposed conditions model at maximum velocity during a 100-year flow event.

Appendix C: Log Jam Calculations



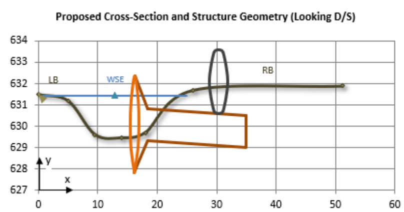
Swale Creek Tributary Restoration — *Spreadsheet developed by Michael Rafferty,*

Single Log Stability Analysis Model Inputs

Site ID	Structure Type	Structure Position	Meander	Station	d_w (ft)	R_c/W_{BF}	u_{des} (ft/s)
Delta	Full-Span	Right bank	Inside	+6	2.00	0.07	13.00

Multi-Log Structures	Layer	Log ID
	Key Log	Key 1

Channel Geometry Coordinates		
Proposed	x (ft)	y (ft)
Fldpln LB	0.00	631.50
Top LB	5.00	631.20
Toe LB	9.50	629.60
Thalweg	14.00	629.45
Toe RB	18.00	629.70
Top RB	26.00	631.70
Fldpln RB	51.20	631.90



Wood Species	Rootwad	L_T (ft)	D_{TS} (ft)	L_{RW} (ft)	D_{RW} (ft)	γ_{Td} (lb/ft^3)	γ_{Tgr} (lb/ft^3)
Pine, Ponderosa	Yes	20.0	1.50	2.25	4.50	28.0	45.0

Structure Geometry	θ (deg)	β (deg)	Define Fixed Point	x_T (ft)	y_T (ft)	$y_{T,min}$ (ft)	$y_{T,max}$ (ft)	A_{Tp} (ft^2)
	290.0	-1.0	Stem tip: Bottom	35.00	629.00	627.85	632.35	7.27

Soils	Material	γ_s (lb/ft^3)	γ'_s (lb/ft^3)	ϕ (deg)	Soil Class	$L_{T,em}$ (ft)	$d_{b,max}$ (ft)	$d_{b,avg}$ (ft)
Stream Bed	Coarse gravel	123.4	76.8	38.0	5	0.00	0.00	0.00
Bank	Coarse sand, dense	120.0	74.7	43.0	5	13.70	1.27	0.97

Vertical Force Analysis

Net Buoyancy Force

Wood	V_{TS} (ft^3)	V_{RW} (ft^3)	V_T (ft^3)	W_T (lbf)	F_B (lbf)
↑WSE	0.0	0.9	0.9	25	0
↓WS↑Thw	27.0	9.3	36.3	1,015	2,265
↓Thalweg	4.4	3.6	7.9	358	496
Total	31.4	13.8	45.2	1,398	2,761

Lift Force

C_{LT}	0.00
F_L (lbf)	0

Soil Ballast Force

Soil	V_{dry} (ft^3)	V_{sat} (ft^3)	V_{soil} (ft^3)	F_{soil} (lbf)
Bed	0.0	0.0	0.0	0
Bank	4.3	15.5	19.8	1,673
Total	4.3	15.5	19.8	1,673

Vertical Force Balance

F_B (lbf)	2,761	↑
F_L (lbf)	0	
W_T (lbf)	1,398	↓
F_{soil} (lbf)	1,673	↓
$F_{W,V}$ (lbf)	0	
$F_{A,V}$ (lbf)	2,156	↓
ΣF_V (lbf)	2,465	↓
FS_V	1.89	

Horizontal Force Analysis

Drag Force

A_{Tp} / A_W	Fr_L	C_{DI}	C_w	C_D*	F_D (lbf)
0.40	1.87	1.10	0.01	3.20	3,817

Passive Soil Pressure / Friction Force

Soil	K_p	F_P (lbf)	L_{Tf} (ft)	μ	F_F (lbf)
Bed	4.20	0	3.85	0.78	337
Bank	5.29	4,424	18.15	0.93	1,897
Total	-	4,424	22.00	-	2,234

Horizontal Force Balance

F_D (lbf)	3,817	→
F_P (lbf)	4,424	←
F_F (lbf)	2,234	←
$F_{W,H}$ (lbf)	44,000	←
$F_{A,H}$ (lbf)	0	
ΣF_H (lbf)	46,840	←
FS_H	13.27	

Moment Force Balance

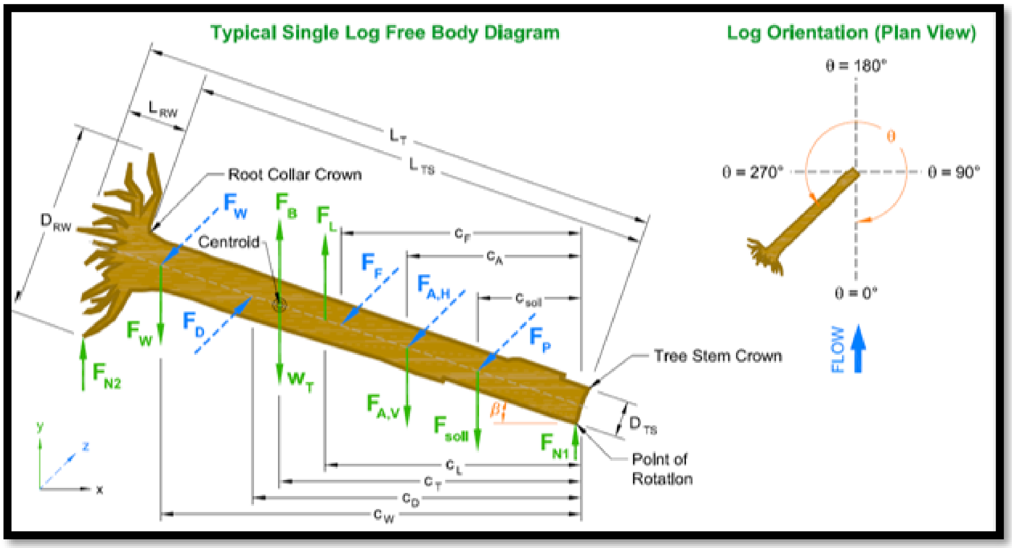
Driving Moment / Resisting Moment Centroids

$c_{T,B}$ (ft)	c_L (ft)	c_D (ft)	$c_{T,W}$ (ft)	c_{soil} (ft)	$c_{F\&N}$ (ft)	c_P (ft)
12.2	0.0	16.9	12.2	6.8	10.0	9.1
*Distances are from the stem tip			Point of Rotation:		Stem Tip	

Moment Force Balance

M_d (lbf)	97,928
M_r (lbf)	346,219
FS_M	3.54

Figure 1: Large wood calculation for a root wad log in the downstream portion of the project



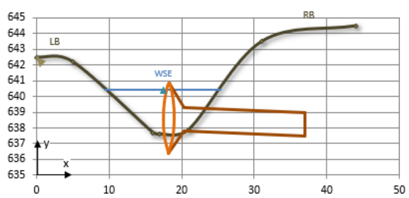
Swale Creek Tributary Restoration — Spreadsheet developed by Michael Rafferty,

Single Log Stability Analysis Model Inputs

Site ID	Structure Type	Structure Position	Meander	Station	d_w (ft)	R_c/W_{BF}	u_{des} (ft/s)
Trib B	Full-Span	Right bank	Straight	+10	2.80	0.07	16.00

Multi-Log Structures	Layer	Log ID
	Key Log	Key 1

Channel Geometry Coordinates		
Proposed	x (ft)	y (ft)
Fldpln LB	0.00	642.50
Top LB	5.00	642.20
Toe LB	16.00	637.70
Thalweg	17.00	637.60
Toe RB	21.00	637.90
Top RB	31.00	643.50
Fldpln RB	44.00	644.50



Wood Species	Rootwad	L_T (ft)	D_{TS} (ft)	L_{RW} (ft)	D_{RW} (ft)	γ_{Td} (lb/ft³)	γ_{Tgr} (lb/ft³)
Pine, Ponderosa	Yes	20.0	1.50	2.25	4.50	28.0	45.0

Structure Geometry	θ (deg)	β (deg)	Define Fixed Point	x_T (ft)	y_T (ft)	$y_{T,min}$ (ft)	$y_{T,max}$ (ft)	A_{Tp} (ft²)
	290.0	-1.0	Stem tip: Bottom	37.00	637.50	636.35	640.85	9.64

Soils	Material	γ_s (lb/ft³)	γ'_s (lb/ft³)	ϕ (deg)	Soil Class	$L_{T,em}$ (ft)	$d_{b,max}$ (ft)	$d_{b,avg}$ (ft)
Stream Bed	Coarse gravel	123.4	76.8	38.0	5	0.00	0.00	0.00
Bank	Coarse sand, dense	120.0	74.7	43.0	5	14.48	4.96	3.31

Vertical Force Analysis

Net Buoyancy Force

Wood	V_{TS} (ft³)	V_{RW} (ft³)	V_T (ft³)	W_T (lbf)	F_B (lbf)
↑WSE	0.0	0.2	0.2	5	0
↓WS↑Thw	31.3	11.6	42.8	1,197	2,671
↓Thalweg	0.1	2.1	2.2	98	136
Total	31.4	13.8	45.2	1,299	2,807

Lift Force

C_{LT}	0.13
F_L (lbf)	308

Soil Ballast Force

Soil	V_{dry} (ft³)	V_{sat} (ft³)	V_{soil} (ft³)	F_{soil} (lbf)
Bed	0.0	0.0	0.0	0
Bank	45.7	25.8	71.5	7,417
Total	45.7	25.8	71.5	7,417

Vertical Force Balance

F_B (lbf)	2,807	↑
F_L (lbf)	308	↑
W_T (lbf)	1,299	↓
F_{soil} (lbf)	7,417	↓
$F_{W,V}$ (lbf)	0	
$F_{A,V}$ (lbf)	0	
ΣF_V (lbf)	5,601	↓
FS_V	2.80	✓

Horizontal Force Analysis

Drag Force

A_{Tp} / A_W	Fr_L	C_{DI}	C_w	C_D*	F_D (lbf)
0.24	2.30	1.10	0.00	1.94	4,639

Passive Soil Pressure / Friction Force

Soil	K_P	F_P (lbf)	L_{Tf} (ft)	μ	F_F (lbf)
Bed	4.20	0	3.20	0.78	692
Bank	5.29	19,615	17.05	0.93	4,398
Total	-	19,615	20.25	-	5,089

Horizontal Force Balance

F_D (lbf)	4,639	→
F_P (lbf)	19,615	←
F_F (lbf)	5,089	←
$F_{W,H}$ (lbf)	0	
$F_{A,H}$ (lbf)	0	
ΣF_H (lbf)	20,066	←
FS_H	5.33	✓

Moment Force Balance

Driving Moment			Resisting Moment Centroids			
$c_{T,B}$ (ft)	c_L (ft)	c_D (ft)	$c_{T,W}$ (ft)	c_{soil} (ft)	$c_{F\&N}$ (ft)	c_P (ft)
12.2	19.2	17.3	12.2	7.2	9.1	9.6

*Distances are from the stem tip — Point of Rotation: Stem Tip

Moment Force Balance

M_d (lbf)	120,212
M_r (lbf)	354,819
FS_M	2.95

Figure 2: Upstream large wood placement calculations for one root wad log.