ASSESSMENT, RESTORATION, AND MANAGEMENT OF THE N PUYALLUP TRAIL, MOUNT RAINIER NATIONAL PARK

Taylor R Kenyon

A report prepared in partial fulfillment of the requirements for the degree of
Master of Science
Earth and Space Sciences: Applied Geosciences

University of Washington
December 2016

Project Mentor:
Paul Kennard, NPS

Internship Coordinator:
Kathy Troost

Reading Committee:
Brian Collins
Alison Duvall

MESSAGe Technical Report Number: 046

Executive Summary

The N Puyallup Trail, on Klapatche Ridge in Mount Rainier National Park, was originally the end of the Westside Road. The N Puyallup Trail has developed issues of surface erosion and landsliding since the area east of Klapatche Point was converted to wilderness area in 1988 (Owens, 2006). The wilderness designation limits the park's ability to provide cyclic maintenance using motorized equipment. As a result many features on the trail are damaged by infilling of soils, erosive damage from the lack of surface water management, and landslides (Owens, 2006). These conditions have resulted in damage to the trail surface and the production of harmful sediment inputs into the N Puyallup River, home to the endangered bull trout (ECOS, 2015).

A major task for this project was to determine and catalogue features on the site worthy of priority status for restoration or repair. The ultimate goal of the investigation was to recommend repairs that would protect the road surface while also minimizing the production of fine sediment and landslides that reach the N Puyallup River. In doing so, this project helps safeguard both the historic trail and the sensitive river ecosystem downslope from further harm.

My results indicate that the most significant concern is unmanaged surface water on the trail. These flows have led to surface erosion to the trail surface and fill slope, deposition of sediments onto the trail surface, and shallow landslides. In many cases issues of drainage occur in combinations at a single point. This can be seen as deposition of alluvial materials coming from multiple channels, excess water incising the trail surface and being pirated down the road grade, and incision leading to a point where the flow path is occasionally directed off the fill slope causing erosion and mass wasting.

Debris flows are the most common form of mass wasting on the trail, and most of these have surface water piracy as either triggers or at least contributing to their instability. All debris flows on site are sourced from the fill slope of the trail. Most debris flows on site transport material into pre-existing channel convergences, but some have scoured new paths downslope that are now being occupied by pirated surface water flows. Rockfall occurs across the length of the trail on several headwalls with slopes greater than 45 degrees, and appears to be independent from drainage problems on site. Points posing the greatest threats to the trail include upslope headwalls producing both dry rockfall and shallow slides. Colluvial hollows left by debris flows show headward retreat, narrowing the width of the trail and oversteepening slopes. The steepest sections of ridge have rockfall accumulating near the fill slopes, narrowing the trail further and loading the already at-risk slopes.

All points mapped for this investigation were at risk of damaging the trail surface, affecting the water quality of the N Puyallup River via fine sediment inputs, or harming the overall quality of the river habitat via landslides. The combinations of surface erosion and mass wasting types were the deciding factor as to what designs are recommended at each point. The list of repairs includes culvert restoration, waterbar installation, segments of ditch clearing, spillways for drainages, soil bioengineering to add root stability, buttressing of colluvial slopes, and gabion reinforcement.

The top priority is the cleaning or replacement of culverts. Culverts in my designs are used to handle areas that need to pass high or constant discharge, and their flow paths are built to drain into stable channel networks. I have recommended that they be replaced by high volume relief drainages to allow them to be maintained without the assistance of machinery. Waterbars should be used to provide erosion-resistant flow paths, allowing us to direct water toward more stable outlet locations

along the fill slope. These will be installed in multiples, enabling the new drainage to handle various flow levels and be able to withstand at least one slope failure. Using waterbars helps reduce the problems of water piracy and direct surface water away from the crowns and scarps of mass wasting features.

Soil bioengineering is a low-cost, easily-installed approach for reinforcement of unstable soils along the site, encouraging a progression toward a naturally stable state (Polster, 2002). I have recommended the use of wattle fences to reinforce the headwalls of colluvial hollows, and live staking on oversteepened fill slopes. I also recommend the use of live staking as buttressing measures intended to reduce effective slope and act as a colluvial storage system. Rockfall should also be unloaded where it is piled near stone walls, near steep slopes, or narrows access to the trail.

After repairs are completed efforts should made to establish annual or bi-annual monitoring and maintenance procedures to ensure that the trail progresses toward a stable state, remaining accessible to visitors and environmentally friendly. Maintenance actions will also be partly dependent on the monitoring process, as some features will not need maintenance unless they fail. This will help determine when maintenance is required and where it should be focused. Regular maintenance procedures should be performed every 2 or 3 years because the chosen designs should make most of the structures somewhat self-cleaning and fail-safe.

Investigation should be performed for any components of the site that I was not able to. The features that I think will need better investigation are of the condition of each of the stone walls, and the natural channels that contact the trail from upslope. For walls investigation should note the slope of the front face and the integrity of walls to see if their condition is deteriorating. Channels contacting the trail from upslope should be investigated to assess the discharge and flow paths of each, allowing for continued monitoring. These channels exist at some of the most unstable points on the trail and have and are generally the primary source of surface water at those points. Increases in discharge or changes in flow path on the trail could necessitate that changes be made to the local drainage networks and other reinforcements.

If all these plans are followed the N Puyallup Trail should remain stable and even become a higher quality experience for park visitors.

Contents

Introduction

The N Puyallup Trail exists along the western edge of Mount Rainier National Park, and was once the last 3 miles of the Westside Road east of Klapatche Point before being designated as a wilderness area during the expansion of the Wilderness Act in 1988 (Figures 1-3). The trail rests midway up the north face of Klapatche Ridge (Figure 3). The Westside is now closed to the public, and the trail is now used much less that it is at least 9 miles on foot from any visitor vehicle access point. In recent years the N Puyallup Trail has not received regular maintenance and has been subjected to landslides and debris flows, damaging the trail and threatening the North Puyallup River downslope.

The restoration of the N Puyallup Trail is important for environmental concerns and infrastructure management. Degradation of the N Puyallup Trail causes the production and transport of harmful sediments into the N Puyallup River which is home to the endangered bull trout (ECOS, 2015), and the accumulation of damages to the trail threatens continued visitor access. Efforts to restore the trail and halt erosion must leave the trail easy to maintain and repair. My goal is to assess the geomorphic conditions and controls on the site in order to recommend repair designs that mitigate erosion of the trail surface and effects on the N Puyallup River. The greatest benefit will be from designs that make the trail as close to self-maintaining as possible while minimizing sediment transport, and fail-safe for at least one destructive event. Such plans will preserve the historic resources of the trail while also protecting the wilderness.

Background

The N Puyallup Trail is located within Mount Rainier National Park within the South Cascade geologic province of Washington State (WA DNR, 2016; Figure 1-2), and begins at the 12.2 mile mark of the Westside Road, called Klapatche Point (Owens, 2006). The trail is 3 miles in length and Klapatche Point exists at GPS coordinates (46.848, -121.919) on the west face of Mount Rainier, at 4100 feet of elevation on the divergent point of Klapatche Ridge (Figures 1 and 2). Klapatche Ridge is bordered on the north and south by the North Fork Puyallup River and St. Andrews Creek, respectively. Klapatche Ridge has up to 1700 feet of relief along its tallest sections, and has slopes with a concave-up profile. Slopes contacting the N Puyallup Trail generally range from 30-55 degrees, but some sections of the trail cross vertical rock cuts.

This trail was once part of the Westside Road after being completed in 1934, but was converted to a trail in 1988. Annual maintenance of the trail was suspended in 2001. The vegetation has grown to match the natural setting of the park, including a coniferous overstory of western hemlock, Douglas fir, western red cedar, Pacific silver fir, and yellow cedar (Owens, 2006). The understory consists of vine maple, red alder, rocky mountain maple, and Sitka alder (Owens, 2006). The trail connects the end of the Westside Road to the Wonderland Trail.

No rain gauge directly relevant to Klapatche Ridge exists, and the closest monitoring point for such data is the Mowich SNOTEL station with GPS coordinates (46.933, -121.950), at an elevation of 3160 feet (NRCS, 2016). Data from 1999 to present shows an average annual rainfall of 392 inches, with 254 inches falling between May and September (NRCS, 2016). Rainfall totals increase across this time with September having the greatest total rainfall and rainfall intensities (NRCS, 2016). Data from the same station detailing the snow depth shows that snow is usually on the ground from

January to April ranging from 0-28 inches during each month, and the greatest depth is usually during March. Snow depth is usually zero by May (NRCS, 2016).

The geologic units available on the N Puyallup Trail include Oligocene andesite flows, Pleistocene andesite flows, lahar deposits, alluvium, and till (Schasse, 1987). Alluvium fills the floodplain of the N Puyallup River and some lahar deposits from the Round Pass Mudflow are also in the valley bottom beneath the eastern mile of the N Puyallup Trail (Schasse, 1987). Pleistocene andesite flows cover just less than 1.5 miles of the western extent of the trail, while Oligocene flows cover the remaining eastern extent (Schasse, 1987). Till is available in this eastern extent mantling the Oligocene andesite, but only within some channel beds and scouring paths downslope of the trail. Available andesite flows are columnar and heavily jointed, with joint spacing ranging from 0.2-0.5 meters.

Soils on Klapatche Ridge range from gravels and silts to peat, and appear to vary in thickness based on elevation. The material used as fill for the road is GM with sand, soils directly up and down slope of the trail are ML, and soils downslope gradually transfer to PT near the river floodplain (ASTM, 2009). At the trail soil mantling is roughly 1 meter thick, and seems to increase to 2-3 meters near the river floodplain. Soils near the trail are colluvial, with no visible regolith and very little sapprolite.

The N Puyallup Trail has slopes varying from 25-50 degrees and the highest number of rock cuts on the Westside road, requiring a high density of culverts and drainage structures (Owens, 2006). The abandonment of the roadway and cessation of maintenance has since led to erosion of the trail, obstruction of culverts, and damage to the historic rock walls (Owens, 2006). Slope failures include rockslides on the steepest sections of the slope and small debris flows in the fill slope (Owens, 2006). Though trail crews have long reported slope failures, their style and causes have not been examined in detail until now.

Methods

To progress with the investigation I made a field assessment of how surface erosion and mass wasting are damaging the trail surface and contributing sediments to the N Puyallup River, performed a risk assessment to identify which areas were deserving of the highest priority, and designated repair schemes for each point of interest on the trail.

This investigation was primarily based on field observations. I mapped erosion and mass wasting features using GPS. For landslides I measured the width of the headwall and the lower extent, depth, and the slope at the trail. I took pictures looking along the trail, up or downslope to show erosion features and channels, and of culverts. Information regarding trail conditions, vegetation, surface water, and slope landforms were collected as field notes. Recognition of the presence and type of slope landforms and mass wasting was performed using the WA State Forest Practices Board Manual (Forest Practices Board, 2015). Estimation of transported sediment volumes and rates of failure/retreat could not be performed due to having only one LiDAR data set from 2008.

Analyses done in GIS were the creation of a drainage network raster and an assessment of upslope drainage area of each point. I used the LiDAR flight from 2008 to make a flow accumulation raster (MORA, 2008), which I then used to make the stream raster. Overlaying my stream raster on my basemap shows where streams are or should be in the site. I took estimates of drainage area from the accumulation raster, and where piracy occurs I added the contributions from all locations leading to a single point. This shows which sites are handling more water than they should, and where more robust drainage designs are needed.

Field mapping collected data detailing trail width and tilt, surface water, vegetation, and mass wasting. I referenced all information to GPS points. GPS points were pinned on individual features like a channel or mass wasting scar, but include observations of areas up to about a 20 meters radius from the point. Features like point sources for surface water or blocked culverts were also pinned with GPS, but only contribute to the understanding of nearby hazards and are not suitable to be included in the risk analysis. Observations of the trail include condition of the inboard ditch, culverts, tilt of the trail surface, and trail width (appendix Table 5). Many of these conditions are closely tied to surface water at each point.

For surface water I noted surface scouring on the trail, flow direction, and upslope sources (appendix Table 1). For channels I describe the width and slope of the channel at slope breaks, channel activity, and if the channel has an alluvial fan (appendix Table 2). These data are needed to determine if a location is contributing to water piracy, how the trail is responding to surface water, and what repairs are needed.

To find water piracy I searched for surface scour parallel to the trail, and where no signs of flow cross the trail but the basemap shows a local flow line. Both indicate that water should flow across the trail if uninterrupted. I also noted where channels flow and any scouring paths sourced to them. These observations were important for using GIS to sum the total drainage area collected by piracy.

Vegetation data include the height of plants and shrubs, the diameter of conifers or alders, the relative density of vegetation, the most common plants, and their distribution around the trail (appendix Table 4). On disturbed soils red alder is a common colonizing tree, and the normal succession is for conifers to begin growing after the canopy establishes (Deal and Harrington, 2006). Mass wasting features with alders with diameters larger than 8" and greater spacing indicate they have not failed in decades, and conifers in the understory show that the slope is working toward the common stable conditions for Western Washington (Deal and Harrington, 2006).

The slope landforms within the field site consist of colluvial hollows, convergent headwalls, inner gorges, tension cracks, benches, and fans. Noting the presence and combination of these landforms gives clues of past or potential landsliding, slide types, and how surface water and trail conditions may either be the cause or result of mass wasting. Benches and cracks indicate the onset of future failures, while hollows show where wasting has likely occurred. Inner gorges show how mass wasting events proceeded downslope, and fans show how slides deposit their materials.

Determining landslide action downslope used data of scouring, fan dimensions, slope, vegetation, surface water, and landslide deposits. Colluvial hollows on steep slopes commonly produce debris flows with long runout in Western Washington (Forest Practices Board, 2015). Narrowed flow paths with deep scour or exposed bedrock, well-graded deposits angular clasts, and deposition of boulders around a 3 degree slope are signs of debris flows (Forest Practices Board, 2015). Observations downslope of mass wasting features were needed to determine if landslides could reach the river or are contributing sediment from surface runoff.

To calculate risk for each point in the field site I used a modified process taken from Riedel (1997). Hazards are defined as the causes leading to damages and include shallow landsliding, debris flows, rockfall, and surface erosion. Value is the monetary value of infrastructure, protected habitat, or replacement of a feature the park wishes to keep. Components include site access, the N Puyallup River, the road surface, stone walls, and engineered aesthetics. Vulnerability is the type and likelihood of damages that hazards can cause and includes surface scouring, outward tilting, trail narrowing, and effects on water quality and fish habitat. To assign numbers to each component I determined a reasonable range of values based on their importance, and assigned a number for each site based on the relative severity of the component. To calculate risk I used,

1) [Haz or Val or Vul] = (a + b + c + d)
2) Risk = (Haz)(Val)(Vul)

where a-d are the listed components of hazard, vulnerability, or value. The assessments made using all the above methods enabled me to tailor a suite of repairs to each site.

Summary of Assessment Results

Frequent issues along the trail include soil creep and tree throw having filled the ditches in many areas, trail scouring and erosion of the fill bank from surface water, and rockfall and failures along steep headwalls that narrow the trail and load the slopes (Owens, 2006, appendix Figure 4-6). Sites with more severe erosion and headward retreat associated with debris flows also occurred with one or more of these low-impact threats.

Soil production on site appears to be primarily from root action of the local forest and weathering from rainfall saturating the soil-bedrock interface during the wet season. The soil mantle is relatively thin, suggesting that the high slope results in relatively fast soil transport rates. Mass wasting that reduces the depth to the bedrock interface likely enhance the soil production in these scars. With most rainfall occurring across summer, and snow being on the ground until early spring, the majority of erosion likely happens from spring to early fall.

The most common condition along the trail is surface incision and fill erosion due to surface water on the trail. Several cases of surface incision from runoff lead directly into mass wasting features, continuously eroding them through time. Some mass wasting appears to be caused by these surface runoff paths (Table 2). Rockfall also occurs at the steepest sections of the trail, and occasionally loads slopes damaged by surface runoff.

Several channels contact the trail from upslope and some are perennially active (Table 2). I found that the road fill was especially thick when crossing large channel features (Owens, 2006). These are called fill-through segments, where the road fill was installed thicker so the road surface doesn’t have sudden changes in grade where it crosses the channel convergence (Owens, 2006). The design handles channels by diverting flow into the ditch toward the next culvert, but most ditches in these features are now lost. The extra thickness of the fill and steep fill slope make these especially susceptible to erosion and mass wasting from surface water piracy. Since they were installed most of the fill-through areas have collected combinations of erosion of the fill surface edge, scouring from water piracy, and colluvial hollows.

Culverts were originally intended to safely divert flows from channels and the ditch to prevent erosion, but some of their inlets have been blocked by sediment accumulation. They are now too few and unfit to handle current discharges. Some culverts on site have been blocked and are sources of some of the most severe surface scouring and erosion in the field area (Table 2). The blocked culverts have scouring paths that start at blocked or unfit entry points, and their scour leads to erosion and surface failures. After these flows trigger mass wasting they continue to flow down the new landslide scar, leading to chronic erosion and production of fine sediment.

Conditions of water piracy, debris flows and rockfall that more severely damage the trail are serious concerns for site access and environmental damage (Tables 2-3). These threats were found in conditions of slope convergence, with an emphasis on colluvial hollows (Forest Practices Board Manual, 2015). Some convergent areas have low relief, often accompanied by changes in the variety and density of vegetation, and surface scour indications. These were noted as sites of surface erosion with no mass wasting. Others were sharply convergent, varied from 10-50 feet wide, roughly as deep at the headwall, had much less vegetation, and some had rockfall piled on the cut slope of the trail. All colluvial hollows on site narrow downslope into an inner gorge.

Debris flows on site are sourced from the available colluvial hollows, and generally have associated surface water inputs. For some it is clear that surface water inputs are the original trigger, while for others the only certainty is that surface water is chronically eroding the landform interior and preventing them from stabilizing. The majority of debris flows were fill materials failing into channels that existed pre-construction, while some created new channeled paths to move downslope. Flows that created new paths were caused by water piracy where the normal surface water regime is overwhelmed, and one was sourced from an obstructed culvert. A few of the flows were initiated where very little surface water flowed but fill slopes near 50 degrees and soils only around 1 meter thick were enough to cause failures. All debris flows investigated in the site originate in a fill slope left by the construction of the Westside Road.

Slide paths of these features all narrow to no wider than 15 feet below the hollow, and almost every hollow contains flow deposits (Table 3). The deposits are matrix supported gravels and cobbles near the trail that transition to matrix supported cobbles and boulders moving downward, reaffirming that these are debris flows. Most slides fan out before reaching their terminus, and fans are sometimes incised by runoff. Runouts of features east of point 13 do not reach the river, while runouts at point 13 and others west have reached the river (Table 3; Figure 3). To reach the floodplain flows in these paths must overcome significant surface roughness in the form of standing and downed trees. All inner gorges collect water and become low-flow tributaries downslope.

Viable Repair Options and Needed Actions

The most significant limitation to repairs is that the field site was classified as a wilderness area in 1988 (Owens, 2006). The Wilderness Act limits actions on site that use any sort of mechanized processes without first getting special approval through permits.

Most structures I consider are for the management of surface water causing surface erosion or contributing harmful sediment to the N Puyallup River via landslides or continuous input of fines. Other designs are intended to either decrease erosive stresses from surface runoff or reinforce the trail. All structures discussed here can be scaled to suit the size of the trail at any point, and the number installed at a point can be adjusted based on available funding (Table 4).

Drainage Structures

Designs suitable for water management on the N Puyallup Trail are waterbars and culverts. These structures are generally considered standard forms of water management on forest roads and trails by the US Forest Service, and are readily scalable to match the size of the N Puyallup Trail. These structures should be built with natural materials like stone or logs to lower the cost and keep with federal compliance and wilderness standards (US Forest Service, 2014).

Waterbars are ideal for diverting pirated surface water or low-discharge flows that need to cross the trail. They can be placed in series to accommodate periodic larger flows, or to support larger drainage structures in case they fail. Waterbars must be skewed a minimum of 30 degrees from perpendicular to the trail centerline to allow proper drainage (US Forest Service, 2014), and may need to be accompanied by a rock spillway at outlets to prevent erosion. Culverts are needed for larger or more continuous flows.

The N Puyallup Trail hosts culverts originally intended to divert ditch water accumulated from upslope. Culverts here are intended to flow into stable natural channels, and any attempt to restore the drainage network should do the same. Malfunctioning culverts need to be cleared or removed for these drainages to function. Removal of culverts will require either backhoe or helicopter assistance. Culverts can either be replaced with steel lengths, by stone or log culverts, or by open-top culverts that behave like robust waterbars. These designs can also be scaled in size (US Forest Service, 2014). Rock spillways will be needed at almost any location where a culvert would be installed (US Forest Service, 2014). Culvert replacements should be larger than their predecessors.

Slope Reinforcement

Some points on the trail will need reinforcement beyond drainage structures. Several areas would benefit from removing rock loading the slope. Sometimes these points are narrowed on the upslope side, but in more severe cases rockfall rests on already destabilized slopes. Less severe areas of rockfall can be mitigated by using buttressing to create a crude wall, allowing for storage of colluvium away from slope breaks. Natural cases of this design occur with trees along the trail, and are very successful.

Instabilities in the trail fill slope would benefit from soil bioengineering. This was done with trees along the trail to fortify the fill slope during construction (Owens, 2006). Live staking and installation of wattle fences using native species would be best, and must be performed during the appropriate growing season (Polster, 2002; Figure 8). Areas with a low risk of mass wasting that experience continuous surface erosion would benefit by reducing erosive forces and adding cohesion, allowing for the possibility of progression to a fully stable state. This would also allow areas with more significant trail narrowing to be widened somewhat while promoting stability along the outer slope (Polster, 2002). This does not ensure immediate stability, as root cohesion must be built over years.

Additional measures that could prove useful are sinking poles and gabion walls. Each is capable of serving as a buttressing measure, while gabions are able to also serve as drainable surfaces. Gabion walls are excellent for creating a flat surface that drains, or as a method of reducing the effective slope in convex landforms. Sinking poles are an effective method of buttressing rockfall areas or places where small surface wasting takes place upslope of the trail. A wall of sinking poles could be used for colluvial storage, holding back materials and giving maintenance time to unload them.

Future Investigation, Monitoring, and Maintenance

There are some aspects of the N Puyallup Trail which I did not cover in-depth because I either found them to be non-essential for the immediate project goals or did not have enough time to include them in the investigation. I recommend additional investigation and monitoring be done for the stone walls, channels, and all implemented repairs.

- Stone walls
  - Investigation is needed to find their slope and condition.
  - Monitoring is needed once per year to track changes in condition or if new problems arise from loading or vegetation.
  - Important to find damages before they become irrecoverable.
- Channels
  - Investigation is needed to find width, depth, bed material, and slope, each measured at slope breaks moving uphill. Estimates of discharge should be made.
  - Monitoring should cover the same details and be performed every 2-3 years to track how climate changes are changing their behavior.
  - Needed to determine if new repairs are necessary.
- Repairs and drainage structures
  - Annual Monitoring is needed to determine if designs are working properly.
  - Waterbars need to have an acceptable grade, and be free of obstructions.
  - Culverts must be clear at the entry and exits with no blocks to the path leading in.
  - Soil bioengineering must be checked to see if parts have failed or not taken root.

All current or newly installed features will need maintenance to ensure they continue functioning. Forgoing maintenance will cause the continuation of current problems, reactivation of old problems, or the creation of new threats to the trail. Proper maintenance of the trail relies on monitoring so crews can be made aware of what upkeep is required and when. This includes the maintenance of drainage structures, soil bioengineering efforts, brush clearing, and removal of materials loading the slope.

- Brush clearing
  - Should be performed before any of the recommended repairs are installed.
  - Will make installation of repairs easier and less time-consuming.
  - Will greatly improve the quality of the trail for hikers and reveal more of its historic character.
- Drainage structures
  - Culverts need their entry, exit, and ditch leading to them cleared of sediment.
  - Waterbars need sediment cleared to maintain grade and prevent blockage.
  - Scheduled maintenance is needed every 2-3 years, and should be done in the same year if monitoring reports damages or obstructions to any drainage design.
  - If unmaintained damages to these structures could begin damaging the trail.
- Soil bioengineering
  - Annual maintenance to fix parts of structures that have failed.
  - Maintenance is needed only for structures that monitoring reports being damaged.
  - If properly maintained these designs will need less input as time goes on. Eventually they will not need any attention as they become fully stable after several years.
- Slope unloading
  - Removal of rockfall or woody debris loading the trail.
  - Due to the physical intensity of this work, unloading should only be performed as a response to monitoring reports that note a loading site as problematic.

Detailed Assessments and Recommendations for Key Locations

The following sections detail four locations of concern along the trail that ranked the highest in the risk classification, along with one zone of slide onset with high hazard potential but low risk. Each section provides assessments based on field observations and recommendations for repair. Detailed site observations for these five example locations are available in the appendix.

Recommendations for sites are based on both what is needed to stabilize the trail while also protecting the N Puyallup River, and the feasibility of repairs. I consider feasibility to be the intersection of funding for equipment and labor, and the total input needed by the crews for a particular design. Some points require one type of design for repair, while other points require a suite of designs to handle all issues present. Budgets (Table 5-6) and a full list of general repairs (Table 1) are included.

P8-P9

Brief Description

Point 8 is a perennial channel flowing with about 0.1 cfs that is captured by an inboard ditch and sent east toward a culvert entrance 20 meters down the trail. This culvert allows water to enter but has a blocked exit (appendix Figure 2). Multiple scouring paths lead east away from the culvert entrance along the trail, converging before heading into point 9, a colluvial hollow on the fill slope.

The colluvial hollow is 10-12 meters wide, 5-6 meters deep, has a slope of 45 degrees at the trail, narrows to a 1-2 meter wide inner gorge downslope, and has no vegetation aside from what has falling in from slumps (appendix Figure 2). The headwall of the hollow has a 1 meter wide slumped bench that slopes about 20 degrees downslope, and is cut by the scour path on its west edge.

The inner gorge has deposits that are matrix supported with the larger clasts coarsening downslope. The flow path of this inner gorge runs through a mature conifer stand and must flow around standing trees and over downed trees with overturned root balls, with some deposition of the flow deposits on these surface roughness features. The flow deposits fan out near the valley bottom and contact the N Puyallup River, with the terminus being truncated by the river's current flow path. See appendix section P8-P9 for the full set of observations.

Assessment

With a perennially flowing channel and an improperly functioning culvert, I think the flow of surface water is the primary concern here. The scour paths leading away from the culvert entrance shows that the culvert cannot handle high flows, allowing flows to spread out on the trail surface. Scouring paths converge heading toward the hollow and come in direct contact with the slumped block at the headwall, suggesting that water is the main source of erosion on the trail at these points, and likely created the hollow. The bare condition of the hollow is a sign of recent instability or continuous surface erosion, which fits if the damage is from surface water. With no exit all water entering the culvert must end as groundwater seepage. Seepage does not appear to cause any immediate concerns, but will likely lower stability over time.

The matrix supported slurry of angular materials with variable deposition along roughness features downslope suggest the landslide here transferred into a debris flow as it entered the inner gorge (Hungr et. al, 2014). The scour depth does generally increase downslope, consistent with the sediment bulking during a debris flow (Hungr et. al, 2014). Since the deposits have reached the river in the past the safe assumption is to say that they are capable of doing so again (Forest Practices Board, 2015), though surface roughness and variable deposition suggest that only large events can reach the floodplain.

Recommendations

Points 8-9 require water management designs, and will also benefit from alterations to the fill surface and soil reinforcements. The primary concern is the replacement of a culvert which currently inputs continuous flow to the subsurface, and allows for surface runoff leading directly into a colluvial hollow that has produced debris flows.

Culvert replacement is needed because the constant discharge of the channel requires a robust drainage to handle winter storm events. To make the new drainage capable of maintenance without machinery I recommend that the culvert be replaced by a structure similar to an open-top box culvert (US Forest Service, 2014), and made of stone for stability. The replacement must be larger to handle heavy winter rainfall. Minor ditch clearing will be needed to direct flow, and can be performed by hand. I also recommend that waterbars be used to make the repairs more effective and fail-safe.

Using waterbars in addition to a new culvert is an effective and relatively inexpensive reinforcement. Waterbars should be made of either stone or logs, and should be skewed 40-45 degrees from the trail to ensure that they are as self-cleaning as possible (US Forest Service, 2014). To provide drainage support that could function without the culvert for a year I think 6-8 waterbars should be installed, with the greater density of bars being west of the current culvert location. This way if the culvert fails the waterbars west of the culvert can still divert most of the flow away from the hollow. I also recommend installing 2-3 additional waterbars just east of the hollow where the valley slope becomes divergent. This allows for excess flow to be directed around the hollow to a stable slope. Installation around the culvert is preferable because the road tilts inward at point 8, making installation at the channel difficult.

To improve stability the colluvial hollow must be reinforced. Here the slumped bench should be removed by trail crews and replaced by wattle fences. The slump at the head of the failure will inevitably fall into the hollow and contribute sediment to the river. Removing the block will both decrease and unload the entry slope, making entering water less erosive. The space left by the block should be replaced by a series of 3 wattle fences with regular drops in height, and backfilled with organic soils (Figure 6). Bioengineering repairs will likely need maintenance, but can become a permanent source of stability if maintained for several years.

Combining soil bioengineering and drainage restoration stabilizes the failure by limiting channeled water input and increasing root cohesion over time. These repairs should allow the hollow to stabilize enough to allow normal colonization from local plant species (Deal and Harrington, 2006), eliminating landslides and the continuous sediment input sourced from rainfall on bare soils (Forest Practices Board, 2015).

P10-P13

Brief Description

Points 10-13 exist along one convergent headwall, with point 10 being a channel flowing at <0.1 cfs near the center of this headwall (appendix Figure 3). Discharge from point 10 ponds on the upslope side of the trail and flows toward point 11, the first of two waterbars here. Point 11 bails the water off the fill slope into the convergence with minor erosion on the fill slope. Scouring leads away from point 11 along the trail to point 12, the second waterbar (appendix Figure 4). Point 12 also has the same fill erosion, but is dry during most of the summer.

Point 13 is a pair of colluvial hollows 5-6 meters east of point 12. At this point each hollow has a slope of about 50 degrees at the trail, no visible scouring leads to the hollows, and rockfall is piled on the upslope side of the trail at 35 degrees. The pair of hollows are about 15 meters wide total, the two scarps merge into one hollow 3 meters downslope, and have a slope of 50 degrees at the trail. The merged hollow narrows to a 2-3 meter inner gorge downslope, and lacks any vegetation.

The inner gorge connects to the channel path originally occupied by point 10 pre-construction, and contains the same flow deposits mentioned above. Deposits here appear to have greater volume, levees that continue down to the floodplain, and are truncated by the N Puyallup River with about 3 meters of vertical offset. See appendix section P10-P13 for the full set of observations.

Assessment

The headward retreat of this hollow is greater than point 9 based on the narrow width of the trail, and the water input being low enough so scouring does not lead to the hollows. After a moderate rain there were indications that some water reaches point 13, so the increased slope is providing more erosive power than point 9, making it important that the surface water be directed away from point 13. The closer the trail edge comes to the rockfall the more it is loaded by the weight, adding to the problem. The point 10 convergence continues upslope, indicating the channel existed pre-construction.

The pair of hollows appear to be a landslide that became a debris flow after travelling a short distance downslope. Here the flows don't encounter the same surface roughness as point 9, and the flow created a larger path as it headed downslope, seen by the presence of continuous levees that reach the river's edge (Hungr et. al, 2015). Flows here do reach the river, and the height difference of the deposit and the river suggest that slides here can deliver large amounts of sediment (Hungr et al., 2015). Large slides are possible here, but conditions suggest that the channel is stabilizing and can handle surface water inputs.

Recommendations

Points 10-13 are in need of water maintenance, but have a greater need for measures that stabilize the slope and halt the trail narrowing. Surface erosion has led to shallow landsliding and resulted in the loss of most of the trail width. Additional narrowing has come in the form of upslope rockfall piled on the trail, adding stress to the already narrowed trail and oversteepened landslide.

Water sourced from the point 10 channel must be diverted downslope with no potential for it to reach point 13. The point 11 and 12 waterbars are already performing properly, but cannot handle all flows that reach them. Since these waterbars are functional I propose the addition of three more to reinforce the drainage. One should be placed at the point where the channel reaches the ditch and ponds. This waterbar can have less skew than others because it is accepting discharge moving perpendicular to the trail. The remaining two should go in the spaces between waterbars. Waterbars here should be built from stone to ensure their longevity. Each of these waterbars must be accompanied by roughly 2 feet of fill pullback for a rock spillway.

I propose buttressing of the rockfall slope and installation of wattle fences in the headwalls of both hollows at point 13. Since the rockfall seems to be at repose significant removal of rockfall materials could produce instability that will later re-fill the slope to its original condition, or cause a larger amount of rockfall than before. Buttressing would hold back rockfall on the slope, allowing for it to be removed periodically without seriously affecting stability. Buttressing here can be performed by live alder staking and weaving branches through for lateral support. Even if small sections fail they can be replaced and rely on the support of the other stakes which have strengthened. These strengthen over time as the plants grow and eventually provide a permanent support feature. I recommend wattle fences to provide crown support of the hollows. There is only enough room for 2-3 wattle terraces for each hollow. These designs may also require instances of repair until the structure is able to fully root and build cohesion. While these designs have already been developed (Polster, 2002), they were not specifically intended for these uses, making my designs experimental.

P21

Brief Description

The area near point 21 is a fill-through section originally built to cross a 30-35 meter wide channel convergence, and has lost the original fill slope in the center of this convergence. There is a colluvial hollow on the east side of this channel convergence, which is point 21 (Figure 6; appendix Figure 6). The perennial channel acts as a source of alluvial sediment that has buried the ditch and surface scouring leading east toward the hollow, but only produces enough water to fill the scour during the wet season.

The hollow is 10-12 meters wide and has a slope of around 50 degrees at the trail. This hollow has a significant amount of new vegetative growth from ferns, berries, and juvenile alder in its interior, with no visible soils. The trail here has been narrowed to 1 meter from headward of the hollow and soil creep on the upslope side, and the surface scouring path passes within 0.5 meters of the hollow without entering the landform (appendix Figure 6).

Downslope the same flow deposits as elsewhere were found, and the deposit fan is tens of meters wide at its base. Scouring on the fan has left a 1-2 meter wide flow path. Juvenile alders are growing out of the fan surface, and a mature conifer stand rests between the fan and the N Puyallup River. Deposits do not reach the active floodplain, but flow of the path on the fan does reach the river. See appendix section P21 for a full set of observations.

Assessment

This scouring at point 21 occurs just above the local hollow, and erosional effects will likely accumulate until the scouring begins contributing to the headward retreat of the hollow. Since no surface scouring leads into the hollow I think this level of incision being directed into the hollow could cause permanent loss of this narrowed section within a few years. The channel here is certainly pre-construction, and this plus the availability of vegetation suggests to me that the safest option will be to direct water into the main convergence.

The downslope channel here is well established to handle surface water. Debris flow deposits here appear larger by volume, they have also since been incised to form the new flow path. The area displays young alders and conifers growing directly out of said deposits. All signs indicating that they have been in place for several years without significant changes since deposition. A mature conifer stand rests between the slide toe and the river. These conditions suggest a progression toward stability, and that the path is unlikely to contribute more than turbid water to the river.

Recommendations

Point 21 has the most severe case of a fill-through section that is degrading rapidly and must be mitigated. I recommend directing water toward the channel convergence to re-occupy the natural flow path and avoid damaging the hollow. A failure on the hollow of point 21 significant enough to cause more headward retreat could mean the end of the trail, requiring drastic measures to restore a useable footpath. Soil bioengineering could also be used to provide slope cohesion, and help deal with water that reaches the fill slope.

Waterbars are likely the best option for this point, and remain preferable due to low cost and ease of maintenance, but must be approached with care. Here waterbars need to be up to 30 feet long to properly direct flow, and entrances to waterbars should be linked to the east scouring to ensure that as much of the flow is captured as possible. Here I recommend that a robust waterbar be installed as the entry and serve as the main flow path. This waterbar can then be used to make 4-5 branches that lead to the fill slope, diverting water before it reaches the hollow at point 21. The existing incision path should be filled in and a small soil berm be installed perpendicular to the trail to prevent flow from continuing beyond the waterbars. Up to 2-3 feet of fill should be removed to make an outlet for each waterbar. These pullbacks should be deep enough to provide a relaxed exit slope even after being filled with rock to resist surface erosion.

Soil bioengineering should be performed to reinforce the fill slope. I suggest live staking of alder be performed around the edge of the larger convergence where water is directed. This will add root stability and hopefully resist the initiation of landslides on the fill slope. The hollow at point 21 is already thoroughly colonized with a variety of vegetation and would gain little from soil bioengineering.

P32

Brief Description

Point 32 is accumulating alluvial sediment from a bedrock channel which has covered the trail. The fan created by this accumulation has a slope of 22 degrees, and rests directly above a small hollow feature on the fill slope (Figure 7). The fan is matrix supported, and contains materials ranging from silt to 50 cm cobbles (appendix Figure 7). The channel is seasonal, but has a flashy response to rainfall. Discharge events large enough to cross the fan surface mostly go to the hollow, but some is directed west toward point 31.

The hollow is 5-6 meters wide at the trail, 2 meters wide at its outlet, and is 6-7 meters long. The slope is 35 degrees at the trail and about 10 degrees at the outlet. The headwall and the outlet are both fixed in place by buried logs 30-50 cm in diameter that are parallel to the trail. Downslope of the hollow is a 50 meter long slope of cobble to boulder sized rubble.

The rubble slope shows no signs of channeling or infilling, and surface water does not reappear until a slope break to the valley bottom. Tributaries after the slope break are slow and no greater than 50 cm wide.

Assessment
Here the road is roughly as wide as the original construction. The alluvial fan is likely to continue accumulating sediment, sending more downslope every year. The fill surfaces of the road are generally unstable unless in perfect design condition, so loading of material from this fan could eventually lead to instability. The other feature of interest here is a small colluvial hollow.

The condition of the small hollow feature seems to be stable based on the size of the feature and the wood that is currently holding the shape of the landform. Since both the top and bottom are reinforced it seems unlikely that the condition will change within 10 years. It is more likely that the hollow will eventually begin being filled by the outward progression of the alluvial fan, but this could lead to instability from loading.

No signs of damage from surface water or landsliding occur downslope, suggesting that landsliding is not a significant risk here, and any sediment inputs into the N Puyallup River from point 32 are limited to washload in surface runoff. In this part of the valley the river occupies the far norther edge, with significant roughness boundaries for surface water to overcome to reaching it. See appendix section P32 for all observations.

Recommendations
The goal here is to ensure that a useable walking surface is available, and that the hollowing landform on the fill surface remain stable. This point has the greatest potential for gabion wall usage because gabions are capable of providing erosion resistance and weight anchor while also being highly permeable to water flows. Some attention should also be paid to flows that bail off the west side of the fan and continue down the trail.

I recommend that a log bordered trail path be established across the fan surface, since a built path does not yet exist on the fan. The path can then be maintained on an annual or bi-annual basis. The installation of 2 gabion cages in the bottom of the hollow should be sufficient to ensure stability. This will provide an erosion resistant anchor where water entering the landform would have the most impact, and reduce the effective slope of the hollow's profile. The fact that the hollow is already anchored by logs at the top and bottom makes the feature fairly stable, and the addition of gabions should help the feature become more stable.

Waterbar installation will improve the quality of the trail here. The west bound flow sourced from the fan causes some degradation of the trail surface and leads to an area where the fill slope has also been eroded. To fix this I recommend the use of about 4 waterbars spaced at about 20 feet beginning where the trail incision begins. Waterbars should again be skewed 40-45 degrees, and fill pullback should be done to provide them low-slope outlets. This should control the erosion of the trail surface while also halting degradation of the fill slope. This site does pose a problem to the trail, but I think less intense structures are appropriate because the conditions do not seem to be an immediate threat.

Deep-Seated Hazard Zone

Brief Description
This section of the trail is 280 meters long and lacks the usual problems of piracy, surface erosion, or shallow landsliding. The site does have a high density of tension cracks and benches, with no greater than 6 meters between any such features on the fill slope (appendix Figure 8). This part of Klapatche Ridge has a nearly planar planform slope. Vegetation profile is a mature conifer stand.

Cracks and benches seem less severe when trees are larger and closer to the trail. See appendix section Deep-Seated Hazard Zone for full set of observations.

Assessment

I think the problems have progressed due to a lack of convergent and divergent slope areas. This section of ridgeline still experiences the same amount of precipitation the rest of the site, but there are no channeled paths. This planar slope coupled with conditions of significant surface roughness would make it difficult for surface flows to accumulate, increasing infiltration. This would lead to greater subsurface saturation, leaving unvegetated surfaces like forest roads vulnerable. The size of trees seems to correlate with the severity of signs of slide onset, and deep-seated slide planes are beneath the rooting depth of available trees (Forest Practices Board, 2015). Vertical offsets also reveal fresh soils, suggesting the progression is recent. If the complex does fail the resulting slides are likely to be multi-behavioral based on the variable orientation of tension cracks (Hungr et. al, 2014)

With no active landslide scars it is unlikely that the area currently impacts to the N Puyallup River. Failure of the complex would be unlikely to self-stabilize on human timescales. If the site does fail it will become an imminent threat to the continuing existence of the trail, severely affecting water quality and fish habitat for the foreseeable future.

Recommendations

Here the only useful measure is to direct as much water away from the area as possible. However, diverting so much water could easily prove disastrous, as seen at other points with water piracy. I recommend installing waterbars at one point, and propose that efforts be made to establish monitoring procedures.

Point 26 is a classic example of surface water causing incision and erosion of the fill surface where it exits the trail. I recommend the installation of 5 waterbars that direct the flow off the trail before the incision reaches the west edge of the hazard area. This should help handle the surface erosion and direct water toward a more stable area of the slope.

Monitoring procedures are needed to track how the area is changing. I recommend that future researchers take care to note where the most significant benching and cracking is. These features should then be pinned in the current GIS file, and standard monitoring points should be established using PVC or rebar. The goal should be to track the vertical offset of benches or the widening of tension cracks. Measurements at these monitoring points should be taken at regular dates.

Summary

The abandonment of the Westside Road and its conversion to a trail east of Klapatche Point has since led to progressive damage of the N Puyallup Trail and negative impacts on the N Puyallup River. Underfit drainage networks installed in the original construction have been filled by soil creep and rockfall over time, causing ditches and culverts to cease functioning. The degradation of these drainages has led to considerable surface water scouring the trail surface, with several areas being pirated along the trail before bailing off the fill slope. These surface water contributions have chronically eroded the trail surface and fill slope, and result in the onset of debris flows in several cases.

Debris flows both damage the trail surface by and have the potential to contribute harmful sediment to the N Puyallup River. Colluvial hollows resulting from these debris flows remain unstable as surface water continues to erode them, contributing fine sediment downslope. Both these fine sediments and the landslide pulses pose a risk to the protected habitat of the N Puyallup River. Steep sections of the trail also have failures upslope resulting in rockfall that further loads already unstable portions of trail, raising the risk for more failures and additional damage to the trail.

To preserve both the trail and river habitat certain repairs need to be performed. Waterbars, culvert replacement, soil bioengineering, and unloading of the slope are all needed to reduce erosion from surface water, reinforce destabilized slopes, and remove driving stresses contributing to landslides. These repairs will keep the trail open for years to come, preserving the historic value of the site while properly stewarding the wilderness.

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Table 1: Risk Ranking and Full List of Suggested Repair Schemes. **Table detailing the calculated risk and types of repairs that I have suggested at each point in the field site. The designs are intended to be general, and can be made more or less robust based on available funding.**

Point Label		Risk		
Figure Label	Field Note Label	Rank	#	Suggested Repair types
P1	P1	28	6	monitor to ensure road does not continue to relax.
P2	P2	15	18	clear culvert entrance, should be low-effort.
P3	P3	33	0	installation of a few water bars to handle H2O piracy to P4/P5
P4	P4	28	6	water bars to handle piracy to/from this point
P5	P5	6	60	water bars to bail water onto slope outside of convergence where current incision terminates, some water can likely be diverted to P6
P6	P6		See P5	
P7	P7	5	105	increase density of drainage points in the flat runoff area. Runoff paths flow beneath debris blockage, I suggest leaving logs and creating paths beneath them if possible
P8	P8	25	9	Install water bars in high density (every ~3-4 ft.) beginning just west of culvert entry. Water should be directed away from colluvial hollow drain path.
P9	P9	2	216	P8 water bar scheme, consider pullback of fill at headscarp of colluvial hollow, also consider addition wattle fences to reinforce headwall of hollow. Removal of culvert and replacement with robust relief drainage.
P10	P10	8	36	Begin installation of additional water bars beginning at the stagnant pool @ base of P10 channel, # of bars should be 2-3x how many already exist, already existing bars should be replaced with more robust bars that can handle greater discharge.
	P10_a	33	0	
P11	P11	15	18	Replace with more robust waterbar and add more waterbars
P12	P12	7	48	Replace with more robust bar and add more bars, little to no runoff can reach P13 if we wish P13 to stabilize (or even remain stable in the short-term)
	P12_a	33	0	Rilling upslope of P11/P12, no repairs
P13	P13	1	270	Improve on quality and # of bars at P10-P12. Recommend placement of Alder Facines in the headwalls of the 2 colluvial hollows at this point, and either wood reinforcement of the rockfall or unloading of the rockfall (buttressing is more long-term).
P14	P14	33	0	no repairs needed
P15	P15	20	12	Unload rockfall by spreading fan out into the neighboring ditches or downslope. No surface water management needed.
P16	P16	13	24	Consider installation of 2 or 3 bars diverting water into the channel downslope or onto the convex slope between P16 and P17
P17	P17	20	12	Consider installation of 1 bar on the W side of stagnation pool, and 2 more between P17 and P18.
P18	P18	12	27	Re-establishment of culvert main priority, addition of up to 4 water bars between P19 and P20. Recommend replacement of culvert with robust relief drainage.
P19	P19		See P18	
P20	P20	8	36	Management of P18/P19 excess is the primary concern. Addition of 2 bars at this pt. could be enough, 1 so a hardened drain path exists for the current erosional feature, and 1 to divert part of the flow slightly W toward the convex section of the slope.
	P20_a	33	0	Channel source for P20 and P21, no repairs
P21	P21	3	108	Recommend fill surface pullback at edge of large headwall where there isn't much root reinforcement. Addition of ~2-3 bars that spread runoff from P20_a across the headwall. Downslope channel should be stable enough to withstand the runoff. E edge of pt has a fresh colluvial hollow, all efforts must be made to direct water away from this feature, either E or W. Consider installation of small berm to block flow moving E, and fill current scour path.
P22	P22	20	12	Point is mostly self-mitigating. Consider installation of 2-3 bars that divert water away from scour towards slope before the obvious bailout point to spread out discharge.
	P22_a	33	0	not a concern
P23	P23	20	12	Point is mostly self-mitigating. Consider the removal of woody debris that restricts the spreading runoff area seen by sand accumulation. Removing wood will widen the runoff path, decreasing the erosive power of the runoff here.
P24	P24	15	18	Consider using bars to send water farther down trail until reaching the convex slope between P24 and P36, then bail downslope before P36 incision begins.
P32	P25	3	108	Gabion cages to create a high permeability trail surface. Second recommendation for the use of wood cribs to create a flat trail surface and fill top with sand/soils. Also recommend the installation of gabions or sinking poles in the small downslope colluvial hollow to reinforce feature and slow headward retreat. Hollow reinforcement is priority, trail establishment is secondary because the slope is readily traversible.

P33	P26	8	36	Trail surface has already been severly incised to create a stream runout for the waterfall, recommend hardening the eges with rock/wood to prevent further erosion. Consider replacing the bed with coarser rock from the P25 alluvial fan.
P34	P27	15	18	Install bars frequently along site. Recommend about 5 (or more) to handle the output. Installation will need careful placement to consolidate runoff, and reduce the already significant degradation of the road surface. Downslope from here can likely handle the input, as long as a large enough number of bars are installed.
P31	P28	20	12	Fix culvert, install relief culvert, or install robust H2O bars.
P30	P29	15	18	Consider the installation of about 4 bars, evenly spaced across the site to handle excess input from P29, and the input from the upslope chute.
P29	P30	13	24	Consider the installation of 2-3 bars between here and P29. Point is already low-threat and small measures are certainly sufficient for full mitigation.
P28	P31	33	0	Deemed outside of project scope, damage seems to stem from snow avalanche issues and does not appear to pose an imminent threat
P27	P32	33	0	Deemed outside of project scope, damage seems to stem from snow avalanche issues and does not appear to pose an imminent threat
HZ_R	P33	28	6	Monitoring efforts should be established by future researchers
HZ_L	P34	28	6	Monitoring efforts should be established by future researchers
P35	P35	25	9	Active culvert. Consider installing 1-2 water bars W of culvert on trail to help handle excess water leading to P27
P25	P36	28	6	Beginning of trail incision leading to P37, install water bars beginning at the incision start to bail water downslope on the convex area near the point to avoid allowing any water to reach P34-P33 area.
P26	P37	8	36	Management of P36 water conditions should be sufficient to eliminate surface sliding/erosion and trail incision at this point.
P36	P38	25	9	Monitoring efforts should be established by future researchers to track the slumping of this block.
Stone Walls	Stone Walls			Establish monitoring of each of the 3 rock walls within the site to ensure that their condition is maintained effectively. Monitoring could be bi-annual, as these walls seem to be the most stable features in the field area.

Table 2: Summary Table of Surface Water and Trail Conditions. Table showing some general conditions of the trail and surface water, and how they relate to damages found during the investigation.

Surface Water on Trail	# of points	pirated	# with culverts	flowing into mass wasting sites	causing surface erosion
Surface Runoff	20	10	1	10	20
Channel Flow	12	9	3	3	6
Culverts	total #	piracy of intended flow	# obstructed	flowing into mass wasting sites	causing surface erosion
18"	2	0	1	1	1
30"	3	2	2	1	2
Trail Conditions	# of points	functioning	not functioning	% of trail functioning	% of trail not functioning
Outward Tilt	11	N/A	N/A	N/A	N/A
Ditches	36	12	24	~40%	~60%

Table 3: Summary Table of Slope Damages. Table detailing conditions of the types of erosion and mass wasting found in the site. Severity lists the range of severity, normal plant succession references if plants indicate a progression toward stability, and the two sediment categories are not independent (i.e. landslides also include chronic sediment).

Slope Damages	# of points	landform	severity	chronic sed. to river	landslide sed. to river	approx. % of trail	normal plant succession
Debris Flows	6	colluvial hollows, inner gorges	10-30 meter wide colluvial hollows	5	4	5%	3
Rockfall	8	rubble, rock slopes	moderate deposition to severe slope loading	0	0	15%	0
Shallow Landslides	14	shallow convergences, colluvial hollows	small revegetated scars to large bare convergences	12	0	20%	4
Surface Erosion	25	scour paths, fluvially altered fill slopes	shallow single incision paths to multiple deep lines of incision with fill slope erosion	14	0	65%	N/A

Table 4: Number of Sites Relevant to Repair Designs. **Table detailing the number of sites that need each type of repair design put forward by the recommendations.**

Viable Repairs	Waterbar Installation	Culvert Replacement	Soil Bioengineering	Slope Unloading
# of points in need of repair	19	3	5	2

Table 5: General Budget for all price scales. **Table detailing the various items associated with different budget scales, and the total estimated cost for each budget scale. Budgets are designed assuming the project will be completed in one summer for the full length of the trail. Class A will require the most additional permitting, class C will require the least.**

General Budgeting Items and Plans							
Item	Description	Budget Class	Qty	Unit	Item Cost	Unit Cost	Explanatory Notes
Personnel	SCA Trail Crew (~1 mo.), 10 members plus crew lead	C	1	lump	$32,000.00	$32,000.00	Trail repairs
Personnel	NPS Trail Crew (~1 mo.), 4 members	B	1	lump	$10,000.00	$10,000.00	Brush clearing
Personnel	Geologist-in-the-Park	C	1	lump	$8,000.00	$8,000.00	
Transport	Vehicle	C	1	lump	$3,000.00	$3,000.00	
Equipment	Helicopter Flights	A	1	lump	$2,000.00	$2,000.00	
Equipment	John Deere Excavator (350) (~0.5 mo.)	B	1	lump	$1,000.00	$1,000.00	
Equipment	Trail Crew hand tools	C	1	lump	$1,000.00	$1,000.00	
Materials	gabion wall cages	B	10	lump	$100.00	$1,000.00	
Materials	culvert (~10')	B	3	lump	$200.00	$600.00	
Materials	stakes and live alders for plant rem.	C	1	lump	$1,000.00	$1,000.00	
Materials	Stone, wood, and soil. Sourced within field site	C	N/A	lump	$0.00	$0.00	
Class A Total		A=	Higher Budget	A + B + C		$59,600.00	assumes culvert removal and replacement at 3 sites
Class B Total		B=	Intermediate Budget	B + C		$57,600.00	culvert replacement at 2 sites
Class C Total		C=	Lower Budget	C		$45,000.00	culvert replacement by relief drainage structures

Table 6: Budget for Recommended Plan. Table detailing the costs of the writers recommended plan for remediation of the field site. Includes the total cost for my recommended suite of plans. Some permitting is required for the use of an excavator, but all other plans are compliant with the Wilderness Act.

Personal Recommendation for Budget							
Item	Description	Budget Class	Qty	Unit	Item Cost	Unit Cost	Explanatory Notes
Personnel	SCA Trail Crew (~1 mo.), 10 members plus crew lead	C	1	lump	$32,000.00	$32,000.00	crew needed for repairs
Personnel	NPS Trail Crew (~1 mo.), 4 members	B	1	lump	$10,000.00	$10,000.00	crew needed for brush clearing
Personnel	Geologist-in-the-Park	C	1	lump	$8,000.00	$8,000.00	
Transportation	Vehicle	C	1	lump	$3,000.00	$3,000.00	
Equipment	John Deere Excavator (350) (~0.5 mo.)	B	1	lump	$1,000.00	$1,000.00	
Equipment	Trail Crew hand tools	C	1	lump	$1,000.00	$1,000.00	
Materials	gabion wall cages	B	2	lump	$100.00	$200.00	
Materials	stakes and live alders for plant rem.	C	1	lump	$500.00	$500.00	
Materials	Stone, wood, and soil. Sourced within field site	C	N/A	lump	$0.00	$0.00	
Total						$55,700.00	culvert removal at 1 location, installation of robust relief drainages at 3 culvert locations

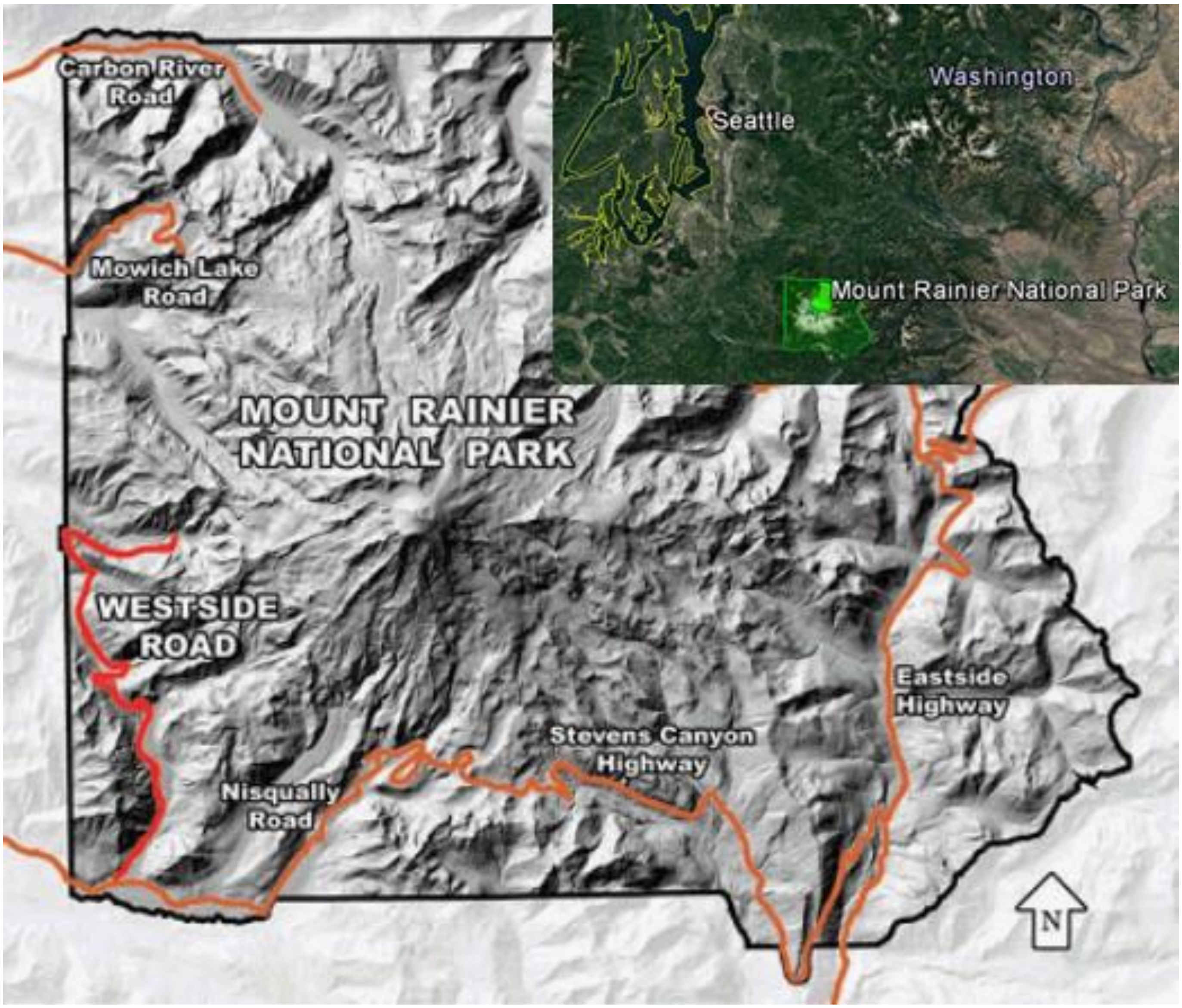

Figure 1: Regional Site Locator and Park Interior Map. Map in upper right details the regional location of Mount Rainier National Park at (47.18, -122.31), picture taken from Google Earth. Main map shows the interior and roadways within Mount Rainier National Park, with the Westside Road highlighted in red. Scale ~1:135,000, figure taken from Owens, 2006.

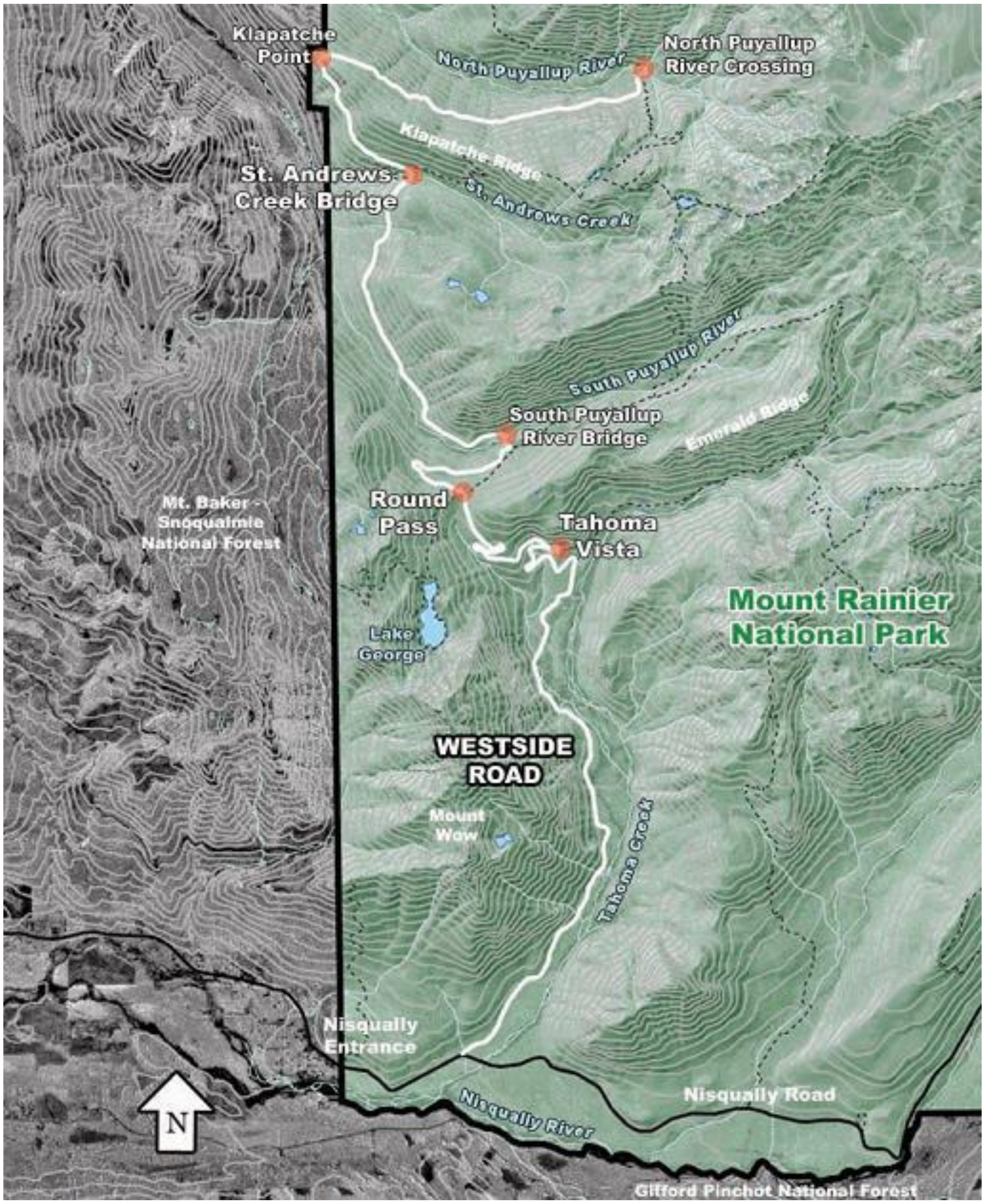

Figure 2: Detailed Layout of the Westside Road. Map detailing the location of my field area inside Mount Rainier National Park. Klapatche Ridge is shown in the north of the map, bounded by the North Puyallup River and St. Andrews Creek in the north and south, respectively. The North Puyallup Trail is the 3 mile stretch from Klapatche Point to the Wonderland Trail. Figure taken from Owens, 2006.

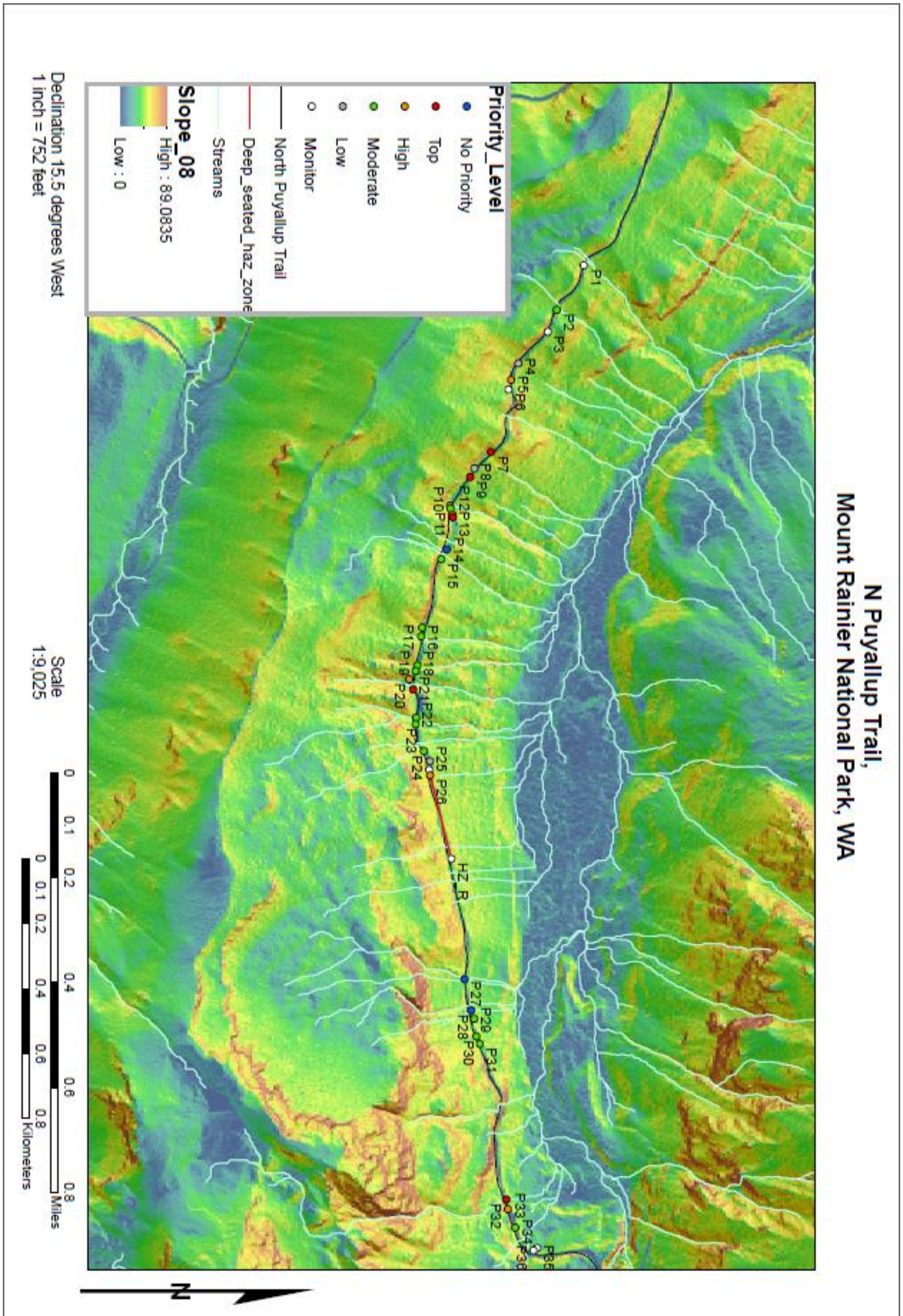

Figure 3: Map of N Puyallup Trail and Points of Interest. Map detailing the location, label, and priority level of each point I considered in the field site. Map is a slope raster overlain onto a hillshade. Slope is in degrees. Priority level for each point is defined by the risk classification I performed.

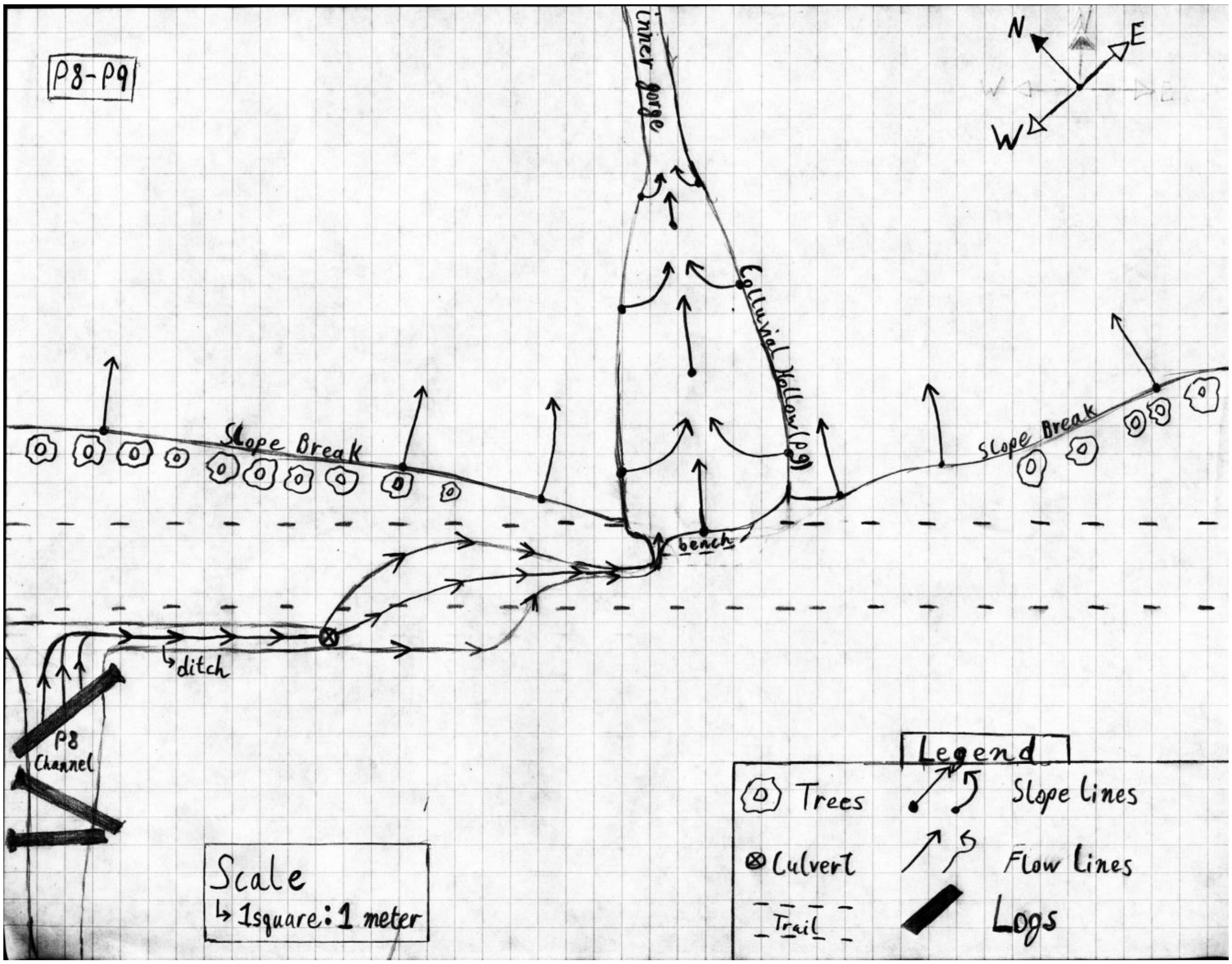

Figure 4: Sketch of P8-P9. Field sketch detailing the plan view of the channel, culvert, and colluvial hollow at P8 and P9. Sketch shows how water paths from the culvert affect the colluvial hollow. Slope lines point in the steepest downslope direction.

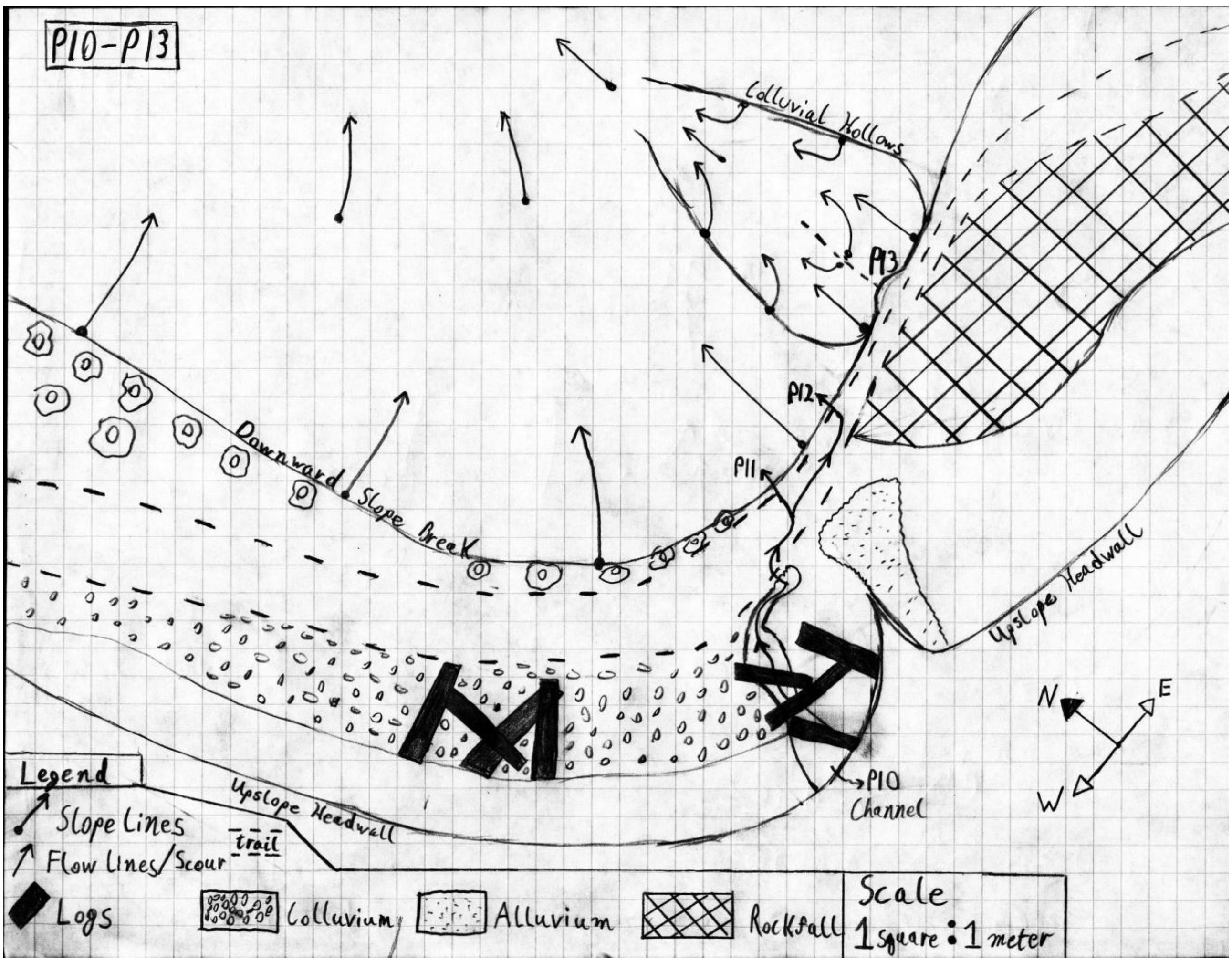

Figure 5: Sketch of P10-P13. Sketch detailing the convergence, channel, and colluvial hollows of P10-P13. Trail narrowing is most significant where rockfall is also most significant. Slope lines point in the steepest downslope direction.

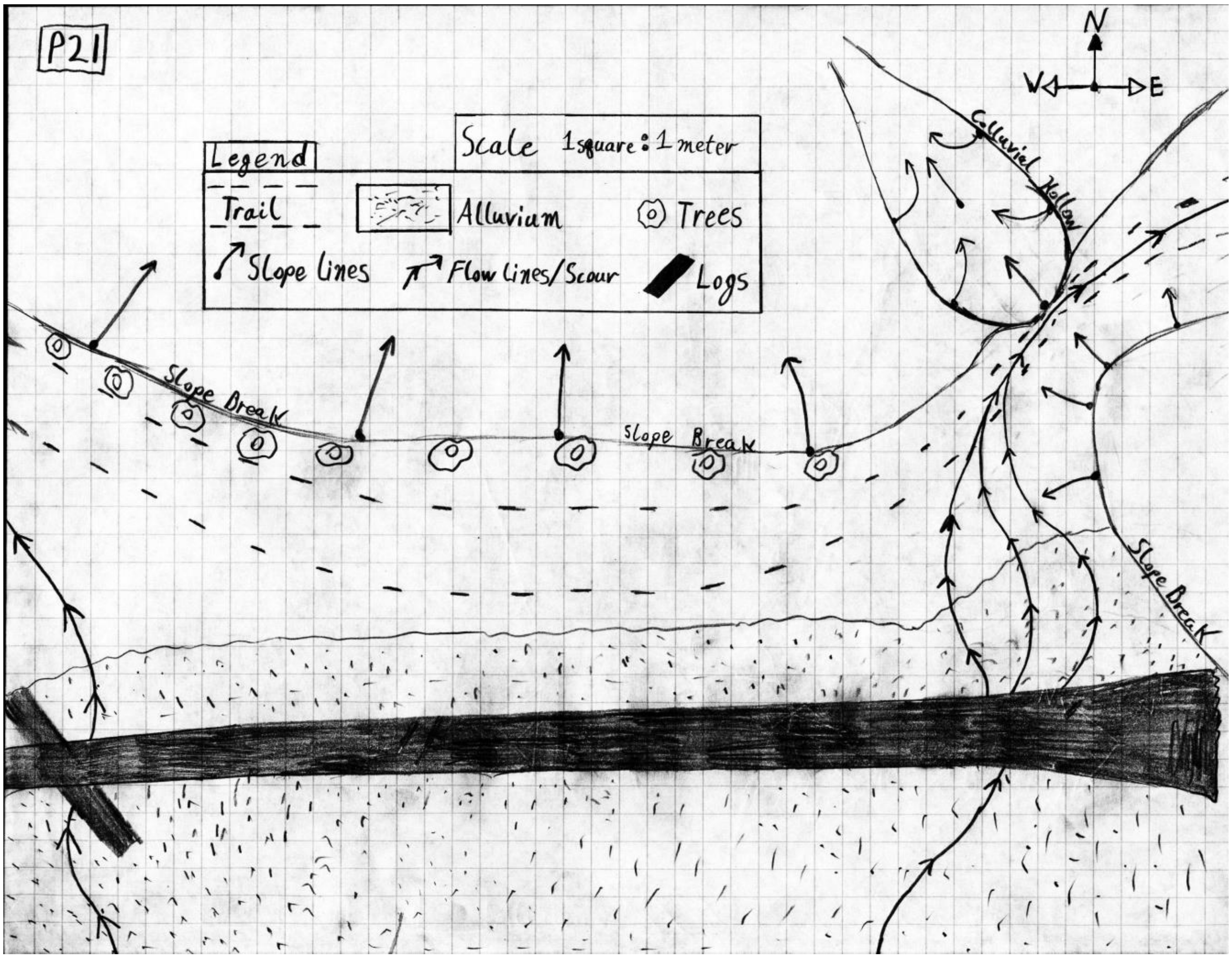

Figure 6: Sketch of P21. Field sketch detailing the plan view of the P21 channel, convergence, and colluvial hollow. Note that the graded surface is lost for a small section, and is replaced by scouring from surface water flows sourced on the east side of the channel. Slope lines point in the steepest downslope direction.

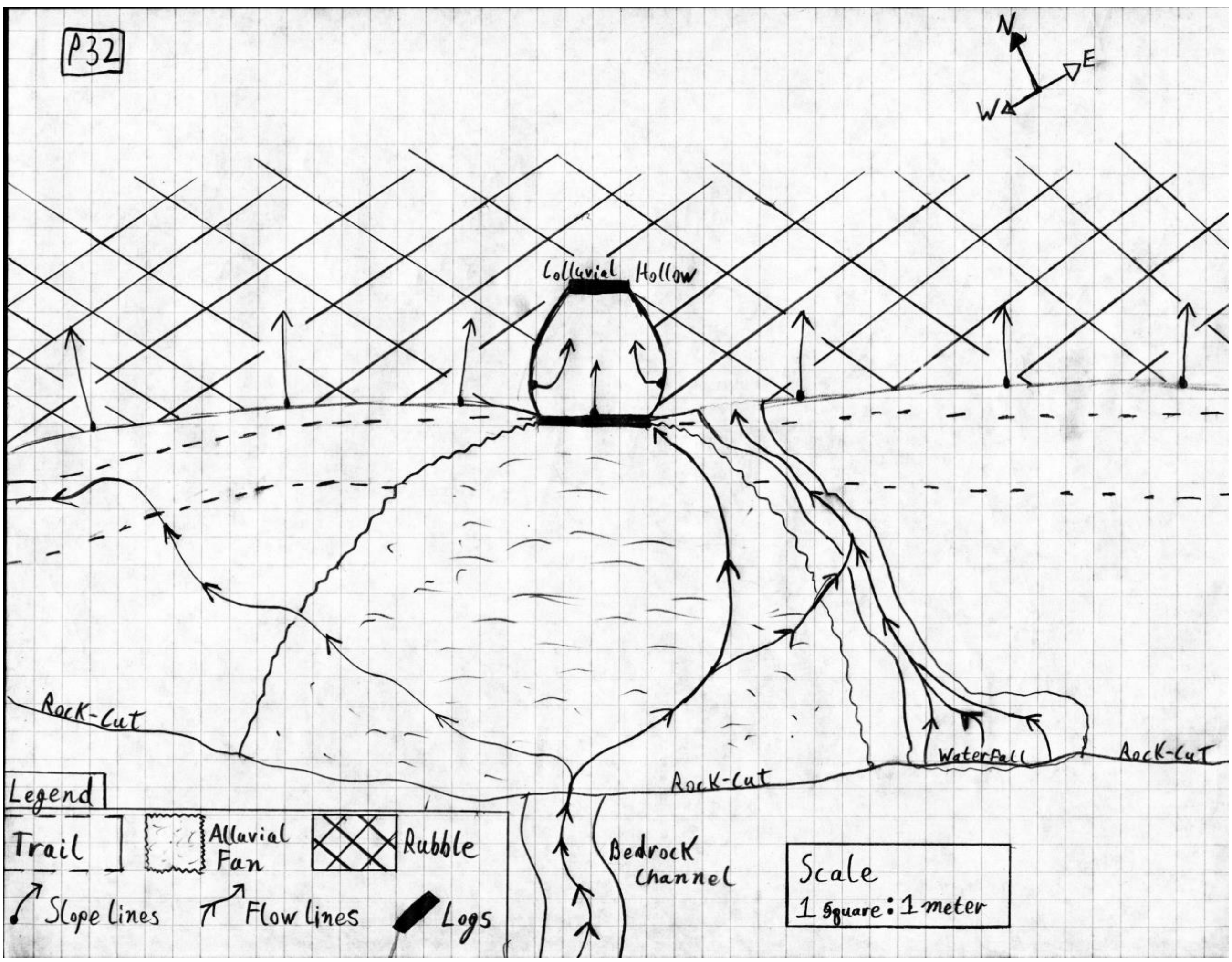

Figure 7: Sketch of P32. Field sketch detailing the alluvial fan, bedrock channel, small hollow, and both surface flow paths sourced from P32. Shows how logs control the relief of the hollow, and the physical position of the fan on the trail surface. Slope lines point in the steepest downslope direction.

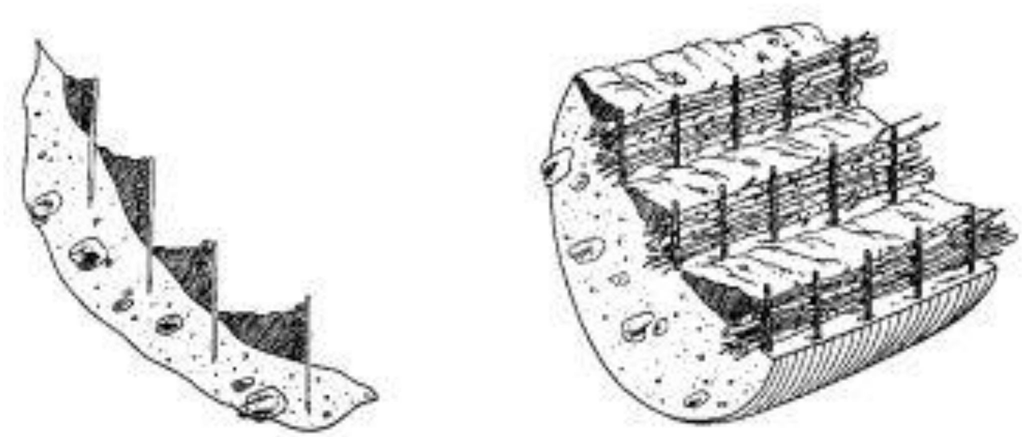

Figure 8: Wattle Fence Schematic. Figure detailing the general design of wattle fences in both side and front views. These plans are scalable and can be built with a variety of vegetation. Figure taken from Polster, 2002.

Appendix

Appendix Table 1: Details on Water Presence. **Table showing my notes detailing water source, road tilt, presence of surface scouring, presence of culverts, and the condition of the ditch at each point. These data were needed for context at each point in the site, and were used to carry out the drainage area estimates shown in Appendix Table Y.**

Point Label		H2O					
Figure Label	Field Note Label	Source	Issue	Culverts	Ditch Condition	Road Tilt	Surface Scour
P1	P1	unclear	soil creep	N	present	inward	N
P2	P2	unclear	soil creep, improper drainage	Y (active)	filled	outward	N
P3	P3	unclear	soil creep	N	present	level	N
P4	P4	upslope + P3	surface scouring	N	obstructed on W	level	Y
P5	P5	P4	runoff to colluvial hollow	N	filled with soil and some veg, recoverable	outward	Y (ends at failure)
P6	P6	unclear	unknown water effect	N	filled with cobbles and soil slumping from above	level, berm	N
P7	P7	unclear	runoff to colluvial hollow	N	filled with rubble, moderately vegetated	level, outward on E side of polygon	Y
P8	P8	channel	water diversion of channel	N	active	level	N
P9	P9	P8	piracy, scour, runoff on failure	Y (entrance only)	filled E of culvert entry, soil and moderate veg.	outward	Y (ends at failure)
P10	P10	channel	piracy	N	lost	level, berm	Y
	P10_a	upslope	surface runoff	N	lost		
P11	P11	P10		N	lost	level	Y
P12	P12	P11/P10		N	lost	level	Y
	P12_a	upslope rills		N	lost		
P13	P13	upslope		N	lost	level	N
P14	P14	N/A		N	slightly filled	inward	Y
P15	P15	channel		N	filled (rockfall)	level	N
P16	P16	from W on trail		N	filled with rubble and large wood, open E of channel	outward, small berm	Y(minor)
P17	P17	ponding		N	filled with soils	level, outward within 3m of fill edge	Y(minor)
P18	P18	ponding		N	filled, recoverable but recovery would pirate water toward a sensitive area, recommend culvert (P19) recovery instead	shallow concave up	Y
P19	P19	from W in ditch	piracy due to dry culvert	Y (exit only, still transmits some water)	see P18	see P18, point made to note location of culvert	Y
P20	P20	Channel, some input from W on trail and in ditch		N	lost on W side. Recovery on E side possible, difficult, and necessary	outward	Y(minor)
	P20_a						
P21	P21	P20		N	see P18. Perhaps a length of culvert would work (rather than incising the toe of a slope)?	level	Y
P22	P22	P20, and P21 headwall upslope		N	active	level, outward at edge	Y

	P22_a						
P23	P23	see P22		N	active	outward	Y(not after pt.)
P24	P24	upslope?		N	lost	outward	Y
P32	P25	bedrock channel upslope, some from P26 and P27		N	lost	inward where trail still exists, otherwise slope is controlled by alluvial fan	Y
P33	P26	engineered waterfall, some surface input from P27		N	present, but W flow is blocked by a plug of rock and wood	outward	Y
P34	P27	upslope, some possible piracy from P35		N	present	level, outward at edge	Y(minor)
P31	P28	some W flowing surface runoff from P25 fan, runoff from small upslope slide channel		Y (exit only, still transmits some water)	buried by alluvium from fan	level at culvert, outward to E, inward to W	Y
P30	P29	upslope chute, some surface flow from E		N	buried by boulders, may still pass water	outward	Y
P29	P30	surface runoff on trail		N	present, some rocky debris	outward	Y(minor)
P28	P31	upslope		N	present	level	N
P27	P32	upslope		N	present	level	N
HZ_R	P33	upslope		N	present, single blockage from slump E of P33 pin (labelled P33_a)	outward	N
HZ_L	P34	mostly upslope, some surface water piracy from W on W edge of zone		N	see P33	level	N
P35	P35	steep upslope channel, all seem to be adequately handled by culvert		Y (active)	active	outward	N
P25	P36	upslope, P24		N	filled	level	Y
P26	P37	P36, leads to the W edge of the scarping zone		N	filled	level	Y (ends at failure)
P36	P38	no significant input		N	active	outward	N

Appendix Table 2: Channel Characteristics. Table detailing the general character of channels that contact the trail from upslope. Grey cells are points of no relevant or collectible data. Yellow cells are data points that I either could not measure or did not have enough time to collect.

Point Label		Channel Characteristics								
					Width (m)			Slope (deg)		
Figure Label	Field Note Label	Present Upslope	Active	Debris Fan	Lower	Middle(ish)	Upper	Lower	Middle(ish)	Upper
P1	P1	N	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
P2	P2	N	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
P3	P3	N	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
P4	P4	N	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
P5	P5	N	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
P6	P6	N	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
P7	P7	N	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
P8	P8	Y	Y (low)	N	13	9	1.1	24	37	60
P9	P9	N	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
P10	P10	Y	Y (trickle)	N	0.9	2.4	0.9	24	short channel	42
	P10_a	N	N/A	Y (alluvial)	N/A	N/A	N/A	N/A	N/A	N/A
P11	P11	N	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
P12	P12	N	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
	P12_a	Y (pt. is the source)	N	Y (alluvial)	13	1.82	0.3	25	40	60-70
P13	P13	N	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
P14	P14	N	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
P15	P15	Y	N	Y (alluvial)	20	3.5	2	40	short channel	65
P16	P16	Y	N	N	10	5	1.1	30	36	43
P17	P17	Y	Y (trickle)	N	4.6	2.2	~2	40	35	35
P18	P18	Y	Y (barely)	N	4.3	3	2	30	41	30
P19	P19	N	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
P20	P20	N	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
	P20_a	Y (pt. is the channel)	Y (farther up)	Y (alluvial)	~25	~20	3	20	30	45
P21	P21	N	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
P22	P22	N	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
	P22_a	Y (pt. is the channel)	Moist	N				45		
P23	P23	N	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
P24	P24	N	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
P32	P25	Y	N							
P33	P26	N	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
P34	P27	N	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
P31	P28	N	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
P30	P29	Y (chute)	N							
P29	P30	N	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
P28	P31	N	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
P27	P32	N	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
HZ_R	P33	N	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
HZ_L	P34	N	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
P35	P35	Y	Y	N		not needed			not needed	
P25	P36	N	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
P26	P37	N	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
P36	P38	N	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A

Appendix Table 3: Calculation of drainage areas. Table detailing the values found for the drainage area analysis performed in GIS. Specific drainage is the flow accumulation that naturally reaches the point, total drainage is the combined input from natural runoff paths and accumulated water piracy. Red cells indicate that only part of the source reaches the point, blue cells detail points of no concern, grey cells are point sources that lead to hazards, and tan cells are points where the calculation is not strictly applicable.

Point Label		Drainage Area		
Figure Label	Field Note Label	Specific Drainage Area (m^2)	Total Drainage Area (m^2)	Notes or special conditions
P1	P1	28701		no piracy or diversion from this point
P2	P2	18960		culvert exists, minor maintenance required
P3	P3	2659		
P4	P4	13005		Pirated to P5
P5	P5	15108	28113	
P6	P6	5279		
P7	P7	6466	6466	
P8	P8	23932		Pirated to P9
P9	P9	4042	27974	
P10	P10	37969		
	P10_a			
P11	P11	13159	51128	this discharge needs to be handled by P11/P12, no discharge can reach P13
P12	P12		~51128	no individual path from flow accumulation, discharge is assumed to be whatever P11/P10 cannot handle
	P12_a			
P13	P13			no individual path from flow accumulation, discharge is assumed to be whatever P12/P10 cannot handle
P14	P14			rockfall boundary
P15	P15	117161		rockfall fan, water is pirated E, water from accumulation lines both W and E of point were counted. Field truthing would suggest that the drainage area calculated does not fully reach P16.
P16	P16	4164	6000	Piracy to P17
P17	P17	40862	45026	Some probable piracy to P18
P18	P18	15014	60040	Major piracy to P20
P19	P19			Same source/drainage as P18, major piracy to P20
P20	P20	19484.7	79524.7	Source is P19 excess and some from P20_a, perhaps up to 20-30% of P20_a (approx.)
	P20_a	64949		
P21	P21	58454.1	58454.1	Source is whatever Q from P20_a does not go toward P20, probably about 80% (approx.)
P22	P22		46763.28	Sourced mostly from P21, some minor input from the convex rocky slope, some loss to ditch leading to P22_a channel
	P22_a	103670		Local conditions make Q from P22_a independent from other sources. Some water is pirated to this ditch, and is also not a concern.
P23	P23			Sourced entirely from P21, some loss to the P22_a ditch

P24	P24	98726	98726	
P32	P25	72533	72533	
P33	P26	19570		does not directly contribute to P25
P34	P27	21796		Receives excess from P35 culvert at high flow
P31	P28	4000		Dry culvert
P30	P29	14713	18713	Gains pirated water from P28
P29	P30		18713	No direct upslope flow accum. line, flow sourced from P29
P28	P31			both pts are classified as issues beyond the project scope
P27	P32			
HZ_R	P33	116673		value of SD represents all accumulation between P33-P34 that hits trail, trail slope is W, so all flow is assumed to go W
HZ_L	P34			value of SD represents all accumulation between P33-P34 that hits trail, trail slope is W, so all flow is assumed to go W
P35	P35	additional investigation needed		
P25	P36	?		Flow accum. Does not lead any trails to this pt., yet I know that this is where P37 is sourced. Probably just assume some number of water bars, 5 seems sufficient
P26	P37			sourced from P36
P36	P38	N/A		not a water management issue

Appendix Table 4: Density, Type, Maturity, and Location of Vegetation at Each Point. **Table detailing the presence of vegetation I investigated at each point in the field site. Tan cells indicate points where vegetation notes were unnecessary due to local conditions or context.**

Point Label		Vegetation			
Figure Label	Field Note Label	Density	Type	Maturity	Location
P1	P1	dense	conifer, ferns, some devils club	mature	up and down on slope
P2	P2	mod.-dense	conifer, standard floor plants	mature	hydrophiles downslope a ways, upslope/downslope are similar otherwise
P3	P3	mod.	conifer	mature	up and down on slope
P4	P4				
P5	P5	mod.	berries, ferns, mosses, alder, devil's club	~<= 10 yr	devil's club on upslope edge of trail, others described are in the downslope failure
P6	P6	dense	ferns, berries, alder, conifer	young(<5 yr)	described are in downslope failure, otherwise slope is a conifer stand
P7	P7	light-mod.	ferns, berries, conifer, sparse alder	mod. Mature	described are in downslope failure
P8	P8	mod.-dense	berries, devil's club, alder, conifer	young-mature	young plants including devil's club, berries, and alders were in the upslope channel. Mature conifers were downslope
P9	P9	bare-mod.	ferns, berries, alder, some cedar	young-mature	inside of failure is bare soil, otherwise plants described were present on what is a partially washed slope, stand had mixed ages of trees
P10	P10	bare-mod.	alder, ferns, berries, hydrophiles	mod.	upslope headwall is a bare soil failure, hydrophiles have surfaces frequently washed by runoff, others exist everywhere including the downslope convergent headwall
	P10_a				
P11	P11	bare-light	ferns, Oregon grape, other scrub	young	runout path is continuously washed by runout from P10, slope edge is bare, scrub starts after ~2m
P12	P12	bare	scrub, little to be found	young	runout path is sourced from P11 overtopping at high flows, resulting scour houses little veg., P10 veg. begins where the wash meets the P10 convergent headwall ~3m down.
	P12_a	light	hydrophiles	young	hydrophilic plants across entire fan
P13	P13	bare	minor scrub, alder	v. young	inside of failure is bare soil, some minor plants colonized at very edge of trail at failure. Upslope is a bare rockfall and soil failed headwall, shared with P11-P14
P14	P14				
P15	P15	light	grasses, berries, hydrophiles, alder	young	fan has berries and hydrophiles, ditch also had alder as well as others
P16	P16	mod.-dense	conifer, alder, ferns, berries	mod.-mature	berries covering trail, more mature alders downslope and on upslope edge of trail, young conifers along outer edge of trail, mature conifers upslope
P17	P17	mod.-dense	alder, ferns, berries	mod.-mature	moderately aged alders up and downslope, ferns and berries everywhere, only ferns and berries in the ditch/pond (lighter density)
P18	P18	light-dense	alder, some cedar, berries, devil's club	mod.	mature alder and moderately aged cedars downslope surrounding what is either a failure or an old channel, young alder and devil's club dense around trail, upslope channel is mostly bare with berries and devil's club where the slope flattens out around the woody debris
P19	P19	see P18	see P18	see P18	see P18
P20	P20	dense	alder, conifer, berries, ferns, hydrophiles	mod.-mature	mature alders downslope with berries and ferns in first failure, mostly lighter berries and ferns in the second failure sourced from a scour path, mature conifers upslope, mod.-mature alders on edges of failure around convergent headwall

	P20_a	light-dense	devil's club, berries, hydrophiles	young	dense devil's club and berries near base of channel where it's mostly flat and sandy, transition to light density of hydrophiles farther up on the alluvial fan
P21	P21	dense	alder, berries, ferns	mod.	dense berries and some ferns with interspersed alders. Hydrophiles all along the downslope section with some berries
P22	P22	light-dense	berries, hydrophiles, short undergrowth, conifer	mature	mod.-dense hydrophiles and berries with thick undergrowth around first part of trail, transfers to light hydrophiles with some berries and a spill leading to a dense stand of conifer with a range of ages
	P22_a				
P23	P23	light-mod.	berries, hydrophiles, short undergrowth, conifer	mature	light berries and hydrophiles surrounding trail until spill, spill has even lighter veg. and leads to a moderately dense stand of conifer ranging from young to middle ages
P24	P24				
P32	P25	mod.	hydrophiles, berries, some flowers	young	hydrophiles along surface of debris fan, denser grouping of berries with some hydrophiles along trail and in downslope "mini" colluvial hollow
P33	P26	light-mod.	hydrophiles, some berries, some alder	young	hydrophiles around edge of ponding and surface scour areas, younger alders at edge of fill along with denser berries
P34	P27	light-mod.	berries, hydrophiles, alder	young	hydrophiles focused in middle of trail (esp. around surface scouring), young alders and denser berries around sides of trail and in ditch
P31	P28	dense	conifer, standard floor varieties	old growth	up and down on slope
P30	P29	dense	conifer, standard floor varieties	mature	up and down on slope
P29	P30	dense	conifer, standard floor varieties	mature	mature conifers downslope and upslope, berries and ferns in the ditch
P28	P31				
P27	P32				
HZ_R	P33	dense	conifer mostly, some ferns, berries, and alders	young-mature	mature conifers downslope and upslope. Berries, ferns, and young alders along the edge of the road and in the ditch
HZ_L	P34	See P33	See P33	See P33	See P33
P35	P35				
P25	P36				
P26	P37	dense	conifer, alder, devil's club, ferns, berries	mature	mature conifers downslope and upslope. Berries, ferns, and hydrophiles in the spill area. Berries, ferns, and young alder along the trail edge and in the ditch
P36	P38	light	moss, berries, ferns	young	moss across entire ground surface with sparse huckleberries and even fewer ferns.

Appendix Table 5: Risk Classification of Points on the N Puyallup Trail. **Table of all assigned values for the various components of my risk classification. Values were found using Risk=(Hazard)(Value)(Vulnerability), with each of the categories being equal to the sum of its subcategories. The rank column uses the numerical risk values to order the points based on their risk score. Points in grey were not suitable for risk calculation.**

Point Label		Risk		Hazard				Value					Vulnerability				
Figure label	Field Note Label	Rank	Value	Rockfall (0-2)	Debris Flows (0-6)	Shallow Landsliding (0-4)	Surface Erosion (0-2)	Masoned Walls (0-1)	Road Surface (0-1)	Designed Features (0-1)	Access (1)	River (1)	Surface Scouring (0-1)	Narrowing/Loss (0-4)	Outward Tilting (0-2)	Water Quality (0-2)	Fish Habitat (0-4)
P1	P1	28	6	0	0	0	1	0	1	0	1	1	0	0	2	0	0
P2	P2	15	18	0	0	1	1	0	1	0	1	1	0	0	1	2	0
P3	P3	33	0	0	0	0	1	0	1	0	1	1	0	0	0	0	0
P4	P4	28	6	0	0	0	1	0	1	0	1	1	1	0	0	1	0
P5	P5	6	60	0	1	2	2	0	1	0	1	1	1	1	0	1	1
P6	P6		See P5														
P7	P7	5	105	0	3	1	1	0	1	0	1	1	1	1	1	2	2
P8	P8	25	9	0	0	0	1	0	1	0	1	1	1	0	0	1	1
P9	P9	2	216	0	5	2	2	0	1	0	1	1	1	2	1	2	2
P10	P10	8	36	1	1	0	1	0	1	0	1	1	1	1	0	1	1
	P10_a	33	0														
P11	P11	15	18	0	0	1	1	0	1	0	1	1	1	1	0	1	0
P12	P12	7	48	1	0	2	1	0	1	0	1	1	1	2	0	1	0
	P12_a	33	0														
P13	P13	1	270	2	5	2	1	0	1	0	1	1	1	4	0	2	2
P14	P14	33	0														
P15	P15	20	12	1	0	0	0	1	1	0	1	1	0	2	1	0	0
P16	P16	13	24	0	0	1	1	0	1	0	1	1	1	1	1	1	0

P17	P18	P19	P20		P21	P22		P23	P24	P32	P33	P34	P31	P30	P29	P28	P27	HZ_R	HZ_L	P35	P25	P26	P36
P17	P18	P19	P20	P20_a	P21	P22	P22_a	P23	P24	P25	P26	P27	P28	P29	P30	P31	P32	P33	P34	P35	P36	P37	P38
20	12		8	33	3	20	33	20	15	3	8	15	20	15	13	33	33	28	28	25	28	8	25
12	27	See P18	36	0	108	12	0	12	18	108	36	18	12	18	24	0	0	6	6	9	6	36	9
0	0		0		0	0		0	1	2	0	0	1	1	0	0	0	0	0	0	0	0	0
0	0		0		2	0		0	0	0	0	0	0	0	0	0	0	2	2	0	0	0	0
1	2		2		2	0		0	0	2	1	1	0	1	1	0	0	0	0	0	0	2	1
1	1		1		2	2		2	1	2	2	2	1	1	1	0	0	0	0	1	1	1	0
0	0		0		0	0		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1	1		1		1	1		1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
0	0		0		0	0		0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0
1	1		1		1	1		1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
1	1		1		1	1		1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
1	1		1		1	1		1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
0	0		1		4	0		0	2	4	1	0	0	0	1	0	0	0	0	0	1	1	1
1	0		1		0	0		0	0	0	0	0	0	0	1	0	0	0	0	1	0	1	1
0	2		1		0	1		1	0	1	1	1	1	1	1	1	1	0	0	1	0	1	0
0	0		0		1	0		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Appendix Figure 1: Point 8 Channel. Photo showing the channel that contacts point 8 from upslope and leads to the point 9 culvert.

Appendix Figure 2: Photos of Point 9 Concerns. Upper photo shows the entrance to the point 9 culvert that has no exit. Lower shows the point 9 colluvial hollow emanating from the fill slope.

Appendix Figure 3: Point 10 Channel. Photo detailing the smaller clogged channel contacting the trail from upslope at point 10. This channel is constricted at its base and produces some ponding near the trail.

Appendix Figure 4: Point 11 and 12 Waterbars. Upper photo details the input and condition of the waterbar that I labeled as point 11. Lower photo shows the same for point 12. Note how point 12 is dry but still has scour sourced from point 11.

Appendix Figure 5: Point 13 Conditions. Upper left and right photos show the W and E colluvial hollow crowns, respectively. The lower photo is taken from the E edge of the point looking W, and shows the rockfall that contacts the trail.

Appendix Figure 6: Point 21 Conditions. Upper photo shows the surface scouring that exists near the point 21 colluvial hollow headwall. Lower photo shows the condition of the interior of the hollow. The scour in the upper photo does not lead into the hollow.

Appendix Figure 7: Point 32 Conditions. Upper left and right photos show the W side of the alluvial fan and the axis of the fan looking upslope at the channel, respectively. Lower photo shows the interior of the small hollow in the fill slope.

Appendix Figure 8: Deep-Seated Hazard Example. Upper photo shows an example of vertical offset above a bench within the hazard zone. Lower photo is a view of the same location looking W. These are just one example of benching and cracking that occur across this 280 meter zone of trail.

Detailed Site Observations

P8-P9

Points 8 and 9 are an example of a channel leading to an obstructed culvert that causes surface erosion and mass wasting. Point 8 is an upslope channel that has a flow I estimate to be about 0.1 cfs, and is active through the year (appendix Figure 1). This channel is intercepted by the inboard ditch and sent about 20 meters east until reaching the culvert inlet (Figure 4). This culvert has no visible exit.

The entry point of the culvert is audible from the water, and inspection shows the culvert is not visible (appendix Figure 2). The entrance is a hole surrounded by soils, and the culvert can only be observed by pushing ones arm into the pipe. I estimate the size of this culvert is 18”. This entry constantly accepts water, but has no exit. Surface scouring begins here, with scour starting at the culvert entrance and spreading out in multiple directions. These flow paths converge after about 3-4 meters of trail. The scour then deepens to be about 40 cm deep, and proceeds to enter the headwall of the colluvial hollow.

The colluvial hollow is roughly 10-12 meters wide, 5-6 meters deep, and has a slope of 45 degrees at the trail (appendix Figure 2). The interior of the hollow is bare, with any vegetation being from small slumps off the edges of the failure. The headwall has a bench that is slumped 30 cm vertically, is 1 meter wide from the edge to the scallop, and slopes 20 degrees toward the failure. Scour leading into the hollow cuts the west side of this bench. The hollow narrows to about 1-2 meters wide roughly 30 meters downslope.

The downslope condition here has the same general trend mentioned above. Deposits are matrix supported for the length of the runout and generally coarsen from cobbles to boulders downslope, suggesting debris flows. There are areas where sediment is stored on points of high surface roughness provided by downed trees and overturned root balls. The inner gorge flow path has occupies a mature conifer stand and is often controlled by standing trees. The gorge is narrower than 1 meter for the entire length and varies in depth, scouring down to the bedrock in several places. The runout of this mass wasting feature does reach the river, with the toe of the fan having been eroded by high flow of the N Puyallup River.

P10-P13

Points 10 through 13 have a similar source for their issues as points 8 and 9, but additional conditions change how the site must be handled. The site is damaged by undermanaged surface water resulting in surface erosion and colluvial hollow landsliding. The difference from points 8-9 comes from a steeper slope, the presence of rockfall, lower water input, and different drainage structures.

Points 10 through 13 are the most severe example of bedrock hollows and rockfall that can be found in the field site. The site is a convergent headwall with two colluvial hollows near the east edge of the landform. Point 10 is the center of the larger convergence and is host to a channel that has been almost completely clogged (appendix Figure 3). This channel is also active for the full year, but its discharge outside of heavy rain is just enough to make a small ponding area handled by one waterbar, less than 0.1 cfs.

This first waterbar is point 11, and leads to minor fill erosion as it bails into the convergent headwall. Scouring leads from point 11 for about 3-4 meters along the trail to the next waterbar, point 12 (appendix Figure 4). This point has the same conditions as point 11, neither showing signs of channelizing or instability. After point 11 signs of surface water lead 5 meters along to the headscarps of two colluvial hollows (Figure 5). This pair hollows is marked as point 13 because their headscarps are under 2 meters apart (appendix Figure 5).

This hollow complex has rockfall, surface erosion, and landsliding posing risks to both the trail and river. Rockfall covers the upslope area, and has a slope of roughly 35 degrees. The rocks are angular to subangular consisting of cobbles to boulders, and materials appear to be at repose. The width of the trail is as little as 1 meter in this section. The hollow system is about 15 meters wide, with two smaller headwalls merging 3 meters downslope. Their greatest relief is about 10 meters. The hollows narrow to a single 2-3 meter inner gorge 15-20 meters downslope. The gorge then merges with the convergent headwall 25-30 meters downslope. The slope of the hollows at the trail is 50 degrees, and exposed bedrock is visible within 5 meters of the trail surface. The interior of the hollows is completely bare.

Downslope of points 10-13 again showed similarities to points 8-9. The downslope deposits showed are the same those mentioned, with the addition of levees bordering the flow path down to the valley bottom. The runout does reach the river with a low slope at its toe, but the toe is truncated by a cut bank of the N Puyallup River with about 3 meters of vertical offset. The flow path is more of an established channel, and should be able to handle surface water from the trail.

P21

Point 21 on the field site is a strong example of how fill-through designs can fail over time. At this location the roadway needed to cross a 30-35 meter wide channel convergence. The resulting fill slope has been lost from the center of the convergence. These fill slopes have since been replaced by a high curvature slope at a near vertical angle, and the east side of this convergence has developed a colluvial hollow, which is point 21 (Figure 6; appendix Figure 6). The current surface is an arc that hugs a contour of the ridge until the next divergence east.

At point 21 channel input is again the main source of damage. Point 21 is the largest channel in the site, and has been accumulating alluvial sediment since the road’s construction, burying inboard ditch. Now the slope of the fan continues down to the inside edge of the trail, allowing high-water events to flow across the trail surface. The resulting scouring leads east. The fan has two paths the water takes during periods of greater discharge. The deeper incision path leads east toward point 21, and the minor path leads west.

The edge of the fill surface has been colonized by now maturing alders and small vascular plants. This condition covers the width of the feature including the hollow on the east side. The hollow has sharply convergent sides, is 10-12 meters wide, and has a slope of about 50 degrees at the trail. This hollow has a significant amount new vegetative growth by hydrophilic plants, berries, ferns, and juvenile alders. The eastward flow from the channel occupies the trail and passes within 0.5 meters of the headwall (appendix Figure 6). The trail has been narrowed to about 1-1.5 meters wide here. The narrowing comes from headward retreat of the hollow and soil creeping on the upslope side of the trail. The loss of the ditch makes this scouring path the only feature directing surface water.

The downslope area here has the same flow deposits already described. Here the deposits fan out, widening to become tens of meters at the base. The depth of the path varies slightly, but the width remains within 1-2 meters. This path contributes to the N Puyallup River as a tributary, but deposits do not reach the active floodplain.

P32

Point 32 is an example of how sediment accumulation can become the primary problem at some locations. The point is an alluvial fan with the range of material from silt to 50 cm cobbles (appendix Figure 7). The fan is matrix supported, and sourced from an upslope bedrock channel in the local rock cut slope. The channel is only seasonally active, but has a flashy response to rainfall. The material of the fan is highly conductive for water. Some flows seem to occasionally exit to the west onto the trail seen by incision paths, continuing toward point 31 where it bails into a mature conifer stand. The slope of the fan is continuous until reaching the edge of the fill slope, where it meets a small hollow. This level of accumulation covers the trail surface completely, yet with a slope of about 22 degrees the fan is still traversable by hikers (Figure 7).

The hollow is at the base of the fan directly along the fans central axis. This landform is about 5 meters wide at max, 2 meters wide at the outlet, 6-7 meters long, and filled with coarse gravels to cobbles (appendix Figure 7). It has a 35 degree slope at the headwall and roughly 10 degrees at the outlet. Both the headwall and the outlet of the feature are controlled by logs buried perpendicular to the profile slope, each measuring 30-50 cm in diameter. Below the hollow the slope becomes a collection of cobble to large boulder sized rubble that continues for roughly 50 meters.

Inspection of the slope below the hollow feature shows no channeling from surface water. The downslope area is rubble of all angular materials with no significant infilling, save for the occasional Pica. Surface water indications do not reappear until the bottom of this rock slope, after which flows are no more than slow tributaries up to 50 cm wide. The N Puyallup River occupies the far northern side of the valley bottom at this section of trail, with significant physical boundaries to overcome before any northward flow could reach it.

Deep-Seated Hazard Zone

This area occurs across a stretch of trail roughly 280 meters long, rather than a section easily represented with a point. The normal problems of piracy, surface erosion, and shallow landsliding, do not appear as issues in this segment. This stretch of trail has multiple benches and tension cracks appearing on the fill slope. The largest gap between such features was only about 5-6 meters of trail. Benches are 1-3 meters in width, with a vertical offset of 0.1-1 meter (appendix Figure 8).

This stretch of the trail has a nearly planar planform slope, and a profile slope of about 35-40 degrees. The vegetation profile is a mature conifer stand including ground cover of ferns and short scrubby brush, with some sections being old-growth. Areas with larger trees on the downslope side seem to generally have a lower abundance of tension cracks, and narrower benches with less vertical offset.