Legacy Roads and Trails Monitoring Project

Road Storage Treatment in the Suiattle River Watershed
Mount Baker-Snoqualmie National Forest

January 2011

Richard Cissel[1], Tom Black[1], Charlie Luce[2], and Brian Staab[3]

[1]Hydrologist
[2]Research Hydrologist

US Forest Service
Rocky Mountain Research Station
322 East Front Street, Suite 401
Boise, Idaho, 83702 USA

[3]Regional Hydrologist

US Forest Service
Pacific Northwest Region
333 SW First Avenue
Portland, OR 97204

Table of Contents

List of Figures

List of Tables

Executive Summary

In Fiscal Year 2008, Congress authorized the Legacy Roads and Trails Program, which is intended to reduce road and trail impacts to watersheds and aquatic ecosystems by decommissioning unneeded roads, removing fish passage barriers, and addressing critical repair and maintenance needs. The US Forest Service (USFS) was appropriated $40 million to begin its implementation in FY2008, followed by $50 million in FY09 and $90 million in FY10.

The USFS, Rocky Mountain Research Station and Pacific Northwest Region are monitoring some of the road decommissioning and maintenance projects in Oregon and Washington to assess their effectiveness in reducing impacts and risks to key watershed processes. Risk profiles are being developed and compared, before and after road treatments, with the Geomorphic Road Analysis and Inventory Package (http://www.fs.fed.us/GRAIP). This suite of robust inventory and analysis tools evaluates the following road impacts and risks: road-stream hydrologic connectivity, fine sediment production and delivery, shallow landslide risk, gully initiation risk, stream crossing failure risk, and drain point condition.

To date, pre-treatment inventories have been conducted at 21 locales where decommissioning or heavy maintenance (i.e., storm damage risk reduction; SDRR) treatments have since or will be implemented. At each of these locations, four miles of road were assessed. Inventories were also completed on four miles of control sites for each locale. 18 post-treatment inventories were executed, as well as three post-storm validation evaluations. This status report focuses only on storage treatment work implemented by the Mount Baker-Snoqualmie National Forest (MBSNF) in the Suiattle River watershed. At the MBSNF sites, treatments included removal of culverts and fills at stream crossings, replacement of culverts with waterbars, construction of new waterbars, insloping of road surfaces, and pullback of unstable sidecast material.

Before-after comparisons using GRAIP indicate that storage treatments resulted in a small to large reduction of many impact-risk metrics, and a moderate increase in others. Road-stream connectivity was reduced by 290 m (16%), from 1820 m of connected road to 1530 m. Delivery of fine sediment was reduced by 1.1 tonnes/yr (9%), from 12.5 tonnes/year to 11.4 tonnes/year. Values of a stream blocking index were reduced from an average of 1.8 before treatment to zero after treatment (n=13), indicating the risk of stream crossings becoming plugged was completely eliminated by excavation and removal of culverts and associated fills. While former crossings sites may contribute fine sediment to streams in the short term, the restoration treatments removed over 400 m^3 of earthen material from areas with a high potential for failure and delivery to stream channels. Diversion potential was eliminated at all 13 crossing sites.

The slope stability risk below drain point locations on the original road was reduced in a few locations as water was redistributed across the hillslope to new drainage points. However, landslide risk experienced an overall increase across even more of the treated road length because the treatments added new concentrated drainage features above steep slopes.

Risk of gully initiation, as determined by comparisons of a gully initiation index (ESI) to an empirically-derived threshold (ESI_{crit}), experienced a moderate increase across the length of treated road. New drainage features reduced the gully index at some of the original drainage points by reducing the length of the road segments discharging to them. In many cases, however, post-treatment index values still exceeded the initiation threshold, indicating elevated risk was still present. Moreover, index values exceeded the threshold at many of the new drainage points. The net effect was that treatments increased the number of drainage points with elevated gully risk by four (11%), and increased the length of road connected to drain points with elevated risk by more than 1 km. The average ESI also increased by 65%. Current calculations are based on conservative assumptions, so the actual performance of the treatments may exceed these initial expectations. Such assumptions will be assessed during future post-storm monitoring.

Risks of stream crossings culverts becoming plugged and overtopping, the potential for diversion onto the road, and total fill at risk (430 m^3 before treatment) were completely eliminated by the treatments. Before treatment, inventoried road segments had problems at 12% of 115 inventoried drainage points. Post-treatment monitoring indicates that these problems were eliminated by the storage treatments and that most replacement drainage features may be somewhat less vulnerable to failure.

Taken collectively, preliminary results indicate the storage treatments should be effective in reducing some of the hydrogeomorphic impacts and risks to aquatic ecosystems, while increasing others. Risk of shallow landsliding and gully formation likely remain where road surface flow path lengths were increased and new concentrated drainage features were installed over steep slopes, and some assessment of tradeoffs between more thorough local treatment and greater treated lengths is warranted for future treatments. GRAIP can be used to address these needs in the design phase of future projects.

Summary of GRAIP road risk predictions for the Suiattle River watershed storage treatment project.

IMPACT/RISK TYPE	EFFECT OF TREATMENT: INITIAL GRAIP PREDICTION	EFFECT OF TREATMENT: POST-STORM VALIDATION
Road-Stream Hydrologic Connectivity	-16%, -290 m	To be determined.
Fine Sediment Delivery	-9%, -1.1 tonnes/year	To be determined.
Landslide Risk	Overall increase	To be determined.
Gully Risk	Overall increase	To be determined.
Stream Crossing Risk		
- plug potential	-100% (eliminated at 11 sites)	To be determined.
- fill at risk	-100% (-432 m^3)	To be determined.
- diversion potential	-100% (eliminated at 11 sites)	To be determined.
Drain Point Problems	-100%, eliminated at 14 drain points	To be determined.

1.0 Background

The National Forest Transportation System is vast and represents an enormous investment of human and financial capital. This road and trail network provides numerous benefits to forest managers and the public, but can have adverse effects on water quality, aquatic ecosystems, and other resources. There is currently a large backlog of unfunded maintenance, improvement, and decommissioning work on national forest roads, and many critical components of the network (e.g., culverts) are nearing or have exceeded their life-expectancy. This significantly elevates risks to aquatic resources. Consequently, in Fiscal Year (FY) 2008, Congress authorized the Legacy Roads and Trails Program and in 2010 allocated the US Forest Service (USFS) $90 million to begin its implementation. This program is intended to reduce road and trail impacts and risks to watersheds and aquatic ecosystems by decommissioning unneeded roads, removing fish passage barriers, and addressing critical repair and maintenance needs.

Recognizing the importance of this program, the USFS, Rocky Mountain Research Station (RMRS) and Pacific Northwest (PNW) Region are implementing the Legacy Roads and Trails Monitoring Project (LRTMP) to evaluate the effectiveness of road restoration treatments being implemented on national forests in Oregon and Washington. This report briefly describes the overall objectives of the Regional-scale study and the methods being used. Specific results presented herein, however, are focused only on road storage treatment work completed by the Mount Baker-Snoqualmie National Forest (MBSNF) in the Suiatttle River watershed in FY2008. As other data become available, similar reports will be developed for additional sites. In addition, syntheses of results at multiple sites will be produced throughout and at the end of this monitoring project.

2.0 Study Objectives

The LRTMP is designed to assess the effectiveness of decommissioning, maintenance, and repair projects in reducing road impacts and risks to several key watershed processes. Specifically, the project is intended to address the following questions.

How effective are USFS road restoration projects in:

1) reducing or eliminating:
    a. the risk of increased peak flows resulting from road-stream connectivity?
    b. fine sediment production and delivery to stream channels?
    c. shallow landslide risk?
    d. gully initiation risk?
    e. the risk and consequences of stream crossing failures?
2) improving the performance of the road drainage system?

3.0 Methods

The Geomorphic Road Analysis and Inventory Package (GRAIP, Prasad et al. 2007a, and Prasad et al. 2007b, http://www.fs.fed.us/GRAIP) is being used to inventory and model the risk profile of each of the road segments included in the study. The GRAIP system consists of a detailed, field-based road inventory protocol combined with a suite of geographic information system (GIS) models. The inventory is used to systematically describe the hydrology and condition of a road system using Geographic Positioning System (GPS) technology and automated data forms (Black, et al., 2009). The GIS models use these data to analyze road-stream hydrologic connectivity, fine sediment production and delivery, shallow landslide potential with and without road drainage, gully initiation risk, and the potential for and consequences of stream crossing failures (Cissel, et al., 2009). Detailed information about the performance and condition of the road drainage infrastructure is also supplied.

Risk profiles are being developed and compared at untreated control segments and treated segments before and after road projects. At a given site, monitored road segments typically comprise 4 miles of both treated and control sites. Control sites were selected based on their similarity to treated sites with respect to road construction methods, maintenance levels, geology, slope position, and hydrologic regimes. Each site investigation also includes a final validation evaluation at both treatment and control sites following a substantial storm event (5-10 year recurrence interval). This will allow testing of the initial GRAIP risk predictions and provide an unbiased comparison between the treated and the untreated roads.

4.0 Monitoring Locations

Regional Monitoring Sites

In FY2008, pre-treatment evaluations were completed at 19 sites[1] on national forests throughout the Pacific Northwest Region. Decommissioning has been implemented at ten of these sites and nine sites have been treated with storm damage risk reduction methods (SDRR)[2] (Figure 1, Table 1). Eleven post-treatment inventories and one post-storm validation evaluation were also completed in FY2008 and FY2009. Post-treatment and, to the degree possible, post-storm evaluations will be completed at the remaining sites in FY2010. In 2009, a similar study was begun in Regions 1, 4, and 5.

---

[1] Each site will include the following evaluations: pre-treatment, post-treatment, and post-storm validation on treated road segments; and pre-treatment and post-storm validation on control segments.

[2] SDRR (also referred to as stormproofing) is used to refer to relatively low-cost treatments applied across extensive portions of the road network with the objective of protecting aquatic resources and infrastructure. These treatments are intended to reduce the chronic effects of roads (e.g., fine sediment delivery) and significantly reduce the likelihood and consequences of catastrophic failures (e.g., diversion of stream flow onto roads) associated with large storm events. A variety of tools may be used to achieve these objectives, depending on site-specific conditions. These include diversion potential dips at road-stream crossings, waterbars, and broad-based drain dips. These simple, extensive treatments are intended to compliment the use of more intensive treatments (e.g., decommissioning, road realignments) that are typically implemented on relatively small segments of the network.

Figure 1. Location of monitored sites, FY2008, FY2009, and FY2010, PNW Region.

Table 1. *The locations and types of road treatments monitored in Region 6.*

NATIONAL FOREST	WATERSHED	TREATMENT
Mt. Baker-Snoqualmie	Baker Lake	Decommissioning
	Skykomish River	Storm Damage Risk Reduction
	Suiattle River	Storage
	Suiattle River	Storm Damage Risk Reduction
Mt. Hood	Bull Run River	Decommissioning
Okanogan	Twisp River	Decommissioning
	Twisp River	Storm Damage Risk Reduction
Olympic	Skokomish River	Decommissioning
	Skokomish River	Storm Damage Risk Reduction
Rogue-Siskiyou	Applegate River	Decommissioning
	Applegate River	Storage
	Applegate River	Storm Damage Risk Reduction
Siuslaw	Alsea River	Decommissioning
	Nestucca River	Decommissioning
Umatilla	Granite Creek	Decommissioning
	Granite Creek	Storm Damage Risk Reduction
	Wall Creek	Decommissioning
Umpqua	South Umpqua River	Decommissioning
Wallowa-Whitman	Chesnimus Creek	Decommissioning
Willamette	Middle Fork Willamette River	Storm Damage Risk Reduction
	Middle Fork Willamette River	Storage

Suiattle Basin Sites

During the summers and falls of 2008 and 2009, field crews inventoried both storage treatment and storm damage risk reduction sites in the Suiattle River watershed (Table 1, Figure 1). The storage treatment sites in this watershed are principally underlain by medium to high grade schist, but the bulk of the surface is veneered with lahar and associated Quaternary deposits. Other units within the Suiattle drainage are predominately metamorphic sedimentary and volcanic rocks. The average precipitation for the basin is on the order of 75 inches per year. The inventoried sites are located between 1400 and 2400 feet above sea level on the west side of the northern Washington Cascades, near the southwest corner of North Cascades National Park, within the transient snow zone. To date, only the results from the storage-treatment sites are available and are the therefore focus of this report (Figure 2). Pre-treatment roads were originally crowned with an inboard ditch, surfaced with gravel and constructed with periodic drainage features. However, most roads were significantly vegetated at the time of the survey. Both treatment and control sites included roads within the range of mid-slope to upper-slope hillslope positions and included frequent live stream crossings. Storage treatments included removal of culverts and fills at stream crossings, replacement of culverts with waterbars, construction of new waterbars, insloping of road surfaces, and pullback of unstable sidecast material. Due to the limited extent of available comparable roads in close proximity to the treatment sites, there is only 1 mile of control road documented here.

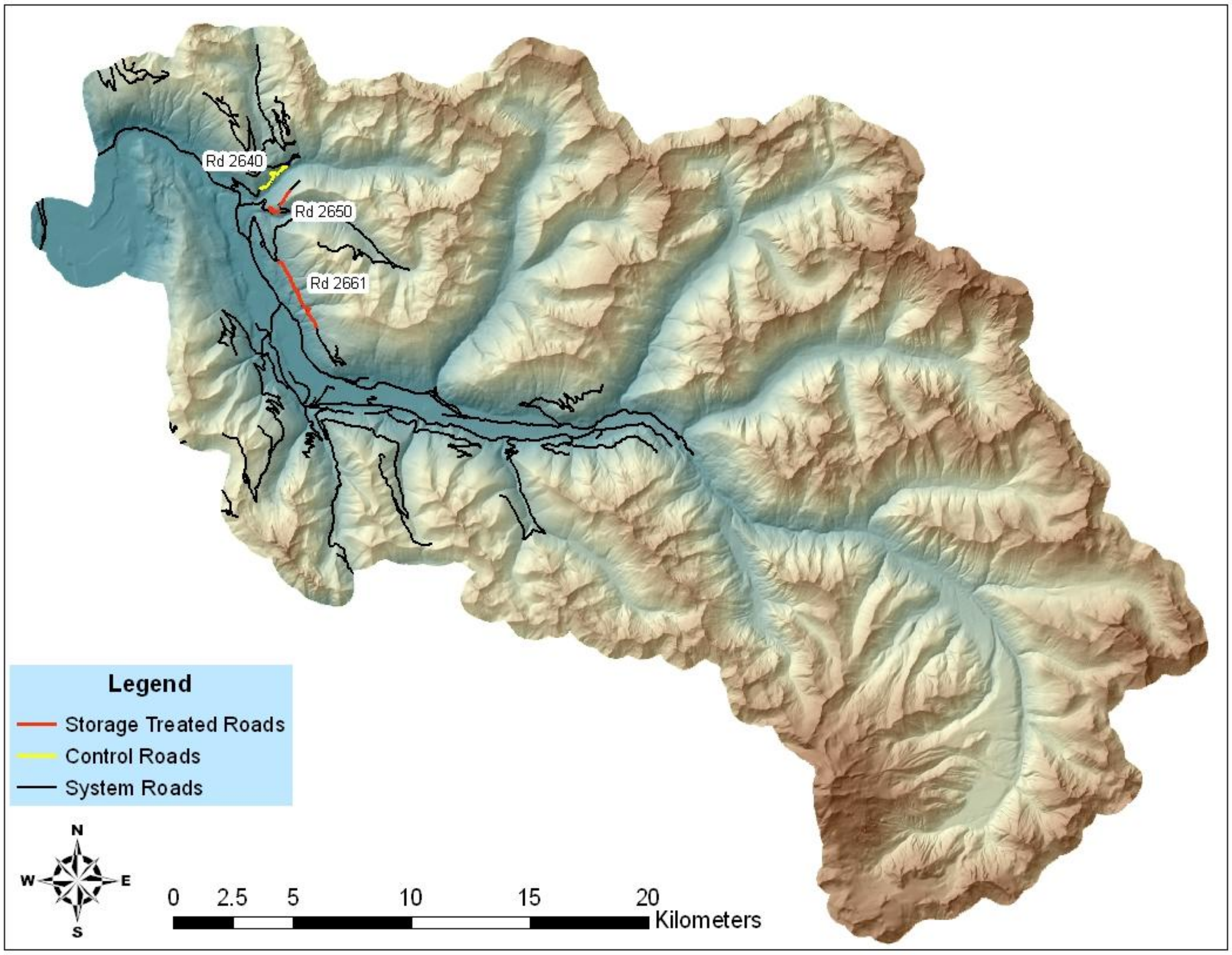

Figure 2. Location of monitored sites in Suiattle River watershed, Mount Baker-Snoqualmie National Forest.

Table 2. *Storage treatments applied by road number.*

STORAGE TREATED ROAD		CONTROL ROAD	
Road #	**Treatment**	**Road #**	**Treatment**
2650 MP 1.4-2.2 and MP 2.7-3.2	Culvert removal, waterbar installation (new features and as replacements for culverts), insloping at locations on steep slopes	2640	None
2661 MP 0-2.3	Culvert removal, waterbar installation (new features and as replacements for culverts), insloping at locations on steep slopes, stream crossing fill removal, sidecast pullback at critical locations	2640	None

5.0 Results

The GRAIP inventory and modeling tools were used to characterize the following types of impacts and risks:

- Road-stream hydrologic connectivity
- Fine sediment delivery
- Landslide risk
- Gully initiation risk
- Stream crossing failure risk
- Drain point problems

The storage treatments are designed to reduce the risk of stream crossing failure and flow diversion, and to create a road prism that does not require annual maintenance.

5.1 Road-stream Hydrologic Connectivity

Roads can intercept shallow groundwater and convert it to surface runoff, resulting in local hydrologic impacts when that water is discharged directly to channels (Wemple et al. 1996). Additional runoff is also produced from the compacted road surface. Basin-scale studies in the Oregon Cascades suggest that a high degree of integration between the road drainage system and the channel network can increase some peak flows (Jones and Grant 1996).

GRAIP calculates the hydrologically-connected portion of the road using the field assessment of drain point connection and a road segment flow routing system. The flow path below each drain point is followed until evidence of overland flow ceases or the flow path reaches a natural channel. In the Suiattle River watershed, even though the total number of drain points decreased after the treatments, the storage treatments added drain points at locations where there had not previously been drain points, which redistributed water back onto the hillslope. Prior to the treatments, 1817 m out of 5470 m of inventoried road (33%) were hydrologically connected to the stream. After the treatments, 1526 m out of 5359 m of monitored road (28%) were connected. Thus, the treatments resulted in a net reduction of 291 m of hydrologically connected road, which is 16% less than the pre-treatment condition.

5.2 Fine Sediment Production & Delivery

Fine sediment production for a road segment (E) is estimated based on a base erosion rate and the properties of the road (Luce and Black 1999), as shown below.

$$E = B \times L \times S \times V \times R$$

B is the base erosion rate[3] (kg/m)
L is the road length (m) contributing to the drain point
S is the slope of the road segment discharging to the drain point (m/m)
V is the vegetation cover factor for the flow path
R is the road surfacing factor

Delivery of eroded sediment to the channel network is determined by observations of each place that water leaves the road. Each of these drain points is classified as delivering, not delivering, or uncertain. No estimate of fractional delivery is made because there is insignificant hillslope sediment storage in locations where there is a clear connection to the channel under most circumstances. For this analysis, uncertain observations were treated as delivering. A map

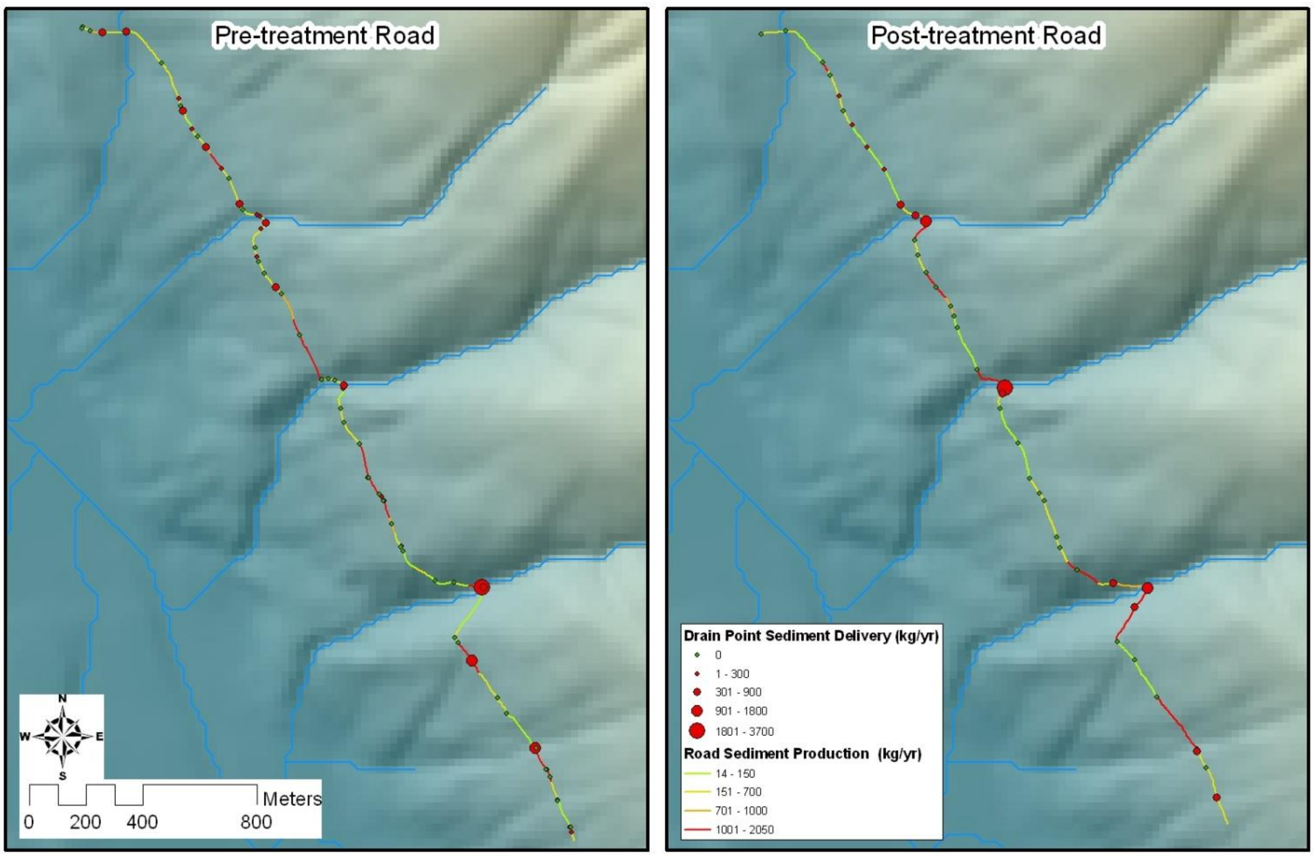

Figure 3. Fine sediment delivery to channels by road segment and drain point, pre-treatment road (left) and post-treatment road (right; rd 2661). The road line is colored to indicate the mass of fine sediment that is generated on the road surface. The size of the circle indicates the accumulated mass of sediment delivered through each drain point.

[3] For this analysis, a base erosion rate of 79 kg/m of road length was assumed, based on observations in the Oregon Coast Range (Luce and Black 1999). Further work could determine if this rate is appropriate for this climate, geology and road system.

of the road surface sediment production and the accumulated sediment delivered through drain points is shown for the 2661 road (Figure 3).

Pre-treatment

Delivery of fine sediment occurs through a mix of road drainage features including ditch relief culverts, waterbars, stream crossings and others. Appendix A provides a key to the drain point types described in the inventory. In Table 3, sediment delivery is broken out by drain type to assess their effectiveness in preventing sediment from entering the channel. However, the sample shown here is too small for extensive statistical analysis by drain point. On-hundred fifteen drain points were documented, 27% of which were hydrologically connected to stream channels. These points delivered 12.5 tonnes/year of sediment, or 38% of the sediment generated by the road surfaces and ditches.

Table 3. *Summary of sediment production and delivery at drain points, pre-treatment road.*

DrainType	Count	∑ Sediment Production (kg)	∑ Sediment Delivery (kg)	% Sediment Delivery	Length Connected (m)	% Length Connected
Broad Based Dip	3	300	260	85%	60	55%
Diffuse Drain	35	8650	840	10%	80	5%
Ditch Relief Culvert	24	6750	2370	35%	520	37%
Lead Off Ditch	1	20	0	0%	0	0%
Non-Engineered	2	0	0	0%	0	0%
Stream Crossing	13	7590	7590	100%	1080	100%
Sump	6	2890	0	0%	0	0%
Waterbar	31	7100	1450	20%	79	9%
All Drains	**115**	**33300**	**12500**	**38%**	**1820**	**33%**

Post-treatment

In some locations, road surfaces were graded and insloped, which had the effect of increasing sediment production by removing vegetation from the road surface, and eliminating diffuse drainage by directing water towards the cutslope and ditch if present. In other places, vegetation, litter, and duff was removed either to facilitate the movement of large equipment, or by the movement of large equipment, which also had the effect of eliminating diffuse drainage as water now flows down the road without infiltrating due to vegetal litter and duff in its path. In these locations, the removal of vegetal litter and duff exposed the underlying gravel road surface, which changed the surface type to be less erodible than the pre-treatment native surface, and so had the effect of lowering the sediment production on those road segments. The net effect of these contradicting factors on sediment production was a slight decrease to 31.3 tonnes/year. As vegetation grows back on the bare ditches on these roads, sediment production is expected to decrease further.

The elimination of all culverts and installation of waterbars in their places, as well as the addition of waterbars at other critical locations that did not previously have drainage features, and the small reduction in sediment production, had the net effect of reducing sediment delivery. Post-treatment, the 24% of connected drain points delivered 11.4 tonnes/year, or 36% of eroded sediment.

Table 4. *Summary of sediment production and delivery at drain points, post-treatment road.*

DrainType	Count	∑ Sediment Production (kg)	∑ Sediment Delivery (kg)	% Sediment Delivery	Length Connected (m)	% Length Connected
Broad Based Dip	1	0	0	0%	0	0%
Diffuse Drain	7	3220	750	23%	110	22%
Ditch Relief Culvert	0	0	0	0%	0	0%
Lead Off Ditch	1	13	0	0%		0%
Non-Engineered	0	0	0	0%	0	0%
Stream Crossing	11	8440	8440	100%	1030	100%
Sump	1	44	0	0%		0%
Waterbar	45	19570	2220	11%	380	10%
All Drains	**66**	**31290**	**11400**	**36%**	**1530**	**28%**

The modeled change in sediment delivery following the treatments shows a decline of 1.1 tonnes/year to a total of 11.4 tonnes/year. The largest reductions occurred at ditch relief culverts (through removal of the features), with smaller reductions from the removal of diffuse drainage and broad based dips over stream crossings. There was a modest increase in the number of waterbars (14). Many new waterbars were placed to avoid delivery to the channels and drained shorter road segments. Other waterbars replaced delivering ditch relief culverts and so waterbars ultimately show an increase in delivery of 0.7 tonnes/year. Road segments that drained to stream crossings were often disturbed so that sediment production drastically increased (graded and insloped, sidecast pullback), and no additional drainage was added (such as a waterbar) before the substantial road lengths reached the stream. The result was an increase in sediment delivery of 0.8 tonnes/year at stream crossings.

Table 5. *Changes in sediment production and delivery, pre-treatment vs. post-treatment road.*

DrainType	Count	Δ Sediment Production (kg)	Δ Sediment Delivery (kg)	Δ Sediment Delivery (%)	Δ Length Connected (m)	Δ Length Connected (%)
Broad Based Dip	-2	-300	-260	-100%	-60	-100%
Diffuse Drain	-28	-5430	-90	-11%	30	38%
Ditch Relief Culvert	-24	-6750	-2370	-100%	-520	-100%
Lead Off Ditch	0	-3	0	0%	0	0%
Non-Engineered	-2	0	0	0%	0	0%
Stream Crossing	-2	850	850	11%	-50	-5%
Sump	-5	-2840	0	0%	0	0%
Waterbar	14	12480	770	53%	310	384%
All Drains	**-49**	**-2010**	**-1100**	**-9%**	**-290**	**-16%**

5.3 Landslide Risk

Existing Landslides

The Suiattle area has a moderately high incidence of shallow landsliding due to the combination of steep slopes and high rainfall. Landslide volume was estimated for all landslides visible from the road that are greater than a minimum threshold of 6 feet in slope length and slope width. The pre-treatment road inventory recorded 5 road related landslides; all cutslope failures with an estimated volume of 330 yd^3 (Figure 4). Four failures had an estimated age less than five years, and one failure had an estimated age between five and ten years.

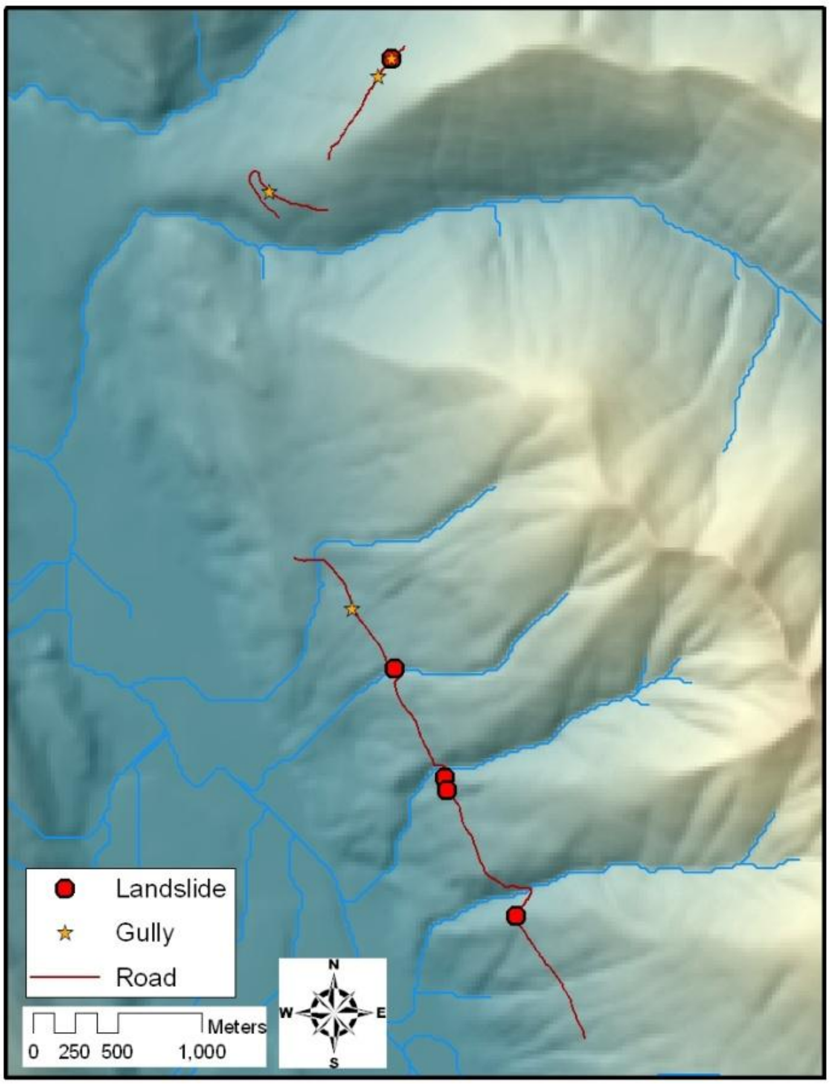

Figure 4. Landslide locations on the monitored Suiattle basin roads.

Changes in Landslide Risk

The risk of shallow landslide initiation is predicted using SINMAP 2.0 (Pack et al., 2008, http://hydrology.neng.usu.edu/sinmap2/), modified to account for contributions of road runoff, and locally calibrated to known locations of landslides in the rock type underlying the treatment road (dominantly schist). SINMAP has its basis in the infinite plane slope stability model and produces raster grids that illustrate slope stability based on hillslope and specific catchment area at each DEM grid cell. Pre- and post-treatment landslide risk grids are subjected to a series of mathematical operations that result in grids that show the important changes to landslide risk due to the treatments. These change grids are compared to the natural landslide risk grid to show how the treatment affects slope stability in the context of the background risks (i.e. the risks without the influence of the road drainage). Important grid cell changes are those pre- to post-treatment differences that show a risk change from stable to unstable, unstable to stable, or that become more or less stable while remaining unstable after treatment.

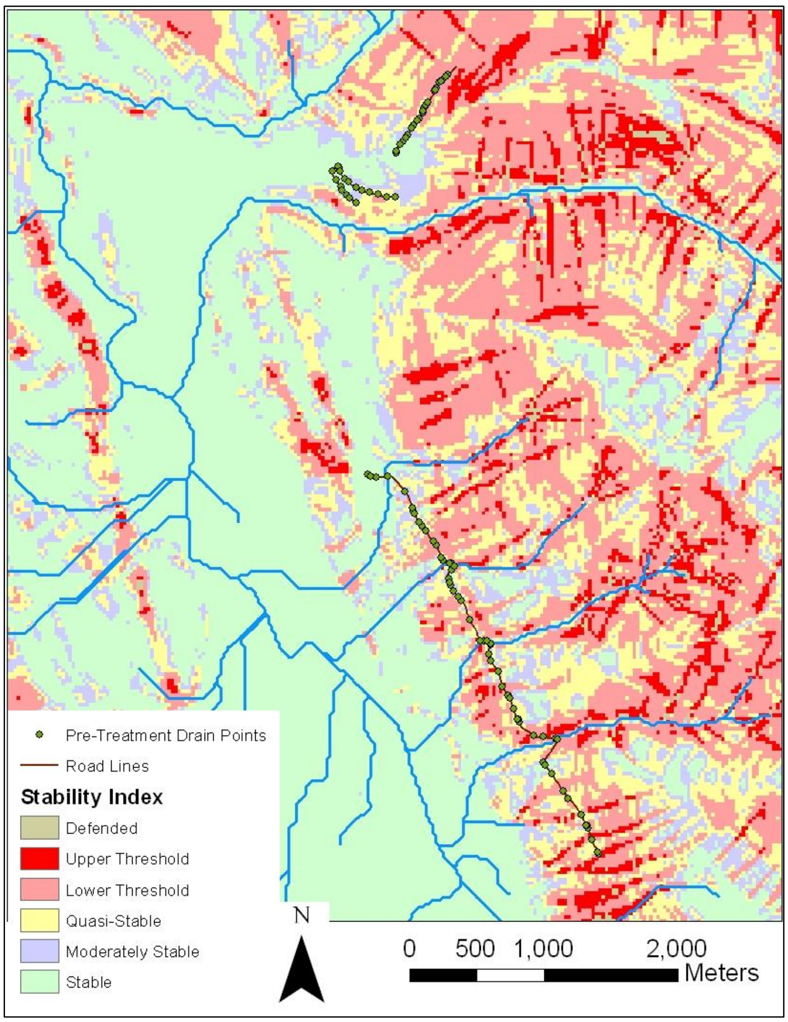

Figure 5. Natural slope stability in the area of the monitored Suiattle basin roads. The yellow, blue, and green cells are generally qualified as stable, while the pink, red, and tan cells are generally qualified as unstable.

Figures 5 through 8[4] illustrate the risk and change in risk in the area. SINMAP was calibrated using local landslide data (Washington DGER 2008) and run initially to determine the intrinsic stability of the slopes over which the road traverses and to identify locations that are at high risk of failure without the road. The inherent landslide risk is high in the area of the treated road (Figure 5).

A second calibrated stability index (SI) run was performed to address the effects of road water contribution to drain points on the original, pre-treatment road network. A third calibrated model run was performed to illustrate the risk of shallow landsliding with the modified road drainage system resulting from the restoration treatments. In Figure 6, the areas along the

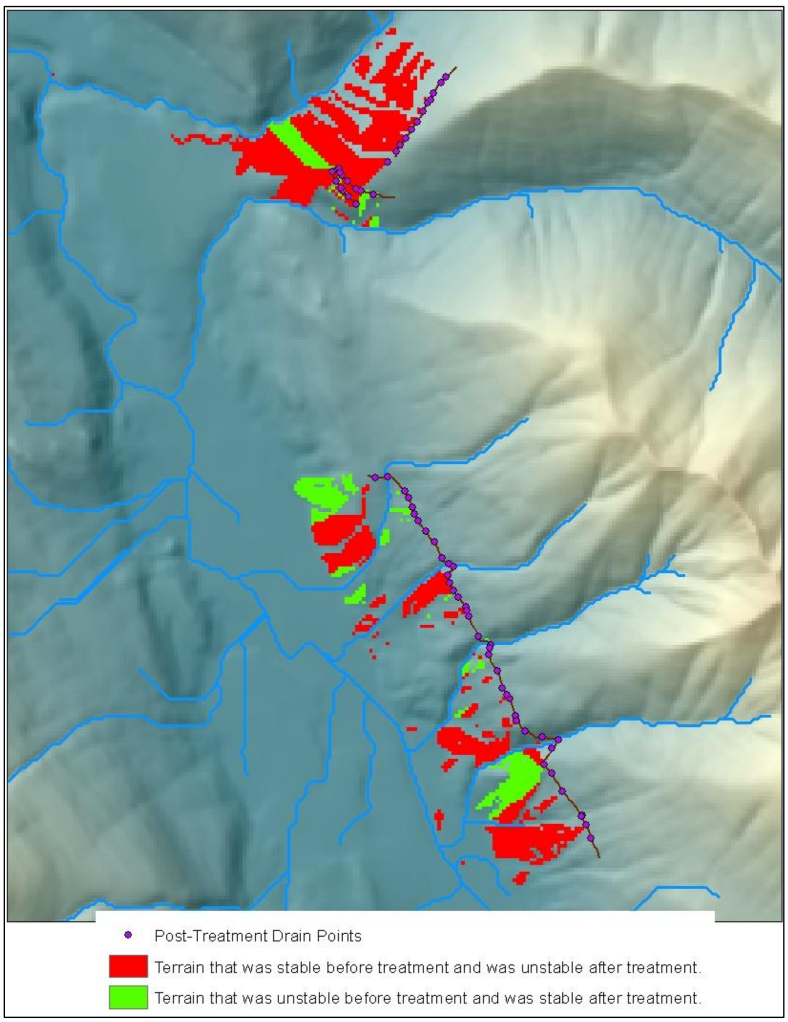

Figure 6. The most significant slope stability risk changes along the treated roads. The risk of the areas in green was sufficiently reduced, while the risk in the red areas was significantly increased. There is substantially more area that experienced a significant increase in risk than there is area that experienced a sufficient decrease.

[4] Figures 5 through 8 are rendered at the same scale. The legend items for each figure are consistent from one figure to the next.

Suiattle monitored roads where the treatment changed the risk from the unstable category (defended, upper threshold, and lower threshold from Figure 5, above) to the stable category (quasi-stable, moderately stable, and stable) are shown in green, and areas where the treatment changed the risk from the stable category to the unstable category are shown in red. These are the areas where risk has been sufficiently reduced (green), or where risk has been increased significantly (red).

There was a relatively large area that experienced a significant increase in risk, especially on the northernmost road (2650 upper and lower). This increase is due to the addition of new drainage features, or drainage features that drained more water after treatment. The largest increases occurred along the 2650 upper road, where the surface was devegetated, so on-road flow paths became concentrated, and many new waterbars were installed over slopes that already nearly fell into the unstable category. This addition of new road water moved the slopes below those drain points into the unstable category. The areas where risk was sufficiently reduced are smaller, but important. In these areas, drain points were either removed or drained less water after treatment, and so the risk was reduced to the stable category. However, this redistribution of road water did not eliminate the shallow landslide risk, so much as displace it to other locations along the road.

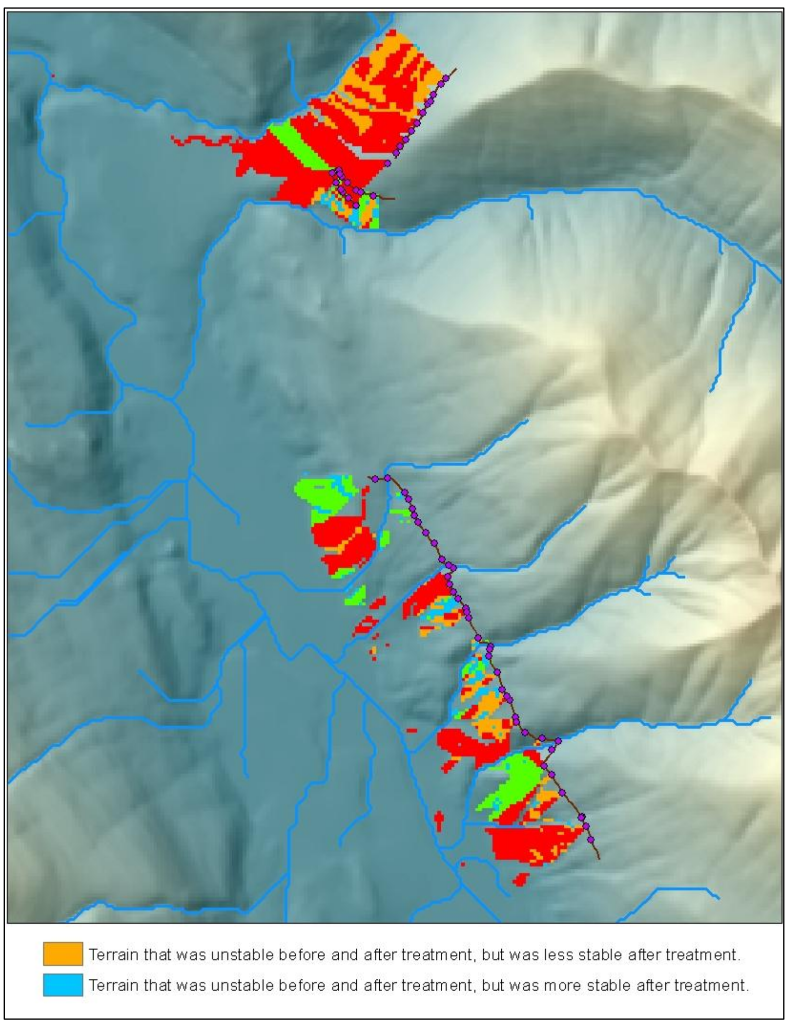

Figure 7. Changes in slope stability risk along the Suiattle monitored roads where the terrain was unstable before and after treatment. The blue areas are locations where the risk was lowered, and the orange areas are where the risk increased.

Figure 7 shows the areas where the risk of shallow landsliding was high (unstable grid cells) both before and after treatment. The light blue cells are areas where the risk decreased (became more stable), but the terrain was still unstable after treatment. For the most part, this was because the inherent (road drainage not considered) landslide risk is high at those locations (Figure 8). This may also be due to a decrease in the length of road that drained to each point, but was not enough of a reduction to move the risk category to stable. The orange cells are areas where the risk increased (became less stable) after treatment, and the terrain was already unstable before treatment. This is mostly due to the addition of drainage over slopes that were unstable without considering the effect of road drainage. In some locations, extra water was diverted to pre-existing drain point locations (though the drain point type may have changed due to treatment) that already drained to slopes in the unstable category due to road drainage.

In some locations, where a drain point that existed before treatment received less water after treatment (therefore, the risk was reduced and the hillslope became more stable), the underlying stability risk category without considering any road drainage was unstable. In these

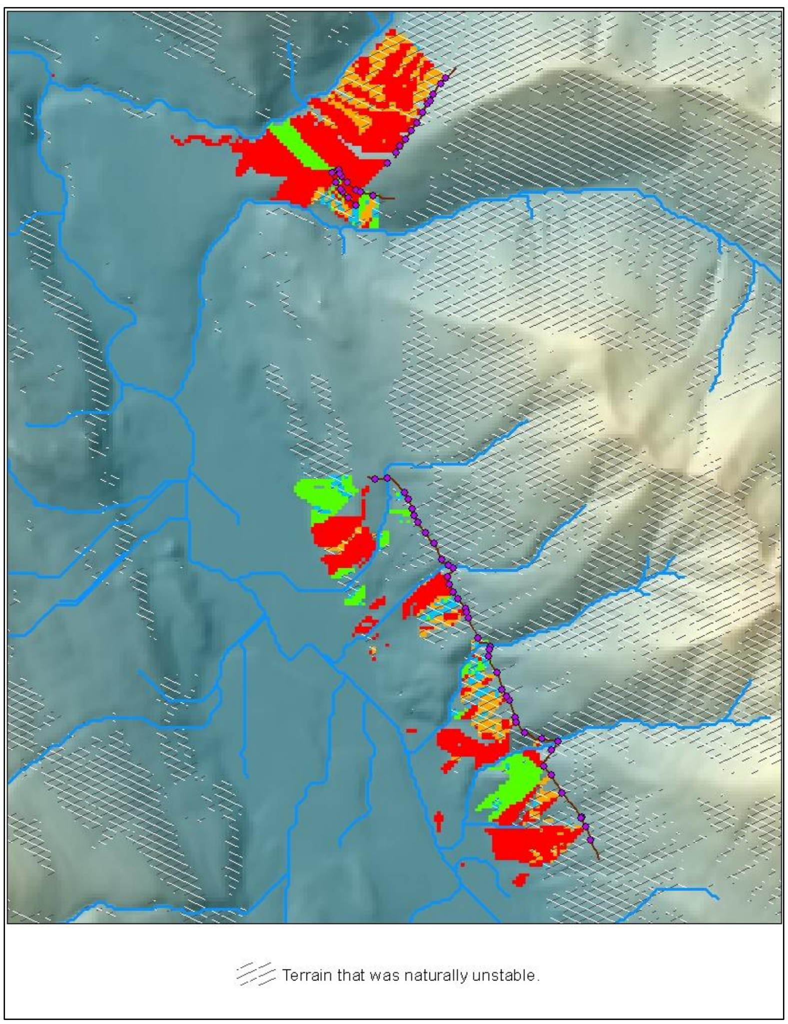

Figure 8. Background slope stability and the changes in slope stability. The cross-hatch pattern indicates the areas that were unstable without consideration of road drainage.

locations, there was no way to reduce the overall shallow landslide risk to be stable. These locations are shown in Figure 8, where the cross-hatch areas were unstable without consideration of road drainage and cross-hatch over blue shows the areas that also experienced reduced risk. In some of these locations, the treatment may have reduced the stability category to background (natural) levels, due to a drastic reduction in flow, or due to the removal of the pre-treatment features. Areas where the underlying risk (without a road) was unstable and the stability risk increased after the treatment (cross-hatch over orange) show that drainage was added over a slope that was inherently unstable (without consideration of road drainage).

In locations such as this, where terrain is steep and landslide risk is already high without considering the additional water from the road, it is very difficult to fully mitigate the risk of landslides by adding or removing drain points. For example, on the 2650 lower road, a section of road was insloped to direct water away from an especially steep slope (Figures 9 and 10). This achieved the goal of reducing the risk to that portion of the slope, but the risk below the next drain point down, which drained the rerouted water from above, increased significantly.

The net effect of the storage treatments, which redistributed water across steep slopes, achieved the goal of reducing risk at some of the highest risk locations in the sample area. However, risks were increased significantly in more locations because in steep, dissected terrain, it is difficult to redirect discharge from one location without elevating the risk in other locations.

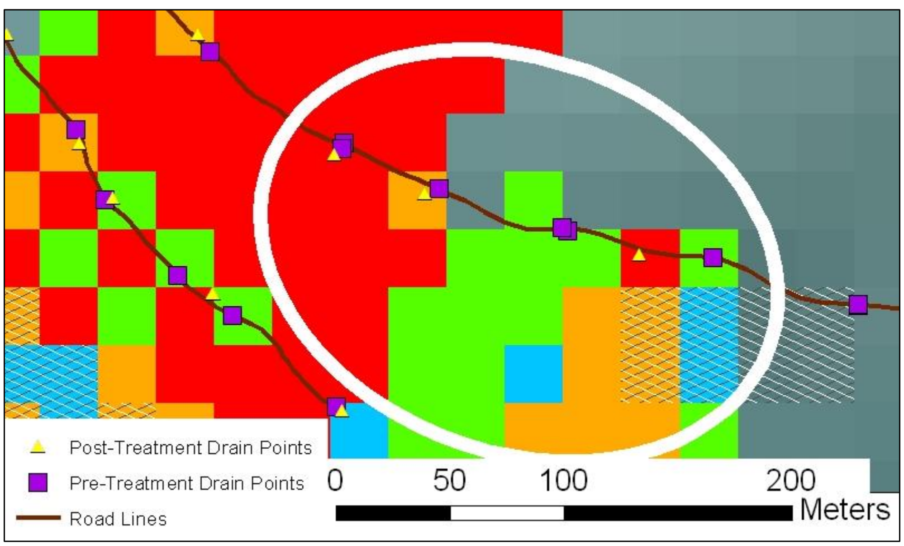

Figure 9. Portion of the 2650 lower road where water was rerouted from a steep slope, and landslide risk was displaced (white circle). The green and blue area below the purple pre-treatment drain points is where risk was lowered by the elimination of drain points by the treatment. The red and orange area below the yellow post-treatment drain points is where that water was rerouted to by the treatments. Most of this area fell into the stable category without considering any road drainage.

Figure 10. Insloping on Rd 2650, at the location shown in Figure 9, above.

The inventory and modeling done here should help better characterize the needs for treatment in these locations and quantify potential risks to downslope resources. For example, in some areas, new waterbars and other drainage features may need to be spaced more closely and placed more strategically to reduce the risk of shallow landslides. Post-storm monitoring will help refine these initial results.

5.4 Gully Initiation Risk

Gullying at drain points below roads can be a substantial source of sediment to stream channels. Gully initiation occurs when the shear stress applied by runoff exceeds the strength of the soil surface on the hillslope (Reid et al. 2010). GRAIP computes the Erosion Sensitivity Index (ESI) (Istanbulluoglu et al. 2003), as shown below, at each drain point.

$ESI = L \times S^2$, where:
L is the road length contributing to the drain point
S is the slope of the hillslope below the drain point

Calculated ESI values for each drain point are then compared to a critical ESI threshold (ESI_{crit}) to identify areas with a high risk of gully formation (i.e., where ESI > ESI_{crit}). ESI_{crit} is empirically-derived for each study area using inventoried gullies, and is the ESI value above which the risk of gullying increases significantly. Here, ESI_{crit} = 12.5, as the risk of gully initiation increases by a factor of 3 above that value (Table 6). ESI_{crit} is determined using all GRAIP data available for a watershed. Here, the treatment and control sites were used for the 2008 storage treatments, as well as the treatment site for the 2009 SDRR that is in the same watershed. However, the risk of gullying is generally low along the treatment roads, and there were only six drain points with observed gullies in this area, so the ESI_{crit} value cannot be derived to a high degree of certainty. Gully volumes for the observed gullies totaled about 10 yd^3.

Table 6. *ESI values for all concentrated drain points at the control and treatment sites for the 2008 and 2009 Suiattle River monitored locations. At this site ESIcrit = 12.5, as gully frequency increases significantly above that value.*

ESI Value	< 4	4 - 12.5	12.5 - 24	> 24
# sites with gullies	0	1	3	2
# sites without gullies	58	61	54	52
% Gullied	0%	2%	6%	4%

Diffuse drain points, stream crossings, and drain points that do not have an associated road surface flow path (i.e. orphan drain points) are not included in the following analysis, because these points do not behave in such a way that the ESI is a useful metric. Diffuse points represent a road segment that does not concentrate flow, and so does not pose a gully risk. Streams have their own, often non-road related, controls on their propensity to incise, and so cannot be treated the same as other drain points. Orphan drain points have a contributing road length of zero, and so have an ESI of zero, which throws off a meaningful average.

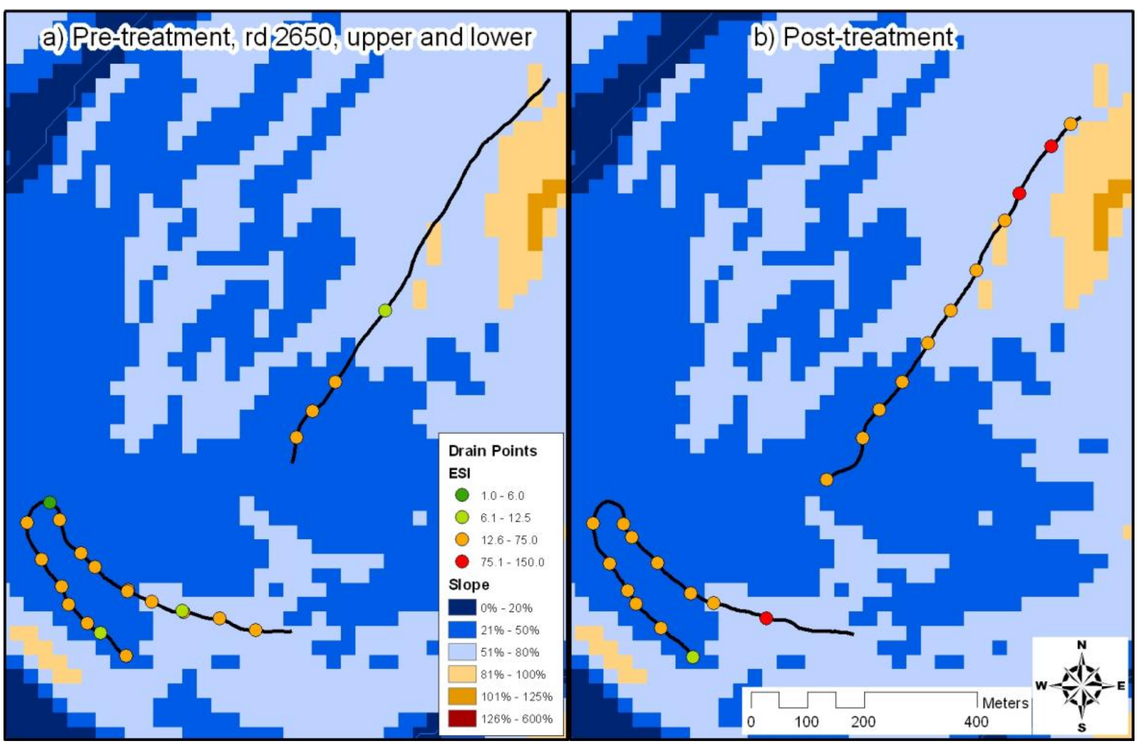

Figure 11. ESI values for drain points concentrating discharge on the 2650 upper and lower roads. (a) pre-treatment and (b) post-treatment. Drains with high risk of gullying (ESI >12.5) are shown in orange and red. Diffuse and orphan drain points, and stream crossings are excluded (the upper road was mostly diffuse in the pre-treatment). The slope map in the background indicates the component of gully risk due to hillslope gradient.

The average pre-treatment ESI was 24.4, with an average contributing road length of 55 m. 71% (37 of 52) of the pre-treatment drain points fell into this high risk group (Figure 11). These drain points drained 2201 m of road length, or about 40% of the total road length. Post-treatment ESI values had a mean of 40.3. This increase is due to increased contributing road length to each drain point, to 81 m. 87% of the post-treatment drain points (41 of 47 total points) still had ESI values in excess of 12.5. These drain points drained 3364 m, which is about 63% of the total road length. Therefore, using the conservative assumption that the post-treatment value of ESI_{crit} is the same as the pre-treatment condition, the total number of drain points with a high risk of gully initiation was calculated to have been increased by four (11%) as a result of the storage treatments. The length of road that drains to these high risk points also increased, by 1163 m, or 21%. The risk of gully initiation may still exceed the threshold while remaining generally low across the sampled landscape.

5.5 Stream Crossing Failure Risk

Besides contributing fine sediment to streams through surface erosion, stream crossings may fail catastrophically when blocked and deliver large sediment pulses to stream channels. Stream crossing failure risks were assessed using the Stream Blocking Index (SBI, Flanagan et al. 1998). The SBI characterizes the risk of plugging by woody debris by calculating the ratio of the culvert diameter to the upstream channel width (w*) and the skew angle between the channel and the pipe inlet.

The SBI values for the pre-treatment stream crossings were low with an average value of 1.5 for the 13 pre-treatment stream crossings (Figure 11). This is out of a range of 1 to 4, where 1 suggests no risk of blockage. Three stream crossings were natural fords, and so had no SBI score, because the SBI only applies when there is a culvert present. All 10 stream crossing pipes were removed during storage treatments, which completely eliminated the risk of pipe plugging (Figure 12). The 3 natural fords were excavated and reconstructed. Thus, the post-treatment SBI score was effectively zero at all crossings.

The risk of a stream crossing failure can also be viewed in the context of the consequences of failure (Flanagan et al. 1998). A consequence of concern at these stream crossings is the erosion of fill material into the stream channel. We calculated the fill material that would likely be excavated in an overtopping type failure. We modeled the prism of fill at risk as bounded at the base by an area 1.2 times the channel width, with side slopes climbing to the road surface at an angle of 33%. The fill volume at risk in the pre-treatment road configuration was approximately 432 m^3. All of this material was excavated during the restoration work.

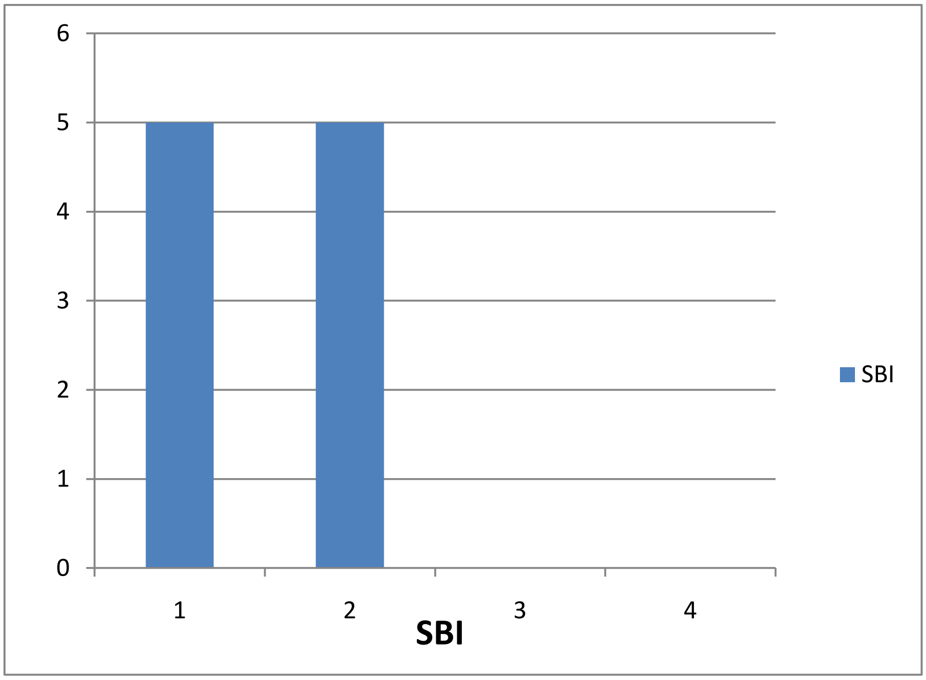

Figure 12. Distribution of Stream Blocking Index values for pre-treatment group.

A second, and perhaps greater, consequence of concern at failed stream crossings is the diversion of stream flow onto road surfaces and unchanneled hillslopes. Once a crossing becomes occluded and begins to act as a dam, failure can occur in several ways. If the road grade dips into and rises out of the crossing, the failure is likely to be limited to a localized overtopping of the stream crossing. However, if the road grades away from the stream crossing in one or more directions, the flow may be diverted down the road and ditch and onto adjacent hillslopes, where it can cause gullying and/or landsliding (Furniss et al. 1998, Best et al. 1995). In these situations, volumes of sediment far exceeding those at the crossing can be at risk.

GRAIP addresses this issue by classifying the potential for stream crossings to divert streamflow down the adjacent road as: no potential, potential to divert in one direction, or potential to divert in two directions. At this site, 53% (7 of 13) of the stream crossings on the original roads had the potential to divert streamflow down the road in at least one direction. The restoration treatments eliminated these risks at all of the stream crossing sites (Figure 13).

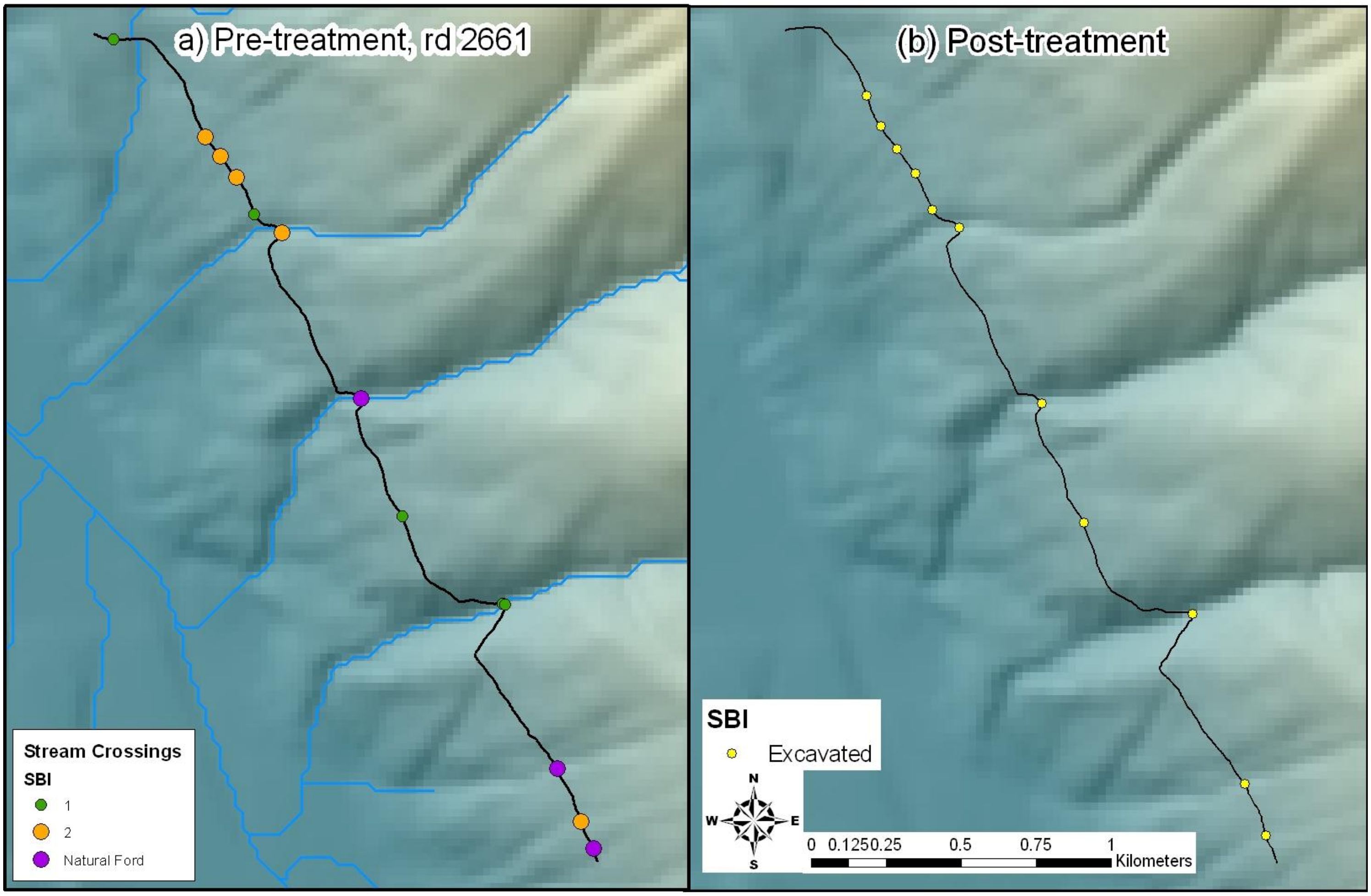

Figure 13. SBI values on the 2661 road stream crossings. (a) pre-treatment and (b) post-treatment.

5.6 Drain Point Condition

The GRAIP inventory involves an assessment of the condition of each drain point and a determination of how well it is performing its intended function. Problems with drain point condition are pre-defined for each drain type. Broad based dips are considered to be in poor condition if they are insufficiently outsloped and pond water on the road. Culverts are defined to be in poor condition if they have more than 20% occlusion of the inlet by sediment, substantial inlet crushing, significant rust, or flow around the pipe. Lead off ditches are considered problematic if they have excess deposition or gullying. Non-engineered features are almost always a problem due to a blocked ditch, a gully, or a broken outside berm. Stream crossings are considered a problem if they are blocked by sediment or wood, crushed or rusted significantly, incising, scouring or loosing much water from flow around the pipe. Sumps are a problem if they pond water on the road surface or cause fill saturation. Waterbars that are damaged, under sized, or do not drain properly are defined as problematic. Diffuse drains (outsloped roads) are rarely observed to have drain point problems.

At this site, ditch relief and stream crossing culverts were observed to have the highest rate of problems (33% and 38%, respectively), while diffusely drained roads were least likely to have problems (Table 7). So far, no problems have been observed after the decommissioning treatments. However, there has been little time for such problems to develop as a result of significant storms. Therefore, final conclusions regarding the new drainage system cannot be made until the post-storm validation monitoring is completed.

Table 7. *Drain point condition problems and fill erosion below drain points, pre- and post-treatment.*

	Pre-treatment			Post-treatment		
Drain Type	**Count**	**Problems**	**Fill Erosion**	**Count**	**Problems**	**Fill Erosion**
Broad Based Dip	3	33%	0%	1	0%	0%
Diffuse Drain	35	0%	0%	7	0%	0%
Ditch Relief Culvert	24	25%	0%	0	0%	0%
Lead Off Ditch	1	0%	0%	1	0%	0%
Non-Engineered	2	100%	50%	0	0%	0%
Stream Crossing	13	38%	0%	11	0%	0%
Sump	6	0%	0%	1	0%	0%
Waterbar	31	0%	0%	45	0%	0%
Total	**115**	12%	**1%**	**66**	**0%**	**0%**
Problems change	**-100%**					

6.0 Summary & Conclusions

The USFS, RMRS and PNW Region initiated a Legacy Roads and Trails Monitoring Project in the summer of 2008. As part of the study, field crews inventoried road segments on the Mount Baker-Snoqualmie National Forest, before and after storage treatments, as well as a set of control roads. These roads received medium-intensity treatments that included removal of culverts and fills at stream crossings, replacement of culverts with waterbars, construction of new waterbars, insloping of road surfaces, and pullback of unstable sidecast material.

The GRAIP model was used to predict the change in level of impact/risk between the pre-existing road and the storage-treated road. The restoration treatments reduced the length of the sampled road that was hydrologically connected to streams by 290 m, or 16% from pre-treatment conditions. The model predicts that fine sediment delivery was reduced by 1.1 tonnes/year (9%), from 12.5 tonnes to 11.4 tonnes annually. The risks presented by stream crossings becoming plugged by debris and sediment were completely eliminated by the excavation and removal of the culverts and fills. These locations will contribute fine sediment to the channel in the short-term, but this treatment will prevent over 400 m^3 of earthen material from eroding into the channel when the stream crossings ultimately become plugged or fail from rusting. The potential for streamflow to be diverted onto roads and unchanneled hillslopes was eliminated at 13 crossing sites.

The slope stability risk below drain point locations on the original road was reduced in a few locations as water was redistributed across the hillslope to new drainage points. However, overall landslide risk was increased across the treated road length because the treatments added new concentrated drainage features above steep slopes. Values of a gully index were reduced at some of the original drainage points. Nonetheless, values still exceed conservative initiation thresholds at most sites. The same is true for most of the new discharge points. Thus, across the entire sampled road length, the total number of sites with elevated gully risk was increased by four, and increased the length of road connected to drain points with elevated risk by more than 1 km. Post-storm validation monitoring will determine whether the conservative initiation thresholds used in this analysis are correct, or if gully risk was reduced more than these initial predictions indicate. Existing drain point problems, which were present at 12% (14 of 115) of inventoried sites, were eliminated by the restoration efforts. These new drainage features, however, have not yet been evaluated after a large storm event.

Risks of stream crossings culverts becoming plugged and overtopping, the potential for diversion onto the road, and total fill at risk (430 m^3 before treatment) were completely eliminated by the treatments. Before treatment, inventoried road segments had problems at 12% of 115 inventoried drainage points. Post-treatment monitoring indicates that these problems were eliminated by the storage treatments and that most replacement drainage features may be somewhat less vulnerable to failure.

As a whole, these initial results indicate that the storage treatment work in the Suiattle River watershed should be effective in reducing some of the hydrogeomorphic impacts and risks that these roads posed to aquatic ecosystems, while increasing others (Table 8). It is worth noting that landslide and gully initiation risks were moderate to low to begin with. The final post storm inventory assessment will enable a closer examination of the hydrologic function of the newly storage-treated road system and will answer important questions about gully initiation thresholds and landslide risk. This report will be updated when these data become available.

Table 8. *Summary of GRAIP model risk predictions for the Skokomish decommissioning project.*

IMPACT/RISK TYPE	EFFECT OF TREATMENT: INITIAL GRAIP PREDICTION	EFFECT OF TREATMENT: POST-STORM VALIDATION
Road-Stream Hydrologic Connectivity	-16%, -290 m	To be determined.
Fine Sediment Delivery	-9%, -1.1 tonnes/year	To be determined.
Landslide Risk	Overall increase	To be determined.
Gully Risk	Overall increase	To be determined.
Stream Crossing Risk		
- plug potential	-100% (eliminated at 11 sites)	To be determined.
- fill at risk	-100% (-432 m^3)	To be determined.
- diversion potential	-100% (eliminated at 11 sites)	To be determined.
Drain Point Problems	-100%, eliminated at 14 drain points	To be determined.

Appendix A: Glossary of Terms

Below is a list of terms, mostly of drainage point types, but also of some other commonly used terms, for the purpose of clarification. Adapted from Black, et al. (2009), Fly, et al (2010), and Moll (1997).

Broad based dip. ***Constructed:*** This drain point is a grade reversal designed into the road for the purpose of draining water from the road surface or ditch (also called dip, sag, rolling grade, rolling dip, roll and go, drainage dips). ***Natural:*** A broad based dip point is collected at the low point where two hillslopes meet, generally in a natural swale or valley. This is a natural low point in the road that would cause water on the surface of the road to drain out of the road prism.

Cross drain. This is not a feature collected specifically in GRAIP, and it can refer to a number of other drainage features. It is characterized by any structure that is designed to capture and remove water from the road surface or ditch. Ditch relief culverts, waterbars, and broad based dips can all be called cross drains.

Diffuse drain. This is a point that is characterized by a road segment that does not exhibit concentrated flow off the road. Outsloped roads or crowned roads often drain half or all of the surface water diffusely off the fillslope. Although collected as a drain point, this feature is representative of an area or a road segment rather than a concentrated point where water is discharged from the road prism. A drop of water that lands on a diffuse road segment will not flow down the road or into the ditch, but more or less perpendicular to the centerline off the road surface and out of the road prism. Also called sheet drainage or inter-rill flow.

Ditch relief culvert. This drain point is characterized by a conduit under the road surface, generally made of metal, cement, or wood, for the purpose of removing ditch water from the road prism. This feature drains water from the ditch or inboard side of the road, and not from a continuous stream channel.

Flow path. This is the course flowing water takes, or would take if present, within the road prism. It is where water is being concentrated and flowing along the road from the place where it enters the road prism, to where it leaves the road prism. This can be either on the road surface, or in the ditch.

Lead off ditch. This drain point is characterized by a ditch that moves flow from the roadside ditch and leads it onto the hillslope. Occurs most often on sharp curves where the cutslope switches from one side of the road to the other. Also known as a daylight ditch, mitre drain, or a ditch out (though this term can also describe other types of drainage features).

Non-engineered drainage. This drain point describes any drainage feature where water leaves the road surface in an unplanned manner. This can occur where a ditch is dammed by debris, and the water from the ditch flows across the road, where a gully crosses the road, where a wheel rut flow path is diverted off the road due to a slight change in road grade, or where a berm is broken and water flows through. This is different from a diffuse drain point, which describes a long section of road that sheds water without the water concentrating, whereas this point describes a single point where a concentrated flow path leaves the road.

Orphan drain point. This is any drain point that does not drain any water from the road at the time of data collection. Examples include a buried ditch relief culvert, or a water bar that has been installed on a road that drains diffusely.

Stream crossing. This drain point is characterized by a stream channel that intersects the road. This feature may drain water from the ditch or road surface, but its primary purpose is to route stream water under or over the road via a culvert, bridge, or ford. A stream for the purposes of GRAIP has an armored channel at least one foot wide with defined bed and banks that is continuous above and below the road and shows evidence of flow for at least some part of most years.

Sump. ***Intentional:*** This drain point is a closed depression where water is intentionally sent to infiltrate. ***Unintentional:*** Any place where road water enters and infiltrates, such as a cattle guard with no outlet, or a low point on a flat road.

Waterbar. This drain point is characterized by any linear feature that is perpendicular to the road that drains water from the road surface and/or ditch out of the road prism or into the ditch. Waterbars may be constructed by dipping the grader blade for a short segment, or adding a partly buried log or rubber belt across the road. Some road closure features may also act as a waterbar, such as a tank trap (also known as a closure berm or Kelly hump). Cattle guards that have an outlet that allows water to flow out are also considered to be water bars. These features may also be known as scratch ditches if they drain water into the ditch.

References

Best, D. W., Kelsey, H. M., Hagans, D.K. and M. Alpert. 1995. Role of fluvial hillslope erosion and road construction in the sediment budget of Garret Creek, Humboldt County, California. In Geomorphic Process and Aquatic Habitat in the Redwood Creek Basin, Northwestern California. Nolan, K. M., Kelsey, H. M., and Marron, D. C. editors. USGS professional paper #1454. pp m1-m9.

Black, T. A., Cissel, R.M., and Luce, C. H. 2009. The Geomorphic Road Analysis and Inventory Package (GRAIP) Data Collection Method. USDA Forest Service Rocky Mountain Research Station, Boise Aquatic Science Lab.

Cissel, R.M., Black, T.A., Luce, C.H., Tarbotan, D.G., Shreuders, K.A.T., and Prasad, A. 2009. The Geomorphic Road Analysis and Inventory Package (GRAIP) Office Procedure Manual. USDA Forest Service Rocky Mountain Research Station, Boise Aquatic Science Lab.

Flanagan, S. A., Furniss, M. J., Theisen, S., Love, M., Moore, K., and Ory, J. 1998. Methods for Inventory and Environmental Risk Assessment of Road Drainage Crossings. USDA Forest Service Technology and Development Program 9877-1809-SDTDC 45pp.

Fly, C.M., Grover-Weir, K., Thornton, J., Black, T.A., Luce, C.M. 2010. Bear Valley Road Inventory (GRAIP) Report; Bear Valley Category 4b Assessment, Boise National Forest. USDA Forest Service, Boise National Forest.

Furniss, M. J., Love, M., and S. A. Flanagan. 1997 Diversion Potential at Road Stream Crossings. USDA Forest Service Technology and Development Program 9777-1814-SDTDC 12pp.

Istanbulluoglu, E., Tarboton, D.G., Pack, R.T., Luce, C.H. 2003. A sediment transport model for incision of gullies on steep topography. Water Resources Research. 39(4): 1103-1117.

Jones, J. A., and G. E. Grant, 1996. Peak flow responses to clear-cutting and roads in small and large basins, western Cascades, Oregon, Water Resour. Res., 32, 959-974.

Luce, C.H., and T. Black. 1999. Sediment production from forest roads in western Oregon. Water Resources Research. 35(8): 2561-2570.

Madej, Mary A. 2001. Erosion and Sediment Delivery Following Removal of Forest Roads, Earth Surface Landforms and Processes, 26(2) pp.175-190.

Moll, J. 1997. Glossary of Water/Road Interaction Terminology for Water/Road Interaction Technology Series. USDA Forest Service Technology and Development Program 9777-1806-SDTDC 14pp.

Pack, R. T., Tarboton, D.G., Goodwin, C.N. and A. Prasad, 2005. SINMAP 2. A Stability Index Approach to Terrain Stability Hazard Mapping, technical description and users guide for version 2.0, Utah State University.

Prasad, A. 2007. A tool to analyze environmental impacts of road on forest watersheds. MS Thesis. Utah State University, USA.

Prasad, A, Tarboton, D. G., Schreuders, K. A., Luce, C.H., and T.A. Black. 2007. GRAIP1.0 Geomorphic Road Analysis and Inventory Package: A tool to analyze the environmental impact of roads on forested watersheds. Tutorial and Reference Manual. http://WWW.engineering.usu.edu/dtarb/graip.

Reid, L.M., Dewey, N.J., Lisle, T.E., Hilton, S. 2010. The incidence and role of gullies after logging in coastal redwood forest, Geomorphology, 117, 155-169.

Washington Division of Geology and Earth Resources. 2008. Landslides of Washington State 1:24,000 scale, version 2.0, landslide24k shapefile, Washington Division of Geology and Earth Resources, Olympia, Washington. Accessed online February 2010 from http://www.dnr.wa.gov/ResearchScience/Pages/PubData.aspx .

Wemple, B. C., Jones, J. A., and Grant, G. E. 1996. Channel network extension by logging roads in two basins, western Cascades, Oregon, Water Resources Bulletin, 32, 1195-1207.