Legacy Roads and Trails Monitoring Project

Road Decommissioning in the Mammoth Creek Watershed

Dixie National Forest

August 2012

Nathan Nelson[1], Richard Cissel[1], Tom Black[1], and Charlie Luce[2]

[1]Hydrologist
[2]Research Hydrologist

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

Table of Contents

Table of Figures

Table of Tables

Executive Summary

In Fiscal Year 2008, Congress authorized the Legacy Roads and Trails Program and allocated the US Forest Service (USFS) $40 million to begin its implementation. Based on continued success, the program has been allocated $90 million in FY2010. This program 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 USFS, Rocky Mountain Research Station (RMRS) and Intermountain (INT) Region, Pacific Northwest Region (PNW), Pacific Southwest Region (PSW) and the Northern Region (NR) are monitoring a sample of the road decommissioning and maintenance projects 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.

Since FY 2009, inventories have been conducted at eight sites in the Intermountain Region. A site consists of a group of road segments totaling four miles treated with either decommissioning or Storm Damage Risk Reduction (i.e., stormproofing). Post-storm inventories have been collected at four of these sites during FY2010. This report focuses on how decommissioning work implemented by the Dixie National Forest in the Mammoth Creek watershed compared to untreated control roads following a significant storm event. At the Mammoth Creek sites, treatments involved recontouring and tilling of the road prism during June and July of 2010. Crews conducted inventories of both the treatment and control roads three times: pre-treatment (June, 2010), post-storm (August, 2010), and post-season (August, 2011).

Three major storm events were recorded by the rain gage installed at the Mammoth Creek campground between July 22, 2010, and August 2, 2011. The return intervals for the precipitation intensities measured during these events ranges from 7 years up to 20.5 years.

Before-after comparisons using GRAIP indicate that decommissioning treatments resulted in a large reduction of many impact-risk metrics, while control roads experienced large increases in the same impact-risk metrics. Comparing pre-treatment and post-season inventories, road-stream connectivity was decreased by 2,771 m (43% of total road length), from 4,289 m of connected road to 1,518 m. Delivery of fine sediment was reduced by 100.2 Mg/yr (-83%), from 119.6 Mg/year to 19.4 Mg/year. Control roads saw an increase of 1,736 m (24% of total road length) connected road length, from 2,743 m to 4,479 m. This was accompanied by an increase in delivered fine sediment of 45.4 Mg/yr (76%), from 59.8 Mg/yr to 105.2 Mg/yr.

Gully activity at the Mammoth Creek site was confined to a single geologic unit which showed extensive post-storm and post-season gully activity even on un-roaded hillslopes. Gully

volumes on the control roads nearly doubled between the June, 2010, and August, 2011, while gully volumes on the treatment roads were not increased.

Taken collectively, results indicate the decommissioning treatments have been effective in reducing the hydrogeomorphic impacts and risks to aquatic ecosystems. Risks associated with the control roads, however, increased in most cases, and remained the same in others.

Impact/Risk Type	Treatment Roads	Control Roads
	Post-storm	Post-storm
Road-Stream Hydrologic Connectivity	-2,820 m (-43%)	+1,116 m (16%)
Fine Sediment Delivery	-96,785 kg/yr	+30,860 kg/yr (52%)
Drain Point Problems	-7 problems	+17 problems

Measured as change from pre-treatment conditions.

Impact/Risk Type	Treatment Roads	Control Roads
	Post-season	Post-season
Road-Stream Hydrologic Connectivity	-2,771 m (-43%)	+1,736 m (24%)
Fine Sediment Delivery	-100,213 kg/yr (-83%)	+45,395 kg/yr (76%)
Drain Point Problems	+16 problems	+27 problems

Measured as change from pre-treatment conditions.

Acknowledgements

We would like to thank the field crew members, Scott Bergandorf and Ian Bell, for collecting the inventory data. Rich Jaros greatly assisted with the site selection for this study.

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 Intermountain (INT) 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 Idaho and Utah. 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 decommissioning work completed by the Dixie National Forest (DNF) in the Mammoth Creek watershed in FY2010. 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., 2012). 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., 2012). 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

4.1 Regional Monitoring Sites

Through 2011, pre- and post-treatment evaluations were completed at nine sites[1] on national forests throughout the Intermountain Region. Decommissioning has been implemented at five of these sites, one site has received long-term closure treatments, two sites have been treated with storm damage risk reduction methods (SDRR)[2], and one site received other treatments similar to road-trail conversion (Figure 1, Table 1). Four post-storm inventories were completed in 2010, and a post-season inventory was conducted at the Mammoth Creek site in 2011.

---

[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.

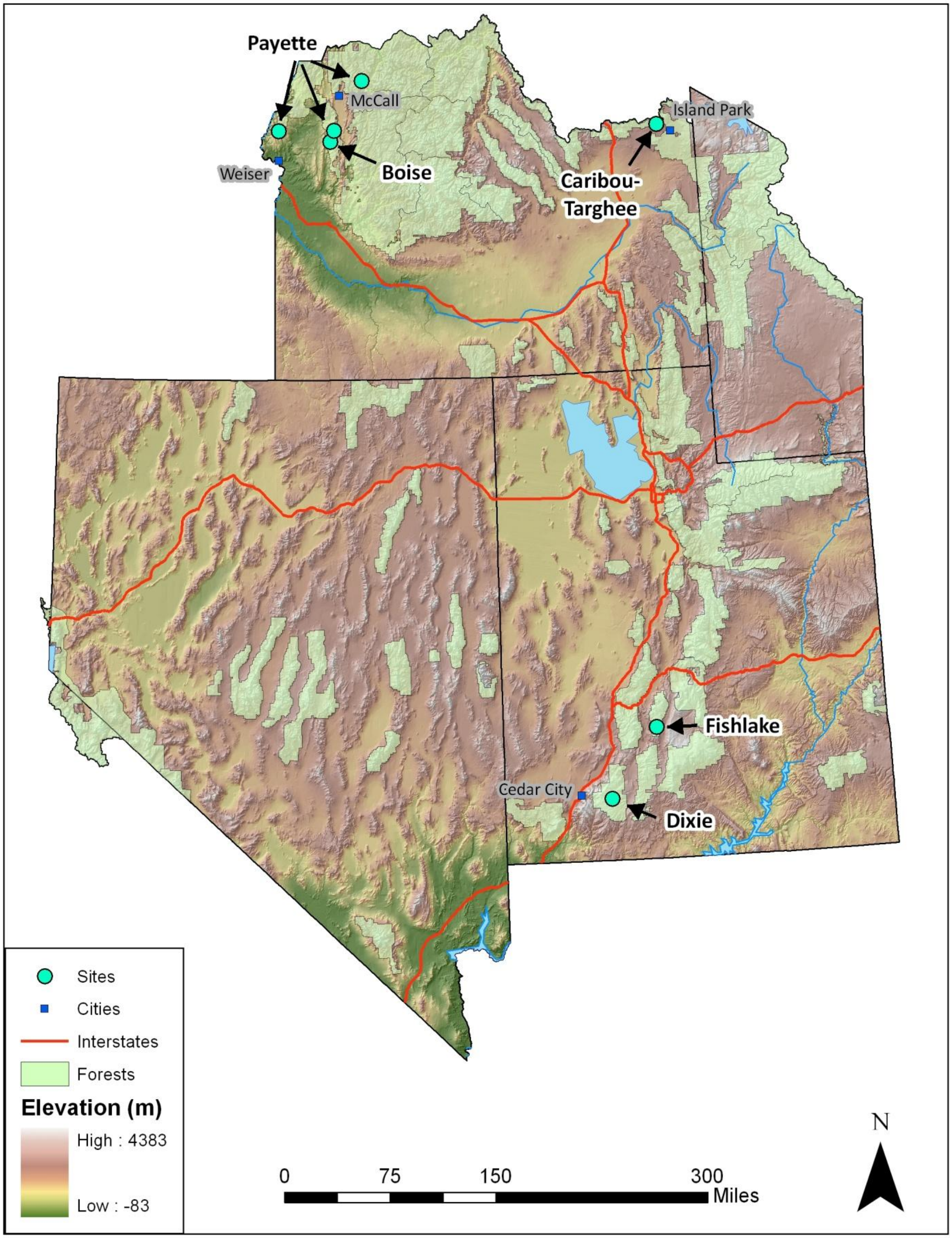

Figure 1: Location of monitored sites, INT Region.

Table 1: List of sites and treatments in Region 4.

National Forest	Start Year	Treatment	Watershed
Payette	2009	Decommissioning	Mann Creek
Payette	2009	Decommissioning	Calf Creek
Boise	2009	Decommissioning	Squaw Creek
Caribou-Targee	2009	Storm Damage Risk Reduction	Island Park
Caribou-Targee	2009	Other Treatment	Island Par
Payette	2010	Long-Term Closure	Little Weiser
Boise	2010	Storm Damage Risk Reduction	Rice Creek
Dixie	2010	Decommissioning	Mammoth Creek
Fish Lake	2010	Decommissioning	Monroe Mountain

4.2 Mammoth Creek Sites

The Mammoth Creek watershed covers an area of ~87 square miles of Garfield county near the western edge of Utah's Colorado Plateau. The treatment roads are located in the central part of the Mammoth Creek watershed, which appears to be largely underlain by the Tertiary Brian Head formation, with possible windows into the upper portion of the Claron formation and some Quaternary or later Tertiary basalt flows. Elevations within the watershed range from 7,500 to 11,300 feet above sea level; the roads described in this study are between 8,000 and 8,900 feet above sea level. Annual precipitation is between 22" and 28". Vegetation communities along the roads are dominantly Ponderosa pine woodlands, with some mixed conifer and sub-alpine.

Decommissioning techniques applied to roads within the Mammoth Creek watershed included excavation and removal of stream crossing and ditch relief culverts, and recontouring or tilling the road surface. About 50% of the road surface was recontoured, 43% was tilled, and 7% was untreated.

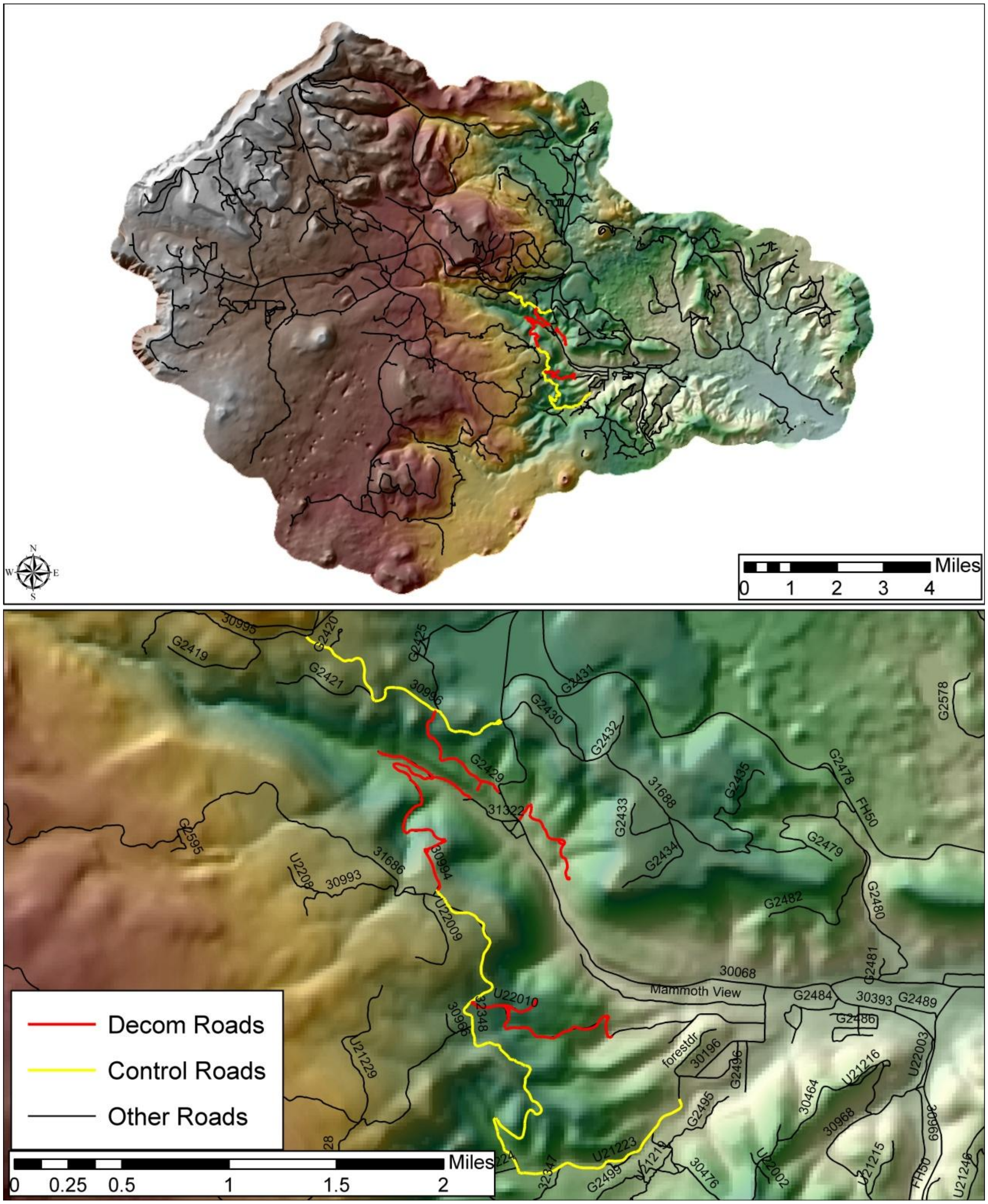

Figure 2: Locations of monitored roads in the Mammoth Creek watershed, Dixie National Forest.

5.0 Storm Events

A rain gage was installed at the Mammoth Creek campground on July 22, 2010, and recorded 24.15" of precipitation from that date until it was taken down on August 2, 2011. The maximum distance from this gage to any of the study roads was ~2.7 km. The precipitation intensity threshold that we generally use is a 7-year return interval event of one, six, or twenty-four hour durations.

The Mammoth Creek site recorded three precipitation events exceeding the 7-year return interval threshold (Figure 3). The first of these storms occurred on July 31, 2010, before crews could arrive to conduct the post-treatment inventory and only days after treatment work was completed. Rain started at 2:00 in the afternoon and stopped around 3:30 pm with a few sprinkles until 4:30 pm. This storm delivered 1.43" of rain in the first hour and a total of 1.69" by 4:30 pm, exceeding the precipitation intensity thresholds for both 1 and 6 hour events. An intensity of 1.43" per hour has a return interval of approximately 17 years; the threshold for a seven-year, six hour storm is 1.62" in six hours. This storm was responsible for causing much of the damage on treated roads; few areas not damaged by this storm were damaged by the subsequent storms.

The next storm was a 24 hour event in October that delivered a peak intensity of 2.68" in 24 hours (approximately 12.5 year return interval). Between the morning of October 4 and the evening of October 5, the area received a total of 3.82" of rain. The last event was a 6 hour event that occurred during the evening of July 8, 2011. This series of thunderstorms delivered 2.11" of rain to the area between 5:00 pm and 11:00 pm; a storm of this intensity has a return interval of approximately 20.5 years.

Most of the storm-related damage along the treatment roads was caused by the first storm. While the damage along the treatment roads tends to be more dramatic, it is far less extensive than the damage found along the control roads. The most obvious and dramatic damage occurred on a tilled section of the road just east of the Mammoth Creek campground. Flash floods associated with the first rain event were diverted onto the freshly tilled road surface, rapidly eroding a channel more than six inches deep (Figure 4). Other damage caused by this storm included erosion at intermittent stream crossings (Figure 5) and gullies that crossed the treated road (Figure 6). The later storms generally did not cause damage in new areas, but did exacerbate the damage caused by the first storm (Figures 7 and 8).

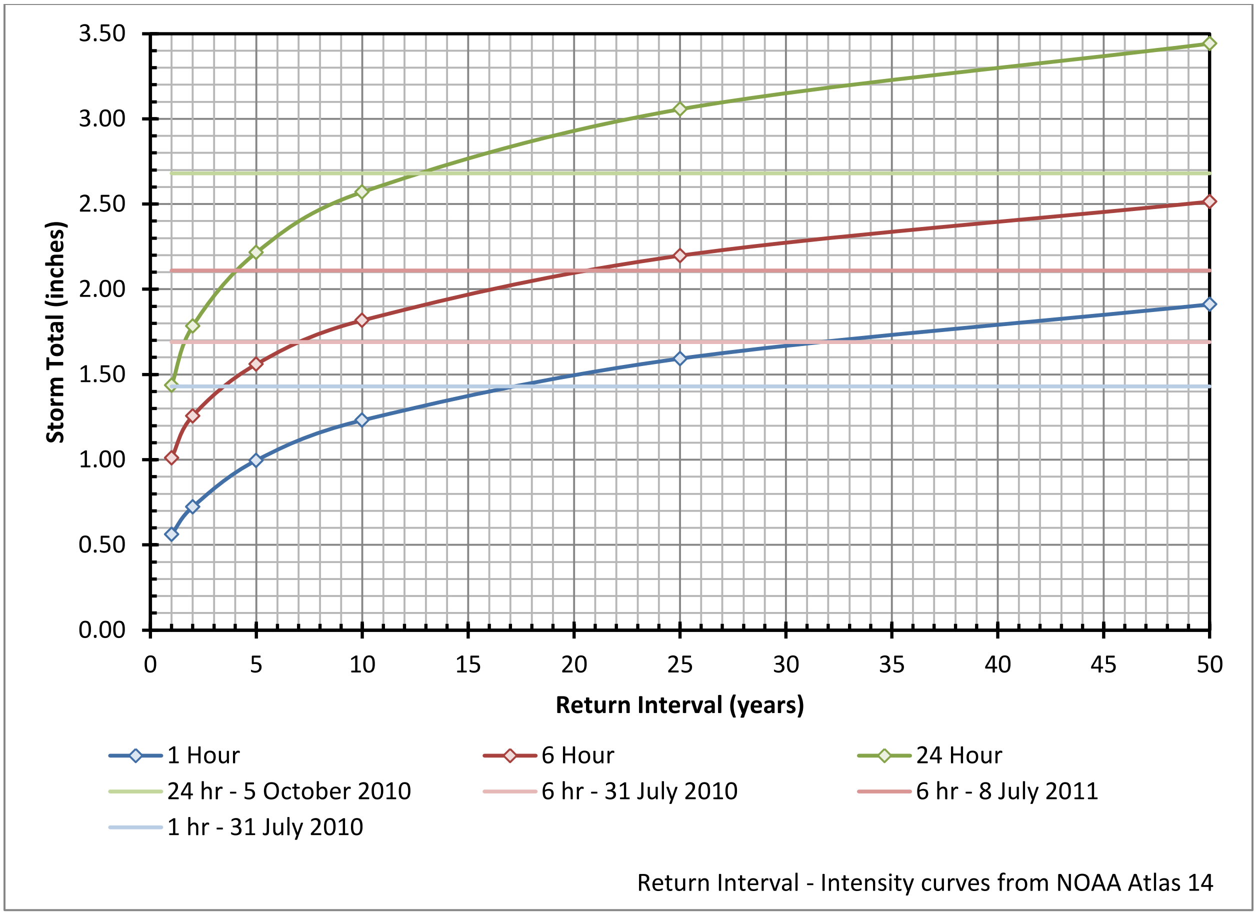

Figure 3: Precipitation intensity curves and intensities from the three storm events that hit the Mammoth Creek site.

Figure 4: Storm damage on tilled road surface. The road intercepted flow in an intermittent stream channel.


Figure 5: Erosion at intermittent stream crossing, erosion extent is wider than Scott's height. Pictured flood flow generated by 0.20" of rain in 30 minutes.


Figure 6: Hillslope gully crossing recontoured road.

Figure 7: Stream course incised into tilled road.

Figure 8: Gullies crossing recontoured road.

6.0 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 decommissioning treatments are designed to reduce road-related risks and remove unauthorized roads.

6.1 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 Mammoth Creek, treatments decreased the amount of road connected to the stream network by more than 2.7 km. Prior to treatment, 65% (4,289 m out of 6,626 m) of the road was connected to the stream network; following treatments and the first of the large storm events, 22% (1,470 m out of 6,797 m) of the road network was connected, and 22% (1,518 m out of 6,839 m) was connected one year after treatment.

Un-treated control roads had a connection rate of 39% (2,743 m out of 7,080 m) prior to decommissioning work on the treatment roads. After first storm event, the connection rate on the control roads increased to 54% (3,859 m out of 7,106 m). One year after decommissioning work was completed, the connection rate had increased again to 63% (4,479 m out of 7,113 m).

6.2 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

[3] For this analysis, a base erosion rate of 79 kg/m of road elevation 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. This study is concerned with the effects of the applied treatments; hence the relative change, not the absolute numbers, is the primary concern.

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.

While GRAIP works well with typical roads, where water generally flows along the road for some distance before draining from the road, it was not designed to specifically handle the altered flow on a recontoured road. Erosion and flow on recountoured surfaces is similar to that on disturbed hillslopes. The result is that flow on a recontoured road is transverse, rather than longitudinal as on other roads, and this presents a geometry problem for GRAIP's sediment production calculations. Sediment production from recontoured road segments was manually re-calculated during the GRAIP model run using a slope-area method derived from cutslope sediment data obtained during the Low Pass sediment study (Luce and Black, 1999); the Low Pass sediment study was also used to develop the default baserate used by GRAIP. This allows better predictions of sediment production from the recontoured surfaces.

Treatment Roads

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.

Pre-treatment roads were found to be in generally poor condition, though 16% of the roads were found to be in good condition. Thirty percent of the roads were rilled or eroded, 29% were rutted, and 26% were rocky; rocky roads may result from erosion of finer road materials. All but a few road segments were surfaced with native material; the few exceptions had an armored surface most likely the result of natural processes. Figure 9 provides examples of typical road conditions.

Figure 9: Typical pre-treatment road conditions.

In Table 2, sediment delivery is characterized 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. Figure 10 shows sediment production and delivery along the pre-treatment roads. Ninety-four drain points were documented, 43% of which were hydrologically connected to stream channels. These points delivered 174.9 tonnes/year of sediment, or 68% of the sediment generated by the road surfaces and ditches.

Table 2: Summary of sediment production and delivery by drainpoint type, pre-treatment road.

Pre-Treatment								
Drain Type	**Count**		**Sediment Received (kg/yr)**	**Sediment Delivered (kg/yr)**	**Total Effective Length (m)**	**Stream Connected Length (m)**	**Percent Sediment Delivery**	**Percent Connected Length**
	Total	**Connected**						
Broad-based Dip	36	16	44,741	22,828	2,039	951	51%	47%
Diffuse Drain	7	0	2,812	0	245	0	0%	0%
Ditch-relief Culvert	0	0	0	0	0	0	0%	0%
Lead-off Ditch	0	0	0	0	0	0	0%	0%
Non-engineered Drain	32	16	95,039	75,133	3,296	2,575	79%	78%
Stream Crossing	6	6	20,952	20,952	737	737	100%	100%
Sump	0	0	0	0	0	0	0%	0%
Water Bar	13	2	11,379	702	309	25	6%	8%
Excavated Stream Crossing	0	0	0	0	0	0	0%	0%
Total	**94**	**40**	**174,923**	**119,614**	**6,626**	**4,289**	**68%**	**65%**

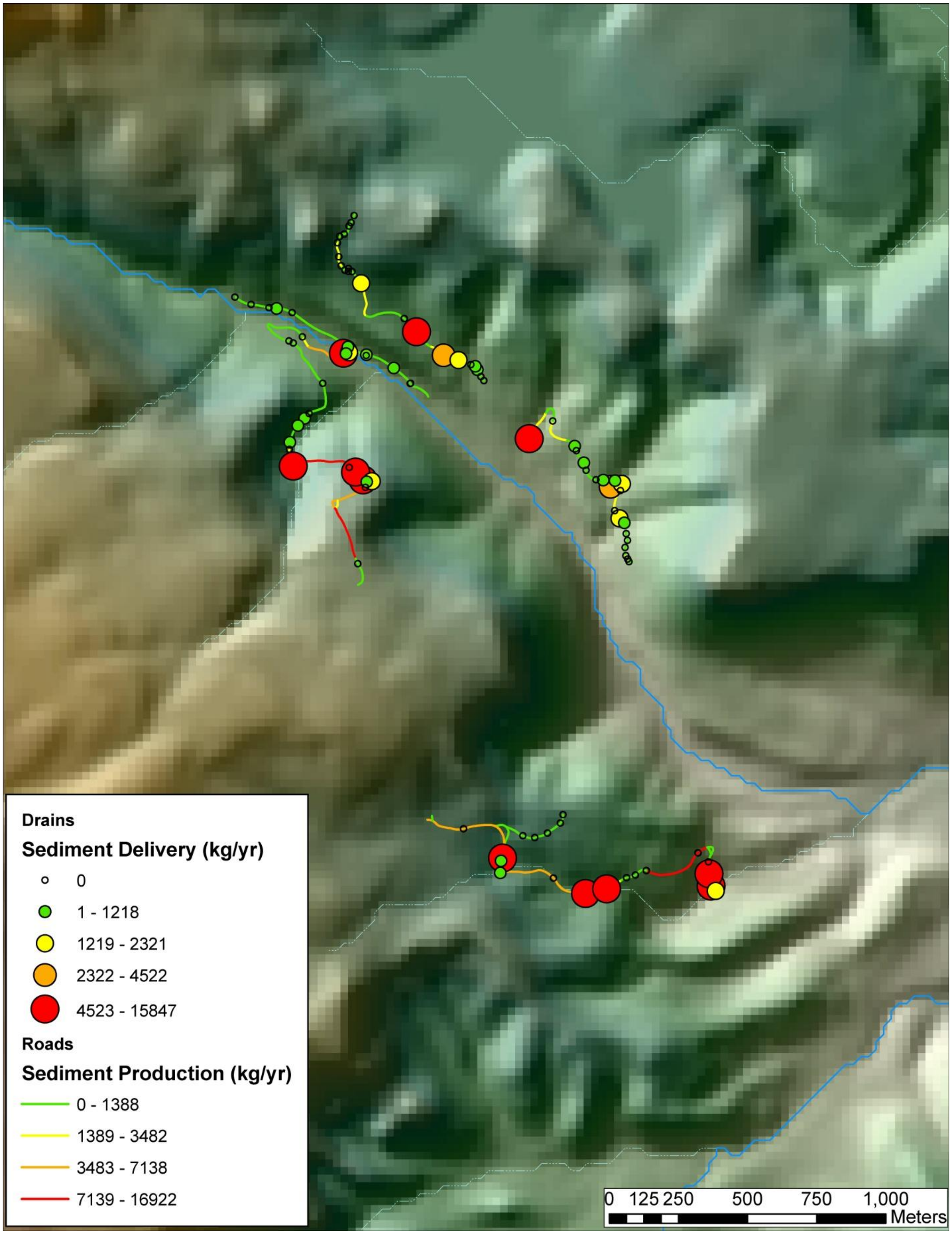

Figure 10: Sediment production and delivery, pre-treatment roads.

Post-storm
Roads in the Mammoth Creek project area were decommissioned using a combination of recontouring and tilling treatments, which were applied to about 95% of the treated roads. Typical treatments are shown in Figure 11.

Following treatment and the first storm event on July 31, 2010, sediment production decreased from 174.9 Mg/yr to 43.0 Mg/yr and sediment delivery decreased from 119.6 Mg/yr to 22.8 Mg/yr, mostly at non-engineered drains (Table 3; Figure 12).

Table 3: Summary of sediment production and delivery by drainpoint type, post-storm treatment road.

Post-Storm Treatment								
Drain Type	**Count**		**Sediment Received (kg/yr)**	**Sediment Delivered (kg/yr)**	**Total Effective Length (m)**	**Stream Connected Length (m)**	**Percent Sediment Delivery**	**Percent Connected Length**
	Total	**Connected**						
Broad-based Dip	14	8	3,406	3,342	356	309	98%	87%
Diffuse Drain	24	0	13,648	0	4,909	0	0%	0%
Ditch-relief Culvert	0	0	0	0	0	0	0%	0%
Lead-off Ditch	0	0	0	0	0	0	0%	0%
Non-engineered Drain	103	57	25,011	18,535	1,397	1,026	74%	73%
Stream Crossing	6	6	478	478	106	106	100%	100%
Sump	0	0	0	0	0	0	0%	0%
Water Bar	1	1	434	434	17	17	100%	100%
Excavated Stream Crossing	3	3	41	41	11	11	100%	100%
Total	**151**	**75**	**43,017**	**22,830**	**6,797**	**1,470**	**53%**	**22%**

Figure 11: Typical post-storm road conditions. Tilled road on top; recontoured road on bottom.

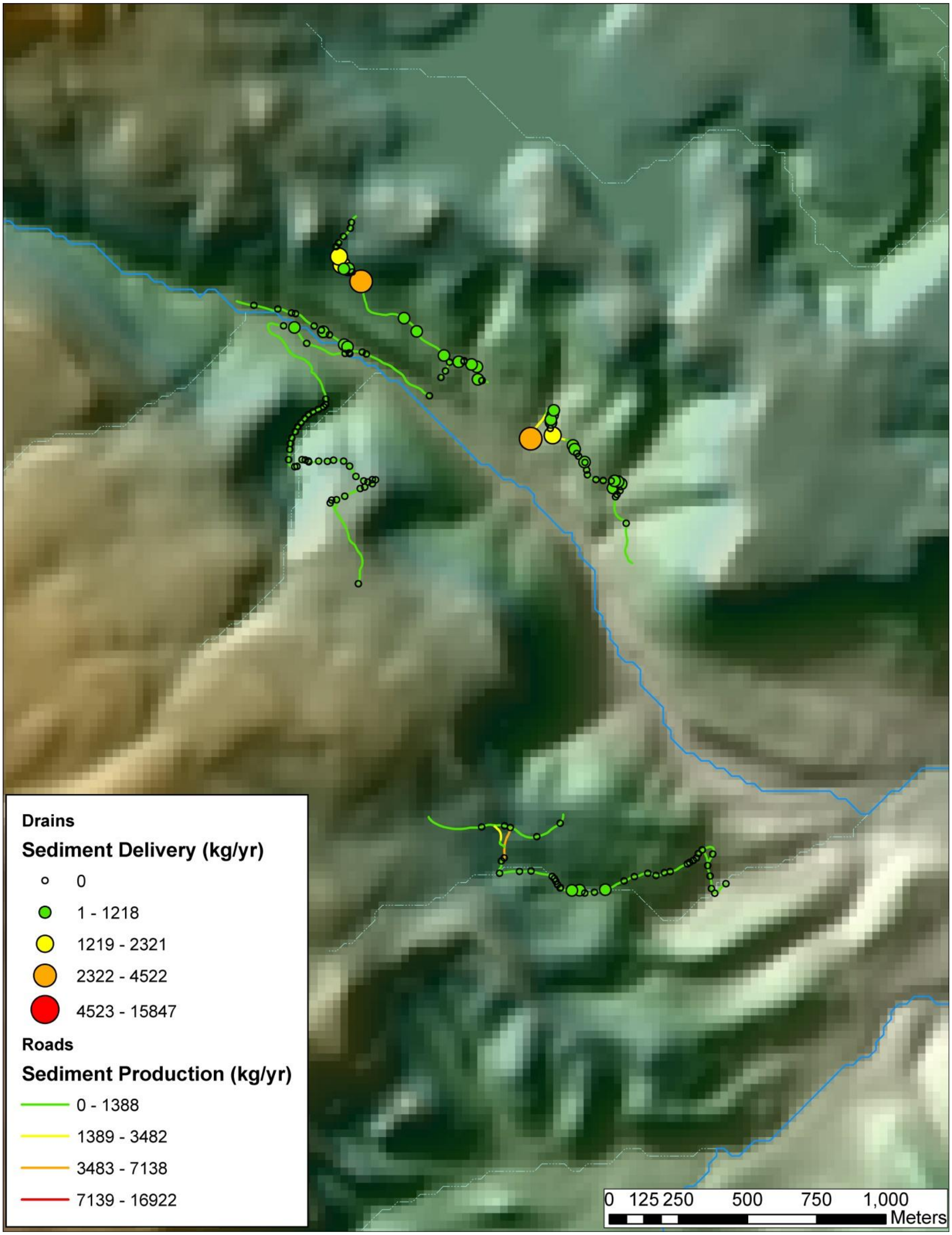

Figure 12: Sediment production and delivery, post-storm treatment roads.

The applied treatments resulted in significant decreases in sediment production and delivery, despite significant local storm damage on treated roads. All told, sediment production decreased by 131.9 Mg/yr and sediment delivery decreased by 96.8 Mg/yr (Table 4).

Table 4: Changes in sediment production and delivery by drainpoint type, post-treatment v. pre-treatment.

Pre-Treatment to Post-Storm, Treatment Roads								
Drain Type	**Count**		**Sediment Received (kg/yr)**	**Sediment Delivered (kg/yr)**	**Total Effective Length (m)**	**Stream Connected Length (m)**	**Percent Sediment Delivery**	**Percent Connected Length**
	Total	**Connected**						
Broad-based Dip	-22	-8	-41,335	-19,486	-1,682	-642	47%	40%
Diffuse Drain	17	0	10,836	0	4,665	0	0%	0%
Ditch-relief Culvert	0	0	0	0	0	0	0%	0%
Lead-off Ditch	0	0	0	0	0	0	0%	0%
Non-engineered Drain	71	41	-70,029	-56,598	-1,898	-1,549	-5%	-5%
Stream Crossing	0	0	-20,474	-20,474	-631	-631	0%	0%
Sump	0	0	0	0	0	0	0%	0%
Water Bar	-12	-1	-10,945	-268	-292	-8	94%	92%
Excavated Stream Crossing	3	3	41	41	11	11	100%	100%
Total	**57**	**35**	**-131,906**	**-96,785**	**171**	**-2,820**	**-15%**	**-43%**

Post-season

One year after the post-storm inventory, a crew re-inventoried the treatment and control roads. Local storm damage was limited to areas damaged before the post-storm inventory, though further erosion likely occurred in these areas. Typical conditions are shown in Figure 13.

Figure 13: Typical road conditions during the post-season inventory.

Sediment delivery was predicted to be 19.4 Mg/yr, or 58% of production (Table 5). The majority of this sediment is delivered by non-engineered drains in areas where storm damage has occurred (Figure 14).

Table 5: Summary of sediment production and delivery by drainpoint type, post-season treatment road.

Post-Season Treatment								
Drain Type	**Count**		**Sediment Received (kg/yr)**	**Sediment Delivered (kg/yr)**	**Total Effective Length (m)**	**Stream Connected Length (m)**	**Percent Sediment Delivery**	**Percent Connected Length**
	Total	**Connected**						
Broad-based Dip	11	7	1,889	1,045	385	253	55%	66%
Diffuse Drain	27	1	8,603	24	4,889	39	0%	1%
Ditch-relief Culvert	0	0	0	0	0	0	0%	0%
Lead-off Ditch	0	0	0	0	0	0	0%	0%
Non-engineered Drain	53	32	20,824	16,175	1,426	1,132	78%	79%
Stream Crossing	6	6	2,158	2,158	85	85	100%	100%
Sump	1	0	160	0	19	0	0%	0%
Water Bar	1	0	68	0	27	0	0%	0%
Excavated Stream Crossing	3	3	0	0	9	9	0%	100%
Total	**102**	**49**	**33,702**	**19,401**	**6,839**	**1,518**	**58%**	**22%**

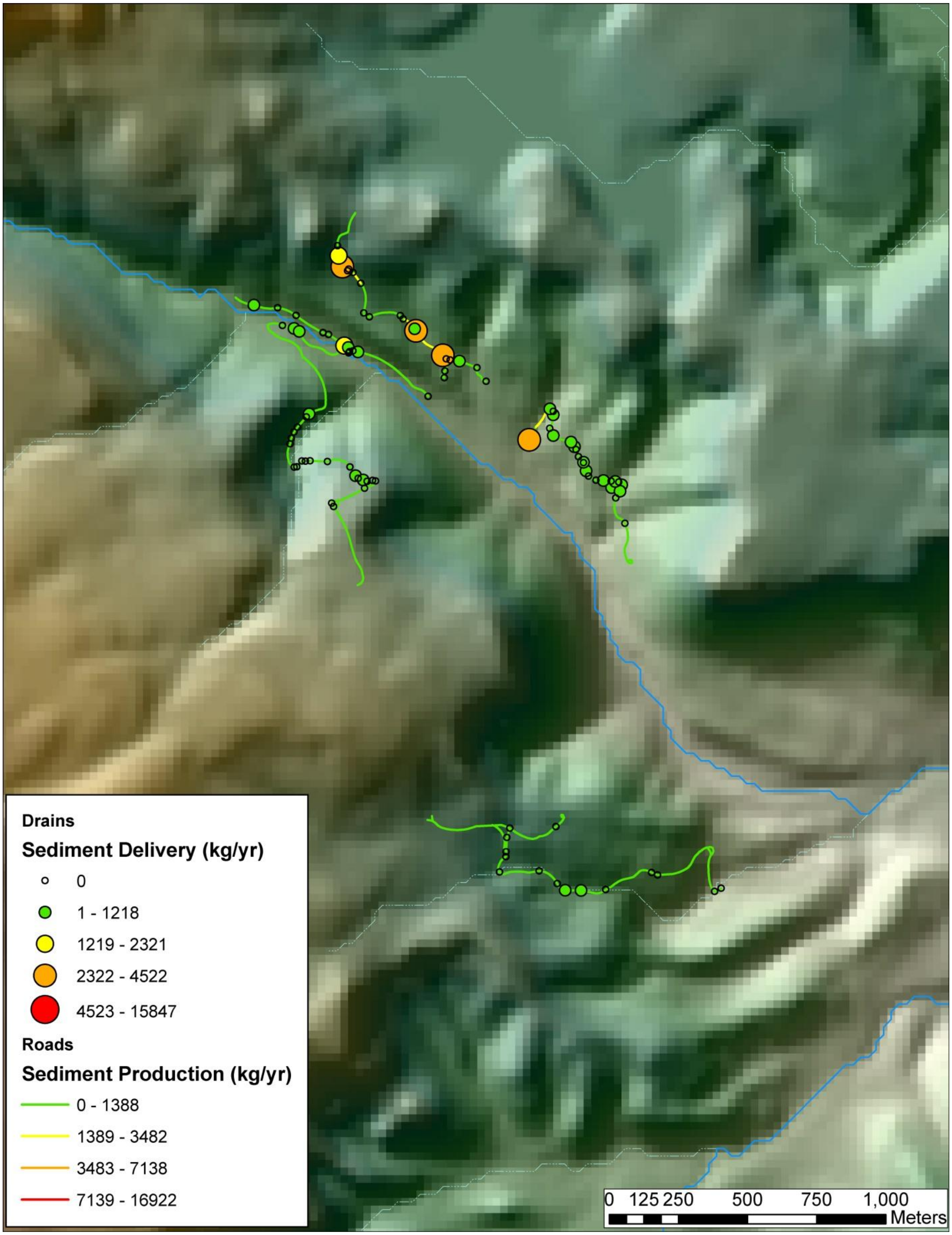

Figure 14: Sediment production and delivery, post-season treatment roads.

Stream connected length increased by about 50 m between the post-storm and the post-season inventories, yielding a net decrease of 2,771 m between pre-treatment and post-season inventories. Further growth of vegetation in the flowpaths resulted in reductions in sediment production and delivery of 9.3 Mg/yr and 3.4 Mg/yr, respectively, from the post-storm inventory. Net reductions from the pre-treatment inventory are 141.2 Mg/yr and 100.2 Mg/yr, respectively.

Table 6: Changes in sediment production and delivery by drainpoint type, post-season v. post-storm.

Post-Storm to Post-Season, Treatment Roads								
Drain Type	**Count**		**Sediment Received (kg/yr)**	**Sediment Delivered (kg/yr)**	**Total Effective Length (m)**	**Stream Connected Length (m)**	**Percent Sediment Delivery**	**Percent Connected Length**
	Total	**Connected**						
Broad-based Dip	-3	-1	-1,517	-2,296	28	-56	-43%	-21%
Diffuse Drain	3	1	-5,045	24	-20	39	0%	1%
Ditch-relief Culvert	0	0	0	0	0	0	0%	0%
Lead-off Ditch	0	0	0	0	0	0	0%	0%
Non-engineered Drain	-50	-25	-4,187	-2,360	29	106	4%	6%
Stream Crossing	0	0	1,680	1,680	-22	-22	0%	0%
Sump	1	0	160	0	19	0	0%	0%
Water Bar	0	-1	-366	-434	10	-17	-100%	-100%
Excavated Stream Crossing	0	0	-41	-41	-1	-1	-100%	0%
Total	**-49**	**-26**	**-9,315**	**-3,428**	**43**	**49**	**4%**	**1%**

Table 7: Changes in sediment production and delivery by drainpoint type, post-season v. pre-treatment.

Pre-Treatment to Post-Season, Treatment Roads								
Drain Type	**Count**		**Sediment Received (kg/yr)**	**Sediment Delivered (kg/yr)**	**Total Effective Length (m)**	**Stream Connected Length (m)**	**Percent Sediment Delivery**	**Percent Connected Length**
	Total	**Connected**						
Broad-based Dip	-25	-9	-42,852	-21,782	-1,654	-698	4%	19%
Diffuse Drain	20	1	5,791	24	4,644	39	0%	1%
Ditch-relief Culvert	0	0	0	0	0	0	0%	0%
Lead-off Ditch	0	0	0	0	0	0	0%	0%
Non-engineered Drain	21	16	-74,215	-58,958	-1,870	-1,443	-1%	1%
Stream Crossing	0	0	-18,794	-18,794	-653	-653	0%	0%
Sump	1	0	160	0	19	0	0%	0%
Water Bar	-12	-2	-11,310	-702	-282	-25	-6%	-8%
Excavated Stream Crossing	3	3	0	0	9	9	0%	100%
Total	**8**	**9**	**-141,221**	**-100,213**	**214**	**-2,771**	**-11%**	**-43%**

Control Roads

Pre-storm

The control roads were selected and first inventoried at the same time the pre-treatment inventory was conducted. The initial survey found that 49% of the road was in good condition, 29% was rilled or eroded, 16% was rocky, and 7% was rutted. Figure 15 shows examples of general road conditions.

Figure 15: Typical control road sections, pre-storm.

Sediment production on the control roads at the time of the pre-treatment inventory was predicted to be 161.9 Mg/yr, with 59.8 Mg/yr (37%) delivered to the stream network (Table 9). Thirty-nine percent of the control roads were found to be hydrologically connected to the stream network. Figure 16 shows the sediment production and delivery along the control roads.

Table 8: Summary of sediment production and delivery by drainpoint type, pre-storm control road.

Pre-Storm Control								
Drain Type	**Count**		**Sediment Received (kg/yr)**	**Sediment Delivered (kg/yr)**	**Total Effective Length (m)**	**Stream Connected Length (m)**	**Percent Sediment Delivery**	**Percent Connected Length**
	Total	**Connected**						
Broad-based Dip	42	16	59,189	17,283	2,876	771	29%	27%
Diffuse Drain	6	0	7,965	0	380	0	0%	0%
Ditch-relief Culvert	1	1	0	0	0	0	0%	0%
Lead-off Ditch	4	4	4,126	4,126	316	316	100%	100%
Non-engineered Drain	28	15	53,228	22,261	1,843	821	42%	45%
Stream Crossing	2	2	1,142	1,142	90	90	100%	100%
Sump	2	0	1,181	0	113	0	0%	0%
Water Bar	32	16	35,095	14,986	1,462	745	43%	51%
Excavated Stream Crossing	0	0	0	0	0	0	0%	0%
Total	**117**	**54**	**161,926**	**59,797**	**7,080**	**2,743**	**37%**	**39%**

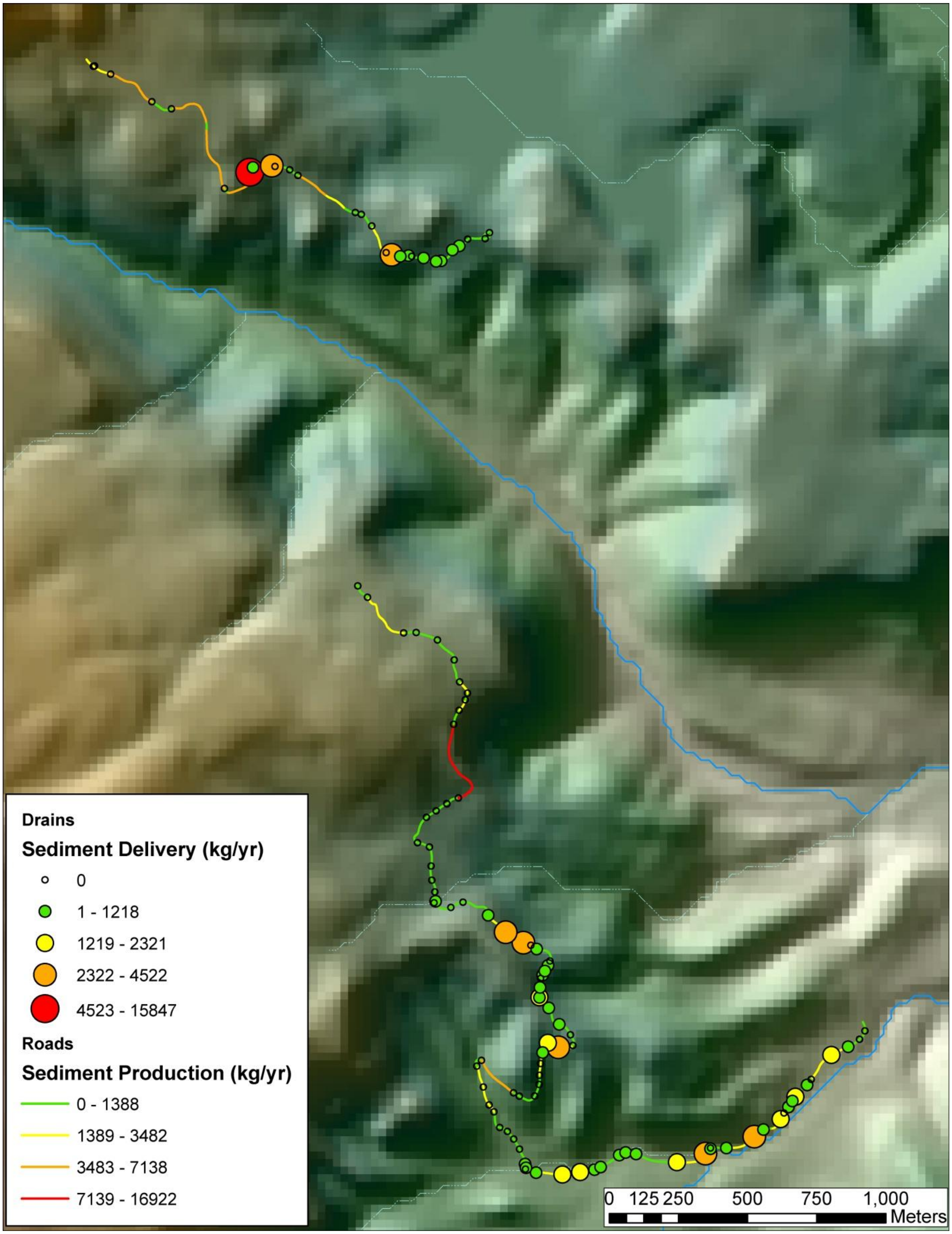

Figure 16: Sediment production and delivery, pre-storm control roads.

Post-storm

The post-storm inventory took place in August, 2010. Sixty-three percent of the road was reported to be rilled or eroded, 17% was rocky, 13% was in good condition, and 8% was rutted. Typical conditions are shown in Figure 17.

Figure 17: Typical control road conditions, post-storm.

Sediment production was predicted to have decreased slightly to 161.7 Mg/yr. Sediment delivery, however, increased to 90.7 Mg/yr (56% of the produced sediment; Table 9). Figure 18 shows sediment production and delivery along the control roads following the first storm event.

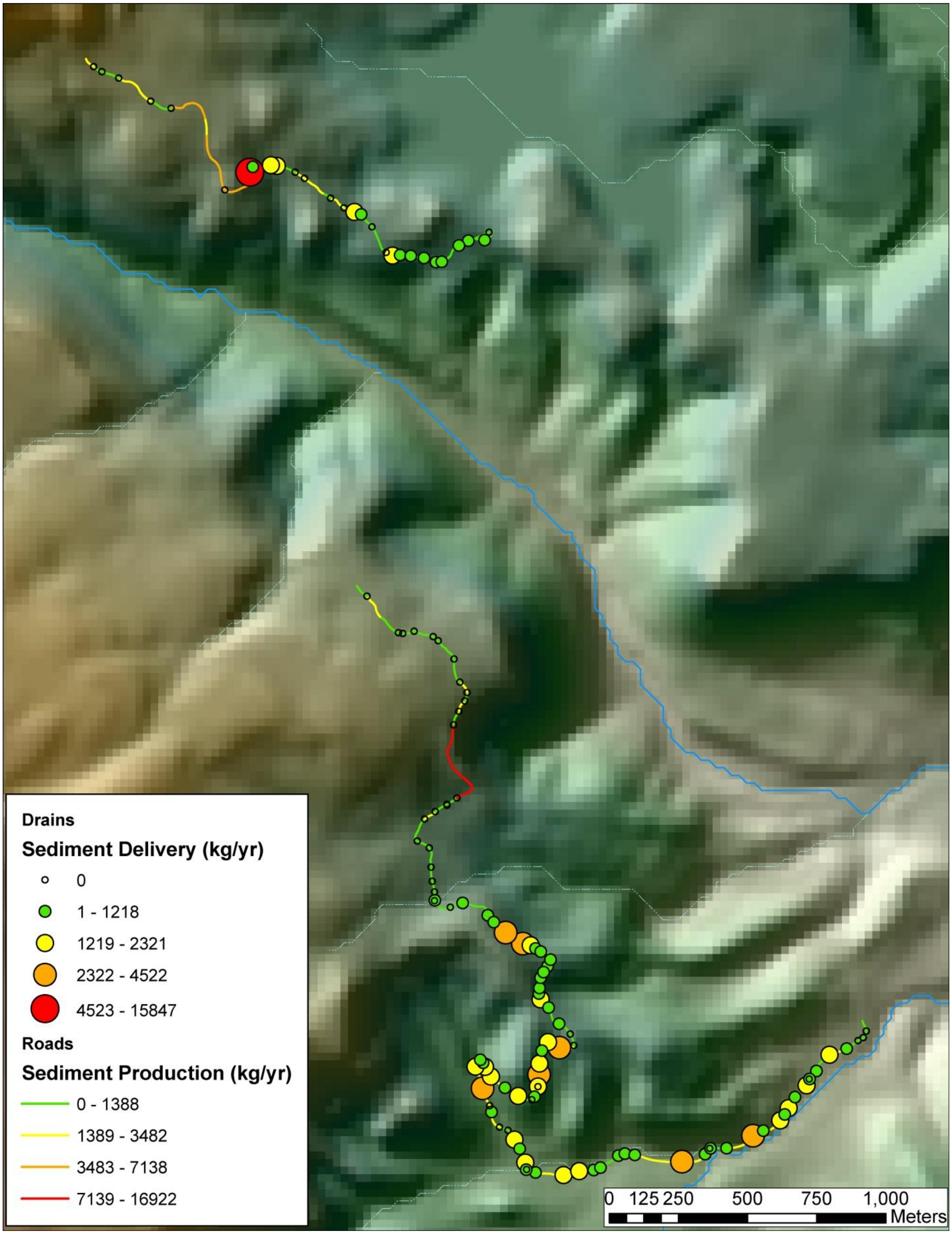

Figure 18: Sediment production and delivery, post-storm control roads.

Table 9: Summary of sediment production and delivery by drainpoint type, post-storm control road.

Post-Storm Control								
Drain Type	**Count**		**Sediment Received (kg/yr)**	**Sediment Delivered (kg/yr)**	**Total Effective Length (m)**	**Stream Connected Length (m)**	**Percent Sediment Delivery**	**Percent Connected Length**
	Total	**Connected**						
Broad-based Dip	41	18	58,312	20,091	2,983	999	34%	33%
Diffuse Drain	1	0	857	0	50	0	0%	0%
Ditch-relief Culvert	0	0	0	0	0	0	0%	0%
Lead-off Ditch	4	4	6,389	6,389	352	352	100%	100%
Non-engineered Drain	44	30	58,902	31,980	2,083	1,174	54%	56%
Stream Crossing	3	3	926	926	84	84	100%	100%
Sump	2	0	371	0	73	0	0%	0%
Water Bar	32	27	35,970	31,271	1,479	1,250	87%	85%
Excavated Stream Crossing	0	0	0	0	0	0	0%	0%
Total	**127**	**82**	**161,727**	**90,657**	**7,106**	**3,859**	**56%**	**54%**

Table 10: Changes in sediment production and delivery by drainpoint type, post-storm v. pre-storm control road.

Pre-Storm to Post-Storm, Control Roads								
Drain Type	Count		Sediment Received (kg/yr)	Sediment Delivered (kg/yr)	Total Effective Length (m)	Stream Connected Length (m)	Percent Sediment Delivery	Percent Connected Length
	Total	Connected						
Broad-based Dip	-1	2	-877	2,809	107	228	5%	7%
Diffuse Drain	-5	0	-7,109	0	-329	0	0%	0%
Ditch-relief Culvert	-1	-1	0	0	0	0	0%	0%
Lead-off Ditch	0	0	2,263	2,263	36	36	0%	0%
Non-engineered Drain	16	15	5,674	9,720	240	353	12%	12%
Stream Crossing	1	1	-216	-216	-6	-6	0%	0%
Sump	0	0	-810	0	-39	0	0%	0%
Water Bar	0	11	875	16,285	17	506	44%	34%
Excavated Stream Crossing	0	0	0	0	0	0	0%	0%
Total	**10**	**28**	**-199**	**30,860**	**26**	**1,116**	**19%**	**16%**

Post-season

The post-season inventory took place in August, 2011. Fifty-one percent of the roads were found to be rilled or eroded, 46% were in good condition, 2% were rocky, and 1% were rutted. Typical conditions are shown in Figure 19.

Figure 19: Typical control road conditions, post-season.

Sediment production was predicted to have decreased to 146.0 Mg/yr. Sediment delivery, however, increased to 105.2 Mg/yr (72% of the produced sediment; Table 11). Figure 20 shows sediment production and delivery as predicted from the post-season inventory.

Table 11: Summary of sediment production and delivery by drainpoint type, post-season control road.

Post-Season Control								
Drain Type	**Count**		**Sediment Received (kg/yr)**	**Sediment Delivered (kg/yr)**	**Total Effective Length (m)**	**Stream Connected Length (m)**	**Percent Sediment Delivery**	**Percent Connected Length**
	Total	**Connected**						
Broad-based Dip	35	19	40,769	18,616	2,775	1,089	46%	39%
Diffuse Drain	0	0	0	0	0	0	0%	0%
Ditch-relief Culvert	0	0	0	0	0	0	0%	0%
Lead-off Ditch	14	7	8,525	5,933	724	512	70%	71%
Non-engineered Drain	42	28	64,285	49,496	2,327	1,738	77%	75%
Stream Crossing	3	3	0	0	0	0	0%	0%
Sump	1	0	140	0	9	0	0%	0%
Water Bar	25	22	32,313	31,146	1,279	1,139	96%	89%
Excavated Stream Crossing	0	0	0	0	0	0	0%	0%
Total	**120**	**79**	**146,031**	**105,192**	**7,113**	**4,479**	**72%**	**63%**

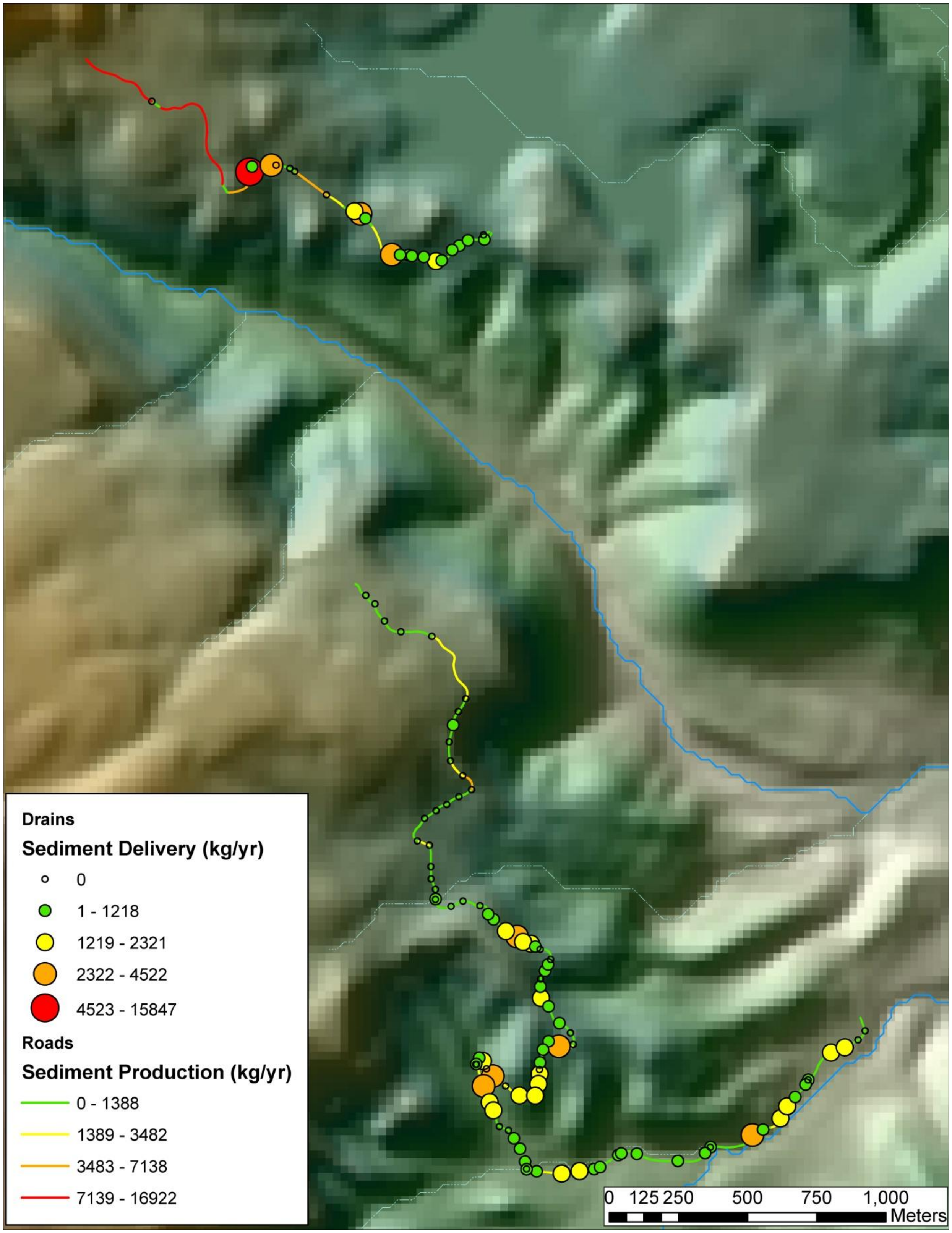

Figure 20: Sediment production and delivery, post-season control roads.

While increased flowpath vegetation reduced sediment production by 15.7 Mg/yr from post-strom levels, sediment delivery increased by 14.5 Mg/yr (Table 12). Total changes, measured from the pre-storm inventory, indicate a decrease in sediment production of 15.9 Mg/yr and an increase in sediment delivery of 45.4 Mg/yr (Table 13). These increases in sediment delivery are the result of increases in the length of connected road; 620 meters of road became connected between the post-storm inventory and the post-season inventory. Since the pre-storm inventory, the amount of control road connected to the stream has increased by 1.7 km.

Table 12: Changes in sediment production and delivery by drainpoint type, post-season v. post-storm.

Post-Storm to Post-Season, Control Roads								
Drain Type	**Count**		**Sediment Received (kg/yr)**	**Sediment Delivered (kg/yr)**	**Total Effective Length (m)**	**Stream Connected Length (m)**	**Percent Sediment Delivery**	**Percent Connected Length**
	Total	**Connected**						
Broad-based Dip	-6	1	-17,543	-1,475	-209	91	11%	6%
Diffuse Drain	-1	0	-857	0	-50	0	0%	0%
Ditch-relief Culvert	0	0	0	0	0	0	0%	0%
Lead-off Ditch	10	3	2,136	-456	372	160	-30%	-29%
Non-engineered Drain	-2	-2	5,383	17,516	243	564	23%	18%
Stream Crossing	0	0	-926	-926	-84	-84	-100%	-100%
Sump	-1	0	-231	0	-64	0	0%	0%
Water Bar	-7	-5	-3,657	-125	-201	-112	9%	5%
Excavated Stream Crossing	0	0	0	0	0	0	0%	0%
Total	**-7**	**-3**	**-15,696**	**14,534**	**8**	**620**	**16%**	**9%**

Table 13: Changes in sediment production and delivery by drainpoint type, post-season v. pre-storm.

Pre-Storm to Post-Season, Control Roads								
Drain Type	**Count**		**Sediment Received (kg/yr)**	**Sediment Delivered (kg/yr)**	**Total Effective Length (m)**	**Stream Connected Length (m)**	**Percent Sediment Delivery**	**Percent Connected Length**
	Total	**Connected**						
Broad-based Dip	-7	3	-18,420	1,334	-101	318	16%	12%
Diffuse Drain	-6	0	-7,965	0	-380	0	0%	0%
Ditch-relief Culvert	-1	-1	0	0	0	0	0%	0%
Lead-off Ditch	10	3	4,399	1,807	408	196	-30%	-29%
Non-engineered Drain	14	13	11,057	27,236	484	918	35%	30%
Stream Crossing	1	1	-1,142	-1,142	-90	-90	-100%	-100%
Sump	-1	0	-1,041	0	-103	0	0%	0%
Water Bar	-7	6	-2,782	16,160	-184	394	54%	38%
Excavated Stream Crossing	0	0	0	0	0	0	0%	0%
Total	**3**	**25**	**-15,895**	**45,395**	**33**	**1,736**	**35%**	**24%**

6.4 Gully Initiation Risk

While numerous gullies were located during the inventories, especially following the storm events, nearly all of the gullies occurred within a single geologic formation. Extensive gullying was also noted on hillslopes not impacted by roads, suggesting that natural risks are high within this unit and that any concentrated drainage from a road may pose a risk of gully initiation especially during convective thunderstorm events.

Following the storm events, gully volumes were considerably higher along the control roads than along the treatment roads and most gullies located along the treatment roads originated higher on the hillslope above the decommissioned road. During the post-season inventory, the crew estimated gully volume to be about 9 m^3 on the treatment roads and about 128 m^3 on the control roads.

6.5 Stream Crossing Failure Risk

Stream crossing failure risks on treatment roads were negligible because all stream crossings were natural fords. The few crossings on the control roads that were not natural fords exhibited low blockage risks, had little fill that could be eroded if the culvert were to become blocked, and did not have any potential to divert flow down the road.

6.6 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. Non-engineered features are almost always a problem, most often because of diverted wheel track flow. 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. Water bars 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.

Prior to treatment, drainpoint-related problems were located at non-engineered drains, water bars, and broad-based dips (Table 14). Fewer problems were located during the post-storm inventory; however, during the post-season inventory there was an increase in drainpoint-related problems, especially at non-engineered drains. Fill erosion was estimated to be ~300 cubic feet during the post-season inventory.

Drainpoint problems on the control roads occurred less frequently (Table 15), both before and after the storm event. Non-engineered drains and broad based dips were the most common problem drainpoints in all three inventories. The overall problem rate increased from 15% (pre-storm) to 38% (post-season). Fill erosion was estimated to be approximately 600 cubic feet during the post-season inventory.

Table 14: Drainpoint condition problems and fill erosion, treatment roads. Fill erosion in cubic feet.

	Pre-Treatment			Post-Storm			Post-Season		
Drain Type	**Count**	**Problems**	**Fill Erosion**	**Count**	**Problems**	**Fill Erosion**	**Coun t**	**Problems**	**Fill Erosion**
Broad Based Dips	39	10	27	17	3	0	11	0	210
Diffuse Drains	7	0	0	24	0	0	27	0	0
Ditch Relief Culverts	0	0	0	0	0	0	0	0	0
Lead-off Ditches	0	0	0	0	0	0	0	0	0
Non-engineered Drains	35	23	0	106	26	0	53	51	72
Stream Crossings	6	0	0	9	1	0	9	1	25
Sumps	0	0	0	0	0	0	1	1	0
Water Bars	13	4	0	1	0	0	1	0	0
Total	**100**	**37**	**27**	**157**	**30**	**0**	**102**	**53**	**307**

Table 15: Drainpoint condition problems and fill erosion, control roads. Fill erosion in cubic feet.

	Pre-Storm			Post-Storm			Post-Season		
Drain Type	**Count**	**Problems**	**Fill Erosion**	**Count**	**Problems**	**Fill Erosion**	**Count**	**Problems**	**Fill Erosion**
Broad Based Dips	42	7	8	41	8	8	35	9	55
Diffuse Drains	6	0	0	1	0	0	0	0	0
Ditch Relief Culverts	1	0	0	0	0	0	0	0	0
Lead-off Ditches	4	0	0	4	0	0	14	0	0
Non-engineered Drains	28	7	5	44	21	25	42	34	505
Stream Crossings	2	1	0	3	1	0	3	1	0
Sumps	2	1	0	2	1	0	1	0	0
Water Bars	32	2	0	32	4	0	25	1	30
Total	**117**	**18**	**13**	**127**	**35**	**33**	**120**	**45**	**590**

7.0 Summary and Conclusions

Three major storm events were recorded by the rain gage installed at the Mammoth Creek campground between July 22, 2010, and August 2, 2011. The return intervals for the precipitation intensities measured during these events ranges from 7 years up to 20.5 years.

Before-after comparisons using GRAIP indicate that decommissioning treatments resulted in a large reduction of many impact-risk metrics, while control roads experienced large increases in the same impact-risk metrics (Tables 16 and 17). Comparing pre-treatment and post-season inventories, road-stream connectivity was decreased by 2,771 m (43% of total road length), from 4,289 m of connected road to 1,518 m. Delivery of fine sediment was reduced by 100.2 Mg/yr (-83%), from 119.6 Mg/year to 19.4 Mg/year. Control roads saw an increase of 1,736 m (24% of total road length) connected road length, from 2,743 m to 4,479 m. This was accompanied by an increase in delivered fine sediment of 45.4 Mg/yr (76%), from 59.8 Mg/yr to 105.2 Mg/yr.

Gully activity at the Mammoth Creek site was confined to a single geologic unit which showed extensive post-storm and post-season gully activity even on un-roaded hillslopes. Gully volumes on the control roads nearly doubled between the June, 2010, and August, 2011, while gully volumes on the treatment roads were not increased.

Taken collectively, results indicate the decommissioning treatments have been effective in reducing the hydrogeomorphic impacts and risks to aquatic ecosystems. Risks associated with the control roads, however, increased in most cases, and remained the same in others.

Table 16: Summary of changes, pre-treatment to post-storm.

Impact/Risk Type	Treatment Roads	Control Roads
	Post-storm	**Post-storm**
Road-Stream Hydrologic Connectivity	-2,820 m (-43%)	+1,116 m (16%)
Fine Sediment Delivery	-96,785 kg/yr	+30,860 kg/yr (52%)
Drain Point Problems	-7 problems	+17 problems

Measured as change from pre-treatment conditions.

Table 17: Summary of changes, pre-treatment to post-season.

Impact/Risk Type	Treatment Roads	Control Roads
	Post-season	**Post-season**
Road-Stream Hydrologic Connectivity	-2,771 m (-43%)	+1,736 m (24%)
Fine Sediment Delivery	-100,213 kg/yr (-83%)	+45,395 kg/yr (76%)
Drain Point Problems	+16 problems	+27 problems

Measured as change from pre-treatment conditions.

Appendix A: Glossary of Selected 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. (2012), Fly, et al (2010), and Moll (1997).

Broad based dip. ***Constructed:*** 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 dip, grade dip). ***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:*** 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, Thomas A.; Cissel, Richard M.; Luce, Charles H. 2012. **The Geomorphic Road Analysis and Inventory Package (GRAIP) Volume 1: Data Collection Method.** Gen. Tech. Rep. RMRS-GTR-280WWW. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 110 p.

Cissel, Richard M.; Black, Thomas A.; Schreuders, Kimberly A. T.; Prasad, Ajay; Luce, Charles H.; Tarboton, David G.; Nelson, Nathan A. 2012. **The Geomorphic Road Analysis and Inventory Package (GRAIP) Volume 2: Office Procedures.** Gen. Tech. Rep. RMRS-GTR-281WWW. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 160 p.

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.

Nelson, N., Clifton, C., Black, T., Luce, C., and McCune, S. 2010. Wall Creek Watershed GRAIP Roads Assessment, North Fork John Day Subbasin, Umatilla National Forest. USDA Forest Service, Rocky Mountain Research Station, Boise Aquatic Science Lab.

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.

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.