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Sediment concentration and turbidity changes during culvert removals

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Abstract

The concentrations of sediment and turbidity in stream water were monitored during culvert removals to determine the short term effects of road obliteration. Sediment concentration was measured at 11 stream crossings among two locations in Idaho and one in Washington. Sediment concentration immediately below the culvert outlet exceeded levels above the culvert outlet by at least three orders of magnitude at all stream crossings. Sediment yields ranged from 170 to less than 1 kg in the 24-h period following culvert removal. Turbidity exceeded the regulatory limits during culvert removal at all locations monitored in this study and remained above the limits beyond the monitoring periods of 24 h at four of the locations. Sediment concentrations 100 m downstream of the culvert outlet were reduced by an order of magnitude, but did not change the turbidity values sufficiently to meet regulatory limits. Sediment concentrations an average of 810 m downstream of the culvert outlet were similar to sediment concentrations above the culvert for the entire excavation period and turbidity regulations were met. Mitigation consisting of two straw bales placed in the stream caused a significant reduction in sediment yield from an average of 67 kg to an average of 1.6 kg.

Keywords: Soil erosion; Road obliteration; Sediment; Stream water quality; Culvert removal

1. Introduction

Between 1950 and 1990, the number of unpaved forest roads constructed each year on national forest lands for timber harvesting, mining and forest management activities increased. In 2005, the forest road inventory indicated 609 300 km of roads on forest lands managed by the United States Forest Service (USFS). Most unpaved USFS roads created for past forest operations are no longer used for their original purposes and less than 20% are maintained according to originally specified safety and environmental standards (USDA Forest Service, 2002). Unmaintained forest roads can become unstable, present safety hazards, and increase surface erosion and sediment loss from landslides during large storms.

Removing roads from service, or decommissioning roads, is an increasingly common management alternative applied on roads with low resource management priority, high risk of failure, or in environmentally sensitive areas. Methods of road decommissioning range from simply blocking the road entrance to completely removing and recontouring the former road surface. Road obliteration is the most comprehensive degree of decommissioning and involves decompacting the road surface (road ripping), removing culverts, re-establishing stream channels, and reshaping the roadbed to match the hillside contour.

The first extensive road obliteration operations took place in Redwood National Park where chronic landslides in the Redwood Creek watershed prompted intense mitigation of old, unstable logging roads. Between the years of 1978 and 1992, over 300 km of roads were obliterated to reduce sediment delivery to downstream salmon habitat. When over 200 obliterated stream crossings were examined, following a 12-year storm event in

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1997 in the Redwood National Park, Madej (2001) determined that road obliteration greatly reduced long-term sediment yields compared to untreated roads. This study prompted many forest managers to apply road obliteration techniques on national forests. Since 1991, over 50 000 km of forest roads have been decommissioned on national forest lands (USDA Forest Service, unpublished data).

In addition to removing unstable fills, road obliteration increases infiltration, which helps reestablish vegetation and restore hillslope hydrology. Luce (1997) measured infiltration rates of 0–12 mm/h on road surfaces prior to ripping and infiltration rates of 14–31 mm/h following ripping. Foltz and Maillard (2003) measured an increase in infiltration from 2 to 10 mm/h in the 2–3 year period following road obliteration. While still far below infiltration rates of undisturbed forest floors, which range from 36 to 80 mm/h (Robichaud, 2000), increases in infiltration capacity following road ripping can decrease runoff events. Foltz and Maillard (2003) used computer modeling to demonstrate that the increased infiltration capacity from road obliteration in central Idaho could reduce the number of runoff events from three per year to one event every other year.

The studies by Madej, Luce, and Foltz and Maillard indicate potential long-term benefits resulting from road obliteration with decreased occurrence of road related landslides and increased infiltration capacity of road surfaces. However, short-term effects of road obliteration have not been quantified. As with any excavation activity, there is risk of erosion during and immediately after road obliteration before exposed soil is stabilized by revegetation. Road obliteration, particularly culvert removal, has the potential to degrade water quality substantially during excavation.

Culvert replacement has been studied more than the removal of culverts during road obliteration (Faurot, 2005; Jakober, 2002). The two are similar in that both involve potential diversion of the stream, removal of the fill, and removal of the existing culvert. In road obliteration, the streambed is prepared to receive the stream flow while in culvert replacement, a new culvert is placed in the streambed.

Faurot (2005) reported that 90% of the increased turbidity due to culvert replacement was believed to occur during the reintroduction of stream flow into the channel and that rain events during and after construction might mobilize some sediment into the stream. Each of these observations was based on opinions by experienced field personnel rather than measurements. Jakober (2002) studied a culvert replacement in the Bitterroot National Forest in Montana and reported that 95% of the construction-related sediment occurred in the first 2 h after diversion removal. He further stated that sediment concentrations decreased to near pre-project levels within 24 h. He sampled stream sediment concentrations after the new culvert had been installed and the stream returned to its bed.

Allowable suspended sediment/turbidity standards for surface water quality are set individually by each state in the United States. Idaho state criterion for cold water aquatic habitat require that turbidity not exceed the background level by more than 50 NTU instantaneously or more than 25 NTU for more than 10 consecutive days (IDEQ, 1994). Other states are more stringent. Washington state criterion for Class AA (high priority) surface waters, which includes forested lands, requires that turbidity not exceed 5 NTU above the background level if the background turbidity is 50 NTU or less (WDE, 1997). California forested lands criterion vary by region from 1 NTU above background to 20% above background (Rosetta, 2005).

These criteria are intended to provide protection to cold water species. More specific criteria are available for selected species. Suspended sediment concentrations of 6000 mg/L for 1 h have caused avoidance behavior in coho salmon (Noggle, 1978). Concentrations of 500 mg/L for 3 h were observed to cause sublethal stress in adult steelhead (Redding and Shreck, 1982). Concentrations of 25 mg/L for 1 h resulted in decreased feeding rates in juvenile coho salmon (Noggle, 1978).

Road obliteration proceeds with the assumption that long-term benefits outweigh short-term effects on stream water quality. Measurements of in-stream sediment concentrations, especially during and immediately after excavations, would provide data to support or refute this assumption. The purpose of this study was to measure the effects of culvert removal on stream water quality. Stream flow and sediment concentrations were measured on multiple stream crossings for two national forests in Idaho and one in Washington. Specific objectives of this study were to:

1. Determine sediment concentrations during culvert removal;
2. Compare regulatory turbidity criteria to measured turbidity; and
3. Identify correlations between stream crossing characteristics and stream sediment concentrations and yields.

2. Methods

This study was not conducted in an experimental framework, but as an observational study. Skill and technique of the equipment operators, soil moisture, stream flow, and weather conditions were a few of the factors expected to have an impact on sediment concentrations and yields. Some of the locations were not independent because the culvert removal operations encountered crossings on streams that had upstream road obliteration a few days previous. The authors have chosen to use a significance level of 0.10 to account for this lack of experiment control. The results of this study should be considered an exploratory study.

2.1. Location descriptions

Horse Creek, located on the Nez Perce National Forest in Idaho, is a tributary to Meadow Creek in the Selway River drainage and is an important habitat for anadromous and resident fish. The Horse Creek drainage was an Administrative Research Study area from 1965 to 1988 when roads were constructed for a harvest operation. Stream flow and sediment concentrations were monitored year-round and sediment deposition was measured each year at dams constructed on multiple tributaries to Horse Creek (King, 1994). In 1998, monitoring stations, which had been discontinued in 1988, were restored on three streams in the Horse Creek drainage. Research and monitoring efforts have spanned a variety of successive activities including road installation, harvesting, and now road obliteration.

The Main Fork of Horse Creek has a drainage area of 1630 ha. The average annual precipitation ranges from 100 to 115 cm and the majority of runoff is spring snowmelt. Watershed elevations range from 1300 to 1700 m. Most hillside slopes range from 20% to 50%. The predominant geologic parent material is gneiss and schist derived from the Idaho Batholith Border Zone. Soils are moderately deep, well drained, loam to sandy loam with surface layers containing loessal silt. The dominant habitat type is western red cedar with subalpine fir and grand fir habitat types are also present (USDA Forest Service, 1981).

The Horse Creek drainage (Fig. 1) has a road density of 1.7 km/km^2. A 7.2-km mid-slope road was obliterated in 2003 and 2004. Three watersheds (H10, H14, and H16), 63, 58, and 24 ha in area, respectively, were monitored for this study. All three watersheds have similar southerly aspects and range in elevation from 1300 to 1700 m. The Rosgen channel type of each of the three streams is A4a+ (Rosgen and Silvey, 1998). All culverts removed from these streams were 0.61-m (24 in) corrugated metal pipe (CMP). The fill volumes removed during road obliteration were 180, 890, and 220 m^3 at H10, H14, and H16, respectively.

A second study area was located on the North Fork Granite Creek, a tributary to Priest Lake, on the Kaniksu National Forest in Washington. The North Fork Granite Creek has a drainage area of 7700 ha. Average annual precipitation ranges from 114 to 144 cm. Watershed elevations range from 1100 to 1400 m and hillslopes are typically 20–60%. The predominant geologic parent material is composed of glacial till and soils are heavily influenced by volcanic ash. Soils are shallow and poorly developed in some areas. The surface layers are mostly silt loam. The dominant habitat types surrounding Granite Creek are western red cedar and subalpine fir (USDA Forest Service, 2004).

The Granite Creek drainage (Fig. 2) has a road network with a density of 2.5 km/km^2. Periodic mass failures on unmaintained roads have resulted in increased sediment delivery to the North Fork Granite Creek that supports bull trout and westslope cutthroat trout. Maintenance of grizzly bear habitat is another ecological concern in the Granite Creek drainage. In 2005, the road network of 12.9 km was obliterated to reduce the risk of mass failures and to improve grizzly bear habitat. The removal of three culverts were monitored in the Granite Creek drainage: two on the North Fork Granite Creek, G1 and G2, and one on a tributary, G3. The Rosgen channel types are B4 for Granite Creek 1 and 2 and B5 for Granite Creek 3 (Rosgen and Silvey, 1998).

Unlike Horse Creek, these three monitored stream crossings were not all similar in size and aspect. Granite Creek had a larger drainage area and exhibited higher flows than the other study areas, but had lower gradients (Table 1). The drainage areas above G1 and G2 were 400 and 700 ha, respectively. The drainage area above G3 was

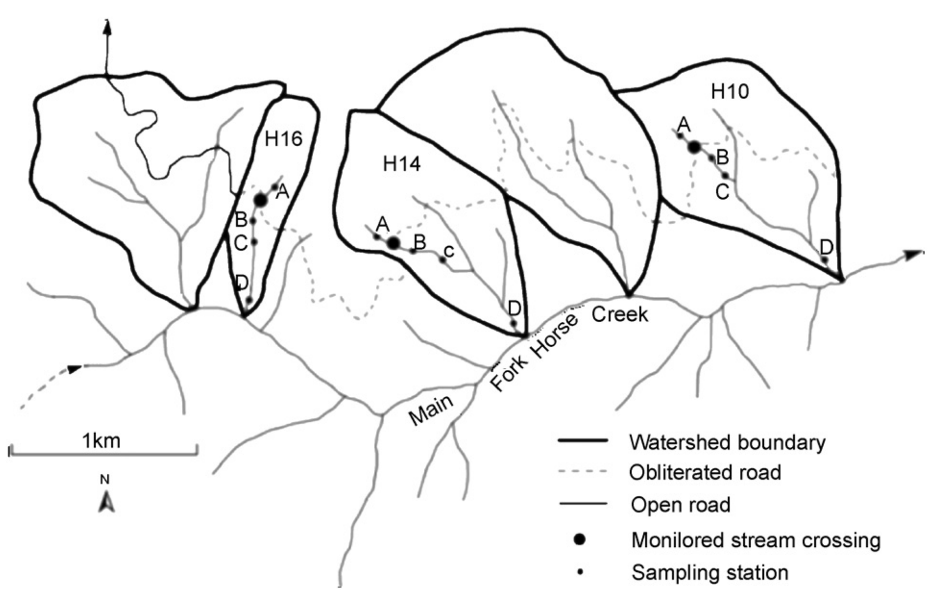

Fig. 1. Tributary watersheds and obliterated road network in the Horse Creek drainage of the Nez Perce National Forest, ID.

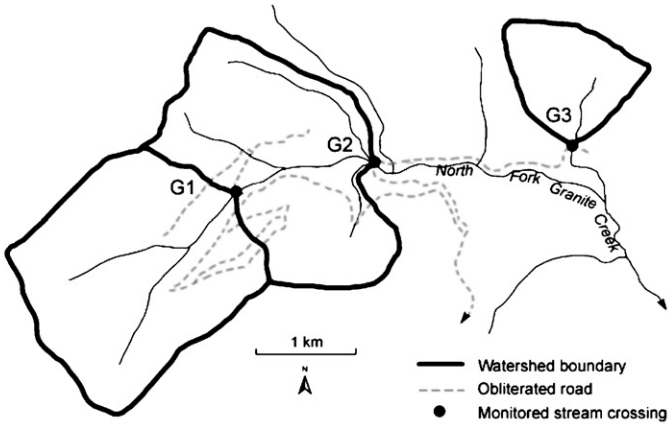

Fig. 2. Tributary watersheds and obliterated road network in the Granite Creek watershed of the Kaniksu National Forest, WA.

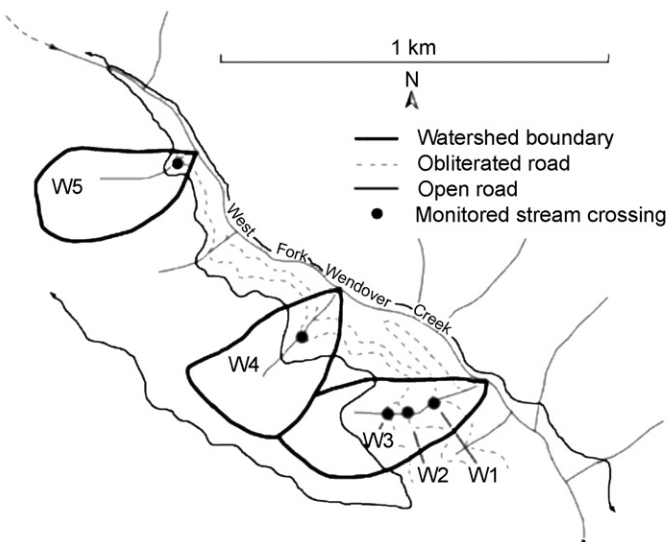

Fig. 3. Tributary watersheds and obliterated road network in the Wendover Creek drainage of the Clearwater National Forest, ID.

91 ha. Not all segments of the obliterated roads in Granite Creek were fully recontoured. Road segments with a lower risk of failure were partially recontoured. Road segments that were partially recontoured were ripped to a depth of 0.3–0.6 m and only the areas with fills judged to be unstable were recontoured. Culverts were removed and channel crossings were restored on all obliterated roads.

The third study area was Wendover Creek, a tributary to the Lochsa River, located on the Clearwater National Forest in Idaho on the western slopes of the Bitterroot Mountains. Wendover Creek is characterized by steep valley walls that have slopes of 60–90%. Average annual precipitation is 122 cm. The elevations of the monitoring locations ranged from 1130 to 1190 m. The parent material is granitic and surface soils are silt loam with weak granular structure. The dominant habitat type is western red cedar. The obliteration of five stream crossings (W1, W2, W3, W4, and W5) on three tributary streams to Wendover Creek were monitored. The drainage areas upslope of the stream crossings ranged between 16 and 19 ha (Brown, 2002).

Historically, Wendover Creek (Fig. 3) and the surrounding area were intensively logged, and had a higher road density (11.5 km/km^2) than Horse Creek (1.7 km/km^2) and Granite Creek (2.5 km/km^2). The roads in Wendover Creek had log stream crossings rather than CMP culverts like Horse Creek and Granite Creek. Log stream crossings are constructed by placing logs in the stream and placing soil on top of the logs. Such crossings are known in California as Humboldt crossings and in Idaho as log culverts. This method was popular in the 1940s and 1950s but is not currently used.

2.2. Stream crossing characteristics

The three study areas exhibited a range of stream flow rates and watershed characteristics (Table 1). Flow rates

Table 1
Road crossing and stream characteristics on Horse Creek, Granite Creek, and Wendover Creek locations

Location	Stream crossing	Flow rate[a] (L/s)	Drainage area[b] (ha)	Gradient (m/m)	Stream power (W/m)	Culvert length (m)	Culvert type	Culvert diam. (m, inches)	Fill volume (m^3)
Horse Creek	H10	0.6	9.0	0.25	1.4	18	CMP	0.6, 24	305
	H14	0.1	3.4	0.42	0.53	24	CMP	0.6, 24	805
	H16	0.1	10.4	0.19	0.22	17	CMP	0.6, 24	200
Granite Creek	G1	13	400	0.05	6.0	15	CMP	1.5, 60	100
	G2	12	696	0.04	4.7	14	CMP	1.5, 60	350
	G3	9	91	0.10	8.8	12	CMP	0.9, 36	200
Wendover Creek	W1	0.4	19	0.28	1.0	23	Log	NA	460[c]
	W2	0.4	19	0.32	1.1	28	Log	NA	380
	W3	0.4	19	0.34	1.2	22	Log	NA	460[c]
	W4	0.4	19	0.29	1.0	15	Log	NA	460[c]
	W5	0.4	16	0.23	0.90	14	Log	NA	460[c]

[a]Average flow rate during road obliteration activity.
[b]As measured from stream crossing at obliterated road. This is the contributing area associated with monitoring station B.
[c]These values are not consistent with Brown (2002); however, the authors had greater confidence in these estimates.

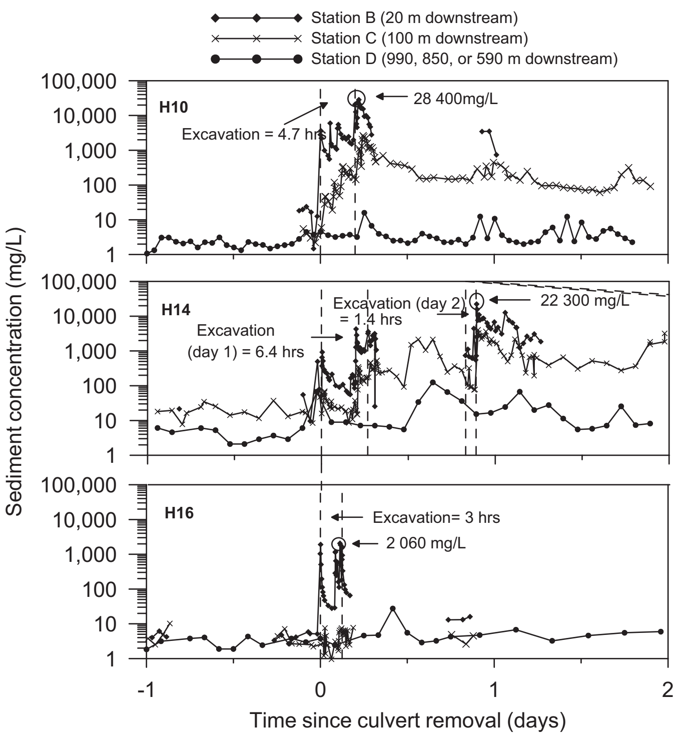

Fig. 4. Sediment concentrations at Horse Creek during culvert removal at 20, 100 m, and mouth of the drainages. Background concentrations at Horse Creek ranged from 5 to 13 mg/L. Dotted lines indicate beginning and end of excavation in stream bed.

were highest at the Granite Creek stream crossings, up to two orders of magnitude higher than flow rates at the Wendover and Horse Creek locations. The stream crossings at the Wendover and Horse Creek study locations were located on midslope roads, had smaller contributing areas, and steeper gradients. Stream power was greatest at the Granite Creek locations due to the larger stream flow rates even though they had the smallest stream gradients. The smaller stream gradients at Granite Creek required shorter culverts, which averaged 13 m in length while the culverts at Horse and Wendover Creeks both averaged 20 m in length. There were larger diameter culverts at Granite Creek.

2.3. Sampling

All obliteration activities took place during low stream flow in late summer. Sampling techniques were similar but not identical at each location.

Stream crossings at Horse Creek were sampled at four locations: A (5–15 m above the culvert inlet), B (20 m downstream from the culvert outlet), C (100 m downstream from the culvert outlet), and D (at the mouth of the tributary). The stations at D were located at distances of 990, 850, and 590 m downstream of the stream crossing at H10, H14, and H16, respectively. Stations A and C had permanent 2-in, 45° WSC trapezoidal flumes installed in 2000. WSC trapezoidal flumes were developed by Washington State College (now Washington State University) for field irrigation use. Their ability to pass sediment and range of flow made them well suited for this application. Depth of water in the flume was recorded by a Campbell Scientific CR10X data logger every half hour. Water depths were converted to flow rates using the rating curve of the WSC flume. A temporary overflow that captured the entire stream was placed at station B for taking grab samples. Sampling at Horse Creek began at least one day prior to culvert removal and continued throughout the culvert removal activity. During culvert removal activities, grab samples were taken every 30 min in 500 mL bottles from flumes at the B and C locations and at the beginning and end of each day's work at the A station. Grab samples were taken from a free overfall, to ensure a well mixed sample. Additional grab samples were taken when excavator activity caused a visible change in sediment concentration, often as frequently as every 5 min. Samples were also taken with an ISCO 3700 sampler every hour at station D for the entire sampling period and at station C during the night.

Stream crossings at Granite Creek and Wendover Creek were sampled at two locations—one upstream and one downstream of the road crossing at distances approximating the "A" and "B" locations at Horse Creek. The samples at Granite Creek were taken with ISCO 3700 samplers and the samples at Wendover Creek were grab samples. Sampling began at least 8 h prior to culvert removal and continued throughout the culvert removal activity. Samples were taken every hour and when sediment concentrations changed visually because of excavator activity.

Turbidity and total sediment were determined using standard methods (American Public Health Association, 1998). Turbidity was determined using a Hach Model 2100N Turbidity Meter. All Horse Creek samples were analyzed for turbidity. At Wendover Creek a relationship between turbidity and concentration was developed (r-square $= 0.84$; mean square error $= 0.132$) from 227 randomly selected samples taken at all Wendover Creek locations. Turbidity was estimated for each sediment concentration sample at Wendover Creek using this relationship. Turbidity was not determined for Granite Creek samples.

2.4. Culvert removal methods

Culvert removal proceeded differently at Horse, Granite, and Wendover Creeks due to variations in management objectives, levels of oversight, operator techniques and stream crossing characteristics. Major differences among the three operations included log stream crossings versus CMP culverts, use of flow diversions, equipment contact with water, in-stream erosion mitigation, and stream structure additions (Table 2).

Wendover Creek had log stream crossings and stream diversion. Removal of log stream crossings was more difficult than removal of CMP culverts. It was difficult to

Table 2
Comparison of culvert removal techniques of Horse Creek, Granite Creek, and Wendover Creek locations

Location	Stream crossing	Culvert removal date/s	Flow diversion	Equipment in live water	In-stream erosion control[a]	Accumulated sediment[b]
Horse Creek	H10	10 Sept 03	No	No	Straw	Yes
	H14	24&25 Aug 04	No	No	Straw	No
	H16	29 Sept 04	No	No	Straw	Yes
Granite Creek	G1	10 Aug 05	No	Yes	No	ND
	G2	7 Sept 05	No	Yes	No	ND
	G3	14 Sept 05	No	Yes	No	ND
Wendover Creek	W1	25 Jul 01	No	Yes	No	ND
	W2	8 Aug 01	Yes	Yes	SB (1)	ND
	W3	14 Aug 01	Yes	Yes	SB (2)	ND
	W4	16&17 Aug 01	Yes	Yes	SB (2)	ND
	W5	22 Aug 01	Yes	Yes	SB (2)	ND

[a]Erosion control material placed in streambed before or during disturbance. Stream crossings at Wendover Creek had 0 or 2 sediment traps noted by straw bale (SB).
[b]Sediment accumulated at inlet of culvert.

separate soil from the logs of the log stream crossing before they were removed. The logs were often decayed, broke apart easily, and were extracted piecemeal by an excavator.

Stream flow at Wendover Creek was diverted at least one day prior to culvert removal. A metal dam with a 100 mm diameter flexible pipe was placed in the stream. The flexible pipe with the stream flowing inside was routed around the working area with the outlet placed downstream of any mitigation. The pipe had to be moved occasionally to prevent the excavator from running over it. No diversion was used at Horse Creek where the intent was to measure the unmitigated impact of culvert removals. No diversion was used at Granite Creek because the stream flow was too large.

Allowing the equipment to contact either water or the saturated stream bed was different among the locations (Table 2). The excavator operator at Horse Creek avoided traversing live water by planning excavator moves so that it was not necessary. At Wendover Creek the operator moved across either the water or saturated soils. At Granite Creek, the operator crossed the water many times to work on both sides of the crossing.

At every location, straw was spread in the stream crossing and on the recountoured road bed. At Wendover Creek, in-stream straw bales were used in various combinations among the five plots (Table 2). At all three locations, rocks were placed in the stream following culvert removal. Grass seed and additional straw were spread over the stream crossing within a few days following culvert removal.

2.5. Stream crossing characteristics and sediment response

Among the Horse, Granite, and Wendover Creek locations, culverts were removed at 11 stream crossings. The sediment response to culvert removal was analyzed and compared based on the physical characteristics of the stream crossings. Sediment yield was calculated for each stream crossing for a 24-h period starting at the time of first impact ($t = 0$), which was approximately the time the first culvert section was removed.

A Spearman's Nonparametric Test (SAS, 2003) was conducted to identify correlations between ranked stream crossing characteristics and sediment responses. Stream crossing characteristics included flow rate, culvert length, drainage area, stream gradient, stream power, and fill volume. Stream responses were sediment yields and peak sediment concentrations. All of the stream response comparisons were based on samples taken 20 m downstream of the outlet of the former culvert (Station B).

3. Results

Eleven culvert removals were monitored. All but one, Horse Creek H14, were carried out during periods without rain. The rain at H14 during culvert removal resulted in a unique response, will be discussed separately, and was not included in statistical analysis. Of the 10 remaining locations, three (Wendover Creek W3, W4, and W5) had two straw bales in the stream. Where appropriate the effect of this mitigation will be noted.

3.1. Sediment concentrations

Sediment concentrations were measured at the outlet of the culvert for all ten locations and are shown in Figs. 4–6. The three Horse Creek locations also had sediment concentrations measured 100 and 900 m below the culvert outlets. Sediment concentrations above the culvert were unchanged by culvert removal and values were less than 10 mg/L.

At the culvert outlet for all ten locations there was an immediate response in sediment concentration beginning as soon as the first culvert section was removed ($t = 0$).

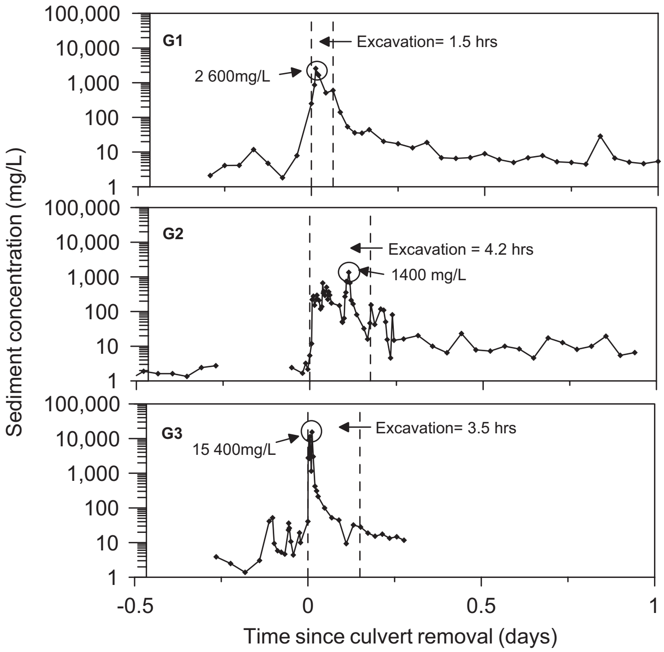

Fig. 5. Sediment concentrations at Granite Creek for station B (20 m downstream) during culvert removal. Background concentrations at Granite Creek ranged from 1 to 7 mg/L. Dotted lines indicate beginning and end of excavation in stream bed.

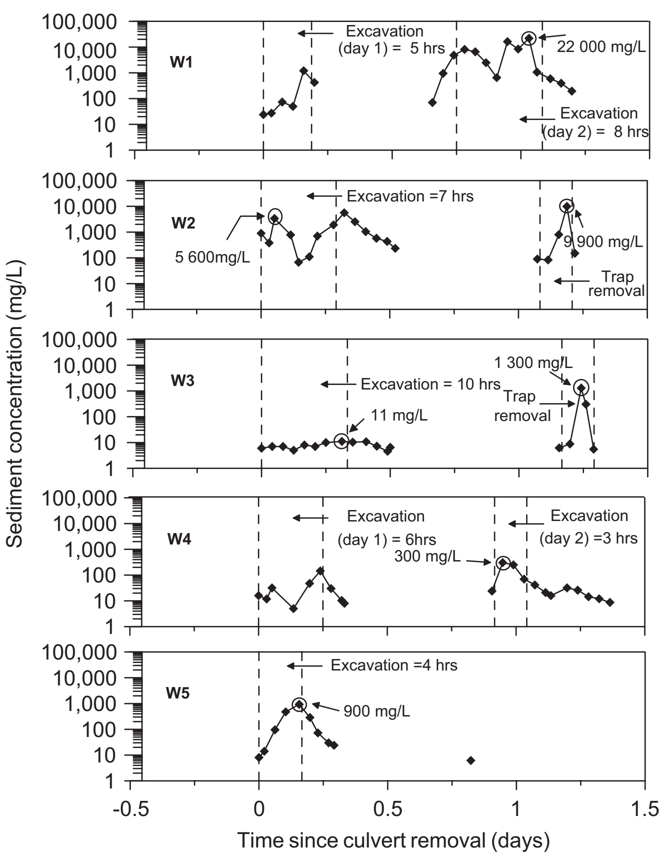

Fig. 6. Sediment concentrations at Wendover Creek for station B (20 m downstream) during culvert removal. Background concentrations at Wendover Creek ranged from 2 to 13 mg/L. Dotted lines indicate beginning and end of excavation in stream bed.

Removal of additional culvert sections, moving the excavator across the stream, or placement of rocks in the stream channel were the activities that caused the peaks in sediment concentration. The highest sediment concentration occurred during culvert removal activities, usually removal of the last culvert section, or within a half-hour after cessation of the days activity. Sediment concentration peaks for locations without mitigation ranged from 28 400 mg/L at H10 to 2060 mg/L at H16. The average for unmitigated locations was 13 000 mg/L. The range for mitigated locations was 900 at W5 to 11 mg/L at W3 with an average of 830 mg/L.

Sediment concentrations were measured 100 m below the culvert outlet at only three locations, all in Horse Creek. Peak sediment concentrations for these locations closely followed sediment concentrations at the culvert outlet, but were typically one order of magnitude less.

Sediment concentrations were measured at the mouth of the tributary, an average of 810 m downstream of the culvert outlet, for the same three Horse Creek locations. Sediment concentrations at these locations did not exceed sediment concentrations above the culvert, i.e., 10 mg/L. Dilution of the sediment from tributaries would decrease sediment concentrations. The tributaries had less flow than the main stream. Neither flows at the mouth nor the tributaries were measured which was an oversight and should be performed on future studies.

3.2. Sediment concentration and duration

The number of hours that sediment concentrations exceeded various cold water fish criteria are shown in Table 3. Three of the locations had sediment concentrations at the culvert outlet that exceeded 6000 mg/L for

Table 3
Duration of sediment concentrations exceeding various coldwater habitat criteria at 20 m downstream (B), 100 m downstream (C), and at the mouth of the stream (D)

Station	Location	Hours exceeding		
		6000 mg/L	500 mg/L	25 mg/L
B	H10	1.7	> 10	> 10.5
B	H14	3.4	> 14	> 14
B	H16	0	1.3	> 3.1
B	G1	0	1.5	6.0
B	G2	0	0.9	5.5
B	G3	0.4	0.5	3.8
B	W1	4.3	12.9	> 18
B	W2	0.5	11.7	> 17
B	W3	0	0.6	1.7
B	W4	0	0	10.3
B	W5	0	1.7	6.3
C	H10	0	5	> 47
C	H14	0	> 18	> 30
C	H16	0	0	0
D	H10	0	0	0
D	H14	0	0	10
D	H16	0	0	0.5

more than 1 h (the juvenile coho salmon avoidance criterion). These locations had no mitigation. At 100 m below the culvert (C station), none of the locations exceeded the juvenile coho salmon avoidance criterion. Similarly, at the mouth of the three streams that were monitored for sediment an average of 810 m downstream, this criterion was not exceeded. The sublethal stress criteria of 500 mg/L for 3 h was exceeded immediately below the culvert outlet at four of the 11 locations. Each of these locations had no mitigation. This criterion was exceeded at two of the three locations 100 m downstream and was never exceeded an average of 810 m downstream. The criterion for decreased feeding in juvenile coho salmon of 25 mg/L for 1 h was always exceeded at the outlet of the culvert, always exceeded 100 m downstream, and was exceeded at one of three locations 850 m downstream. Mitigation did not prevent exceeding the juvenile coho salmon feeding criterion.

3.3. Turbidity and regulatory compliance

Only Horse Creek and Wendover Creek, for a total of seven locations, had turbidity data to compare to Idaho regulatory compliance. All locations exceeded the Idaho allowable turbidity level for the instantaneous criterion (50 NTU above background) immediately below the culvert outlet. Peak turbidity values ranged from nearly 27,000 to 620 NTU. One hundred metre below the culvert outlet two of the three Horse Creek locations (H10 and H14) exceeded the instantaneous criteria. At the tributary mouths, an average of 810 m below the culvert outlet, none of the Horse Creek locations exceeded the instantaneous turbidity criteria. Moving 100 m downstream was not sufficient to meet the instantaneous criteria. However, moving an average of 810 m downstream was sufficient as long as rain sufficient to produce runoff from the bare road did not occur.

3.4. Sediment yields

Sediment yields based on a 24-h monitoring period at the culvert outlet were used to compare sediment delivery from each location (Table 4). Unbalanced ANOVA results indicated there was a statistically significant difference (p-value of 0.079) in sediment yield between the mitigated and the unmitigated locations. The range of sediment yield for the unmitigated locations was 170 kg (H10) to 2.6 kg (H16) with an average of 67 kg. The range for the mitigated locations was 3.1 kg to 0.2 kg, all at Wendover Creek. The average mitigated location sediment production was 1.6 kg.

3.5. Stream crossing characteristics and sediment response

Four stream crossings were not monitored for 24 h following the initiation of culvert removal because the water at the stream crossing appeared to have returned to pre-work sediment concentrations. For these four locations (H16, G2, G3, and W5), sediment concentration values for the 1–17 h from the end of sampling to the full 24-h period were estimated based on the last measured sediment concentration values. All estimated concentrations were less than 16 mg/L.

Table 4
Concentration, turbidity, and sediment yields immediately below culvert outlet

Location	Peak sediment concentration (mg/L)	Instantaneous peak turbidity at station B (20 m downstream) (NTU)	24-h Sediment yield	
			(kg)	(m^3)
Unmitigated locations				
H10	28 400	26 890	171.0	0.21
H14	22 300	25 758	19.2	0.024
H16	2100	2527	2.6	0.033
G1	2600	ND[a]	98.6	0.12
G2	1400	ND[a]	49.2	0.062
G3	15 400	ND[a]	99.0	0.12
W1	22 000	>1000[b]	70.4	0.088
W2	9900	>1000[b]	25.5	0.032
Mitigated locations				
W3	1300	>1000[b]	0.2	0.003
W4	300	616	1.4	0.018
W5	900	>1000[b]	3.1	0.039

[a]Turbidity was not measured at Granite Creek stream crossings.
[b]Sediment concentration relationship determined from Wendover Creek samples could not be applied to samples exceeding 1000 NTU.

The stream characteristics considered were stream flow and volume of the fill above the culvert. All other stream characteristics listed in Table 1 were highly correlated to each other with p-values less than 0.10. The culvert removal sediment responses were 24-h sediment yield, 1-h peak sediment concentration, peak sediment concentration, and the duration of turbidity values above background. One hour peak sediment concentration was the highest sediment concentration that occurred in the first hour after initiation of culvert removal. The peak sediment concentration was the highest sediment concentration during the culvert removal period. The excedence duration corresponded to the number of hours the turbidity levels were above the Idaho standard for cold water aquatic habitat (50 NTU above background). Because there was a statistically significant difference between mitigated and unmitigated locations, the two were analyzed separately. The only significant correlations between stream characteristics and the culvert removal sediment responses were between stream flow and 24-h sediment yield (correlation coefficient = 0.69; p-value = 0.06) and fill volume and duration of turbidity values above the background (correlation coefficient = 0.90; p-value = 0.04). Stream flow explained 48% of the variation in the 24-h sediment yield. As stream flow increased, so did 24-h sediment yield. Higher flows eroded more material. The fill volume at the stream crossing explained 81% of the duration of turbidity values above the background. Larger fills resulted in a longer duration above the turbidity thresholds.

3.6. Culvert removal and storm events

The culvert removal in watershed H14 at Horse Creek was carried out during a period of five consecutive days of rain that totaled 77 mm and provided a unique opportunity to observe the impact of rain on sediment yield during culvert removal on sediment yield. During the night of August 24–25 and the day of August 25 (time since culvert removal of 8–26 h), there were three periods of rain that totaled 60 mm (Fig. 7). The first storm began 8 h after the removal of the first culvert section. The storm lasted 2 h, produced 5 mm of rain with a peak 30-min intensity of 5 mm/h. It was followed half an hour later by a storm that lasted 5 1/2 h, produced 35 mm of rain with two peak 30-min intensities of 15 and 14 mm/h. This storm was the 7th largest in the 44-month period that rainfall was recorded (October 2001–June 2005). The final storm began 4 h after the second one, lasted 8 h, produced 12 mm of rain with a peak 30-minute intensity of 9 mm/h.

Prior to the first storm at the end of the work day on August 24, all sections of the culvert were removed and the stream banks were reshaped. The road had been reshaped on one side of the stream crossing. On the side of the stream crossing where the equipment was working, the road was ripped but not reshaped. No straw was placed on either side of the stream crossing. These activities left a strip of bare soil 134 m long and 10 m wide, the former road, that could contribute runoff and sediment to the stream and two shorter strips 10 m wide and 10 m long, where the fill had been removed, immediately adjacent to the stream.

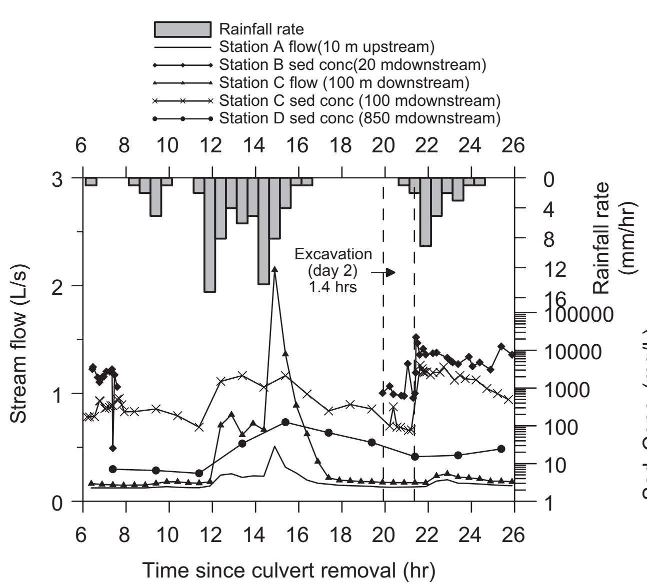

Fig. 7. Rainfall, runoff, and sediment concentration at location H14 during a storm.

The first storm did not change stream flow 26 m above the road (station A) nor 100 m below the former culvert outlet (station C). Sediment concentrations remained unchanged at station C and at the stream mouth 850 m downstream (station D). The former road prism that was disturbed infiltrated the first storm, which implies an infiltration capacity of at least 5 mm/h.

During the second storm, stream flows at station A increased from 0.3 to 0.5 L/s. This increase in stream flow of 66% reflected the response of the undisturbed forest to the storm. Stream flows at station C increased from 0.3 L/s to a peak of 2.2 L/s. This increase in stream flow of 630% reflected the contribution of the 134 m long strip of bare, disturbed road section and an additional 4000 m^2 of forest floor, the additional contributing area between the former road and the C station. The stream returned to its pre-storm flow rate two hours after the cessation of rainfall at the A and C stations. Sediment concentrations at station C increased by an order of magnitude from 100 to 2000 mg/L in response to the second storm. The storm related sediment concentrations were an order of magnitude larger than during culvert removal the previous day (Fig. 4). Sediment concentrations at C were near pre-storm concentrations 2 h later, similar to the A station. At the stream mouth, the sediment concentration peaked by an order of magnitude and was elevated for at least 10 h until the start of the third storm. The former road prism that was disturbed was not able to infiltrate the second storm, which implies an infiltration rate of less than 15 mm/h.

Culvert removal began again the morning of August 25 between the second and third storms, continued for 1.4 h, and ceased just prior to the third storm. The increases in stream flow at the A and C stations from the third storm were minor compared to the stream flow increases from the second storm. Stream flow at the A station increased from 0.14 to 0.20 L/s, a 43% increase. At the C station stream flow increased from 0.17 to 0.26 L/s, a 53% increase.

Sediment concentrations at the culvert outlet reached the highest value caused by excavation activity, a value of 8100 mg/L, immediately prior to the start of the third storm. During the third storm, but in the absence of culvert removal activities, the sediment concentrations reached a maximum of 22 300 mg/L for this crossing. Unlike the other locations, the highest sediment concentration was not during culvert removal activities, but during rain.

Sediment concentration at station C increased from 100 to 4000 mg/L and remained above 1000 mg/L for over 2 h. This increase in sediment concentration was due to the strips of bare soil adjacent to the stream crossing.

3.7. Road construction and culvert installation versus culvert removal

The construction of the road and installation of culverts at Horse Creek was monitored in 1978 and 1979. Sediment generated from road pioneering and building activities was

Table 5
Comparison of sediment yields from culvert installation and culvert removal

Location	Monitoring time (hr)	Average stream flow rate (L/s)	Sediment yield (kg)		
			Station A	Station B	Station C
Removal					
H10	25	0.6	0.31	170	19
H14	30	0.1	0.23	33	10
H16	21	0.1	0.10	2.23	0.05
Construction[a]					
H14 (I)	26	0.6	0.13	12.8	84.1
H16 (I)	12.2	1.1	0.86	9.3	ND
H14 (P)	23	1.1	0.30	ND	96.7

[a]USDA (1981) Pioneering (P) and culvert installation (I).

monitored in watersheds H14 and H16 (USDA, 1981). More sediment reached station C during road pioneering and culvert installation work at H14 and H16 than from the culvert removal operations (Table 5).

4. Discussion

Road obliteration and the associated culvert removals often proceed under the assumption that long-term benefits outweigh short-term consequences. During a 25-year return period rain-on-snow event on the Clearwater National Forest, there were 526 landslide events that occurred on roads similar to those obliterated at Wendover Creek and Horse Creek (McClelland et al., 1999). Their data implied an average of 400 000 kg of sediment were delivered to the stream from each road related landslide. Short term impacts of culvert removals reported in the present study were sediment yields from culvert removals without mitigation ranging from 170 to 2.6 kg. Idaho turbidity and salmon tolerance sediment concentration requirements were exceeded in the stream where the work was conducted but not an average of 810 m downstream. This comparison suggests that sediment loss from culverts is small and short lived and eliminates the risk of culvert plugging and failure.

At Horse Creek much of the sediment yield was observed to come from sand sized material placed for culvert bedding when the culvert was installed. As each culvert section was removed this material formed a cast of the outside of the culvert and became the bed of the stream. Over the course of a day the stream transported this material. Placement of rocks in the stream bed caused transport of the bedding material. The authors observed more scour of this material than bank caving. At Granite Creek there was no bedding material. Most of the sediment was observed to come from the stream bed as it adjusted to the bare soil and recently placed rocks. At Wendover Creek most of the sediment was observed to originate from the stream bed.

The authors observed several 150 mm by 150 mm by 25 mm depositions behind logs at Horse Creek between the B and C stations. There were few such deposits below the C station. A year after the culvert removals the authors did not observe these deposits. At Willow Creek fine material was observed coating rocks in the pool below the culverts, but not a year later.

Horse Creek H10 had elevated sediment concentrations and the highest sediment yield. Sediment had deposited at the culvert inlet for 25 years since the installation of the culvert. When the most upstream section of culvert was removed, the stream began to erode the accumulated sediment and did so for several hours. The authors suggest that this accumulated sediment contributed to the high sediment concentrations and yield. Removal of this sediment might have reduced the duration of the high turbidity and the sediment concentrations.

All of the stream crossings at Wendover Creek were constructed of logs rather than metal pipes. Although the study contained log and metal culvert locations, a comparison between the two was confounded by diversion and mitigation. All Wendover locations had stream diversion. This was physically possible at Horse Creek, but not at Granite Creek due to the higher flows. Comparison of the removal of log stream crossings with stream diversion to the removal of CMP without diversion suggests that sediment yields were consistent among all three locations. Without stream diversion, flows would access loose sediment around the log stream crossings and have increased sediment concentrations and yields, which suggests that stream diversion when log stream crossings are removed is necessary to allow them to have similar sediment yields as the removal of CMP.

Wendover Creek, W3, W4, and W5, were the only locations with mitigation using two straw bales. These mitigation measures were sufficient to reduce the peak sediment concentrations and turbidity as well as their duration. Because of these reductions, the sediment yield was also reduced. A large portion of the sediment yields at the locations with erosion mitigation came from cleaning sediment traps (Fig. 6). Before the straw bale sediment traps were removed, sediment was shoveled by hand from behind the bale onto the hillside. Some of this material was delivered to the stream and resulted in spikes of sediment concentration and minor increases in sediment yields. Improved cleaning techniques could further reduce the sediment load at mitigated locations.

Postponing the culvert removal activities after storms would reduce sediment yields. The total sediment yield at H14, C station was 33 kg of which 11 kg was produced during a rain storm. Postponing the removal activities would have reduced the sediment yield by one-third. While the amount and intensity of storms cannot be anticipated, wet ground and the amount of rain would provide justification to postpone operations. Ensuring ground cover on fresh soil at the end of each day and prior to anticipated rainfall would reduce sediment yield.

This study does not replicate Jakober's conclusion that 95% of construction-related sediment occurs in the first 2 h following diversion removal (Jakober, 2002). At Horse Creek locations where flows were low and sediment concentrations were elevated for several hours after culvert removal, less than 15% of the sediment yield was attained in 2 h. To achieve 95% of the culvert related sediment required 23 h. At the Granite Creek locations where flows were higher, 40–95% of the sediment was attained in 2 h.

5. Conclusions

Culvert removals during road obliteration operations were monitored at 11 locations on national forest lands in Idaho and Washington. Sediment concentration and turbidity were measured for a day prior to removal, during removal, and for at least a day afterwards. Based on this study, a similar culvert removal operation without in-stream mitigation would be expected to (1) have a peak sediment concentration between 28 400 and 2060 mg/L with an expected value of 13 000 mg/L, (2) have a sediment yield of between 170 and 3 kg with an expected value of 67 kg, and (3) exceed the Idaho instantaneous cold water turbidity criterion at the culvert outlet, but not an average of 810 m downstream. For a location with two in-stream straw bales the expectations would be to (1) have a peak sediment concentration of between 1300 and 300 mg/L with an expected value of 830 mg/L, (2) have a sediment yield of between 3 and 0.2 kg with an expected value of 1.6 kg, and (3) exceed the Idaho instantaneous cold water turbidity criteria at the culvert outlet, but not an average of 810 m downstream. Sediment yield from culvert removal was less than from road pioneering and culvert installation.

Sediment concentrations and turbidity dropped with distance from the culvert outlet. Moving 100 m downstream, sediment concentrations were one order of magnitude less than at the culvert outlet and exceeded the Idaho instantaneous turbidity criterion at two of the three locations. Moving 810 m downstream, sediment concentrations returned to near background levels and none of the three locations exceeded the instantaneous turbidity criteria. Only where a storm increased runoff and flushed sediment to the stream mouth was it possible to discern that culvert removal occurred an average of 810 m upstream.

Sediment concentrations also dropped with time. At the culvert outlet only three of the 11 locations (27%) had sediment concentrations that exceeded 6000 mg/L for more than 1 h. Four of the 11 locations (36%) had sediment concentrations that exceeded 500 mg/L for 3 h.

Mitigation consisting of stream diversion and two in-stream straw bales resulted in a statistically significant difference in sediment yield. This level of mitigation is recommended. Mitigation is necessary to keep sediment concentrations from log stream crossing removals comparable to CMP removals.

A series of rainstorms with a total rainfall of 60 mm exacerbated sediment concentrations and sediment yield compared to culvert removal alone. While the impacts of the storm could have been reduced by placement of erosion control material and ceasing operations, neither the sediment concentrations nor yield was inconsistent with other locations in the study. When soils are wet and storms are forecast, extra erosion control material should be placed on the bare soil adjacent to the culvert removal location.

This study is a portion of an on-going assessment of road obliteration impacts. At Horse Creek, one of the primary impacts of roads was increased sediment yields that remained above pre-disturbance levels eight years after road construction. Currently, efforts are underway to determine recent sediment transport between the Horse Creek tributaries of this study and 3–6 km downstream at the confluence of the Main Fork and the East Fork Horse Creek. These data will help to predict whether culvert removals associated with road obliteration will allow streams to return to their pre-development sediment loads. Long-term stream flow rates and sediment deposition measurements will help to identify bedload transport rates and the amount of time required for stream recovery following culvert removals. This information will allow insight on the potential of restoration to return logged and roaded watersheds to pre-road conditions.

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Disclaimer

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