Effects of Timber Harvest on Suspended Sediment Loads in Mica Creek, Idaho

Diana L. Karwan, John A. Gravelle, and Jason A. Hubbart

Abstract: Long-standing concerns exist regarding timber harvest and subsequent sediment impacts on aquatic resources. Intensive studies on contemporary harvest practices remain rare, particularly in the interior Pacific Northwest. To investigate this, a network of seven automated stream monitoring flumes was installed in the Mica Creek Experimental Watershed, in northern Idaho. Beginning in 1991, water samples collected at each flume under both flow-based and stream-stage storm rise conditions have been analyzed for total suspended solids (TSS). This period of record encompasses a pretreatment time interval from 1991 to 1997, and two treatment time intervals: post-road from 1998 to 2001 and post-road/post-harvest from 2001 through 2004. Treated and control catchments were statistically compared using a paired watershed approach for immediate and recovery time intervals corresponding to each treatment activity, road construction and timber harvest. The impacts corresponding to road construction remain difficult to discern. The impacts corresponding to timber harvest differ based on harvest treatment and time period of analysis. Results suggest a correlation between increased sediment loads and clearcutting for a brief period following the harvest. No significant correlation was found in the partial cut watershed. Continued monitoring at these sites is planned to evaluate trends over subsequent years. For. Sci. 53(2):181–188.

Keywords: watershed, paired watershed study, total suspended solids, best management practices, Interior Northwest

Transport of suspended solids plays a fundamental role in biogeochemical cycling within forested watersheds. In excess, suspended sediment degrades aquatic and fish habitat, disrupts hyporheic connection, enhances the transport of sorbed pollutants, and increases treatment costs associated with municipal water withdrawal (Rehg et al. 2005). In forested watersheds, disturbance due to management often correlates with increased suspended sediment yields (Megahan et al. 1995), posing considerable challenges to forest and water quality managers.

Several researchers have quantified annual watershed total suspended solid (TSS) load, often in long-term forested watershed studies (Beschta 1978, Gomi et al. 2005). In particular, studies in the western United States and Canada have shown increased erosion and altered stream sediment loads coincide with the modified hydrologic regime following road construction and timber harvest (Troendle and King 1985, Lewis 1998, Megahan et al. 1995). More recent work indicates the effectiveness of roadside erosion control measures and riparian buffer retention at reducing the impact of harvest activities on annual sediment load (Megahan et al. 2001, MacDonald et al. 2003). Studies of current practices often lack long-term monitoring, distinct road and harvest treatment periods, and an extensive calibration period which encompasses interannual hydrologic variability.

TSS particles are composed of both organic and inorganic material, each with multiple hillslope and channel origins. In a forested watershed, eroded material from harvested areas, unharvested areas, and roads can be carried in concentrated overland flow to the stream channel. Studies in the northern Rocky Mountains indicate that roads contribute more sediment per area than other hillslope sources, depending on their location and design (Megahan and King 2004, Wemple et al. 2001). Suspended solids also originate from within the stream channel, such as stream organic matter, bank erosion, and scoured channel materials (Bonniwell et al. 1999).

This study examined the impacts of road construction and timber harvest on the load of total suspended solids in a forested watershed in northern Idaho. Road construction and timber harvest treatments were carried out in accordance with current best management practices (BMP) and Idaho Forest Practices Act guidelines. Differences in suspended loads were examined following road construction and also following timber harvest using two different treatments, clearcut and partial cut. Patterns in total volatile solids (TVS) load, peak TSS concentrations, and downstream cumulative effects were also investigated.

Methods

Study Site

This study was conducted in the Mica Creek Experimental Watershed, a 27 km^2 watershed in northern Idaho (Figure 1). The watershed elevation ranges from 1,000 to 1,600 meters above mean sea level with hillslopes of 15 to 30%

Diana L. Karwan, Yale School of Forestry and Environmental Studies, 210 Prospect Street, New Haven, CT 06511—Phone: (203) 906-6137; Fax: (203) 436-4404; diana.karwan@yale.edu. John A. Gravelle, University of Idaho, Environmental Science Program, PO Box 441133, Moscow, ID 83844-1133—grav1954@uidaho.edu. Jason A. Hubbart, Department of Forest Resources, College of Natural Resources, University of Idaho, Moscow, ID 83844-1133; hubb8662@uidaho.edu.

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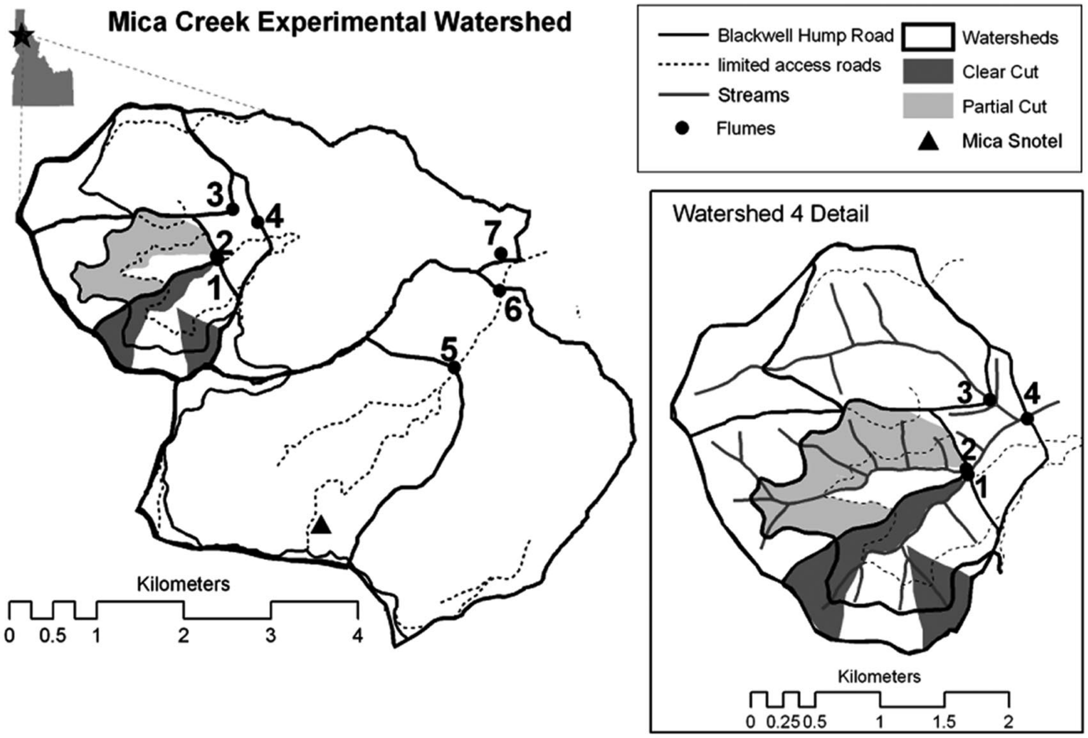

Figure 1. Location of Mica Creek Watershed in northern Idaho, USA with flumes and roads.

and stream gradients of 5 to 20%. Its geology is predominantly gneiss/quartzite parent material, overlain by silty soils. Although dominated by V-shaped valleys and moderately sloped hillsides, landslide activity and mass failure potential within the study area are low.

The average air temperature is approximately 5°C, with summer high temperatures reaching 30°C and winter temperatures reaching −20°C. On average, the watershed receives 1,450 mm of precipitation, over half of which falls as snow between the months of November and March. The remainder of the precipitation often occurs in the spring and fall as low- to medium-intensity rain. Occasionally, summer thunderstorms deliver localized, high-intensity rainfall.

The study area was last harvested in its entirety, with post-harvest burning, in the 1920s and early 1930s. The second-growth forest is composed of dense, naturally regenerated, even-aged stands now approximately 65 years old with approximately 300 trees per acre. Stands average 75% crown closure. Major species include grand fir (*Abies grandis*), Douglas-fir (*Pseudotsuga menziesii*), western redcedar (*Thuja plicata*), and western larch (*Larix occidentalis*) with some western white pine (*Pinus monticola*), lodgepole pine (*Pinus contorta*), Engelmann spruce (*Picea engelmanni*), and subalpine fir (*Abies bifolia*).

Before the study, the primary road in Mica Creek (the Blackwell Hump road in Fig. 1) followed railroad lines associated with historic harvest operations. Many of the older secondary roads were overgrown with tree regeneration and other vegetation. All roads in the study area were native-surfaced, with gravel excavated within the watershed, during data collection. Before harvest treatment, most roads in the watershed received little to no traffic, but the Blackwell Hump road did receive moderate to heavy seasonal use by recreational vehicle traffic.

To compare both direct and cumulative effects, the study area was divided into a series of nested subwatersheds. A paired-watershed experiment was established at the highest nested level, in watersheds of second-order streams. Watersheds 1, 2, and 3 (Figure 1) are respectively 1.4 km^2, 1.77 km^2, and 2.27 km^2 in size. Downstream watersheds 4 and 5 are 5.97 km^2 and 6.67 km^2, respectively. In 1990, a new road was constructed for access to West Fork Mica Creek for installation and maintenance of the monitoring flumes. This road was built to have minimal hydrologic impact, with no stream crossings, an outsloped road design, grass seeding immediately after construction, and drainage features installed to divert surface flow into a filter windrow. The effects of this road, if any, are fully accounted for in the pretreatment calibration.

The 1997 road treatment consisted of existing road improvement and new road construction. In September 1997, the existing Blackwell Hump road transecting watersheds 1, 2, and 3 underwent improvements to allow heavy truck traffic. The study design entailed grading and slightly widening the road surface, and removing trees and brush from the cut and fill slopes. Since watershed 3 was designed to be the control catchment for treatment activities in watersheds 1 and 2, care was given to minimize any road construction impact. The existing Blackwell Hump road made up the only road-stream crossing in watershed 3. This occurred in the headwater portion of the watershed. In an effort to make road sediment contribution negligible, the following steps were taken to keep the integrity of the control watershed intact: (1) the crossing was covered with rock for 30.5 m (100 ft) on either side of the stream crossing to minimize erosion from the road, (2) rolling water bars and relief culverts were installed to divert surface runoff away from the crossing, and (3) straw bales were placed near the road-stream crossing to trap any remaining sediment particles.

New harvest access roads were also constructed through watersheds 1 and 2. Their design specifications accommodate the heavy truck traffic associated with timber harvest. Road construction BMP included an outsloped road design, installation of relief culverts near stream crossings, and creation of filter windrows along the road fillslope. Right-of-way timber had to be removed during construction, with residual slash serving as material for filter windrows along the fillslope. Steel culverts were installed at all stream crossings. Relief culverts near stream crossings minimized the amount of road connected directly to the stream. Watersheds 1 and 2 each have more road-stream crossings than watershed 3, with 6 and 10, respectively. In addition, a larger fraction of their watershed area is roads—2.8%, 2.5%, and 1.3% for watersheds 1, 2, and 3, respectively.

Timber harvesting and heavy road use by logging trucks occurred in 2001. The harvest treatments were as follows: watershed 1: 50% clearcut in 2001, broadcast-burned and replanted within the last week of May 2003; watershed 2: 50% partial cut in the fall of 2001, with the final 10% of log processing and hauling in early summer of 2002; watershed 3: control watershed, no harvest. Watershed 1 experienced a commercial clearcut on 50% of the watershed area. Watershed 2 underwent a partial cut in which half the canopy was removed in 50% of the watershed.

Timber harvest followed the Idaho Forest Practice Act guidelines, including 22.86 m (75 ft) stream protection zones (SPZs) on each side of fish-bearing (Class I) streams. The inner 50 ft is an equipment exclusion zone where no ground-based skidding machinery is allowed. Timber harvesting is allowed in Class I SPZs, but 75% percent of existing shade must be retained. Along non-fish-bearing (Class II) streams, harvesting equipment was excluded from entering within 9.14 m (30 ft) of definable stream channels and any cut trees were felled away from the stream; however, there were no tree retention requirements. In the clearcut and partial cut units, line skidding was used on slopes in the watershed exceeding approximately 20%, while tractor skidding was used on the lower gradient slopes. On all skid trails, drainage features, such as water bars, were installed for erosion control at the end of the harvest period.

Clearcut units were broadcast-burned for site preparation before their replanting in the spring of 2003. Fire lines were used to exclude fire from the riparian areas on both perennial and ephemeral channels. The fire was low-intensity, only burned small fuels, and left only occasional patches of exposed mineral soils. Larger residual logs and sticks appeared to have trapped most to all of this bare soil from reaching the stream channels. Ocular surveys were taken near the stream channels in 2003 and 2004, and no sediment plumes originating from the hillslopes were found to have reached the stream channels. Hydrophobic soils did not develop anywhere within the watershed.

Data Collection and Analysis

Stream monitoring flumes were installed at seven locations in the Mica Creek Watershed in 1991 (Figure 1). By May 1991, flumes 1, 2, and 3 were fully operational and regularly collecting measurements of stream discharge and total suspended solids (TSS). Measurements at flumes 4 and 5 began in September 1991. Stream discharge was measured with a nitrogen bubbler-type pressure transducer at 30-min intervals and recorded with Campbell Scientific CR10 dataloggers. TSS samples were collected at variable time intervals using ISCO 3700 automatic samplers based on one of two criteria: (1) cumulative stream discharge from the time of the previous TSS sample, and (2) stage change increasing above a predetermined threshold from the previous 30 min. When one of the two criteria was satisfied, the datalogger sent an electronic pulse to the ISCO, and a sample was collected. With the variable time interval sampling schedule in place, cumulative stream discharge caused flumes to sample as much as several times each day during high flow and as little as several times per month during base flow periods. The stage change criteria produced samples at any time it was satisfied, regardless of flow regime. During road construction in September and October 1997, sampling frequency was deliberately increased to monitor construction and culvert installation effects. At other times, additional TSS samples were collected on regularly timed intervals to more closely monitor sediment concentration patterns before, during, and after short rainstorm events. Samples were collected year-round with the exception of winter conditions, due to ice in the stream channel and frozen sample lines. Water samples were analyzed for TSS and total volatile solids (TVS) using gravimetric methods of the US Fish and Wildlife Service for nonfilterable residue and outlined in Standard Methods for the Examination of Water and Wastewater (American Water Works Association 1989). All TSS samples taken more recently than July 1998 were analyzed for TVS. Before the summer of 1998, TVS was not consistently analyzed.

Time series data were compiled for all measured TSS values from May 1991 through September 2004 for flumes 1, 2, and 3 and from September 1991 for flumes 4 and 5. Time series data for TVS values were compiled from August 1998 through September 2004 for flumes 1–5. Unmeasured TSS data points were interpolated for each 30-min time step using linear relationships between measured data points. Linear interpolation was used for the simplicity of analysis and the reasonable range of results. This technique was chosen over linear regression due to the lack of correlation between TSS and discharge measurements. Furthermore, linear interpolation has a history of use in suspended sediment records (Benaman and Shoemaker 2005). Sediment loads were calculated for 30-min intervals based on measured and interpolated TSS concentrations and measured discharge. For this analysis, values of TSS and discharge were assumed constant over 30-min intervals. Although this may not be accurate during very intense storms, as illustrated by Nistor and Church (2005), we feel it was reasonable when evaluating the overall 14-year sediment record.

Thirty-minute sediment loads were aggregated to monthly values to analyze sediment load at a time interval over which multiple TSS measurements were taken, yet sensitive to individual hydrologic events. During initial data analysis, we observed a difference in suspended loads immediately following road construction and timber harvest, including the first postmanagement activity spring runoff period, and future loads. To account for this observation and better characterize treatment effects, the time periods after each treatment were evaluated in two parts: immediately following disturbance, including the first spring runoff period, and subsequent monitoring of recovery. Monthly loads were then compared across watersheds for five time intervals: (1) pretreatment, (2) immediate post-road construction, (3) recovery post-road construction, (4) immediate post-harvest, and (5) recovery post-harvest (Table 1).

Trends in the relationship between treatment and control watersheds were statistically examined for each of the time intervals described above. Analysis of covariance (ANCOVA) models were developed for each treatment-control watershed pair. Within the ANCOVA models, contrasts were used to test for statistical significance between sediment loads during different analysis periods at a significance level of $\alpha = 0.05$. SAS version 9.1 was used for statistical analysis as well as linear interpolation between measured sediment concentrations. In addition to the load comparison, trends were also examined in the individual TSS and TVS measurements. Statistical comparisons were performed to determine whether loads changed with watershed treatment as well as a more qualitative analysis to characterize the peak TSS measurements, in particular, when they occur with regard to the peak monthly sediment loads.

Results

Annual TSS loads averaged 4,500 kg km^{-2} in the upper watersheds, with variation between watersheds and years (Table 2). Annual suspended load correlated well with annual watershed precipitation (Figure 2). Transport of suspended solids did not occur evenly within a single year. Monthly TSS loads from watersheds 1, 2, and 3 ranged from 0.4 kg km^{-2} to above 10,000 kg km^{-2}, with a maximum in the spring months and minimum in the winter and late summer months similar to intra-annual trends in water yield, as discussed in Hubbart and others (2007). The seasonal pattern also held true downstream in watersheds 4 and 5, with higher annual loads averaging 6,100 kg km^{-2} and monthly loads between 5 kg km^{-2} and 9,600 kg km^{-2}.

Similar road construction in both watersheds did not result in statistically significant ($\alpha = 0.05$) impacts on monthly sediment loads in either treated watershed during the immediate or recovery time intervals (Table 1). Downstream of their confluence, no significant differences ($\alpha = 0.05$) were found between suspended loads in the downstream treated watershed 4 and its control, watershed 5 (Table 1).

Harvest treatment resulted in a significant and immediate impact on monthly sediment loads only in the clearcut watershed (Table 1). As hypothesized, the result was highly significant immediately following treatment in the clearcut watershed 1 ($P = 0.00011$) and marginal in the partial cut watershed relative to the control watershed ($P = 0.081$). Total sediment load from watershed 1 over the immediate harvest interval exceeded predicted load by 152% (6,791 kg km^{-2}); however, individual monthly loads varied around this amount. The largest increases in percentage and magnitude occurred during snowmelt months, namely April 2002 (560%, 2,958 kg km^{-2}) and May 2002 (171%, 3,394 kg km^{-2}). October 2001 and January 2002 experienced a large percentage increase above predicted loads, but the actual increase was very small in comparison with snowmelt months.

Neither watershed 1 nor watershed 2 showed a statistical difference in suspended load during the recovery time interval when compared with calibration loads ($P = 0.2336$ and $P = 0.1739$, respectively). The broadcast burn in the clearcut watershed took place in May 2003, during the recovery time interval. It was of low intensity, did not produce hydrophobic soils, and was excluded from riparian areas. Suspended load did not increase during or following the burn in the clearcut watershed.

Volatile sediment load was not altered significantly in either treated watershed between any of the three analysis time intervals for which it was calculated (recovery road, immediate harvest, recovery harvest). The downstream watershed 4 also lacked significant difference in volatile sediment load when compared with its control, watershed 5.

Although we have presented simple statistical models, the level of statistical significance is notably higher for the change in suspended load following the clearcut harvest treatment than the partial cut or road treatment (Table 2). The harvest treatment corresponds to change in suspended load that is highly significant ($P = 0.0011$), while the partial

Table 1. Temporal definition of analysis intervals and ANCOVA *P* values from monthly suspended load comparisons in three Mica Creek treated watersheds

Interval	Analysis period	Duration (date)	Duration (months)	Watershed 1 ANCOVA *P* value	Watershed 2 ANCOVA *P* value	Watershed 4 ANCOVA *P* value
1	Pre-treatment	May 1, 1991–August 31, 1997	76			
2	Immediate post-road construction	Sept. 1, 1997–June 30, 1998	10	0.0820	0.3369	0.6909
3	Recovery post-road construction	July 1, 1998–June 30, 2001	36	0.9381	0.4400	0.7383
4	Immediate post-harvest	July 1, 2001–June 30, 2002	12	**0.0011**	0.0809	0.2838
5	Recovery post-harvest	July 1, 2002–Sept. 30, 2004	27	0.2336	0.1739	0.3358

The *P* value in bold indicates significance at $\alpha = 0.05$.

Table 2. Annual suspended sediment loads in Mica Creek watersheds

Water year	Treatment interval	Watershed 1 (kg km^{-2})	Watershed 2 (kg km^{-2})	Watershed 3 (kg km^{-2})
1992	calibration	2,493.1	1,797.8	1,949.6
1993	calibration	4,007.7	7,932.2	3,696.5
1994	calibration	2,725.3	2,510.3	1,953.9
1995	calibration	5,341.9	3,344.3	3,523.8
1996	calibration	7,959.5	5,474.4	7,468.6
1997	calibration	10,449.5	14,730.9	7,724.9
1998	immediate road	7,146.2	2,723.1	2,444.4
1999	recovery road	5,188.5	7,196.4	3,122.8
2000	recovery road	2,918.3	3,809.3	2,380.3
2001	recovery road	1,963.8	2,375.8	1,258.3
2002	immediate harvest	11,550.9	7,648.9	3,511.7
2003	recovery harvest	3,090.2	2,666.6	1,138.0
2004	recovery harvest	4,325.3	3,684.8	1,433.1

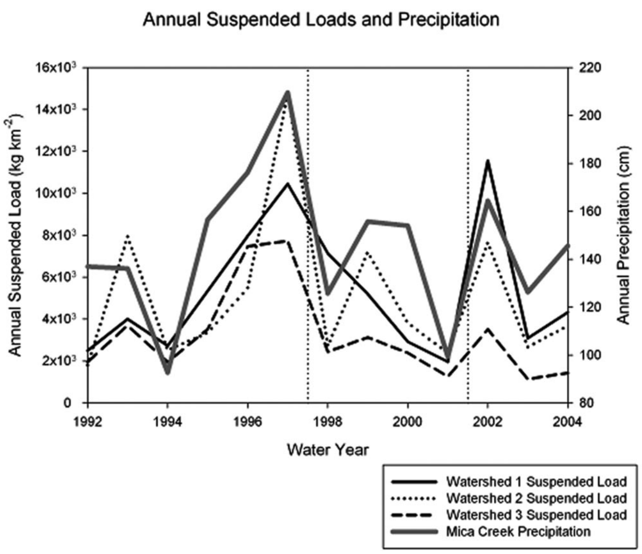

Figure 2. Annual suspended sediment loads at flumes 1, 2, and 3 shown with annual precipitation. Dashed vertical lines show treatments—road construction in the fall of 1997 and timber harvest in the summer and fall of 2001.

cut treatment corresponds to a change in suspended load that is not significant at the $\alpha = 0.05$ ($P = 0.081$). The road treatment in watershed 1 shows similar results to the partial cut treatment ($P = 0.082$). This supports in situ observations that timber harvest impact, with the combination of 50% clearcut treatment along with intensive road use by logging equipment, provided greater suspended loading potential than road construction alone.

A thorough water yield analysis is presented by Hubbart and others (2007). Unlike the sediment loads, annual water yields did not differ in significance ($\alpha = 0.05$) between the immediate and recovery posttreatment intervals. Road treatments were shown to have a significant effect on water yield in watershed 1 only, while harvesting corresponded to a significant increase in both watersheds 1 and 2. Downstream, no significant increase in water yield followed road construction in watershed 4, but a significant increase in water yield followed harvest in both the immediate and recovery time intervals. A significant sediment load increase occurred in the presence of a significant water yield increase, though there is not necessarily a significant sediment increase for all times there was a significant water yield increase.

Discussion

Double mass plots illustrate the increase in cumulative sediment load following harvest in the treated watersheds (Figure 3). A difference in the immediate and prolonged cumulative sediment load can be seen in watershed 1 following both treatments (Figure 3), although only the increased suspended load immediately following clearcut harvest was statistically significant. All post-road and recovery post-harvest suspended loads in watershed 1 were not statistically significant, as were all posttreatment loads in watershed 2. No differences were detected at the downstream watersheds 4 and 5 (Figure 3). Although this was expected for the downstream watersheds and the harvest treatment in the upper watersheds, it was not expected for the road treatment, as the road treatment was similar in both watersheds 1 and 2. This disparity in results could be attributed to underlying differences in the watersheds themselves, the difference in road access and traffic patterns, or the sampling design and data analysis. As in all paired watershed designs, watersheds 1, 2, and 3 have slight physical differences between them and localized thunderstorm events can produce different hydrologic consequences at the event time scale. For example, a rainfall event on May 20, 1998 delivered nearly 25 mm (1 in.) of rain at the USDA Natural Resource Conservation Service climate station (SNOTEL station) within the watershed. Spatially distributed data, such as rainfall recorded at a subset of the flumes, indicated this localized thunderstorm cell did not affect the entire study area equally. For example, 37 mm (1.46 in.) of rain was recorded at flume 1. Streamflow and TSS measurements increased, but not equally among watersheds: watershed 1 experienced peak TSS concentrations quadruple that of watersheds 2 and 3 (Figure 4). Because this event took place in the first spring following road construction, it could explain the discrepancy in results in the immediate post-road treatment.

Within the road treatment, comparable road distances and stream crossings on both first- and second-order streams were constructed in watersheds 1 and 2. The predominant difference between the watersheds may relate to

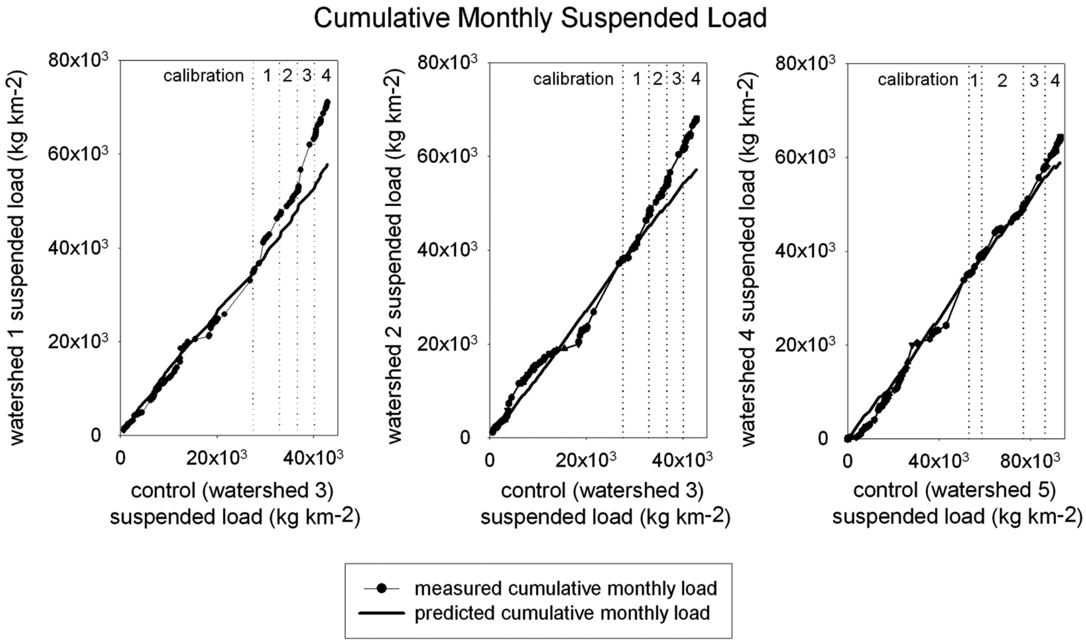

Figure 3. Double mass plots illustrating the relationship between cumulative monthly suspended loads in treated watersheds and their respective control watershed. Dashed vertical lines indicate different analysis time interval calibration or pretreatment. (1) Immediate road, (2) recovery road, (3) immediate harvest, (4) recovery harvest.

the traffic patterns; the newly constructed road connects to the existing road network in such a way that one must drive through watershed 1 to gain access to watershed 2. This likely caused watershed 1 to receive more traffic than watershed 2 during right-of-way timber removal in the road construction phase and timber removal during the harvest treatments. Previous studies illustrated traffic patterns influence sediment delivery more than the physical presence of the road (Reid and Dunne 1984). Traffic patterns and their impacts on sediment transport mechanisms may help explain at least a portion of the observed results in the Mica Creek Watershed.

The results of watershed 1, but not watershed 2, agree with previous work that suggests a disproportional amount of erosion occurs during and immediately after road construction and intensive use due, in part, to the increased road traffic (Megahan et al. 2001, Reid and Dunne 1984). These previous studies assume that the suspended sediment originates from the hillslope, more specifically, the roads. While this finding has been corroborated by other Interior West watershed studies (Megahan and King 2004), it may not be the case in Mica Creek, particularly following harvest. The highly significant sediment yield response to timber harvest in watershed 1 may not be attributed solely to hillslope or road erosion. Although the average TSS concentration in watershed 1 increased from 10.1 mg l^{-1} during the calibration period to 13.3 mg l^{-1} immediately following harvest, this increase was not statistically significant ($\alpha = 0.05$). During the immediate post-harvest time interval in watershed 1, average sediment concentration increased by 31% and suspended sediment yield more than doubled. This increase in average TSS concentration would not have been enough to produce the highly significant increase in suspended load without a concurrent increase in water yield. Moore and Wondzell (2005) reviewed other Northwest watersheds and also identified coincident increases in sediment yield and water yield. Increased streamflow leads to increased shear stress within the stream channel, thereby providing the force necessary to erode the stream channel or to resuspend sediments previously deposited in the channel and carry sediment downstream. This explanation assumes the majority of the sediment originates within the channel itself or was delivered to the channel before the monitoring period. Sediment source tracing provides a topic for future research.

The volatile sediment records do not indicate a substantial change in the percentage of total volatile sediments in treated watersheds relative to control during any of the analysis periods. Throughout the duration of the study, the proportion of volatile sediment remains near or above 40% and often exceeds 60%. This suggests a sizeable fraction of the suspended sediment is organic material, which is less likely to originate from the road and is likely mobilized from within the stream channel or riparian areas. The volatile sediment loads did not differ significantly for the time intervals over which they were calculated (1998–2004).

According to the suspended sediment record, the clearcut harvest treatment can be distinguished from the broadcast burn that followed it. Unlike the clearcut treatment, the broadcast burns did not have an impact on the TSS concentrations or load during May 2003, the month in which the burn occurred. Measured concentrations following the burn did not exceed 2 mg l^{-1} km^{-2}, which are equivalent to background concentrations measured in watershed 1 before any management activity. The lack of increased TSS concentration and load following the burn could be a result of its low burn severity and the lack of subsequent intense rainfall.

The variable time-flow sampling in place at Mica Creek makes pure time-series analysis more difficult. Variable

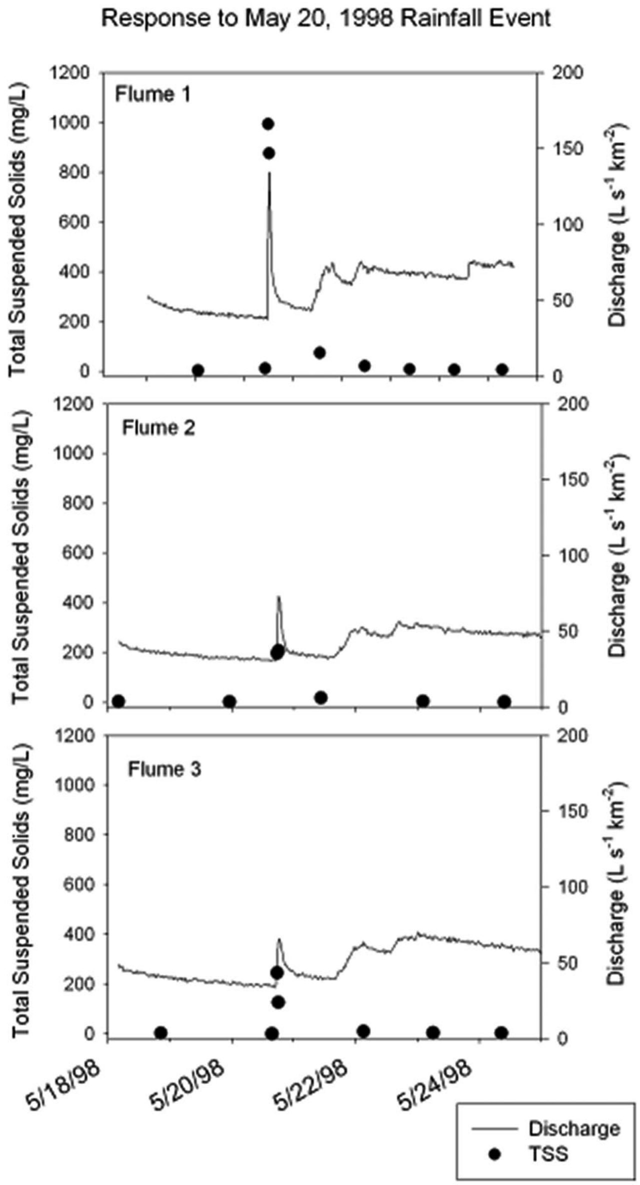

Figure 4. Discharge and TSS measurements from May 18 to May 24, 1998. On May 20, 1998, a rain event measured 25 mm (1 in.) at the Mica Creek SNOTEL site and produced differing hydrologic consequences at flumes 1, 2, and 3.

time-flow sampling was chosen as a compromise between dealing with the site remoteness and capturing both a comprehensive and intensive storm sampling data set. The majority of the samples were taken proportional to flow (sample criterion 1) using the variable time-flow sampling method. This concentrates samples during times of higher streamflow even though sediment concentrations do not correlate directly to measurements of streamflow. While this may lead to concern that the sampling design could have yielded a sample set that is not representative of the pattern in TSS concentration by either under- or over-sampling the peak concentrations, further examination at individual storm events indicates that TSS concentration is much more dependent on precipitation intensity and temporal location within a storm hydrograph rather than a simple measurement of streamflow. For example, during a June 1992 storm, TSS measurements changed incongruently with discharge measurements, with a high peak early in the storm receding to pre-storm conditions more slowly than discharge. The lack of direct correlation between TSS measurements and discharge has been found elsewhere (Nistor and Church 2005). A focused examination of peak TSS measurements over the entire monitoring period indicated a correlation to rainfall events. The highest 1% of individual, instantaneous TSS measurements, not the monthly aggregate values, from watersheds 1, 2, and 3 took place on a total of 23 days, 20 of which received rain in the absence of snow cover.

While monthly sediment loads track water discharge and yield, the instantaneous TSS concentration measurements peak at different times. Individual peaks in measured TSS tend to occur with intense rainfall events. The intense rainfall could provide the energy necessary to activate an additional mechanism and/or source of sediment to the stream. The dislodgment of soil particles at the soil surface by energy imparted to the surface by falling raindrops is a primary agent of erosion, particularly on soils with sparse vegetative cover. For example, intense rainfall on the road surface could exceed an intensity threshold necessary to dislodge surface particles, thereby providing a pulse of road sediment associated with intense rainfall. Alternately, a small but abrupt increase in stream discharge associated with the storm could scour channel banks, thereby increasing suspended sediment within the channel. While the majority of peak TSS measurements are associated with intense rainfall, not all rainfall events yield high TSS measurements. Further investigation is necessary to establish the precise sources of suspended sediment in the Mica Creek Watershed and the conditions that produce peak sediment concentrations.

The suspended sediment patterns identified in Mica Creek differ from previous studies at other experimental forests in the western United States. Within the Pacific Northwest, the annual suspended loads before harvest in Mica Creek were at least an order of magnitude less than those reported in the Alsea Watershed in Oregon's Coast Range (Beschta 1978). The same pattern holds when post-harvest data from Mica Creek and the Alsea studies are compared. Mica Creek's annual suspended sediment loads compare better to those in the Fraser Experimental Forest for the pretreatment and long-term recovery time intervals (Alexander et al. 1985). However, the patterns emerging from individual hydrologic events differ from those in the Fraser watersheds. While the highest TSS concentration records at Mica Creek happen in conjunction with rainfall in the absence of snow, Fraser's only significant hydrologic impacts occur with spring snowmelt (Troendle and King 1985). Although the patterns in annual sediment loads observed at Mica Creek more closely resemble other interior, mountainous watersheds, they do not completely match any other previous paired watershed studies. Such differences may be attributed to differing geology, the continental/maritime climate regime, and/or the use of current best management practices and timber harvest methods.

Road construction and timber harvest, carried out with current best management practices, resulted in variable impacts on stream sediment loads. Road construction, including improvement of existing roads, did not produce a significant difference in monthly suspended sediment load relative to a control watershed. Clearcut harvesting did produce a significantly higher suspended load immediately following the harvest. However, within one year following the harvest, sediment load became statistically indistinguishable from that of the pretreatment calibration period. Monthly sediment loads did not differ between the partial cut watershed and its control, nor did the loads further downstream differ from their control. Overall, the 14 years of data used in this study showed variability in suspended sediment load, tracking precipitation and discharge, and the effectiveness of best management practices to maintain suspended sediment load within the range of natural variability. The difference seen from clearcut harvesting could be attributed to the increase in discharge and water yield associated with the clearcut, thereby carrying more sediment to the monitoring flume. Even this elevated level returned to the background range of variability shortly after the harvest. Continued sampling will monitor these patterns into the future. These results have particular relevance regionally, as they demonstrate the effectiveness of best management practices, as well as differences between the streams of the interior Northwest and the more often studied headwater streams of the coastal Pacific Northwest.

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