Effects of Logging Road Removal on Suspended Sediment Loads and Turbidity[1]

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Abstract

Poorly designed and unmaintained logging roads pose serious risks to aquatic ecosystems through sediment delivery from stream crossing failures and landslides. Redwood National Park (RNP) in northern coastal California has been implementing a restoration program for almost four decades, focused primarily on removing (decommissioning) abandoned logging roads on former commercial timberlands that were acquired by expansion of RNP onto large areas of cutover timberlands in 1978. Road decommissioning reduces sediment threats over the long term, however there are shorter-term impacts arising from ground disturbance that occurs when roads are removed. To better understand the magnitude and duration of sediment impacts, RNP conducted both onsite and offsite monitoring in a small watershed, Lost Man Creek, where nearly all legacy logging roads were removed from 2000 through 2010. Onsite turbidity increases were initially high at some locations, but diminished rapidly with time. Annual maximum peak discharge explained most of the variability in suspended sediment loads and turbidity at offsite gaging stations. Although restoration-driven increases in offsite turbidity and suspended sediment loads were likely detectable for part of the study period, legacy logging and natural sediment sources, triggered by larger storms, tended to confound the ability to quantify offsite effects with confidence. The year-to-year variability in road treatment intensity was high, and 2 consecutive years with high treatment intensity (2007 and 2008) likely caused concomitant, albeit brief, increases in suspended sediment loads. Since completion of restoration in 2010, sediment loads and turbidity have diminished rapidly despite the occurrence of the largest peak discharges of the study period, suggesting that the elimination of potential legacy sediment sources far outweighs sediment increases arising from road decommissioning.

Keywords: logging roads, road decommissioning, turbidity, suspended sediment.

Introduction

For almost 4 decades, Redwood National Park (RNP) has conducted an erosion control and prevention program to reduce long-term sediment delivery from logging roads into streams in the Redwood Creek basin, northern California. Lands acquired in the 1978 park expansion included logged over timberlands and an extensive network of poorly designed and often failing logging roads and skid trails that posed risks to the aquatic ecosystem, including threatened species such as coho salmon (*Oncorhynchus kisutch*). The goal of the ongoing program is to reduce logging road-related erosion and sedimentation of streams and thereby speed the recovery of the watershed and native ecosystems toward pre-disturbance conditions.

Logging road removal (decommissioning) in RNP typically consists of outsloping unstable road benches and excavating stream crossing fill material, thereby restoring channels close to their original courses, and placing excavated fill in stable locations to mimic pre-disturbance topography and drainage patterns. Preventing erosion and turbidity increases following road removal is physically impossible, but minimizing erosion and the resultant effects on downstream water quality is an

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important goal of the program. To that end, RNP has monitored post-decommissioning erosion and sediment responses using a variety of methods.

Studies of erosional responses to road removal work (Bloom 1998, Flanagan et al. 2012, Keppler et al. 2007; Klein 1984, 2008; Madej 2001, PWA 2005) and over 25 years of observations in RNP indicate that: 1) erosional responses are skewed, i.e., most sites will likely generate low to moderate erosion while a few generate relatively large volumes of erosion, 2) the greatest erosional responses occur within the first several years following road removal, and greatly diminish with time, 3) although crossing site conditions (e.g., slope steepness, contributing drainage area) exert strong control on post-decommissioning erosional responses, inexperience and/or inattentiveness on the part of those conducting road decommissioning can have a large effect as well (PWA 2005).

This paper departs from most previous work by emphasizing downstream (offsite) water quality response (continuous turbidity and suspended sediment loads), whereas most previous studies focused on onsite responses. Over an 11-year period (2000 to 2010), nearly all unmaintained legacy logging roads were decommissioned in Lost Man Creek (fig. 1). Post-road removal monitoring began in 2003, 2 years into the restoration project. The objectives of the monitoring program were to: 1) assess the effects of road removal on downstream turbidity and suspended sediment loads, and 2) quantify onsite erosion and turbidity responses from crossing removal.

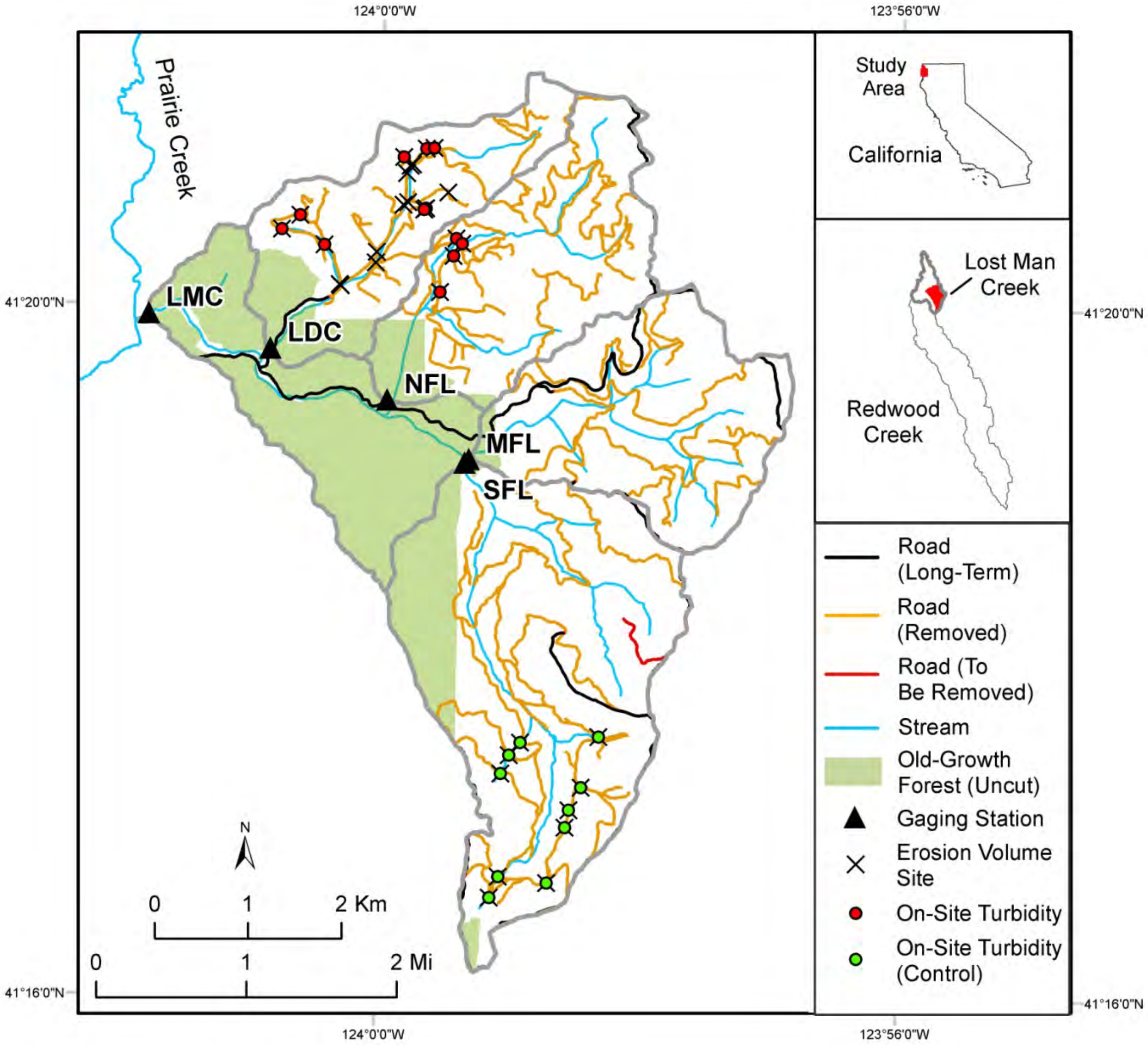

Figure 1—Lost Man Creek watershed and surrounding areas.

Study Area

Lost Man Creek is a major tributary to Prairie Creek which joins with Redwood Creek about 10 km (6 mi) upstream from its mouth at the Pacific Ocean (fig. 1). Mean annual precipitation in the study area is 1750 mm (69 inches). Coastal northern California has a Mediterranean climate, with most precipitation falling as rain from December through May. Streamflow varies greatly from wet to dry season with summer lows flows approaching zero and winter storm peaks commonly varying from 0.5 to 2 cms/km^2 (46 to 183 cfs/mi^2). Prairie Creek is recognized for its vital role in sustaining salmonid runs in Redwood Creek. Recent fish trapping in Prairie Creek and Redwood Creek just upstream from the mouth of Prairie Creek revealed that 1+ juvenile coho salmon production from Prairie Creek was "exponentially higher" than that of the larger Redwood Creek watershed area upstream (M. Sparkman, California Dept. of Fish and Wildlife, 2012, personal communication). A main objective of road decommissioning in Lost Man Creek is to sustain and fortify its role as a stronghold for regionally-declining salmonid species.

Like the vast majority of timberlands in north coastal California, most of Lost Man Creek was heavily logged and roaded during the 1950s to early 1970s, prior to implementation of state forest practice rules in 1975. Forest land use during this period consisted of largely unregulated road and landing construction and large areas were clearcut with intense ground disturbance from tractor yarding. Lost Man Creek experienced severe erosion and sediment delivery to streams during the 1955, 1964, and later floods and was highly disturbed by 1978, when the entire watershed became parkland.

Table 1 gives physical characteristics of Lost Man Creek and its sub-watersheds along with two other Prairie Creek sites used as controls. Figure 1 shows the Lost Man Creek watershed hydrography, stream gaging stations that provided data for this study, and logging roads removed between 2000 and 2010. A significant portion (about one-third) of Lost Man Creek is underlain by the Prairie Creek Formation (*PPpc*), lying mostly in the upper slopes of the tributary watersheds. Almost all of the rest of the watershed is underlain by the Coherent Unit of Lacks Creek (Franciscan Assemblage, *Kjfl*). Cashman et al. (1995) describe the *PPpc* as composed of 'weakly consolidated shallow marine and alluvial sediments' and the *Kjfl* as composed of interbedded sandstone and mudstone, with sandstone being the dominant rock type. Anecdotal observations indicate that hillslopes within some areas of the *PPpc* are particularly susceptible to surface erosion following disturbance due to low cohesion and coarse fragment content. Shallow landsliding is commonly associated with hillslopes underlain by rocks of the *Kjfl* (Cashman et al. 1995).

Table 1—Attributes of study watersheds (Lost Man Creek is located at the treatment basin outlet, thus data listed for this site integrates all upstream attributes)

Watershed (station code)	Drainage area (km^2)	Mean basin slope (%)	Basin relief (m)	%Prairie Creek Fm. (PPpc)	Area in old growth (%)	Pre-treatment road density (km/km^2)[a]
Lost Man Creek watershed treatment sites						
Larry Damm Creek (LDC)	4.8	43	475	70	19	2.8
North Fork Lost Man Creek (NFL)	5.7	44	471	48	10	3.6
Middle Fork Lost Man Creek (MFL)	5.8	45	518	38	2	2.7
South Fork Lost Man Creek (SFL)	10.6	43	731	6	14	2.6
Interfluves	4.7	41	431	15	96	1.0
Lost Man Creek at Hatchery (LMC)[b]	31.5	43	731	32	24	2.6
Control sites						
Little Lost Man Creek (LLM)	9.3	43	679	5	89	0.1
Prairie Creek above Boyes (PAB)	20.2	46	442	90	93	0.2

[a] Unpaved roads only; [b] Integrates all of the above sites.

Two long term stream gaging stations located elsewhere in Prairie Creek were used as controls for this study (LLM and PAB, table 1). PAB is underlain almost exclusively by *PPpc* and drains less steep terrain than Lost Man Creek and LLM is dominated by *Kjfl*. Both are predominantly pristine, old-growth redwood (*Sequoia sempervirens*(D. Don) Endl.) forest (table 1), but have minor influences from past road building.

Road Decommissioning History

Table 2 lists annual lengths of roads decommissioned and numbers of stream crossings excavated in Lost Man Creek by subwatershed. Approximately 95 km (59 mi) of logging haul roads existed in the watershed prior any treatments, with a total of 81.4 km (50 mi) removed over the life of the project, reducing road density in the watershed from about 3 to 0.4 km/km^2 (4.8 to 0.7 mi/mi^2). The remaining roads consist of a service road traversing the longitudinal axis of the watershed along the main channel and a short segment slated for future removal with low risk of failure (fig. 1).

Table 2—Road decommissioning history in Lost Man Creek and tributaries as of fall 2010 when work was completed (both lengths (km) of roads treated and number of stream crossings excavated (# exc.) are shown)

Year	LDC		MFL		NFL		SFL		LMC	
	# exc.	km	# exc.	km	# exc.	km	# exc.	km	# exc.	km
2000	0	0	7	3.6	18	6.6	18	3.9	43	14
2001	0	0	5	2.7	11	2.2	1	0.5	17	5.4
2002	23	4.7	0	0	16	4.7	0	0	39	9.4
2003	35	7.6	0	0	0	0	0	0	35	7.6
2004	3	0.8	0	0	0	0	0	0	3	0.8
2005	0	0	0	0	0	0	0	0	0	0
2006	0	0	0	0	0	0	23	1.8	23	1.8
2007	0	0.4	3	2.0	4	1.6	38	14	45	18.3
2008	0	0	13	4.5	23	7.1	16	3.8	52	15
2009	0	0	2	2.4	0	0	5	2.8	7	5.2
2010	0	0	2	1.5	0	0	3	1.9	5	3.4
Total	61	13.5	32	16.7	72	22.2	104	29.0	269	81.4

Figure 2 shows examples of road decommissioning at RNP and ground conditions following completion of the work. Despite often heavy mulching of bare soil and placement of large volumes of coarse woody debris in channels after earth-moving, erosion and sediment delivery to channels and downstream elevation of turbidity and suspended sediment loads is inevitable.

Figure 2—A. stream crossing being excavated; B. outsloped road with heavy mulching; C. recently excavated stream crossing with large woody debris placed within the exhumed channel; D. excavated stream crossing with a relatively large volume of woody debris added.

Methods

This study included both onsite monitoring at selected stream crossing excavation sites and offsite monitoring at a network of continuous stream gaging stations. Onsite monitoring occurred for 2 consecutive years (2002 and 2003) and was discontinued after erosional activity appeared to have ceased and it became clear that the results were consistent with other studies. Offsite monitoring was performed the entire length of this study, however, the four gaging stations at the sub-watershed scale were discontinued in 2011, 1 year after road removal work was completed. Offsite monitoring now consists of just the station at the watershed outlet (LMC, fig. 1), which will be continued indefinitely.

Onsite Monitoring at Excavated Stream Crossings

Onsite monitoring at crossings excavated in 2002 consisted of both turbidity sampling during three winter rainfall events during the first wet season, and estimates of eroded volumes after the first and second wet seasons, following excavation. The sites were selected to represent the range of crossing excavation sizes in Lost Man Creek, with additional consideration for the relative ease and safety of winter storm access. Eroded volumes were measured at 20 selected stream crossing excavations (fig. 1) following each of two consecutive wet seasons (2003 and 2004) by measuring erosional voids and tallying volumes.

A subset (n = 12) of the crossing excavations monitored for erosion volumes were selected for storm turbidity sampling in Larry Damm Creek (LDC) and North Fork Lost Man Creek (NFL) (fig. 1). Upstream and downstream stormwater samples were collected at these sites and turbidity was measured upon return to the lab. In addition, 11 untreated stream crossings in South Fork Lost Man Creek (SFL, fig. 1) were similarly monitored to compare with the excavated crossings, bringing the total number of onsite turbidity sampling locations to 23.

Offsite Monitoring

Offsite monitoring consisted of collecting continuous stage and turbidity data at gaging stations at the mouths of four main tributaries to Lost Man Creek and at the mouth of Lost Man Creek (fig. 1). Two of the sites (LMC and SFL, fig. 1) were set up as recording stations in water year 2003 (WY2003; a water year extends from October 1 from one year until September 30 of the following year) with automated equipment (data logger, stage sensor, and turbidity sensor) recording at 10-minute intervals. LMC is just upstream of its confluence with Prairie Creek, while SFL is the tributary basin farthest upstream from the confluence with Prairie Creek (fig. 1). The three tributaries between SFL and LMC (LDC, NFL, and MFL, fig. 1) were manual sampling sites in WY2003, but equipment for monitoring continuous turbidity and stage was installed in WY2004.

Suspended sediment samples at the Lost Man Creek stations were taken manually during storm periods at the five gaging stations. Most samples were depth- and width-integrated samples (DIS), but occasional point samples were also taken at a representative spot on the gaging section. Sampling at the control sites (PAB and LLM, table 1) was accomplished using an automated pumping sampler, with sampling increasing in frequency at higher turbidities, a method known as turbidity threshold sampling, or TTS (Lewis and Eads 2008).

Suspended sediment samples were transported to the laboratory soon after collection and analyzed for suspended sediment concentration (SSC) using filtration methods. Depending on the rainfall and storm magnitudes for a given year, 20 to 50 samples were taken at each gaging station and processed for suspended sediment concentration (SSC); more during the wetter years. Stage readings and discharge measurements were also taken manually, and discharge rating curves were constructed to convert recorded stage data to discharge. Equations for converting recorded turbidity to suspended sediment concentration (SSC) were developed by regressing SSC from the samples against simultaneous turbidity measurements. SSC to turbidity fits were always strong, with R-squared values always greater than 0.90 and often above 0.95. The regression equations were used to estimate 10-minute SSC values that were then multiplied by the associated 10-minute discharge volume to compute incremental suspended load. Annual suspended sediment loads were computed by summing 10-minute loads for each stormflow season.

As with flow duration analyses, the continuous turbidity data were sorted from largest to smallest and the percentages of time each value was equaled or exceeded (i.e., exceedence probability) were computed for December through May each year. The turbidity level exceeded 10 percent of the time provides a single value summarizing conditions for the entire season.

Results

Annual Maximum Peak Discharge

Instantaneous peak discharges and their recurrence intervals at LMC are shown in fig. 3. The largest annual maximum, about a 14-year event, occurred in WY2013. The three largest peaks occurred within the latter 4 years of the study (WY2003 to 2016).

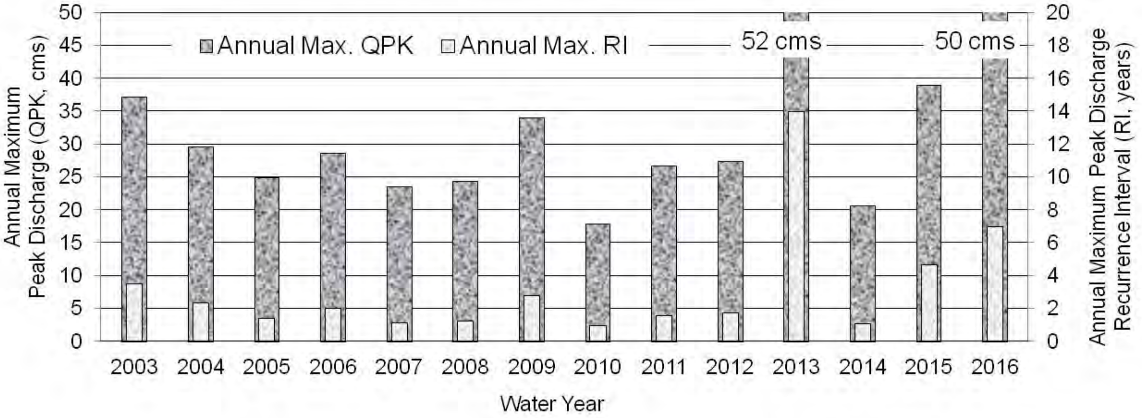

Figure 3—Annual maximum peak discharges and recurrence intervals at the Lost Man Creek (LMC) gaging station for 2003 to 2016.

Onsite Results

Figure 4 shows upstream-to-downstream turbidity increases during three storm samplings in the following rainy season at a subset of stream crossings excavated in 2002. Downstream turbidity ranged to over 5000 NTU during the first storm sampled (Dec. 14, 2002). Percent increases in turbidity through the crossings ranged from zero to nearly 2000 percent, with half the sites exhibiting increases exceeding 500 percent and the other half not exceeding 200 percent. Because no information existed for comparing hydrograph position (rising limb, peak, falling limb), an important context for the turbidity observations is lacking. Nonetheless, there was a strong trend for the most turbid sites (LDC2 to NFL7, fig. 4) to exhibit rapidly declining turbidity responses as the winter progressed, with the exception of Site 1 for which the largest turbidity response occurred in the second storm (Dec. 16, 2002). Turbidities at intact stream crossings exhibited virtually no increases from upstream to downstream.

Cumulative eroded volumes from excavated stream crossings after 2 years following treatment were distributed similar to many previous studies, with a strong skew toward low volumes and a small number with high eroded volumes. Figure 5 plots these results in order of decreasing eroded volumes. Mean for the sample was 19 m^3 (25 yd^3) ranging from zero (four sites) to 204 m^3 (267 yd^3).

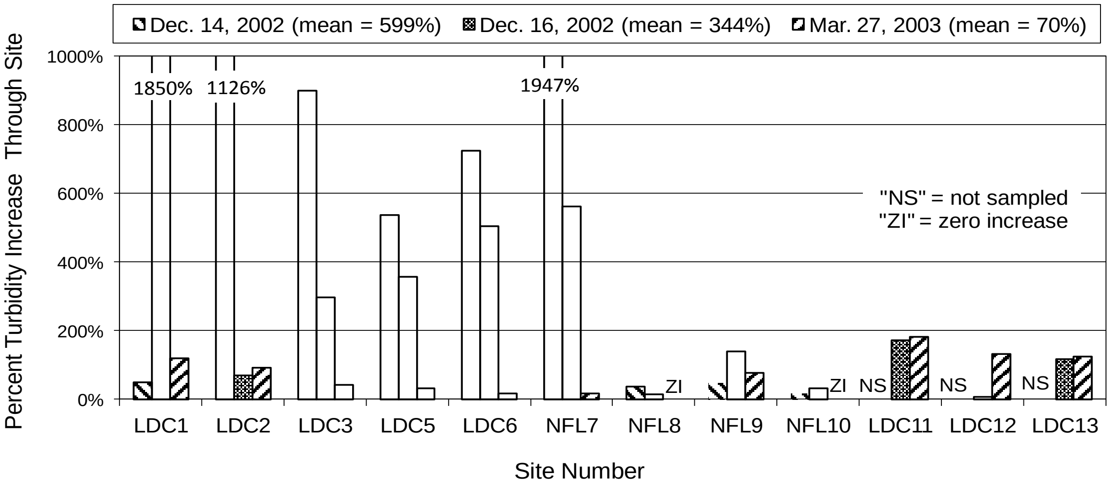

Figure 4—Turbidity increases through selected stream crossing excavations in Lost Man Creek, WY2003.

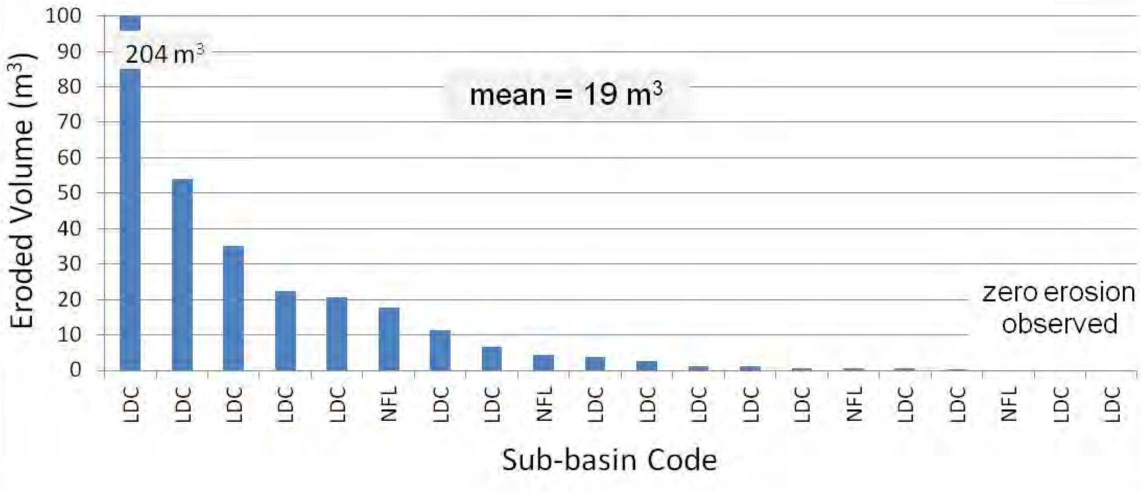

Figure 5—Eroded volumes at stream crossing excavations through selected stream crossing excavations in Lost Man Creek sub-basins (NFL = North Fork Lost Man Creek; LDC = Larry Damm Creek; note that site numbers denote sub-basin and correspond to the same numbering in fig. 4, above).

Offsite Results

Winter stormflow turbidity varied widely among sites and years (table 3). Turbidities at the 10 percent exceedence level were far lower at the control sites (PAB and LLM) than at any of the Lost Man Creek treatment sites, often by an order of magnitude or more, owing to the near pristine conditions of the contributing watershed. Turbidities among the Lost Man Creek sites were inconsistent from year to year, partly because of legacy logging and natural erosion processes triggered by larger storms.

Table 3—10 percent turbidity exceedence for Lost Man Creek and control sites (PAB and LLM), WY2003-16

		Turbidity at the 10 percent exceedance level					
WY	**SFL**	**MFL**	**NFL**	**LDC**	**LMC**	**PAB**	**LLM**
2003	37	---[a]	---	---	58	---	8
2004	14	21	19	25	19	4	4
2005	19	19	15	14	18	2	16
2006	30	25	28	19	33	4	8
2007	35	19	21	6	22	3	8
2008	29	16	15	12	21	1	8
2009	55	17	21	13	27	1	9
2010	28	16	18	10	16	1	7
2011	30	18	18	17	19	1	8
2012	---	---	---	---	20	1	9
2013	---	---	---	---	16	1	7
2014	---	---	---	---	11	4	6
2015	---	---	---	---	17	5	6
2016	---	---	---	---	35	7	9
Mean	31	19	19	15	24	3	8

[a] = Station not operated.

Annual suspended sediment loads per unit area for WY2003 to 2016 are shown in table 4 for the Lost Man Creek sites and the two control sites (PAB and LLM). The downstream-most site in Lost Man Creek (LMC) integrates all loads originating upstream, including MFL, NFL, LDC, SFL, and approximately 2.8 km^2 (1.1 mi^2) of ungaged interfluve areas. WY2003 and 2006 stand out as exceptionally high sediment load years, and at least some of the reason for this is explained by non-road related erosion and sediment delivery. In WY2002, the year before the first year of data collection, a debris torrent contributed high sediment volumes to Larry Damm Creek, which accounted for the high load downstream at LMC. A field reconnaissance in fall 2006 (near the end of WY2006) revealed the likely reason for the elevated LMC loads. Several hundred meters upstream of LMC, a concrete dam spillway was blocked by a large log causing the channel to breach the earthen walls and flow around the structure. Large volumes of sediment formerly composing the channel banks and bed and flood terraces had recently eroded as the channel diverted around the dam, and the suspendable (finer) portion of eroded sediment would have elevated WY2006 loads at LMC. After the effects of these two events subsided, annual loads were more consistent with peak discharges, although the relationship shifted over time (fig. 6).

Table 4—Suspended sediment loads (tonnes/km^2) for Lost Man Creek sites and control sites (PAB and LLM), WY2003-2016

				Annual suspended sediment load tonnes/km^2)			
WY	**SFL**	**MFL**	**NFL**	**LDC**	**LMC**	**PAB**	**LLM**
2003	59	---[a]	---	---	349	---	81
2004	140	78	76	163	117	9	25
2005	81	73	43	75	83	4	6
2006	112	127	135	104	186	12	29
2007	63	84	49	40	61	6	35
2008	99	38	64	38	86	4	9
2009	208	69	74	55	150	11	44
2010	53	33	35	16	36	3	9
2011	118	30	61	31	58	6	15
2012	---	---	---	---	93	7	22
2013	---	---	---	---	104	11	23
2014	---	---	---	---	32	9	14
2015	---	---	---	---	73	18	13
2016	---	---	---	---	129	8	32
Mean	104	67	67	65	111	8	25

[a] = Station not operated.

Figure 6 shows a time series of annual results from LMC for the study period. The influence of the 2002 debris torrent is clear, with WY2003 sediment loads far above all other years despite the relatively moderate peak discharge. Except for WY2009, there is no discernible direct relationship between treatment intensity (road length treated) and either loads or turbidity. The high load in WY2009 relative to peak discharge is coincident with a high rate of road treatment in the two prior seasons. An apparent temporal shift in the sediment load response to peak discharge is suggested in fig. 6 with loads declining relative to peak discharge in the latter years (WY2010 to 2016), a time when 96 percent of the planned road removal work had been completed and many potential sediment sources had been treated.

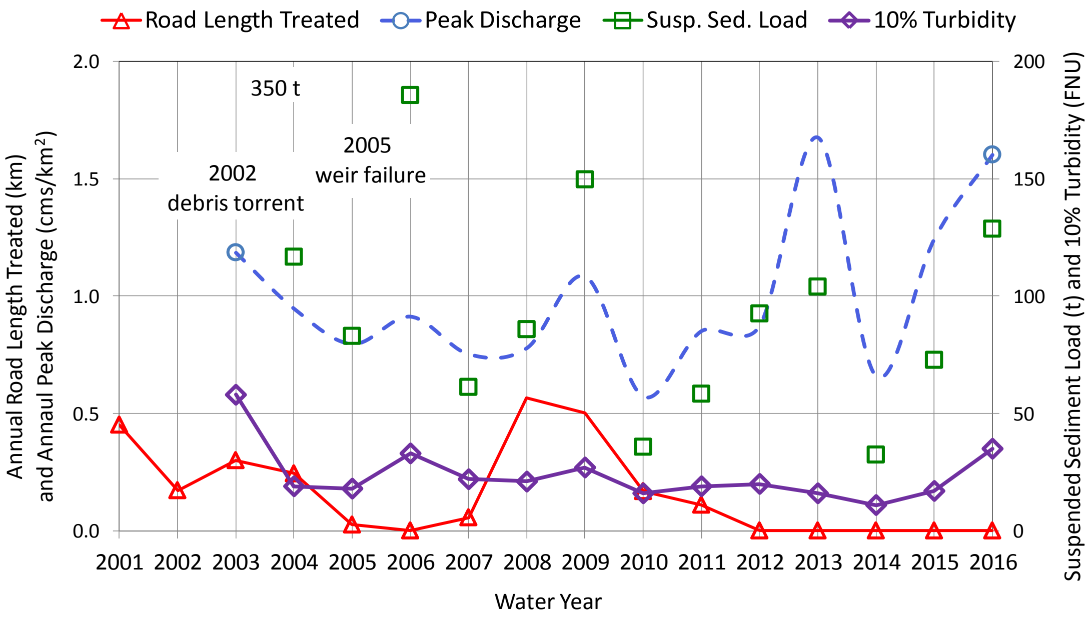

Figure 6—Upstream road lengths treated, peak discharges, sediment loads and turbidities for the Lost Man Creek watershed (LMC site), WY2001 to 20016.

Figure 7 plots these same data as scattergrams (with WY2003 and WY2006 omitted because of the two anomalous erosion events described above), partitioning the load and peak discharge data pairs into two groups (2003 to 2009 and 2010 to 2016). Simple linear regression on each period gave a line slope for the earlier period of over three times that of the later period, with both regressions yielding fairly high R-squared values. Road length treated (RLT) had no discernible relationship with loads.

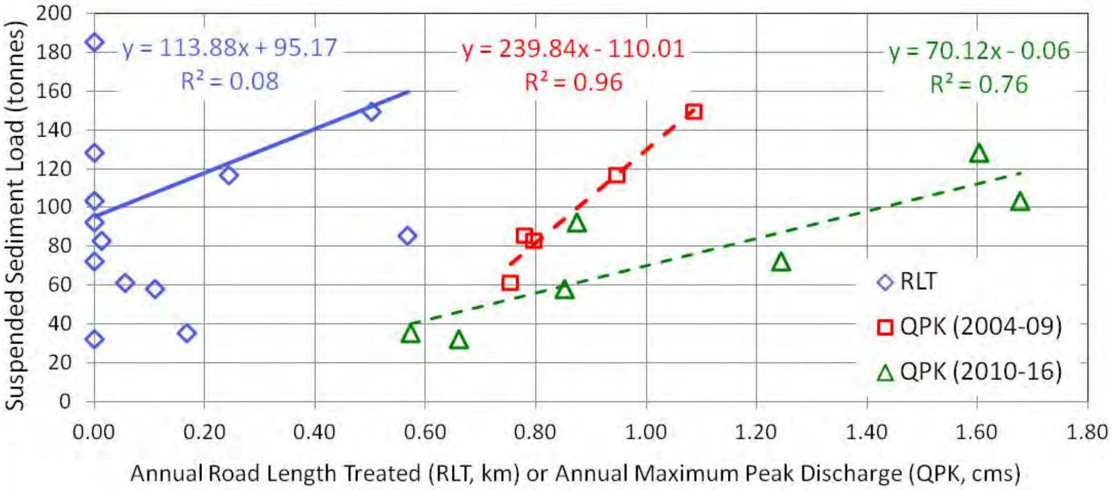

Figure 7—Road lengths treated (RLT) and peak discharges (QPK) versus annual loads for the Lost Man Creek watershed (LMC site), WY2004 to 2016.

Because of the differing geology, use of the control streams' (PAB and LLM) suspended sediment loads presented some difficulty: the treatment watersheds have mixtures of two geologic types with differing erodabilities in varying ratios (see table 1) while the controls are each dominated by one of the two (*Kjfl* in LLM and *PPpc* in PAB) and, as shown in table 4, had very different suspended sediment loads, with PAB far lower than LLM. Several analyses were performed to attempt to use data from the control sites to condition data from the treatment sites for examining road treatment effects. In one case, control site suspended sediment loads were subtracted from treatment site loads; in another, treatment site loads were divided by control site loads. The means of the loads for the two control sites also were compared with the treatment sites, but none of these analyses suggested a treatment effect.

Conclusions

Road treatments in Lost Man Creek were both extensive and, at times, intensive during the 11-year span of the restoration project. Erosion events unrelated to road treatments during the early years of this study (2003 and 2006) overshadowed and obscured any potential treatment effects during the subsequent high flow seasons. Later, peak discharge events exerted the dominant control over annual suspended sediment loads, with a shift in the relationship occurring after 2009 when loads declined relative to peak flows. By that time 96 percent of the roads planned for treatment had been treated, decreasing the number of unstable legacy sediment sources. Although some legacy and natural sediment delivery sources were likely still active in those years, a reduction in loads relative to peak discharges would be an expected outcome from road decommissioning. Thus, rather than providing clear evidence of water quality degradation because of disturbances associated with road treatment, this study's strongest conclusion is an apparent large improvement in water quality indicated by diminishing suspended sediment loads despite the three largest peak discharges of the study period occurring in within the most recent 4 years of the study (WY2013, 2015 and 2016).

In addition to the 2003 debris torrent in LDC and the dam failure upstream of LMC in 2006, failures on yet-to-be-treated roads (both road bench and crossing failures) were observed by RNP staff while driving and hiking areas of the Lost Man Creek watershed during the study period. Although not a complete inventory or systematic sampling of erosional features, it became clear that legacy sediment sources were a large, if unquantified, factor contributing to suspended sediment loads. In retrospect, confining monitoring to smaller areas in which complete inventories or sediment sources could have been made may have allowed a more complete understanding of the relative contribution of road decommissioning to suspended sediment loads in a legacy watershed.

The most definitive results of this study were those measured onsite, which showed sometimes very large erosional and turbidity responses at selected stream crossing excavations. Turbidity increased greatly passing through some stream crossing excavations during the first few storms of the season immediately following treatment and then dropped rapidly in later storms. The causes for differences among the monitored excavation sites are unknown, but the channel and side slope steepness, degree of mulching, and volume of coarse wood addition likely played key roles. Eroded volumes at excavated crossings exhibited the skew typical of previous work; most sites had low erosional responses, but a few were relatively large. Although intact stream crossings had essentially zero effect on stream turbidity during the brief 'snapshot' of monitoring done for this study, un-excavated stream crossings on unmaintained forest roads will eventually fail and degrade downstream water quality and habitat.

The relatively long duration of monitoring in Lost Man Creek (14 years as of this writing) allowed a sufficient length of time for the two opposing responses to road removal (increased sediment from ground disturbance, decreasing sediment from elimination of legacy sources) to play out. The gaging station at the watershed outlet (LMC, fig. 1) will be continued indefinitely and provide data to allow evaluation of the longer term effects of road removal. Future suspended sediment loads in Lost Man Creek are expected to continue to decline relative to peak discharges, punctuated by larger storms triggering episodic legacy and background erosion events and increasingly infrequent post-treatment adjustments from stream crossing excavation sites. A return to pristine conditions will not occur for decades, if not centuries, being dependent on a return to old growth forest conditions and exhaustion of erosion features from legacy logging. Nonetheless, road removal in this watershed has shortened that recovery time by permanently reducing the threat to the aquatic system from road-related legacy sediment impacts.

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