

# EROSION AND TURBIDITY MONITORING IN LOST MAN CREEK, REDWOOD NATIONAL AND STATE PARKS, WATER YEARS 2003-2011

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## BACKGROUND AND STUDY OBJECTIVES

Redwood National and State Parks (RNSP) conducts an erosion control and prevention program to reduce long-term sediment yield from lands in the Redwood Creek basin, northern California. The extensive network of abandoned and failing logging roads in the basin poses risks to water quality of streams and dependent, federally listed threatened species. RNSP initiated a watershed restoration program in 1978, following expansion of the park (PL 95-250). The goal of the program is to reduce erosion and sedimentation of streams, and to restore the natural ecosystems to conditions similar to what would have existed without the logging disturbance. The program addresses roads both within the park as well as those outside the park through cooperative agreements with landowners.

Typically, road removal in RNSP consists of excavating stream crossing fill material, restoring channels close to their original configuration, and placing excavated fill in stable locations to best mimic pre-disturbance topography and drainage patterns. Although completely preventing erosion following road removal is physically impossible, minimizing erosion and the resultant effects on downstream turbidity and suspended sediment concentrations (SSC) is an important goal of the program that reduces detrimental effects of excessive and chronic turbidity on federally listed threatened salmonid species (Sigler and others, 1984; Newcombe and MacDonald, 1991; Henley and others, 2000; Klein and others, 2003).

Studies of erosional responses to road removal work (Klein, 1984; Weaver and Sonnevill, 1984; Weaver et al, 1987; Madej, 2001), and over 25 years of observations of road removal work in RNSP indicate that: 1) erosional responses are skewed, i.e., most sites will likely experience modest erosion with a few experiencing relatively large volumes of erosion, 2) the greatest erosional responses occur within the first several years following road removal, and greatly diminish with time as vegetation grows on excavation sideslopes and channels find stable grades and armor themselves with rock and woody debris, and 3) that causative factors cannot always be anticipated or mitigated. Since the inception of the program in 1978, the parks have employed adaptive management to modify restoration treatments to best meet National Park Service management policies and minimize post-treatment erosional responses.

Road removal began in Lost Man Creek in 2000 and was completed in 2009. Before work began, RNSP developed a Biological Assessment (BA) in consultation with NOAA Fisheries to evaluate the possible effects of road removal on listed salmonids in Lost Man Creek, a tributary to Prairie Creek, and ultimately Redwood Creek. The BA included a proposal to undertake a post-restoration monitoring program which began in 2003. The objectives of the monitoring program were: 1) to assess the effects of the road removal program on downstream turbidity and suspended sediment concentrations; and 2) to provide adaptive management feedback for refining erosion control methods and application criteria aimed at minimizing downstream effects and maximizing cost-effectiveness. In response, NOAA Fisheries issued a Biological Opinion (BO) supporting the restoration work with terms and conditions requiring (among other things) the proposed monitoring program. The monitoring program was concluded in 2011, one year after road removal work was completed. This final report presents results for the entire monitoring period: WY2003-2011.

## STUDY AREA

### Lost Man Creek

Lost Man Creek is a major tributary to Prairie Creek, composing about one-third of total basin area (see Fig. 1), and was the main focus of road removal activities in RNSP for a decade. Table 1 gives physical characteristics of sub-basins in Lost Man Creek along with other Prairie Creek sites used as controls. Figure 2 shows the Lost Man Creek watershed and sub-basins along with geology, streams, monitoring sites and treatment history.

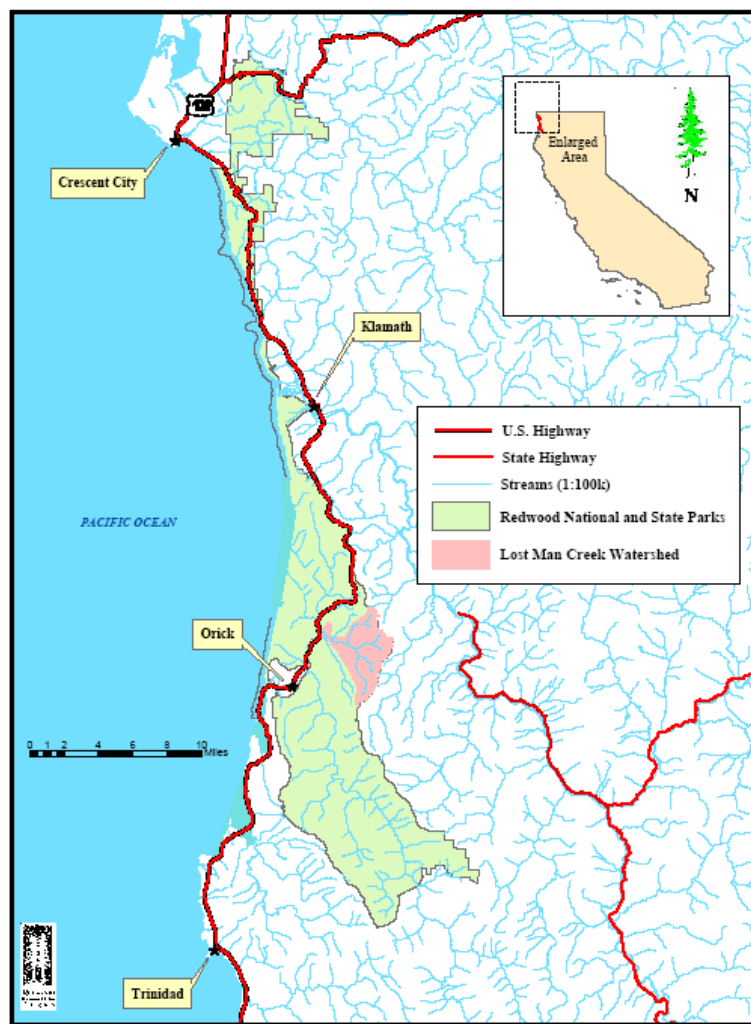


Figure 1. Location of Lost Man Creek watershed in northwestern California.

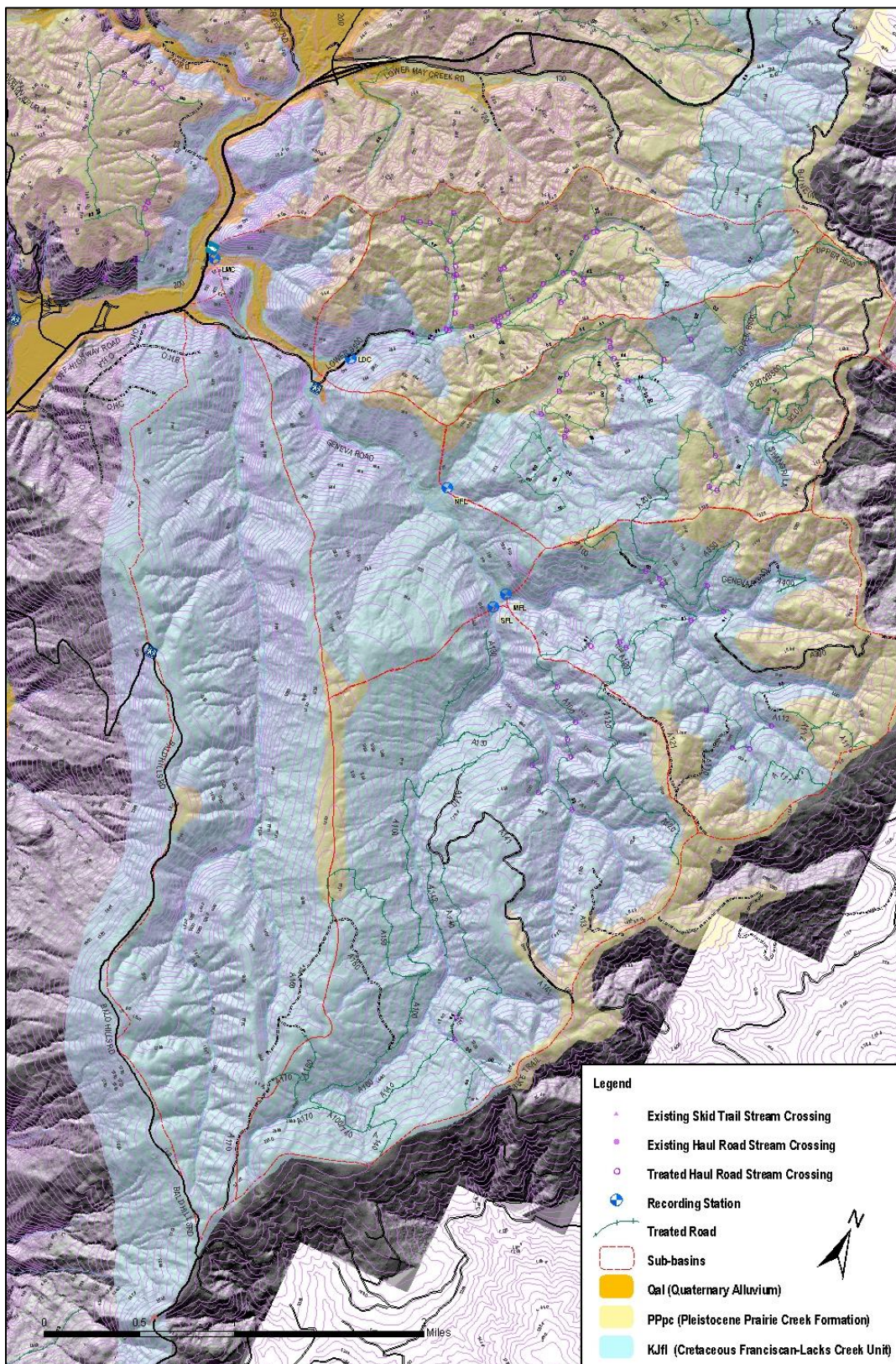


Figure 2. Lost Man Creek watershed and sub-basins, stream gaging stations, geology and road network.

Table 1. Characteristics of Lost Man Creek watershed and sub-basins.

| <i>Sub-basin (station code)</i>                      | <i>Drainage Area (mi<sup>2</sup>)</i> | <i>Drainage Area (acres)</i> | <i>Mean Basin Slope (%)</i> | <i>Basin Relief (ft)</i> | <i>Area in Prairie Creek Fm.(PPpc) (acres [%])</i> | <i>Acres in Old Growth (% of area)</i> |
|------------------------------------------------------|---------------------------------------|------------------------------|-----------------------------|--------------------------|----------------------------------------------------|----------------------------------------|
| <b>Lost Man Creek Watershed</b>                      |                                       |                              |                             |                          |                                                    |                                        |
| Larry Damm Creek (LDC)                               | 1.9                                   | 1181                         | 27.6                        | 1600                     | 853 [72%]                                          | 245 (21%)                              |
| North Fork Lost Man Creek (NFL)                      | 2.4                                   | 1422                         | 35.6                        | 1440                     | 742 [52%]                                          | 135 (9%)                               |
| Middle Fork Lost Man Creek (MFL)                     | 2.4                                   | 1444                         | 37.0                        | 1600                     | 583 [40%]                                          | 35 (2%)                                |
| South Fork Lost Man Creek (SFL)                      | 4.3                                   | 2522                         | 39.3                        | 1920                     | 177 [7%]                                           | 304 (12%)                              |
| Interfluves                                          | 1.1                                   | 1160                         | ---                         | ---                      | 106 [9%]                                           | 1116 (96%)                             |
| <b>Basin Mouth: Lost Man Creek at Hatchery (LMC)</b> | <b>12.1</b>                           | <b>7729</b>                  | <b>34.9</b>                 | <b>2180</b>              | <b>2461 [32%]</b>                                  | <b>1835 (24%)</b>                      |
| <b>Other Prairie Creek Control Sites</b>             |                                       |                              |                             |                          |                                                    |                                        |
| Little Lost Man Creek (LLM)                          | 3.5                                   | 2214                         | ~45%                        | 1860                     | 2100 [~5%]                                         | 2174 (98%)                             |
| Upper Prairie Creek (above Brown: PRU)               | 4.1                                   | 2624                         | 29.1                        | 1350                     | 2360 [~90%]                                        | (~95%)                                 |
| Prairie Creek above Boyes (PAB)                      | 8.0                                   | 5120                         | ~30%                        | 1430                     | 4610 [~90%]                                        | (~95%)                                 |
| Prairie Creek above May (PRW)                        | 12.6                                  | 8064                         | ~30%                        | 1670                     | 7260 [~90%]                                        | (~88%)                                 |

As shown in Table 1, a significant portion (32%) of Lost Man Creek is underlain by the Prairie Creek Formation (PPpc, Fig. 2), with virtually all of the rest of the watershed (75%) underlain by the Coherent Unit of Lacks Creek (Franciscan Assemblage) (Kjfl, Fig. 2). Observations indicate that hillslopes within some areas of the Prairie Creek Fm. are particularly susceptible to surface erosion following disturbance (prior logging, recent road removal) due to low cohesion and coarse fragment content for armoring.

Similar to virtually all redwood areas in north coastal California, Lost Man Creek was heavily logged and roaded during the 1950s to early 1970s, prior to implementation of the state's forest practice rules in 1975. Forest land use during this period consisted of largely unregulated road and landing construction, and many large areas were clearcut with intense ground disturbance from tractor yarding. Lost Man Creek, experienced widespread erosion and sedimentation during the 1955, 1964 and later floods in response to this unregulated logging. The Middle and South Forks and the remaining old growth along the lower main stem were acquired by the National Park Service in 1968; the area north of Geneva Road, including most of the North Fork and Larry Damm Creek, was not acquired until 1978, and experienced particularly severe ground disturbance during the final phase of logging, just prior to the park expansion.

The other Prairie Creek sites listed in Table 1 are gaging stations that, like the Lost Man Creek sites, provide continuous turbidity data. In addition, these sites have automated pumping samplers controlled by turbidity threshold sampling (TTS) programs developed by USFS Redwood Sciences Laboratory (RSL). As indicated, lithology of areas draining to these sites is composed of either virtually all Franciscan Fm (LLM) or all Prairie Creek Fm (PRU, PAB,

and PRW), and the range of drainage areas is similar to that in Lost Man Creek. Thus, these nearby gaging stations provide potential controls to compare with the Lost Man Creek sites.

Following are descriptions of stream gaging stations and contributing basin areas in Lost Man Creek:

**Lost Man Creek at Fish Hatchery Site (code: LMC):** This site drains nearly the entire basin area of Lost Man Creek, about 12.1 mi<sup>2</sup>. The area above LMC consists of a combination of residual and old growth redwood stands and areas disturbed by extremely destructive logging practices of the 1950s-70s. Geology consists primarily (about 66% of basin area) of Franciscan sedimentary rocks (Coherent Unit of Lacks Creek, or KJfl, Fig. 2), with virtually all of the rest (32% of basin area) underlain by Prairie Creek Fm rocks derived from fluvial and marine sediments (PPpc, Fig. 2). Road removal work has been underway since 2000, with almost all (96%) of the total number of road miles planned for restoration completed as of 2009. Because of its location at the downstream end of the watershed, LMC reflects an amalgam of processes occurring upstream, not all of which are related to restoration work.

**Larry Damm Creek (code: LDC):** This is the first named tributary entering Lost Man Creek upstream from LMC, entering the main channel from the north. Drainage area upstream from the sampling site is about 1.9 mi<sup>2</sup>. Clearcut logging and tractor yarding in the 1960's and 70's caused extensive ground disturbance in all but the lowest portion, where substantial old growth was left behind and remains today. The geology is primarily Prairie Creek Fm. (72% of basin area) with the remainder underlain by Franciscan Fm. The most intense logging occurred in the area underlain by the Prairie Creek Formation. Extensive road removal work occurred in 2002 and 2003, with a minor amount performed in 2004, at which time about 91% of treatment work (in terms of road miles) had been completed. The only road reach still contemplated for removal is the lower-most reach near the Lost Man Creek picnic area. This reach has low risk of failure, so treating it is low priority and may never happen. A large debris slide occurred in 2002 on a fill site near a stream crossing excavation, triggering extreme downstream turbidity. This event led NOAA to mandate the monitoring program reported on here.

**North Fork Lost Man Creek (code: NFL):** This is the second named tributary entering Lost Man Creek upstream from LMC, entering the main channel from the north. This site drains about 2.4 mi<sup>2</sup> of watershed area. While land use and remnant old growth is similar to Larry Damm Creek in the middle and lower portions of the sub-basin, the upper watershed was selectively logged in the 1950's and 1960's, and ground disturbance was moderate. The geology consists of both the Franciscan and Prairie Creek formations in approximately equal proportion. Road removal work began aggressively in 2000 (6.9 miles) and continued, albeit at a slower pace, through 2002, at which time about 71% of the total number of road miles planned for treatment had been completed. No restoration occurred during the subsequent four years (2003-2006), but as of 2008 road removal work was completed. In fact, more road length was treated than originally planned due to discovery of additional road reaches posing sediment delivery risks.

**Middle Fork Lost Man Creek (code: MFL):** Drainage area upstream from this site is about 2.4 mi<sup>2</sup>. This sub-basin was selectively logged in the 1950's and 1960's, and ground disturbance was moderate. The geology consists of both the Franciscan (60%) and Prairie Creek (40%) formations. Road removal work occurred in 2000 and 2001 (about 42% of the total planned), with no further work occurring until 2007. In 2007-09, seven miles of road were treated, completing road removal work in the watershed. As with North Fork, more road length was treated than originally planned due to discovery of additional road reaches posing sediment delivery risks.

**South Fork Lost Man Creek (code: SFL):** This was the site of a former USGS synoptic stream gaging station (No. 11482450, "Lost Man Creek near Orick", 1974-75). Drainage area above the site is 4.3 mi<sup>2</sup>. This sub-basin was selectively logged in the 1950's and 1960's, and ground disturbance was moderate. The geology consists of primarily the Franciscan Fm (93%), with only a very minor proportion underlain by Prairie Creek Fm. (7%). A substantial tract of old growth remains in the lower western part of the basin. Road removal work occurred in 2000 and 2001 (about 15% of the total planned), with no further work until 2006-2009 when almost 11 miles of road were treated. Although additional road lengths were planned for treatment, these may not be treated in the near future, or perhaps not at all.

## Prairie Creek Control Sites

To provide untreated study controls, turbidity data from three stream gages in Prairie Creek but outside Lost Man Creek were also used for comparison with Lost Man Creek sites (see Table 1). A long-term gaging station on Little Lost Man Creek (LLM, drainage area = 3.5 mi<sup>2</sup>) is adjacent to Lost Man Creek and provided a near pristine control representative of predominantly Franciscan Fm lithology. In addition, two gages on main channel Prairie Creek (PRU and PAB, Table 1) provided additional controls representative of predominantly Prairie Creek Fm lithologies.

The Upper Prairie Creek gage (PRU) provides turbidity data for the entire study period (WY2003-09); the other gage, Prairie Creek above Boyes (PAB) only began providing turbidity data in WY2004, one year after the beginning of data collection in Lost Man Creek. Neither of these gages can be considered absolutely pristine. The area upstream of PRU and PAB includes an older, low-impact two lane road (formerly US Highway 101, now a park visitor access road), as well as a four-lane freeway along the eastern headwaters. In the late 1980s and 1990s, a freeway (US Highway 101 Prairie Creek Bypass) was constructed along the eastern divide of Prairie Creek. During construction, severe erosion occurred in the construction area, sending large volumes of fine sediment into several Prairie Creek tributaries, including Brown, Big Tree, Boyes and May creeks. While the freeway is far more erosionally stable than in the late 1980s and early 1990's, peak stormflows have been permanently increased due to the large amount of paved area, but the effects are probably very small at present, thus these features probably add very little to Prairie Creek turbidity at present.

## Restoration Plans and Progress

Table 2 lists annual data on road removal work in the watershed. Approximately 52 miles of haul roads had been identified for removal as part of the restoration of the Lost Man Creek watershed. Between the beginning of restoration work in Lost Man Creek (in 2000) and fall, 2009, 96% of this road length had been treated, with restoration work considered essentially done with the exception of one short road segment in Larry Damm Creek (see above).

Road lengths presented in Table 2 represent a simplistic means to evaluate the level of watershed disturbance attributable to road removal annually. A better method to characterize potential effects on water quality would be measures more directly linked to sediment delivery to channels, such as disturbed surface area draining to channels, slope length, steepness and soil characteristics, as used in predictive surface erosion models, but such data are not available.

Table 2. Restoration progress (in miles of treated road) in Lost Man Creek as of fall, 2010, when work was completed.

| <b>Watershed</b>                        | <b>2000</b> | <b>2001</b> | <b>2002</b> | <b>2003</b> | <b>2004</b> | <b>2005</b> | <b>2006</b> | <b>2007</b> | <b>2008</b> | <b>2009</b> | <b>2010</b> | <b>Total</b> |
|-----------------------------------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|--------------|
| Larry Damm Creek (LDC)                  | 0.0         | 0.0         | 2.9         | 4.7         | 0.2         | 0.0         | 0.0         | 0.0         | 0.2         | 0.0         | 0.0         | <b>8.1</b>   |
| North Fork Lost Man (NFL)               | 2.2         | 1.7         | 2.9         | 0.0         | 0.0         | 0.0         | 0.0         | 1.2         | 2.8         | 1.5         | 0.9         | <b>13.3</b>  |
| Middle Fork Lost Man (MFL)              | 4.1         | 1.4         | 0.0         | 0.0         | 0.0         | 0.0         | 0.0         | 1.0         | 4.4         | 0.0         | 0.0         | <b>10.9</b>  |
| South Fork Lost Man (SFL)               | 2.4         | 0.3         | 0.0         | 0.0         | 0.0         | 0.0         | 1.1         | 8.9         | 2.4         | 1.8         | 1.2         | <b>18.1</b>  |
| <b>Lost Man Creek at Hatchery (LMC)</b> | <b>8.8</b>  | <b>3.3</b>  | <b>5.8</b>  | <b>4.7</b>  | <b>0.2</b>  | <b>0.0</b>  | <b>1.1</b>  | <b>11.1</b> | <b>9.8</b>  | <b>3.3</b>  | <b>2.1</b>  | <b>50.3</b>  |

## METHODS

The main focus of this project was to document the effects of road removal disturbance on water quality, specifically turbidity and suspended sediment concentrations and loads. A suite of both onsite and offsite water sampling stations was established in the first year of this project (see monitoring report of July, 2003), and additions were made for WY2004 (untreated stream crossings in South Fork Lost Man were added). Beginning in WY2005, onsite sampling was discontinued (explained below). Consequently, monitoring after WY2004 included only offsite sampling for discharge, turbidity and suspended sediment at the one mainstem and four tributary recording stations.

## Onsite Turbidity Sampling

As mentioned above, onsite (upstream and downstream sampling at stream crossing excavations) water sampling for turbidity was dropped from the program beginning in WY2004 (winter 2003-2004). The reasons for this were: 1) the usefulness of the results was limited by the necessity of manual sampling: while providing ‘snapshots’ of effects of post-excavations channel adjustments and sideslope erosion, lack of continuous data failed to provide enough information for a well-founded assessment of water quality impacts ; 2) after two years of collecting and analyzing onsite data, it was apparent that we had learned all we could given the limitations of manual sampling: that occasionally large increases in turbidity occurred with recently excavated stream crossings and that the effects were short-lived; and 3) the limited utility of onsite sampling results did not justify the high expense.

## Onsite Qualitative Monitoring

Onsite monitoring also included estimates of erosion volumes activity and photo-documentation (photopoints) during periodic visits to the project sites by the responsible project geologists (RNSP staff).

Observations of erosion processes and conditions were made at stream crossings excavated in 2003-2008 and will also be done at 2009 sites. Photos were taken and observations of erosion and sedimentation (processes, quantities, and possible causes) were recorded on field forms. Though mostly qualitative, such observations are important for documenting the timing and magnitude of erosion processes and for understanding the causes of post-treatment erosion and sediment delivery, thus providing important insights for adaptive management.

**Photopoints:** Photopoints are monumented locations where repeated photographs are taken of the same location over time to document changes (e.g., erosion, and vegetation growth). They are typically taken before and immediately after excavation, and in the spring/summer following each winter storm season for several years. Additional photos were occasionally taken during mid-winter site reconnaissance visits, depending on whether or not there were any noticeable changes. Sequential photos began with the excavations done in 2003 and continued for several subsequent years.

Photopoint locations are monumented, either by use of permanent features (e.g., a stump) or by establishing a monument using a PVC stake. Some photos are taken as montages to span the broader distances and are ‘stitched’ for use in reports. Depending on the stream crossing and the ability to capture the entire excavated area, the number of photopoints may differ from site to site. A typical site would have a likely minimum of 2 or 3 photopoints. One photopoint was typically established proximal to the channel at the upstream end of the excavation with a view looking downstream. Others were established on the excavation side slopes and at the downstream end of the excavation. Where the length of the excavated channel was exceptionally long, additional photopoints were established to adequately document original conditions and the subsequent changes.

**Erosion Assessment Forms:** Erosion was also tracked during the winter by use of simple assessment forms. The forms require separate information on three types of erosion: surface erosion, mass wasting erosion (referred to as “bulk erosion” on the forms), and channel erosion. Visual estimates were made of volumes displaced from hillslope positions and the proportion of those volumes that was ‘delivered’ (entered a stream channel), along with possible causes and mechanisms of failure.

Surface erosion, generally in the form of rilling, was categorized as high, medium, or low, with the surface area estimated. Channel erosion dimensions (length, width and depth) were visually estimated and recorded to estimate volume. Mass wasting features were categorized as bank slumps (referred to as “channel scallop” on the forms), shallow debris slides and earth flows. The dimensions (length, width, and depth) were visually estimated to quantify volume. The delivery volume (as a percentage of the entire mass) was also estimated. Features such as seeps or springs that could give rise to future failure were documented.

The assessment form also included a sketch of both new and enlarged erosion features that were noted on each site visit. Initially, a site-specific template sketch was prepared that included permanent features useful as reference markers (stumps and large woody debris). On each visit, the template was updated to show new erosion features and

changes to existing features as they evolved through the wet season. Erosion volumes from these assessments are presented in the results section of this report.

At the end of the wet season, each geologist summarized the post-excavation erosional activity observed on his or her respective projects. These were included in the previous monitoring reports and in this report. The project reports, previous monitoring reports, and erosion assessment forms are archived at RNSP's South Operations Center (SOC) in Orick, CA. No assessments were done after 2008.

## Offsite Water Quality Methods and Watershed Descriptions

Offsite monitoring refers to monitoring downstream of restoration sites, near the mouths of tributaries. Water quality at these locations reflects the summed effects of all erosion and sedimentation occurring upstream. Our study objectives required an assumption that water quality differences among tributaries were due primarily to the amount of recent road treatments in each tributary, an assumption that we know to be only partly true owing to the erosional activity of both natural and legacy erosion features unrelated to restoration work. This limits our ability to document the effects of road restoration because it is just one of three possible sources of instream turbidity: natural erosion features, legacy features, and road removal disturbances.

The spatial distribution of offsite sampling locations (Fig. 2) was initially selected to provide, to the extent possible, treatment and control subbasins to evaluate effects of road removal on downstream water quality. Two of the sites ('LMC', or Lost Man Creek at the former Prairie Creek Fish Hatchery, and 'SFL', or South Fork Lost Man Creek) were set up as recording stations for WY2003, where stage and turbidity was electronically recorded at 10-minute intervals. LMC is near the basin outflow to Prairie Creek, while SFL is a tributary basin farthest upstream from the confluence with Prairie Creek (Fig. 2).

Three tributaries located between SFL and LMC: Larry Damm Creek (LDC), North Fork Lost Man Creek (NFL), and Middle Fork Lost Man Creek (MFL) (see Fig. 2) were manual sampling sites in WY2003. To obtain a more complete picture of each tributary's responses to restoration work, the three tributary stations (LDC, NFL, and MFL) were retrofitted with automated equipment (data logger, stage sensor, and DTS-12 turbidity sensor) to record hydrologic information on 10-minute intervals beginning in WY2004. The DTS-12 turbidity sensor, made by FTS, Inc. was used at all recording sites. Turbidity sensors are occasionally factory calibrated, which requires removing them from the field during low flow season and re-deploying before winter. USGS-recommended units for turbidity readings obtained by this type of sensor are "FNU" (formazin nephelometric unit, USGS 2004).

To evaluate turbidity levels within Lost Man Creek, some comparisons were made with data collected at several other stations in Prairie Creek (LLM, PRU, and PAB; see Introduction and Table 1, above) that could serve as control sites. Although these sites are not within Lost Man Creek, they are all within Prairie Creek and have basin attributes similar to those in Lost Man Creek (see Table 1).

While all sites in Lost Man Creek use the DTS-12 (units of FNU, or formazin nephelometric units) turbidity sensor, data from two of the other stations (LLM and PRU) used the OBS-3 (units of FBU, or formazin backscatter units) sensor until WY2007. As shown by Lewis and others (2007), different types of sensors can give substantially different turbidities for the same suspended sediment mixture. Thus it was necessary to adjust the OBS-3 FBU data to equivalent values for the sensor used in Lost Man Creek (DTS-12 FNU). Since some of the sediment used by Lewis and others (2007) was from Prairie and Lost Man Creeks, their data was used to derive equations for converting OBS-3 data to equivalent DTS-12 values. The conversion equations used for this were:

$$\begin{aligned} \text{FNU} &= 0.8132 \cdot \text{FBU}^{1.0914} \text{ [for LLM]} \\ \text{FNU} &= 1.0802 \cdot \text{FBU}^{1.0335} \text{ [for PRU]} \end{aligned}$$

Water samples were taken manually during storm periods at the five recording sites. Almost all samples were depth-integrated samples (DIS), but occasional point ("box") samples were also taken at a single representative spot on the gaging section. Samples were transported to a laboratory soon after collection and tested for turbidity using a Hach

2100P portable turbidity meter and then analyzed for suspended sediment concentration (SSC) using filtration methods. The Hach turbidity data were not used in turbidity analyses, thus no conversion to equivalent DTS-12 values was needed. Stage readings and discharge measurements were also taken manually, and discharge rating curves were constructed to convert recorded stage data to discharge. Turbidity-SSC relationships were developed by plotting SSC from the manual samples against simultaneous DTS-12 turbidities, which were used to estimate 10-minute SSC values. Suspended sediment loads (annual yields) were estimated by integrating suspended sediment concentration estimates with discharge for the winter period.

## RESULTS

Following are results from data collection for WY2003-2011. An important preface to discussing turbidity sampling results is to put the study period into hydrologic perspective. Figure 3 shows annual maximum instantaneous peak discharges ('QPK') and the mean of the ten largest peaks ('10-QPK Mean') at Lost Man Creek at Hatchery (LMC) for WY2003-11. Although annual maximum instantaneous peak discharge is commonly used to index hydrologic severity, it often masks the role of lesser storms. The mean of the ten largest storms each year is also presented to attempt to overcome the problem of using just the largest storm. It is noted here that because of the ever-changing watershed conditions in Lost Man Creek, storm magnitude alone provides only a partial explanation of turbidity and suspended sediment yields.

### Storm Hydrology

Peak discharges for all water years rank as follows, from highest to lowest: 2003, 2009, 2004, 2006, 2011, 2005, 2008, 2007, and 2010. The mean of ten largest peaks followed a similar trend, with several exceptions. Most notable was WY2006 in which the ten-peak mean was relatively much higher than the annual maximum peak flow because there were numerous storm peaks just slightly lower than the annual maximum.

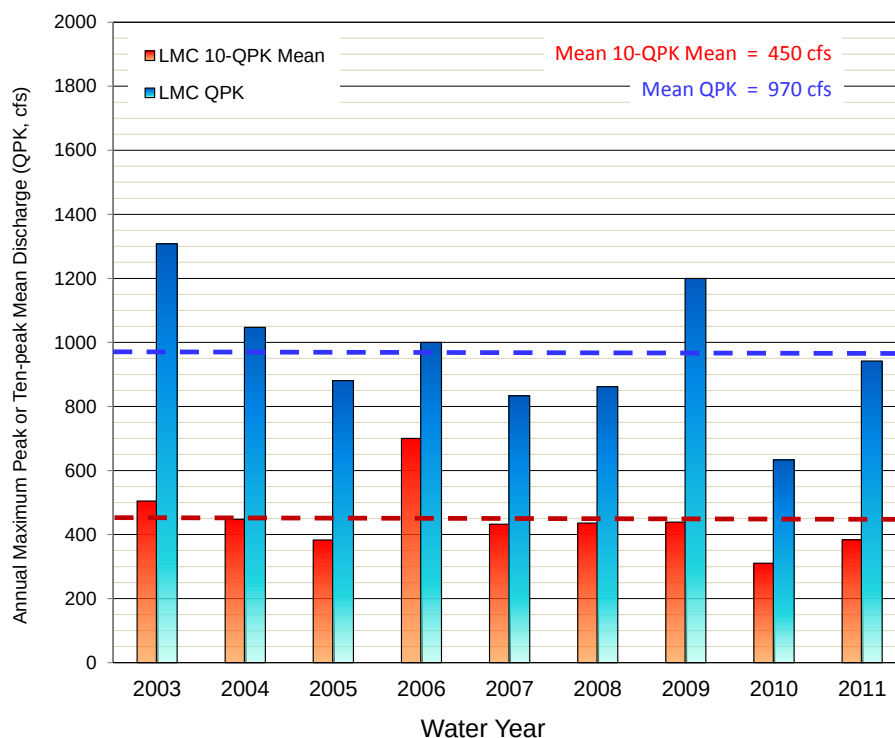


Figure 3. Annual maximum peak discharges and ten-peak means at Lost Man Creek (LMC) site, WY2003-2011.

Figure 4 shows the departures from the period mean for the two variables used in Figure 3. At 56% above the period mean 10-QPK, WY2006 stands out as perhaps the most hydrologically severe winter of the study period, despite an

annual maximum peak discharge just above the period mean, followed by WY2003. WY2010 was the lowest in terms of hydrologic stress by both measures. Other years were close to the period mean.

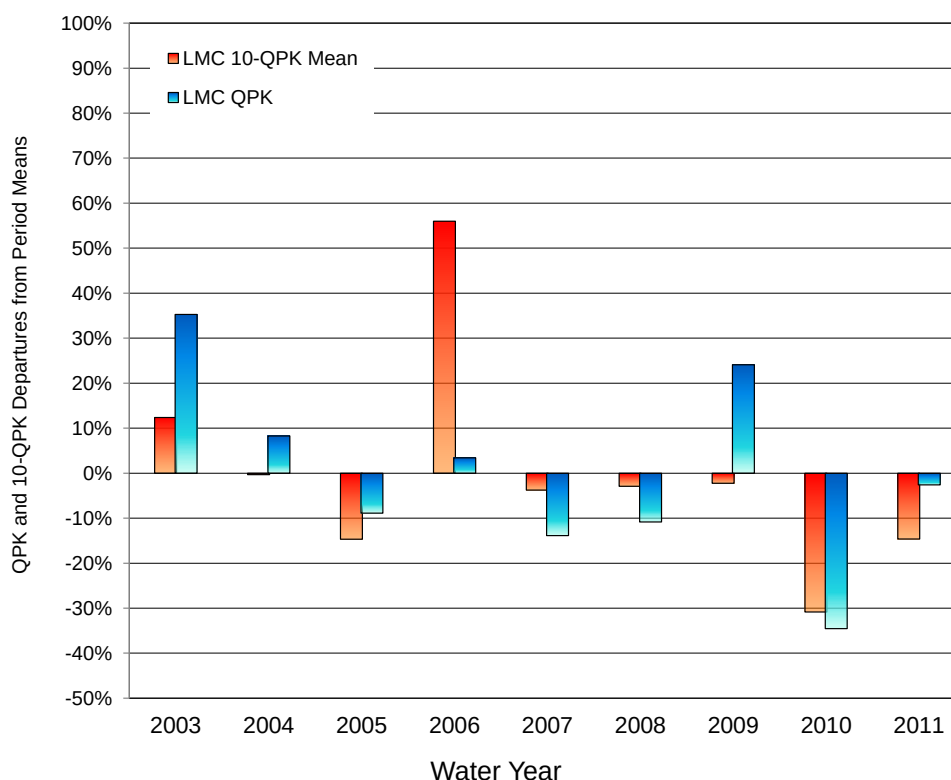


Figure 4. Departures from period mean of annual maximum peak discharges and ten-peak means at Lost Man Creek (LMC) site, WY2003-2011.

## Evaluating Control Sites

Despite having treatment and control sites, the ability to discern restoration effects in Lost Man Creek is far from perfect. The gaging stations are located near the mouths of the main tributaries and near the mouth of Lost Man Creek, thus water quality data from the stations reflects the integration of all erosion and sedimentation processes within the watershed upstream of each station. In addition to restoration disturbances, both natural and legacy erosion features also contribute to downstream turbidity. To address this problem, observations of erosion at a sample of stream crossing excavations were made for part of the study period. However, this only provided a rough approximation of onsite erosion and did not include data collection in the later years of the study period. The greatest confidence in interpreting the gaging station data would be to conduct watershed-wide erosion inventories, including a complete erosion inventory of road removal sites and all other erosion/sediment delivery features (i.e., natural and legacy). This would be a much larger task and was not feasible except for the limited inventory of streamside landslides in the South Fork Lost Man Creek (SFL, discussed later).

Little Lost Man Creek (LLM), a possible control site for Lost Man Creek, had relatively high suspended sediment yields for WY2003 and WY2007. Although nearly pristine, several streamside landslides became re-activated in LLM in 2003, causing suspended sediment yields to increase temporarily, exceeding that of SFL. LLM exceeded LMC slightly in WY2007, most likely due to the three prior years of low levels of road removal work in the watershed, which caused the second lowest suspended sediment yields at all Lost Man Creek monitoring sites over the entire study period. The occurrence of infrequent landsliding and temporarily elevated suspended sediment yields made LLM less desirable as a control site for Lost Man Creek. Prairie Creek above Boyes (PAB) was also sub-optimal as a control because this gage was not yet installed at the beginning of monitoring in Lost Man Creek. Upper Prairie Creek (PRU), however, was free from anomalous behavior and its record spanned the entire monitoring period for Lost Man Creek, so it seemed the best control site and was relied on for this purpose. Thus, to attenuate the effects of variable hydrologic stresses from year to year on suspended sediment yields, Lost Man Creek data were compared with that

from Upper Prairie Creek (PRU) as a control assuming it was subject to the same relative hydrologic stresses. Its proximity to Lost Man Creek (a few miles away) makes this assumption reasonable.

### Peak Storm Turbidities

Comparison of peak turbidities at treatment and control sites during storms provides a means to evaluate restoration effects. For each winter, storms were ranked by peak discharge as measured at the downstream-most site (LMC), and peak turbidities for the ten largest storms were extracted from the dataset for each gaging station. Figures 5a-5i show these data graphically from WY2003-11, and the data are tabulated in Appendix A. Peak storm water discharges at the downstream-most station (LMC) are also shown.

For WY2003 (Fig. 5a), only two continuous gages were operating in Lost Man Creek (SFL, the upstream control site, and LMC, the downstream treatment site). These are plotted along with two sites elsewhere in Prairie Creek (Little Lost Man Creek (LLM), and Upper Prairie Creek (PRU)). The treatment site (LMC) had the highest peak turbidities in each of the ten storms plotted, while PRU was the cleanest. LLM (pristine) was slightly more turbid during several storms than the Lost Man control site (SFL) used at that time. Intervening suspended sediment sources between LMC and SFL account for the fact that LMC was far more turbid than SFL. The primary source of this sediment was likely originating from restoration sites in Larry Damm Creek (LDC), as indicated by manual samples collected there in WY2003 (before continuous monitoring).

Figure 5b shows peak turbidities from WY2004, when we had three additional recording turbidity stations operating in Lost Man Creek (Middle Fork (MFL), North Fork (NFL), and Larry Damm (LDC)) as well as two additional control sites in Prairie Creek (Prairie Cr above Boyes (PAB) and Prairie Creek above May (PRW)). The downstream-most station (LMC) remained higher than the upstream site (SFL) except for the first (and largest) storm of the season (Dec. 12). With data for the intervening tributaries, some explanations for the high downstream turbidities become apparent. Larry Damm (LDC), and to a lesser extent, North Fork Lost Man (NFL) stood out as large contributors to mainstem/downstream turbidity. It is likely that these two tributaries also contributed disproportionately to mainstem/downstream turbidities in WY2003, prior to installation of gaging stations in each. The high peak turbidity at the upstream control site (SFL) during the largest storm (Dec 12) most likely indicates the re-activation of legacy erosion features. A reconnaissance of the SFL main channel in spring, 2005, revealed eight recently active streamside debris slides within 1¼ mile upstream of the gaging station, most of which were fairly small. Our investigation didn't ascertain the causes for these debris slides (i.e., legacy features vs natural erosion), but regardless, they indicate an increased level of erosional activity likely unrelated to road decommissioning in the South Fork. The three control sites (PRU, LLM and PAB) were consistently much lower than the two Lost Man Creek sites.

In WY2005, peak turbidities were much lower at all sites than in WY2003-04, never exceeding 1000 FNU (Fig. 5c). As with WY2004, SFL was a relatively large contributor to downstream peak turbidities in most storms of WY2005. Unlike previous years, MFL became a more prominent source of mainstem/downstream turbidity, while LDC dropped significantly.

In WY2006 (Fig. 5d) the downstream-most station (LMC) exhibited relatively high peak turbidities, much higher than any upstream site in two storms (Dec 1 and 30). This suggests some fine sediment source(s) originating along the main channel of Lost Man Creek that contributed to turbidities only at the main channel site (LMC). A field reconnaissance done in fall, 2006, revealed a likely source for this fine sediment. Just several hundred yards upstream of LMC, the channel had anastomized, abandoning a concrete weir remaining from hatchery operation days. Large volumes of fine sediment formerly composing the channel banks had recently eroded as the channel diverted around the old weir, and much of the eroded material certainly would have been reflected in turbidities at LMC in WY2006.

Despite the numerous moderate to large peak stormflows (see Fig. 4), WY2006 peak turbidities were relatively low for half of the ten largest events (Fig. 5d). It is important to note that no road decommissioning occurred the preceding summer/fall in Lost Man Creek, consequently tributary turbidities remained relatively low because there was very little new ground disturbance from road decommissioning in the preceding two summers (2004 and 2005).

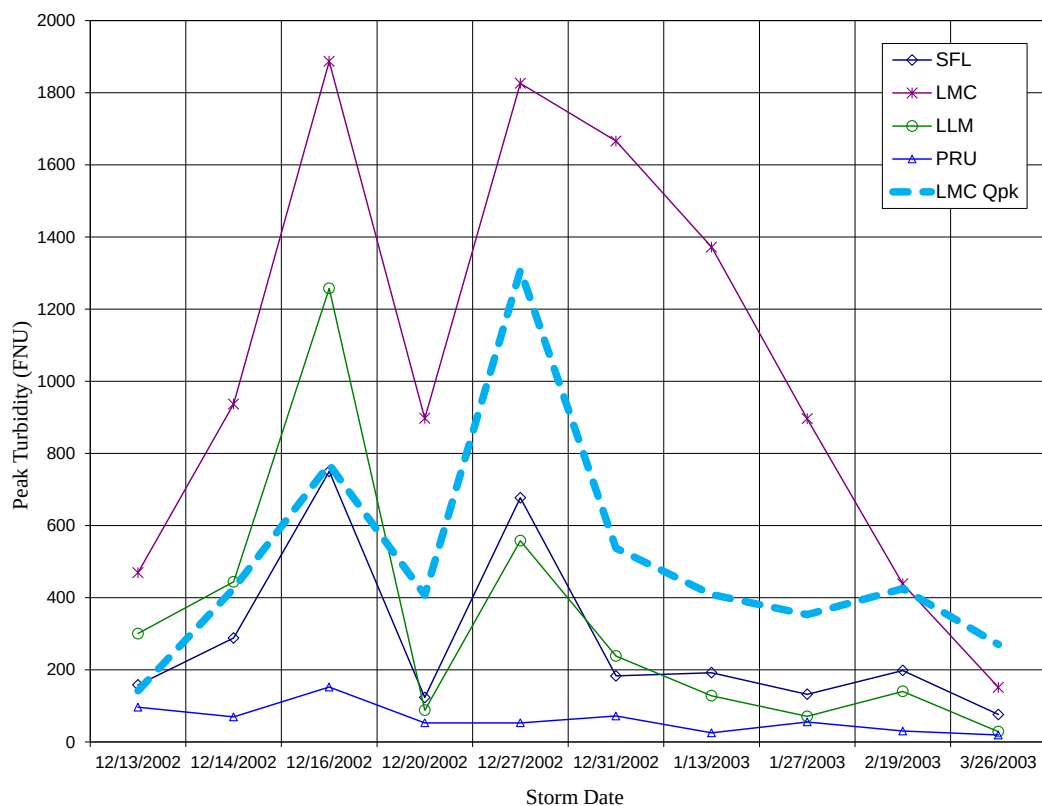


Figure 5a. Peak storm turbidities in Lost Man Creek and at Prairie Creek control sites, WY2003.

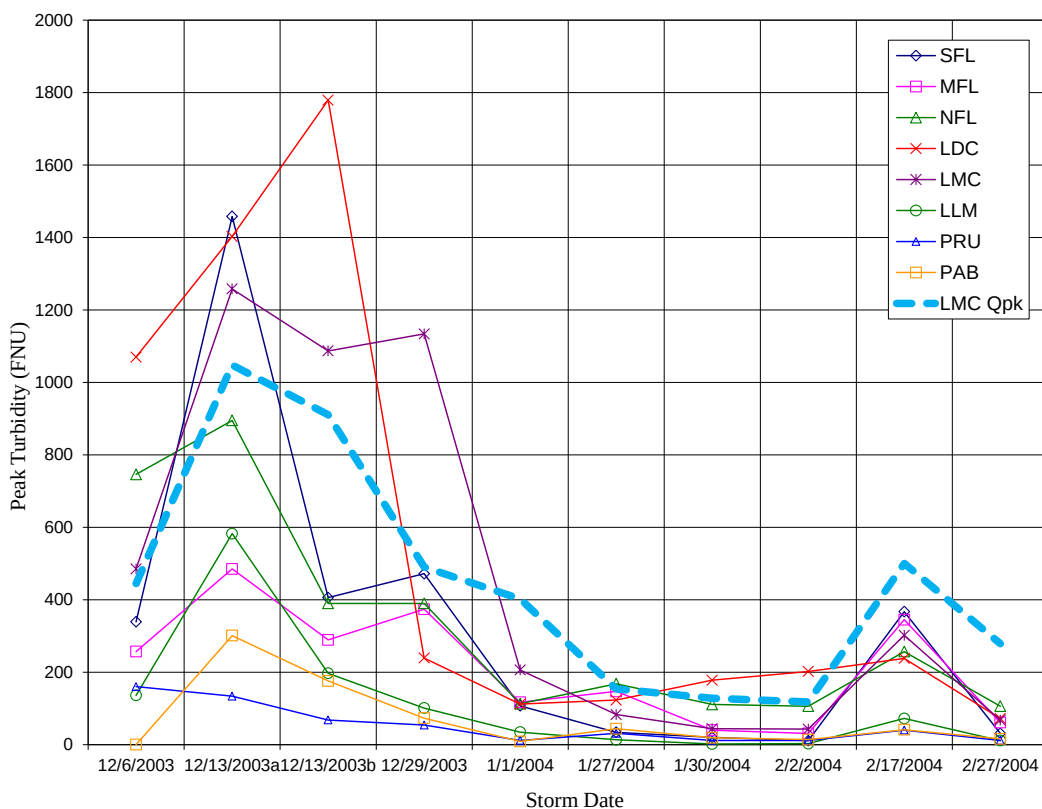


Figure 5b. Peak storm turbidities in Lost Man Creek and at Prairie Creek control sites, WY2004.

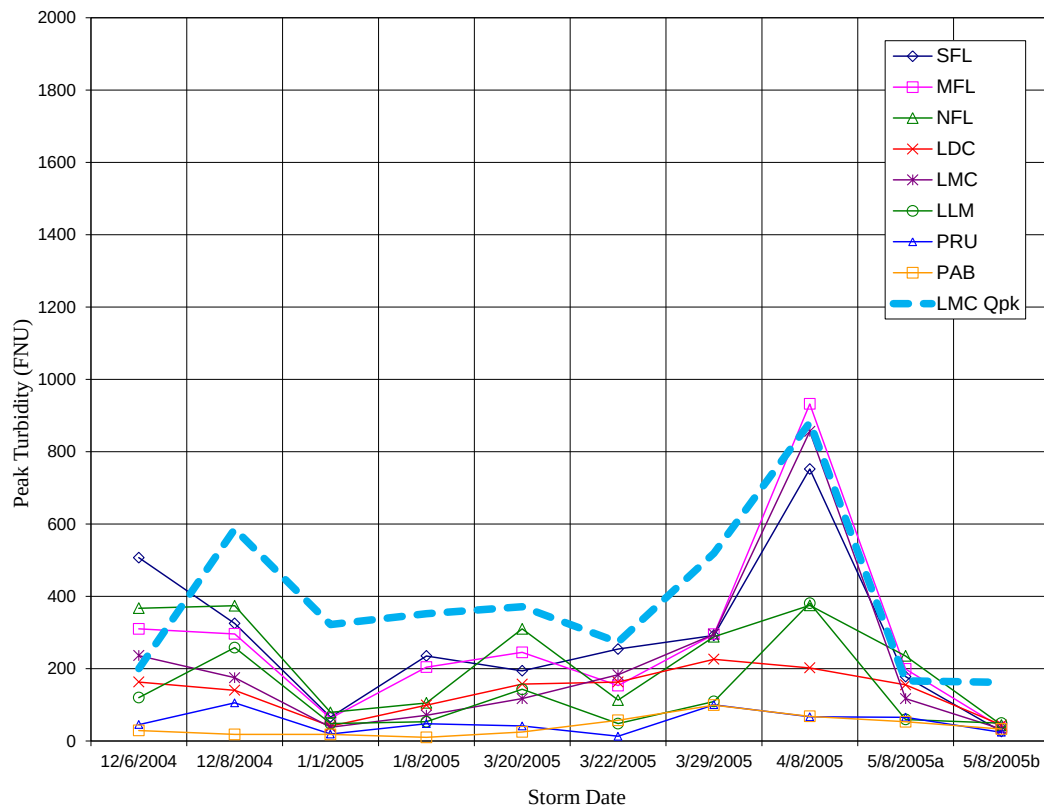


Figure 5c. Peak storm turbidities in Lost Man Creek and at Prairie Creek control sites, WY2005.

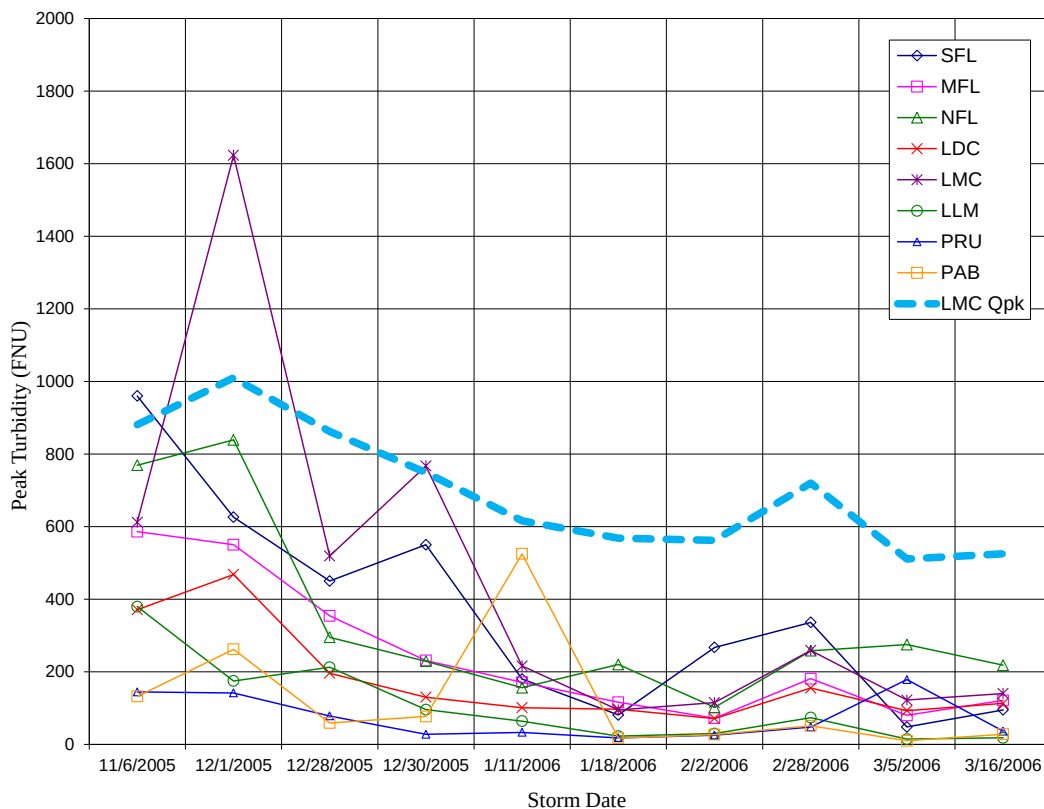


Figure 5d. Peak storm turbidities in Lost Man Creek and at Prairie Creek control sites, WY2006.

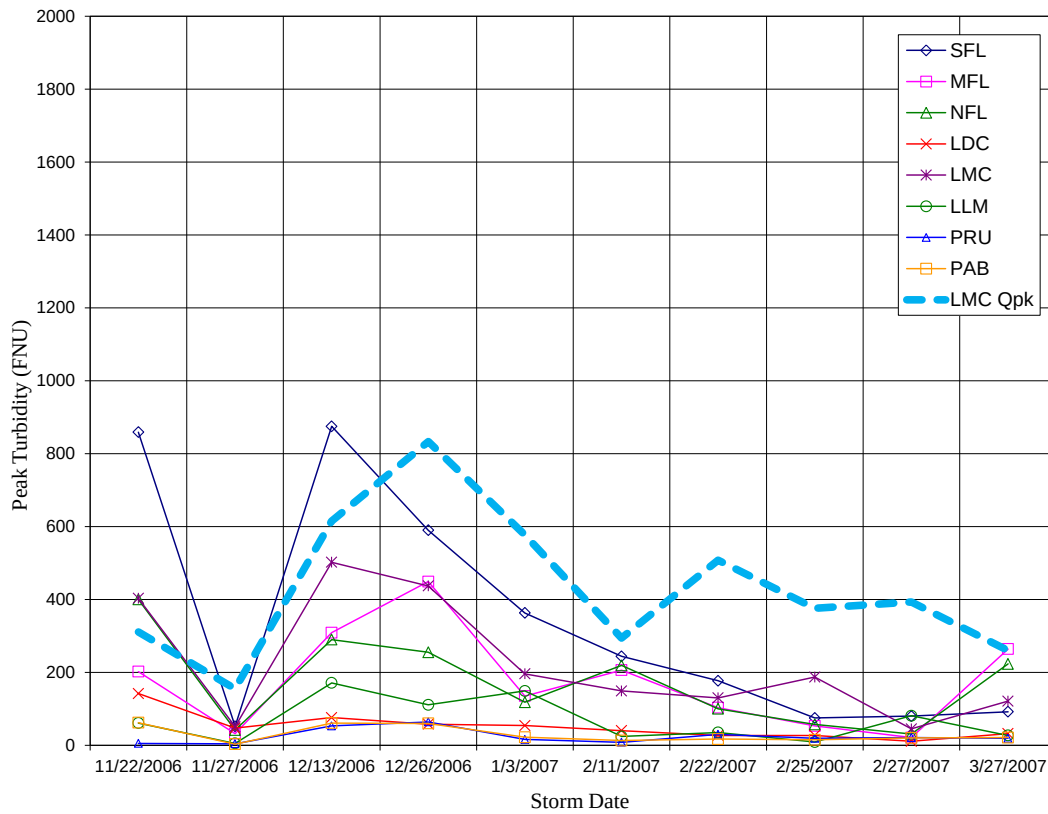


Figure 5e. Peak storm turbidities in Lost Man Creek and at Prairie Creek control sites, WY2007.

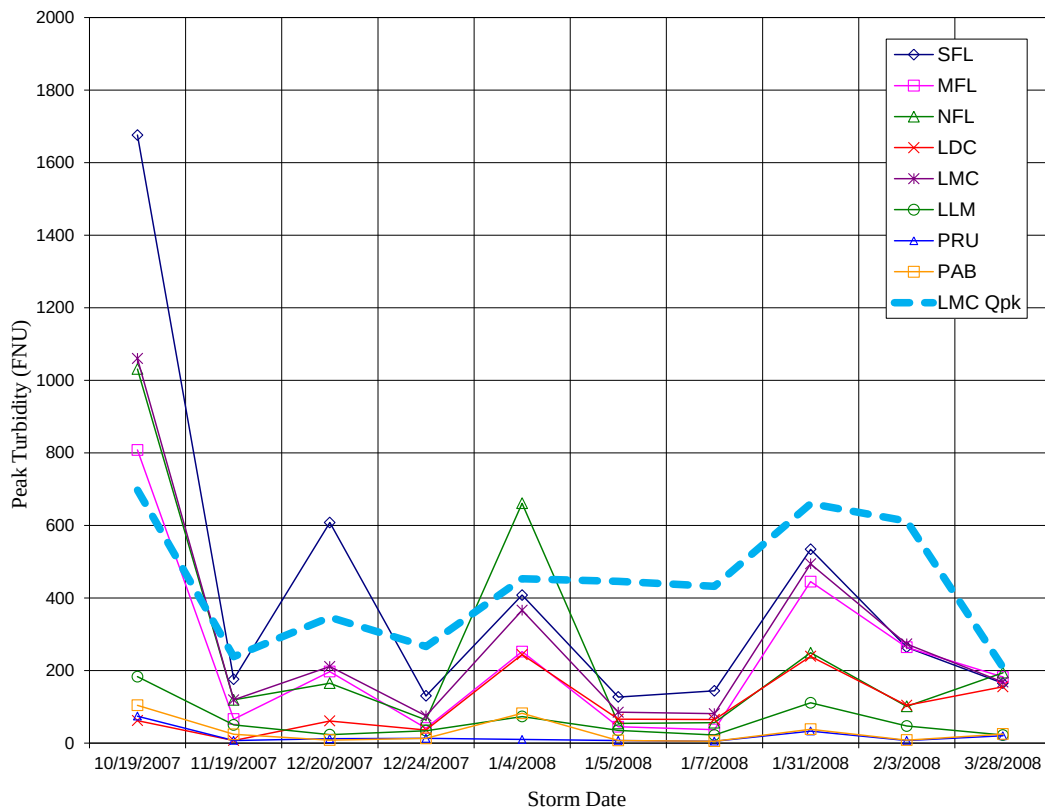


Figure 5f. Peak storm turbidities in Lost Man Creek and at Prairie Creek control sites, WY2008.

WY2007 was a relatively dry year, thus peak turbidities were generally lower than previous years (Fig. 5e). The highest turbidities during most storms were in SFL, implicating both restoration effects (this was the only sub-basin that had treatment in the preceding 2006 summer) and legacy erosion processes mentioned earlier. The channel erosion that occurred upstream of LMC appears to have subsided, as suggested by the relative reduction of peak turbidities at LMC compared to those in WY2006.

In WY2008 (Fig. 5f), SFL again was most often the most turbid among the sites. This could be expected because SFL had the greatest level of treatment in the preceding summer of 2007 (6.4 miles) and appeared to have the greatest level of activity from legacy and natural erosion and sediment delivery features. An exception to this is the January 4, 2008, storm event, during which the North Fork Lost Man (NFL) exceeded SFL. NFL also exhibited unusually high turbidity during the first storm of the WY2008 season (Oct. 19, 2007, Fig. 5f). A likely explanation for this is a dry season sediment delivery event that occurred at an active stream crossing excavation in July and August, 2007. Multiple events occurred where slurries of extremely turbid water escaped the relatively wet excavation site and traveled approximately two miles downstream in the North Fork channel and depositing fine sediment in both the North Fork and in Lost Man Creek mainstem downstream from the confluence. This sediment remained in-channel for the remainder of the dry season and was subsequently re-mobilized by winter flows, thus adding to suspended sediment loads derived from new erosion sources within the watershed.

In WY2009 (Fig. 5g), SFL continued to exhibit the highest peak turbidities, exceeding all other sites in nine of the ten largest storms. Other sites in Lost Man Creek alternated for second place. This was especially apparent in the two largest storms on Dec. 28, 2008, and Mar. 16, 2009. SFL represented the most important site affecting peak turbidities at the downstream-most site (LMC).

As mentioned above, road removal was completed in summer, 2009, just prior to WY2010, the year with the lowest peak discharge of the study period (Fig. 3). As might be expected, WY2010 turbidity peaks were also the lowest of the study period (Fig. 5h), but rose in the subsequent year (WY2011, Fig. 5i) with higher discharges (Figs. 3 and 4).

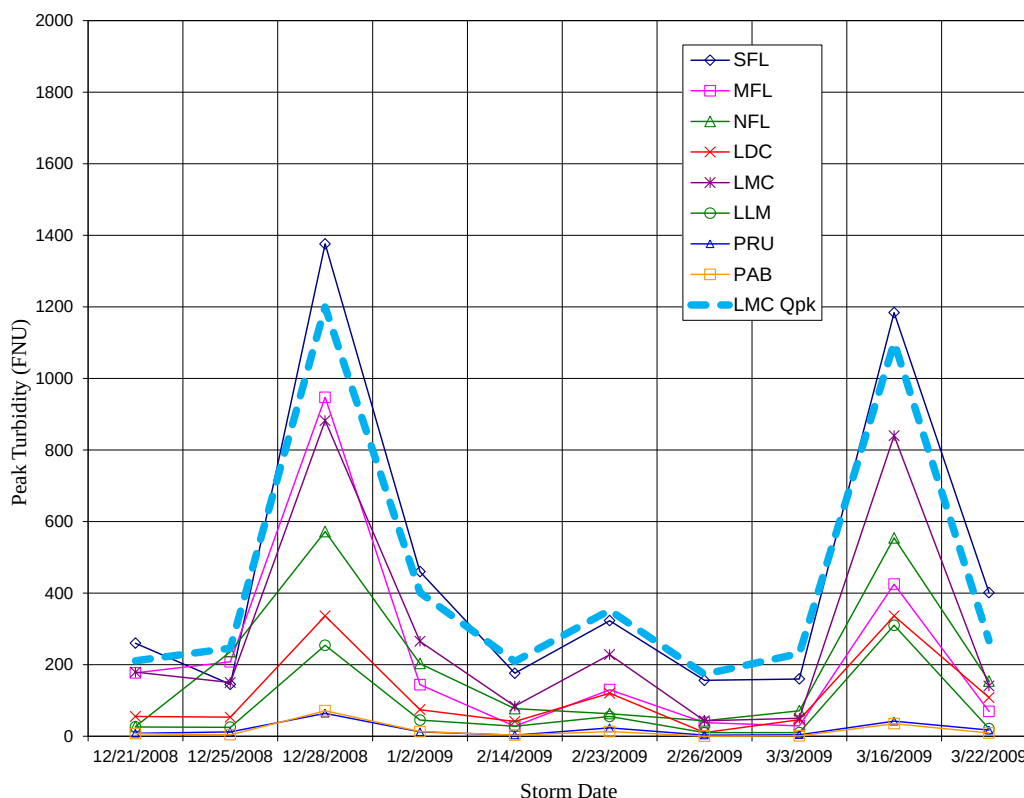


Figure 5g. Peak storm turbidities in Lost Man Creek and at Prairie Creek control sites, WY2009.

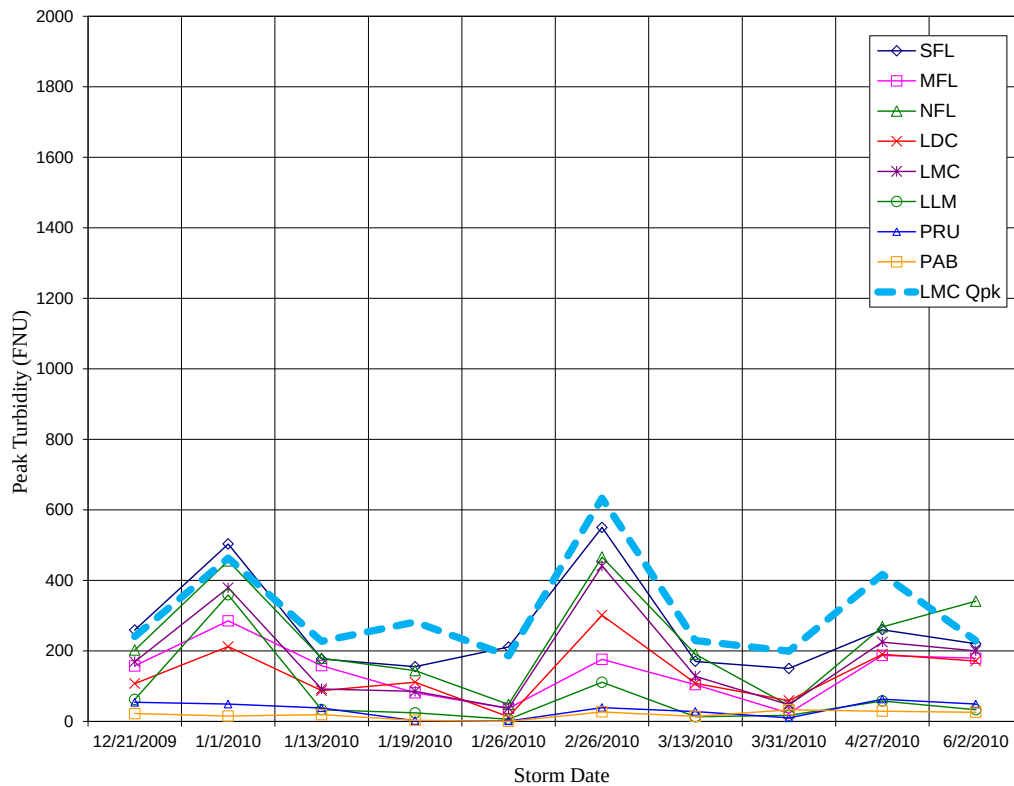


Figure 5h. Peak storm turbidities in Lost Man Creek and at Prairie Creek control sites, WY2010.

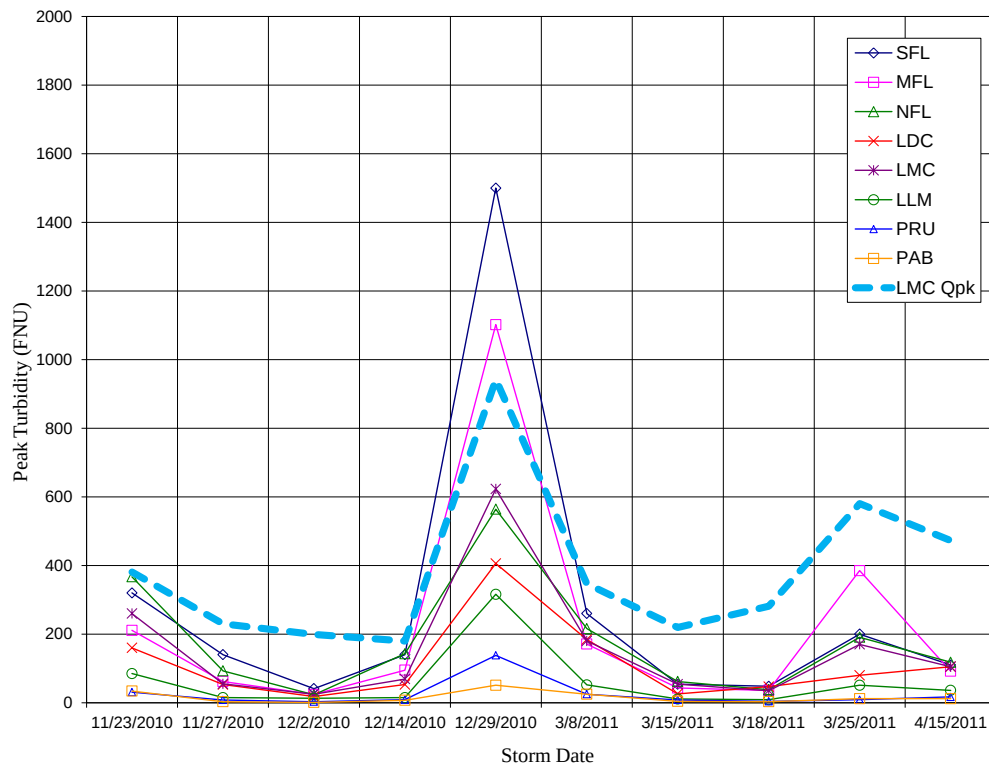


Figure 5i. Peak storm turbidities in Lost Man Creek and at Prairie Creek control sites, WY2011.

## Turbidity Duration Analysis

As with peak turbidity, turbidity duration characteristics of a stream can be diagnostic of disturbance-related erosional activity in the contributing watershed. Exceedence probability analyses applied to continuous turbidity data is an expression of the likelihood of a given turbidity level being exceeded; the lower the exceedence probability, the higher the turbidity. In this analysis, several approaches to quantifying turbidity durations were used. Continuous (10-minute) turbidity data from the five Lost Man Creek stations, along with several control sites from elsewhere in Prairie Creek, were analyzed using a technique traditionally used for stream discharge (flow duration analysis). The 10-minute turbidity data for the winter runoff period (December through May) are ranked in descending order and the percent of time a specific turbidity level is equaled or exceeded (percent exceedence probability) is calculated.

Table 4 presents turbidity exceedences for the entire study period for the Lost Man Creek sites and three sites located elsewhere in Prairie Creek representing undisturbed watershed conditions (i.e., controls). Turbidity at the 0.1% exceedence level (exceeded 0.1% of the time) corresponds to high (infrequent) conditions that occur near peak conditions during storms. Turbidity at the 1% exceedence level (exceeded 1% of the time) corresponds to somewhat lower, more frequent stormflows, and turbidity at the 10% exceedence level (exceeded 10% of the time) corresponds to more chronic (longer in duration, more frequent) conditions that commonly occur during recessional limbs of storms, and thus are much lower than turbidities at the lower exceedence levels.

Table 3. Prairie Creek turbidities at various exceedence levels, WY2003-11 ('---' indicates no data because gage was not yet installed).

| % Exc.                                                                                          | SFL  | MFL | NFL | LDC | LMC  | LLM <sup>1</sup> | PRU <sup>1</sup> | PAB |
|-------------------------------------------------------------------------------------------------|------|-----|-----|-----|------|------------------|------------------|-----|
| <b>WY2003 Turbidity Exceedences (FNU)</b>                                                       |      |     |     |     |      |                  |                  |     |
| <b>0.10</b>                                                                                     | 598  | --- | --- | --- | 1695 | 549              | 100              | --- |
| <b>1.0</b>                                                                                      | 210  | --- | --- | --- | 831  | 216              | 38               | --- |
| <b>10</b>                                                                                       | 37   | --- | --- | --- | 58   | 18               | 8                | --- |
| <b>WY2004 Turbidity Exceedences (FNU)</b>                                                       |      |     |     |     |      |                  |                  |     |
| <b>0.10</b>                                                                                     | 446  | 353 | 630 | 878 | 817  | 215              | 87               | 176 |
| <b>1.0</b>                                                                                      | 157  | 156 | 127 | 195 | 254  | 47               | 21               | 29  |
| <b>10</b>                                                                                       | 14   | 21  | 19  | 25  | 19   | 5                | 4                | 4   |
| <b>WY2005 Turbidity Exceedences (FNU)</b>                                                       |      |     |     |     |      |                  |                  |     |
| <b>0.10</b>                                                                                     | 537  | 560 | 334 | 206 | 458  | 248              | 77               | 78  |
| <b>1.0</b>                                                                                      | 155  | 143 | 124 | 96  | 116  | 69               | 24               | 21  |
| <b>10</b>                                                                                       | 19   | 19  | 15  | 14  | 15   | 14               | 6                | 2   |
| <b>WY2006 Turbidity Exceedences (FNU)</b>                                                       |      |     |     |     |      |                  |                  |     |
| <b>0.10</b>                                                                                     | 160  | 137 | 146 | 90  | 234  | 46               | 30               | 27  |
| <b>1.0</b>                                                                                      | 50   | 44  | 46  | 32  | 65   | 14               | 10               | 9   |
| <b>10</b>                                                                                       | 30   | 25  | 28  | 19  | 33   | 8                | 6                | 4   |
| <b>WY2007 Turbidity Exceedences (FNU)</b>                                                       |      |     |     |     |      |                  |                  |     |
| <b>0.10</b>                                                                                     | 198  | 108 | 116 | 31  | 133  | 36               | 17               | 18  |
| <b>1.0</b>                                                                                      | 78   | 33  | 39  | 11  | 41   | 13               | 6                | 8   |
| <b>10</b>                                                                                       | 35   | 19  | 21  | 6   | 22   | 8                | 3                | 3   |
| <b>WY2008 Turbidity Exceedences (FNU)</b>                                                       |      |     |     |     |      |                  |                  |     |
| <b>0.10</b>                                                                                     | 345  | 264 | 196 | 198 | 310  | 64               | 27               | 34  |
| <b>1.0</b>                                                                                      | 123  | 80  | 64  | 58  | 105  | 25               | 8                | 7   |
| <b>10</b>                                                                                       | 29   | 16  | 15  | 12  | 21   | 8                | 2                | 1   |
| <b>WY2009 Turbidity Exceedences (FNU)</b>                                                       |      |     |     |     |      |                  |                  |     |
| <b>0.10</b>                                                                                     | 1045 | 419 | 467 | 311 | 662  | 187              | 36               | 64  |
| <b>1.0</b>                                                                                      | 431  | 197 | 211 | 138 | 323  | 76               | 19               | 21  |
| <b>10</b>                                                                                       | 55   | 17  | 21  | 13  | 27   | 9                | 2                | 1   |
| <b>WY2010 Turbidity Exceedences (FNU)</b>                                                       |      |     |     |     |      |                  |                  |     |
| <b>0.10</b>                                                                                     | 410  | 168 | 388 | 198 | 356  | 154              | 42               | 26  |
| <b>1.0</b>                                                                                      | 135  | 71  | 111 | 70  | 98   | 35               | 17               | 10  |
| <b>10</b>                                                                                       | 28   | 16  | 18  | 10  | 16   | 7                | 2                | 0   |
| <b>WY2011 Turbidity Exceedences (FNU)</b>                                                       |      |     |     |     |      |                  |                  |     |
| <b>0.10</b>                                                                                     | 680  | 603 | 309 | 260 | 401  | 130              | 48               | 33  |
| <b>1.0</b>                                                                                      | 110  | 86  | 82  | 75  | 93   | 27               | 17               | 9   |
| <b>10</b>                                                                                       | 30   | 18  | 18  | 17  | 19   | 8                | 3                | 1   |
| <sup>1</sup> Shaded cells indicate OBS-3 data (FNU) converted to DTS-12 equivalent values (FNU) |      |     |     |     |      |                  |                  |     |
| using data from Lewis and others (2007).                                                        |      |     |     |     |      |                  |                  |     |

The Lost Man Creek stations (SFL, MFL, NFL, LDC and LMC) typically had turbidity exceedences substantially above the other Prairie Creek stations (LLM, PRU, PAB), often by a factor of four or more. Figure 6 plots exceedence curves for four water years (WY2004, WY2006, WY2009, and WY2011) for LMC (at the lower end of Lost Man Creek) and PRU (best control). These years were selected because peak discharges at LMC were close to the study period mean for these years, making the comparison more constant in terms of hydrologic stresses. LMC turbidity exceedences were far higher than those at PRU among all water years portrayed in Figure 6, with the PRU (control) curves plotting approximately an order of magnitude below those for LMC (treatment). Individually, the exceedence

curves for PRU are similar for most water years, while those for LMC are more variable, possibly reflecting the varying magnitude of road removal performed each year. Following completion of road removal, turbidity durations in LMC in WY2011 fell well below the earlier data, contrasting with the control, for which WY2011 turbidity durations fell in the mid-range.

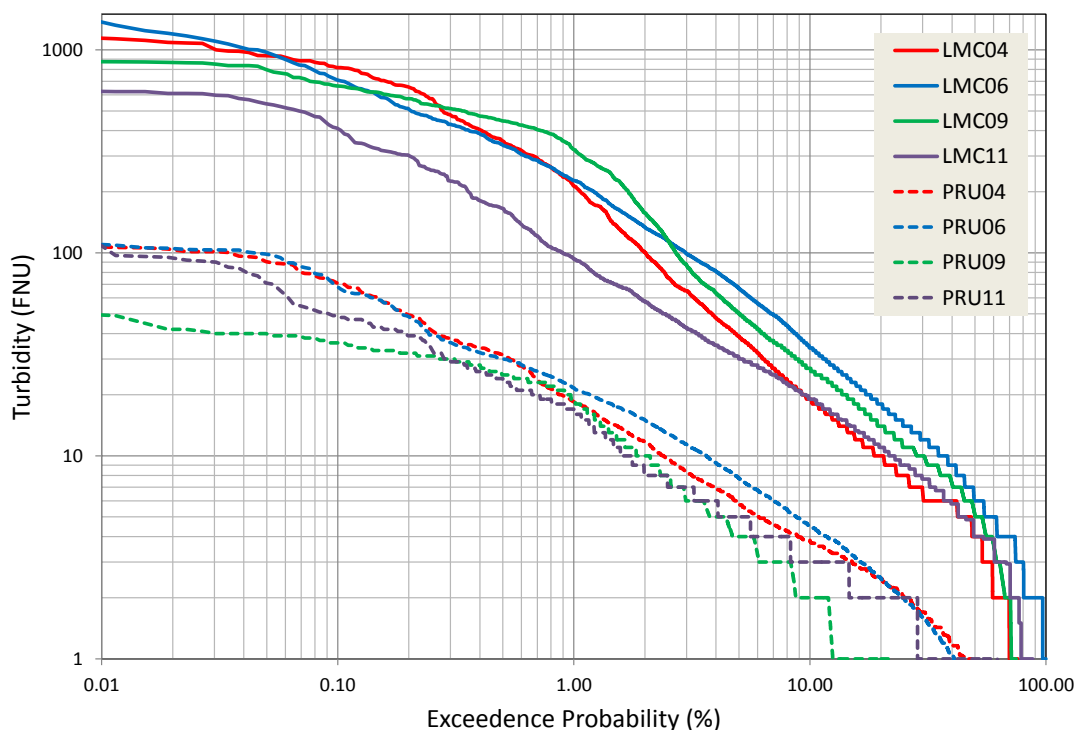


Figure 6. Turbidity duration curves for LMC and PRU (control) for selected water years.

### Suspended Sediment Yields

Figure 7 shows annual suspended sediment yields (SSY) for Lost Man Creek and its tributaries, along with the other Prairie Creek gaging stations, for the entire study period. Since 2003, the various sites in Lost Man Creek were consistently higher than elsewhere in Prairie Creek. Lost Man Creek tributary sites also shifted in relative magnitudes of suspended sediment yields as road removal disturbances moved around the basin and other erosion features, both natural and legacy, alternated between active and dormant states.

In the first year of monitoring in the Lost Man Creek watershed (WY2003) only SFL and LMC were operational. That year, upstream (SFL) loads were only about half those downstream at LMC (basin outlet), indicating that large volumes of suspended sediment were being contributed by the intervening tributaries (MFL, NFL, and LDC). Most of the additional sediment was likely originating in Larry Damm Creek (LDC) from re-mobilization of in-channel sediment deposited downstream of a debris slide that occurred the previous year (the event that led NMFS to mandate the monitoring program). LLM (a potential control) had a relatively high load that year because of natural streamside landslides that had become active. In WY2004, following activation of three additional tributary gaging stations (MFL, NFL, and LDC), LDC remained the dominant sediment contributor to loads at the basin outlet (LMC), but legacy erosion features in SFL became active and elevated its contributions to basin loads. WY2005 was a relatively dry year preceded by very little road removal (see Table 2), so loads were among the lowest of the study period.

WY2006 suspended sediment loads were relatively high in all the Lost Man Creek tributaries despite near normal annual maximum peak flow (Fig. 3) and no road removal disturbances in the previous summer (2005). As discussed earlier, although WY2006 had a near normal annual peak discharge, there were several other storm peaks that were

nearly as large, as indicated in Figure 5, so the ten-peak mean provides a better index of hydrologic stresses than the annual maximum. WY2006 loads in the control streams were near normal and well below those in Lost Man Creek.

In WY2007, MFL had the highest suspended sediment loads despite having had no road removal during the preceding five years. Natural and/or legacy erosion and sediment delivery provide the most plausible explanation. In WY2008 and thereafter, MFL sediment loads returned to the more characteristic lower levels. Beginning in WY2008 loads in SFL ramped upward and were the highest among all study watersheds through WY2011. In WY2009, SFL loads were the highest of any site for the entire study period at 590 tons per square mile. This level of suspended sediment yield is on a par with many watersheds in the region that are actively managed for commercial timber harvest.

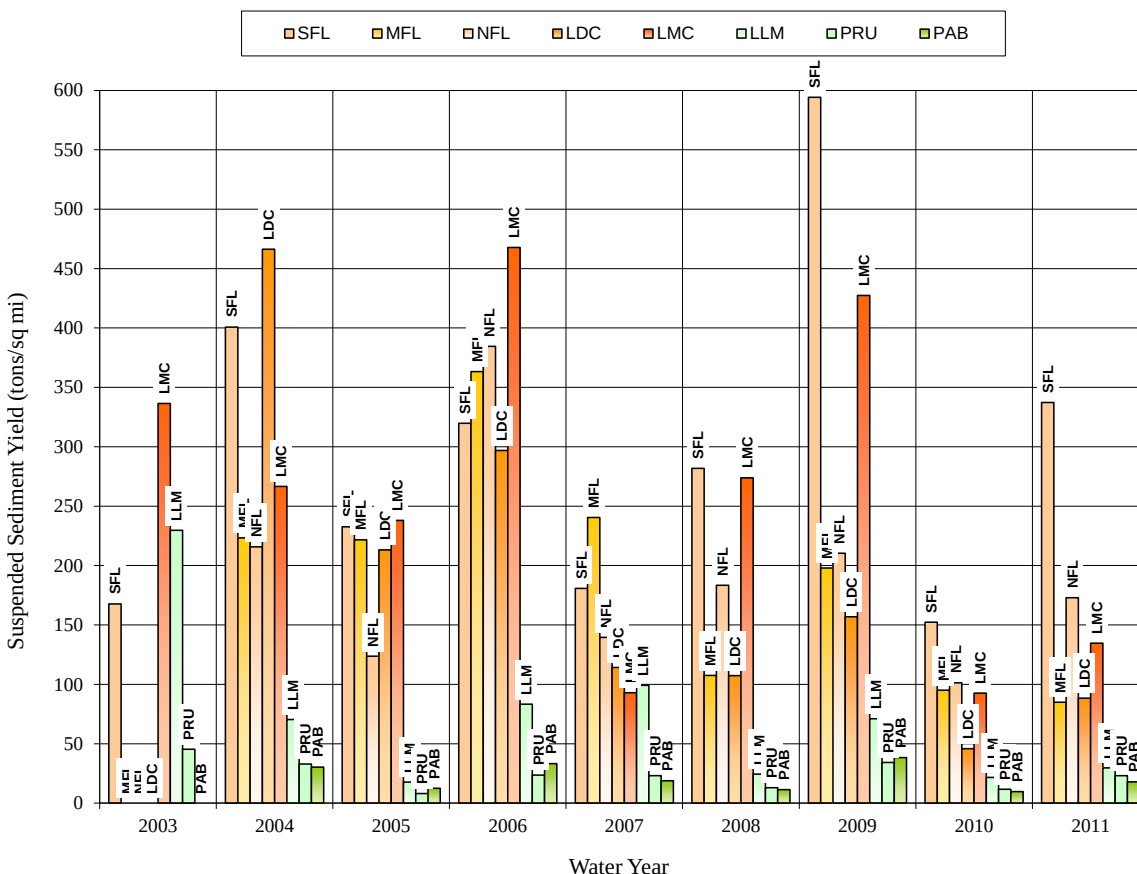


Figure 7. Suspended sediment loads for Prairie Creek gaging stations, WY2003-11.

Suspended sediment yields (SSY) from the Lost Man Creek gages were divided by those from of Upper Prairie Creek (PRU, control) to compute load ratios to remove the effects of annual variability in storm magnitude. Figure 8 shows these ratios for WY2003-2011: the greater the ratio, the relatively higher the yield from a Lost Man Creek gage in any given year. As with the other turbidity parameters evaluated and suspended sediment yields, the treatment/control ratios shifted among the tributaries upstream of LMC over the study period. At times, MFL was among the highest in terms of its ratio to Upper Prairie Creek (PRU, e.g., WY2005-07), but SFL was most often among the highest, particularly in the wetter years (WY2005, WY2006, WY2007, and WY2009) and LDC has been relatively low since WY2005.

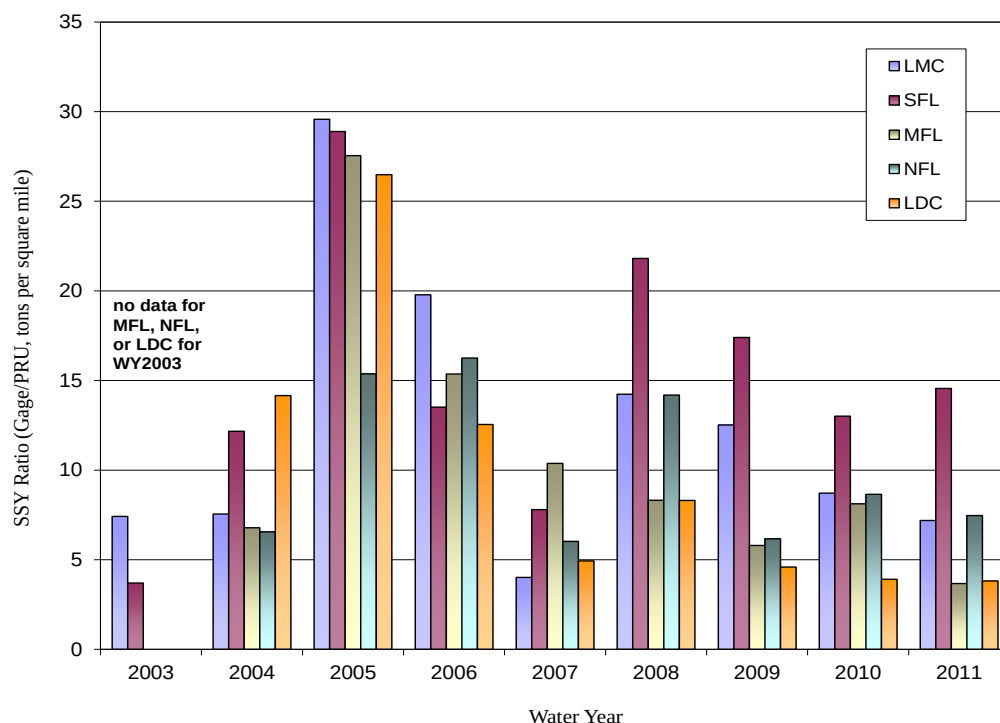


Figure 8. Ratio of Lost Man Creek suspended sediment yields to those at Upper Prairie Creek (PRU), WY2003-11.

### Treatment Intensity vs Peak Storm Turbidities

Figure 9 shows the relationship between road miles treated ('RMT', i.e., treatment intensity) in the prior summer and the treatment/control ratios for three water quality variables: 1) the mean of peak turbidity for the ten largest storms of each year (PTR), 2) the 10% turbidity ('10%TU'), and 3) suspended sediment yield ('SSY'). The use of the treatment/control ratios for these variables normalizes for annual variations in storm intensities. No treatments in earlier years were considered because a previous analysis (described in the WY2008 report) showed the strongest correlation was with just the prior year's road treatments. Note that because of the activation of legacy landslides in SFL in WY2005 and terrace erosion around the weir just upstream of LMC that occurred in WY2006 (mentioned earlier), suspended sediment loads for those years were anomalously high. Consequently, SSY data for those years were omitted in the regression analysis in Figure 9. The PTR data point for WY2003 (first year of study; circled point in Fig. 9) lies the farthest off its regression line, and its position above the line indicates a relatively higher turbidity ratio than the other years. This anomalously high value almost certainly reflected the large debris flow event that occurred on a restoration site in Larry Damm Creek in WY2002. Channel-stored fine sediment from this event likely was likely re-mobilized in WY2003, elevating turbidities downstream at LMC. Unfortunately, continuous monitoring in Larry Damm Creek did not begin until the following year (WY2004).

The R-squared values for all three water quality variables in Figure 9 suggest fairly strong relationships with treatment intensity despite the known and potentially confounding influences of natural and legacy erosion and sediment delivery. The small data sets used for the regressions, however, severely limit the predictive capabilities of these relationships. Figure 10 plots the time series of annual road miles treated upstream of LMC at the watershed mouth (RMT) and the mean treatment/control turbidity ratio (LMC/PRU) for the ten largest storms each subsequent winter. For the overlapping period (WY2003-11) these two variables track very well, consistent with the relationship apparent in Fig. 9. One exception is WY2003, the first year of monitoring, when the peak turbidity ratio was relatively high. As discussed above, the higher turbidities in WY2003 occurred because of residual effects of the large debris flow in Larry Damm Creek in WY2002, as discussed above.

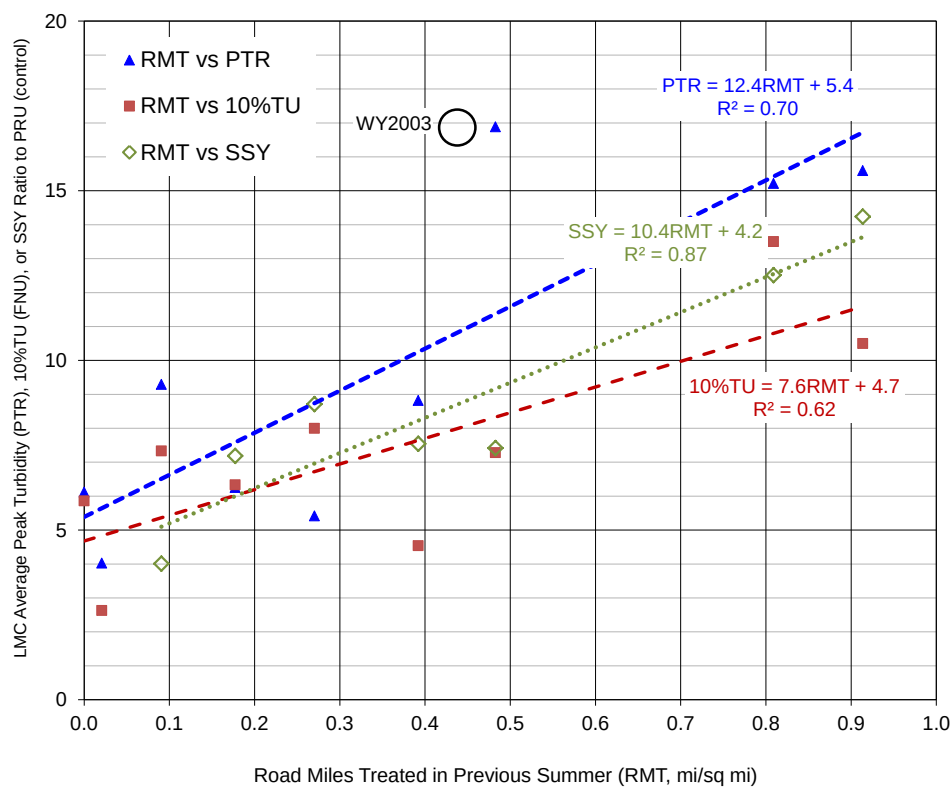


Figure 9. Ratio of Lost Man Creek (LMC) to control site (PRU) of mean peak turbidity for 10 largest annual winter storms (PTR), 10% exceedence turbidity (10%TU), and suspended sediment yield (SSY) versus prior season road treatment lengths (RMT), 2003-2011.

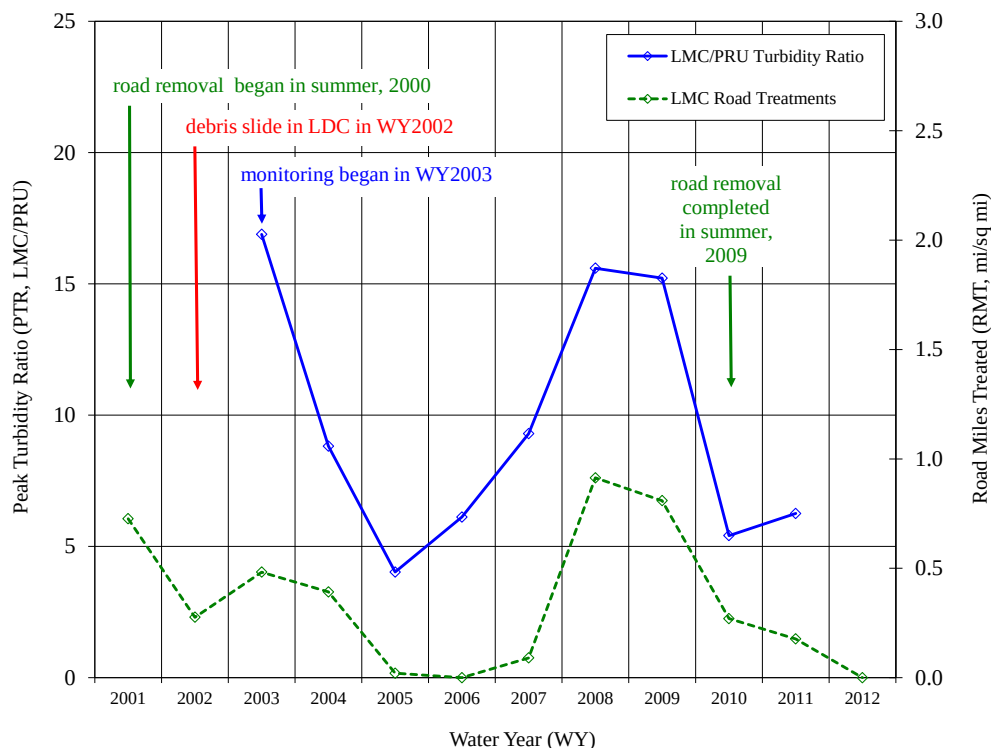


Figure 10. Ratio of Lost Man Creek (LMC) to control site (PRU) of mean peak turbidity for 10 largest annual winter storms (PTR) and prior season road treatment lengths (RMT), 2003-2011.

## Sub-watershed Responses

Larry Damm Creek (LDC) was a disproportionately large source of suspended sediment and turbidity to downstream areas in WY2003 and WY2004. This might be expected from the intensity of road removal in preceding years (7 miles in 2002-2003, Table 2) and the residual effects of the debris slide that failed in 2002. However, by WY2006, its relative contribution had diminished considerably, suggesting that the former instability from road decommissioning work was short lived. Despite a slight rise in WY2008, Larry Damm Creek continued its relatively low sediment contributions through the end of the study period.

North Fork Lost Man Creek (NFL) was consistently a smaller turbidity/sediment contributor among the treated sub-watersheds for WY2004-2005, despite having had substantial road work in 2000-02 (almost 11 miles of road removal), prior to the beginning of the monitoring project. NFL's turbidity increased somewhat relative to the other sites in WY2006-2011.

Middle Fork Lost Man Creek (MFL) was similarly low to the North Fork (NFL) in sediment contributions for the first two years of monitoring, until WY2005, when it jumped to nearly twice that of the North Fork. Although this could be a delayed effect of road work done in 2000-01, because it occurred several years after the most recent road work (in 2001) it was more likely caused by either natural or legacy erosion. MFL contributed similar suspended sediment to NFL in WY2006 and WY2009, but exceeded NFL in WY2007 and was less than NFL in WY2008. Explanations for this see-saw relationship are likely not due to differences in road removal: between 2007 and 2008: MFL had twice as much road length treated as NFL in 2006 (just prior to WY2007 monitoring) and less than half that in NFL in 2008 (just prior to WY2009 monitoring), the opposite of what would be expected were the turbidity differences due to road treatments. Consequently, differences must be due to legacy and natural erosion sources operating within the watersheds. As of WY2011, was second only to SFL in both road miles treated and sediment loads among the Lost Man Creek tributaries.

South Fork Lost Man Creek (SFL): In the first year of monitoring (WY2003), turbidities were much lower in SFL than the downstream station (LMC) that included the effects of road treatments in Larry Damm Creek (LDC), and were quite similar to those in Little Lost Man Creek (LLM), an adjacent undisturbed basin of similar size (see Table 3 and Fig. 5a). However, in WY2004 SFL turbidities greatly increased relative to those at the control sites (see Fig. 5b), suggesting increased erosion activity upstream. Legacy roads and skid trails are the most likely culprits, with natural erosion processes contributing a relatively smaller proportion. During WY2005, SFL was on par with the other Lost Man Creek sites except the North Fork (NFL) which was a low contributor (Fig. 5c). During WY2006 SFL contributions were similar to those from the three other Lost Man tributaries (MFL, NFL, and LDC), suggesting legacy and natural features might be becoming less active. With resumption of treatments in 2006, SFL peak turbidities and sediment yields rose again (see Figs. 5d-5i, 7, and 8), most likely a response to the recent road decommissioning in combination with active legacy and natural erosion. SFL remained the most turbid site through WY2011, and will likely continue to be the most turbid even with waning road decommissioning effects because of the active legacy features persisting in the watershed.

## SUMMARY AND CONCLUSIONS

### Summary

To our knowledge, the monitoring project to quantify road removal effects in Lost Man Creek is unique in scope and intensity. The use of continuous turbidity and discharge monitoring provided insights that would be very difficult, if not impossible, to gain by relying solely manual sampling. The role of road removal in elevating downstream sediment yields and turbidities was demonstrated with a fair amount of certainty. However, for making site-specific adaptations to reduce sediment delivery, onsite reviews are essential. Although we cannot precisely quantify the benefits mitigations derived from onsite observations provide on past and future erosion and sediment delivery, we can say that the more rigorously they are applied, the greater the total amount of road removal can occur while triggering a similar magnitude of offsite effects. In other words, the more aggressively we pursue decommissioning of roads in a watershed, the more intensively we should apply mitigations to minimize post-treatment sediment delivery.

On the question of concentrating versus dispersing restoration activities in time and space, the best answer we can provide at present is equivocal: it depends on issues specific to the watershed being considered, such as what species are of special interest (e.g., endangered salmon), where critical habitat for those species is located in relation the restoration work being contemplated, what attributes of the habitat may be at risk from restoration work (e.g., fine sediment intrusion into spawning gravels, benthic food availability, etc.), and others. For example, had we completed restoration work in Lost Man Creek sub-basin by sub-basin, we might have done Larry Damm Creek, the farthest downstream, first. This would have limited the effects of, say, fines intrusion on mainstem spawning gravel quality to a much smaller portion of the available main stem spawning habitat (only the reach downstream of the mouth of Larry Damm Creek). But a tradeoff that arises with limiting geographic scope in this way would have been to intensify localized effects downstream from the mouth of Larry Damm Creek.

Having information on spawning gravel or juvenile rearing quality could assist in decisions on dispersing versus concentrating restoration effects, but weather, or the unpredictability thereof, would tend to confound decision making. For example, fines intruded from an upstream, one-time sediment-producing disturbance can be flushed away rather quickly if the sediment source diminishes rapidly with time (as with road decommissioning) and storms of sufficient magnitude to mobilize the streambed soon follow. But if instead a series of low magnitude storm seasons follow, intruded fines can reside for years after the one-time event, thus prolonging the downstream effects of restoration on habitat.

As indicated by the preceding discussion, many factors can affect the magnitude and persistence of restoration effects, perhaps too many to incorporate into a decision-making framework. This argues strongly for aggressively applying mitigations, as stated above, rather than applying some scheme that depends heavily on assumptions to allocate impacts in a particular temporal or spatial pattern.

## Conclusions

1. Onsite turbidity sampling performed in WY2003-2004 revealed that some stream crossing excavations contributed large amounts of sediment to downstream channels on occasion, but contributions generally decreased rapidly over time. These findings are consistent with similar studies.
2. Onsite monitoring for turbidity proved to be of limited value. It was abandoned after two years because it cannot provide hydrologically consistent or complete data.
3. Peak storm turbidities, turbidities at the 10% exceedence level, and suspended sediment yields varied directly and approximately linearly with treatment intensity.
4. Legacy and natural erosion processes are still active in Lost Man Creek, particularly in the upstream portions of the watershed (above SFL) and tended to confound the ability to quantify restoration effects.
5. Adaptive management informed by this monitoring project has likely reduced erosion and sediment delivery from road treatments.
6. The year-to-year variability in road treatment intensity was high, resulting in several years of very intense treatments and resultant turbidity increases. A more modulated treatment approach could reduce maximum restoration effects.
7. Road work in Lost Man Creek, completed in 2010, should reduce suspended sediment loads and turbidities over the coming years, although legacy and natural erosion and sediment delivery will continue indefinitely on an episodic basis.

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## APPENDIX A.

Peak turbidities of ten largest storms of WY2003-11 in Lost Man Creek and elsewhere in Prairie Creek (blank cells mean no data; shaded cells contain data converted from OBS-3 to DTS-12 turbidity sensor equivalent values).

|                                                                                                                                                       | Storm Date | SFL  | MFL | NFL | LDC  | LMC <sup>1</sup> | LLM <sup>2</sup> | PRU <sup>2</sup> |
|-------------------------------------------------------------------------------------------------------------------------------------------------------|------------|------|-----|-----|------|------------------|------------------|------------------|
| WY2003                                                                                                                                                | 12/13/02   | 158  | --- | --- | ---  | 469              | 1212             | 1405             |
|                                                                                                                                                       | 12/14/02   | 288  | --- | --- | ---  | 937              | 79               | 151              |
|                                                                                                                                                       | 12/16/02   | 750  | --- | --- | ---  | 1887             | 260              | 211              |
|                                                                                                                                                       | 12/20/02   | 123  | --- | --- | ---  | 897              | 47               | 79               |
|                                                                                                                                                       | 12/27/02   | 677  | --- | --- | ---  | 1826             | 340              | 888              |
|                                                                                                                                                       | 12/31/02   | 183  | --- | --- | ---  | 1666             | 52               | 67               |
|                                                                                                                                                       | 01/13/03   | 192  | --- | --- | ---  | 1372             | 42               | 69               |
|                                                                                                                                                       | 01/27/03   | 132  | --- | --- | ---  | 896              | 632              | 324              |
|                                                                                                                                                       | 02/19/03   | 198  | --- | --- | ---  | 438              | 357              | 127              |
|                                                                                                                                                       | 03/26/03   | 76   | --- | --- | ---  | 151              | 238              | 250              |
| WY2004                                                                                                                                                | 12/06/03   | 339  | 257 | 746 | 1070 | 485              | 231              | 33               |
|                                                                                                                                                       | 12/13/03a  | 1458 | 485 | 895 | 1403 | 1258             | 276              | 306              |
|                                                                                                                                                       | 12/13/03b  | 406  | 289 | 390 | 1779 | 1087             | 1441             | 764              |
|                                                                                                                                                       | 12/29/03   | 472  | 374 | 390 | 239  | 1134             | 184              | 262              |
|                                                                                                                                                       | 01/01/04   | 107  | 117 | 113 | 112  | 206              | 31               | 96               |
|                                                                                                                                                       | 01/27/04   | 34   | 147 | 168 | 123  | 83               | 165              | 78               |
|                                                                                                                                                       | 01/30/04   | 20   | 40  | 111 | 178  | 44               | 43               | 53               |
|                                                                                                                                                       | 02/02/04   | 11   | 31  | 106 | 202  | 43               | 32               | 88               |
|                                                                                                                                                       | 02/17/04   | 367  | 345 | 257 | 238  | 301.8            | 601              | 739              |
|                                                                                                                                                       | 02/27/04   | 31   | 61  | 106 | 72   | 67.5             | 83               | 197              |
| WY2005                                                                                                                                                | 12/06/04   | 507  | 310 | 367 | 163  | 236              | 203              | 261              |
|                                                                                                                                                       | 12/08/04   | 325  | 296 | 374 | 140  | 175              | 389              | 603              |
|                                                                                                                                                       | 01/01/05   | 66   | 63  | 79  | 41   | 38               | 204              | 230              |
|                                                                                                                                                       | 01/08/05   | 235  | 204 | 105 | 99   | 71               | 98               | 184              |
|                                                                                                                                                       | 03/20/05   | 194  | 245 | 310 | 157  | 117              | 42               | 59               |
|                                                                                                                                                       | 03/22/05   | 254  | 153 | 113 | 163  | 183              | 230              | 618              |
|                                                                                                                                                       | 03/29/05   | 292  | 295 | 288 | 226  | 295              | 129              | 245              |
|                                                                                                                                                       | 04/08/05   | 752  | 932 | 375 | 202  | 856              | 25               | 55               |
|                                                                                                                                                       | 05/8/05a   | 178  | 199 | 235 | 155  | 117              | 245              | 349              |
|                                                                                                                                                       | 05/8/05b   | 26   | 37  | 44  | 44   | 33               | 234              | 448              |
| WY2006                                                                                                                                                | 11/06/05   | 960  | 586 | 769 | 371  | 612              | 280              | 483              |
|                                                                                                                                                       | 12/01/05   | 626  | 550 | 839 | 468  | 1623             | 74               | 117              |
|                                                                                                                                                       | 12/28/05   | 450  | 354 | 295 | 196  | 519              | 26               | 28               |
|                                                                                                                                                       | 12/30/05   | 550  | 231 | 229 | 130  | 767              | 117              | 182              |
|                                                                                                                                                       | 01/11/06   | 180  | 171 | 156 | 101  | 216              | 64               | 33               |
|                                                                                                                                                       | 01/18/06   | 81   | 116 | 220 | 97   | 95               | 222              | 279              |
|                                                                                                                                                       | 02/02/06   | 267  | 72  | 102 | 71   | 115              | 49               | 77               |
|                                                                                                                                                       | 02/28/06   | 336  | 181 | 258 | 155  | 259              | 41               | 46               |
|                                                                                                                                                       | 03/05/06   | 48   | 80  | 275 | 93   | 122              | 539              | 246              |
|                                                                                                                                                       | 03/16/05   | 95   | 121 | 218 | 113  | 140              | 113              | 150              |
| WY2007                                                                                                                                                | 11/22/06   | 859  | 202 | 400 | 142  | 403              | 61               | 5                |
|                                                                                                                                                       | 11/27/06   | 52   | 32  | 42  | 47   | 51               | 5                | 4                |
|                                                                                                                                                       | 12/13/06   | 875  | 309 | 290 | 76   | 502              | 171              | 53               |
|                                                                                                                                                       | 12/26/06   | 590  | 449 | 255 | 58   | 437              | 111              | 64               |
|                                                                                                                                                       | 01/03/07   | 363  | 135 | 118 | 54   | 196              | 149              | 16               |
|                                                                                                                                                       | 02/11/07   | 244  | 206 | 219 | 40   | 149              | 24               | 8                |
|                                                                                                                                                       | 02/22/07   | 177  | 103 | 100 | 27   | 130              | 35               | 30               |
|                                                                                                                                                       | 02/25/07   | 75   | 53  | 57  | 27   | 187              | 9                | 19               |
|                                                                                                                                                       | 02/27/07   | 80   | 21  | 31  | 11   | 45               | 81               | 21               |
|                                                                                                                                                       | 03/27/07   | 92   | 264 | 223 | 32   | 121              | 27               | 19               |
| <sup>1</sup> Peak turbidities estimated for LMC for Dec 17 and 27, 2004.                                                                              |            |      |     |     |      |                  |                  |                  |
| <sup>2</sup> OBS-3 data (FBU) converted to DTS-12 equivalent values (FNU) in shaded cells using equations based on data from Lewis and others (2007). |            |      |     |     |      |                  |                  |                  |

**APPENDIX A. (cont'.)**

Peak turbidities of ten largest storms of WY2003-11 in Lost Man Creek and elsewhere in Prairie Creek (blank cells mean no data; shaded cells contain data converted from OBS-3 to DTS-12 turbidity sensor equivalent values).

|        | Storm Date | SFL  | MFL  | NFL  | LDC | LMC <sup>1</sup> | LLM <sup>2</sup> | PRU <sup>2</sup> | PAB |
|--------|------------|------|------|------|-----|------------------|------------------|------------------|-----|
| WY2008 | 10/19/07   | 1676 | 808  | 1031 | 62  | 1060             | 183              | 74               | 104 |
|        | 11/19/07   | 176  | 66   | 119  | 7   | 119              | 50               | 7                | 24  |
|        | 12/20/07   | 608  | 197  | 165  | 61  | 211              | 23               | 12               | 8   |
|        | 12/24/07   | 130  | 41   | 64   | 36  | 75               | 34               | 13               | 13  |
|        | 01/04/08   | 408  | 252  | 661  | 244 | 366              | 73               | 10               | 82  |
|        | 01/05/08   | 127  | 45   | 54   | 66  | 85               | 35               | 7                | 7   |
|        | 01/07/08   | 144  | 37   | 56   | 65  | 81               | 22               | 5                | 5   |
|        | 01/31/08   | 534  | 445  | 249  | 239 | 494              | 111              | 33               | 38  |
|        | 02/03/08   | 264  | 264  | 101  | 104 | 273              | 47               | 7                | 8   |
| WY2009 | 03/28/08   | 165  | 182  | 194  | 155 | 168              | 22               | 20               | 25  |
|        | 12/21/08   | 260  | 177  | 27   | 55  | 179              | 26               | 8                | 7   |
|        | 12/25/08   | 145  | 208  | 236  | 53  | 150              | 25               | 12               | 4   |
|        | 12/28/08   | 1376 | 947  | 572  | 336 | 882              | 254              | 64               | 71  |
|        | 01/02/09   | 460  | 144  | 203  | 74  | 265              | 45               | 12               | 13  |
|        | 02/14/09   | 176  | 28   | 77   | 41  | 84               | 28               | 3                | 3   |
|        | 02/23/09   | 323  | 130  | 63   | 120 | 228              | 55               | 23               | 13  |
|        | 02/26/09   | 156  | 38   | 43   | 10  | 43               | 10               | 3                | 0   |
|        | 03/03/09   | 160  | 29   | 71   | 46  | 50               | 10               | 4                | 1   |
| WY2010 | 03/16/09   | 1184 | 425  | 554  | 336 | 840              | 310              | 42               | 35  |
|        | 03/22/09   | 401  | 69   | 154  | 108 | 140              | 21               | 17               | 9   |
|        | 12/21/09   | 259  | 157  | 202  | 107 | 169              | 62               | 54               | 22  |
|        | 01/01/10   | 503  | 285  | 455  | 212 | 379              | 359              | 49               | 15  |
|        | 01/13/10   | 177  | 158  | 179  | 87  | 92               | 33               | 38               | 19  |
|        | 01/19/10   | 155  | 81   | 144  | 111 | 85               | 24               | 2                | 3   |
|        | 01/26/10   | 211  | 37   | 48   | 13  | 37               | 6                | 1                | 0.1 |
|        | 02/26/10   | 550  | 176  | 466  | 301 | 441              | 111              | 39               | 27  |
|        | 03/13/10   | 170  | 104  | 190  | 108 | 128              | 13               | 28               | 14  |
| WY2011 | 03/31/10   | 150  | 23   | 45   | 59  | 47               | 17               | 10               | 33  |
|        | 04/27/10   | 260  | 187  | 268  | 190 | 225              | 58               | 63               | 29  |
|        | 06/02/10   | 220  | 179  | 341  | 171 | 200              | 33               | 49               | 26  |
|        | 11/23/10   | 320  | 211  | 367  | 160 | 260              | 85               | 31               | 34  |
|        | 11/27/10   | 140  | 62   | 93   | 53  | 55               | 15               | 8                | 3   |
|        | 12/02/10   | 41   | 24   | 23   | 18  | 25               | 13               | 3                | 1   |
|        | 12/14/10   | 140  | 95   | 143  | 53  | 69               | 15               | 9                | 7   |
|        | 12/29/10   | 1500 | 1102 | 564  | 406 | 623              | 316              | 138              | 51  |
|        | 03/08/11   | 260  | 171  | 216  | 184 | 180              | 52               | 25               | 25  |
|        | 03/15/11   | 54   | 43   | 62   | 26  | 54               | 11               | 8                | 4   |
|        | 03/18/11   | 48   | 36   | 38   | 47  | 35               | 9                | 4                | 3   |
|        | 03/25/11   | 200  | 385  | 191  | 80  | 170              | 51               | 9                | 12  |
|        | 04/15/11   | 110  | 92   | 118  | 105 | 105              | 36               | 17               | 12  |