Cover Sheet

The Effects of Selected Post-fire Emergency Rehabilitation Techniques on Small Watershed Sediment Yields in Southern California

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Abstract: Over the past five years, Forest Service Research has quantified the effects of selected BAER treatments on small watershed sediment yields by constructing dams to impound runoff and measure debris from several burn sites in southern California. In 1999 the Mixing Fire burned over 1200 hectares of mixed pine/oak forest with a brush understory on granitic terrain in the San Bernardino National Forest. A 1 hectare watershed treated with log erosion barriers (LEBs) was compared to a nearby control catchment. Results indicate that, although the LEBs retained considerable sediment, unforeseen differences in site characteristics masked any differences in treatment effectiveness. The 2002 Williams Fire burned over 15,000 hectares of chaparral on largely metamorphic terrain on the Angeles National Forest. Seven different 1-2 hectare watersheds were used to compare the effects of polyacrylamide (PAM), a soil flocculent, and prefabricated small-diameter log structures as channel check dams against nearby controls. Results indicate that PAM had no effect but that the channel checks significantly reduced sediment yield. In 2003 the Cedar Fire burned about 117,000 hectares of brush on granitic terrain in the Cleveland National Forest. Three 2-3 hectare watersheds were used to compare two levels of an aerial hydromulch treatment (100 percent treated and 50 percent contour strips) to a nearby control. Preliminary results indicate that the 50 percent treatment produced more sediment than the control but the 100 percent treatment generated less than half the sediment of the untreated watershed. Rigorous testing needs to continue before these treatments become standard practice.

Keywords: fire, post-fire erosion, erosion control, monitoring, debris basins, sediment yield, BAER treatments

<H1>Introduction

In fire-prone Southwestern ecosystems, it has been well documented that wildfire can dramatically alter the erosion response of upland landscapes (Kraebel 1934; Wells 1981; Heede et al. 1988), primarily by removing the protective vegetation canopy and ground surface organic material. In addition, the combustion of soil organic matter can create a subsurface water-repellent layer that restricts infiltration and promotes overland flow (DeBano 1981), thereby enhancing sediment production (Hamilton et al. 1954; Hibbert 1985). In southern California, first-year post-fire sediment yield is 35 times greater on average than comparable unburned annual levels (Rowe et al. 1954).

Accelerated post-fire erosion and sedimentation can threaten life, property, and infrastructure at the southern California wildland/urban interface, where growing population centers meet the adjacent steep mountain fronts. Moreover, post-fire environmental degradation can destroy habitat and populations of endangered species along sensitive riparian corridors. To mitigate these undesirable post-fire consequences, federal land managers have developed a Burned Area Emergency Response (BAER) program of hillslope and stream channel rehabilitation treatments for the purpose of erosion control. The goal of these treatments is to cost-effectively protect both the onsite and downstream values at risk until the native vegetation community develops to the point that watersheds function normally again.

Landscape-level post-fire erosion control treatments attempt to reduce and delay the accelerated erosion and sedimentation that typically follows wildfires. Although many types of treatments have been utilized over the years, they can be grouped into three different classes: 1) ground covers (mulch, seeding) to reduce the erosive power of rainsplash and overland flow; 2) mechanical barriers (log erosion barriers, straw wattles) to retain debris; and 3) chemical sprays (wetting or flocculating agents) to promote infiltration thereby reducing overland flow. Unfortunately, the benefits of many of these erosion control measures have yet to be quantitatively demonstrated in rigorous field studies (Robichaud et al. 2000).

Over the past five years, Forest Service Research has quantified the effects of selected BAER treatments on small watershed sediment yields from several burn sites in southern California. The purpose of this research is to evaluate the effectiveness of these rehabilitation efforts as erosion control practices, as well as to document the post-fire sediment yield response from a variety of different field locations. Eventually, the results will be incorporated into numerical models for planning and risk assessment.

<H1>Study Sites and Treatment Descriptions

The study sites are located on Forest Service lands in the mountains of southern California (Figure 1). The study areas all have differing site characteristics, but they were all burned in wildfires during the late summer or early fall. Fires in southern California are especially severe at this time of year, coming at the end of the summer drought and often fanned by strong Santa Ana winds. For this study we chose small burned watersheds, 1-3 hectares in size, which were treated operationally with various rehabilitation measures. Sediment yield from these treated watersheds was then compared with similar nearby burned but untreated control watersheds.

<H2>The Mixing Fire

In September 1999, the Mixing Fire burned over 1200 ha on the San Jacinto Ranger District of the San Bernardino National Forest. The fire occurred in an area of granitic terrain at an elevation of 1500 m in the San Jacinto Mountains. The general location receives an annual average precipitation of 550 mm, including snow in the winter and occasional thunderstorms in the summer. The specific study site supported a mixed forest of pine (*Pinus coulteri*), black oak (*Quercus kelloggii*), and canyon live oak (*Quercus chrysolepis*) with an understory of buckbrush (*Ceanothus leucodermis*) and manzanita (*Arctostaphylos spp.*) (Wohlgemuth et al. 2001). Selected site characteristics are arrayed in Table 1.

Much of the Mixing Fire was treated with log erosion barriers (LEBs). LEBs are built by felling and placing fire-killed trees along the hillside contours. The LEBs are designed to retard the overland flow of water and sediment on hillside slopes, reducing post-fire hillslope erosion and sediment delivery to stream channels (Robichaud et al. 2000). LEBs are placed in an overlapping arrangement that maximizes ponding (fostering infiltration and sediment deposition) and minimizes potential barrier failure.

<H2>The Williams Fire

In September 2002, the Williams Fire burned over 15,000 ha on the San Gabriel River Ranger District of the Angeles National Forest. The fire occurred in an area of metamorphic terrain at an elevation of 900 m in the San Gabriel Mountains. The general location receives an annual average precipitation of 700 mm that is generated almost exclusively by winter cyclonic storms. The specific study site supported brushfields of mixed chaparral dominated by buckbrush (*Ceanothus spp.*), chamise (*Adenostoma fasiculatum*), and scrub oak (*Quercus berberidifolia*) (Wohlgemuth 2003). Selected site characteristics are arrayed in Table 1.

A portion of the Williams Fire was treated with polyacrylamide (PAM), a proprietary soil-flocculating agent. The intent of this helicopter-applied treatment is to aggregate the fine soil particles, thus promoting infiltration and thereby reducing overland flow (Flanagan and Chandhari 1999), especially in areas of suspected water repellent soils. Other sections of the Williams Fire were treated with prefabricated small-diameter log structures placed roughly 5-10 m apart along the stream courses. These barriers were intended to serve as sediment storage sites and grade control structures to prevent the scouring of the channel bed and banks by accelerated post-fire runoff (Wohlgemuth 2003).

<H2>The Cedar Fire

In October 2003, the Cedar Fire burned over 117,000 ha on the Descanso Ranger District of the Cleveland National Forest. The fire occurred in an area of granitic terrain at an elevation of 700 m in the foothills of the Laguna Mountains. The general location receives an annual average precipitation of 415 mm primarily generated by winter cyclonic storms with rare summer thunderstorms. The specific study site supported chaparral brushfields composed almost exclusively of chamise (*Adenostoma fasiculatum*) (Kirsten Winter, personal communication). Selected site characteristics are arrayed in Table 1.

Approximately 350 ha of the Cedar Fire were treated with aerial hydromulch. A wood and paper fiber matrix with a non water-soluble binder, the mulch was mixed as a slurry and applied by helicopter. It was delivered at two application rates: 100 percent cover, and 50 percent cover in 30 m contour strips. The intent of the mulch treatment was to bind the loose surface soil together, reducing detachment and transport by rainsplash and overland flow, while still allowing infiltration across the landscape.

<H1>Methods

Monitoring facilities and equipment were installed at the Mixing Fire site within two months after the wildfire. One watershed was instrumented in an area treated with LEBs and a nearby catchment was instrumented as an untreated control. The installations consisted of wood and sheet metal debris dams constructed across the stream channels to impound sediment, raingages, and a weather station (temperature, relative humidity, solar radiation, wind speed, and wind direction). Initial LEB sediment storage capacities were estimated by measuring 2-3 ground surface profiles across the storage area perpendicular to the log, obtaining an average, and multiplying by the length of the log. LEB accumulations were determined by periodically re-surveying the profiles and calculating the difference in storage volumes. Sediment yield was measured by collecting the trapped debris from behind the dam in buckets and weighing it on a portable scale. Subsamples of the sediment were taken back to the laboratory to correct the field weights for moisture content. Results were normalized by watershed area as megagrams per hectare to facilitate comparison.

The Williams Fire burned over existing small watershed monitoring facilities on the San Dimas Experimental Forest. Two watersheds were selected for a PAM application and two nearby catchments were chosen as untreated controls. Two other watersheds had 25-35 log structures placed in the channels and were compared against a single nearby control catchment. The facilities consisted of earth-fill dams with concrete outflow structures (Rice et al. 1965), raingages, and a weather station (temperature, relative humidity, solar radiation, wind speed, and wind direction). Sediment yields were calculated as volumes using an engineering end-area formula (Eakin 1939) based on repeated sag tape surveys of permanent cross sections (Ray and Megahan 1978). The volumes were converted to weights using measured debris densities, and the results were normalized by watershed area as megagrams per hectare to facilitate comparison.

Monitoring facilities and equipment were installed at the Cedar Fire site within three months after the wildfire. One watershed was instrumented in an area treated with 100 percent aerial hydromulch cover, a second nearby catchment was instrumented in an area with 50 percent contour strips, and a third nearby catchment was instrumented as an untreated control. As with the Mixing Fire sites, the installations consisted of wood and sheet metal debris dams constructed across the stream channels to impound sediment, raingages, and a weather station (temperature, relative humidity, solar radiation, wind speed, and wind direction). Sediment yield was similarly measured by collecting the trapped debris from behind the dam in buckets and weighing it on a portable scale. Subsamples of the sediment were taken back to the laboratory to correct the field weights for moisture content. However, large sediment accumulations were handled differently. As with the Williams Fire sites, volumes were calculated from sag-tape surveys and converted to weights using measured debris densities. The sediment was then removed with a mechanical excavator and the surveys were performed again to obtain the new baseline geometry. Regardless of the measurement technique, results were normalized by watershed area as megagrams per hectare to facilitate comparison.

<H1>Results and Discussion

The 1.2 ha treated watershed at the Mixing Fire site contained 157 LEBs with an initial total sediment storage capacity of 72 m^3. Overall, the LEBs performed quite well. Only about 6 percent of the LEBs failed by undermining and only another 6 percent had a significant flow of water around the ends of the logs (Wohlgemuth et al. 2001). At present, less than 4 percent of the LEBs have had their storage area filled with sediment, while about 5 percent have been rendered useless after being struck by wind-toppled fire-killed trees. The LEB accumulations for the first four years of the study are arrayed in Table 2. Cumulatively, a total of 17 m^3 of sediment has been trapped by the LEBs, less than 25 percent of their capacity. Note that the vast majority (over 75 percent) of the material accumulated in the first two years of the study.

Sediment yield for the Mixing Fire, separated by winter cyclonic storm and summer thunderstorm seasons, is arrayed in Table 3. These values are small compared to the Williams Fire and Cedar Fire sites, as well as to other published rates of southern California post-fire sediment yield (Rowe et al. 1954; Loomis et al. 2003). However, there are spectacular differences in sediment yield between the treated and untreated watersheds.

Initially, the treated catchment on the Mixing Fire site produced an order of magnitude more sediment than the control. This can be explained in part by the fact that the soil depths on the treated watershed are only half those of the control (Wohlgemuth et al. 2001). With the fire in late summer, the soils must have been nearly de-watered. With the low precipitation in the first post-fire winter (see Table 3), water storage in the soils was presumably exceeded on the treated watershed but not on the untreated catchment. This generated sediment delivery from the hillslopes to the streams by overland flow, and the routing of this sediment to the debris basin by channel runoff.

The pattern of watershed response on the Mixing Fire then reversed itself, starting with the second summer after the fire (see Table 3). A high-intensity thunderstorm produced a large sediment pulse in the control watershed, but had little effect on the treated catchment. Site inspection revealed that the source of the sediment in the untreated watershed was a large area of bare ground directly adjacent to the stream channel. The massive overland flow off this bare patch extensively rilled the hillside and scoured the channel bed and banks. Erosion from this bare ground section continued to generate high levels of sediment yield into the winter of 2002 (Table 3).

It is unfortunate that sediment yield on the Mixing Fire site was governed more by the inherent site characteristics than by the presence or absence of the LEBs. This demonstrates the need to carefully choose comparable study watersheds. It also points out a problem with no replication in the study design. However, because of the differences in soil depths and vegetation cover, any watershed response that would relate to the efficacy of the LEBs as a post-fire rehabilitation treatment has been effectively masked.

The sediment yield results of the post-fire treatment comparisons for the Williams Fire are arrayed in Table 4. These values indicate that, for this study site, PAM does little to reduce small watershed sediment yields. Although site differences may once again be a factor, with multiple treated and untreated catchments (with Treated 1 paired with Control 1, and Treated 2 paired with Control 2), minimum replication was achieved. Observations over the course of the first post-fire winter revealed pervasive rilling on all watersheds, suggesting substantial overland flow. Although infiltration tests were not performed on the different watersheds, presumably the PAM did not work as it was intended. Alternatively, it is possible that these coarse-textured upland soils had too few fines for the PAM to be effective.

In contrast, the results in Table 4 indicate that, on the Williams Fire, the log structures in the two treated watersheds reduced the sediment yield by two-thirds compared to the single untreated control. Although the control catchment is unreplicated, previous work (Rice et al. 1965) suggests that the sediment yield in the untreated watershed was actually lower than the two treated catchments prior to the Williams Fire. Virtually all of the storage space created by the log structures filled with sediment, and only a few of the structures failed by undercutting or side cutting. The savings in debris retention and the protection against downstream channel incision could easily account for the observed difference in watershed sediment yield (Wohlgemuth

2003). Note also in Table 4 the rapid sediment yield decline in all watersheds during the second post-fire year. This presumably attests to the rapid watershed recovery in this area, although low precipitation values were undoubtedly partially responsible.

The sediment yield results of the aerial hydromulch treatment comparisons for the Cedar Fire are arrayed in Table 5. These first-year post-fire values indicate that the 100 percent coverage produced less than half the sediment of the untreated control. Paradoxically, the 50 percent coverage generated half again as much material as the control watershed. This suggests that perhaps the hydromulch treatment is only effective at full coverage. Alternatively, with no replication, there is a distinct possibility that inherent site characteristics may again be obscuring treatment effects. However, tests of water repellency, infiltration, soil depths, and landscape morphometry have thus far revealed no differences between the watersheds.

Curiously, there is little evidence across the study area of hillslope overland flow, as observed on the Williams Fire. In contrast, there is a dramatic hydrologic response in the ephemeral stream channels to even comparably small rainstorms of moderate intensity (less than 10 mm of rain in an hour). In the absence of overland flow, it is unclear how the water reaches the channels so quickly after a burst of rain. Observations in the stream courses also reveal substantial erosion of the channel bed and banks. This suggests that the majority of the material captured in the debris basins consists of remobilized channel sediments. Thus, the whole premise of treating hillslopes to reduce watershed sediment yields may be unfounded in this environment. However, the catchment with the 100 percent aerial hydromulch treatment produced fewer runoff events with smaller stormflow peaks than the other two watersheds under very similar rainfall patterns. This perhaps indicates that the value of this rehabilitation treatment is not to reduce hillslope erosion but rather to control water on the hillsides before it can reach the stream channels.

<H1>Conclusions

Accelerated post-fire erosion is inevitable, increasing the risk to biological and human communities at the wildland/urban interface. Land managers will continue to seek out post-fire erosion control measures that are both effective and environmentally benign. Results of the studies presented here suggest that LEBs were successful in retaining some sediment on the Mixing Fire, but that a test of treatment effectiveness was inconclusive because differences in site characteristics may have masked LEB performance. For coarse-textured upland soils, PAM may be ineffective. Log structures placed in the stream channels showed great promise as a BAER treatment on the Williams Fire. Aerial hydromulch may have been an effective treatment on the Cedar Fire, but exactly how it worked remains unclear. The foregoing uncertainties illustrate the need for continued testing on these and other BAER treatments before they become standard practices. Furthermore, robust economic analyses are necessary to determine if the various treatments are cost-effective.

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Figure Captions

Figure 1. Study locations in southern California.

Table 1. Selected study site characteristics.

Attribute	Mixing Fire	Williams Fire	Cedar Fire
Elevation (*meters*)	1500	900	700
Bedrock	Granitic	Metamorphic	Granitic
Soil Texture	Loamy sand	Loamy sand	Sand
Watershed Area (*hectares*)	1	1-2	2-3
Aspect	N to NW	SW to SE	W to S
Hillslope Angle (*percent*)	37	68	21
Channel Gradient (*percent*)	27	34	14

Table 2. Sediment accumulation behind the log erosion barriers (LEBs) on the Mixing Fire site by survey date. Initial survey – January 2000.

Survey Date	*Meters^3*
September 2000	3.5
July 2001	5.5
January 2002	4.0
July 2002	2.0
June 2003	2.0

Table 3. Precipitation amounts and sediment yield results for the Mixing Fire by rain season.

	2000		2001		2002		2003	
	Winter	Summer	Winter	Summer	Winter	Summer	Winter	Summer
	Precipitation (*millimeters*)[a]							
	254	47	301	68	167	8	550	49
	Sediment Yield (*Megagrams hectare*$^{-1}$)							
Watershed Treatment								
Log Erosion Barriers	0.20	0.20	0.04	0.06	0.10	Trace	0.05	Trace
Control	0.01	0.02	0.01	1.70	1.10	Trace	0.05	Trace

[a] Average annual precipitation – 550 mm

Table 4. Precipitation amounts and sediment yield results for the Williams Fire by year.

Watershed Treatment	2003	2004
	Precipitation (*millimeters*)[a]	
	525	435
	Sediment Yield (*Megagrams hectare^{-1}*)	
Polyacrylamide (PAM)		
Treated 1	33.7	0
Control 1	24.6	1.5
Treated 2	53.9	0
Control 2	59.8	0
Log Structures		
Treated 1	10.0	1.3
Treated 2	8.4	0
Control	34.7	0

[a] Average annual precipitation – 700 mm

Table 5. Precipitation amount and sediment yield results for the Cedar Fire.

Watershed Treatment	2004
	Precipitation (*millimeters*)[a]
	170
	Sediment Yield (*Megagrams hectare*$^{-1}$)
Aerial Hydromulch	
100 percent cover	6.7
50 percent cover	20.5
Control	14.9

[a] Average annual precipitation – 415 mm