

The Effects of Selected Postfire Emergency Rehabilitation Techniques on Small Watershed Sediment Yields in Southern California

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Forest Service Research has quantified the effects of selected Burned Area Emergency Response (BAER) treatments on sediment yields from small watershed by constructing dams to impound runoff and measure debris from several burn sites in southern California. In this paper, we cite examples from three studies to demonstrate the effectiveness of these treatments. 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 untreated burned 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- to 2-hectare watersheds were used to compare the effects of the soil flocculent polyacrylamide (PAM) or prefabricated small-diameter log structures as channel check dams against nearby untreated watersheds. Results indicate that PAM had no effect but that the channel check dams 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- to 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 untreated watershed. Preliminary results indicate that the 50 percent treatment produced more sediment than the untreated but the 100 percent treatment generated less than half the sediment of the untreated watershed. Rigorous testing needs to continue before these erosion control treatments become standard practice.

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

INTRODUCTION

In fire-prone ecosystems of the southwestern United States, 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 annual levels in comparable unburned areas (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 adversely affect 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 can recover to the point that the watershed functions normally again.

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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 used 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).

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 models for planning and risk assessment.

STUDY SITES AND TREATMENT DESCRIPTIONS

The study sites are located on Forest Service lands in the mountains of southern California (Figure 1). Although the study areas have differing site characteristics (Table 1),

Figure 1. Study locations in southern California.



Table 1. Selected study site characteristics

Attribute	Mixing Fire	Williams Fire	CedarFire
Elevation	1500 m	900 m	700 m
Bedrock	Granitic	Metamorphic	Granitic
Soil Texture	Loamy sand	Loamy sand	Sand
Watershed Area	1 ha	1-2 ha	2-3 ha
Aspect	N to NW	SW to SE	W to S
Hillslope Angle	37%	68%	21%
Channel Gradient	27%	34%	14%

they were all burned in wildfires during the late summer or early fall. Fires in southern California are especially intense at this time of year, occurring at the end of the summer drought and often fanned by strong Santa Ana winds. For this study, we chose small burned watersheds, 1 to 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.

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 area receives 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).

Much of the area burned by the Mixing Fire was treated with log erosion barriers (LEBs). LEBs are built by felling and placing fire-killed trees along the hillside contours (Figure 2). They 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.

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

Figure 2. Overlapping network of log erosion barriers (LEBs) on the Mixing Fire site.



area of metamorphic terrain at an elevation of 900 m in the San Gabriel Mountains. The general area receives annual average precipitation of 700 mm generated almost exclusively by winter cyclonic storms. The specific study site supported brushfields of mixed chaparral dominated by buckbrush, chamise (*Adenostoma fasciculatum*), and scrub oak (*Quercus berberidifolia*) (Wohlgemuth 2003).

A portion of the Williams Fire area 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 perpendicular to the flow, 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).

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 area receives 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 (Kirsten Winter, Cleveland National Forest, personal communication).

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.

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 monitoring 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 two or three 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 from the watershed 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, Mg/ha (metric tons), 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; PAM application occurred two months after the fire. Two other watersheds had 25 to 35 log structures

placed in the channels and were compared against a single nearby control catchment. The monitoring 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 Mg/ha 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 catchment was instrumented as an untreated control. The monitoring installations were configured as for the Mixing Fire, above. Small sediment accumulations were also handled in the same way as those from the Mixing Fire. 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 repeated to obtain the new baseline geometry. Regardless of the measurement technique, results were normalized by watershed area as Mg/ha to facilitate comparison.

RESULTS AND DISCUSSION

Mixing Fire

The 1.2-ha treated watershed at the Mixing Fire site contained 157 LEBs with an initial total sediment storage capacity of 72 m³. Overall, the LEBs performed as designed. Only about 6 percent of the LEBs failed due to undermining and 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 shown in Figure 3. Cumulatively, a total of 17 m³ 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 during the first two years of the study (Figure 3).

Sediment yield for the Mixing Fire, separated by winter cyclonic storm and summer thunderstorm seasons, is shown in Table 2. 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 untreated. This can be explained in part by the fact that the soil depths on the treated watershed are only half those of the untreated (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

Figure 3. Sediment accumulation behind the log erosion barriers (LEBs) on the Mixing Fire site by survey date. Initial survey – January 2000.

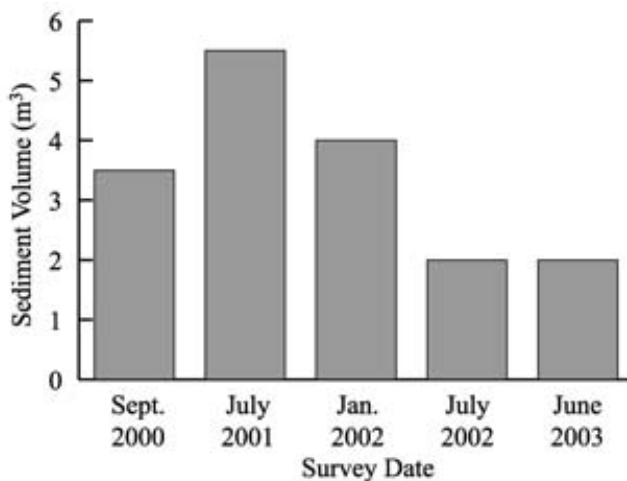


Table 2. Precipitation amounts and sediment yield results for the Mixing Fire by rain season.

	2000		2001		2002		2003	
	Winter	Summer	Winter	Summer	Winter	Summer	Winter	Summer
Precipitation (mm) ^a	254	47	301	68	167	8	550	49
Watershed Treatment	Sediment yield (Mg/ha)							
Log erosion barriers	0.20	0.20	0.04	0.06	0.10	Trace	0.05	Trace
Untreated	0.01	0.02	0.01	1.70	1.10	Trace	0.05	Trace

^a Average annual precipitation is 550 mm.

Table 3. Precipitation amounts and sediment yield results for the Williams Fire by year.

	Watershed	2003	2004
Precipitation (mm) ^a		525	435
<i>Watershed Treatment</i>		Sediment Yield (Mg/ha)	
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 is 700 mm.

Table 2), water storage in the shallow soils was presumably exceeded on the treated watershed but not on the untreated catchment. The saturated soils in the treated catchment 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 2). A high-intensity thunderstorm produced a large sediment pulse in the untreated 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 channelized flow scoured the channel bed and banks. Erosion from this section of bare ground continued to generate high levels of sediment yield into the winter of 2002 (Table 2).

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 the problem with lack of replication in the study design. 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.

Williams Fire

The sediment yield results of the post-fire treatment comparisons for the Williams Fire (Table 3) 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

Table 4. Precipitation amount and sediment yield results for the Cedar Fire.

		2004
Precipitation (mm) ^a		170
		Sediment Yield (Mg/ha)
<i>Watershed Treatment</i>	100 percent cover	6.7
Aerial hydromulch	50 percent cover	20.5
	Untreated	14.9

^a Average annual precipitation is 415 mm.

[with Treated 1 paired with Control 1 (untreated), and Treated 2 paired with Control 2 (untreated)], 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 intended. Alternatively, it is possible that these coarse-textured upland soils had too few fines to allow the PAM to be effective.

In contrast, the results 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 (Table 3). Although the untreated 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. Debris retention and the protection against downstream channel incision could easily account for the observed difference in watershed sediment yield (Wohlgemuth 2003). There was also a rapid sediment yield decline in all watersheds during the second post-fire year (Table 3). This presumably attests to rapid watershed recovery in the fire area, although low precipitation values were undoubtedly partially responsible.

Cedar Fire

The first-year post-fire sediment yield results for the aerial hydromulch treatment comparisons on the Cedar Fire indicate that the 100 percent coverage produced less than half the sediment of the untreated control (Table 4). Paradoxically, the 50 percent coverage watershed generated half again as much material as the untreated watershed. This suggests that perhaps the hydromulch treatment is effective only 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 Cedar Fire 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 indicates that perhaps 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.

CONCLUSIONS

Accelerated erosion following fire is inevitable, magnifying the risk of sedimentation-related damage 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. The methods of erosion control employed in this study show some promise, but were not an unqualified success. 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. Results from the Williams Fire were likewise inconclusive, but suggest that for coarse-textured upland soils, PAM may be ineffective. However, log structures placed in the stream channels soon after burning showed great promise as a means of reducing sediment yield downstream. Aerial hydromulch at high percent coverage rates 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 whether the various treatments are a cost-

effective means of reducing erosion from hillslopes and sediment yields from burned watersheds.

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LITERATURE CITED

- DeBano, LF. 1981. Water repellent soils: a state-of-the-art. Gen. Tech. Rep. GTR-PSW-46. Berkeley, CA: U.S. Department of Agriculture, Forest Service, Pacific Southwest Forest and Range Experiment Station. 21 p.
- Eakin, HM. 1939. Instructions for reservoir sedimentation surveys. In: Silting of reservoirs. Tech. Bull. 524. Washington, DC: U.S. Department of Agriculture: 153-165.
- Flanagan, DC, and K Chandhari. 1999. Erosion control with polyacrylamide on steep slopes. In: Proceedings, annual meeting American Society of Agricultural Engineers. St. Joseph, MI: American Society of Agricultural Engineers: 153-162.
- Hamilton, EL, JS Horton, PB Rowe, and LF Reimann. 1954. Fire-flood sequences on the San Dimas Experimental Forest. Tech. Paper No. 6. Berkeley, CA: U.S. Department of Agriculture, Forest Service, California Forest and Range Experiment Station. 29 p.
- Heede, BH, MD Harvey, and JR Laird. 1988. Sediment delivery linkages in a chaparral watershed following a wildfire. *Environmental Management* 12: 349-358.
- Hibbert, AR. 1985. Storm runoff and sediment production after wildfire in chaparral. In: Proceedings, hydrology and water resources in Arizona and the southwest. Las Vegas, NV: American Water Resources Association: 31-42.
- Kraebel, CJ. 1934. The La Crescenta flood. *American Forests* 40: 251-254, 286-287.
- Loomis, J, P Wohlgemuth, A Gonzalez-Caban, and D English. 2003. Economic benefits of reducing fire-related sediment in southwestern fire-prone ecosystems. *Water Resources Research* 39(9): 1260-1268.

- Ray, GA, and WF Megahan. 1978. Measuring cross sections using a sag tape: a generalized procedure. Gen. Tech. Rep. INT-47. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station. 12 p.
- Rice, RM, RP Crouse, and ES Corbett. 1965. Emergency measures to control erosion after a fire on the San Dimas Experimental Forest. In: Misc. Pub. 970. Washington, DC: U.S. Department of Agriculture: 123-130.
- Robichaud, PR, JL Beyers, and DG Neary. 2000. Evaluating the effectiveness of postfire rehabilitation treatments. Gen. Tech. Rep. RMRS-63. Ft. Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 85 p.
- Rowe, PB, CM Countryman, and HC Storey. 1954. Hydrologic analysis used to determine effects of fire on peak discharge and erosion rates in southern California watersheds. Berkeley, CA: U.S. Department of Agriculture, Forest Service, California Forest and Range Experiment Station. 49 p.
- Wells, W.G., II. 1981. Some effects of brushfires on erosion processes in coastal southern California. In: TRH Davies and AJ Pearce, eds. Erosion and sediment transport in Pacific rim steeplands. Publ. 132. Washington, DC: International Association of Hydrological Sciences: 305-342.
- Winter, K. 2004. Personal communication. Biologist, Cleveland National Forest, 10845 Rancho Bernardo Road, Suite 200, San Diego, CA 92127-2107.
- Wohlgemuth, PM. 2003. Post-fire erosion control research on the San Dimas Experimental Forest: past and present. In: KG Renard, SA McElroy, WJ Gburek, et al., eds. Proceedings, first interagency conference on research in the watersheds. Washington, DC: U.S. Department of Agriculture, Agricultural Research Service: 645-650.
- Wohlgemuth, PM, KR Hubbert, and PR Robichaud. 2001. The effects of log erosion barriers on post-fire hydrologic response and sediment yield in small forested watersheds, southern California. *Hydrological Processes* 15: 3053-3066.