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The effects of log erosion barriers on post-fire hydrologic response and sediment yield in small forested watersheds, southern California

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Abstract:

Wildfire usually promotes flooding and accelerated erosion in upland watersheds. In the summer of 1999, a high-severity wildfire burned a series of mixed pine/oak headwater catchments in the San Jacinto Mountains of southern California. Log erosion barriers (LEBs) were constructed across much of the burned area as an erosion control measure. We built debris basins in two watersheds, each about 1 ha in area, one with LEBs, the other without, to measure post-fire hydrologic response and sediment yield and to evaluate the effectiveness of the LEBs. The watersheds are underlain by granitic bedrock, producing a loamy sand soil above large extents of weathered bedrock and exposed core stones (tors) on the surface. Measured soil water-repellency was similar over the two catchments. Rain gauges measured 348 mm of precipitation in the first post-fire year. The ephemeral stream channels experienced surface flow after major rainstorms, and the source of the water was throughflow exfiltration at the slope/channel interface. Post-fire overland flow produced some rilling, but hillslope erosion measured in silt fences away from any LEBs was minor, as was sediment accumulation behind the LEBs. Stream channels in the catchments exhibited minor net scour. Water yield was much greater in the LEB-treated watershed. This resulted in 14 times more sediment yield by weight than the untreated watershed. Average soil depths determined by augering were nearly double in the catchment without the LEBs compared with the treated watershed. This suggests that differences in water and sediment yield between the two catchments are due to the twofold difference in the estimated soil water-holding capacity in the untreated watershed. It appears that the deeper soils in the untreated watershed were able to retain most of the precipitation, releasing less water to the channels and thereby reducing erosion and sediment yield. Thus, the test of LEB effectiveness was inconclusive in this study, because soil depth and soil water-holding capacity may have masked their performance. Published in 2001 by John Wiley & Sons, Ltd.

KEY WORDS sediment yield; hydrologic response; fire; erosion control; log erosion barriers; upland watersheds; soil depth; water repellency

INTRODUCTION

In the fire-prone southwestern USA, post-fire erosion, sedimentation, and flooding threaten life, property, and infrastructure. In addition, post-fire environmental degradation can extirpate refugia populations of endangered species in sensitive riparian corridors. This has prompted expensive emergency watershed rehabilitation measures on the part of land managers to protect downstream sites at risk (Robichaud *et al*., 2000).

It has been well documented that wildfire can alter the hydrologic and erosion response of watersheds in southern California (Kraebel, 1934; Rowe *et al*., 1954; Rice, 1974; Wells, 1981). With the removal of the vegetation canopy and surface organic material, rainfall interception is reduced (Hamilton and Rowe, 1949) and the bare hillslopes are subjected to unimpeded raindrop impacts (Wells, 1981). Moreover, the combustion

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of soil organic matter often creates a subsurface water-repellent layer that restricts infiltration and promotes overland flow (DeBano, 1981). This enhances both catchment water yield (Anderson, 1949; Rowe *et al.*, 1954; Baker, 1990) and sediment yield (Hamilton *et al.*, 1954; Pase and Ingebo, 1965; Hibbert, 1985; Heede *et al.*, 1988).

Log erosion barriers (LEBs) are built by felling and placing fire-killed trees parallel to the hillside contours. The LEBs are designed to retard overland flow of water and sediment on hillside slopes, thereby reducing post-fire hillslope erosion and sediment delivery to stream channels (Robichaud *et al.*, 2000). Ideally, the LEBs are placed in an overlapping arrangement that maximizes ponding (fostering infiltration and deposition) and minimizes potential barrier failure. LEB performance has been closely tied to initial construction, *e.g.* positioning along the slope contour, horizontal dip, and sealing the log with the ground surface (Robichaud *et al.*, 2000).

In September 1999, the Mixing Fire burned over 1200 ha of brushfields and forest in the San Jacinto Mountains of southern California. Following the fire, USDA Forest Service personnel constructed LEBs across a portion of the Mixing Fire site as an erosion control measure. The purpose of this study is to quantify the post-fire hydrologic response and the sediment yield from two small watersheds, while evaluating the effectiveness of the LEBs as an erosion control practice.

STUDY SITE AND WATERSHED DESCRIPTION

The study area is located at an elevation of 1500 m in the San Jacinto Mountains (33° 41′ N, 116° 44′ W), about 150 km east of Los Angeles, California (see Figure 1). The region is underlain by granitic bedrock that is weathered to a depth of several metres with exposed core stones (tors) on the surface. The bedrock is generally friable, such that it can be chopped and dug with pick and shovel, and chunks of it can be broken or crumbled by hand, matching the criteria for weathering classes 5 or 6 of Clayton and Arnold (1972). The overlying soils are coarse-loamy, mixed, mesic Typic Xerorthents. Surface soils are largely loamy sands with infiltration rates ranging from 20 to 50 mm h^{-1}. Vegetation at the site consists of a mixed forest of Coulter pine (*Pinus coulteri*), black oak (*Quercus kelloggii*), and canyon live oak (*Quercus chrysolepis*) with a brush understory of buckbrush (*Ceanothus leucodermis*) and manzanita (*Arctostaphylos spp.*). Although classified as having a Mediterranean climate—characterized by cool, wet winters and hot, dry summers—some 8–18% of the 550 mm of average annual precipitation at the nearby town of Idyllwild is generated by summer thunderstorms.

Based on the reduction in vegetation and ground cover compared with nearby unburned landscapes, the study area burned with high fire severity (Robichaud *et al.*, 2000). Trees were killed and their canopies were largely consumed, and the brush understory was completely incinerated. The post-fire forest floor consisted primarily of rock, mineral soil, and ash. Two small catchments were chosen for this study: Watershed A, untreated, and Watershed B treated with LEBs (Figure 1). The study watersheds are about 1·12 ha and 1·20 ha in size respectively, and are both northerly facing. Average hillslope angles in the watersheds are 20° (36%), with channel gradients of 14° (25%). Stream channels are dry most of the year, and support surface flow only after heavy rains. Table I summarizes the physical characteristics of the two study watersheds.

METHODS

Monitoring facilities and equipment were installed in the two small burned watersheds 2 months after the September 1999 Mixing Fire. The installations consisted of debris dams constructed across the stream channels to impound sediment, flumes attached to the downstream side of the dams to measure runoff, rain gauges, and a weather station (temperature, relative humidity, solar radiation, wind speed and wind direction). In December 1999 and January 2000, we performed a variety of site characterization inventories as described

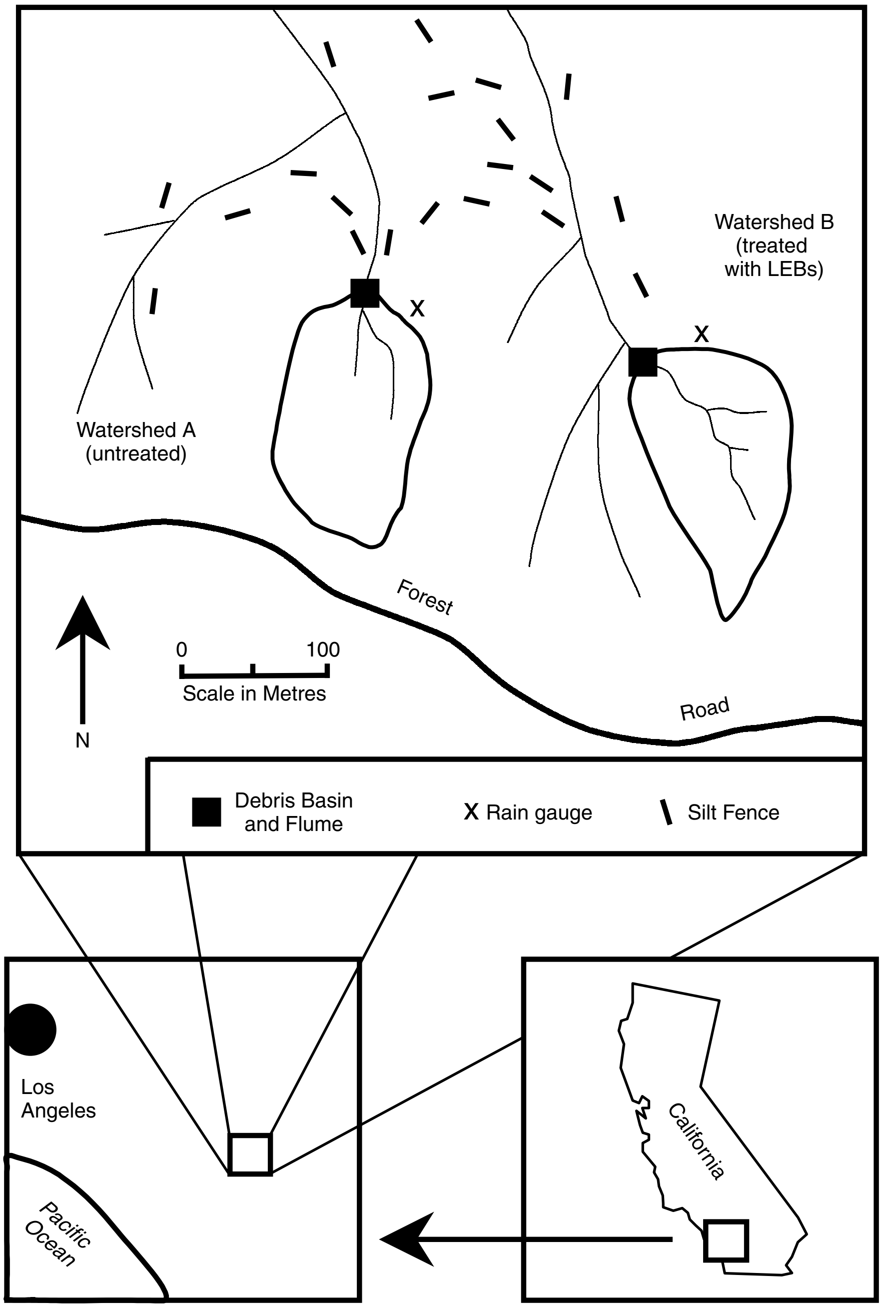

Figure 1. Map showing locations of the two 1 ha watersheds and drainages. Locations of the measuring facilities are noted

below. Equipment installation and all of the site characterization work were completed before the study area received more than 5 mm of rainfall.

We determined soil non-wettability using the water drop penetration test (DeBano, 1981). We placed drops of water on the soil and recorded the time it took them to penetrate or infiltrate into the soil mass. Testing was done at 16 locations in each watershed, stratified by hillslope position (crest, midslope, and toeslope).

Table I. Characteristics of the study watersheds

	Watershed A	Watershed B
Treatment	Untreated control	LEB treated
Size (ha)	1·12	1·20
Aspect	NNE	NW
Average slope angle (deg)	20	21
Average channel gradient (deg)	14	15
Total channel length (m)	93	219
Drainage density (km km^{-2})	8·30	18·25
Channel sediment storage (m^3 m^{-1})	0·32	0·16
Average soil texture	loamy sand	loamy sand
Average soil depth (m)	1·01	0·54
Average soil organic matter content by weight (%)	6·63	6·60

At each location, we performed the test five times for each of three soil strata: the top of the ash layer, the mineral soil surface, and 1 cm into the mineral soil.

Rock, litter, and vegetation all provide ground cover that offers some watershed protection against raindrop impact and surface runoff. To assess ground cover in the study area, we randomly chose 25 sampling points in each watershed and monumented them with sections of rebar. Four 1 m × 1 m plots were established at each sampling point, with the near corner of each plot located 1 m from the rebar along diagonals to the cardinal compass points. The plots were repeatedly surveyed by ocular estimate by the same operator to quantify ground cover.

We measured hillslope erosion in the Mixing Fire study area with silt fence barriers (Robichaud *et al.*, 2000). These barriers, constructed of silt cloth wired to t-posts (see Figure 2), retained sediment from plots that ranged from 3·7 to 4·3 m wide by 12 to 30 m long. The average contributing area for each silt fence was 83·6 m^2. We sprinkled construction chalk just uphill of the barriers to identify the initial ground surface, then removed and measured the captured material as it accumulated. Twenty silt fences were installed in the project area outside of the study watershed boundaries (Figure 1).

We initially inventoried the LEBs in the Mixing Fire study area to determine the number, size and spacing, and estimated storage capacity (see Figure 3). We inspected the LEBs periodically for sediment accumulation and leakage. Sediment accumulation was determined by ocular estimate compared with initial capacity assessments, but, unlike the silt fences, we never removed the sediment.

We documented changes in stream channel morphometry after the Mixing Fire by repeatedly surveying monumented cross-sectional profiles in the study watersheds. Because of the disparity in channel lengths between the two catchments (see Table I), more cross-sections were established in treated Watershed B than in untreated Watershed A. The cross-sectional profiles can be used to compute the changes in cross-sectional area between the ground surface and the local datum reference line. Channel fill would reduce the area at a given cross-section, whereas channel scour would increase the area.

Sediment yield was measured by collecting the impounded sediment from the metal floor of the debris basin and weighing it on a portable scale. Subsamples were taken back to the laboratory to correct the field weights for moisture content. Once dry, the subsamples were also analysed for particle size and organic matter content.

The average depth of soil to weathered bedrock and the average extent of weathered bedrock to hard bedrock were determined by hand augering. Eleven holes were augered at Watershed A, and 16 at Watershed B. Sampling points were stratified by aspect and degree of slope.

Figure 2. Photograph of a silt fence to measure surface erosion

RESULTS

The following sections detail the results of the first year's response of the two small watersheds to the Mixing fire.

Vegetation cover

Initial vegetation surveys, performed in January 2000, revealed very little cover in either watershed, with bare ground averaging 86% and 83% in Watershed A and Watershed B respectively. Vegetation averaged 1–2%, all in the form of standing dead trees. The litter category, which included the felled dead trees (LEBs), was twice as great in Watershed B (9% versus 4%), as the LEBs themselves provide cover. The remaining 6–8% cover was rock. Surveys were made again in May 2000, with little change from the initial cover estimates. Bare ground averaged 81% in each watershed, and the vegetation covered 8% and 5% of Watershed A and Watershed B respectively. Vegetation regrowth consisted primarily of forbs and grasses, as well as sprouts from the base of the oaks. Pine seedlings were very rare. Qualitative observations in

Figure 3. Photograph of Watershed B showing the LEBs

November 2000 indicated that the dominant vegetation regrowth providing cover protection to the watersheds was resprouting oaks.

Soil and weathered bedrock depths

Average soil depth to weathered bedrock was 1·01 m at Watershed A, and 0·54 m at Watershed B (Table I). Weathered bedrock extended on average 0·94 m to hard bedrock at Watershed A, and 0·99 m at Watershed B. Assuming a volumetric water content of 0·13 $\text{cm}^3\ \text{cm}^{-3}$ for the loamy sand soil profile (Hillel, 1982) and 0·08 $\text{cm}^3\ \text{cm}^{-3}$ for the weathered bedrock (Jones and Graham, 1993), we can estimate a water storage capacity of 13·2 cm for soil and 12·8 cm for weathered bedrock (26 cm combined) at Watershed A, and 7·1 cm for soil and 13·5 cm for weathered bedrock (20·6 cm combined) at Watershed B. Estimated water storage capacity for the soil depth in Watershed A is about twice that of Watershed B (the ratio of B to A is 0·54). Soil water-holding capacity (cm) is the total water contained in the soil after gravitational water has freely drained away. This water volume is expressed as depth of water in a depth of soil (e.g. 13·2 cm of water in 101 cm soil depth).

Soil non-wettability

Results of the water drop penetration times are shown in Table II. As expected, the drops penetrated the ash layer virtually instantaneously in both watersheds. Non-wettability was uniformly the greatest at the surface of the mineral soil in both watersheds, with 68% of the drops exceeding 1 min or more before infiltrating. Non-wettability was most heterogeneous within the mineral soil: 28% of the drops exceeded 40 s before infiltrating, 12% penetrated in under 20 s, and the rest of the drops took between 20 and 40 s.

Rainfall

The precipitation records from the rain gauges at each study watershed are very similar to each other. The total rainfall for the first year of the study at the two gauges was within 1%, and a correlation analysis of daily rain yields an r^2 value of 0·98. Slightly higher peak rainfall intensities were recorded in the gauge

Table II. Soil non-wettability determinations

Slope aspect (Deg)	Slope angle (Deg)	Slope position	Drop penetration time[a] (sec)		
			Top of ash	Mineral soil surface	1 cm in mineral soil
Watershed A					
300	12	Crest	0	>60	>60
285	17	Midslope	0	0	5
270	19	Midslope	0	>60	35
250	12	Toeslope	0	40	35
005	23	Toeslope	0	25	45
285	25	Toeslope	0	>60	35
030	17	Toeslope	0	50	20
300	25	Midslope	0	>60	40
300	12	Crest	0	>60	40
000	20	Midslope	0	>60	30
020	18	Midslope	0	>60	35
010	23	Midslope	0	>60	35
000	23	Midslope	0	25	40
015	8	Crest	0	55	20
105	13	Midslope	0	30	40
345	20	Crest	0	>60	>60
Watershed B					
005	17	Crest	0	>60	45
005	18	Crest	0	>60	55
000	18	Midslope	0	55	15
000	17	Midslope	0	50	25
025	21	Toeslope	5	>60	40
240	20	Toeslope	0	>60	45
285	15	Crest	0	>60	10
285	16	Midslope	0	>60	35
205	15	Crest	0	>60	15
230	17	Midslope	0	>60	45
265	12	Midslope	0	>60	45
250	19	Toeslope	0	>60	25
020	18	Toeslope	0	50	50
355	18	Midslope	0	>60	20
355	18	Midslope	0	>60	20
005	17	Midslope	0	>60	20

[a] Each time represents the average of five determinations.

at Watershed B, but there was no consistent pattern from storm to storm and a correlation analysis of peak 10 min storm intensities yields an r^2 of 0·93 between the two gauges. Field calibration tests show that both gauges accurately measured controlled volumes of water. Therefore, the following rainfall summaries are based on the average of the two gauges.

The rain gauges were installed in early November 1999, and the first rain was recorded on January 1, 2000. For the purposes of this paper, the final rain of the year was recorded on November 5, 2000. Total precipitation over this period (some of which fell as snow in February) was 348 mm, well below the average annual value of ~550 mm. Winter cyclonic storms produced 254 mm of rain and snow between January and April. Summer thunderstorms yielded a total of 46 mm of rain in August and September. Cyclonic storms returned in October and early November, producing another 48 mm of rain, and marking the start of the second post-fire winter season. Cyclonic storms typically generated peak 10 min rainfall levels of 1·3 to 1·9 mm (7·8–11·4 mm h^{-1}). In contrast, thunderstorms produced peak 10 min rainfall levels of 1·8 to 2·6 mm (10·8–15·6 mm hr^{-1}). These rainfall intensities are less than the soil infiltration rates generally found in the study area.

Streamflow

Not surprisingly, the below-normal precipitation and relatively low peak rainfall intensities produced unspectacular streamflow events. In fact, no runoff records were ever generated because the water impounded in the debris basin never reached the level of the flume. Rather, once the runoff ceased, the ponded water would slowly percolate through the porous floor of the reservoir, and we observed that the basin was usually dry before the next rain. However, flow was sporadically observed in the stream channels of both watersheds, with observations indicating the source of the water was throughflow exfiltration at the slope/channel interface rather than any sustained hillslope overland flow. Based on the level of the high-water marks recorded on the dam face in each debris basin after every significant storm, treated Watershed B appears to have consistently produced more runoff than did untreated Watershed A.

Hillslope erosion

Hillslope erosion in the study area, measured in the silt fences, was minor compared with reported post-fire erosion levels in southern California (see Table III). Although we observed some rilling in swales and below rock outcrops, there were not the pervasive rills commonly associated with burned watersheds in southern California (Wells, 1981). Flux rates, the movement of sediment past a unit width of slope contour per unit time (g cm^{-1} day^{-1}), were greater in the winter, but total soil loss was greater during the summer (Table III). Some of this response undoubtedly reflects the below-normal rainfall experienced during the study period.

LEBs

The intent of the LEBs is to disrupt the overland flow of water and sediment off the hillslopes and, in turn, delay water and sediment from entering the channels. Capturing and retaining sediment is only of secondary

Table III. Hillslope erosion and soil loss in the project area measured behind the silt fences. Total number of silt fences is 20. Average contributing area to each fence is 83·6 m^2

Collection date	Average eroded sediment (kg)	Average sediment flux (g cm^{-1} day^{-1})	Average soil loss (kg ha^{-1})
2/22/00	0·88	0·002	105
2/24/00	1·43	0·084	171
4/20/00	0·90	0·002	108
11/7/00	6·86	0·004	821
Total per fence	10·07	0·004	1205

importance (Robichaud *et al*., 2000). However, one measure of the performance of the LEBs is the amount of sediment caught. Another performance indicator is evidence of any leakage or spillage under or around the LEB. Table IV provides summary statistics of the initial inventory of the 157 LEBs, established at a density of 131 LEBs p ha^{-1}. Generally, LEB sediment accumulation was minor, as would be expected with the level of hillslope sediment yield measured behind the silt fences. Only about 10% of the LEBs caught more than 0·1 m^3, while two-thirds captured less than 0·01 m^3 and nearly one-quarter caught nothing. The total site storage capacity of 182 m^3 was reduced by only about 5% (9·1 m^3) after the first post-fire year. Although there were some dramatic examples of LEB failure and water cascading from LEB to LEB, only nine of the 157 LEBs showed evidence of leakage, and another nine LEBs had spills around the end of the log.

Stream channel erosion

Table V summarizes the channel surveys for the study watersheds. The initial surveys were performed in early January 2000, prior to significant rain. Surveys in mid-February indicated that the channels in Watershed A were filling slightly, whereas the channels were scouring in Watershed B. However, surveys at the end of February showed that this pattern had reversed, although both catchments indicated a slight cumulative channel scour from the initial baseline. By early May, both watersheds exhibited considerable channel filling from the late winter and early spring rains. In September, channels in both watersheds had scoured again,

Table IV. Summary statistics of the LEBs (n = 157) in Watershed B

	Log length (m)	Average log diameter (cm)	Slope length[a] (m)	Horizontal dip[b] (deg)	Storage capacity (m^3)	Estimated catch (m^3)	Estimated soil loss[c] (kg ha^{-1})
Mean	5·5	22·5	9·0	5·5	1·16	0·057	13 939
Std. Dev.	2·6	8·4	4·2	3·9	1·81	0·106	25 922
Median	4·8	20	8·2	5	0·57	0·003	734
Maximum	16·3	55	21·0	16	13·14	1·596	390 300
Minimum	1·2	7	2·1	0	0·03	0	0

[a] Upslope distance to drainage divide or next LEB.
[b] Contour placement deviation.
[c] Loss = catch volume × density/mean contributing area, density assumed to be 1·2 g cm^{-3}; contributing area = log length × slope length.

Table V. Stream channel cross-section profile summaries

Survey date	Average cross-sectional area (m^2)[a]	
	Watershed A (n = 8)	Watershed B (n = 27)
1/6/00 (initial measurements)	0·538 69	0·464 46
2/16/00	0·533 52	0·478 34
2/29/00	0·541 07	0·472 35
5/03/00	0·496 53	0·427 53
9/15/00	0·549 98	0·482 25
12/27/00	0·546 23	0·478 25
Net change	0·007 54	0·013 79
Computed volume[b] (m^3)	0·70	3·02
Sediment loss[c] (kg ha^{-1})	750	3020

[a] An increase in area represents channel scour, a reduction in area represents channel fill.
[b] Volume = channel length × net change in cross-sectional area.
[c] Loss = volume × sediment density/watershed area; density assumed to be 1·2 g cm^{-3}.

presumably in response to the summer thunderstorms. A subsequent survey in December indicated a slight channel filling with the return of winter cyclonic storms. Assuming a sediment density of 1·2 g cm^{-3}, by the end of the season the two catchments had produced net channel scours of 750 kg ha^{-1} and 3020 kg ha^{-1} for Watershed A (untreated) and Watershed B (treated) respectively (see Table V).

Watershed sediment yield

Table VI summarizes rainfall, sediment yield, and soil loss for the two study watersheds in the Mixing Fire project. Watershed B (treated) produced over 14 times as much total sediment as Watershed A in the first year after the fire, and the differences were even greater for some individual collections. Watershed B consistently generated more sediment than Watershed A. The sediments in the debris basins were both finer-textured (equivalent to a loam soil) and much richer in organics than the surface soil samples collected in each watershed (as seen by comparing organic matter contents in Tables I and VI).

DISCUSSION

Fire can dramatically alter the physical environment, making the post-burn landscape more sensitive to the agents of erosion (Wells, 1981). The production of non-wettable soil layers is thought to govern much of the post-fire watershed hydrologic and erosion response (DeBano, 1981; DeBano *et al.*, 1998). Following the Mixing Fire, fairly uniform non-wettability was documented at the top of the mineral soil in both study watersheds, regardless of hillslope position (Table II). However, based on field observations, pervasive sheetwash and rilling were absent in the study area. The inference is that the non-wettable layer did not significantly restrict rainfall infiltration. This reaffirms the difficulty of testing a spatially variable landscape feature with point samples (Robichaud, 1996), and suggests that a model of a discontinuous or porous non-wettable layer is more realistic (Booker *et al.*, 1993).

Hillslope erosion can be extensive in burned watersheds. Soil material at steep angles will often be transported solely by gravitational forces in the process known as dry ravel (Krammes, 1960). Burned hillslopes, denuded of cover, are also subjected to unimpeded raindrop impacts that preferentially move soil particles downhill (Wells, 1981). Moreover, with the production of a classic non-wettable soil layer and the attendant reduction in infiltration, sheetwash and rilling are promoted (DeBano, 1981). However, hillslope erosion in the study area was remarkably subdued. Annual soil losses of 1200 kg ha^{-1} in the first post-fire year (Table III) pale in comparison with other studies in southern California that have measured post-burn hillslope erosion

Table VI. Rainfall, sediment yield, and soil loss by collection date. The instrumentation was in place in November 1999

Collection date	Rainfall (mm)			Watershed A			Watershed B		
	Total	Daily max.	10 min max.	Sediment yield (kg)	Soil loss (kg ha^{-1})	Organic matter (%)	Sediment yield (kg)	Soil loss (kg ha^{-1})	Organic matter (%)
1/28/00	33·3	10·4	1·8	6·60	5·89	15	18·53	15·44	46
2/16/00	47·3	15·2	2·0	0·03	0·03	51	3·80	3·17	50
2/17/00	12·8	11·2	2·0	0·42	0·38	12	146·73	122·28	36
2/24/00	60·6	21·8	1·8	1·44	1·29	22	15·97	13·31	24
2/29/00	10·9	9·4	1·5	0·74	0·66	16	2·70	2·25	31
5/3/00	88·9	23·9	1·8	6·53	5·83	16	74·47	62·06	17
8/18/00	17·1	12·2	3·0	0	0	–	106·74	88·95	34
8/31/00	16·0	14·0	2·8	0·15	0·13	72	72·69	60·58	31
9/15/00	13·4	13·4	2·0	19·02	16·96	37	77·44	64·53	29
11/7/00	47·9	15·5	1·5	2·70	2·41	43	8·09	6·74	31
Total	348·2			37·63	33·58		527·16	439·31	

at over 20 000 kg ha^{-1} (Wohlgemuth, 2001). Much of this response is undoubtedly a function of the below-normal rainfall and the evidence of little or no overland flow, as noted previously. Not unexpectedly, more hillslope erosion was likely generated by the summer thunderstorms than by the winter cyclonic storms (Table III).

Some of this hillslope erosion was caught by the LEBs. However, comparing Tables III and IV, the estimated soil loss calculated from the LEBs was an order of magnitude greater than the loss computed from the silt fences. This disparity can be explained by the different hillslope topographic locations of the silt fences and the LEBs. The silt fences, constructed specifically to measure surface erosion, were placed on fairly uniform slope facets. The LEBs, constructed operationally by Forest Service personnel, were located not only on uniform facets but also in swales, and several were even placed directly in the channels. These latter locations accumulated far more sediment than did the LEBs on planar slopes. Omitting these outliers and re-computing the estimated soil loss generates values that are roughly comparable to those from the silt fences.

Stream channels receive water and sediment from the hillslopes and convey them out of the watershed. Generally, in post-fire environments, channels initially fill with sediment washed off the hillslopes, then scour through these deposits after the sediment supply of easily mobilized ash and organic material is depleted (Campbell *et al.*, 1987; Florsheim *et al.*, 1991). The channels in the study watersheds exhibit this same fill–scour pattern, although it is as subdued as the erosion activity on the hillsides. There was evidence of aggradation and degradation at most cross-sections (often simultaneously), but the net change between successive surveys was never more than 5% (Table V). Channel filling appears to be associated with the lower intensity winter cyclonic storms, whereas channel scour appears to be associated with the higher intensity summer thunderstorms.

Sediment yield is the integrated output of sediment from a watershed unit. Sediment is stripped off the hillslopes, scoured out of the channels, and transported to the watershed outlet. Sediment yield reflects the complicated balance of rainfall amounts and intensities, hillslope erosion, and channel scour and fill. One significant finding of this project is the great disparity in sediment yield between the two study watersheds. Rain-derived streamflow is the only mechanism by which sediment can be delivered to the debris basins. Unfortunately, there is no simple relationship between either rainfall totals or intensities that appears to govern sediment yield (see Table VI). Over half the total sediment yield in Watershed A was the result of a single thunderstorm on September 7, 2000, with total depth and peak intensity that were singularly unspectacular (Figure 4).

Two catchments with similar attributes are often compared to evaluate the effectiveness of a management practice. If all other physical factors are constant, any differences in erosional response should reflect the watershed treatment (*i.e.* the LEBs). However, the conclusion that the relatively large sediment yields in Watershed B are produced by the LEBs is counterintuitive and not supported by observations in the field. The higher level of watershed disturbance associated with LEB installation did not appear to be the source of the higher levels of sediment yield. Moreover, the performance evaluations of the LEBs indicate that treatment failure was not the cause of accelerated watershed erosion. Thus, if the treatment was not responsible for the observed watershed differences, then the physical factors between the two catchments must not have been constant, which was the case.

Although many of the environmental characteristics between the study watersheds were very similar, some important ones differed. Watershed size and topography, fire severity, soil non-wettability, vegetation cover, and rainfall amounts and intensities were virtually identical across the two study catchments. Lacking any field evidence to the contrary, hillslope erosion must also be treated as uniform across the study area. In fact, the only major differences between the two watersheds are the soil depths and the drainage densities. These factors are related, and together may account for the disparity in watershed sediment yield.

The drainage network in Watershed B is much more extensive than the channel system in Watershed A (the total length of channels is 219 m as opposed to 93 m in comparably sized watersheds). The hillslope soil depths in Watershed B are only about half as deep as those in Watershed A (Table I). Further, although runoff was never recorded, streamflow was consistently greater in Watershed B compared with Watershed A

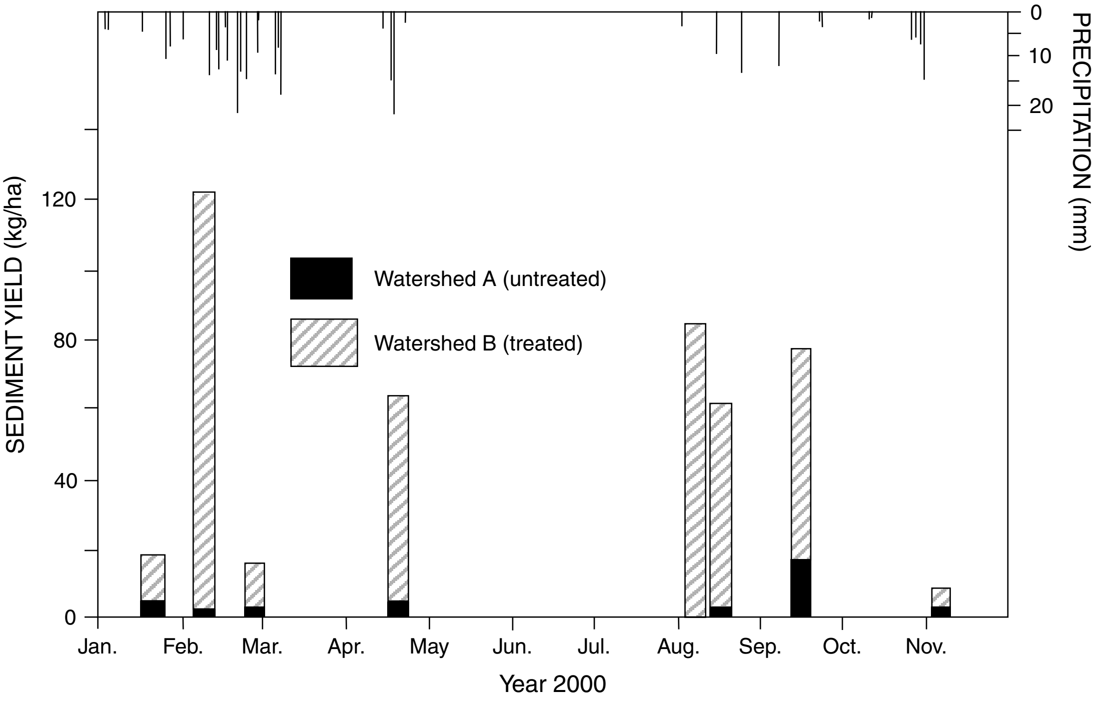

Figure 4. Sediment yields measured throughout the year for Watershed A (untreated) and Watershed B (treated) in relation to recorded precipitation events

(based on the high-water marks left on the debris basin dam face after each significant storm). If, as seems likely, the deeper soils in Watershed A can hold more water than the shallower soils in Watershed B, then a greater proportion of the rainfall could be stored in the soil mantle. This would account for the reduced streamflow and the less extensive channel network needed to convey the smaller surface runoff. Conversely, the shallower soils in Watershed B promote a greater streamflow hydrologic response—with a concomitantly larger channel network. The larger and more frequent streamflow events in Watershed B appear to be the delivery mechanism for the greater levels of sediment yield compared with Watershed A. It is unclear how the burned watersheds would have responded in a normal rainfall year, although the relative development of the channel networks suggests that this soil depth/runoff condition has existed for a long time. However, a review of the geomorphic literature indicates that this inverse relationship between soil depth and drainage density has not previously been documented.

Even if variable watershed hydrologic response can explain the difference in catchment sediment yields, there is still a question concerning the source of the sediment. The small net scour of stored channel sediment over the life of the project alone could account for the material collected in the debris reservoirs. From Table V, the channels in Watershed A produced 0·70 m^3 of sediment compared with a calculated volume of 0·03 m^3 for the watershed sediment yield (Table VI). Similarly, the channels in Watershed B scoured 3·02 m^3 compared with a calculated volume of 0·41 m^3 for the watershed sediment yield (compare Tables V and VI). On the other hand, the hillslope erosion values measured by the silt fences are three times greater than the debris basin accumulations in Watershed B and 36 times those of Watershed A (Tables III and VI). Similarly, LEB accumulations are 32 times greater than the soil loss from Watershed B and 415 times that of Watershed A (Table IV and VI). However, this would require the excess sediment to be stored in the channel networks, and this is not supported by the cross-sectional profiles (Table V). It would thus appear that there are intermediate sources and sinks of sediment that are not accounted for by the foregoing field data.

SUMMARY AND CONCLUSIONS

Two study watersheds were instrumented after the Mixing Fire in the San Jacinto Mountains of southern California to quantify post-fire hydrologic and erosion response, and to assess the performance of LEBs as an erosion control measure. These values, in units of kilograms per hectare, are small compared with the results of similar research throughout the region, and may reflect the effects of below-normal rainfall. The first-year LEB assessments indicate that treatment implementation was excellent, and nearly 90% of the LEBs performed as planned. However, because of the low rainfall and the minor hillslope erosion, the LEBs were not subjected to design storm conditions. It is unclear how the LEBs would have performed in a normal or above-normal rainfall year. Also, because of the huge variation in watershed hydrologic response, it is difficult to evaluate the treatment effectiveness of LEBs as a management practice. The test of LEB effectiveness was inconclusive in this study, because soil depth and soil water-holding capacity may have masked their performance. In order to ascertain the treatment effect, the influences of the inherent site characteristics must first be normalized across both watersheds. Normalization is difficult for such spatially variable data, no pretreatment calibration, and a sample size of one. However, the information from this project for subsequent years will put this initial data into the larger context and may help answer these broader questions.

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