EFFECTIVENESS OF DEBRIS FLOW MITIGATION METHODS IN BURNED AREAS

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Abstract: The fire-flood sequence, in which recently burned areas generate debris flows and floods in response to relatively small rainstorms, is common in the Western United States. To reduce the likelihood and magnitude of these debris flows, hillslopes and channels are often treated by mulching, seeding, and construction of erosion barriers and fences. The effectiveness of these treatment methods in reducing debris-flow volume has not been thoroughly evaluated; therefore, the goal of this study was to quantify the effectiveness of post-fire debris flow mitigation techniques. Debris volumes were measured and sediment sources were identified for 46 recent debris-flow events. Graphs of debris flow volume accumulation along the length of the flowpath were generated to identify sources of debris and to develop a predictive model to estimate expected debris-flow volumes. Extensive field observations and interpretations of surveys of wildfire emergency response personnel provided additional information on effectiveness and applicability of various treatment methods. Based on this information we conclude that hillslope treatments are most effective in reducing water runoff and enhancing infiltration, and channel treatments are effective at capturing debris and reducing potential for debris flow growth. Engineering design, installation methods, density of treatment, and maintenance of mitigation elements are critical to their success.

INTRODUCTION

The vulnerability of recently burned areas to debris flows has been shown by a number of research efforts, including Wells (1987), Spittler (1995), Cannon (2001), Moody and Martin (2001), Wondzell and King (2003), and Meyer et al. (2005), for example. Wildfire enhances runoff by consuming rainfall-intercepting canopy and litter, and it reduces infiltration by formation of water repellent soils and through introduction of fine ash (Cannon and Gartner, 2005). Consequently, debris flows can be generated in burned areas from smaller rainfall events than would be needed to generate flows in unburned areas.

To reduce the potential for debris flow occurrence and also the size of flows that do occur, typical mitigation methods include both widespread hillslope treatments as well as more focused channel treatments. Santi et al., (2006) concluded that hillside treatments reduce debris flow potential by increasing infiltration of rainfall, reducing runoff, and thereby reducing the water available within the stream channel that could mobilize sediment into a debris flow. They also noted that channel treatment methods both reduced the volume of debris flows and reduced the capacity for debris flows to grow in transit by incorporating channel sediment into the moving flow.

The most commonly applied hillside treatments are seeding, construction of log erosion barriers, and mulching (Robichaud et al., 2000). Seeding incorporates both aerial and hand-spread distribution of fast growing plant seed intended to re-establish a vegetative cover as quickly as possible. The roots of the plants stabilize soil material, reduce the effects of raindrop impact, and increase infiltration (Miles, 2005). Seeding is generally considered a short-term erosion control method, most effective within one to three years following a fire, as plants will not establish themselves immediately, and natural vegetation will take over after a few years (Santi et al., in review).

Log erosion barriers (LEBs) are felled and limbed trees, aligned along contour, and held in place with stumps or wooden stakes (deWolfe et al., in review). Their intent is to disrupt overland flow, reduce runoff velocity and erosion potential, and to enhance infiltration. Other barrier materials, such as straw wattles, function similarly. LEBs can serve for both immediate and short-term mitigation.

Mulching includes the spreading of organic material, often with a binder or "tackifier", to reduce the effects of raindrop impact, disperse overland flow, and enhance reestablishment of vegetation (deWolfe et al., in review). It may be spread aerially or by hand, and is considered both immediate and short-term mitigation.

Channel treatments often include debris racks and fences, check dams, debris basins, silt fences, and deflection berms. Debris racks are engineered cage-walls designed to trap coarse debris and pass finer sediment and water. They are often located in front of culverts or bridges to protect those structures from clogging and damage. Debris fences are flexible versions of debris racks, constructed from ring-nets and fencing material rather than solely from concrete and thick-walled pipes.

Check dams are small dams, often built in series within channels, aimed at inducing deposition of debris in increments along the length of the channel. Debris basins are usually not constructed in series, but consist of individual, large dams, usually built near the base of the canyon. Silt fences are thin geotextile fabric barriers supported by wooden stakes or rebar. They are installed in series across the channel with the intent of intercepting debris in increments much like check dams. Deflection berms are earthen, timber, concrete, or rock walls strategically placed and aligned to direct debris flows away from valuable structures and into areas where the impacts of the debris will be minimal.

While widespread in use, the effectiveness of these treatment methods in reducing debris-flow volume has not been thoroughly or quantitatively evaluated. The goals of this study are to: assemble previously published evaluations of effectiveness, quantitatively assess the impacts of some of these methods on debris flow volume, and conduct extensive field observations in numerous burned areas to directly evaluate various mitigation methods.

PREVIOUS WORK

Detailed discussions of previous research evaluating the effectiveness of erosion control and debris flow control methods are presented in deWolfe et al. (in review) and deWolfe (2006). An abbreviated summary of those discussions is included below. Most previous research in burned areas evaluated erosion control rather than debris flow control (Miles, 2005; Robichaud et al., 2000; Beyers et al., 1998; Wohlgemuth et al., 1998, 1999, 2001, for example), and much of this previous work was at the plot scale or monitored individual hillslopes, rather than entire burned watersheds. However, it may be assumed that the performance of mitigation measures at the plot or hillslope scale will also reflect their performance at the watershed scale, at least with regards to reducing overland flow and enhancing infiltration. Therefore, our discussion will not be limited to debris-flow-specific treatments.

The broadest evaluation of erosion control effectiveness was a compilation of surveys of emergency response personnel, published by Robichaud et al. (2000). Four categories of effectiveness were used: excellent, good, fair, and poor. The rating for mulching was considered dominantly "excellent," and hand seeding was dominantly "good." LEB performance was variable, with many responses in the "good" and "excellent" categories. Aerial seeding was evenly split amongst the four categories, and check dams also received mixed reviews, with many "fair" and "poor" ratings.

Other studies assessed only one erosion control method at a time. Most seeding studies produced negative results, where treated slopes did not show significantly less erosion than untreated slopes (Wagenbrenner et al., 2006; Taskey et al., 1989; Beyers et al., 1998; Wohlgemuth et al., 1998; Roby, 1989; Geier-Hayes, 1997; and Beyers, 2004).

Conversely, the majority of the mulching studies reviewed concluded that proper application of mulch reduced erosion effectively (Wagenbrenner et al., 2006; Bautista et al., 1996; Kay, 1983; Buxton and Caruccio, 1979; Miles et al., 1989; Robichaud, 2006; and Dean, 2001).

The performance of LEBs was mixed. Gartner (2003) and Wohlgemuth et al. (2001) concluded that LEBs were easily bypassed by flowing water and were mostly ineffective. Dean (2001) considered them to be effective, but at a site that had also been mulched and seeded. Robichaud (2006) and Wagenbrenner et al. (2006) found LEBs to be effective only during low to moderate intensity rainfall events and not during high intensity events.

No studies evaluating the effectiveness of channel treatment measures were found, although there are published reports of the use of ring-net debris fences (Thommen and Duffy, 1997; Duffy and DeNatale, 1996) and check dams (Okubo et al., 1997), the function of check dams in unburned watersheds (Leys and Hagen, 1971; Eisbacher and Clague, 1984; Government of Japan, 1984; Thurber Consultants, 1984; Heierli and Merk, 1985; Whittaker et al., 1985; and Chatwin et al., 1994), and reports of check dam failure (Robichaud, 2006; White et al., 1998; and Hubbert and Associates, 2005).

Debris basins and deflection berms may be constructed at the mouth of a debris-producing watershed. They require larger amounts of space, but are considered very effective if designed and constructed properly (Santi et al., 2006).

DEBRIS VOLUME MEASUREMENTS

Debris volumes were measured for 46 debris-flow events in California, Utah, and Colorado (Santi et al., in review). For each canyon, a series of channel cross sections were surveyed up the length of the canyon. By interpreting the erosion and deposition evidence at each cross section, the area of scour or debris deposition was calculated. The incremental volume of debris incorporated into the passing flow or deposited as levees was then calculated as the average for two successive cross sections, multiplied by the distance between them. These incremental volumes were plotted as both the cumulative volume along the length of the channel and the total volume eroded and deposited, as shown on Figure 1. These graphs show sources of debris, whether from side channels, erosion of the main channel, or hillslope rilling. The slope of the graph indicates the yield rate, or intensity of scour and erosion.

Based on an analysis of these graphs, Santi et al. (in review) concluded that the highest contribution of sediment to a debris flow (at least 90%) was from channel erosion, with an average of one-fourth of that sediment coming from side channels and three-fourths from the main channel. Hillslope rilling accounted for an average of 3% of the total debris, with a maximum measured amount of 10%. Because of these results, they concluded that mitigation methods within the channel would be beneficial in reducing scour and growth of debris flows, and mitigation methods applied on the hillsides should be aimed at reducing water runoff rather than focusing solely on erosion control.

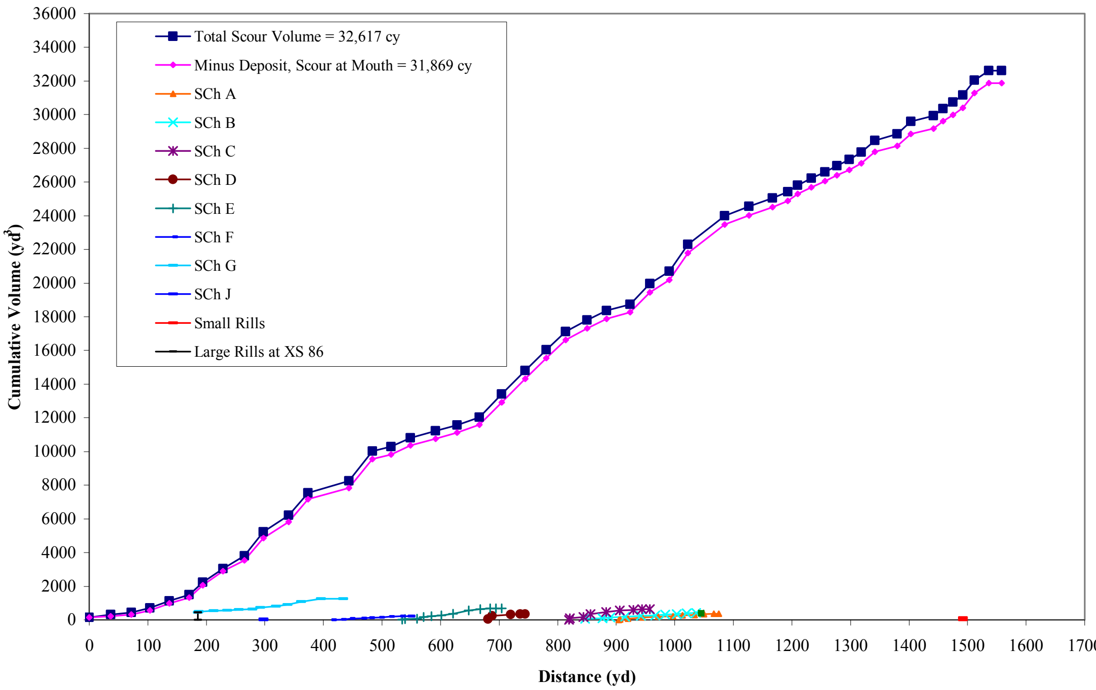

Figure 1. Example of a cumulative debris flow volume graph produced for this study, from Devore, CA. Note the contribution of side channels ("Sch") and rills, as well as the effect of levee deposition (pink "Minus Deposit" line).

VARIABILITY IN DEBRIS PREDICTION

Using data from Santi et al. (in review), Santi et al. (2006), and U.S. Army Corps of Engineers (in press), Gartner (2005) used multiple regression analysis to develop an equation to predict debris-flow volume in burned areas in the Western U.S.:

$$V = EXP(0.65(\ln S) + 0.86(B^{1/2}) + 0.22(R^{1/2}) + 6.46) \qquad \text{(Equation 1)}$$

Where: V = Volume (m^3)
S = area with slopes $\geq$ 30% (km^2)
B = area burned at moderate and high severity (km^2)
R = storm rainfall total (mm)

This model was considered the best of several generated, based on the R^2 of 0.83, the residual standard error of 0.90, the ease in measuring the input parameters, and support from independent validation with data points outside the set used in the regression (Gartner, 2005).

Santi et al. (2006) used Equation 1 to calculate the volume of material that could issue from a basin outlet for each of the basins in their study that had been treated with some kind of erosion control mitigation. Of the 46 basins studied, 12 included some erosion control mitigation, the largest of which was 2 km^2 in area. Treatments included various concentrations and coverages of seeding, mulching, and LEBs. Figure 2 shows the relationship between measured and predicted volumes. Values for six of the 12 basins (50%) are within one standard error of the predicted value, while five others are very close to the error envelope. Eight of the 12 data points (66%) show lower measured volume than was predicted, and four of the points (33%) are completely above the error envelope. Only four points (33%) show more measured volume than predicted, with two of those below (17%) the error envelope.

The fact that the majority of the predicted volumes are less than the measured volumes indicates that erosion and sediment control treatments can be effective in reducing debris-flow volume. The point to the far left is the most extreme case, and is discussed in more detail in the section below for Lemon Dam.

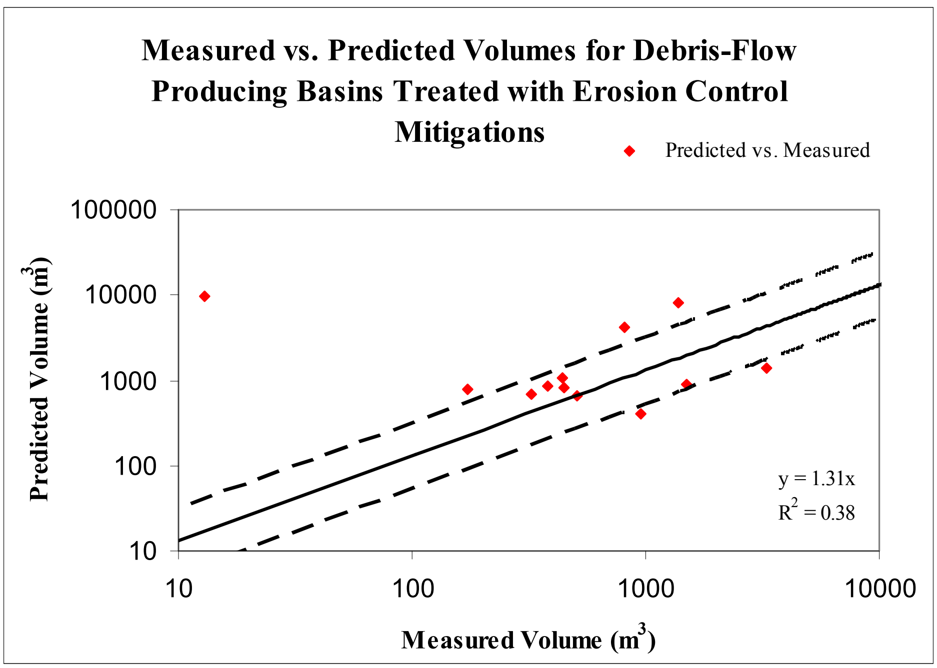

Figure 2. Relationship between measured and predicted volumes for treated basins. Dashed lines represent one standard deviation off the mean (68% confidence interval).

FIELD OBSERVATIONS

The field observations conducted for this study are reported in detail in deWolfe (2006) and Santi et al. (2006) and are summarized below. The field work included analysis of 46 burned watersheds producing debris flows and less detailed observation of several other burned watersheds.

Seeding did not appear to substantially reduce debris flow potential. Since seeding is a hillslope treatment method, its usefulness rests in its ability to reduce runoff and enhance infiltration. Because of the time required for germination, it was not effective for immediate treatment, and natural vegetation seemed to re-establish itself within the same time frame as seeded growth. Its effectiveness seemed to be improved when combined with mulch.

Mulch was effective at reducing surface runoff and enhancing infiltration, but only when placed properly. If evenly spread, as is usually done by hand, the mulch protects most of the soil. If spread by helicopter, the mulch was often clumped, providing poor coverage and preventing plant growth (Figure 3). Mulch was frequently redistributed by wind, which also resulted in clumping around trees and bushes and creating large areas with no coverage. Crimping of mulch into the soil, discussed in the next section, greatly improved its effectiveness.

LEBs can be effective at reducing hillslope runoff, as indicated in the next section, but are frequently undercut by runoff, rendering them ineffective. For example, deWolfe (2006) reports undercutting for a range of 17-83% of the LEBs in four different watersheds in the Missionary Ridge burn area in Colorado.

Figure 3. Poorly dispersed mulch applied by helicopter on burned slopes near Silverwood, CA. Note how clumping has prevented vegetation growth.

Check dams show promise as effective debris flow reducing structures, but only if designed and installed properly. They were successful at Lemon Dam in Colorado (see below), yet the dams failed and exacerbated the debris flow problem at the Piru Fire in California (Hubbert and Associates, 2005). Furthermore, they are expensive, labor intensive, and difficult to build in the steep upper reaches of channels where access is limited.

Silt fences were ineffective for erosion control as the fine mesh of the geotextile trapped fine sediment and water as well as coarse debris, causing them to be quickly filled and overwhelmed (Figure 4).

Figure 4. Failed silt fences near Farmington, UT.

Debris racks are less likely to be filled and overrun because their large size allows finer material and water to pass (Figure 5). Although limited observations were made, they performed well, as described in the next section.

While ring nets and deflection berms were observed at various sites within this study, their effectiveness could not be adequately gauged.

CASE STUDY AT LEMON DAM

Detailed case studies of the debris flow mitigation treatment and performance near Lemon Dam, Colorado are published in Coe (2006) and deWolfe et al. (in review) and summarized below. Because Lemon Dam is a critical part of the water supply system for the city of Durango, transport of sediment or debris flow into the reservoir following the 2002 Missionary Ridge Fire could have deteriorated water quality or interfered with the water intake system. The Florida Water Conservancy District (FWCD) was directed to prevent significant sediment movement into critical portions of the reservoir. Their mitigation efforts consisted of construction of LEBs, mulching, seeding, and construction of check dams and debris racks.

Figure 5. Debris rack installed near Lemon Dam, CO.

The LEBs at Lemon Dam appeared to have successfully reduced hillslope erosion and enhanced infiltration because they were constructed in dense concentrations and in conjunction with other erosion control measures. Ninety-three hectares of a severely burned watershed above the dam's spillway and intake structures were treated with concentrations between 220 and 620 LEBs/hectare. LEBs are usually applied to large areas in National Forests in concentrations of 100 LEBs/hectare (BAER, 2002). The LEBs were rehabilitated multiple times after being filled by hillside erosion during rainfall, by hand digging sediment from the uphill side and packing it under the downhill side of the barrier (Ey, 2004).

At Lemon Dam over 172 metric tons of mulch were spread by hand and crimped into over 100 hectares of burned slopes (WWE, 2005). Our field observations over the next three years indicated that the mulch remained in place, facilitated regrowth of vegetation, and protected the soil from erosion.

Critical areas near Lemon Dam were seeded at a rate of 67-84 kg/hectare (typical application concentrations are around 45 kg/hectare). Observations of those slopes show that spreading this concentration among crimped mulch helped re-establish a vegetative cover during the first growing season (Figure 6). We postulate that the mulch and LEBs reduced hillslope erosion and held the seeds in place until germination.

Thirteen earthen check dams were constructed in the main channel of Knight Canyon above Lemon Dam. Figure 7, taken on September 9th, 2003 (14 months after the fire, approximately 2-year recurrence interval storm), shows a check dam filled with an ash/mud deposit during a heavy rain in the watershed. In the background, another check dam can be seen in the series. The dams were monitored by the FWCD and cleaned out after such erosional events. The dams were properly constructed and sized, and effectively reduced both the volume of debris that reached the canyon mouth and the potential growth of the debris flow within the canyon (deWolfe et al., in review).

Five debris racks were constructed between October and December 2002. Only one rack was located in a channel that produced a debris-flow, intercepting ~130 m^3 of a debris-flow measured to be about 445 m^3 in total volume (Figure 7). The design of this debris rack prevented failure and allowed the fine material to continue down channel, where it was partially trapped by a second debris rack. Only muddy water reached the Florida River.

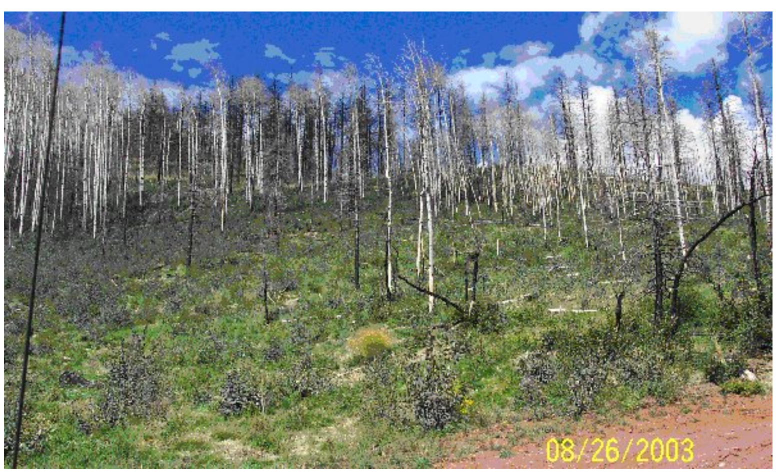

Figure 6. Natural and seeded revegetation near Lemon Dam, CO.

Figure 7. Check dam that captured ash/mud runoff following a rainstorm near Lemon Dam, CO.

The debris flow control methods at Lemon Dam were effective in virtually eliminating sedimentation into the reservoir, which can be attributed to a number of factors: the density of application of each mitigation method, the enhancement of methods working in concert, quality of installation, and rehabilitation of mitigation features to extend their useful life.

CONCLUSIONS

As a result of this study, we conclude that 1) the vast majority of material in post-fire debris flows comes from erosion of the canyon channel and not from hillslope erosion, 2) based on predictive modelling, there is a slight, but measurable reduction in debris volume from hillside treatment by mulch, seeding, and log erosion barriers (although seeding alone does not appear to reduce erosion), 3) installation methods, density of treatment, and maintenance of mulch, seeding, and log erosion barriers are critical to their success, 4) check dams and debris racks, if constructed properly and in $< 2km^2$ drainage watersheds with channel gradients less than 25 degrees (criteria suggested by Santi et al., 2006) have some potential for reducing debris-flow volume, 5) silt fences installed in channels were ineffective, as they quickly filled and were torn out.

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