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Sources of debris flow material in burned areas

Paul M. Santi [a,*], Victor G. deWolfe [a], Jerry D. Higgins [a], Susan H. Cannon [b], Joseph E. Gartner [b]

[a] *Department of Geology and Geological Engineering, Colorado School of Mines, Golden, CO 80401*
[b] *U.S. Geological Survey, Golden, CO 80401*

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Abstract

The vulnerability of recently burned areas to debris flows has been well established. Likewise, it has been shown that many, if not most, post-fire debris flows are initiated by runoff and erosion and grow in size through erosion and scour by the moving debris flow, as opposed to landslide-initiated flows with little growth. To better understand the development and character of these flows, a study has been completed encompassing 46 debris flows in California, Utah, and Colorado, in nine different recently burned areas. For each debris flow, progressive debris production was measured at intervals along the length of the channel, and from these measurements graphs were developed showing cumulative volume of debris as a function of channel length. All 46 debris flows showed significant bulking by scour and erosion, with average yield rates for each channel ranging from 0.3 to 9.9 m^3 of debris produced for every meter of channel length, with an overall average value of 2.5 m^3/m. Significant increases in yield rate partway down the channel were identified in 87% of the channels, with an average of a three-fold increase in yield rate. Yield rates for short reaches of channels (up to several hundred meters) ranged as high as 22.3 m^3/m. Debris was contributed from side channels into the main channels for 54% of the flows, with an average of 23% of the total debris coming from those side channels. Rill erosion was identified for 30% of the flows, with rills contributing between 0.1 and 10.5% of the total debris, with an average of 3%. Debris was deposited as levees in 87% of the flows, with most of the deposition occurring in the lower part of the basin. A median value of 10% of the total debris flow was deposited as levees for these cases, with a range from near zero to nearly 100%. These results show that channel erosion and scour are the dominant sources of debris in burned areas, with yield rates increasing significantly partway down the channel. Side channels are much more important sources of debris than rills. Levees are very common, but the size and effect on the amount of debris that reaches a canyon mouth is highly variable.

Keywords: Debris flow; Erosion; Scour; Levees; Rills

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1. Introduction

The vulnerability of recently burned areas to debris flows has been well established (Wells, 1987; Spittler, 1995; Cannon, 2001; Moody and Martin, 2001; Wondzell and King, 2003; Meyer et al., 2005). Likewise, it has been shown that many, if not most, post-fire debris flows are initiated by runoff and erosion (Cannon et al., 2001; Cannon and Gartner, 2005). This type of debris flow will grow in size through erosion and scour as the debris moves down-channel (Santi, 1988; Jaeggi and Pellandini, 1997). Runoff-initiated debris flows,

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* Corresponding author. Tel.: +1 303 273 3108.
E-mail address: psanti@mines.edu (P.M. Santi).

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therefore, are significantly different from landslide-initiated flows, which start with a large volume of failed material coming from one location, transforming into a flowing mass downslope from the initiation site (Johnson, 1984; Hungr, 2005), and often have little growth below the initiation site.

The potential for volume growth of runoff-initiated debris flows influences the analysis and mitigation efforts for these flows. The peak flow and total volume vary over time and distance. Treatment methods do not usually account for these variations, nor does assessment of risk at the mouth of the canyon. Consequently, it is important to identify and quantify the sources of material in these debris flows. This type of information will help clarify the processes by which debris is entrained into the flow, identify channel reaches and characteristics of contributing areas, and ultimately develop a better model for the initiation, growth, and deposition of debris flows.

2. Purpose of study

The purpose of this study was to identify the source of debris in a growing flow (whether from the channel thalweg, the hillsides, or both), to quantify how the debris flow grows as it travels down the channel, and to measure values for specific bulking rates along the length of the flow. This information allows a more meticulous analysis of the bulking processes in debris flows than has been possible in the past, and it leads to remediation goals that better target the factors influencing the growth of debris flows. The geomorphic process data generated from the study has never before been measured at this quantity or level of detail. This data adds to the current knowledge of the initiation of debris flows by sediment bulking by quantifying the proportions of material produced by different types of erosion from different parts of the drainage basin.

3. Previous observations and measurements of bulking

While previous research has documented bulking of debris flows, especially in burned areas, no studies have provided the level of detail, number of debris flows analyzed, and breadth of geologic conditions necessary to fully identify the sources of material for the debris flow and the potential implications for remediation. For

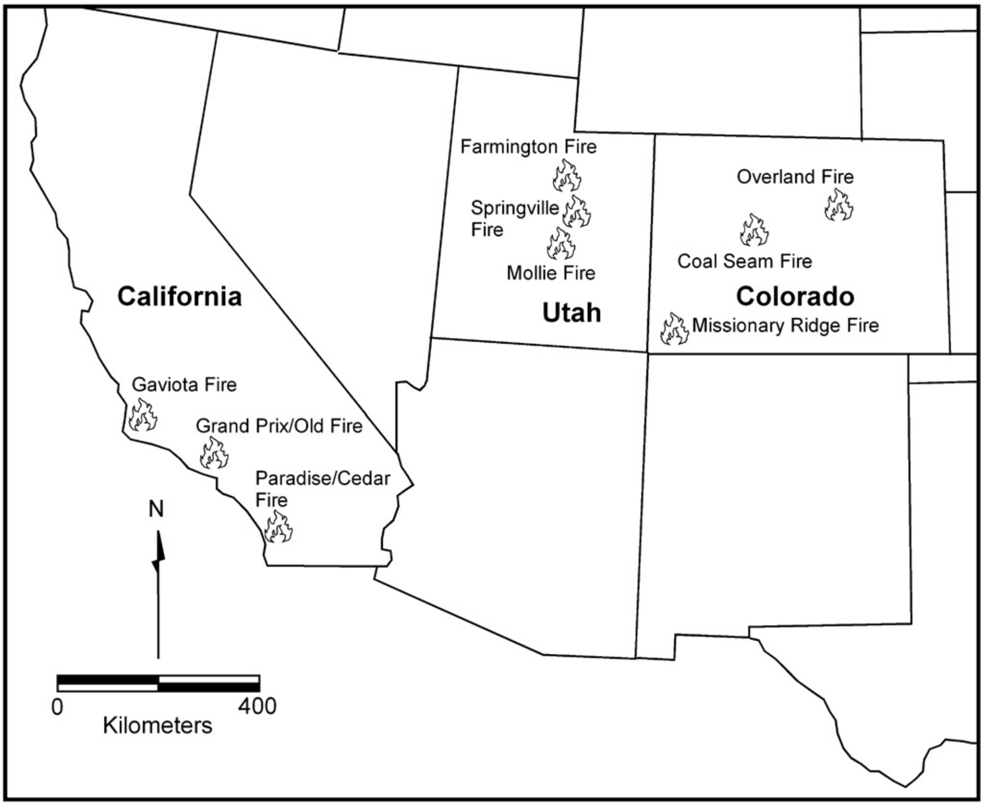

Fig. 1. Locations of wildfires where debris flows channels were measured for this study.

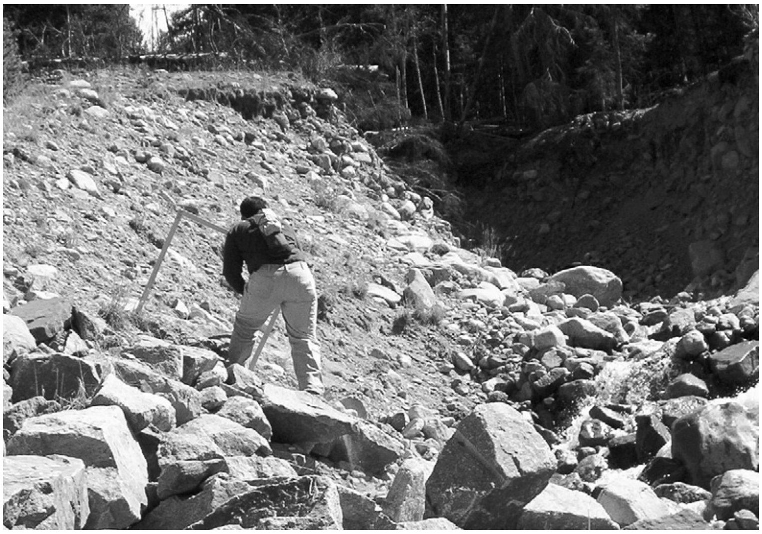

Fig. 2. Photograph showing the use of the slope profiler, advancing one length at a time across a scoured debris flow channel, recording the angle of inclination for each length.

example, Cannon and Gartner (2005) observed bulking for 160 out of 210 (76%) recently burned basins, but their dataset has no quantitative information regarding the degree of bulking or the sources of bulked debris. Meyer et al. (2005) estimates that 58% of the volume of a debris flow in Yellowstone National Park came from bulking through channel incision and 30% from rilling. These values are estimates from field observation, and while quantitative, they should be considered approximate. Santi (1988) provides accurate volume measurements for the growth of a debris flow for a single basin in Davis County, Utah. The current study uses similar methodology, but greatly expands the type and number of basins studied.

Cannon et al. (2001, 2003) examined the process of progressive sediment bulking in burned areas using detailed field mapping of transitions from debris floods to debris flows within channels. This work identified a threshold location within channels where sufficient eroded material is incorporated into surface runoff, to generate debris flows that persist down the length of the channel. Above this location in a given basin, the attainment of conditions for debris flows can be transitory; and variations in sorting and grain-size distributions in the deposits indicate that the flow fluctuates between debris flow and more dilute flows before persistent debris flow conditions are achieved. Although Tognacca and Bezzola (1997), Tognacca et al. (2000), and Istanbulluoglu et al. (2003), describe possible theoretical frameworks and experimental and field work to characterize channel erosion, they do not specifically address the critical transition from sediment-laden water flow to debris flows. This is an important consideration in burned areas because channel incision can occur in nearly every basin, given sufficient rainfall, but debris flows are not necessarily generated from all incised channels.

4. Methods

The database for this study includes 46 debris flows in California, Utah, and Colorado, in nine different recently burned areas (Fig. 1) (deWolfe, 2006). For each

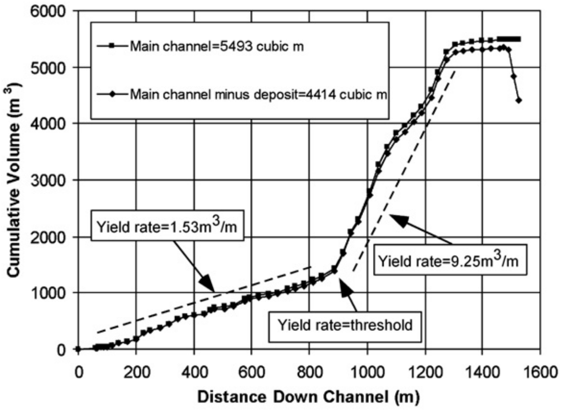

Fig. 3. Example graph produced for this study, showing the cumulative volume of moving debris along the length of the channel, in this case for Elkhorn Canyon within the Missionary Ridge Fire in Colorado (Table 1). Notice the effect of levee deposition in decreasing the scoured volume that continues downchannel. Example changes (thresholds) in yield rate are also shown. Yield rate thresholds were identified in 40 of the channels (87%).

Table 1
Summary of data from graphs of cumulative volume of debris

Basin Name (Fire)[a]	Total debris volume	Vol. debris from rills	Percent debris from rills	Vol. debris from side channels	Percent debris from side channels	Number of side channels	Vol. debris as levees	Percent debris as levees	Overall yield rate[b]	Rate[c] before change	Rate[d] after change	Ratio after/before change
	m^3	m^3		m^3			m^3		m^3/m	m^3/m	m^3/m	
Haflin (A)	23967			1349	5.6	4	2805	11.7	5.09	1.95	5.66	2.9
Kroeger (A)	8324						283	3.4	2.78	2.07	3.18	1.5
Woodard (A)	6541						491	7.5	3.27	1.04	1.07	1.0
Elkhorn (A)	5493						1079	19.6	3.60	1.53	9.25	6.0
Air Jordan (A)	4454			421	9.5	1	130	2.9	4.46	4.42	4.71	1.1
Root Creek (A)	1476						24	1.7	2.70	0.70	5.14	7.3
Mayer (A)	3485			1000	28.7	1			1.76	1.30	5.28	4.0
Gut (A)	818						72	8.8	0.89	0.71	1.66	2.3
Ey (A)	448			27	6.0	1	29	6.5	0.71	0.70	2.74	3.9
Coal Seam A (B)	1391						38	2.7	1.61	0.65	2.98	4.6
Coal Seam F (B)	250								0.60			
Coal Seam G (B)	574						102	17.8	1.22	0.95	1.81	1.9
Coal Seam H (B)	325						115	35.3	0.67	0.49	1.10	2.2
Coal Seam L (B)	257						67	26.2	0.56	0.38	1.02	2.7
Coal Seam O (B)	260						709		0.33			
Jamestown P.O. (C)	326			65	19.9	4			0.38	0.31	0.78	2.5
Tower (C)	174						116	66.7	0.39	0.38	0.84	2.2
Heil Ranch 2 (C)	951						950	99.9	0.92	1.05	2.07	2.0
Santaquin T2 (D)	4119			417	10.1	1	294	7.1	1.71			
Santaquin T3 (D)	6262						716	11.4	1.86	0.99	2.03	2.0
Santaquin T4 (D)	9251			2141	23.1	2	357	3.9	2.08	0.83	3.90	4.7
Santaquin T5 (D)	3061						279	9.1	2.05			
Santaquin T6 (D)	5282						495	9.4	2.20	1.31	4.42	3.4
Buckley Draw (D)	810						643	79.3	0.30	0.33	0.52	1.6
Compton Bench M (E)	1515						551	36.4	1.20	0.63	2.42	3.9
Compton Bench S (E)	511								1.23	0.87	2.53	2.9
Intake (E)	3311			857	25.9	2	216	6.5	2.32	1.71	4.73	2.8
Janet Creek J3 (F)	6293			120	1.9	3	372	5.9	2.98	1.76	5.46	3.1
Gaviota S (F)	1315	94	7.2	336	25.5	4	26	2.0	1.09	0.89	1.39	1.6
El Capitan I (G)	441	28	6.4				21	4.9	0.43	0.43	0.49	1.1
El Capitan II (G)	382	9	2.4	11	3.0	1			0.47			

(continued on next page)

Table 1 (*continued*)

Basin Name (Fire)[a]	Total debris volume m^3	Vol. debris from rills m^3	Percent debris from rills	Vol. debris from side channels m^3	Percent debris from side channels	Number of side channels	Vol. debris as levees m^3	Percent debris as levees	Overall yield rate[b] m^3/m	Rate[c] before change m^3/m	Rate[d] after change m^3/m	Ratio after/before change
Silverwood O (H)	6119											
Silverwood M (H)	4510	472	10.5	998	22.1		1157	25.6	1.66			
Devore (H)	24937	434	1.7	3051	12.2	8	572	2.3	9.93	6.92	22.32	3.2
Lytle W (H)	10387	95	0.9	742	7.1	7	5219	50.2	5.82	5.27	8.15	1.5
Sweetwater C (H)	3802	94	2.5	1124	29.6	15	196	5.1	1.38	0.86	2.17	2.5
X (H)	4341	47	1.1	1280	29.5	9	11	0.2	3.02	1.10	7.04	6.4
XX (H)	1094	47	4.3	213	19.5	8	156	14.3	0.81	1.08	1.36	1.3
Cleghorn le (H)	1528	9	0.6	1001	65.5	10	184	12.1	1.08	0.79	1.10	1.4
Lytle Hourglass (H)	683	1	0.1				485	71.0	6.33			
Lytle AQ1 (H)	561	5	0.8				407	72.5	3.36	1.47	8.73	5.9
Cleghorn Water Tank (H)	2218	47	2.1	287	12.9	4	375	16.9	3.04	2.62	10.50	4.0
Waterman N (H)	2279	9	0.4	714	31.3	3	59	2.6	1.93	0.49	2.54	5.2
Sawpit (H)	59281			22301	37.6	6	12653	21.3	8.25	3.61	8.01	2.2
Sawpit A (H)	8542			1456	17.0	3			2.71	1.20	6.15	5.1
Sawpit B (H)	14143			8045	56.9	6	3629	25.7	5.16	5.05	11.91	2.4
Silverwood Pe (H)	31817			8670	27.2	8	4145	13.0	4.56	3.04	10.76	3.5
Silverwood Pw (H)	22826			9448	41.4	7	1731	7.6	5.22	4.87	7.19	1.5
Average Values	6274	99	2.9	2643	22.8	5	1023	20.7	2.47	1.67	4.63	3.0
Median Values	2670	47	1.9	998	22.1	4	357	10.4	1.86	1.05	3.08	2.6
Minimum	174	1	0.1	11	1.9	1	11	0.2	0.30	0.31	0.49	1.0
Maximum	59281	472	10.5	22301	65.5	15	12653	99.9	9.93	6.92	22.32	7.3

[a] Fire, location, year: A = Missionary Ridge, CO, 2002; B = Coal Seam, CO, 2002; C = Overland, CO, 2003; D = Mollie and Springville, UT, 2001; E = Farmington, UT, 2003; F = Gaviota, CA 2004; G = Cedar, CA, 2003; H = Grand Prix and Old, CA, 2003.

[b] "Overall yield rate" is the average debris production, in m^3 per linear m of channel, for the entire length of the debris flow.

[c] "Rate before change" is the yield rate in the upper part of the channel, before the threshold of increased yield rate is reached.

[d] "Rate after change" is the yield rate below the threshold region, where yield rate has noticeably increased.

debris flow, the progressive production of debris was measured at intervals along the length of the channel, and from these measurements graphs were developed showing cumulative volume of debris as a function of channel length. The basins were selected for study based on size, accessibility, and mitigation characteristics. Small basins (0.5–2 km^2) were desirable because they could be measured more rapidly, but basins up to 5 km^2 were later targeted to expand the breadth of the database.

The volume of material scoured from each channel during the passage of the debris flows was measured during the summers of 2004 and 2005 by surveying a series of channel cross-sections within the basins. The cross-sections were measured at various intervals perpendicular to flow using a slope profiler (Keaton and DeGraff, 1996). This method was previously used by Santi (1988) to characterize erosion by debris flows in Davis County, Utah. A slope profiler consists of two legs fixed at right angles to a 0.91 m (one-yard) long cross piece so that the legs span 0.91 m (one linear yard). An angle finder is attached to the middle of the cross piece, and is used to measure the angle when placed on a slope (Fig. 2). Some estimation must be made as to the shape of the channel pre-debris flow: this shape was assumed to be similar to observed nearby channels that did not produce debris flows. For each basin, between 9 and 254 cross-sections were measured, depending on basin size. Over 2500 cross-sections were surveyed for the project.

As each of the cross-sections was surveyed, geologic details were recorded which allowed for later interpretation. These details include the channel and hillslope gradients, the locations of channel incision (or debris flow scour), locations of deposits, levees, muddy veneers, bedrock, and slumps. Particular attention was paid to the location of channel incision on each side of the channel so that a representative area (in square meters), eroded by the debris flow, could be calculated. The distance between successive cross-sections was recorded, as well as the azimuth (orientation) of the section. By calculating the average area scoured between consecutive cross-sections and multiplying this value by the distance between the cross-sections, an incremental volume of eroded material was calculated for that reach of channel. The total volume of material eroded from a channel was calculated as the sum of the incremental values. At locations within the basin where extensive rilling was observed, the average depth and width of the rills was measured, the space between them and the area impacted was recorded.

Graphs showing the cumulative volume of material eroded along the length of the channel were developed for each of the 46 basins. Fig. 3 is an example graph for Elkhorn Canyon, located near Durango in southwestern Colorado, which burned in the 2002 Missionary Ridge Fire (Fig. 1). The slope of any segment of the graph is the channel yield rate (in m^3/m), or the volume of material eroded per unit length of channel (Hungr et al., 1984). Where the slope of the line increases, more material is being eroded because of a steeper channel gradient, a thicker sediment supply, or in some cases the entrance of a side channel. Correspondingly, where the slope of the line decreases, less material is being eroded because of either a decrease in channel gradient or the presence of bedrock, which limits channel incision. The graphs of cumulative volume can also show the entrance of significant side channels, rills, and sheetwash, along with their respective estimated volumes.

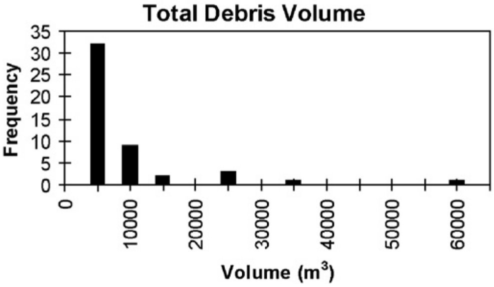

Fig. 4. Volumes of debris flows measured for this study (*N*=46). Data is shown in Table 1.

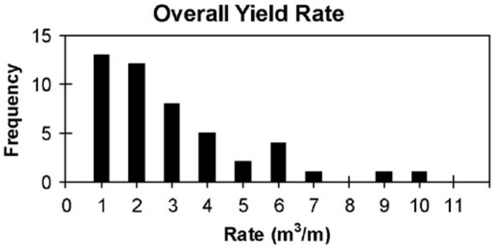

Fig. 5. Average yield rates for each channel measured for this study. Yield rate is the volume of debris produced for each unit of channel length, in this case in m^3/m.

Santi and deWolfe (2005) addressed the accuracy and precision of the slope profiler measurement method. Based on total measured volume of the debris flow, they calculated an error range of −23% to +23%, which is

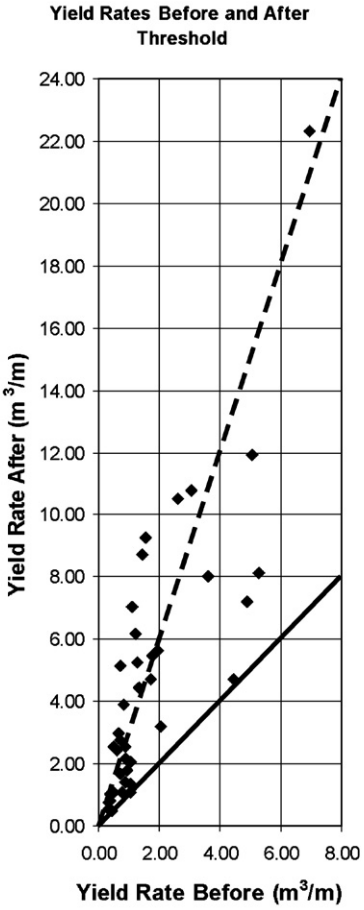

Fig. 6. Plot of yield rates for channels where significant changes occur. Yield rates before and after thresholds are shown. Solid line (1:1 slope) indicates no change. Dashed line (3:1 slope) marks the average increase in yield rate of 300%.

less than half the expected error when measuring debris volume by truck counts during cleanouts of debris basins (−45% to +80%) or CAD measurements of volumes of debris fans (−48% to +83%), and is less than the expected error when measuring the volume of debris fans in the field with GPS units (−27% to +37%). Precision was quantified by comparing volumes measured by two individuals using the slope profiler on the same channel reach, where the relative percent difference (RPD) in their values was 17%. For comparison, RPD between CAD measurements of the volume of a fan made by two different agencies was 28%. Finally, the sensitivity to the selection of the location of the cross-section measurement was measured by calculating the volume of debris for a channel reach using two offset sets of cross-sections. The RPD for this test was 5 to 16% (two different individuals made independent measurements). These calculations show that the slope profiler method is substantially more accurate than other methods typically used to estimate the volume of debris flows, and that the calculated volumes may be assumed to lie within 23% of the true value.

5. Results

Graphs similar to Fig. 3 were produced for all 46 debris flows studied. These graphs of cumulative volume of debris allow detailed evaluation of several aspects of the growth of debris flows, as summarized in Table 1. The first several columns of the table include the total volume of debris produced in each basin, as well as the volume of debris generated from side channels and rills and their percentage of the total volume. Likewise, volumes of debris deposited as levees along the sides of channels are reported, as well as their percentage of the total volume. The “Overall Yield Rate” column in Table 1 is the average production of debris, in cubic meters per linear meter of channel, for the entire length of the debris flow. It represents the overall slope of a graph of cumulative volume of debris such as Fig. 3. The two columns following “Overall Yield Rate” are the yield rates of short channel stretches before and after significant increases in slope of the graph. The final column is the ratio of the slope after the increase in yield rate to the slope before the increase in yield rate. The bottom rows of Table 1 show average, median, minimum and maximum values for each column. The reader

Fig. 7. Deeply incised channel reach with high yield rate. This channel section is in Devore Canyon near San Bernardino, CA, directly above the San Andreas Fault.

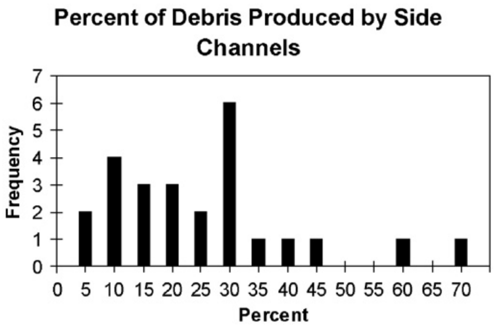

Fig. 8. Summary of percent of total debris produced by side channels. Side channels contributed debris in 25 (54%) of the measured flows.

should note that drainage basins “Sawpit A” and “Sawpit B” are sub-basins feeding into “Sawpit.” The sub-basins were large enough that we considered them valid data points independent from the larger basin.

5.1. Volumes of debris flows

The debris flows evaluated for this study ranged in size from 174 to 59,281 m^3. As shown on the volume histogram, included as Fig. 4, the dataset is positively skewed, with most values falling in the lower range. The median size of debris flows was 2670 m^3 and the mean was 6274 m^3.

5.2. Yield rates

All 46 basins showed significant bulking by scour and erosion, with average yield rates for each channel ranging from 0.30 to 9.93 m^3 of debris produced for every meter of channel length, with an overall average of 2.47 m^3/m and a median value of 1.86 m^3/m, as summarized on Fig. 5. Significant increases in yield rate partway down the channel were identified in 87% of the basins, an example of which is shown in Fig. 3. The average increase in yield rate at this threshold, shown on Fig. 6, is 304% (a 3-fold increase), with increases ranging from 103% to 732%. Yield rates for some channel reaches (up to several hundred meters in length) ranged as high as 22.3 m^3/m.

The yield rate changes, as illustrated in Fig. 6, were the most dramatic and obvious changes in the slope of the graphs of cumulative volume, with yield rates before and after the threshold representing long reaches of the channels, with lengths of at least 300 meters. Short channels were deeply incised (Fig. 7), but did not necessarily show clear threshold jumps from lower to higher yield rates and were not included in the data in Fig. 6.

5.3. Side channels

Debris was contributed from side channels into the main channels for 54% of the debris flows, with an average of 23% of the total debris coming from those side channels, ranging from a high of 66% to a low of 2%. A frequency graph of the contribution from side channels, as a percent of the total debris flow volume, is included as Fig. 8. An example of a contributing side channel is shown in the photograph in Fig. 9.

5.4. Rills

Rill erosion was identified for 30% of the debris flows, with rills contributing between 0.1 and 10.5% of

Fig. 9. Example side channel (from Devore Canyon) that contributed several hundred cubic meters of debris to the main channel.

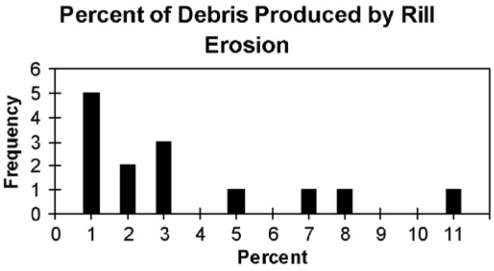

Fig. 10. Summary of percent of total debris produced by rill erosion. Rills contributed debris in 14 (30%) of the measured flows.

the total debris volume, with an average of 2.9% (median of 1.9%). A frequency graph of the contribution from rills is included as Fig. 10 and a photograph of a rilled hillside is shown in Fig. 11. Because rills are, by definition, short-lived features that may disappear not long after formation, it is possible that these values underestimate the contribution of rill erosion to the total volume of debris. We observed well-formed rills in some areas, however, and no evidence at all of rilling in other areas, with little evidence of partly eroded or subdued rill features, which would indicate rilled areas that might be missed if field observation was not done promptly after the debris flow. These observations support our conclusion that if rills were a contributing factor, they were adequately accounted for by field observation.

5.5. Levees

Debris was deposited as levees in 87% of the flows, with most of the deposition occurring in the lower part of the basin. A median value of 10% of the total volume of the debris flows was deposited as levees for these cases (a mean value of 21%), with a range from near zero to nearly 100% (where almost no debris reached the canyon mouth). A frequency graph of levee volume as a percentage of total volume of the debris flow is included as Fig. 12 and a photograph of typical levee deposits is shown in Fig. 13.

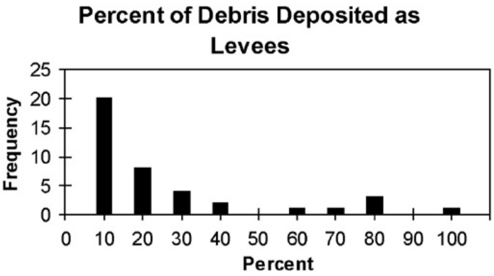

Fig. 12. Summary of percent of total debris deposited as levees along the sides of the main channel and above the canyon mouth. Levees were observed in 40 (87%) of the measured flows.

6. Discussion

The measurements for the growth of debris flows made for this study indicate that the majority of the debris comes from channel erosion and incision, with very little coming from hillside rill erosion (an average of only 3%, occurring in only 30% of the debris flows). Consequently, mitigation efforts to reduce channel incision, by using properly constructed check dams or debris racks, for example, will reduce the volume of debris and the resultant impacts at the mouth of the canyon. A place

Fig. 11. Rilled hillside above main channel (Devore Canyon). Arrows mark rills. Height of hillside shown is about 30 m.

Fig. 13. Levees formed near the mouth of the main channel. This example is from Red Mountain, south of Glenwood Springs, CO. Log is about 8 m long.

exists, however, for hillside erosion-control methods. deWolfe (2006) demonstrated that drainage basins treated for hillside erosion (with various combinations of mulching, seeding, and log erosion barriers) produced smaller debris flows than would be predicted with a multivariate regression model developed for the same geological/hydrologic settings by Gartner (2005) and Gartner et al. (2008-this volume). Because very little debris comes from the hillsides, the logical conclusion is that the hillside erosion-control methods reduced rainfall runoff and promoted infiltration. This counteracts the changes brought about by wildfire, where runoff is increased and infiltration is decreased because of the loss of leaf litter and duff, ash accumulation, and hydrophobic soil development (Spittler, 1995; Doerr et al., 2000; Shakesby et al., 2000; Martin and Moody, 2001; Wondzell and King, 2003; Meyer et al., 2005). Therefore, hillside treatment to manage water runoff decreases the fluid component that drives the growth of debris flows, and channel treatment to reduce scour decreases the fluid and sediment components of the flow.

Substantial increases in debris yield rates were identified for a majority of the basins measured (83%). These increases indicate that some threshold was exceeded and volume of debris started increasing drastically (an average of 3 times the previous rate, and in some cases as high as 7 times). No clear explanation for this increase could be identified: it did not correspond to channel slope before and after the change, nor to a threshold volume of debris or channel length, nor to a soil mechanics explanation using debris height as a parameter representing loading of underlying saturated sediment. We suspect, but are as yet unable to satisfactorily demonstrate, that this threshold represents the transition from hyperconcentrated flow (more akin to streamflow) to debris flow (more akin to “viscous slurry flow,” as per Pierson and Costa (1987)). Future analysis of this phenomenon may produce a satisfactory explanation as well as a set of mitigation approaches that will most efficiently minimize erosion and perhaps avoid exceeding this threshold.

Like yield rate thresholds, levees were widely observed (for 87% of the debris flows studied), but the occurrence could not be directly tied to some simple characteristic, such as channel slope or total volume of debris at the onset of levee deposition. Most likely, levee development is a result of a combination of several factors, including channel slope, channel geometry and depth, volume of debris, and sediment/water ratio. Levee deposition reduces the volume of debris that reaches the canyon mouth, which usually presents the greatest hazards to human structures. Therefore, mitigation measures, such as channel reconfiguration or mid-canyon debris basins, will encourage levee or other types of mid-canyon deposition and reduce debris flow hazards.

The last general observation noted from the graphs of the cumulative volume of debris is the importance of side channels to the main debris flow. Runoff-initiated debris flows would be expected to be more likely to have branched, tributary sources than would landslide-initiated debris flows. This was clearly demonstrated by our dataset, where over half of the flows (52%) received debris from side channels (contributing an average of

23% of the total debris volume). As a result, mitigation should not focus on the main channel alone, but should include any sub-basin that could potentially add debris to the flow.

7. Conclusions

Channel erosion and scour are the dominant sources of debris in burned areas, with yield rates increasing after a threshold is exceeded partway down the channel. No method of predicting the size or location of these thresholds has been found. Beneficial mitigation methods include hillside treatment to reduce water runoff, thereby reducing the potential for the occurrence of debris flows and the size of any flows that do occur, as well as channel treatment to reduce scour and growth of debris flows.

Side channels are much more important sources of debris than hillslope rilling, and mitigation programs should address the potential contributions from these tributaries. Levees are very common, but the size and effect on the amount of debris that eventually reaches a canyon mouth is highly variable.

Future research in this area should focus on developing an understanding of yield rate thresholds and levee deposition thresholds. Control of these parameters will reduce the rate of growth of the debris flow as it travels, and enhance the deposition of debris higher in the basin, where fewer structures are usually at risk.

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