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A process for fire-related debris flow initiation, Cerro Grande fire, New Mexico

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Abstract:

In this study we examine factors that pertain to the generation of debris flows from a basin recently burned by wildfire. Throughout the summer 2000 thunderstorm season, we monitored rain gauges, channel cross-sections, hillslope transects, and nine sediment-runoff traps deployed in a steep, 0·15 km^2 basin burned by the May 2000 Cerro Grande fire in New Mexico. Debris flows were triggered in the monitored basin during a rainstorm on July 16, 2000, in response to a maximum 30 min rainfall intensity of 31 mm h^{-1} (return period of approximately 2 years). Eleven other storms occurred before and after the July storm; these storms resulted in significant runoff, but did not generate debris flows.

The debris flows generated by the July 16 storm initiated on a broad, open hillslope as levee-lined rills. The levees were composed of gravel- and cobble-sized material supported by an abundant fine-grained matrix. Debris-flow deposits were observed only on the hillslopes and in the first and second-order drainages of the monitored basin. No significant amounts of channel incision were measured following the passage of the debris flows, indicating that most of the material in the flows originated from the hillslopes.

Sediment-runoff concentrations of between 0·23 and 0·81 kg l^{-1} (with a mean of 0·42 kg l^{-1}) were measured from the hillslope traps following the debris-flow-producing storm. These concentrations, however, were not unique to the July 16 storm. The materials entrained by the July 16 storm contained a higher proportion of silt- plus clay-sized materials in the <2 mm fraction than the materials collected from storms that produced comparable sediment-runoff concentrations but not debris flows. The difference in materials demonstrates the critical role of the availability of fine-grained wood ash mantling the hillslopes in the runoff-dominated generation of post-wildfire debris flows. The highest sediment-runoff concentrations, again not unique to debris-flow production, were produced from maximum 30 min rainfall intensities greater than 20 mm h^{-1}. Copyright © 2001 John Wiley & Sons, Ltd.

KEY WORDS debris flow; wildfire; erosion; hazards; hillslope processes; rainfall

INTRODUCTION

The occurrence of debris flows is one of the most hazardous consequences of wildfires in the urban/wildland interface. Debris flows can occur with little warning, are capable of transporting large material over relatively gentle slopes, and may develop momentum and impact forces that cause considerable destruction to the built environment. Thus, the mitigation of debris-flow hazards is often more difficult than the mitigation of flood hazards. Understanding the processes that lead to the generation of fire-related debris flows is important for the design and implementation of effective and appropriate mitigation measures.

In this study, we evaluate a post-wildfire debris-flow initiation process by measuring rates of hillslope sediment and runoff production, rates of channel erosion, and storm rainfall accumulations in a basin burned by the Cerro Grande fire of May 2000 near Los Alamos, New Mexico (Figure 1).

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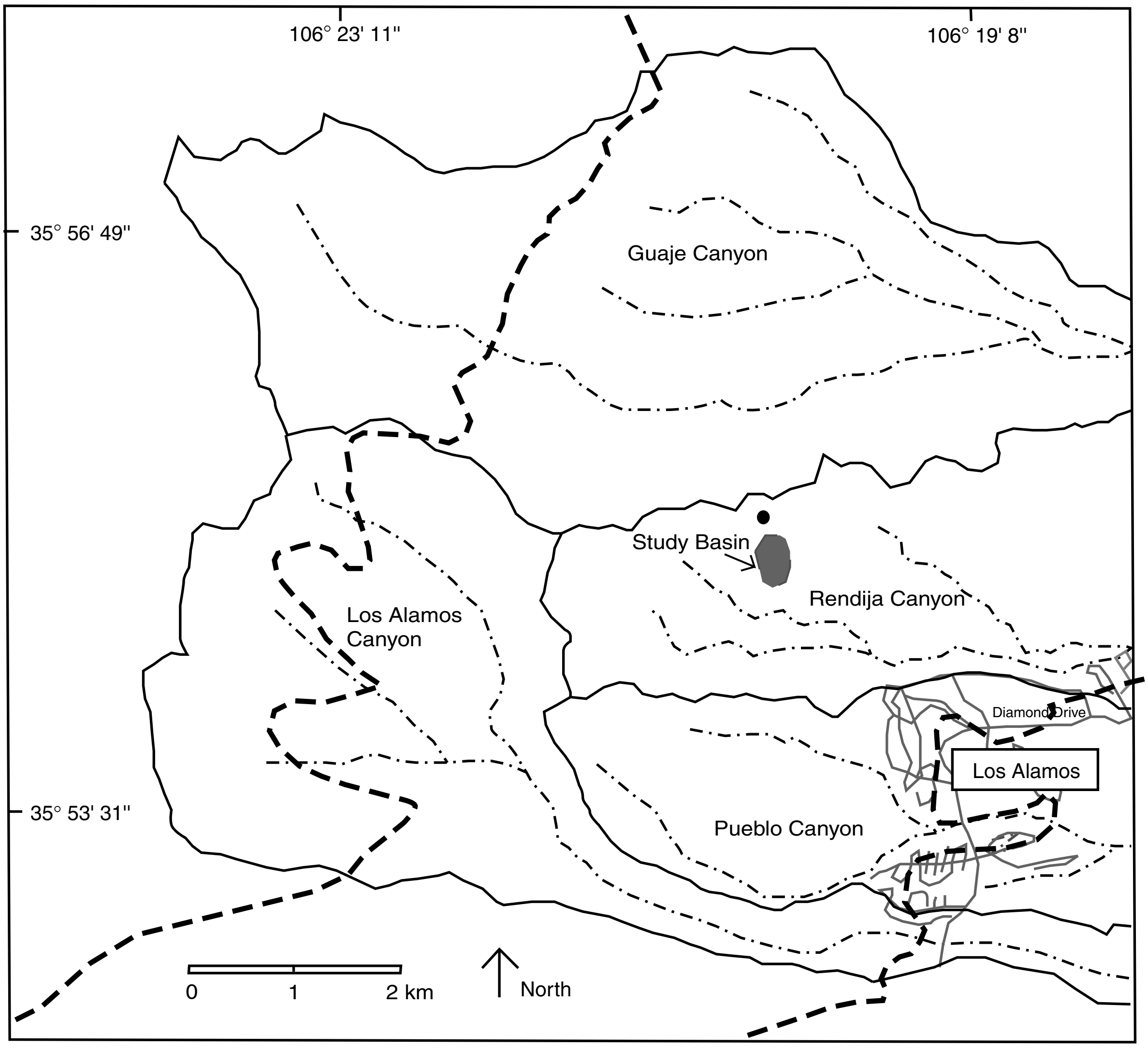

Figure 1. Location map showing Los Alamos and nearby canyons, and location of study basin. Solid lines delineate major drainage basins, thick dashed line shows fire boundary, and thin dashed lines show locations of streams. Solid dot marks basin where debris-flow deposits were also observed following the July 16, 2000, storm

Previous work

Two initiation processes for fire-related debris flows have been identified in the literature: infiltration-triggered soil slip, and runoff-dominated erosion by surface overland flow. The process of soil slip-debris flow has been documented in burned areas by Wells (1987), Morton (1989), Booker (1998), and Cannon (1999). The occurrence of soil slips on the hillslopes indicates a failure mechanism triggered by rainfall infiltration. Debris-flow generation by failure of a discrete landslide in burned areas has also been attributed to reduced evapotranspiration rates and the consequent increase in soil moisture (Klock and Helvey, 1976; Helvey, 1980; Swanson, 1981; Megahan, 1983) and decay of roots that anchor colluvium (e.g. Swanson, 1981; DeGraff, 1997). Root decay processes are generally thought to affect slope stability up to 10 years after the fire.

Alternatively, debris-flow initiation has been attributed to significantly increased rates of rainfall runoff in recently burned areas. Johnson (1984) and Wells (1987) traced debris-flow deposits directly upslope through small gullies and into a series of rills. These workers concluded that the debris flows initiated high on the hillslopes from material eroded by surface runoff, and that the debris flows increased in volume by entraining material from the channels. In Wells' (1987) model, debris flows initiate as miniature soil slips in a saturated layer of soil a few millimetres thick above a subsurface water-repellent zone. Shallow, narrow debris flows form rills as they travel downslope.

Meyer and Wells (1997) describe a somewhat different process attributed to increased runoff rates in burned areas. These workers observed that debris-flow features, such as levees and mud coatings, first occurred in the middle reaches of the main basins and concluded that debris flows initiated through progressive bulking of surface runoff with sediments entrained by rill erosion in steep upper basin slopes, followed by deep incision as the flows progressed down channels. Parrett (1987) also noted the lack of landslide scars in a burned area that experienced debris flows and suggested a similar mechanism. Meyer and Wells (1997) and Parrett (1987) emphasize that both hillslope sediment input from rills and gullies and the material entrained by extensive channel incision are important in the bulking process that led to the formation of debris flows. Meyer and Wells (1997) further hypothesized that the addition of fine-grained sediment eroded from hillslopes to the generally coarser-grained channel material was important in both the development of debris-flow conditions and in maintaining the mobility of the flow.

More recently, Cannon (1999) and Cannon *et al.* (2001) described evidence of both runoff- and infiltration-dominated debris-flow initiation processes within individual burned basins. However, Cannon *et al.* (2001) found that considerably more material was contributed to the debris flows from hillslope runoff and erosion than from the soil slip scars on the hillslopes, and concluded that runoff-dominated processes were prevalent in recently burned environments.

Furthermore, Cannon *et al.* (2001) formulated a conceptual model for fire-related debris-flow generation based on field mapping of the initiation locations of debris flows generated from six recently burned basins in Colorado. Here, the generation of debris flows started with significant sheetwash, rill, and rainsplash erosion and transport of burned mineral soil from the hillslopes high within the contributing areas of each basin. Surface runoff, bulked with material eroded from the hillslopes, converged into small, zero- and first-order drainages. At the point within the drainages defined by a threshold value of upslope contributing area and its gradient, sufficient eroded material had been incorporated, relative total volume of contributing surface runoff, to generate debris flows. Within a contributing area, the down-gradient increase in entrained sediment was relatively greater than the down-gradient increase in surface runoff, which resulted in a progressive increase in the sediment–water ratio. This increase in the proportion of sediment to water was sufficient to generate debris flows. The lack of significant erosion of both low- and higher-order channels with the passage of the debris flows indicated that the flows were composed primarily of material eroded from the hillslopes.

Here, we examine fire-related debris-flow initiation processes using a field-monitoring experiment designed to evaluate the following questions.

(1) What sediment-runoff concentrations are produced from recently burned hillslopes, and at what concentrations are debris flows generated?
(2) How much material is contributed to debris flows by channel erosion?
(3) Is there a relation between rainfall intensity and sediment-runoff concentrations?

Setting

The Cerro Grande fire burned approximately 17 200 ha of ponderosa pine and mixed conifer forest and piñon–juniper woodland between May 4 and June 6, 2000, along the eastern flank of the Jemez Mountains and the western side of the Pajarito Plateau near the town of Los Alamos, New Mexico (Los Alamos National Laboratory, 2000) (Figure 1). Elevations range between about 2200 and 3000 m, and the town of Los Alamos is at 2260 m. The area experiences a southwest monsoon-type climate and Los Alamos receives 490 mm of mean annual precipitation (Bowen, 1990). The period from late April through the end of June is usually dry, and is followed by the onset of a summer monsoon season. Some 60% of the annual precipitation falls in July through September, with thunderstorms reported for 58% of the days in July and August (Bowen, 1990). During the rest of the year the precipitation is generally associated with the passage of frontal storms and tends to be less intense.

The experimental results described here are derived from a hillslope and channel-monitoring array established in a zero- to second-order tributary to Rendija Canyon (Figures 1 and 2). Elevation of the monitored basin ranges between 2400 and 2700 m, and the pre-fire vegetation was mixed conifer forest consisting of three species: ponderosa pine, white fir, and Douglas fir (Balice *et al.*, 1997). The channel that drains the monitored basin has a gradient of about 16°. The hillslopes that form the amphitheatre at the head

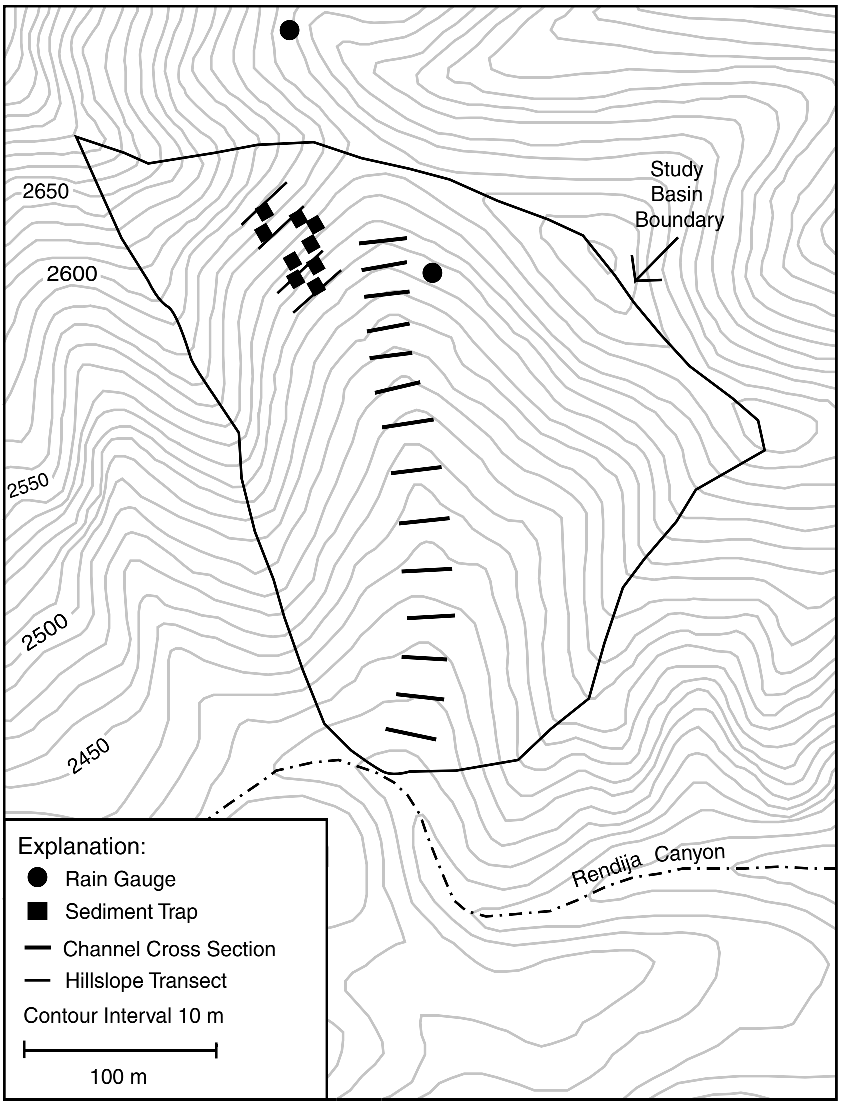

Figure 2. Monitoring configuration showing the locations of sediment-runoff traps, hillslope transects, channel cross-sections and rain gauges

of the 0·15 km^2 basin have gradients of between 25 and 35°, and are underlain by dacites of the Tschicoma Formation (Smith *et al.*, 1970). The hillslopes are mantled with a coarse gravel- to cobble-sized lag that overlies a minimum thickness of 0·5 m of silty, sandy gravel (Unified Soil Classification; Craig, 1987). The basin was severely burned by the fire; all trees were killed, foliage, twigs and the litter and duff layer were completely consumed, and the organic matter in the soil was charred. Immediately after the fire the hillslopes were also mantled with up to 5 cm of wood ash, and strongly water-repellent soils were detected at a depth of between 2 and 4 cm using the water-drop penetration time test (e.g. Letey, 1969). The water repellency did not persist throughout the summer, however. We detected less water repellency with time, and all evidence of water repellency was gone by the end of October.

Methods and approach

The monitoring array consisted of nine traps installed on the southeast-facing headwall hillslope to measure both runoff and sediment yields, four 40 m long hillslope transects to determine the spatial distribution of hillslope erosion, 14 channel transects to measure the amount of within-channel erosion, and a 0·01 mm tipping bucket recording rain gauge (Figure 2). The rain gauge and two sediment traps were installed on June 8, 2000, and the entire monitoring array was in place by July 2, before the onset of significant summer rainfall in the basin. Although a storm on June 28 produced significant runoff from basins burned by the Cerro Grande fire south of Rendija Canyon, the rain gauge at the study site recorded only 1·02 mm of rainfall from this storm and we observed no effects of surface runoff from this event at the site.

The sediment-runoff traps consisted of a 1·5 m length of 10 cm diameter PVC pipe with a 1 m long and 8 cm wide collection slot (Gerlach, 1967; Fitzhugh, 1992; Moody and Martin, 2001). Sediment was collected both in the trap and in a bucket attached to the trap; runoff could collect in two additional overflow buckets. The traps were installed perpendicular to the slope at locations with no significant flow obstructions between the ridge crest and the trap. The traps were not bounded, because our aim was to collect all sediment and runoff contributed from upslope in storm events of varying intensities and durations. Traps were installed on gradients between 26 and 30°, and at varying distances from the ridge crest (Table I).

After each rainfall event the volume of runoff collected in the buckets was measured, the sediment accumulated in the traps was collected, and observations were made of the processes acting on the hillslopes and in the channel. If the runoff contained suspended sediment, the runoff was churned in a churn splitter (Meade and Stevens, 1990), and a 1 to 3 l subsample collected, depending on the volume of runoff collected in the buckets. Following most storms, data were collected from all nine traps. For the events of July 16, August 4, and August 18, however, all of the traps were not emptied before the onset of the subsequent storm. Here we consider only the data collected in traps from single storm events. After each storm, materials deposited in the channel were examined to determine if debris flows had been produced, and if so, how far debris-flow conditions persisted within the channel. Sedimentologic and morphologic criteria defined by

Table I. Gradients at each sediment trap and distances from the ridgecrest

Trap	Gradient (deg)	Distance from ridge crest (m)
A	26	175
B	25	185
C	26	190
D	26	200
E	29	220
F	28	160
G	30	130
H	26	185
I	29	105

Cannon (1999) for distinguishing fire-related sedimentation events within channels were used for this purpose. We resurveyed the hillslope transects and channel cross-sections, and measured the width and depth of rills at each sediment-runoff trap four times during the summer.

We determined the storm rainfall totals, durations, and maximum 30 min rainfall intensities I_{30} from the tipping bucket rain gauge record. The I_{30} for each storm was calculated as the maximum rainfall accumulation in any 30 min period within the storm, and is expressed as a rate in millimetres per hour. A measured accumulation of 10 mm in 30 min would thus result in an I_{30} of 20 mm h^{-1}. We used the 30 min time period rather than any other time period for calculating maximum rainfall intensities because we found that, for the storms that occurred during the summer of 2000, between 61 and 99%, or the great majority, of the total storm rainfall fell during the peak 30 min period.

In the laboratory, the trap sediment was air-dried and weighed, and its grain-size distribution was determined using sieve and hydrometer techniques following ASTM standard D421-85. The mean sediment-runoff concentrations produced during each storm from all the traps were calculated. Confidence intervals (95%) were determined for the means based on the data range and factors for small sample sizes (Skoog and West, 1976).

In this paper, we examine the three research questions posed above by describing the summer of 2000 rainfall and the hillslope and channel processes observed throughout the summer. We then present the measurements of sediment and runoff fluxes, and compare the mean sediment-runoff concentrations for each storm with maximum 30 min rainfall intensities. Evaluation of particle-size data from samples collected in the sediment-runoff traps is used to explain some results.

SUMMER OF 2000 RAINFALL AND HILLSLOPE AND CHANNEL RESPONSE

Following the installation of the monitoring array, 12 storms of varying intensities and durations occurred over the basin (Table II). The five largest storms of the season were those of July 16, July 18, August 5, August 28, and September 8. Return periods for the I_{30} for each of these storms varied between 1 and 4 years (Table II). The remaining storms had lower storm totals, I_{30} return periods of less than 1 year, and produced similar or greater total storm intensities (Table II). Note that there is some uncertainty associated with these recurrence intervals; extrapolation of available rainfall intensity relations, largely obtained from relatively low-lying areas, to the higher, more mountainous study area with higher annual rainfall can be ambiguous.

Table II. Summer of 2000 storm dates, rainfall totals, storm durations, mean storm intensities, maximum 30 min rainfall intensities, and return intervals of maximum 30 min intensities from Herschfield (1961). Data from rain gauge located at monitoring site

Storm date	Storm total (mm)	Storm duration (h)	Mean storm intensity (mm h^{-1})	Max. 30 min intensity (mm h^{-1})	Return interval of max. 30 min intensities (years)
7/9/00	2·54	0·22	11·55	7·10	<1
7/16/00	25·40	1·26	20·16	31·00	~2
7/18/00	11·68	0·67	17·43	22·40	~1
7/29/00	5·33	1·68	3·18	6·10	<1
8/2/00	7·62	0·68	11·21	10·16	<1
8/4/00	7·37	0·49	15·03	14·20	<1
8/5/00	23·11	1·71	13·52	36·60	~4
8/9/00	3·30	0·37	8·92	6·60	<1
8/18/00	9·91	10·37	0·96	3·60	<1
8/28/00	10·41	0·50	20·82	20·80	~1
9/8/00	17·27	1·56	11·07	24·90	~1·5
9/29/00	7·62	0·28	27·21	15·20	<1

July 9 2000 storm

The first storm following the installation of the monitoring array produced only slight surface runoff from the hillslopes. Some burned soil and wood ash was moved downslope, as evidenced by observations of lightening of the initially black surface in some locations and the collection of small amounts of ash and fine sand in the hillslope traps. No rilling, or evidence of concentrated flow, was observed on the hillslopes. Within the channel that drains the basin, surface flow flushed the black ash veneer from the main course, but no significant incision was observed.

July 16 debris-flow event

Evidence of debris-flow activity was observed following the storm of July 16. The dominant hillslope response to the storm was the development of an extensive rill network (Figure 3). Measurements of the four hillslope transects show that approximately 50% of the hillslope area was occupied by rills following this storm. Levees or inter-rill areas occupied the remaining 50% of the hillslope. Removal of some of the fine wood ash that mantled the gravel lag in inter-rill areas suggests that erosive sheetwash and rainsplash impact were also active. The rills initiated between 5 and 10 m from the ridge crest at locations of subtle flow concentration. Small-scale headscarps at rill heads indicating failure by soil slip (Wells, 1987) were not observed. However, such subtle and delicate features could have been destroyed by rainfall during the storm. No water repellency was detected at the base of the rills, indicating that, although this phenomenon did not control rill depth, it could have been removed by the flow event. At downslope distances between 10 and 25 m from the initiation point the rills became lined with continuous levees, and between 20 and 50 m from the initiation point the levees consisted of poorly sorted, predominately gravel-sized, but with some cobble-sized, material in an abundant fine-grained matrix that supported the clasts. Field textural testing indicated the presence of silts and clays in the matrix material. The levees attained a maximum height of

Figure 3. Photograph of rill network that developed above a sediment-runoff trap following the July 16, 2000, storm. View is upslope, and length of the white PVC pipe is 1·5 m

25 cm, widths of 10 cm, and they lined rills up to 60 cm wide. We measured up to 8 cm of incision into hillslope materials in the base of some rills. Poorly sorted, matrix-supported deposits are common indictors of fire-related debris-flow activity (e.g. Cannon, 1999; Meyer and Wells, 1997). The presence of these deposits indicates that, at some distance downslope, flow over the hillslope was as that of debris flow.

Material transported over the hillslope converged into the zero- and first-order channel that drains the basin. Within the channel we observed only isolated deposits from the hillslope-generated debris flow. The deposits showed that some boulder-sized (up to 0·5 m α-axis) material and burned vegetation had been incorporated into the debris flow, but resurveys of the channel cross-sections did not reveal significant amounts of erosion. However, a cross-section located in the tributary approximately 20 m up channel from the junction with the main stem of Rendija Canyon showed 1·3 m^2 of erosion and 0·3 m^2 of deposition that occurred between June 27 and July 20 (J. Moody, personal communication, 2000).

Deposits from the July 16 event were observed at the intersection with the main tributary of Rendija Canyon in the form of a small alluvial fan. The debris-flow deposits consisted of up to 0·5 m thick, poorly sorted, matrix-supported gravels. The surface of the deposits had been washed by higher-discharge flows, leaving a clean sand surface. Downstream from this junction debris-flow deposits could not be distinguished from sediment deposited by floodwaters within the main channel. Presumably the debris-flow slurry was diluted by the higher discharge flow in Rendija Canyon.

The July 16 storm also produced debris flows in the adjacent basin immediately north of the monitored basin (Figure 1). The deposits consisted of levees containing up to boulder-sized material (up to 0·8 m α-axis) supported in an abundant fine-grained matrix. Deposits from these flows were observed only on the hillslopes; either the debris flows did not travel into the main channel, or the channel had been washed clean of any deposits from this event by high discharge streamflow. From records of rain gauges installed in both basins, we determined that the storm rainfall that moved boulder-sized material on hillslopes in this basin was similar to that which moved gravel- and cobble-sized material from the hillslopes in the adjacent monitored basin.

Remainder of summer season

Although one storm of higher I_{30} intensity and several storms of longer durations impacted the monitored basin during the remainder of the summer season, no further evidence of debris-flow activity was observed. Resurveys of the hillslope transects at the end of the summer indicate that approximately 54% of the hillslope was occupied by rills, a slight increase (and perhaps within survey error) from the survey following the July 16 storm. Measurements of rill width and depth made at each of the sediment-runoff traps also indicated an approximate 5% increase in rill width, and rill depths increased between 0 and 6 cm. We did not make observations of headward migration of the rills. Additional ash and burned soils were removed from some interill surfaces, as evidenced by a gradual lightening of the surface over time. Within the channel, isolated deposits of well-sorted and stratified sands and gravels were observed ponded behind obstructions. Although no significant incision into the channel bed was detected by resurveys of the channel cross-sections, we observed that, following the September 8 2000, storm, the channel banks within about 10 m of the junction with the main fork of Rendija Canyon were incised to a depth of approximately 1 m. In conclusion, the storms that followed the July 16 storm appeared to produce surface runoff that moved some sediment, but no debris-flow activity was observed.

SEDIMENT AND RUNOFF FLUX MEASUREMENTS AND SEDIMENT-RUNOFF CONCENTRATIONS

We measured the amount of runoff and sediment collected in the hillslope traps following each storm of the summer of 2000 (Figure 4). The data are presented as a flux across a 1 m length, rather than the usual volume or weight per unit area, due to the difficulties of determining the upslope contributing area for storms of varying intensities and durations (e.g. Martin and Moody, 2001). Measured sediment fluxes ranged between 0·01 and 21·5 kg m^{-1}, and runoff fluxes ranged between 0·15 and 42 l m^{-1}.

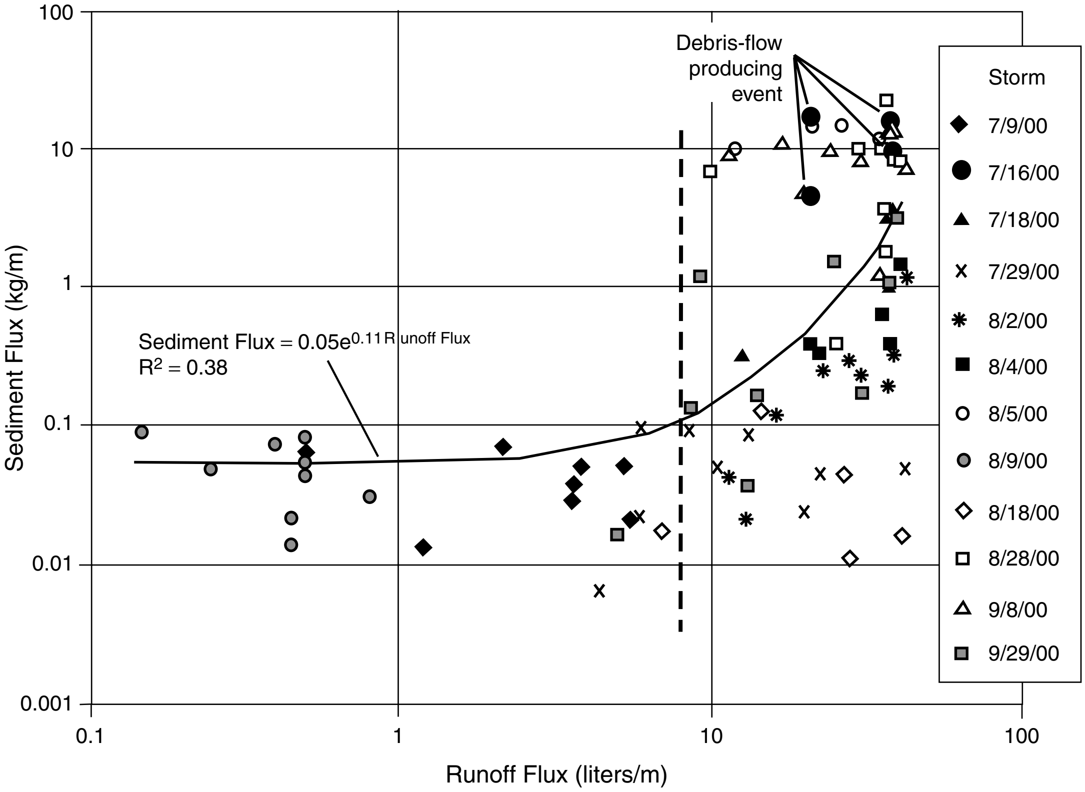

Figure 4. Sediment and runoff flux measurements for all hillslope traps. The solid line shows a general exponential increase in sediment flux with increasing runoff flux. The dashed vertical line delineates a threshold value of runoff flux above which a wide range of sediment fluxes are produced. Note that although the sediment and runoff yields from the July 16 debris-flow-producing storm are among the highest measured, storms on August 5, August 28 and September 8 that did not produce debris flows yielded similar sediment and runoff fluxes

The data shown in Figure 4 suggest that, in general, sediment mass increases exponentially with runoff volume. The small amount of the variance explained by the regression line, however, indicates that this is not the best way to characterize the data. Rather, it appears that for runoff flux measurements of less than about 9 l m^{-1}, sediment fluxes of between 0·01 and 0·1 kg m^{-1} are common. At a threshold value of runoff flux greater than about 9 l m^{-1}, sediment fluxes vary anywhere between 0·01 and 40 kg m^{-1}.

We collected data from only four hillslope traps following the July 16, 2000, debris-flow-producing storm before another storm moved into the area. The sediment yields measured were between 4·6 and 16·8 kg, and the runoff yields ranged from 20·4 to 38·0 l. Although the sediment and runoff yields for the July 16 storm were among the highest measured, they were not unique; similar amounts of sediment and runoff were collected following the storms of August 5, August 28, and September 8 (Figure 4). However, debris flows were not produced during these storms.

Note that the late-season storm of August 28 produced similar runoff and sediment yields as early-season storms. Field observations indicate that the strong water repellency present immediately after the fire dissipated throughout the summer, and all evidence of water repellency was gone by the end of October. The production of significant runoff events even with the dissipated water repellency suggests that water repellency may have had little or no influence on the hydrologic response of these hillslopes.

Sediment-runoff concentrations, calculated by dividing the sediment yield by the runoff volume, measured at each trap ranged between 0·001 and 0·81 kg l^{-1} (Figure 5). Sediment-runoff concentrations of 0·23 to

0·81 kg l^{-1} were measured from the four traps for which we have data following the July 16 debris-flow-producing storm. Although these were among the highest concentrations measured, they were not unique to this storm, or to the debris-flow response to this storm.

Comparison of data collected using similar methods for other burned areas with the measurements made here illustrate the wide variations, as well as the site- specificity, of such measurements. The maximum values for sediment flux determined in this study are approximately four times less than the maximum value measured by Marxer *et al.* (1998) from 30 m^2 bounded plots on steep burned hillslopes mantled with gneiss-derived colluvium. In addition, the maximum runoff fluxes measured in this study are approximately 20 times less that those measured by Marxer *et al.* (1998). No rainfall data are available for comparison in this case. The maximum values of sediment-runoff concentrations measured in this study are approximately 25 times higher than those reported from hillslopes in weathered granite terrain a year after a wildfire (Moody and Martin, 2001). In addition, the maximum I_{30} values of storms evaluated here were approximately 10 to 12 times greater than those reported by Moody and Martin (2000).

To evaluate the effect of storm rainfall on sediment-runoff concentrations and debris-flow production, the I_{30} for each storm was determined from the rain gauge record, and compared with the sediment-runoff concentrations produced during each storm. Although the storm of August 5 had I_{30} values greater than those measured from the July 16 debris-flow-producing storm, the sediment-runoff concentrations produced from these two storms were similar (Figure 5). Figure 5 also shows that the mean sediment-runoff concentrations produced during the July 16, August 5, August 28, and September 8 storms were greater than those produced from the eight other summer-season storms. This suggests the existence of a threshold value for I_{30} of around 20 mm h^{-1} above which significant sediment-runoff concentrations are produced. This threshold, however, does not distinguish debris-flow-producing events from other high runoff events.

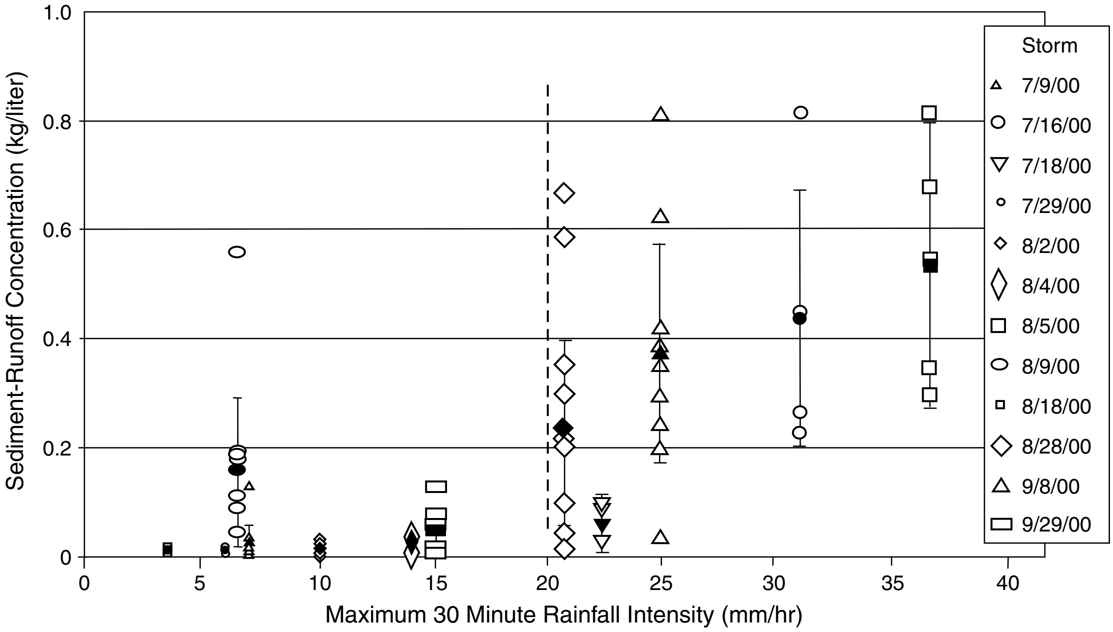

Figure 5. Sediment-runoff concentrations for all traps (open symbol), and the means (corresponding solid symbol), for each storm. Confidence intervals (95%) for the means are calculated based on the data range and factors for small sample sizes (Skoog and West, 1976). Dashed vertical line delineates an approximate threshold value of maximum 30 min rainfall intensities above which large sediment-runoff concentrations are produced

PARTICLE-SIZE DISTRIBUTIONS OF SEDIMENT

The grain-size distribution of materials and the presence of fine-grained wood ash mantling the hillslopes appear to be an important control on the generation of post-fire debris flows, more so than maximum rainfall intensities. We compared the grain-size distributions of materials collected in the hillslope traps following the July 16 debris-flow-producing storm with those from the July 18, August 5, August 28, and September 8 storms that did not produce debris flows. The mean percent of silt plus clay-sized material in samples collected in the traps following the July 16 debris-flow-producing storm is not significantly different from the proportions of silt plus clay-sized material in sediments collected from the other storms (Table III). However, the data in Table III indicate that the sediment collected following the July 16 event was unique in terms of the proportion of silt plus clay-sized material relative to the total <2 mm size fraction. This suggests that the silt plus clay content in the non-gravel fraction of transported material is a key factor in the development of debris flows from burned hillslopes.

Abundant fine-grained wood ash mantled the hillslopes prior to the July 16 event, but this had been completely removed in areas occupied by rills, and locally removed from inter-rill areas by the time the later storms impacted the area. The ash was incorporated into the sediment collected in the hillslope traps and was included in the grain-size distribution testing. Our findings suggest that the addition of the wood ash to material eroded from the hillslopes supplied the critical proportion of fines in the <2 mm size fraction to generate debris flows in the July 16 storm. The absence of abundant wood ash mantling the hillsides when the storms later in the season impacted the area precluded the development of debris flows. Further work is necessary to clarify the role of the wood ash in the mechanics of debris-flow generation. However, the indication of the importance of wood ash mantling hillslopes indicates that debris flows are more likely to be generated from the first substantial storms to impact a recently burned area than from storms later in the season.

SUMMARY AND CONCLUSIONS

In this study we describe a process for fire-related debris-flow initiation based on field observations and data collected from a basin monitored by an array consisting of hillslope sediment-runoff traps, hillslope transects, channel cross-sections and a recording rain gauge. We found that debris flows can be generated in response to I_{30} rainfall with an approximately 2 year return period. The debris flows we observed initiated primarily high on a broad, open hillslope, at distances between 10 and 25 m from the ridge crest, as levee-lined rills. The levees were composed of gravel- and cobble-sized material, and at distances between 20 and 50 m from the initiation point of the rill an abundant fine-grained matrix supported the larger material. Debris-flow conditions persisted through the second-order channel in the basin, with little contribution of material from channel incision to the flow. No debris-flow deposits were observed in the third-order channel, suggesting that the flow had been diluted by higher discharge stream flow in this reach.

Table III. Comparison of average grain-size distributions of sediment collected in hillslope traps following the July 16 debris-flow-producing storm, and storms on July 18, August 5, August 28, and September 8 that produced high sediment-runoff concentrations, but not debris flows. Confidence interval (95%) of mean calculated using Skoog and West (1976)

Storm date	*n*	Mean percent gravel & cobbles	Mean percent sand	Mean percent silt and clay	Percent silt + Clay in fine fraction (<2 mm)
7/16/00	4	66·8 ± 8·8	25·0 ± 7·0	8·2 ± 2·0	25
7/18/00	3	46·8 ± 23·3	42·6 ± 18·7	10·7 ± 4·5	20
8/5/00	9	65·1 ± 4·5	27·7 ± 4·5	7·2 ± 1·2	21
8/28/00	8	41·3 ± 3·2	50·5 ± 6·8	8·0 ± 1·9	14
9/8/00	9	57·4 ± 6·5	34·2 ± 5·2	8·2 ± 1·7	20

Measurements of sediment and runoff fluxes made following storms of the summer of 2000 showed that for runoff fluxes greater than a threshold value of about 9 l m^{-1} a wide range of sediment fluxes (0·01 to 40 kg m^{-1}) was produced. We found that above a threshold value of I_{30} of around 20 mm h^{-1}, significant sediment-runoff concentrations were produced. This threshold does not, however, distinguish debris-flow-producing events from other high runoff events.

Sediment-runoff concentrations between 0·001 and 0·81 kg l^{-1} were measured during the summer storm season, and debris flows were produced from sediment-runoff concentrations of between 0·23 and 0·81 kg l^{-1}, with an average of 0·42 kg l^{-1}. These concentrations were not unique, however, to the debris-flow-producing storm. Four other high-intensity storms produced similar or higher sediment-runoff concentrations, but debris flows were not observed following these storms. Comparison of the grain-size distribution of materials collected in the sediment-runoff traps following each storm suggests that the incorporation of fine-grained wood ash mantling the hillslopes in the first significant runoff event of the season is critical in the generation of fire-related debris flows. The lack of availability of this material for entrainment in runoff from later storms of comparable or greater intensities and durations precluded debris-flow generation. This finding indicates that debris flows are much more likely to be generated from the first substantial storms to impact a recently burned area than from storms later in the season, and that a quick mitigation response is needed to counter this potential hazard. The potential for debris-flow activity is greatly reduced, however, once a watershed has shown a significant response.

It is important to note that the debris-flow initiation process described here was in response to a storm with an approximately 2 year return period. Responses to longer-recurrence storms may be considerably different in at least three ways: (1) the initiation location of debris flows within a basin [e.g. in zero-to first-order drainages, as described by Cannon *et al.* (2001), or within the channel, as described by Meyer and Wells (1997)]; (2) the volumetric contribution of material to the flow by channel incision; and (3) the magnitude and downstream persistence of the event. It is possible that the range in debris-flow initiation processes described from other recently burned areas may be partly due to variations in storm rainfall intensities and durations.

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REFERENCES

Balice RG, Ferran SG, Foxx TS. 1997. *Preliminary land cover classification for the Los Alamos region*. Los Alamos National Laboratory, LA-UR-97-4627.

Booker FA. 1998. *Landscape and management response to wildfires in California*. MS thesis, University of California, Berkeley; 436.

Bowen BM. 1990. *Los Alamos climatology*. Los Alamos National Laboratory Report LA-11735-MS.

Cannon SH. 1999. *Debris-flow response of watersheds recently burned by wildfire*. PhD dissertation, University of Colorado, Boulder; 200.

Cannon SH, Kirkham RM, Parise M. 2001. Fire-related debris flow initiation processes, Storm King Mountain, Colorado. *Geomorphology* **39**(3–4): 171–188.

Craig RF. 1987. *Soil Mechanics*, 4th edn. Von Nostrand Reinhold (UK) Co. Ltd: Berkshire, UK.

DeGraff JV. 1997. *Geologic investigation of the Pilot Ridge debris flow, Groveland Range District, Stanislaus National Forest*. USDA Forest Service, 20.

Fitzhugh R. 1992. *Construction of simple surface runoff sampler*. Department of the Interior, US Geological Survey, Water Resources Division, WRD Instrument News, no. 58; 1–4.

Gerlach T. 1967. Hillslope troughs for measuring sediment movement. *Revue Geomorphologie Dynamique* **17**(4): 173–174.

Helvey JD. 1980. Effects of a north central Washington wildfire on runoff and sediment production. *Water Resources Bulletin* **16**(4): 627–634.

Hershfield DM. 1961. *Rainfall frequency atlas of the United States for the durations from 30 minutes to 24 hours and return periods from 1, 10, 100 years*. US Department of Commerce Technical Paper No. 40; 107 pp.

Johnson AM (with contributions by Rodine JR). 1984. Debris flow. In *Slope Instability*, Brunsden D, Prior DB (eds). John Wiley and Sons: New York; 257–361.

Klock GO, Helvey JD. 1976. Debris flows following wildfires in north central Washington. In *Proceedings of the Third Federal Inter-Agency Sedimentation Conference*, Denver, Colorado; 91–96.

Letey J. 1969. Measurement of contact angle, water drop penetration time, and critical surface tension. In *Water Repellent Soils*, DeBano LF, Letey J (eds). University of California: Riverside; 43–47.

Los Alamos National Laboratory. 2000. *A special edition of the SWEIS Yearbook, Wildfire 2000.* LA-UR-00-3471.

Martin DA, Moody JA. 2001. The flux and particle-size distribution of sediment collected in hillslope traps after a Colorado wildfire. In *Proceedings of the Seventh Inter-Agency Erosion and Sedimentation Conference*, Reno, Nevada; III40–47.

Marxer P, Condera M, Scaub D. 1998. Postfire runoff and soil erosion in sweet Chestnut forests in south Switzerland. In *Proceedings, IIIrd International Conference on Forest Fire Research, 14th Conference on Fire and Forest Meteorology*, vol. 2 Viegas DX (ed.), Luso, Portugal, November 16–20; 1317–1331.

Meade RH, Stevens HH. 1990. Strategies and equipment for sampling suspended sediment and associated toxic chemicals in large rivers—with emphasis on the Mississippi River. *Science of the Total Environment* **97**(97): 125–135.

Megahan WF. 1983. Hydrologic effects of clearcutting and wildfire on steep granitic slopes in Idaho. *Water Resources Research* **19**(3): 811–819.

Meyer GA, Wells SG. 1997. Fire-related sedimentation events on alluvial fans, Yellowstone National Park, U.S.A. *Journal of Sedimentary Research* **67**(5): 776–791.

Moody JA, Martin DA. 2001. *Hydrologic and sedimentologic response of two burned watersheds.* US Geological Survey Water-Resources Investigation Report 01-4122.

Morton DM. 1989. Distribution and frequency of storm-generated soil slips on burned and unburned slopes, San Timoteo Badlands, Southern California. In *Landslides in a Semi-Arid Environment with Emphasis on the Inland Valleys of Southern California*, Sadler PM, Morton DM (eds). Publications of the Inland Geological Society, **2**: 279–284.

Parrett C. 1987. *Fire-related debris flows in the Beaver Creek drainage, Lewis and Clark County, Montana.* US Geological Survey Water-Supply Paper 2330, Denver, CO; 57–67.

Skoog DA, West DM. 1976. *Fundamentals of Analytical Chemistry*, 3rd edn. Holt, Reinhart, and Winston: New York; 804 pp.

Smith RL, Bailey RA, Ross CS. 1970. *Geologic map of the Jemez mountains, New Mexico.* US Geological Survey Miscellaneous Geologic Investigations Map I-571, 1 : 125 000 scale.

Swanson FJ. 1981. Fire and geomorphic processes. In *Fire Regimes and Ecosystem Properties*, Mooney HA, Bonnicksen TM, Christensen NL, Lotan JE, Reiners WA (eds). USDA Forest Service General Technical Report WO-26, Washington, DC; 401–420.

Wells WG. 1987. The effects of fire on the generation of debris flows in southern California. In *Debris Flows/Avalanches, Process, Recognition, and Mitigation*, Costa JE, Wieczorek GF (eds). Geological Society of America Reviews in Engineering Geology **VII**: 105–114.