Debris-Flow Generation From Recently Burned Watersheds

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ABSTRACT

Evaluation of the erosional response of 95 recently burned drainage basins in Colorado, New Mexico and southern California to storm rainfall provides information on the conditions that result in fire-related debris flows. Debris flows were produced from only 37 of 95 (~40 percent) basins examined; the remaining basins produced either sediment-laden streamflow or no discernable response. Debris flows were thus not the prevalent response of the burned basins. The debris flows that did occur were most frequently the initial response to significant rainfall events. Although some hillslopes continued to erode and supply material to channels in response to subsequent rainfall events, debris flows were produced from only one burned basin following the initial erosive event. Within individual basins, debris flows initiated through both runoff and infiltration-triggered processes. The fact that not all burned basins produced debris flows suggests that specific geologic and geomorphic conditions may control the generation of fire-related debris flows. The factors that best distinguish between debris-flow producing drainages and those that produced sediment-laden streamflow are drainage-basin morphology and lithology, and the presence or absence of water-repellent soils. Basins underlain by sedimentary rocks were most likely to produce debris flows that contain large material, and sand- and gravel-dominated flows were generated primarily from terrain underlain by decomposed granite. Basin-area and relief thresholds define the morphologic conditions under which both types of debris flows occur. Debris flows containing large material are more likely to be produced from basins without water-repellent soils than from basins with water repellency. The occurrence of sand-and gravel-dominated debris flows depends on the presence of water-repellent soils.

INTRODUCTION

A commonly held expectation following wildfires is that any steep, burned watershed will produce debris flows. This expectation has promoted extensive efforts to mitigate the hazard by rehabilitating hillslopes and constructing retention and diversion structures. These efforts are often at huge public expense (e.g., Schuster et al., 1997; Booker, 1998). Recent studies show that the response of burned watersheds to even intense rainfall can range broadly, from nuisance flooding at canyon mouths to destructive debris-flow activity along the length of the channel (Florsheim et al., 1991; Meyer and Wells, 1997; Cannon et al., 1998; Cannon, 1999; and Cannon and Reneau, 2000). Debris flows pose a hazard distinct from other sediment-laden flows because of their unique destructive power; debris flows can occur with little warning, can exert great impulsive loads on objects in their paths, and even small debris flows can strip vegetation, block drainage ways, damage structures, and endanger human life (Iverson, 1997a). The discrepancy between expectation and experience points to the need for a better understanding of the processes and conditions that result in fire-related debris flows. This understanding is necessary to make effective and appropriate public safety and hillslope rehabilitation decisions.

The primary goal of this study is to define the conditions under which fire-related debris flows occur. I investigate the processes involved in fire-related debris-flow initiation and evaluate the effects of lithology, water repellency, basin configuration, and burn extent on the generation of debris flows from burned drainage basins.

Two initiation processes specific to fire-related debris flows have been identified in the literature: infiltration-triggered soil slips, and runoff-dominated erosion and progressive sediment bulking of surface runoff. These two processes have been observed in widely disparate environments. Infiltration-triggered soils slips have been described on burned hillslopes in southern California (Wells, 1987; Morton, 1989; and Booker, 1998) and Colorado (Cannon, 1999; Cannon et al., 2001). Johnson (1984) and Wells (1987) described debris flows that appeared to initiate from very small landslides at the heads of rills on recently burned hillslopes in Big Sur, Monterey County, California, and in the San Dimas Experimental Forest in southern California, respectively. Meyer and Wells (1997) describe the processes of progressive bulking of surface runoff with material eroded from both hillslopes and channels as the mechanism for formation of fire-related debris flows in Yellowstone National Park. Similarly, Parrett (1987) concluded that a lack of soil slip scars on hillslopes and extensive channel erosion in a burned area near Helena, Montana, indicated a similar process.

Although a number of workers (e.g., Swanson, 1981) have described physical conditions that affect erosion after wildfires, Wohl and Pearthree (1991) and Spittler (1995) identified geologic and geomorphic factors that indicate a susceptibility specifically to post-fire debris-flow activity. Cannon and Reneau (2000) quantified the relative influence of the factors identified by these workers on debris-flow production by evaluating the erosional responses of three burned drainage basins in New Mexico. Cannon and Reneau (2000) concluded that, in this setting, drainage basin morphology and lithology best separated the debris-flow producing drainage from those that produced sediment-rich streamflow. In an evaluation of 253 drainage basins in the Santa Monica Mountains of southern California, Menitove (1999) also found that drainage-basin morphology and lithology were the factors that best determined a debris-flow response from watersheds burned two years before significant storm events. Furthermore, Meyer and Wells (1997) concluded that, in Yellowstone National Park, steep basins less than about 2 km^2 typically produced debris flows while larger basins were more likely to produce floods.

In this paper, I explore the nature of the debris-flow response of 95 recently burned drainage basins in three different environments. The study includes six basins burned by the South Canyon fire of 1994 on Storm King Mountain, near Glenwood Springs, Colorado (Figure 1); three basins burned by the Dome fire of 1996 in Capulin Canyon, New Mexico (Figure 2); and 86 basins burned by 20 fires in southern California in 1997 (Figure 3). I first document the channel and hillslope responses of the 95 recently burned basins to rainstorms. A key element in this evaluation is the definition of a set of sedimentological and morphological criteria that distinguish deposits of fire-related debris flows from those of sediment-laden streamflow. Linking observations of channel and hillslope response provides information on the processes that result in initiation of fire-related debris flows. I next examine the effects of lithology, water repellency, basin morphology, and burn extent on debris-flow occurrence by comparing conditions in basins that produced debris flows to conditions that produced other channel responses. This comparison defines the conditions under which fire-related debris flows are most likely to occur, and provides critical information for appropriate and effective hillslope rehabilitation decisions.

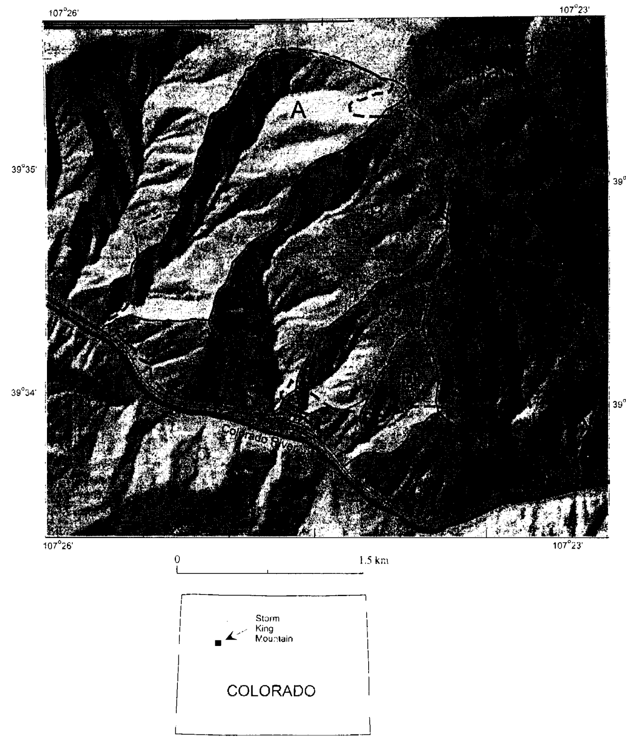

Figure 1. Storm King Mountain study area, showing drainage basins evaluated (labeled A through F) and fire perimeter (dashed line).

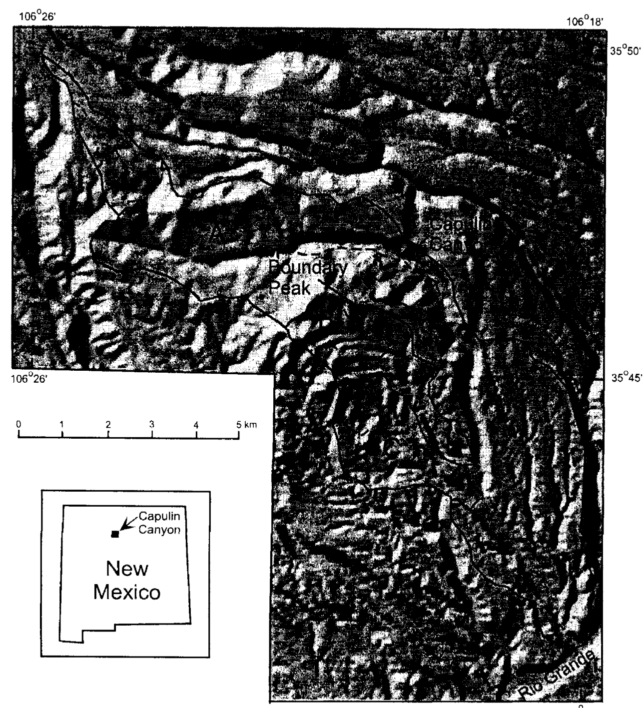

Figure 2. Capulin Canyon study area, showing drainage basins evaluated (labeled A though C and bounded by solid lines) and area burned by moderate and high fire intensities (bounded by a combination of dashed and solid lines).

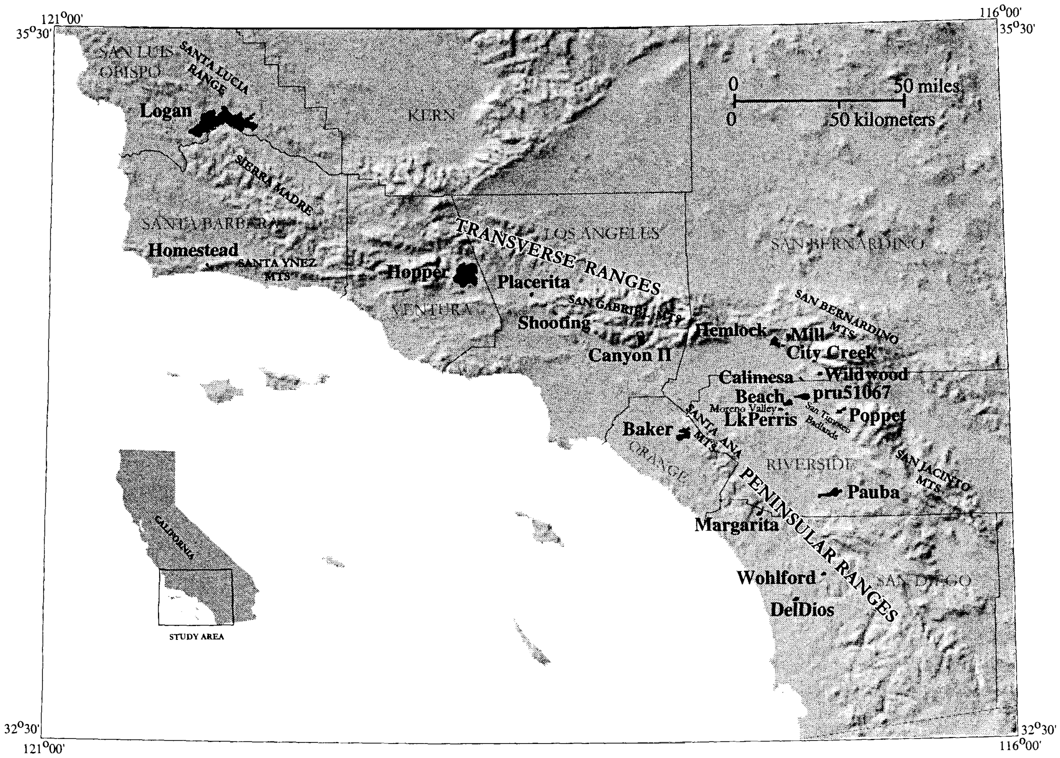

Figure 3. Southern California study area and perimeters of 20 wildfires evaluated. Extent of wildfires are shown by irregular black areas, and county boundaries are light gray lines.

Study Areas

The Storm King Mountain study area consists of six intermittent drainage basins (Figure 1; Appendix). All six basins are direct tributaries of the Colorado River, and have steep stream channels (>30 percent) and precipitous (>65 percent) side slopes. The South Canyon fire burned approximately 6.5 km^2, or 80 percent of the entire study area, at high to moderate severity. Drainage basins experienced between 48 and 95 percent burn coverage (Appendix). Before the fire, the hillslopes supported sparse piñon-juniper woodland primarily on southeast-facing hillslopes. The remainder of the burned area was covered with a nearly impenetrable thicket of oak brush. Weathered sedimentary rocks, consisting primarily of interbedded conglomerates, sandstones, shales and mudstones, underlie the area, and extensive colluvium, sheetwash, and landslide deposits mantle the area (Kirkham et al., 2000). Soils in the burned area are thin (<20 cm thick), poorly developed, and contain abundant rock particles. The climate is semiarid, and the majority of precipitation occurs in July, August, and September as convective thunderstorms.

The Capulin Canyon study area consists of three basins–the main Capulin Canyon watershed and two of its tributaries (Figure 2, Appendix 1). Most of Capulin Canyon burned during the Dome fire, although fire intensities were variable. Areas that experienced high and moderate fire intensities are shown in Figure 2. The upper reach of Capulin Creek flows in a narrow canyon bounded by steep, nearly vertical walls. The canyon widens into a broad, flat alluvial valley in its lower reaches. Tributaries B and C drain the steep flanks of Boundary Peak, and join Capulin Creek where the canyon is no longer tightly confined by the canyon walls. Capulin Creek and its tributaries are cut into a series of horizontal to gently dipping volcanic and sedimentary rocks that make up the Pajarito Plateau and the adjacent San Miguel Mountains (Smith et al., 1970; Goff et al., 1990). The volcanic rocks consist primarily of basalts, andesites and tuffs, and the sedimentary rocks are interbedded conglomerates, sandstones, and mudstones. Soils are thin and poorly developed. In this part of New Mexico the climate is semiarid, and approximately 60 percent of the precipitation occurs from July through September, derived from convective thunderstorms (Bowen, 1990). Vegetation is dominated by ponderosa pine and mixed conifer forests in the watershed headwaters and in some locations on south-facing canyon walls. Piñon-juniper woodlands are prevalent elsewhere.

The southern California study area consists of 86 drainage basins within 20 fires that burned in 1997 (Appendix ; Table 1; Figure 3). Although the great majority of the basins were completely burned, burned coverage ranged between 3 and 100 percent (Appendix). Comparison of the areas burned by the fires evaluated in this

Table 1. *Wildfires evaluated in Southern California.*

Fire	Date of Fire Ignition	Vegetation Type	Hectares Burned in Previous 5 Years
Logan	8/4/97	Chaparral	0
Hopper	8/5/97	Chaparral	0
Homestead	Unknown	Coastal sage scrub and chaparral	0
Placarita	7/3/97	Chaparral	0
Shooting	5/1/97	Chaparral	0
Canyon2	7/1/97	Chaparral	0
Hemlock	7/5/97	Chaparral	198
Mill	9/13/97	Conifer forest	0
City Creek	9/22/97	Chaparral	0.6
Calimesa	6/10/97	Grass	0
Wildwood	Unknown	Chaparral	0
Beach	5/9/97	Grass	311
Lake Perris	4/26/97	Grass	0
PRU51067	9/24/97	Coastal sage scrub and chaparral	144
Poppet	9/23/97	Chaparral	228
Baker	10/12/97	Coastal sage scrub and chaparral	0
Pauba	8/31/97	Coastal sage scrub and chaparral	59
Margarita	9/4/97	Coastal sage scrub and chaparral	6
Wohlford	8/2/97	Coastal sage scrub and chaparral	0
Del Dios	9/24/97	Coastal sage scrub and chaparral	0

study with the California Statewide Fire History Database, which includes all records of fires from the California Department of Forestry and Fire Protection, U.S. Forest Service, and county records, indicates that 14 of the areas evaluated had not been burned in the 5 years prior to 1997, six of the areas had experienced some fire during that time period (Table 1).

In southern California, the Transverse Ranges and the San Bernardino and San Jacinto Mountains are particularly well known for producing large sedimentation events following wildfires (e.g., Anderson et al., 1959; Doehring, 1968; Rice, 1974; Scott and Williams, 1978; Wells, 1981, 1987; Campbell, 1986; and Wohlgemuth, 1986). Watersheds are steep and rugged, rising abruptly from the valley floor to general elevations of 2,000 to 2,500 m, and to extreme elevations of over 3,000 m. Drainage networks are deeply incised with steep side slopes. The mountains are composed of a complex assembly of various rock types ranging from easily weathered, extensively faulted, coarsely crystalline igneous and metamorphic rocks in the south, to sedimentary sequences in the north (State of California, 1967 and 1969; Scott and Williams, 1978). Soils are, for the most part, shallow, rocky, sandy loams, less than one meter in depth, and show little evidence of profile development (Wells, 1981).

The Hopper, Placarita, Shooting, and Canyon II fires occurred in the Transverse Ranges (Figure 3). The Hemlock, Mill, City Creek, and Wildwood fires burned in the San Bernardino Mountains, and the Poppet fire occurred in the San Jacinto Mountains. Fire PRU-51067 burned in the San Timoteo Badlands at the base of the San Bernardino Mountains, and the Calimesa, Beach, and Lake Perris fires occurred on gently-sloping hills in the Moreno Valley (Figure 3). The San Timoteo Badlands and the hills in the Moreno Valley are underlain by marine and non-marine sedimentary sequences (State of California, 1967; Morton, 1978).

The Peninsular Ranges, which include the Santa Ana Mountains in the north, are generally less steep and less deeply incised than their Transverse Range counterparts, and are composed primarily of weathered granite batholiths implaced into marine sediments and volcanic and metavolcanic rocks (State of California, 1965; Hart, 1991). The Baker, Pauba, Margarita, Wohlford and Del Dios fires occurred in the Peninsular Ranges (Figure 3). The Sierra Madre and Santa Lucia Range to the north are composed principally of marine and nonmarine sedimentary rocks with some metamorphic rocks (State of California, 1958). The Logan and Homestead fires occurred in these ranges (Figure 3).

The Mediterranean climate of southern California is characterized by hot, dry summers and cool, sometimes wet winters. The rainy season begins in December and lasts until mid-April, with January and February being the wettest months (Wells, 1981). Mountain-front slopes in southern California are most commonly vegetated with combinations of annual grasses, coastal sage scrub and chaparral, a vegetation complex that is dominated by highly flammable, woody, shrub-like plants. In general, grasses and coastal sage scrub species occupy lower elevations and transition into chaparral at slightly higher elevations, owing to generally increasing precipitation and cooling temperatures with elevation (Minnich, 1989). Chaparral can be replaced by oak woodland and conifer forests at higher elevations (Mooney and Parsons, 1973; Minnich, 1989). Riparian woodland occupies stream courses (Mooney and Parsons, 1973).

METHODS

Hillslopes and channels in these 95 recently burned drainage basins were examined soon after the fires and before the occurrence of heavy rainfall events, and then at intervals throughout the first rainy season after the fire to document their initial and subsequent responses to significant rainfall events. Channels were examined for deposits from debris flow and sediment-laden streamflow. Because a range of flow processes can occur during a single runoff event, I characterized deposits by the most sediment-rich facies observed. Deposits lining and infilling channels, and filling in behind blocked culverts or other obstructions were examined to distinguish flow processes. Vertical sections through deposits exposed either by late- or post-event incision or excavated by shovel were necessary to characterize the sequence of flow processes within an event. Hillslope response was characterized by the processes observed; because the magnitude of response varied considerably within single basins, I did not attempt to quantify this variation.

Geologic materials that underlie the basins were determined from the largest-scale geologic maps available. Although geologic information as detailed as 1:5000 was available for Storm King Mountain (Kirkham et al., 2000), the best information available for some southern California basins was at a scale of 1:250,000, and as a result included little specific information on lithologies (Appendix). The areas of the geologic maps covered by each fire were digitized into a GIS coverage, and six primary rock types were identified: nonmarine sediments; marine sediments, granitic rock, igneous and metamorphic rocks, volcanic rocks, metavolcanic rocks, and basic intrusives. In many cases, more than one rock type existed in a drainage basin. If one unit covered considerably more area than the others, that rock type was selected dominant. If this was not the case, it was necessary to characterize the rock types as a combination. Due to the scale limitations and lack of more specific lithologic information, it was necessary to further classify rock types as sedimentary (including marine and nonmarine sediments and Quaternary landslide deposits), crystalline (including all igneous and metamorphic rock types), or mixed (both sedimentary and crystalline).

Grain-size distributions of samples of deposits and of undisturbed, burned soils on hillslopes were determined by sieve and hydrometer following ASTM standard D 421-85. In addition, the dispersion ratio of burned soil was determined following ASTM standard D 4221-90. The dispersion ratio compares the fraction of fines measured in a hydrometer test with and without dispersant, and is a measure of the portion of fines that supply cohesion when the soil is wet. High ratios indicate that the soil readily disaggregates when water is added. Scott and Williams (1978) found that soils on unburned hillslopes with high dispersion ratios are more prone to be mobilized into debris flows.

Erosion after wildfires is frequently attributed to the presence of a water-repellent layer within the soil, particularly within chaparral environments in southern California (e.g., Krammes and DeBano, 1965; DeBano and Letey, 1969; Holzhey, 1969; Krammes and Osborn, 1969; Campbell et al., 1977; DeBano, 1981; and Booker, 1998). A water-repellent layer can present a barrier to infiltration, and can thus lead to increased runoff. In this study, water repellency was assessed by digging a minimum of three, and often more, small pits throughout each drainage basin. Pits were about 10 cm deep, with one side inclined at about 3:1. Water from a squirt bottle was dripped along the incline. Water repellency was identified if the water beaded on the surface and did not infiltrate for at least 30 seconds. Where water-repellent material was found, its lateral extent was evaluated by dripping more water on either side within the same pit. If a water-repellent layer was also detected in nearby pits, I classified the layer as laterally continuous. Pits were preferentially located in areas mantled with white ash and residual standing fuels greater than about 3 cm in diameter, both indications of high fire temperatures in the burned basins.

I characterized basin morphology by measuring basin area, height, and length from 10-m Digital Elevation Models (DEMs) of the southern California burned areas and the South Canyon fire, and from 1:24,000 topographic maps of the Dome fire (Appendix 1). Following the methodology of Meyer and Wells (1997), basin lengths were measured from the drainage outlet along the length of the longest stream channel, and extended to the drainage divide. A relief ratio for each basin was then calculated as the maximum relief from basin mouth to the divide divided by the length of the longest stream channel.

The proportion of each basin that was burned at high to moderate severities was measured by superimposing coverages of burn perimeters with coverages of drainage basin outlines. Maps that showed the burn perimeters were obtained from the federal, state or county agencies that fought the fires. I used field observations to verify the maps and delineate areas burned at high to moderate fire severities. High to moderate fire severities were characterized by 80 to 100 percent vegetation mortality, and consumption of fuels smaller than about 3 cm in diameter and of the litter and duff layer. Although the type of vegetation burned may affect fire temperatures and thus the physical properties of the burned soils, in this study I examine burned severity as a measure of this effect on debris-flow susceptibility.

Statistical evaluations were used to test for relations between controlling variables and hillslope and channel response. When the controlling variables are in nominal or ordinal form, a series of χ^2 tests are used to examine the null hypotheses of independence. The χ^2 tests evaluate how different the observed frequencies of occurrence are from the frequencies expected if the null hypothesis is true. Discriminant analyses are used to evaluate interval data. This analysis provides a means for evaluating the statistical significance of classes defined by the discriminating variables.

In this study, I make the basic assumption that storm rainfall in the study areas was sufficient to initiate debris flows from burned basins regardless of whether geologic and geomorphic conditions were conducive to such activity. This assumption is necessary in the absence of basin-specific rainfall information. Observations that the winter storms of 1997–98 in southern California, and summer thunderstorms on Storm King Mountain and in Capulin Canyon resulted in significant runoff, flooding, and debris-flow activity in adjacent, unburned basins indicate that this assumption is reasonable (Cannon, 1999; Cannon and Reneau, 2000; and Cannon et al., 2001). In addition, records from 19 rain gages located throughout southern California indicate that the winter of 1997–98 rainfall totals were between 128 and 280 percent of normal (Cannon, 1999). However, the possibility still exists that the response of the burned basins was driven by local and temporal rainfall variations. Measures of storm rainfall intensities and durations collected in individual basins is necessary to examine this possibility.

CHANNEL RESPONSE TO RAINFALL EVENTS

Although it is common practice to distinguish flow and sediment transport processes based on sedimentology and morphology of deposits (e.g., Wells and Harvey, 1987; Costa, 1988; Blair and McPherson, 1994; and Meyer and Wells, 1997), recent research by Major (1997), and Iverson (1997a, 1997b) suggests that such a distinction may be difficult for rapidly deposited, poorly-sorted deposits. In this study, I thus developed criteria to distinguish deposits of fire-related debris flows from those of streamflow with high sediment concentrations. These criteria are best suited to deposits observed lining channels or ponded behind obstructions such as road crossings because most of the deposits used to develop these criteria were thus deposited. The primary characteristics used to distinguish these deposits are shown in Table 2.

Deposit Classification

Sediment-laden Streamflow: Streamflow is defined by Pierson and Costa (1987) as fully turbulent Newtonian flow in which the sediment load does not affect flow behavior, or imparts no yield strength to the flow. Streamflow deposits associated with wildfires are generally attributed to flash-flood discharges, either confined within channels or expanded over fan surfaces as sheetflood (e.g., Meyer and Wells, 1997).

Four types of streamflow deposits were identified from burned areas in the study areas: clast-supported and imbricated boulder and cobble bars; stratified, well-sorted deposits primarily of sand-and gravel-sized material; charcoal- and ash-rich silts and clays; and sand-matrix supported boulder and cobble bars (Table 2). Charcoal and ash produced by the fire could be found as stringers within the sand-and gravel-dominated deposits. Figure 4A shows a section through an example of a stratified sand and gravel-dominated deposit, and Figure 5 shows the particle-size distribution of samples of sediment-laden streamflow deposits. Pierson and Costa (1987) and Costa (1988) attribute deposits intermediate in sorting and stratification between those of debris-flow and streamflow as the result of hyperconcentrated flow (Scott, 1988; Costa, 1988). The fourth type of streamflow deposit listed above could possibly be those of hyperconcentrated flow. These deposits were identified primarily as poorly-sorted gravel- to boulder-sized materials in an abundant sandy matrix (Table 2; Figure 4B). No stratification was observed and very little fine material remained in the matrix, giving the deposits a loose, noncohesive character. The scarcity of fine material and clast-support distinguishes these deposits from those of debris flow. These deposits lack wood ash and fine sediment abundant in burned soils on hillslopes and indicate the possibility of hydraulic sorting, a process not common in debris flows.

Debris flow (Types 1 and 2): Pierson and Costa (1987) define debris flows as non-Newtonian, single-phase slurries with substantial yield strengths, consisting of high concentrations of sediment in water. The onset of debris flow in sediment-water mixtures is defined by Pierson and Costa (1987) to occur at the point were the yield strength increases rapidly with increasing sediment concentration; yield strengths are considered to be caused by internal friction that arises from interlocking of grains. Iverson (1997a, 1997b) proposes an alternative mechanistic model for debris flow, wherein the flows behave primarily as Coulomb grain flows in which intergranular friction is affected by the variable pressure of pore water containing suspended fine sediment; pore-fluid pressures are potentially high enough to produce near-zero strength in the flowing debris. Deposition occurs when motion is impeded by grain-contact and bed friction concentrated at surge margins where sediment is coarsest and high pore pressures are absent (Major and Iverson, 1999).

Two types of fire-related debris-flow deposits were recognized in this study. Type 1 debris flows consist of very-poorly to poorly-sorted, up to boulder-sized materials in the form of levees and lobes with significant relief

Table 2. *Descriptions of deposits from three flow processes identified for fire-related erosion events. Sorting, σ_ϕ is calculated as $(\phi_{84}-\phi_{16})/2$ (Folk, 1974).*

Flow Process	Facies	Morphology	Texture and Composition	Fabric and Structure
Sediment-laden Streamflow	Clast-supported boulder and cobble bars	Narrow curvilinear bars with low to moderate relief and indefinite margins. Maximum height observed 1 m.	Moderate to poor sorting (σ_ϕ = 1.4–2.7ϕ), matrix free imbrication.	Clast-supported, strong to moderate
	Stratified sand- and gravel-dominated deposits	Flat-lying, infilling channels and basins or low relief splays with indefinite margins onto unconfined surfaces. Maximum thickness observed 1.0 m.	Gravel- to sand-dominated beds, individual beds well sorted (σ_ϕ = 1.2ϕ), poorly sorted between beds (σ_ϕ = 1.9–2.7ϕ). Stringers of ash and charcoal.	Surface-parallel, planar, strong stratification, some normal grading.
	Charcoal-and ash-rich silts and sands	Flat-lying, infilling channels and basins or thin splays onto unconfined surfaces. Maximum thickness observed 8 cm.	Sand- to silt-dominated beds, very well-sorted.	Surface-parallel, planar
	Matrix-supported boulder and cobble bars	Bars with low to moderate relief. Maximum height observed 0.75 m.	Poorly sorted (σ_ϕ = 1.9–2.9ϕ), abundant sandy matrix, lacking clays. Some angular charcoal fragments.	Sand matrix support, weak to moderate imbrication, some coarsening upwards.
Type 1 Debris Flow	Levees	Paired ridges with moderate to high relief lining channel, moderate to steep, distinct margins. Maximum height observed 1.5 m.	Poorly to very poorly sorted up to boulder-sized material with woody debris, matrix ranges from abundant fine-grained material to muddy coating on clasts.	Matrix-supported, random clast orientation
	Muddy veneer	Up to 2-cm thick coating on channel walls.	Well-sorted primarily sandy silt, some charcoal fragments.	None
	Lobes	Lobate, moderate to high relief, moderate to steep, distinct margins onto unconfined surfaces. Maximum height observed 2 m.	Very poorly sorted, up to boulder-sized material with woody debris, matrix ranges from abundant fine-grained material to muddy coating on clasts.	Matrix-supported, random clast orientation
	Unsorted, coarse material in fine matrix	Flat-lying to slightly concave downward infilling basins. Maximum thickness observed 2.5 m.	Poorly to very poorly sorted (σ_ϕ = 1.8–4.8ϕ), up to boulder-sized material. Some charcoal fragments and disseminated charcoal and ash.	Matrix-supported, random clast orientation
Type 2 Debris Flow	Silty sand and gravel with abundant disseminated charcoal and ash.	Flat-lying infilling basins. Maximum thickness observed 0.5 m.	Well to poorly sorted (σ_ϕ = 0.7–2.2ϕ) sand and gravel-dominated, with abundant disseminated charcoal and ash.	Abundant fine-grained matrix

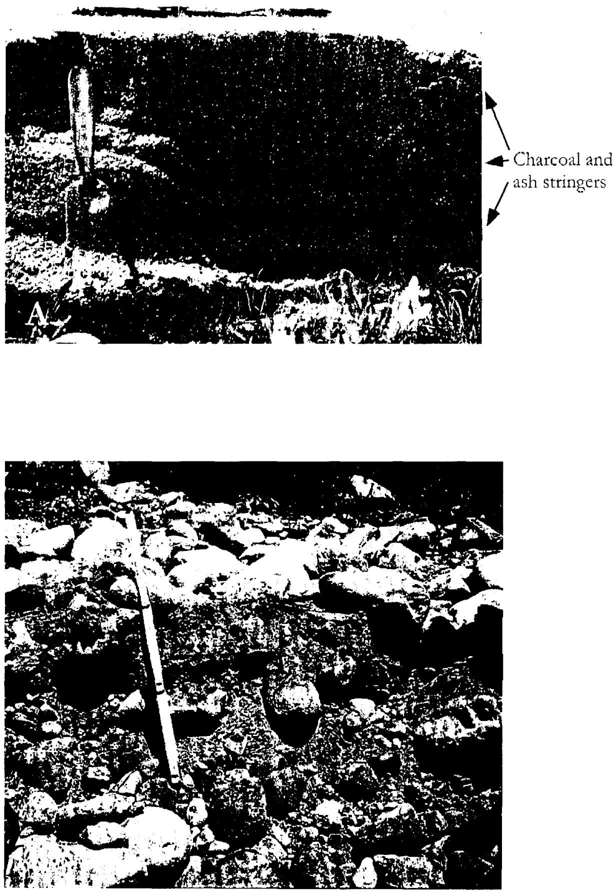

Figure 4. Photographs of A) strongly stratified and well-sorted fire-related streamflow deposit from drainage A of Lake Perris fire in southern California, and B) section through sediment-laden streamflow deposits (which could be considered to be the result of hyperconcentrated flow) consisting of cobbles in abundant sandy matrix. Scale is 60 cm long.

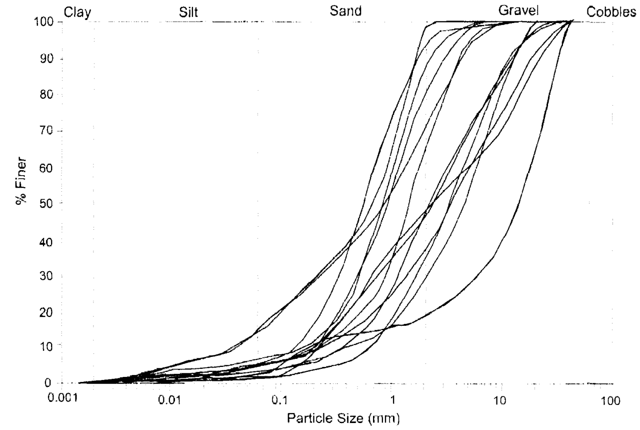

Figure 5. Particle-size distributions of samples of sediment-laden streamflow deposits.

and sharp, well-defined boundaries (Figure 6A). A thin veneer of fine-grained material can be observed lining the debris-flow paths. A primary and diagnostic characteristic of Type 1 debris-flow deposits is the fine-grained matrix support of larger clasts. In the levees and lobes of the fire-related debris flows observed here, the matrix ranged from abundant fine-grained material to muddy coatings on clasts. Where the debris flows pounded behind an obstruction or flowed onto an unconfined surface, the deposits consisted of very-poorly to poorly-sorted, up to boulder-sized material in a fine-grained matrix (Figures 6B and 7A).

Because the Type 1 debris flows transported materials up to and including boulders, these flows can be quite destructive. For example, debris flows issuing from basin B of the Hopper fire destroyed culverts and bridges, and inundated an area of approximately 0.5 km^2. A delta consisting of approximately 0.10 km^2 of debris-flow material was deposited in Lake Piru.

Type 2 debris flows consisted primarily of sand and gravel-sized material in an abundant, ash- and charcoal-rich matrix (Figure 8). The relatively abundant fine fraction includes silts and clays with plentiful disseminated charcoal and ash. The sand fraction was generally well sorted (Figure 7B). The plentiful fine fraction argues for the classification of these deposits as debris flow. Had these materials been transported by any process other than debris flow, the fine material would have been removed by hydraulic sorting. Type 2 debris flows were commonly overlain by either Type 1 debris flow or streamflow deposits, as shown in Figure 8.

Because Type 2 debris-flow events transported smaller-sized materials, they were notably less destructive than their Type 1 counterparts. The similarities between the grain-size distributions of Type 2 debris flows and those of streamflow, including a lack of large material and the presence of a well-sorted sand fraction, suggest that the materials transported by Type 2 debris flows are more similar to those transported by streamflow than to those transported as Type 1 debris flows.

The grain-size distributions of each of the flow processes have distinct forms (Figures 5, 7, 9). For example, in Figure 9, a plot of a sorting coefficient and average grain size, data from Type 1 and Type 2 debris flows occupy distinct fields, and streamflow deposits fall in the same range as Type 2 debris flows. The difference between the deposits from the latter two flow processes lies in the relative abundance of fines in the Type 2 debris-flow deposits, and their relative lack in the streamflow deposits (Figures 5 and 7B).

Relative Abundance of Flow Types

Of the 95 basins examined, evidence for debris flow as the initial erosive response to significant rainfall events was observed in 37 basins (Figure 10A). Twenty-three

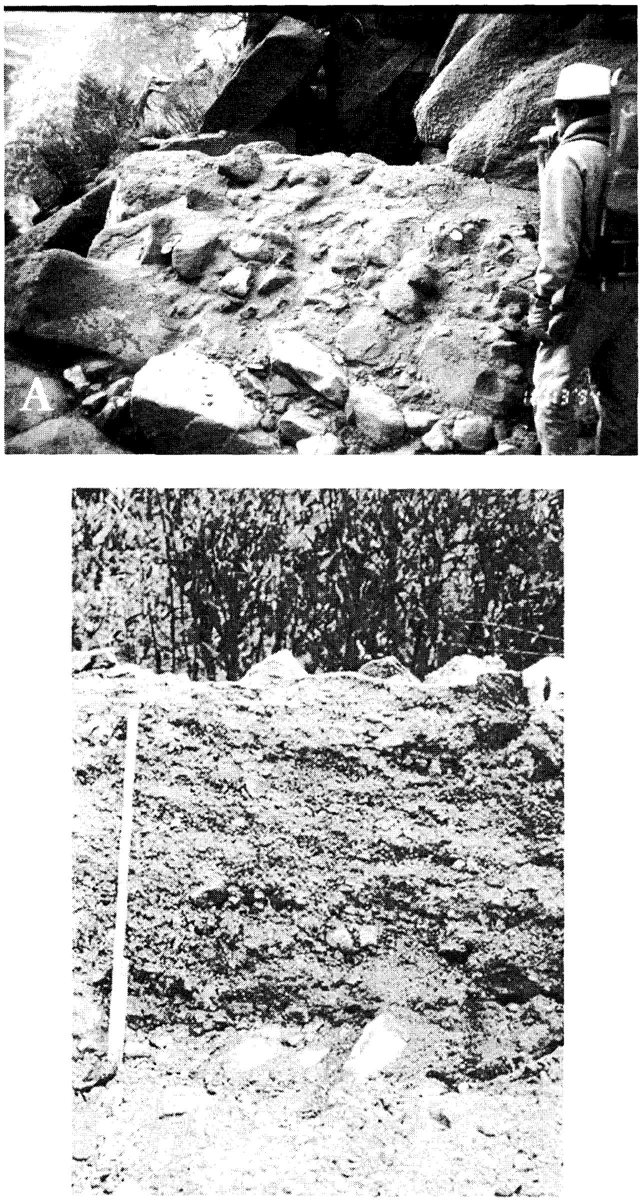

Figure 6. Photographs of Type 1 debris-flow deposits in A) basin B of the South Canyon fire, and B) basin B of the Shooting fire. Scale in photograph B is 80 cm long.

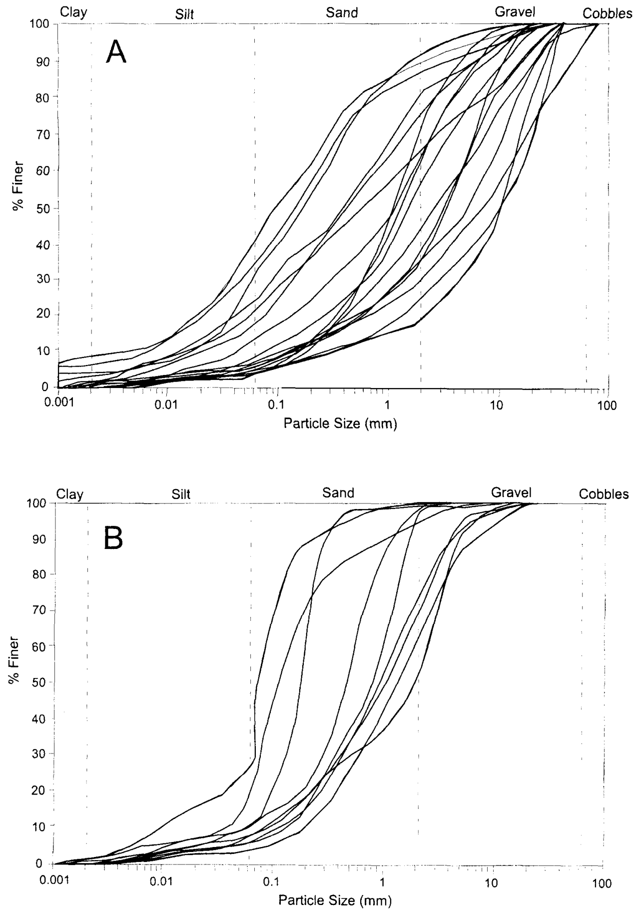

Figure 7. Particle-size distributions of samples of A) Type 1 debris-flow and B) Type 2 debris-flow deposits.

of these were the potentially more destructive Type 1 debris flows. Of the remaining basins, 56 produced sediment-laden floods (11 of which may be hyperconcentrated flows), and two showed no discernable response (Appendix). This comparison indicates that debris flows were not the prevalent initial response of the recently burned watersheds examined in this study. In addition, the fact that not all burned basins produced debris flows suggests that specific geologic and geomorphic conditions may control the generation of fire-related debris flows. This concept is explored in following sections.

Subsequent Response

Evaluation of the subsequent response of the channels to winter storms (southern California), and throughout the summer monsoon season (Storm King mountain and Capulin Canyon study areas), showed that although runoff continued to be generated from the burned basins, most frequently the effect of these later events was to rework and incise the deposits left by the initial events. Debris flows were produced from only one burned basin following the initial erosive event (Figure 10B); debris flows were produced from basin F on Storm King Mountain, and field observations suggest the debris flows initiated from channel-bank and hillslope materials destabilized by incision following the initial event. Some basins continued to produce sediment-laden streamflow in response to storm events. In the case of the Hemlock fire, the debris basin at the mouth of the canyon was filled to capacity at least once with stratified sands and gravels after the initial debris-flow event. Moody and Martin (1998) described similar ongoing sediment production in response to rainstorms following the Buffalo Creek fire in Colorado.

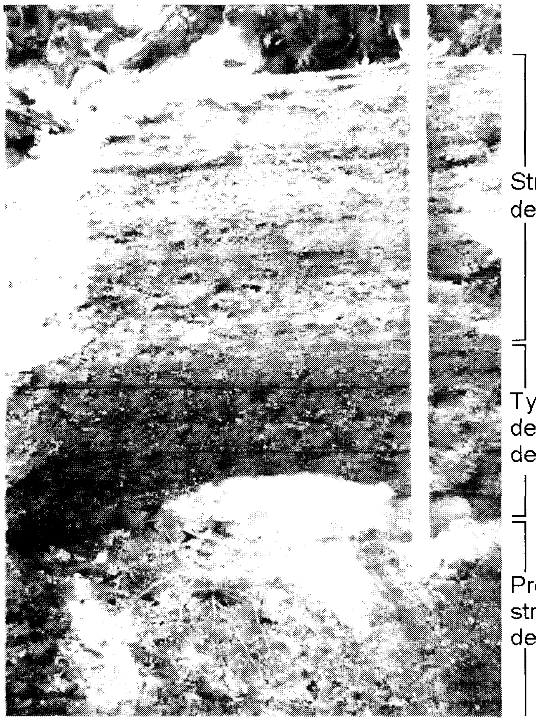

Figure 8. Photograph of Type 2 debris-flow deposit overlying pre-fire fluvial deposits, and overlain by stratified streamflow deposits. Section in basin A of Del Dios fire.

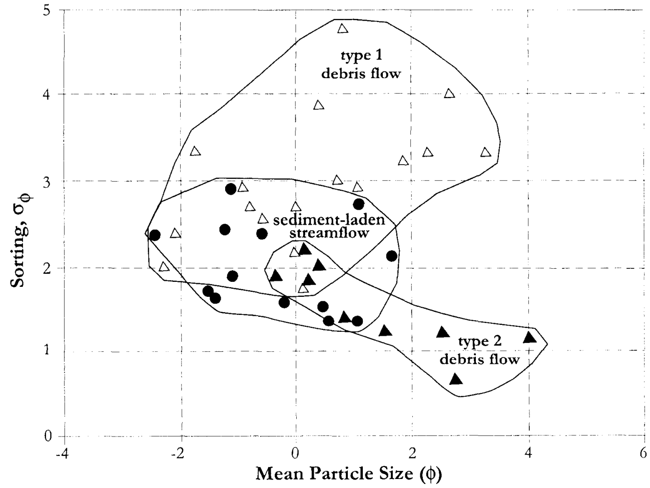

Figure 9. Sorting, σ_ϕ, as a function of mean particle size, M_ϕ, for fire-related deposits. σ_ϕ calculated as $(\phi_{84}-\phi_{16})/2$, and M_ϕ calculated as $(\phi_{84}+\phi_{16})/2$ (Folk, 1974). Type 1 debris-flow deposits represented by open triangles, Type 2 debris-flow deposits by solid triangles, and sediment-laden streamflow deposits by circles.

The lack of subsequent debris-flow activity can perhaps be attributed to both decreasing sediment availability and the establishment of an effective transport network in the initial event. I observed that on burned hillslopes, rilling and sheetwash in the initial event removed the loose, unconsolidated burned soil and ash, leaving more compact, less erodible soil horizons. Rill incision was frequently limited by root mat and shallow bedrock. In channels, the initial debris-flow pulse entrained readily eroded material, and in some cases eroded to bedrock. The initial event served to establish an extensive drainage network that effectively conveyed runoff through the system, which in turn incorporated readily erodible material in sufficient proportions to create debris flows. In subsequent runoff events, considerably smaller amounts of sediment were available for entrainment relative to runoff, and debris flows were rarely produced.

FIRE-RELATED DEBRIS FLOW INITIATION PROCESSES

The hillslopes in each of 94 burned basins in the three study areas were examined to determine their initial response to significant storms. The types of responses observed were:

1. No significant hillslope erosion.
2. Erosion by rilling, sheetwash, and raindrop impact.
3. Generation of soils slips in addition to erosion by rilling, sheetwash, and raindrop impact.

A combination of erosion by rilling, sheetwash, and raindrop impact was the prevalent hillslope response to rainfall events in the great majority of the basins evaluated (Figure 11). In addition, soil slips involving failure of an approximately 1-m thick layer of soil and colluvium, combined with rilling, erosion by sheetwash, and raindrop impact were observed on the hillslopes of 19 basins.

A series of χ^2 tests were conducted to evaluate whether channel response is independent of hillslope response. In the χ^2 tests, I examine the null hypothesis (H_o) that the channel response is independent of the hillslope response. The test results indicate that channel and hillslope response are dependent (Table 3). Basins that showed no channel response or where hillslope response was not observed were not included in the analysis because of the low number of observations. The value of $P>0.05$ in test 3 indicates an unacceptable probability of being wrong in rejecting the null hypothesis; this test is thus inconclusive.

Having established that channel response is dependent on hillslope response, I then calculated the percent of each channel response associated with each primary erosive response observed on hillslopes (Figure 12). Type 1 debris flows occurred in about equal proportions in basins that exhibited erosion by rilling, sheetwash, and raindrop impact and in basins that also experienced soil slips. These data indicate that Type 1 debris flows can initiate through both progressive sediment bulking of hillslope runoff, as

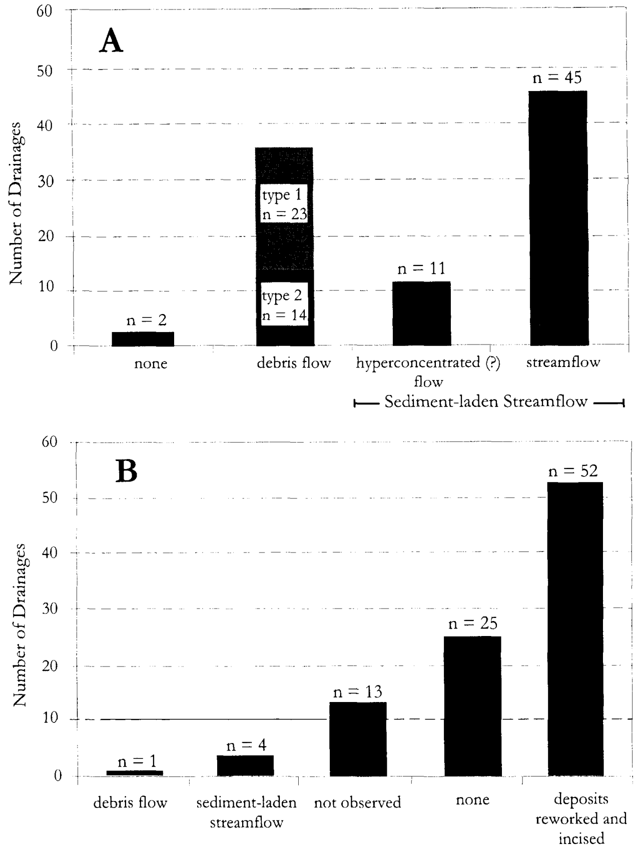

Figure 10. Frequency distributions of A) initial channel response and B) subsequent channel response from 95 basins evaluated.

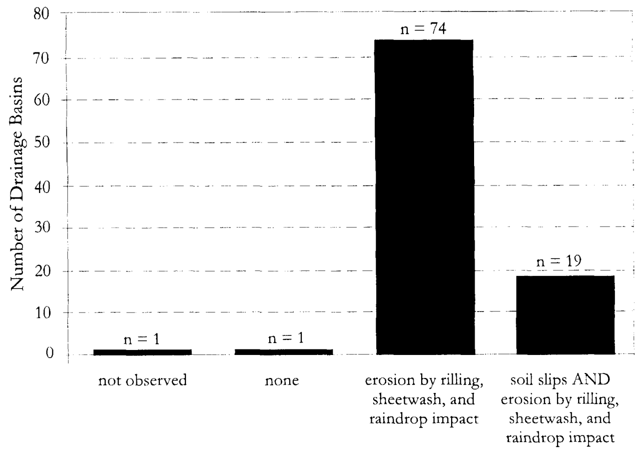

Figure 11. Frequency distribution of initial hillslope response of 95 monitored basins.

indicated by pervasive surface erosion, and by infiltration-triggered slope failure, as indicated by the presence of soil slip scars on hillslopes. Unfortunately, the resolution of the geologic data is not sufficient to determine those rock types most susceptible to infiltration-triggered failure. In contrast, all Type 2 debris flows occurred in basins that experienced only rilling, sheetwash, and rainsplash erosion (Figure 12). The lack of association of Type 2 debris flows with soil slips indicates that these flows initiated exclusively through runoff-dominated processes.

CONTROLS ON HILLSLOPE AND CHANNEL RESPONSE

Lithology

Cannon (1999) described the debris-flow producing potential of a geologic unit in terms of its susceptibility to erosion by raindrop impact, sheetwash, and rilling, and its propensity toward dry-ravel production. With the exception of the drainage basins in Capulin Canyon, every basin examined in this study showed abundant dry-ravel material mantling hillslopes and adjacent to drainages, and all rock types produced dry-ravel material. Because dry ravel appears to be a nearly ubiquitous process in burned areas, and in this study I am trying to determine characteristics unique to debris-flow producing basins, in the following section I examine the materials that make up hillslopes, and the grain-size distributions and dispersivity ratios of burned surficial materials.

To determine the lithologies most common to the generation of debris flows, I examined the proportions of each channel response for each rock type (Figure 13). Of the basins that produced Type 1 debris flows, the great majority were underlain by sedimentary rock types, although a few basins underlain by crystalline rocks also produced Type 1 debris flows. In contrast, Type 2 debris flows were produced exclusively from basins formed in crystalline rocks, and the great majority of these were composed of decomposed granite. Field observations indicate that these hillslopes were commonly mantled by a thick covering of grus. Further, Type 2 debris flows were generated from basins that did not have abundant large material stored in the channels. Had larger material been incorporated, the flow would have been classified as a Type 1 flow.

A series of χ^2 tests were conducted to evaluate whether channel response and rock type are independent. The null hypothesis (H_o) tested is that channel response is independent of rock type. The test results indicate that there is an association between channel response and rock type (Table 4). Basins with no response, or with mixed lithologies, are not included in the analysis because of the low number of observations. The value of $P>0.05$ in test 2 indicates an unacceptable probability of being wrong in rejecting the null hypothesis; this test is thus inconclusive.

I also examined the grain-size distribution of burned surficial materials to determine if differences in the proportion of fine materials could distinguish debris-flow producing basins from basins that produced other responses. Specifically, because the presence of fines in a

Table 3. *Contigency tables and χ^2 tests for independence between channel and hillslope response.*

		Hillslope Response		χ^2_{calc}	$\chi^2_{dof=2,\alpha=0.05}$	P	Conclusion
	Channel Response	Rilling, sheetwash, rainsplash	Soil slips AND rilling, sheetwash, rainsplash				
Test 1	Type 1 debris flow	12	11	15.260	5.991	<0.001	Reject H_0
	Type 2 debris flow	14	0				
	Sediment-laden Streamflow	47	8				
		Hillslope Response		χ^2_{calc}	$\chi^2_{dof=1,\alpha=0.05}$	P	Conclusion
Test 2	Type 1 debris flow	12	11	8.026	3.841	0.005	Reject H_0
	Sediment-laden Streamflow	47	8				
Test 3	Type 2 debris flow	14	0	1.103	3.841	0.294	Inconclusive
	Sediment-laden Streamflow	47	8				
Test 4	Type 1 debris flow	12	11	7.377	3.861	0.007	Reject H_0
	Type 2 debris flow	14	0				

slurry helps to maintain excess pore fluid pressures, they can also enhance the potential mobility of debris flows (e.g., Hampton, 1972; Rodine and Johnson, 1976; Major and Pierson, 1993; and Major and Iverson, 1997). Samples from the upper 2–3 cm of burned soil and ash were taken from hillslopes in drainage basins that produced both Type 1 and Type 2 debris flows (Figure 14A and B), and from basins that produced sediment-laden streamflow (Figure 14C).

Comparison of Figure 14A, B and C indicates that burned surficial materials in basins that produced all three flow types had no significant differences in the proportions of fine materials. However, drainage basins that produced Type 1 and Type 2 debris flows had slightly more sand-sized material than basins that produced sediment-laden streamflow. In addition, materials in basins that produced Type 2 debris flows had slightly less gravel-sized material than those in basins that produced Type 1 debris flows and sediment-rich streamflow. However, these differences offer no explanation for the variation in erosive response. Further, a plot of sorting coefficient as a function of mean particle size did not define any

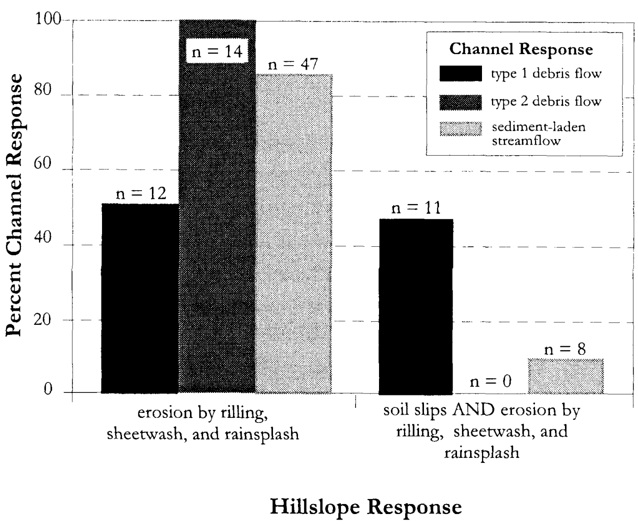

Figure 12. Frequency distribution of percent flow process by hillslope response.

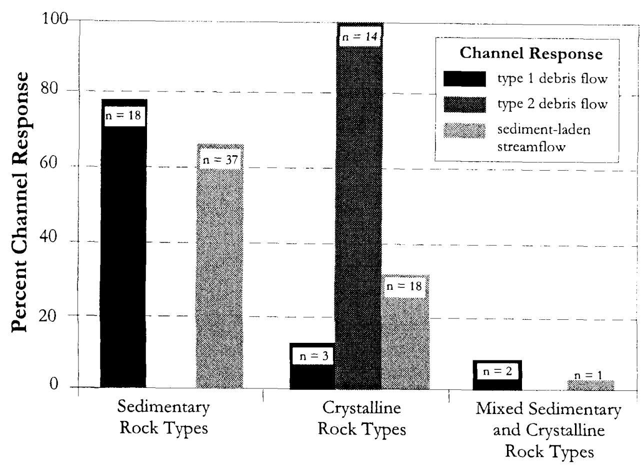

Figure 13. Frequency distributions of channel response by rock type classification.

Table 4. *Contingency tables and χ^2 tests for independence between channel response and rock type.*

		Rock Type		χ^2_{calc}	$\chi^2_{dof=2, \alpha=0.05}$	P	Conclusion
	Channel Response	sedimentary	crystalline				
Test 1	Type 1 debris flow	18	3	28.227	5.991	<0.001	Reject H_o
	Type 2 debris flow	0	14				
	Sediment-laden Streamflow	37	18				
		Rock Type		χ^2_{calc}	$\chi^2_{dof=1, \alpha=0.05}$	P	Conclusion
Test 2	Type 1 debris flow	18	3	1.745	3.841	0.187	Inconclusive
	Sediment-laden Streamflow	37	18				
Test 3	Type 2 debris flow	0	14	17.693	3.841	<0.001	Reject H_o
	Sediment-laden Streamflow	37	18				
Test 4	Type 1 debris flow	18	3	21.394	3.841	<0.001	Reject H_o
	Type 2 debris flow	0	14				

differences between materials that produced debris flows and those that produced streamflow (Figure 15).

Lastly, I examined the dispersion ratios of samples of burned soils on hillslopes to determine if this parameter could be used to distinguish debris-flow producing basins from those that produced other flow types. The dispersion ratio compares the fraction of fines measured in a hydrometer test with and without dispersant, and is a measure of the portion of fines that supply cohesion when the soil is wet. High ratios indicate that the soil readily disaggregates when water is added. Scott and Williams (1978) found that soils on unburned hillslopes with high dispersion ratios are more prone to be mobilized into debris flows.

A series of discriminant analyses indicate that although dispersion ratios for the four rock types could be considered distinct (P<0.06), dispersion ratios could not significantly distinguish either Type 1 or Type 2 debris-flow producing basins from those that produced sediment-rich streamflow (P>0.05) (Table 5).

Water Repellency

I tested for water-repellent soils in 87 of the 95 drainage basins in the study, and found considerably less water repellency than expected. No water repellency was detected in 74 percent of the basins evaluated (Appendix; Figure 16). A discontinuous water-repellent layer was detected in 25 percent of the basins, and only one basin showed a laterally continuous water-repellent layer. These observations, coupled with the strong erosive responses of the burned drainage basins, indicate that the physical properties of the bare, burned soils, without the presence of water-repellent soils, are generally sufficient to cause low infiltration and significant surface runoff in the areas studied. This conclusion is similar to that reached by Meyer and Wells (1987) in their work in Yellowstone National Park.

The lack of water repellency in burned basins is inconsistent with the findings of Krammes and DeBano (1965), who concluded that water repellency was a widespread phenomenon in burned brushland soils of southern California. This determination was based on evaluation of three recent fires, one in the San Dimas Experimental Forest in the San Gabriel Mountains, one in the Verdugo Hills, and one in the San Bernardino Mountains. The disparity between the conclusions of Krammes and DeBano (1965) and those presented here may be due to the fact that I based determination of the existence of water-repellency on a 30-second penetration time, in contrast to the 5-second time assumed by Krammes and DeBano (1965). I used the longer penetration time because I felt that the 5-second interval could reflect the difficulty of water absorption into a dry soil, rather than a persistent water-repellent condition. In addition, Krammes and DeBano (1965) tested for water repellency along transects at constant elevations burned by only three fires, while the conclusions presented here are based on evaluation of 87 drainage basins burned by 22 fires.

A series of χ^2 tests were conducted to determine if channel response depends on the presence or absence of water repellency (Table 6). These tests indicate that channel response depends on the state of water repellency. Type 1 debris flows, however, were more likely to occur in

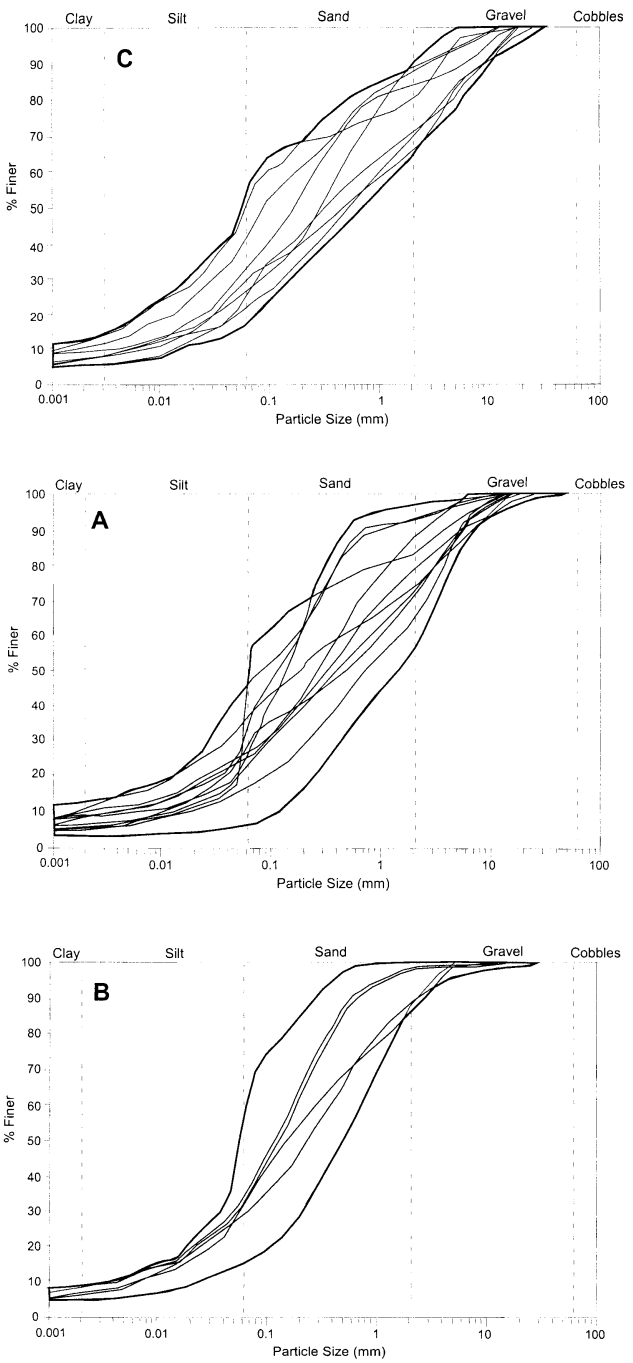

Figure 14. Grain-size distributions of burned surficial materials from drainages that produced A) Type 1 debris flows, B) Type 2 debris flows, and C) sediment-laden streamflow.

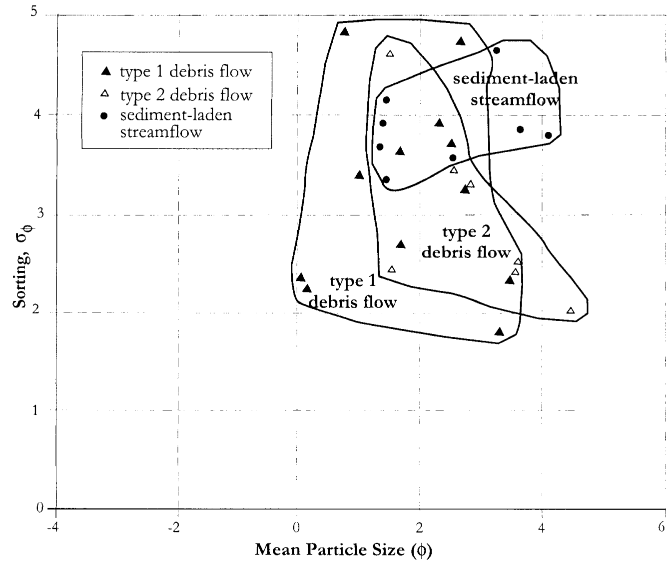

Figure 15. Sorting, σ_ϕ, as a function of mean particle size, M_ϕ, for hillslope materials. sf calculated as $(\phi_{84}-\phi_{16})/2$, and M_ϕ calculated as $(\phi_{84}+\phi_{16})/2$ (Folk, 1974).

basins without a water-repellent soil than to occur in basins with water repellency (Figure 17). The odds ratio, using data from two-by-two contingency tables, can be used as a measure of that association. In this case, the odds ratio gives the proportional increase in the odds of occurrence of Type 1 debris flows, given the existence of water-repellent soils, to the odds that Type 1 debris flows will occur without the presence of water repellency. Using the data in the contingency table from test 2 (Table 6), the odds of Type 1 debris-flow occurrence in basins with water-repellent soils is 8/6 = 1.33. The odds of Type 1 debris flows occurring without the presence of water repellency is 11/46 = 0.24. The odds ratio is thus 1.33/0.24 = 5.54. Since more type 1 debris flow occurred in basins without water-repellent soils than in basins with water repellency, the odds ratio indicates that the odds are approximately 6 times greater that a Type 1 debris flow would be produced from a basin without any water-repellent soils than from a basin with water repellency. This result suggests that an abundant supply of easily erodible material on hillslopes may promote the generation of Type 1 debris flows, more so than the increased surface runoff attributed to a water-repellent soil.

In contrast, considerably more Type 2 debris flows were produced from basins with a discontinuous water-repellent layer than were produced from basins with no water repellency (Figure 17). This suggests that the presence of discontinuous water-repellent soils influences the generation of Type 2 debris flows. An odds ratio of 13.63 indicates that the odds are approximately 14 times greater that a Type 2 debris flow would be produced from a basin with water repellent soils than from a basin without water-repellent soils.

Drainage-Basin Morphology

I found that all flow types were produced from a wide variety of combinations of basin area and relief (Figure 18). Discriminant analyses indicated that although basins that produced the different channel responses could not

Table 5. *Results of discriminant analyses between dispersion ratio and rock type and between dispersion ratio and flow processes.*

Classes	Discriminating Variable	Wilks' λ	χ^2	dof	Significance
Granite Marine and nonmarine sedimentary rocks Metamorphic rocks Mixed	Dispersion ratio	0.745	7.513	3	0.057
Type1 debris flow Type 2 debris flow Sediment-laden streamflow	Dispersion ratio	0.966	0.913	2	0.634
Type 1 debris flow Sediment-laden streamflow	Dispersion ratio	0.944	1.118	1	0.290
Type 2 debris flow Sediment-laden streamflow	Dispersion ratio	.0799	3.037	1	0.081

be distinguished on the basis of area and relief (P>0.05), the area and relief of those basins that produced Type 1 debris flows were distinct from those that produced Type 2 debris flows (P<0.05)(Table 7). The discrete fields occupied by these data are delineated in Figure 18 as shaded boxes. Type 1 debris flows were produced from a range of basins as small as 0.02 km^2 with relief ratios between 0.4 and 0.6, and as large as 10 km^2 with relief ratios between 0.07 and 0.2. Type 2 debris flows were produced from basins as small as 0.02 km^2 with relief ratios between 0.25 and 0.35, and as large as 2 km^2 with relief ratios from 0.08 to 0.18.

Threshold conditions above which the two types of debris flows can be expected are delineated by solid and dashed lines at the lower limit of debris-flow occurrence in Figure 18. For a given relief ratio, larger basins areas were necessary to generate Type 1 debris flows than Type 2 debris flows. Similarly, for a given basin size, higher relief rations were necessary to generate a Type 1 than a Type 2 debris flow.

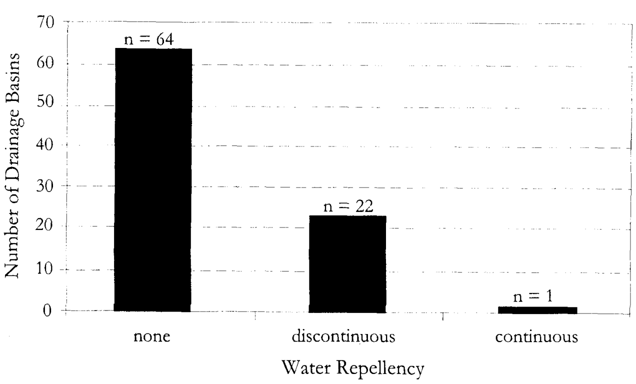

Figure 16. Frequency distribution of occurrence of water-repellent soils in 87 drainage basins.

Burn Extent

The percentage of each basin burned at moderate to high severities ranged from 3 to 100 percent, with a mean of 80 percent (Figure 19 and Appendix). A median, or middlemost value, of 93 percent, and a mode, the most common value, of 100 percent, indicates that most basins were nearly completely burned.

Type 1 debris flows were produced from basins that experienced as little as 5 percent, and up to 100 percent burn, and Type 2 debris flows occurred in basins with a little as 8 percent burn coverage (Appendix; Figure 19). This result indicates either that very little burn coverage can result in increased runoff, or that the storms that impacted the burned areas were severe enough to result in erosion even from unburned hillslopes. Field observations were not sufficient in these cases to separate these effects.

SUMMARY AND CONCLUSIONS

The nature of the erosive response of burned drainage basins to wildfire was explored by evaluating the response of 95 drainage basins in three study areas burned by wildfires. Contrary to expectation, debris flows were not the dominant erosive response from the burned basins. Debris flows were produced from only 37 of the 95 basins examined. Of these, 23 were the more destructive Type 1 debris flow. The remaining basins exhibited deposits from either sediment-laden streamflow or no discernable response. Although some hillslopes continued to erode and supply material to channels in the year following the fire, debris flows were produced from only one burned watershed following the initial erosive event. This lack of subsequent debris-flow activity may be attributed to both a decrease in sediment availability and the establishment of an effective runoff transport network during the initial event.

Table 6. *Contingency tables and χ^2 tests for independence between channel response and presence or absence of water repellent soils.*

		Water Repellency		χ^2«	$\chi^2_{dof = 2\ \alpha = 0.05}$	P	Conclusion
	Channel Response	present	absent				
Test 1	Type 1 debris flow	8	11	18.356	5.991	<0.001	Reject H_o
	Type 2 debris flow	9	5				
	Sediment-laden Streamflow	6	46				
		Water Repellency		χ^2_{calc}	$\chi^2_{dof = 1\ \alpha = 0.05}$	P	Conclusion
Test 2	Type 1 debris flow	8	11	6.396	3.841	0.011	Reject H_o
	Sediment-laden Streamflow	6	46				
Test 3	Type 2 debris flow	9	5	14.600	3.841	<0.001	Reject H_o
	Sediment-laden Streamflow	6	46				

Type 1 debris flows consist of poorly sorted, matrix-supported, up-to-boulder-sized materials with levees and lobes with significant relief and sharp, well-defined boundaries. Because Type 1 debris flows transported up to boulder-sized material, they could be quite destructive. These flows occurred most frequently in drainage basins underlain by sedimentary rock types (including marine and nonmarine sediments and Quaternary landslides), although some flows did occur in basins underlain by crystalline and mixed rock types. Type 1 debris flows were produced from basins as small as 0.02 km^2 with relief ratios between 0.4 and 0.6, and as large as 10 km^2 with relief ratios between 0.07 and 0.2. A basin-area and relief threshold for Type 1 debris-flow production is defined by $R = -0.07\ln(\text{Area}) + 0.16$, where R is the relief ratio. Although most of the Type 1 debris flows initiated through a process of progressive sediment bulking of surface runoff, as indicated by pervasive surface erosion, the presence of soil-slip scars on the hillslopes of nearly half of the basins that produced Type 1 flows indicates that they are also initiated by infiltration-triggered failure. This suggests that the common post-fire hillslope rehabilitation approach of increasing infiltration at the expense of runoff may not be appropriate in basins susceptible to Type 1 debris flows. Type 1 debris flows were produced from basins that experienced as little as 5 percent, and up to 100 percent burn. The majority of the Type

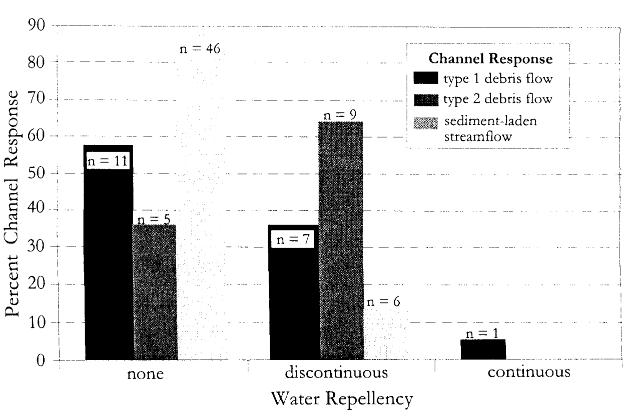

Figure 17. Frequency distribution of channel response by water repellency classification.

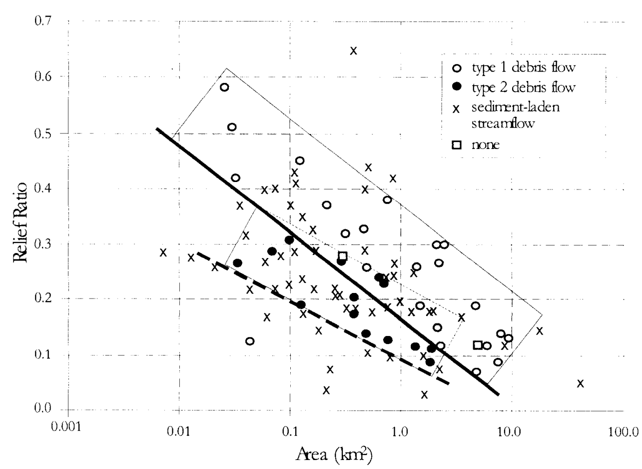

Figure 18. Drainage basin area and relief ratio for the three channel responses. Dark shading highlights the field occupied by Type 1 debris flows, and light shading highlights the field occupied by Type 2 debris flows. Solid line marking lower limit of Type 1 debris-flow occurrence is defined by $R = -0.07\ln(\text{Area}) + 0.16$ and dashed line marking lower limit of Type 2 debris-flow occurrence is defined by $R = -0.04\ln(\text{Area}) + 0.10$, where R is the relief ratio.

Table 7. *Results of discriminant analyses between basin area and relief ratio, and flow processes.*

Classes	Discriminating Variables	Wilks' λ	χ^2	dof	Significance
Type 1 debris flow Type 2 debris flow, sediment-laden streamflow	Basin area Relief ratio	0.968	3.033	2	0.219
Type 1 debris flow Sediment-laden streamflow	Basin area Relief ratio	0.981	1.516	2	0.469
Type 1 debris flow Type 2 debris flow	Basin area Relief ratio	0.587	18.08	2	0.000

1 debris flows occurred without the presence of a water-repellent layer in the burned soil; the odds are approximately 6 times greater that a Type 1 debris flow will be produced from a basin without any water-repellent soils than from a basin with water repellency.

Type 2 debris flows consisted of primarily poorly-sorted sand and gravel-sized material in an abundant matrix rich in charcoal and ash, and were produced exclusively from drainage basins underlain by crystalline rock types; the presence of abundant grus mantling hillslopes appears to be important in the generation of these types of flows. Type 2 debris-flow events generally transported finer material, and were consequently less destructive than their Type 1 counterparts. All of the Type 2 debris flows occurred in basins that experienced extensive rilling and erosive sheetwash, and were not associated with soil-slip failures on hillslopes, indicating that these flows initiated exclusively through runoff-dominated processes. Type 2 debris flows were produced from basins as small as 0.02 km^2 with relief ratios between 0.25 and 0.35, and as large as 2 km^2 with relief ratios from 0.08 to 0.18. A basin area-relief ration threshold for the production of Type 2 debris flows is defined by $R = -0.04\ln(\text{Area}) + 0.10$. Type 2 debris flows occurred in basins with a little as 8 percent, and as much as 100 percent, burn coverage.

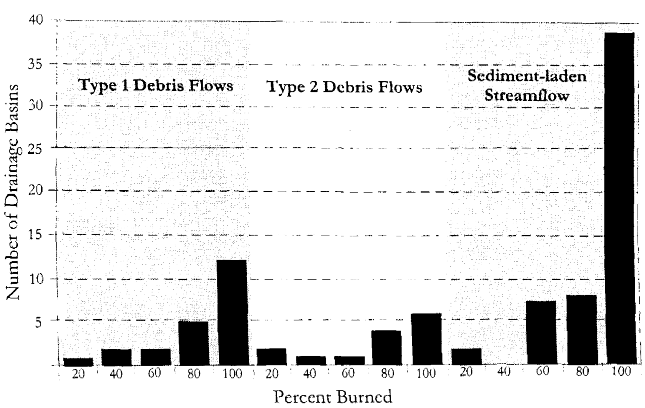

Figure 19. Frequency distributions of percent of drainage basin burned at moderate to high severity.

Considerably more Type 2 debris flows were produced from basins with a discontinuous water-repellent layer than were produced from basins without water-repellent soils, suggesting that the presence of water-repellent soils may influence the generation of these debris flows. The odds are 16 times greater that a Type 2 debris flow would occur in a basin with water-repellent soils than in a basin without any water repellency.

Continuing studies to augment this work are focusing on a multi-variate examination of the factors that control fire-related debris flow susceptibility in order to develop predicative models for debris-flow occurrence, collection of rainfall and peak discharge data from recently burned basins to define quantitative relations between peak discharges and rainfall intensities and durations and basin characteristics, and examination of the effects of material properties on hillslope erosion and debris-flow generation.

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Appendix. *Drainage-basin characteristics and initial channel response.*

Fire	Basin	Area (km^2)	Height (m)	Relief Ratio*	% Burn†	Lithology	Water Repellency	Initial Channel Response
South Canyon, CO	A	2.23	950	0.27	93	Sedimentary§	Discontinuous	Type 1 debris flow
	B	2.46	941	0.30	92	Sedimentary§	Discontinuous	Type 1 debris flow
	C	0.77	772	0.38	95	Sedimentary§	No data	Type 1 debris flow
	D	0.46	449	0.33	63	Sedimentary§	No data	Type 1 debris flow

Appendix. *continued.*

Fire	Basin	Area (km^2)	Height (m)	Relief Ratio*	% Burn†	Lithology	Water Repellency	Initial Channel Response
	E	2.11	853	0.30	48	Sedimentary§	No data	Type 1 debris flow
	F	0.31	526	0.32	75	Sedimentary§	No data	Type 1 debris flow
Dome, NM								
	A	39.90	1024	0.05	55	Mixed#	Discontinuous	Streamflow
	B	6.00	732	0.12	22	Mixed#	Discontinuous	Type 1 debris flow
	C	5.10	575	0.12	3	Mixed#	None	None
Logan, CA	A	8.53	629	0.12	100	Sedimentary**	None	Streamflow
	B	7.53	476	0.09	100	Sedimentary**	None	Type 1 debris flow
	C	0.78	200	0.10	100	Sedimentary**	None	Streamflow
Homestead, CA	A	2.17	638	0.15	45	Sedimentary††	None	Type 1 debris flow
	A2	0.11	268	0.43	50	Sedimentary††	None	Streamflow
	B	1.38	548	0.26	5	Sedimentary††	None	Type 1 debris flow
Hopper, CA	A	0.70	339	0.19	69	Sedimentary§§	None	Hyperconcentrated (?) flow
	B	4.70	691	0.19	74	Sedimentary§§	Discontinuous	Type 1 debris flow
	B2	0.74	428	0.24	100	Sedimentary§§	None	Streamflow
	C	0.12	158	0.24	100	Sedimentary§§	None	Streamflow
	D	0.16	160	0.22	94	Sedimentary§§	None	Streamflow
	E	1.21	437	0.18	96	Sedimentary§§,##	None	Streamflow
	F	0.13	312	0.35	63	Sedimentary§§,##	None	Hyperconcentrated (?) flow
	G	0.11	258	0.41	57	Sedimentary§§,##	None	Streamflow
	H	0.46	383	0.29	74	Sedimentary§§,##	None	Streamflow
	H2	0.12	278	0.45	100	Sedimentary§§,##	None	Type 1 debris flow
	I	0.84	447	0.25	100	Sedimentary§§,##	None	Hyperconcentrated (?) flow
	J	0.11	191	0.29	100	Sedimentary§§,##	None	Streamflow
	K	0.06	125	0.27	98	Sedimentary§§,##	None	Streamflow
	L	0.04	124	0.37	100	Sedimentary§§,##	None	Streamflow
	M	0.07	132	0.22	100	Sedimentary§§,##	None	Streamflow
	N	9.37	812	0.13	96	Sedimentary§§,##	Discontinuous	Type 1 debris flow
	O	0.37	534	0.65	100	Sedimentary§§,##	None	Streamflow
	P	0.02	167	0.58	73	Sedimentary§§,##	None	Type 1 debris flow
Placarita,CA	A	0.13	86	0.18	100	Sedimentary§§,***	Discontinuous	Hyperconcentrated (?) flow
	B	1.57	194	0.10	54	Sedimentary§§,***	None	Streamflow
	C	0.53	184	0.18	12	Sedimentary§§,***	None	Streamflow
Shooting, CA	A	0.21	293	0.37	100	Sedimentary§§,†††	None	Type 1 debris flow
	B	0.48	477	0.26	100	Sedimentary§§,†††	None	Type 1 debris flow
	C	0.22	156	0.08	93	Sedimentary§§,†††	None	Streamflow
	D	0.04	85	0.22	96	Sedimentary§§,†††	None	Streamflow
	D2	0.01	53	0.29	76	Sedimentary§§,†††	None	Streamflow
	D3	0.04	70	0.32	85	Sedimentary§§,†††	None	Streamflow
	D4	0.01	60	0.28	97	Sedimentary§§,†††	None	Streamflow
	F	1.80	481	0.18	7	Crystalline§§,†††	None	Hyperconcentrated (?) flow
	G	0.06	140	0.17	93	Sedimentary§§, †††	None	Hyperconcentrated (?) flow
Canyon II, CA	A	17.35	1133	0.15	70	Crystalline§§§	No data	Hyperconcentrated (?) flow
Hemlock, CA	A	8.09	731	0.14	92	Crystalline§§§	None	Type 1 debris flow
City Creek, CA	B	0.82	817	0.42	66	Crystalline§§§	No data	Streamflow
	C	0.49	733	0.44	99	Crystalline§§§	No data	Streamflow
	D	0.47	684	0.40	92	Crystalline§§§	No data	Streamflow
Mill, CA	A	0.08	574	0.27	100	Crystalline§§§	None	Hyperconcentrated (?) flow
	A1	0.06	194	0.40	100	Crystalline§§§	None	Hyperconcentrated (?) flow
	A2	0.08	145	0.28	100	Crystalline§§§	None	Streamflow
	A3	0.10	213	0.37	100	Crystalline§§§	None	Streamflow
	B	3.54	782	0.17	47	Crystalline§§§	None	Streamflow
Wildwood, CA	A	1.50	543	0.19	100	Mixed§§§	Continuous	Type 1 debris flow
	B	0.04	52	0.13	98	Sedimentary§§§	None	Type 1 debris flow
Calimesa, CA	A	1.59	93	0.03	50	Sedimentary###	None	Streamflow
	B	0.20	55	0.04	71	Sedimentary###	None	Streamflow
Beach, CA	A	0.29	282	0.28	100	Crystalline###,****	None	None
Lake Perris, CA	A	0.12	112	0.19	12	Crystalline###	Discontinuous	Type 2 debris flow
PRU 51067, CA	A	4.84	272	0.07	82	Sedimentary###	None	Type 1 debris flow
Baker, CA	A	0.19	136	0.18	100	Sedimentary###	Discontinuous	Streamflow
	B	0.17	145	0.15	100	Sedimentary###	None	Streamflow

Appendix. *continued.*

Fire	Basin	Area (km^2)	Height (m)	Relief Ratio*	% Burn†	Lithology	Water Repellency	Initial Channel Response
	C	0.26	240	0.21	100	Sedimentary###	None	Streamflow
	D	0.03	164	0.42	23	Sedimentary###	None	Type 1 debris flow
	E	1.25	470	0.25	93	Sedimentary###	None	Streamflow
	F	0.05	91	0.26	100	Sedimentary###	None	Streamflow
	G	0.30	227	0.19	99	Sedimentary###	Discontinuous	Streamflow
	H	1.47	415	0.19	97	Sedimentary###	None	Streamflow
	I	0.09	175	0.23	100	Sedimentary###	None	Streamflow
Poppet, CA	A	0.37	220	0.18	95	Crystalline###	Discontinuous	Type 2 debris flow
	B	0.37	216	0.20	33	Crystalline###	Discontinuous	Type 2 debris flow
	C	1.36	215	0.12	8	Crystalline###	None	Type 2 debris flow
	D	0.63	294	0.24	61	Crystalline###	Discontinuous	Type 2 debris flow
Pauba, CA	A	2.12	238	0.08	71	Crystalline###	Discontinuous	Streamflow
	B	0.07	199	0.40	100	Crystalline###	None	Hyperconcentrated (?) flow
	C	0.48	169	0.11	99	Crystalline###	None	Streamflow
	D	0.25	218	0.22	100	Crystalline###	Discontinuous	Streamflow
	E	2.30	438	0.12	62	Crystalline###	Discontinuous	Type 1 debris flow
	E2	0.03	150	0.51	100	Crystalline###	Discontinuous	Type 1 debris flow
	F	0.39	362	0.19	99	Crystalline###	None	Hyperconcentrated (?) flow
	G	0.95	417	0.20	81	Crystalline###	None	Streamflow
Margarita, CA	A	0.10	236	0.31	82	Crystalline###	Discontinuous	Type 2 debris flow
	B	0.29	246	0.27	66	Crystalline###	Discontinuous	Type 2 debris flow
	C	0.48	182	0.14	88	Crystalline###	Discontinuous	Type 2 debris flow
	D	1.84	239	0.09	54	Crystalline###	None	Type 2 debris flow
	E	0.03	101	0.27	99	Crystalline###	None	Type 2 debris flow
	F	0.07	160	0.29	70	Crystalline###	None	Type 2 debris flow
Wohlford, CA	A	1.89	274	0.11	79	Crystalline###	None	Type 2 debris flow
	B	0.28	202	0.21	59	Crystalline###	None	Streamflow
Del Dios, CA	A	0.69	278	0.23	100	Crystalline###	None	Type 2 debris flow
	B	0.74	198	0.13	95	Crystalline###	None	Type 2 debris flow
	C	0.17	243	0.29	96	Crystalline###	None	Streamflow
	D	0.16	248	0.33	100	Crystalline###	None	Streamflow

* Relief ratio, a measure of basin steepness, is the maximum relief from basin mouth to divide divided by the length of the longest stream channel extended to the divide (Meyer and Wells, 1997).
† High to moderate intensities.
§ Kirkham and others (2000)
# Goff and others (1990); Smith and others (1970)
** State of California (1958); Vedder and others (1989)
†† Dibblee (1981)
§§ State of California (1969)
Huftile and Yeats (1995)
***Yerkes (1996a)
†††Yerkes (1996b)
§§§State of California (1967)
###State of California (1965)
****Morton (1978)