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CONDITIONS FOR GENERATION OF FIRE-RELATED DEBRIS FLOWS, CAPULIN CANYON, NEW MEXICO

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ABSTRACT

Comparison of the responses of three drainage basins burned by the Dome fire of 1996 in New Mexico is used to identify the hillslope, channel and fire characteristics that indicate a susceptibility specifically to wildfire-related debris flow. Summer thunderstorms generated three distinct erosive responses from each of three basins. The Capulin Canyon basin showed widespread erosive sheetwash and rilling from hillslopes, and severe flooding occurred in the channel; the North Tributary basin exhibited extensive erosion of the mineral soil to a depth of 5 cm and downslope movement of up to boulder-sized material, and at least one debris flow occurred in the channel; negligible surface runoff was observed in the South Tributary basin. The negligible surface runoff observed in the South Tributary basin is attributed to the limited extent and severity of the fire in that basin. The factors that best distinguish between debris-flow producing and flood-producing drainages are drainage basin morphology and lithology. A rugged drainage basin morphology, an average 12 per cent channel gradient, and steep, rough hillslopes coupled with colluvium and soil weathered from volcaniclastic and volcanic rocks promoted the generation of debris flows. A less rugged basin morphology, an average gradient of 5 per cent, and long, smooth slopes mantled with pumice promoted flooding. Flood and debris-flow responses were produced without the presence of water-repellent soils. The continuity and severity of the burn mosaic, the condition of the riparian vegetation, the condition of the fibrous root mat, accumulations of dry ravel and colluvial material in the channel and on hillslopes, and past debris-flow activity, appeared to have little bearing on the distinctive responses of the basins. Published in 2000 by John Wiley & Sons, Ltd.

KEY WORDS: debris flow; wildfire; erosion

INTRODUCTION

This study addresses the issue of identifying the hillslope, channel and fire characteristics that indicate a susceptibility specifically to debris flow following wildfire. A common expectation for steep, burned basins is that debris flows are imminent after fire. However, recent experience suggests that the consequences of even heavy rainfall on burned watersheds can cover a spectrum of responses, ranging from slightly increased flooding at canyon mouths (e.g. Morris and Moses, 1987; Helvey, 1980; Florsheim *et al.*, 1991; Scott and van Wyk, 1990; Prosser and Williams, 1998) to disastrous debris-flow activity along canyon lengths (e.g. Cleveland, 1973, 1977; Parrett, 1987; Wohl and Pearthree, 1991; Meyer, 1993; Meyer and Wells, 1997; Booker, 1998; Cannon *et al.*, 1998; Cannon, 1999). 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 denude vegetation, block drainage ways, damage structures and endanger humans (Iverson, 1997). An understanding of the conditions that can result in debris flows following wildfire is necessary to make appropriate mitigation decisions.

The Dome fire was ignited on 25 April 1996 by a campfire abandoned in the Santa Fe National Forest, New Mexico (Figure 1). Because of higher than normal fuel loads, low fuel moisture, and weather and wind patterns, the fire spread rapidly through tinder-dry forest, woodland and grassland plant communities. Within two days the fire had extended eastward into Bandelier National Monument. The Dome fire burned 6684 ha

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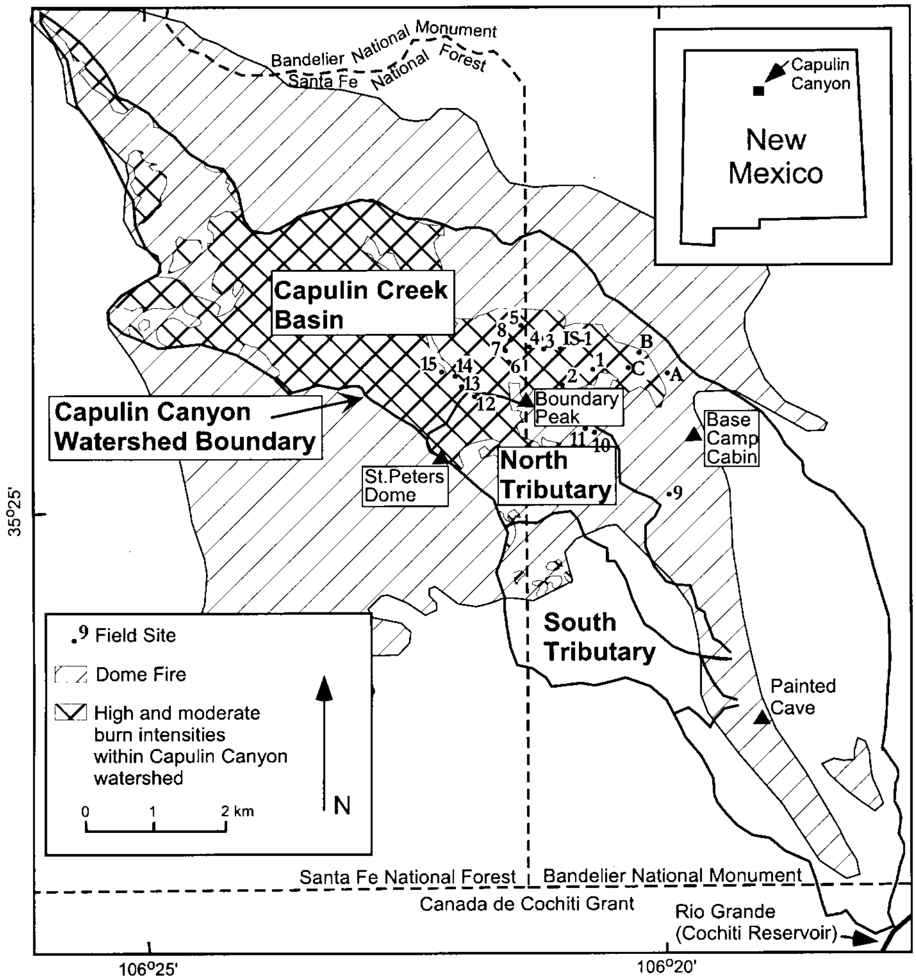

Figure 1. Map of Capulin Canyon watershed. Heavy black lines delineate Capulin Creek drainage, and North and South Tributary basins. Extent of the Dome fire is shown by diagonal lines; areas within the perimeter were burned at different intensities, and some areas are unburned. Areas of high and moderate burn intensity within the Capulin Canyon watershed are shown by cross-hatching. Burn intensity is from unpublished USDA Forest Service mapping. Sites for assessing hillslope conditions are labelled 1 to 15. Rain gauge location is labelled IS-1. Letter A marks the easternmost extent of tributary surface flow generated by the 26 June 1996 storm. Letter B marks the location of possible pre-fire debris-flow deposits on canyon floor. Letter C marks the location of alluvial fan deposit with fire-related sediments

of federal lands, including 4750 ha administered by the US Forest Service and 1934 ha within the Monument (Figure 1) (US Department of Interior, 1996). Although the Dome fire impacted other canyons, the effects of the fire were particularly severe in the Boundary Peak and Capulin Canyon areas (Figure 1).

A series of significant thunderstorms during the summer monsoon season of 1996 affected the headwaters of the three primary drainage basins in Capulin Canyon. These storms produced remarkably distinct responses from the hillslopes and channels of each of the basins shown in Figure 1. Of the three primary basins, the Capulin Creek basin experienced severe flooding (including significant erosion and sediment transport), the North Tributary basin produced at least one debris flow, and the South Tributary basin produced only minor surface runoff.

Although a number of workers have described physical conditions that affect erosion after wildfires, work by Spittler (1995) in southern California and Wohl and Pearthree (1991) in the Huachuca Mountains of southeastern Arizona identified a number of geologic and geomorphic factors that indicate a susceptibility

Table I. Geologic unit, fire intensity, hillslope gradient at site, needle cast and condition of fibrous root mat at field sites

Site	Geologic unit	Fire intensity	Slope (%)	Needle cast	Root mat condition
1	Quaternary landslide El Cajete pumice mantle	moderate	58	sparse	not observed
2	Quaternary landslide El Cajete pumice mantle	low	19	sparse	not observed
3	Quaternary landslide El Cajete pumice mantle	high	18	none	not observed
4	Quaternary landslide El Cajete pumice mantle	high	38	none	intact
5	Quaternary landslide El Cajete pumice mantle	high	53	very sparse	not observed
6	Quaternary landslide El Cajete pumice mantle	low	44	moderate	not observed
7	Quaternary landslide El Cajete pumice mantle	moderate	53	sparse	not observed
8	Quaternary landslide El Cajete pumice mantle	moderate	38	none	intact
9	Upper Bandelier Tuff	low	30	moderate	intact
10	Middle Santa Fe Group	high	42	none	intact
11	Canovas Canyon Tuff	high	44	not observed	intact
12	Paliza Canyon Fm	high	55	none	intact
13	Paliza Canyon Fm pumice mantle	high	34	not observed	intact
14	Paliza Canyon Fm pumice mantle	high	27	none	intact
15	Paliza Canyon Fm	moderate	44	none	not observed

specifically to post-fire debris-flow activity. Although Spittler (1995) and Wohl and Pearthree (1991) did not attempt to quantify the relative influence of the factors they identified on debris-flow occurrence, work by Meyer and Wells (1997) in Yellowstone National Park concluded that steep basins less than about 2 km^2 typically produced debris flows, whereas larger basins produced floods.

By consolidating the factors suggested by Spittler (1995) and Wohl and Pearthree (1991), we created the following list of parameters that, given an appropriate rainstorm, might either influence the occurrence of debris flow following wildfire or indicate that debris flows are possible:

- the intensity and continuity of the burn mosaic;
- the condition of the riparian vegetation;
- the presence of water-repellent soils;
- the condition of the fibrous root mat in hillslope soils;
- accumulations of dry-ravel and colluvial material mantling steep slopes and infilling tributary channels;
- drainage basin morphology (including basin area and gradient, channel gradient, and hillslope inclination, length and roughness);
- drainage basin lithology, and thickness, extent and characteristics of slope-mantling soils;
- evidence of past debris-flow activity.

In this study, the conditions that appear to be most important in determining a debris-flow response for Capulin Canyon are distinguished by comparing the distinct responses of each of the three drainage basins to the geologic and geomorphic factors identified above.

METHODS

To determine qualitatively the relative importance of the factors presented above on sediment movement on hillslopes and the generation of debris flows as a result of the Dome fire, observations were made throughout the Capulin Creek drainage basin and the North and South Tributary basins. Where appropriate, the conditions listed above were evaluated at 15 sites (Figure 1, Tables I and II). Although the sites were selected to characterize the effect of varying fire intensities, rock, soil and vegetation types, and slope conditions, the small number of sites and large variation in these conditions precludes more than a comparative and qualitative evaluation of their effects.

A map of fire intensity generated by the US Forest Service from 1:12 000-scale aerial photography taken after the fire (R. Cassidy, USFS, written communication 1996) was used to evaluate relations between fire

Table II. Rock cover, ash and soil characteristics, water repellency, and summary of effects of 26 June 1996 storm at field sites

Site	Rock cover		Ash and soil characteristics		Water repellency	Summary of storm effects
	Coverage (%)	Diameter	Depth (cm)	Material		
1	20–90		0–3	grey ash	none	Rilling in areas without rock cover, length controlled by presence of rocky patches
			3+	clayey silt	none	
2	not observed		0–3	black ash	none	No rilling or sheetwash
			3+	silty sand	none	
3	pumice blanket		0–3	black ash and pumice	none	Abundant rills averaging 20 cm wide, 3 cm deep through ash and pumice layer
			3–6	brown silt	none	
			6–10	tan silt	present, not continuous	
			10+	brown silt	none	
4	pumice blanket		0–3	black ash, charcoal and pumice	none	Some rilling, averaging 12 cm wide and 2 cm deep
			3–11	brown silt with pumice fragments	present, not continuous	
			11+	tan silt with pumice fragments	none	
5	90	up to 25 cm			none	Sheetwash removed all ash and charcoal fragments less than 1 cm in diameter
6	30	up to 20 cm	0–2	ash	none	Some sheetwash slightly displaced pine needles
			2+	silt with pumice fragments	none	
7	5	up to 20 cm	0–3	ash, charcoal and pumice	none	Approx. 80% of ash layer removed by rilling and sheetwash. Rills average 2 cm deep
			3+	silt with pumice fragments	none	
8	not observed		0–2	black ash, charcoal and pumice	none	Abundant rills averaging 2 cm deep. Approx. 60% of pumice and 100% of burned litter removed by sheetwash
			2+	brown silt with pumice fragments	none	
9	none		0–2	ash and pumice	none	One rill, 5 cm wide
			2–4	tan silt with pumice fragments	present, not continuous	
			4+	brown silt with pumice fragments	none	
10	none		0–3	ash, charcoal and pumice	none	Abundant rilling averaging 5 cm wide
			3–5	silt with pumice fragments	present, not continuous	
			5+	silt with pumice fragments	none	
11	80	up to 30 cm	0–4	ash and charcoal	none	All ash and charcoal less than 2 cm in diameter removed by sheetwash
			4+	brown silt	none	
12	80	up to 50 cm	0–1	gray ash	none	Material up to 50 cm in diameter moved short distances downslope
			1+	brown silt	none	
13	90	up to 50 cm	0–1	black ash and charcoal	none	All ash and charcoal removed by sheetwash. No rilling
			1+	tan silt	none	
14	not observed		0–2	black ash, charcoal and pumice	none	Rills averaging 20 cm wide and 3 cm deep eroded through surficial layer of ash and charcoal
			2–6	tan silt with pumice fragments	none	
			6+	brown silt with pumice fragments	none	
15	not observed		0–5	ash, charcoal, needle fragments	none	Abundant rills through ash layers, averaging 5 cm wide and 4 cm deep

Figure 2. Photograph of hillslope in Capulin Canyon showing complete tree mortality and total consumption of tree needles and ground-covering vegetation and soil duff typical of high-intensity fire

intensity and hillslope erosion, to quantify the areal extent of the burned area, and to assess the condition of the riparian, or streamside, vegetation. Tree mortality of 100 per cent and total consumption of tree needles and ground cover characterize areas mapped as high fire intensity. Figure 2 shows an area of high-intensity fire in Capulin Canyon. Moderate fire intensity is characterized by 80 to 100 per cent tree mortality, but scorched needles remained on most of the trees. The duff and needle layer was generally intact. Areas mapped as light burn intensity experienced generally less than 20 per cent tree mortality, and duff and older needle cast remain intact. Note that a considerable gap exists between the light and moderate designations in percentage tree mortality in the study area. This gap reflects the character of the Dome fire, which tended to be either a light ground fire with little tree mortality, or a crown fire with nearly total tree mortality. In addition, in aerial photographs crown-fire effects appear as very high-intensity burns, and although crown fires are very hot in the tops of trees, the ground does not necessarily experience these high temperatures. Thus, this map might not be entirely representative of conditions on the ground. When supplemented with field observations, however, it is the best tool available.

Erosion following wildfires is often attributed to the development, or enhancement, of a water-repellent layer in the soil by the fire (e.g. DeBano and Letey, 1969; DeBano, 1980; Wells, 1987; Morris and Moses, 1987; Robichaud, 1996). The presence and distribution of water-repellent soils in the area of the Dome fire was evaluated by digging small pits with clean, inclined sides. 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 one minute. Where water-repellent material was found, its lateral extent was evaluated by dripping more water on either side within the pit. In addition, a minimum of three other nearby pits were dug to determine if the layer was laterally continuous.

Measures of drainage basin morphology, including basin area and slope, channel gradient, and hillslope inclination, length and roughness, were determined from 1:24 000 scale topographic maps of the area and field measurements and observations. Drainage basin lithology was determined from 1:24 000 scale mapping by Goff *et al.* (1990) and 1:125 000 scale mapping by Smith *et al.* (1970).

SETTING

The Capulin Canyon watershed (Figure 1) is about 51 km^2 in area, about 22 km long, and ranges in elevation from about 1628 to 2652 m. From its headwaters to approximately 1 km east of the boundary between Santa

Table III. Drainage basin characteristics for Capulin Creek, North and South Tributaries, including area, height, slope, ruggedness and burn intensities. Average gradient is calculated from basin height and length measured from the drainage outlet along length of the longest channel extended to the drainage divide. Ruggedness is calculated from Melton (1965) as basin height divided by the square root of basin area

Drainage basin	Total area (km^2)	Height (m)	Average gradient (%)	Ruggedness	High fire intensity (%)	Moderate fire intensity (%)	Light fire intensity (%)
Capulin Creek	39·9	1024	5	0·16	18	18	10
North Tributary	6·0	732	12	0·30	20	2	10
South Tributary	5·1	575	12	0·26	1	2	0·4

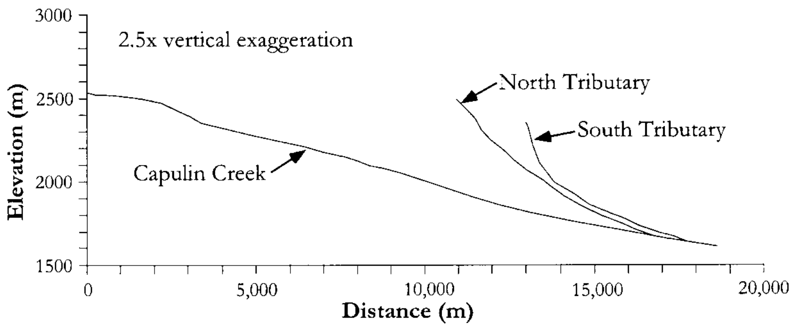

Figure 3. Channel profiles of Capulin Creek drainage and North and South Tributaries constructed from 1:24 000 scale topographic maps with 20 foot contours. Origination point is drainage divide of Capulin Creek, and end point is near Painted Cave (Figure 1)

Fe National Forest and Bandelier National Monument (Figure 1), Capulin Creek flows in a narrow canyon bounded by nearly vertical walls. Downstream from this point, the canyon widens into a broad, flat alluvial valley. The watershed can be divided into three primary basins: the Capulin Creek drainage basin, and the North and South Tributaries (Figure 1). The Capulin Creek basin drains an area of approximately 40 km^2 (Table III) and has a nearly constant gradient of about 5 per cent (Figure 3). The North and South Tributaries drain the steep terrain south of Boundary Peak and St Peters Dome, and join Capulin Creek where the canyon is no longer tightly confined by the canyon walls. The North Tributary drains an area of 6·0 km^2 at gradients between 7 and 18 per cent and an average gradient of 12 per cent (Table III, Figure 3). The South Tributary drains an area of 5·1 km^2 at gradients from between 7 and 35 per cent and an average gradient of 12 per cent (Table III, Figure 3). In contrast with the profile of Capulin Creek, which has a fairly constant gradient over its length, the headwaters of the two tributaries are relatively steep and decline markedly downstream. Hillslope gradients in the headwaters of the tributary drainages of up to 60 per cent are common.

Capulin Creek and its tributaries are incised into a series of horizontal to gently dipping Cenozoic volcanic and sedimentary rocks that make up the Pajarito Plateau and the adjacent San Miguel Mountains. Principal units, from oldest to youngest, include sedimentary rocks of the Eocene Galisteo Formation, sandstones and siltstones of the Miocene Santa Fe Group, the Canovas Canyon Rhyolite and Tuffs, volcaniclastic rocks of the Cochiti Formation, volcanic rocks of the Paliza Canyon Formation, and the Lower and Upper Members of the Bandelier Tuff (Goff *et al.*, 1990; Smith *et al.*, 1970). The Upper Member of the Bandelier Tuff makes up the steep cliffs that bound Capulin Canyon, while the Lower Member is exposed in the base of the canyon. In addition, the El Cajete pumice mantles portions of the hillslopes above the canyon.

Mean annual precipitation at the Bandelier National Monument weather station (approximately 6 km east of Capulin Canyon) is 40·7 cm (Allen, 1989). The period from late April to the end of June is usually dry, followed by the onset of the summer monsoon season. Sixty per cent of the annual precipitation falls in June to September, with thunderstorms reported for 58 per cent of the days in July and August. During the rest of the year precipitation is generally associated with the passage of frontal storms and tends to be less intense (Bowen, 1990).

Much of the Dome fire was a stand-replacing crown fire of an extent and intensity unprecedented in the watershed in the previous 330 years. Between 1664 and 1893 major surface fires swept Capulin Canyon on an average of about every seven years; these fires were generally of low intensity, and kept fuel loads relatively low (Touchan *et al.*, 1996). After 1893 the fire frequency decreased and fuel loads increased associated first with widespread grazing, which reduced the grassy fuels through which most fires spread, and later with active fire suppression (Allen, 1989; Swetnam and Baisan, 1996; Touchan *et al.*, 1996).

CHANNEL AND HILLSLOPE RESPONSE TO 1996 STORMS

The summer rainfall in 1996 occurred as a series of thunderstorms concentrated in the headwaters of the drainage basins. Unfortunately, a recording rain gauge was not installed at Instrument Site 1 (Figure 1) until 23 August 1996, so the rainfall totals from storms prior to this date are not known. However, a retired US. Forest Service hydrologist and teams of archaeologists camping at the Base Camp cabin and near the junction of Capulin Canyon and the Rio Grande (Figure 1) observed the locations and effects of a thunderstorm on 26 June 1996 and of a series of thunderstorms during 19–24 August 1996 (E. Ruby, personal communication, June and August 1996). The authors made additional observations of the hillslope and channel response during field visits in early July, mid-August and mid-November of 1996.

Although the exact rainfall conditions that led to the varying responses of the basins are not known, the observations by Mr Ruby and the archaeologists indicate that all three drainages experienced severe thunderstorms at some time during the monsoon season. In fact, little rainfall is necessary to erode material from burned areas; Booker (1998) describes significant hillslope erosion in small, steep, zero-order basins triggered by rainfall intensities of just 25 mm per hour for durations as short as 15 minutes. Based on the descriptions of rainfall by Mr Ruby and the archaeologists, we assume that the headwaters of each basin experienced at least this rainfall intensity and duration either during the 26 June storm or the August storm series.

26 June 1996 storm

The effects of the June thunderstorm on the hillslopes of Capulin Canyon were most severe in the headwaters of the Capulin Creek drainage basin and the North Tributary (Figure 1). In the late afternoon of 26 June, Mr Ruby observed dark thunderclouds concentrated at the head of Capulin Canyon, where it appeared to be raining. There were only isolated raindrops falling at the Base Camp cabin (Figure 1). About dusk, a surge of water approximately 2 m deep travelled through the stream channel approximately 3 m from the cabin; the flow barely overtopped the channel bank and ran up to the cabin door. Peak discharge for this event was estimated to be 76 to 103 $m^3 s^{-1}$ (J. Veenhuis, unpublished data). The regional area–discharge relations of Waltemeyer (1996) indicate that the magnitude of the 26 June flood was similar to an estimated 100-year recurrence interval discharge.

A visit by the authors in early July of 1996 revealed that in the Capulin Canyon basin floodwaters mobilized large volumes of previously stored coarse sediment along the channel, locally exposing erodible bedrock beneath the streambed and triggering rapid incision. Boulders up to 1·5 m in diameter were moved by the floodwaters, and stream bank undercutting toppled trees, some of which were estimated by Mr Ruby to be more than 200 years old. In many places the floodwaters exceeded the capacity of the pre-flood channel, and either established new channels or spread onto the broad, flat canyon floor. The flood left debris dams of tree limbs and trunks jammed with boulders and sediment, and thick deposits of stratified sand and gravel locally covering the canyon floor. A sample of the less than about 30 mm sized material is classified as a poorly graded sandy gravel with little or no fines, or GP, using the Unified Soil Classification System (Craig, 1987).

The easternmost evidence of surface flow generated in tributary drainages by this storm was observed in the tributary to Capulin Creek shown as location A on Figure 1. The flow was at most 1 m wide, and 10 cm high debris lines consisting of rafted ash, charcoal, pumice fragments and pine needles marked its lateral extent.

Of the hillslopes examined throughout the Capulin Creek drainage basin, those mantled by the El Cajete pumice showed the most pronounced erosive response to the June 1996 thunderstorm (Tables I and II). Based

Figure 4. Photograph of rills developed on hillslope following 26 June 1996 rainstorm. Rills were up to 4 cm deep and 20 cm wide, with generally flat bottoms. Water bottle in centre of photograph is 20 cm long

on field observations, we conclude that the primary response of these hillslopes was considerable overland flow. Low-density pumice, ash, charcoal, pine needles and some burned mineral soil were rafted down the hillslopes and draws by this process. In some places rilling to depths of at most 4 cm and widths of 15 cm stripped the burned soil and ash from the hillslope (Figure 4). Rills started high on the hillslopes. Their frequency, depth and width were extremely variable, apparently depending on slope, materials and distance downslope. When surface water flow passed through an area mantled by abundant pine needles or by loose, gravel-sized pumice fragments, these materials could be incorporated, resulting in the formation of levees lining the rills (Figure 5). The levees were at most 50 cm wide and were composed primarily of pine needles, pumice gravel and charcoal fragments, with some fine-grained wood ash. Field textural characterization indicated the presence of very little silty matrix in the levees. The low-density pine needles and pumice gravel appear to have been rafted along the surface of the flows, rather than being incorporated into a single-phase slurry. The levee deposits may thus represent concentrations of floating materials that were pushed aside or stranded along the rills by more dilute flows. The passage of the surface water flows only cleared a path of loose, low-density materials, with no incision into the base. All observed paths left by these flows stopped at the change in slope at the base of hillsides.

In contrast with the Capulin Creek basin, the North Tributary basin produced at least one debris flow in the June 1996 storm, with discontinuous deposits observed both near the confluence of the tributary with Capulin Canyon and 400 m up the tributary. The deposit near the confluence consisted of a dark brown mud plaster on light-coloured pumice outcrops lining the channel (Figure 6). The plaster was not more than 1 cm thick and contained abundant charcoal fragments, indicating that material was contributed from the burned hillslopes. The upper mud line was approximately 2 m above the channel bottom and a mud splash line 1·5 m above the ground surface was observed on a tree on the right channel bank. The debris-flow plaster was not continuous,

Figure 5. Photograph of levee-lined rills generated on hillslopes during the 26 June 1996 rainstorm. Levees are up to 15 cm high, and consist primarily of low-density pine needles, pumice and charcoal fragments, with some fine-grained wood ash

as it had apparently been preferentially washed off smooth rock surfaces by subsequent floodwaters, either during the same event or later. The debris-flow deposits observed farther up the tributary were at most 70 cm thick, and consisted of material up to 60 cm in diameter in abundant dark brown, silty-sand matrix. A sample of this material can be classified as either a silty sand (SM) or a clayey sand (SC) using the Unified Soil Classification (Craig, 1987); plasticity characteristics are unknown. Abundant large voids, as well as pine needles, were observed within the deposits. The deposit surface was nearly flat and had been washed, either by recessional flow or later flood events, leaving a fine sand lag on the surface. No evidence of this debris-flow deposit could be found along Capulin Creek itself, presumably because of dilution or erosion by the high floodwaters.

The hillslopes of the North Tributary basin showed evidence of significant overland flow and erosion. In the headwaters, sheetwash was generated of sufficient energy to strip all ash and charcoal fragments smaller than 4 cm and erode the mineral soil to 5 cm depth, and to move materials up to 50 cm in diameter downslope (Table II). No discrete soil-slip or landslide scars were observed on the hillslopes of the North Tributary basin. Field observations indicated that only a few sections of the North Tributary channel-bank material were incised, and the incisions were not more than 0·5 m deep and 0·3 m wide. Bedrock was not observed in the base of the channel. It was not possible to discern how much incision occurred during the June rainstorm, as the pre-storm channel configuration was not observed.

The lack of discrete source areas on the hillslopes, the extensive erosion of surficial material in the headwaters, and the paucity of significant channel erosion, suggest that the debris flow in the North Tributary from the June 1996 storm initiated through a process of progressive sediment entrainment of surface flows with material eroded primarily from the hillslopes and with a slight contribution from the channels. This process is similar to that described following wildfires at Big Sur, Monterey County, California (Johnson, 1984), Storm King Mountain in Colorado (Cannon, 1999) and in Yellowstone National Park (Meyer and Wells, 1997), with the important distinction that in Yellowstone a significant proportion of the debris-flow deposits was derived from erosion of channel material.

Figure 6. Photograph of dark brown debris-flow plaster generated during the 26 June 1996 storm deposited on light-coloured pumice outcrops in the North Tributary basin

In the South Tributary to Capulin Creek, high water marks within the channel were observed, indicating slight surface water flooding in response to the June 1996 storm. No significant erosion was observed on the hillslopes. This is expected, as the June storm appeared to be concentrated at the headwaters of the Capulin Creek drainage and the North Tributary.

19–25 August 1996 storm sequence

The effects of the August storm sequence were observed by Mr Ruby and teams of archaeologists camping at Base Camp and at the confluence of Capulin Canyon with the Rio Grande (Figure 1). These observers described dark rain clouds at the head of the Capulin Canyon in addition to the cloud cover over their camps. These observations indicate that in addition to impacting the headwaters of the Capulin Creek drainage and the North Tributary, these storms also affected the South Tributary. Flood crests of 45 cm on 20 August and 94 cm on 22 August 1996 were measured by the archaeologists at a staff gauge near the Base Camp cabin. The flood of 25 August was visually estimated to be 2 m deep at the confluence camp and 3 m deep at Base Camp. The floodwaters were partially bulked with ash, charcoal and sediment. Peak discharges of 24 to 86 m^3 s^{-1} were estimated from crest stage gauges during this period. (J. Veenhuis, unpublished data), although observations by Mr Ruby (personal communication August 1996) indicate that the effects of these events in Capulin Canyon were more severe than those from the June event.

Remainder of the 1996 monsoon season

For the balance of the 1996 monsoon season, the rain gauge installed at Instrument Site 1 on 23 August 1996 recorded accumulations of 5·33 mm of rainfall on 27 August in about an hour, 28·96 mm from 12 to 15

September, 6·86 mm on 18 September and 42·16 mm over an 18·5 hour period on 3 and 4 October. Although no one was in the canyon to observe the effects of these storms, a visit in mid-November by the authors revealed that up to 2 m of incision had occurred in places in Capulin Canyon during the period. Some reaches that had experienced deposition during the June storm were scoured to bedrock, and other reaches showed considerable deposits primarily of sand, ash and charcoal. Boulder and cobble-sized material had moved, and additional large trees had been uprooted, by the high-energy flooding.

During the mid-November visit, no evidence of significant hillslope or channel response to these storms was observed in the South Tributary. No debris flows, additional significant deepening or widening of rills or further hillslope erosion was observed in the Capulin Canyon or North Tributary basins.

We attribute the lack of subsequent debris-flow response from the North tributary to decreased sediment availability, enhanced surface runoff, and the establishment of an effective runoff transport network during the June rainstorm. Field observations indicate that rilling and sheetwash in the June event removed the loose, unconsolidated burned soil and ash from the more compact, less erodible mineral soil, and that the initial debris-flow pulse in the North Tributary entrained any readily erodible material. Further, during the June event, the existing drainage network was expanded through the development of an extensive rill network on the hillslopes. This network effectively conveyed runoff through the system, and incorporated readily erodible material in sufficient proportion to generate debris flows. In the subsequent runoff events, considerably smaller amounts of sediment were available for entrainment relative to enhanced runoff amounts, and debris flows were not produced.

INFLUENCE OF GEOLOGIC AND GEOMORPHIC FACTORS

Fire intensity and extent of the burned area

In general, areas affected by high-intensity fires are considered to be at a high erosive risk; removal of the vegetation by wildfire results in decreased rainfall interception and infiltration, resulting in increased surface runoff, and possibly accelerated erosion of hillslopes (e.g. Swanson, 1981; Spittler, 1995). High-intensity fires are also conducive to the development of water repellency in the soil and generation of dry-ravel materials. High-intensity fires also result in more thorough removal of ground-covering vegetation, the organic duff layer, riparian vegetation, and fibrous root-mat material than do low-intensity fires.

The effects of fire intensity on subsequent sediment movement on hillslopes were evaluated at each of the 15 field sites in Capulin Canyon and its tributaries (Figure 1, Tables I and II). In general, areas of low fire intensity (sites 2, 6 and 9) exhibited very little sediment movement following the June 1996 rainstorm. One effect of low-intensity fire was simply to scorch the needles on the ponderosa pines; following the fire, these needles dropped, and could provide a mulch protection to the underlying soil. At most sites the layer of pine needles mantling the surface was only slightly disturbed by surface runoff from the June storm, although on steeper slopes, the needles were rafted from the hillslope by surface runoff.

Of the four moderate-fire-intensity sites (sites 1, 7, 8 and 15), two exhibited abundant rills up to 5 cm wide and 4 cm deep and the removal of approximately 60 per cent of the blackened surface pumice, indicating that even moderately burned areas are susceptible to considerable erosion or sediment movement. The other two sites showed only slight rill development in areas not mantled by stones.

The sites that experienced a high fire intensity (sites 3, 4, 5, 10, 11, 12, 13 and 14) showed a variety of erosive responses, from sheetwash removal of all ash and charcoal fragments less than 4 cm diameter, to abundant rills that extended through the ash and burned pumice. The most pronounced erosive response was from intensely burned areas in the North Tributary, where mineral soil and ash were stripped from the hillslopes to depths of 5 cm, and overland flow moved materials as large as 50 cm in diameter downslope.

The areal extent of the burned area can determine potential areas of hillslope erosion. A spatially extensive high- and moderate-intensity burned area will produce considerably more material than an area that has been spottily burned by a low-intensity fire. Table III shows the areas of varying fire intensities experienced by the Capulin Creek basin and the North and South Tributary basins. Twenty-two per cent of the North Tributary basin was burned at high or moderate intensity, while 36 per cent of the Capulin Creek basin experienced high or moderate intensities. Only 3 per cent of the South Tributary basin experienced these burn intensities.

Although the Capulin Creek drainage experienced extensive high and moderate burn intensities, it was the steep slopes of the North Tributary that produced the debris flow (Table IV). The relatively small area of burn in the South Tributary appears to have determined the lack of sediment yield and flooding from this basin.

Condition of riparian vegetation

Immediate impacts of fires along channels include the loss of buffering for sediment flux off hillslopes, a decrease in channel hydraulic roughness, and consumption of woody debris jams along channels which can result in the release of stored sediment. A longer-term impact is the loss of root strength anchoring bank sediment.

Over a length of approximately 22 km, approximately 16 per cent of the riparian vegetation in the Capulin Creek drainage experienced high and moderate fire intensities, and 30 per cent was affected by light intensity burn (Figure 1). The fire did not impact riparian vegetation along the North and South Tributaries.

Although the riparian vegetation was intact along the North Tributary, this drainage produced debris flows (Table IV), and flooding was the dominant response of the Capulin Creek drainage, where 16 per cent of the channel experienced high and moderate burn intensities. Based on these limited events, the condition of riparian vegetation does not appear to be a significant factor in separating the debris-flow-producing drainage basin from the drainage basin that produced only flooding.

Water-repellent soils

Water-repellent soils were observed at only four of the 15 test sites in Capulin Canyon (Table II). Three sites were in areas of high-intensity fire, and one was in an area of low-intensity burn. The water repellency was extremely localized within the soils, and was nowhere laterally continuous. Seven additional sites in high burn intensity areas did not exhibit water repellency.

Severe flooding occurred in the Capulin Canyon drainage and debris flow in the North Tributary without the presence of a significant water-repellent layer in the soil (Table IV). The occurrence of large sedimentation events without the presence of water-repellent soils was also documented following the 1988 wildfires in Yellowstone National Park (Meyer, 1993; Meyer and Wells, 1997).

Condition of fibrous root mat

Destroying the fibrous root mat beneath the surface reduces the effective soil cohesion and can result in accelerated erosion by overland flow. The root mat was observed in July 1996 to be intact even in areas of high fire intensity in Capulin Canyon and its tributaries (Table I). Both debris flows and flooding occurred in Capulin Canyon despite the presence of an intact fibrous root mat.

Accumulations of dry-ravel and colluvial material mantling steep slopes and infilling tributary channels

The process of dry ravel has been observed both following and during fires on steep slopes where loose, non-cohesive material was formerly anchored by vegetation. Dry ravel has been described as an important post-fire process in southern California, where channels are loaded with sediment, increasing available sediment for large events (e.g. Doehring, 1968; Florsheim *et al.*, 1991; Wells, 1987). Cannon *et al.* (1998) described aprons of dry-ravel material mantling hillslopes and lining channels on Storm King Mountain, Colorado; material eroded from theses deposits during a high-intensity rainfall event contributed to destructive debris flows. However, few accumulations of dry-ravel deposits were observed on the hillslopes or within Capulin Canyon or its tributaries. The only dry-ravel material observed was along cuts into the hillslope for trails, where small, 0·3 m high, nearly vertical cuts into hillsides supplied material. These deposits were localized, and on average approximately 0·25 m high, 0·20 m wide, and formed slopes between 20 and 30 per cent. It is significant that debris flows were generated from the North Tributary basin without significant accumulations of dry ravel material.

Wohl and Pearthree (1991) concluded that accumulation of sediment in the upper reaches of channels was probably the limiting control on debris generation flow in the Huachuca Mountains of southeastern Arizona.

Table IV. Summary of geomorphic and geologic factors that can influence debris-flow occurrence in the Capulin Creek drainage, and North and South Tributaries. R is a measure of drainage ruggedness, proposed by Melton (1965) and calculated as $H_bA_b^{-0\cdot5}$. For comparison, the Capulin Creek drainage experienced severe flooding in response to every significant rainfall event of the summer of 1996, the North Tributary produced debris flows during the first significant rainfall, and the South Tributary produced only slight surface flow following the first rainfall event

	Capulin Creek drainage	North Tributary	South Tributary
Burn intensity and continuity of mosaic	36% of drainage experienced high and moderate burn intensities	22% of drainage experienced high and moderate burn intensities	3% of drainage experienced high and moderate burn intensities
Riparian vegetation	16% of channel length burned by high and moderate intensity fire	Intact	Intact
Water-repellent soil	Some, not continuous	Some, not continuous	None
Fibrous root mat	Intact	Intact	Intact
Dry ravel and colluvium accumulations	No significant dry-ravel deposits	No significant dry-ravel deposits	No significant dry-ravel deposits
Drainage basin morphology	$R = 0\cdot16$; channel long, at 5% gradient; long, smooth, gentle hillslopes	$R = 0\cdot30$; channel short, at 12% gradient; rocky, steep hillslopes	$R = 0\cdot26$; channel short, at 12% gradient; rocky, steep slopes
Drainage basin lithology	Upper and Lower Bandelier Tuff, Cochiti, Paliza Canyon Formations, and Quaternary landslide deposits, mantled by thick El Cajete pumice	Lithified lahar and debris-flow deposits – Cochiti Fm; weathered volcanics –Paliza Canyon Fm Thin soils	Lithified lahar and debris-flow deposits – Cochiti Fm; weathered volcanics –Paliza Canyon Fm Thin soils
Past debris-flow activity	Some, no relation with fire history; high-energy flooding dominant response	Some, relation with fire history unknown; high-energy flooding dominant response	Some, relation with fire history unknown

For this study, however, we were not able to assess the pre-storm condition of the channels and thus do not address this issue. In their work, Wohl and Pearthree (1991) described the debris flows as evacuating the tributary channels by eroding to bedrock. Because the debris flows in the North Tributary were not observed to scour extensively, this process may not be particularly significant in the study area.

Drainage basin morphology

The drainage basin morphologies of Capulin Creek and the North and South Tributaries differ considerably, and these differences appear to have had a significant impact on debris-flow production. First, the Capulin Creek basin is considerably larger than the North and South Tributary basins, which are of equivalent size (Table III). The combined influence of basin area and height also shows a considerable disparity. Melton (1965) defined basin ruggedness, R, by the following relation:

$$\mathrm{R} = H_{\mathrm{b}}\, A_{\mathrm{b}}^{-0\cdot5}$$

where A_{b} is basin area and H_{b} is basin height measured from the drainage divide to its outlet. Values of basin ruggedness (Table III) indicate that the North and South Tributary basins are more rugged than the Capulin Creek basin. Melton (1965) and Jackson *et al.* (1987) used R in combination with fan slope to distinguish debris-flow-susceptible alluvial fans. Because neither Capulin Creek nor the two tributaries have produced well defined fans, we use this number only as a relative indication of the combined influence of basin area and height on the generation of debris flows.

Other morphologic characteristics distinguish the Capulin Creek drainage from the North and South Tributaries. Capulin Creek flows over a fairly constant low gradient over a long distance, while the profiles of the North and South Tributaries are short, with steep gradients and very steep headwaters (Figure 3, Table III).

In addition, two distinct types of hillslopes occur in the drainage basins. The slopes within the Capulin Creek drainage that were most susceptible to erosion were mantled by the El Cajete pumice. These hillslopes are gentle (around 25 per cent slope), long and smooth (Tables I and II). In areas of intense and moderate burn, the response of these hillslopes to the summer thunderstorms was abundant overland flow resulting in the generation of rills.

In contrast, the hillslopes in the North and South Tributary basins are generally steeper (up to 60 per cent slope) and very rocky (Tables I and II). In places the slopes are nearly covered by boulders up to 50 cm in diameter. We observed that on steep slopes mantled with more than about 50 per cent cobbles and boulders, concentrated flow, and thus rilling, occurred only in the small patches where the rock cover was absent. In addition, at sites with only sparse cobble coverage, rilling and sheetwash removed nearly all the ash and pumice layer. Thus the cobbles and boulders effectively protected the burned hillslopes from surface erosion as long as the slope was not too steep, or the rainfall too intense. However, even with an extensive rock cover, the steep slopes at the headwaters of the North Tributary were severely eroded by the June thunderstorm (Tables I and II). As described previously, up to 5 cm of mineral soil was removed and up to boulder-sized material moved downslope in this area.

It appears that the rugged drainage basin form coupled with a steep channel gradient and steep, rough hillslopes were conducive to the generation of debris flows from the North Tributary (Table IV). This is in contrast with the less rugged basin, gentler channel gradient and long, smooth hillslopes of the Capulin Creek drainage, which produced significant flooding. Further, the South Tributary basin is very similar to the North Tributary basin in terms of drainage basin roughness, channel gradient and hillslope morphology. Because the mostly unburned South Tributary did not produce debris flows, and presumably received significant rainfall during the August storm series, we conclude that the presence of burned hillslopes in the North Tributary was necessary for the generation of debris flows.

Drainage basin lithology

Differences in geologic materials underlying the three drainages also appear to influence the production of debris flows. The Capulin Creek drainage basin is underlain primarily by the Upper and Lower Bandelier

Tuff, with some exposures of Paliza Canyon Formation andesites and dacites and Cochiti Formation lithified debris-flow and lahar deposits near Boundary Peak. With the exception of the steep cliffs formed by the Upper Bandelier Tuff, these units are extensively mantled by up to 2 m of El Cajete pumice. It was this unit that showed the most pronounced erosive response to the summer thunderstorms in the Capulin Creek basin. Samples of this material were classified using the Unified Soil Classification System as gravelly sands with little or no fines (SW) or as either silty sands (SM) or clayey sands (SC).

Spittler (1995) identified loose, friable, cohesionless material as the most likely to produce debris flows in southern California. Although the El Cajete pumice is, in general, a loose, friable material, and the soil developed on it is, in general, non-cohesive, observations following the summer 1996 thunderstorm season indicate that significant debris-flow activity was not produced in this unit.

The North and South Tributary basins, on the other hand, are developed principally on the dacites and andesites of the Paliza Canyon Formation, indurated lahar and debris-flow deposits of the Cochiti Formation, and the interbedded sandstones and siltstones of the Middle Santa Fe Group and the Galisteo Formations. A thin, rocky, colluvial cover with very thin silty loam soils has developed in places on these units.

Given the production of debris flows from the North Tributary during the summer of 1996 and the severe erosion in the headwaters of the tributary, it appears that the materials most prone to producing debris flows in the area are the colluvium and soils overlying the lithified lahar and debris-flow deposits of the Cochiti Formation, and colluvium and soils weathered from the andesites and dacites of the Paliza Canyon Formation (Table IV). The presence of fine-grained materials in these units, in contrast to the well drained El Cajete pumice, may have affected the generation of debris flows in that fine materials in a slurry maintain excess pore fluid pressures, and enhance the potential mobility of such flows (e.g. Iverson, 1997; Major and Iverson, 1999).

Although other soil properties, particularly porosity, water content, grain-size distribution and bulk density, are thought to influence the erosive response of hillslopes, this study did not address these parameters.

Evidence of past debris-flow activity

The Capulin Creek drainage and its tributaries were examined for evidence of significant past debris-flow activity to determine (1) if the drainage basins are at any time susceptible to debris flow, and (2) if possible, to determine the relation with the fire history of the canyon.

Although most of the high-energy deposits in the Capulin Creek drainage, of which there are many, appear to be unequivocally those of dilute stream flow (i.e. abundant open framework and imbricated boulder and cobble bars that contain very little matrix, or well sorted and stratified deposits of boulders and cobbles in a sandy matrix) (Costa, 1988), possible debris-flow deposits were detected. At location B (Figure 1), a large lobe of boulders and cobbles up to 1 m in diameter in an abundant silty-sand matrix nearly fills the canyon bottom. The lobe is approximately 2 m high, at least 5 m wide, and has steep margins. No imbrication or sorting that would indicate a fluvial origin was observed. Further, no charcoal-rich laminae or deposits or burned material that could indicate the relation of this deposit to the fire history in the canyon were noted. In addition to the lobe of material, a small fan has formed at the mouth of the secondary tributary drainage immediately down channel from location B, and the morphology of a deposit on the right channel bank suggests a set of nested debris-flow levees. The deposits contain boulders up to 50 cm in diameter in abundant matrix material. The nested morphology may also be a result of incision into the fan by the tributary stream. Again, no connection with the occurrence of wildfires could be discerned.

Some indication of the historic response of the watershed to fire events is evident in an incision into a fan surface of the secondary tributary mentioned above (C, Figure 1). This stream cut exhibits a stratigraphy similar to the sediments deposited on the floodplain of Capulin Creek itself during June flooding–lenses of primarily sandy matrix containing cobbles and pebbles, resting on fine sand laminae containing abundant ash and charcoal (Figure 7). Two or three buried soils separate packets of these units, and the stratigraphy suggests a direct relation between the youngest two depositional packets and fires. Specifically, the sediments overlying the upper two buried soils are similar in that they both possess basal laminae of fine sand with abundant charcoal. The charcoal-rich sediments provide evidence for sedimentation events closely following

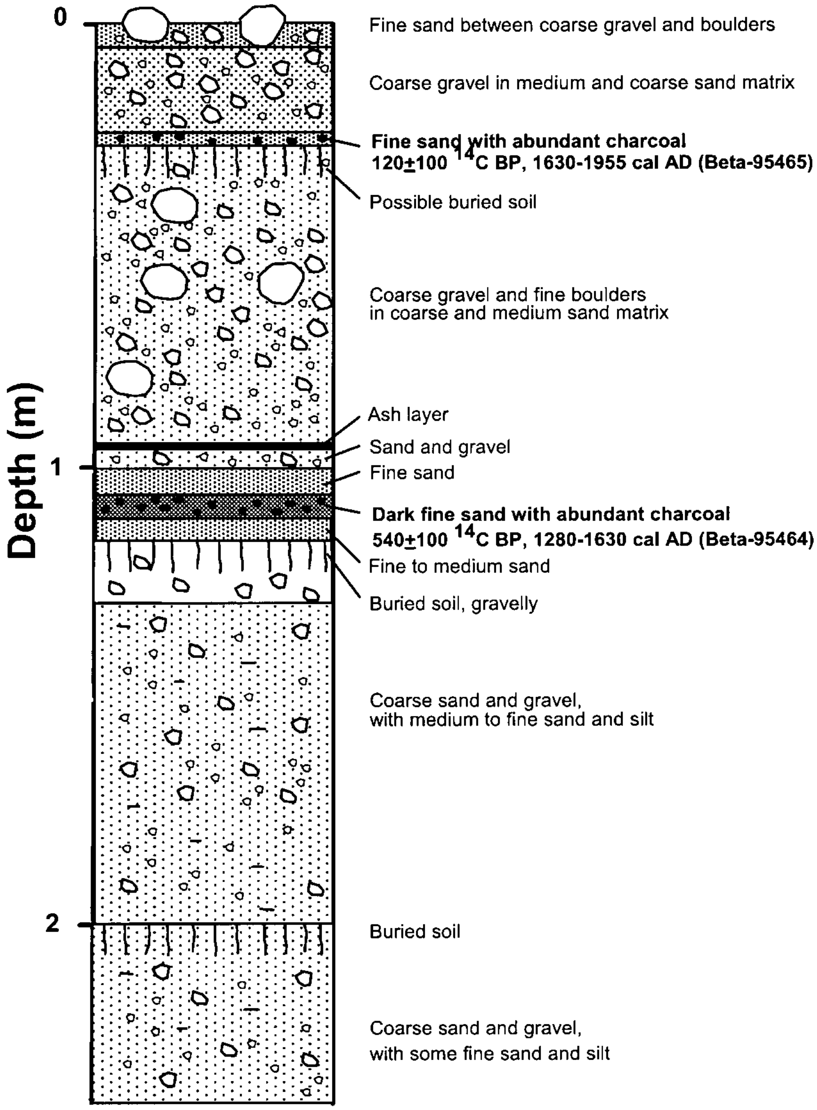

Figure 7. Stratigraphic section through alluvial fan at location C (Figure 1) showing locations of ^{14}C-dated material. Calibrated ages were obtained using CALIB 3·03 (Stuiver and Reimer, 1993), 2-σ uncertainty, and an error multiplier of 1·0

major fires. Radiocarbon dates on charcoal from these sediments indicate that the youngest depositional packet post-dates AD 1630, and that the previous depositional packet dates to AD 1280–1630, providing a general time scale of major depositional events that are probably related to fires in this basin.

The internal stratigraphy of the fan did not indicate a debris-flow response to fires, but rather of sediment-laden streamflow. In addition, the fan surface is covered with abundant openwork boulder and cobble bars, made up of clast-supported and imbricated materials, also suggesting a streamflow origin (Costa, 1988).

Both the North and South Tributaries have deposited a significant amount of material at the junction with Capulin Creek. Although stream cuts show some unsorted and matrix-rich boulder and cobble lenses that could be debris-flow units, the majority of these deposits exhibit the sorting and stratification that indicates a dilute streamflow origin (Costa, 1988). In addition, a series of boulder bars containing boulders up to 1·5 m in diameter, some of which were imbricated, was observed in the North Tributary at the confluence with

Capulin Creek. Although these deposits indicate an event of significant size, a lack of matrix material even deep within the deposit, a lack of associated matrix-rich facies nearby, and the presence of imbrication would indicate that the depositional event was that of a significant flood rather than debris flow.

In conclusion, although there has been significant high-energy flooding in the Capulin Creek basin in the past, large-scale debris flows do not appear to have been widespread. The character of the deposits indicates that the watershed response to fires or to severe meterological events in the past has been primarily as flooding, but not unequivocally debris flow. The lack of a debris-flow response to wildfire might, however, be due to the less intense and extensive character of fires in the last several hundred years, as described by Touchan *et al.* (1996) and Allen *et al.* (1996). The North Tributary also shows evidence of significant flood events, with some occurrence of debris flow. The relation with fire history, however, is not known. Of further interest is the response in canyons north of Capulin Canyon following the 1977 La Mesa fire, reported to have been the largest and most intense fire in the Jemez Mountains this century (Allen *et al.*, 1996). Summer thunderstorms resulted in large flood events in Frijoles Canyon, but debris flows were not described (White, 1981; White and Wells, 1984). This fire was more intense and produced a more continuous burn mosaic than did the Dome fire (C. Allen, USGS, Bandelier National Monument, personal communication, 1996).

SUMMARY AND CONCLUSIONS

Of the three primary drainage basins of Capulin Canyon burned by the April 1996 fire, the Capulin Creek basin responded with severe flooding (including significant erosion and sediment transport) during significant rainfall events of the 1966 monsoon season. Widespread erosive sheetwash and rilling occurred on hillslopes within this basin in response to the first storm of the season. The South Tributary basin showed only minor surface flow from the channel and hillslopes throughout the season. The North Tributary basin produced at least one debris flow in response to the first storm of the season, and the hillslopes exhibited extensive erosion of the mineral soil to a depth of 5 cm and downslope movement of up to boulder sized material.

By comparing these channel and hillslope responses with geologic and geomorphic factors that may indicate a susceptibility specifically to fire-related debris flows, conditions necessary to generate debris flow following wildfire in this area were distinguished. First, the lack of an extensive burn mosaic in the South Tributary basin appears to have determined the scarcity of sediment yield or flooding from this drainage. Only 3 per cent of this drainage basin experienced either moderate or high burn intensities. When contrasted with the more extensive areal extent of the burn in the Capulin Creek drainage basin and the North Tributary basin (36 and 22 per cent, respectively), it appears that the small area of burn determined the negligible response to the summer thunderstorms. Similarities between the drainage basin roughness, channel profile, hillslope ruggedness; and materials of the North and South Tributary basins, and differences in the extent in burn mosaic between the two basins, show that burned hillslopes were necessary to generate debris flow.

When geologic and geomorphic factors are compared for the Capulin Creek drainage basin and the North Tributary basin, it appears that a number of factors had little bearing on the distinctive erosive responses of the basins. Although the Capulin Creek basin experienced the most extensive high and moderate burn mosaic, it was the steep slopes of the North Tributary basin that produced debris flow. Further, although the riparian vegetation was intact along the North Tributary, and 16 per cent of the Capulin Creek drainage experienced high and moderate burn intensities, it was the North Tributary basin that generated debris flow. In addition, severe flooding occurred in the Capulin Canyon basin, and at least one debris flow occurred in the North Tributary basin, without the presence of a significant water-repellent layer in the soil or substantial dry-ravel deposits, and with an intact fibrous root mat. The factors described above may influence the magnitude of erosive events following wildfire, but do not separate the debris-flow-producing drainage from the one that produced flooding.

The factors that best define the difference between the debris-flow and flooding response in the Capulin Creek drainage basin and the North Tributary basin are indicated by the contrasts between drainage basin morphologies and lithologies. Given the production of debris flows from the North Tributary, it appears that the rugged drainage basin morphology ($R = 0{\cdot}30$), coupled with an average 12 per cent channel gradient and steep, rough hillslopes, promoted debris-flow generation from this basin. This is in contrast with the less rugged basin ($R = 0{\cdot}16$), gentler channel gradient (5 per cent) and long, smooth hillslopes of the Capulin Creek drainage, which produced significant flooding. Colluvium and soil weathered from lahar and ancient debris-flow deposits of the Cochiti Formation and from the andesites and dacites of the Paliza Canyon Formation are more likely to produce debris flow than are the loose, friable deposits of the El Cajete pumice.

This study is based on evaluation of a limited number of drainage basins in a specific setting. However, the approach defined here could be useful for evaluating fire-related debris-flow susceptibility in other environments. Similar comparisons of post-fire conditions and responses of a large number of recently burned basins to rainfall events could potentially produce sufficient information to allow for development of models for debris-flow susceptibility from burned basins.

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