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Evaluation of the Potential for Debris and Hyperconcentrated Flows in Capulin Canyon as a Result of the 1996 Dome Fire, Bandelier National Monument , New Mexico

By Susan H. Cannon

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EVALUATION OF THE POTENTIAL FOR DEBRIS AND HYPERCONCENTRATED FLOWS IN CAPULIN CANYON AS A RESULT OF THE 1996 DOME FIRE, BANDELIER NATIONAL MONUMENT, NEW MEXICO

By **Susan H. Cannon**

Abstract. The Dome fire of April 1996 burned 6,684 ha in Bandelier National Monument and the adjacent Sante Fe National Forest. The potential for significant debris- and hyperconcentrated-flow activity in Capulin Canyon is evaluated through (1) a systematic consideration of geologic and geomorphic factors that characterize the condition of the hillslope materials and channels following the fire, (2) examination of sedimentologic evidence for past debris-flow activity in the canyon, and (3) evaluation of the response of the watershed through the 1996 summer monsoon season. The lack of accumulations of dry-ravel material on the hillslopes or in channels, the absence of a continuous hydrophobic layer, the relatively intact condition of the riparian vegetation and of the fibrous root mat on the hillslopes, and the lack of evidence of widespread past debris- and hyperconcentrated-flow activity, even with evidence of past fires, indicate a low potential for debris-flow activity in Capulin Canyon. In addition, thunderstorms during the summer monsoon of 1996 resulted in abundant surface overland flow on the hillslopes which transported low-density pumice, charcoal, ash and some mineral soil downslope as small-scale and non-erosive debris flows. In some places cobble- and boulder-sized material was moved short distances. A moderate potential for debris- and hyperconcentrated-flow activity is identified for the two major tributary canyons to Capulin Canyon based on evidence of both summer of 1996 and possible historic significant debris-flow activity.

INTRODUCTION

The Dome fire was ignited on April 25, 1996, by a campfire abandoned west of the Dome Wilderness on the Jemez District of the Santa Fe National Forest. Due to 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, and within 2 days had extended eastward into the Bandelier National Monument. The Dome fire burned approximately 6684 ha of federal lands, including 4750 ha administered by the U.S. Forest Service and 1934 ha within Bandelier (fig. 1) (U.S. Department of Interior, 1996). The effects of the fire were particularly severe in the Boundary Peak and Capulin Canyon areas (fig. 2).

The connection between forest fires and major sedimentation events has been recognized for some time, particularly in southern California where the concept of "fire-flood sequences" was first defined (for example, Kotak and Kraebel, 1935). Conditions at Bandelier National Monument immediately after the fire were evaluated by the Burned Area Emergency Rehabilitation (BAER) Team; their report identified the potential for debris flows in Capulin Canyon within the Monument, and recommended further evaluation (U.S. Department of Interior, 1996).

Debris-flow susceptibility in a burned watershed depends on the condition of the hillslope materials and channel following the fire, and, most importantly, subsequent rainfall events. Geologic and geomorphic factors that have been identified as contributing to post-fire debris-flow activity are (modified from Spittler and others, 1994):

- Friable bedrock units and cohesionless soils
- Long, smooth and regular slopes inclined more steeply than 65% and denuded of ground-covering vegetation
- Concentrations of dry-ravel material mantling steep slopes and infilling tributary channels
- The development of a continuous layer of water-repellent soil
- The removal of riparian vegetation in or next to stream channels
- A destroyed fibrous root mat
- A continuous burn mosaic

The presence of these factors, given an appropriate rainstorm, can indicate a high susceptibility to debris flow. Note that the relative importance of each of the factors is unknown, and methods to quantitatively evaluate their possible effects have not been explored. To assess the potential for debris flow as a result of the Dome fire, these conditions were described and qualitatively evaluated at 15 sites in Capulin Canyon (fig. 3, app. A). The sites were located to characterize the effect of varying fire intensities, rock, soil, and vegetation types, and slope conditions. In addition, the occurrence of thunderstorms throughout the summer monsoon season

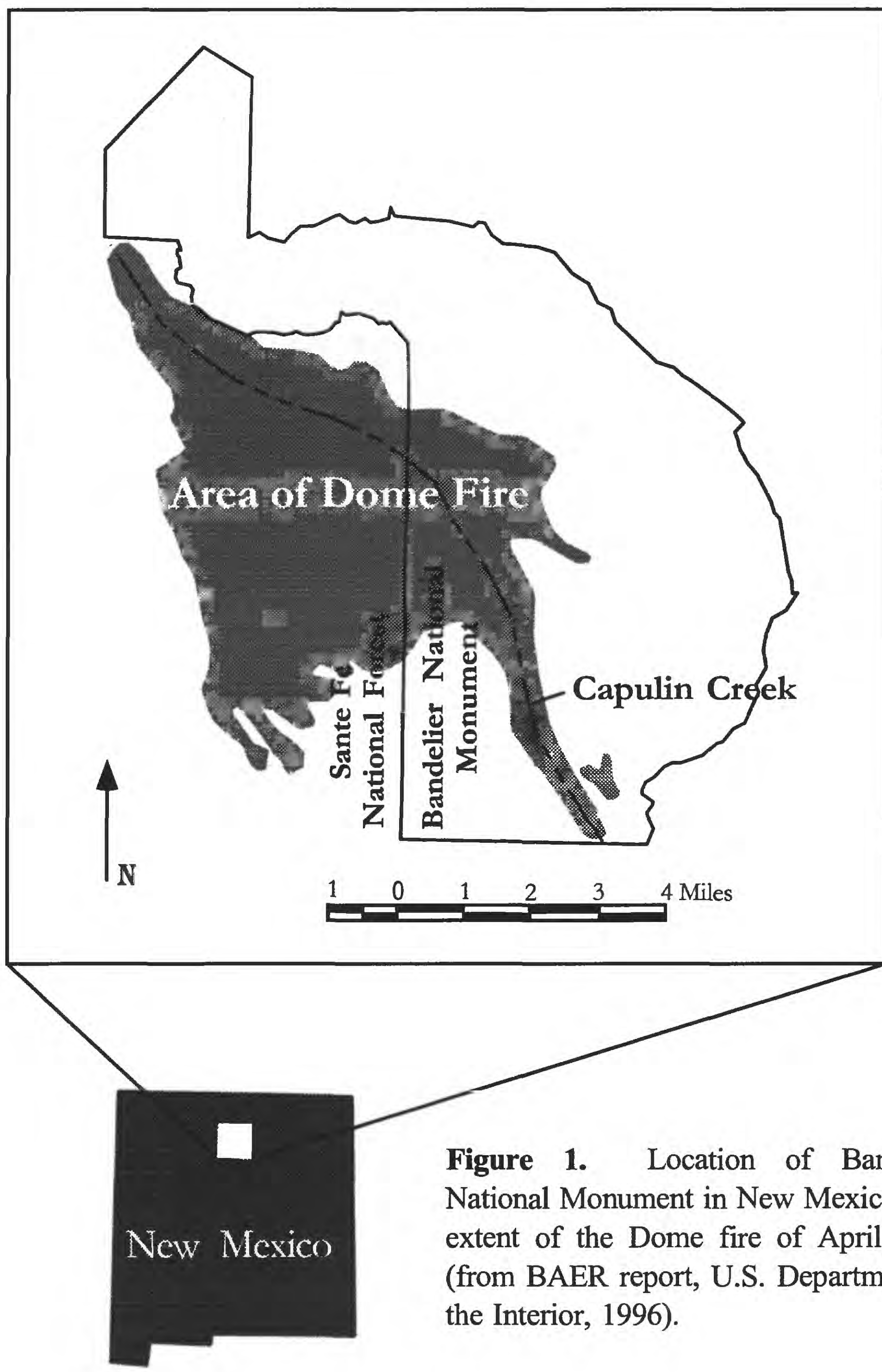

Figure 1. Location of Bandelier National Monument in New Mexico, and extent of the Dome fire of April 1996 (from BAER report, U.S. Department of the Interior, 1996).

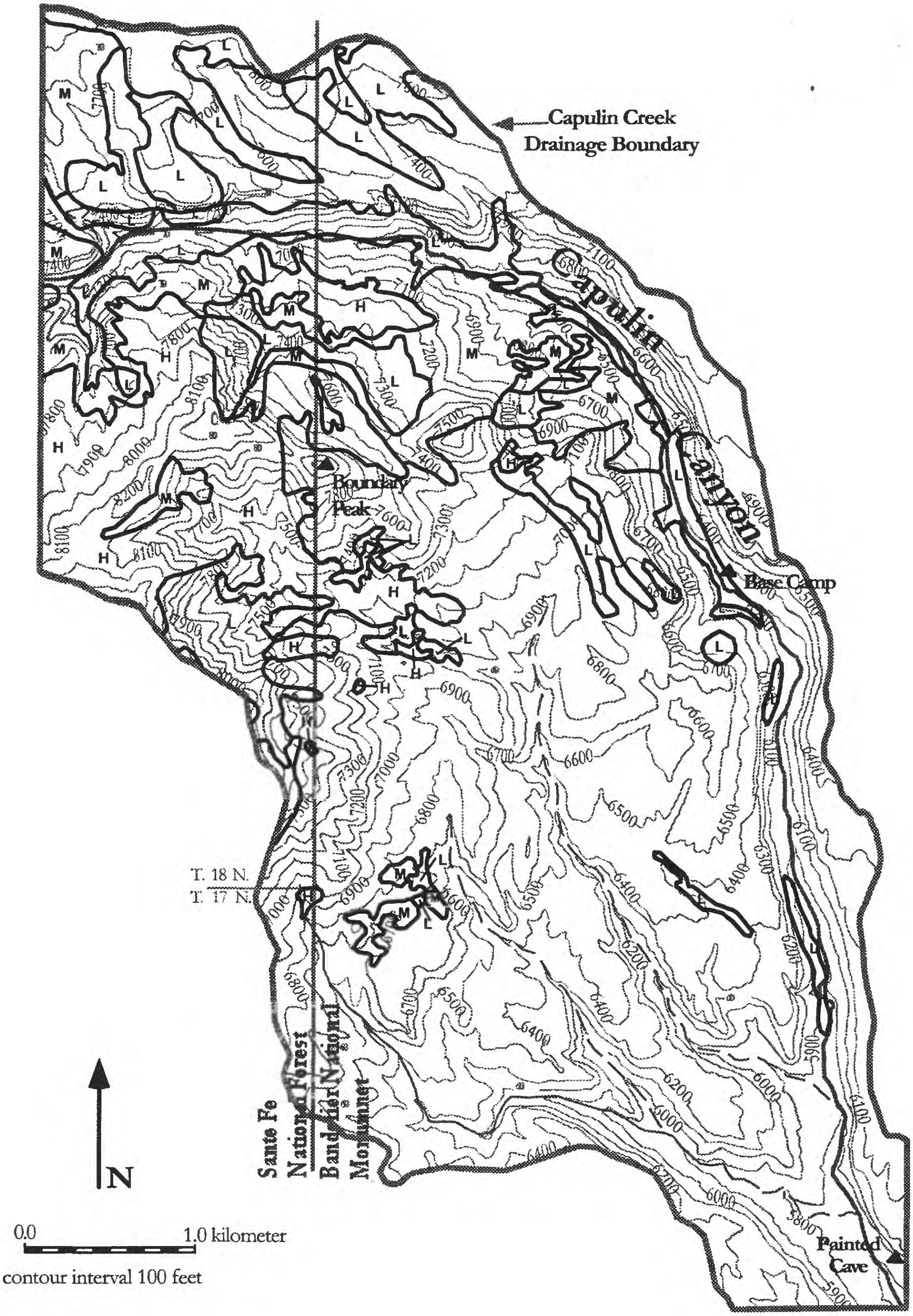

Figure 2. Fire intensity map of portion of Capulin Canyon in Bandelier National Monument. Burn intensity mapped by Regis Cassidy, U.S. Department of Agriculture, Forest Service, for the Dome fire salvage-sale analysis file. Mapping is from 1:12,000-scale color aerial photographs taken after the fire by the U.S. Department of Agriculture. Base from U.S. Geological Survey Frijoles and Cochiti Dam 7.4' quadrangles.

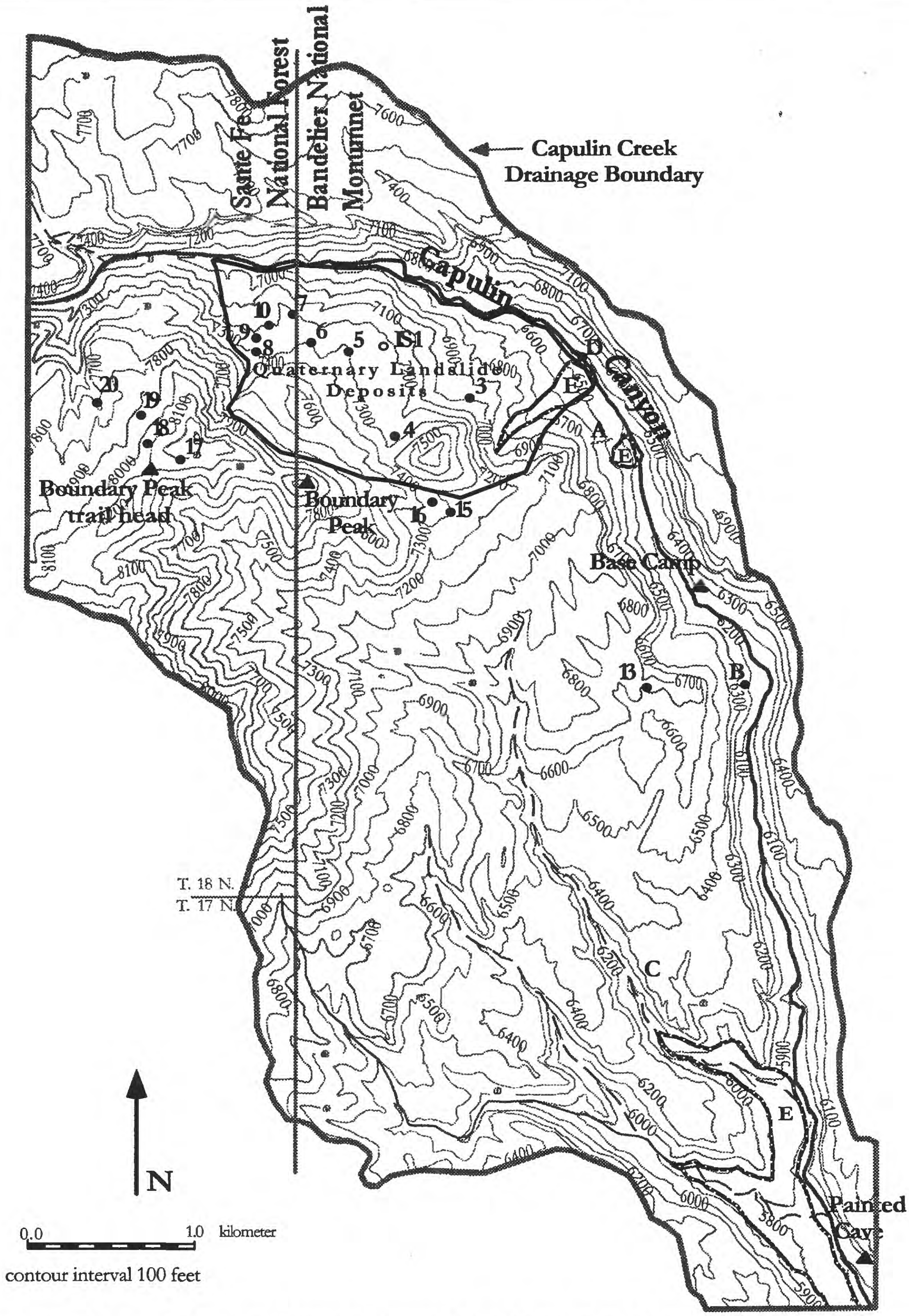

Figure 3. Topographic map of portion of Capulin Canyon in Bandelier National Monument. Locations of sites used to assess hillslope conditions are labeled 1 through 15. Rain gage site is labeled IS-1. Letter A denotes easternmost extent of tributary surface flow generated by the June 26, 1996 storm. Letter B indicates location of summer of 1996 debris-flow deposits that originated in Gallesteo formation colluvium. Letter C marks the location of tributary in which a very fluid debris flow occurred in summer of 1996. Letter D denotes the location of possible old debris-flow deposits on canyon floor. Letter E marks the locations of fan deposits at the mouths of tributaries. The northern-most fan contains dateable charcoal. Base from U.S. Geological Survey Frijoles and Cochiti Dam 7.5' quadrangles.

made it possible to assess the hillslope and channel response to heavy rainfall events. Finally, the Capulin Creek drainage was examined for evidence of past debris-flow activity to determine if conditions in the drainage are anytime conducive for generating debris flow.

This report presents the following items:

- Brief descriptions of the two processes by which debris flows initiate, and the classification system used to define debris-flow processes.
- Descriptions of the geological, ecological and climatological frameworks at Bandelier and of the summer rainfall record, with particular attention to the storm of June 26, 1996, and the storm sequence of August 19-25, 1996.
- Descriptions of the influence of fire intensity and of the geologic and geomorphic factors listed above on the generation of sediment for debris flows in Capulin Canyon, in part evidenced by the hillslope response to the June storm.
- A description of evidence for past debris-flow activity in the canyon.
- Conclusions regarding the potential for the generation of debris flows in Capulin Canyon.
- Recommendations for short-term recreational use and further evaluation, and discussion.

DEBRIS-FLOW INITIATION AND CLASSIFICATION

In general, debris flows can initiate by one of two processes: by landsliding or by sediment bulking of surface water flows. Landsliding occurs as either a rotational slump or a translational slide. The material fails as an intact block and then mobilizes into a muddy slurry, the muddy slurry being the debris flow. With this process, the flow path can then be traced up a channel to a landslide-scar source. This type of initiation is triggered by rainfall infiltration into the slope and failure on a discrete failure plane within the hillslope materials (for example, Campbell, 1975; Cannon, 1988). Sediment bulking occurs when high surface-water flows erode material or incorporate loose material from hillsides or channels; this eventually results in sufficient concentrations of sediment within the flow so that it behaves as a debris flow (for example, Davies and others, 1992; Wells, 1987). This is the process most frequently described following forest fires (for example, Cannon, 1995; Meyer, 1993; Florsheim and others, 1991).

Debris flow is a member of a classification system based on definition of the sediment-water flow continuum (Pierson and Costa, 1987). In this system, each of the flow types defined represents a continuous range of properties within the sediment-water flow continuum, and the different types of flow are distinguished based on ranges of sediment concentration and rheologic behavior. The three major flow types are briefly described below.

Dilute streamflow: Flows in which the sediment load does not affect flow behavior, or imparts no yield strength to the flow, are considered as normal streamflow (Pierson and Costa, 1987). Sediment concentrations up to 50% by volume for mixtures of coarse particles of uniform size and up to 35% by volume for more poorly sorted mixtures impart no yield strength to flowing water (Pierson and Scott, 1985). Turbulence is the primary mechanism for sediment transport in such flows (Smith, 1986). The conditions of sediment transport and deposition are controlled by a complex set of variables, including flow velocity and depth, and channel configuration. Streamflow results in deposits generally associated with flooding and water transport, may range in size from boulders to silt, and generally exhibit a high degree of sorting. High-energy streamflow can result in deposits of open framework boulder and cobble bars that contain very little matrix. These bars occur as high-relief trains of well sorted and often imbricated clasts.

Hyperconcentrated flow: Sediment-water flows in which the concentration, size distribution, and/or composition of the entrained sediment lead to a measurable, but low, yield strengths have been described as hyperconcentrated flow (Pierson and Costa, 1987). Intermediate ranges of sediment concentration and low to moderate silt and clay contents result in generally low yield strengths. Hyperconcentrated flow is usually used to refer to non-Newtonian flows with almost no strength that produce deposits that are intermediate in nature between those of streamflow and debris flow (Smith and Lowe, 1991). Turbulence, particle dispersive forces, and buoyancy all potentially contribute to particle support. Deposition occurs by particles dropping out of the flow as individual grains, and the remaining fluid continues to move.

Hyperconcentrated flow results in deposits with particles in contact with each other (that is, clast supported), and that show some sorting and gradation, depending on the velocity and depth of the flow at the time of deposition. Deposits can exhibit some weak horizontal stratification and poor sorting, but are generally better sorted and have lower silt and clay contents than debris-flow deposits (Wells and Harvey, 1987). Coarser facies can exhibit horizontal clast orientations and partial filling of interstices by sand or silt matrix material.

Debris flow: Debris flow is characterized by a substantial yield strength and plastic behavior, yet a slurry retains at least partially liquid properties (that is, it will spontaneously assume the shape of its container). The onset of debris flow in sediment-water mixtures is defined by Pierson and Costa (1987) to occur at the point where the yield strength increases rapidly with increasing sediment concentration due to internal friction that arises from interlocking of grains. In contrast with hyperconcentrated flow (where the particles are deposited as individual grains from suspension and remaining fluid continues to move), in debris flow the sediment-water mixture moves as a single phase, and only the largest particles may fall out of suspension.

Debris-flow deposits are characterized by significant relief and sharp, well-defined flow boundaries. Levees lining the flow path, or a veneer of mud coating the channel sidewalls, as well as steep, lobate deposits of matrix-supported material at the path terminus are characteristic of this flow process. Debris-flow deposits show little, if any, internal stratification and may contain gravel-sized and larger particles supported in a fine-grained matrix. Although for the entire deposit clay contents may only be a few percent of the overall size-distribution (Costa, 1984), clay-sized material often comprises a significant part of the matrix material (for example, 10-15% of the <2-mm fraction, Wells and Harvey, 1987). Matrix material with a significant silt component (30-35% of <2 mm) can also result in debris flow (Pierson and Costa, 1987). Vesicles formed by trapped air may be abundant in debris-flow matrix, but are rare in fine sediments deposited by other flow processes (Sharp and Nobles, 1953).

The matrix support of larger clasts and significant clay or silt component of the matrix are particularly useful diagnostic characteristics for recent debris-flow deposits. They are, however, less useful in older deposits; matrix material may be lost with time (Costa, 1984; Blair and McPherson, 1992), or interstices can be filled in with less clay-rich material. Further, because debris flows form relatively high relief deposits that fill channels and depressions, and because debris-flow events include later, more dilute flows, debris-flow deposits are prone to reworking by streamflow processes, thus obscuring their debris-flow origin (Costa, 1984; Wells and Harvey, 1987).

GEOLOGICAL, ECOLOGICAL AND CLIMATOLOGICAL FRAMEWORKS

Geology

As much as 400 m of horizontal to slightly dipping Miocene, Pliocene, and lower Quaternary- age rocks make up the sidewalls of Capulin Canyon and the flanks of Boundary Peak. Principal units, from oldest to youngest, include sedimentary rocks of the Eocene Galisteo Formation, sandstones and siltstones of the Miocene Sante 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, and others, 1990). The Lower Member of the Bandelier Tuff, which was erupted from the Jemez volcanic field about 1.6 Ma (Izett and Obradovich, 1994), is exposed in the base of the canyon, while the Upper Member makes up the steep cliffs that bound the canyon. The Upper Member of the Bandelier Tuff was erupted from the Jemez Mountains about 1.2 Ma (Izett and Obradovich, 1994). Mapping by Smith and others (1970) shows an exposure of the Sante Fe Group near the toe of a large Quaternary-aged landslide deposit on the northeast flank of Boundary Peak (fig. 3), and exposures of the Paliza Canyon olivine basalt were observed upstream from the Quaternary-landslide deposits. Further, patches of pumice of the El Cajete Member from the youngest eruptions from the Valles caldera about 50 to 60 ka (Reneau, and others, 1996) mantle portions of the hillslopes in the canyon. The nearly north-south trending Pajarito fault cuts across the canyon approximately 0.5 km south of Base Camp (fig. 3). What appears to be brick red Galisteo sandstones and siltstones are exposed on the down thrown block of this fault on the west canyon wall.

Ecology

For this report we consider three major plant communities within Capulin Canyon: pinon-juniper, which is dominated by a pinon pine and one-seed juniper overstory with a grass/herb, shrub understory; Ponderosa pine, which is dominated by a Ponderosa overstory with a variety of understories depending on stand density and recent fire history; and a riparian vegetation type that includes elements from adjacent slopes along with species requiring enhanced moisture regimes (U.S. Department of Interior, 1996).

The fire history of Capulin Canyon has been reconstructed by dating fire-scar material on trees by Touchan and others, 1996. This record indicates that for the period 1664-1893, surface fires swept the area about every 6.8 years. These frequent fires could be widespread, but generally did not exhibit high burn intensities over extensive areas. In the years subsequent to 1893, fires were infrequent and not as widespread, allowing for the accumulation of significant fuel loads. The change in fire frequency has been attributed to intense grazing by large numbers of free-ranging livestock which reduced the grassy fuels through which most fire spread (Allen, 1989, Swetnam and Baisan, in press; Touchan and others, in press). Active fire suppression practices during this century has allowed the buildup of unnaturally high densities of trees and amounts of ground fuels that were formerly thinned by frequent surface fires (Allen, and others, 1996). In contrast with the historical record, the Dome fire exhibited high burn intensities over an extensive area.

Climate

The climate of the Jemez Mountains and Bandelier National Monument is described by Allen (1989). Mean annual precipitation at the Monument weather station is 40.7 cm. Usually, the period from late April through the end of June is dry, followed by the onset of the summer monsoon season. Sixty percent of the annual precipitation falls between June and September, with thunderstorms reported for 58% of the days in July and August. These convectional thunderstorms bring 40% of the total annual precipitation in July and August. During the rest of the year precipitation is generally associated with the passage frontal storms and tends to be less intense (Bowen, 1990). In winter these storms bring snow to all elevations.

Local climate is also temporally variable, with wide fluctuations in annual precipitation common (Allen, 1989). Cyclic El Nino Climate events bring increased spring and summer precipitation to this area about every four years (Andrade and Sellers, 1988).

The June 26, 1996 Storm: The June 26 storm was a convectional thunderstorm and, due to the lack of an extensive rain gage network, its areal extent and rainfall output is unknown. The hydrologic response of Capulin Creek to the rainstorm, however, was observed by a team of archeologists staying at the Base Camp cabin (fig. 3). The team observed dark thunder clouds concentrated at the head of the canyon where it appeared to be raining, although there were only isolated raindrops falling at the cabin. About dusk on the evening of the 26th, a surge of water approximately 2 m high traveled through the stream channel located approximately 3 m from the cabin; the flow barely overtopped the channel bank and ran up to the cabin door. The team members had only a few moments of warning once they heard the flood wave approaching.

The effects of the June storm on hillslopes in the Capulin Creek drainage were observed to concentrate near Boundary Peak and westward (fig. 2). The easternmost extent of evidence of tributary surface flow generated by this storm was observed on July 3 in a small drainage to Capulin Creek shown as location A on figure 2. The flow was at most 2 m wide and its lateral extent was marked by 15-cm-high levees consisting of rafted ash, charcoal, pumice fragments, and pine needles. The effects of surface overland flow on hillslopes were observed, in general, to increase from this point to the west. The impact on the steep, south flank of Boundary Peak was particularly severe, where cobbles of up to 20 cm in diameter were observed to have been transported short distances down the steep slopes, and up to 3 cm of the mineral soil was removed in places.

Because the storm appeared to be concentrated near Boundary Peak, and its effect on the hillslopes appeared to dissipate toward the east, the proximity to high intensity rainfall was quantified by considering the distance of each of the 15 sites from a north-south line drawn through the Boundary Peak trail head (fig. 3, app. A).

The August 19-25, 1996 Storm Sequence: The effects of this storm sequence were again observed by a team of archeologists, this time camping near the junction of Capulin Canyon and the Rio Grande (Earl Ruby, Hydrologist, oral commun., Sept. 1996). Flood crests of 45 cm on August 20 and 94 cm on August 22, 1996, were measured at Base Camp. The flood of August 25 was estimated to be 2 m deep in lower Capulin Canyon and 3 m deep at Base Camp. The archeologists measured an accumulation of 1.27 cm of rain in 29 minutes during the August 25 event, and described dark rain clouds at the head of the canyon, in addition to the cloud cover at their camp. The leading edge of the flood was reported to have reached the camp 45 minutes after the rainfall stopped. This event was described as flood waters that were partially bulked with ash, charcoal and sediment. A rain gage installed at Instrument Site 1 (IS-1, fig. 3) on August 23, 1996 (considerably upslope from the archeologist's camp), measured only 0.30 cm of rain in an 8-hour period on August 25, 1996 (fig. 4). Note also that an accumulation of 0.30 cm of rainfall was measured on August 27 in a time span of 1 hour and 9 minutes. The effects of this high-intensity rainfall event were not observed by anyone in the canyon.

Remainder of the Monsoon Season: Summer thunderstorms occurred throughout the summer in the canyon, but a recording rain gage was not installed at Instrument Site 1 (fig. 3) until August 23, 1996. Thus, no record of rainfall accumulations exists until this date. For the balance of the monsoon season, the rain gage at Instrument Site 1 recorded accumulations of 3.58 cm from September 12-16, 0.89 cm on September 18 and 4.22 cm in a very short time period on October 4 (fig. 4). Although no one was in the canyon to personally observe the effects of each of these storms, a visit during November 11-15, 1996 revealed up to 2 m of incision in places in Capulin Canyon. Some reaches that had experienced deposition during the June storm were scoured clean, and other reaches showed considerable deposits of primarily sand, ash, and charcoal. Some large boulder and cobble-sized material had also been moved, and large trees uprooted, by the high-energy summer flooding.

A pending comparison of the summer of 1996 rainfall data with the historic rainfall records from Frijoles Canyon by Jack Veenhuis of the U.S. Geological Survey, Water Resources Division, will indicate the magnitude of severity of these summer storms in the watershed.

INFLUENCE OF GEOLOGIC AND GEOMORPHIC FACTORS

The geomorphic and geologic factors listed in the Introduction have been identified as contributing to the generation of debris flows from hillslopes following fires. The presence of these factors, given an appropriate rainstorm, can indicate a high susceptibility to debris flow. Note that at this time the relative importance of each of the factors is unknown, and methods to quantitatively evaluate their possible effects have not been explored. In the following section, the influence of fire intensity and the geologic and geomorphic factors on the generation of sediment for debris flows in Capulin canyon, in part evidenced by the hillslope response to the June thunderstorm, are described.

Fire Intensity

The intensity of a fire can be characterized by the size of fuels consumed and the completeness of consumption, which is indicated by the color of the remaining ash. For this assessment, the presence of black ash, scorched needles that remain on the trees, and an intact ground cover were taken as indicators of a low fire intensity. Moderate fire intensity was defined by the consumption of materials greater than 0.5 cm and less than 2 cm in diameter, including ground cover material, and the presence of gray or mixed-color ash. The consumption of materials greater than 2 cm in diameter, including nearly all tree needles and ground cover, nearly total tree mortality, and the presence of white or red ash indicates a high fire intensity.

In general, areas affected by high-intensity fires are considered to be a higher erosive risk; higher intensity fires are more conducive to the formation of hydrophobic layers and generation of dry-ravel, and result in more thorough removal of ground-covering and riparian vegetation and fibrous root mat material.

Fire intensity was evaluated at each of the 15 field sites in Capulin Canyon (fig. 3, app. A). In general, areas of low fire intensity exhibited very little sediment movement following the June rainstorm. One effect of low intensity fire was to simply scorch the needles on the Ponderosa pine; 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 in areas of high rainfall intensity, the needles were rafted from the hillslope by surface runoff. Interestingly, a noncon-

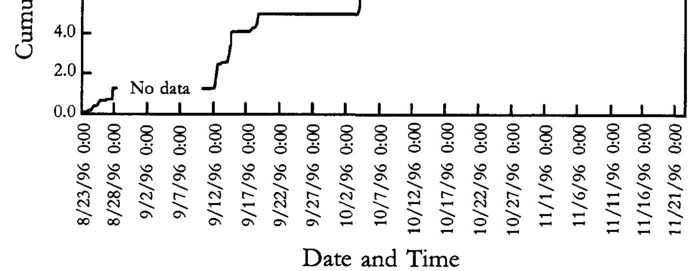

Figure 4. Cumulative rainfall record for the period Aug. 23-Nov. 18, 1996, recorded at Instrument Site 1 (fig. 3).

tinuous hydrophobic surface was observed in one low intensity site.

Following the June rainstorm, of the four moderate fire intensity sites, two exhibited abundant rills that measured up to 5 cm wide and 4 cm deep, and the removal of approximately 60% of the blackened surface pumice. The other two sites showed only slight rill development in areas not mantled by surface stones. The occurrence of surface erosion at the moderately burned sites can be explained by the close proximity to the high intensity storm cell.

Friable Bedrock Units and Cohesionless Soils

The Capulin Creek drainage is underlain by a number of volcanic and sedimentary rock units (Goff, and others, 1990) which show a variety of responses to weathering. Welded ash-flow tuffs of the Upper Bandelier tuff that forms the cliffs and lower sidewalls of the canyon are not decomposing into significant deposits of loose, friable material. The porphyritic dacites and andesites of the Paliza Canyon Formation are also quite competent, and are not contributing substantial colluvial material that could be mobilized into debris flows. According to the 1978 Soil Survey of the Bandelier National Monument (Earth Environmental Consultants), the steeper slopes underlain by these units show almost no soil development, and very cobbly or stony surfaces. In addition, even though the lithic-rich ash-fall and ash-flow tuffs of the Canovas Canyon tuffs could potentially erode into loose, friable material, the aerial extent of this unit in the canyon is limited, and is thus not considered to be a high risk. The El Cajete pumice, however, which blankets some hillslopes in the region, is an extremely erodible unit.

Although the El Cajete Pumice does supply abundant loose, friable material that is potentially available for mobilization into debris flow, and the soil developed on this unit is, in general, noncohesive, observations following the summer of 1996 thunderstorm season indicate the potential for the generation of only minor debris-flow activity. The primary response of hillslopes mantled by the El Cajete pumice to summer thunderstorms was considerable surface overland flow; low-density pumice, ash, charcoal, pine needles, and some mineral soil were rafted down the hillslopes and draws by this process. In some places rills that were at most 4-cm deep and 15-cm wide stripped the burned soil and ash from the hillslope, as shown in figure 5. When surface water flows passed through an area mantled by abundant pine needles, significant volumes of pine needles were often incorporated. These flows then took on the character of debris flows; the yield strength imparted by the pine needles allowed for the formation of discrete levees lining the flow margins (fig. 6). The levee and lobe deposits lining the draws and rills were, in general, clast supported, with very little silty matrix, and appear to have formed by rafting of the low-density materials along the surface of the flows, rather than being incorporated into a slurry. Note that these debris flows were at most 50-cm wide, and of low strength; figure 6 shows a debris flow path easily deflected by a fallen log. Further, the passage of the flows served only to clear a path of loose, low-density materials, and no incision into the base of the paths were observed. Such incision would be necessary to generate debris flows of significant size.

Of further note is that the scale of these debris flows is very small in comparison with the surface water flows in Capulin Creek itself during and following the rainfall events. Presumably, any debris-flow material that reached the creek would be diluted significantly so as not to impart any significant strength to the flowing water.

Note that most of the movement of materials from the hillslopes mantled by the El Cajete pumice occurred during the first significant rainfall event following the fire; no substantial deepening or widening of rills, or further hillslope erosion was observed during the November visit.

Material weathered from red Gallesteo sandstones and siltstones, however, does appear to be susceptible to more significant debris-flow activity. Colluvium exposed on the west canyon wall 0.5 km south of Base Camp mobilized into a small debris flow sometime during the summer of 1996. This flow occurred in a small tributary to Capulin Canyon, and its location is shown on figure 3 by the letter B[1]. The deposits of this flow consisted of paired levees approximately 0.3 m high that terminated in an approximately 0.5-m-thick lobe of gravel- and cobble- sized material in a red, clayey matrix.

In addition, material from the lahar and debris-flow deposits of the Cochiti Formation and possibly local areas of non-indurated sandstones and siltstones within the Sante Fe Group appeared to supply material to the very fluid debris flow that was observed near the confluence of the tributary labeled C on figure 3 with Capulin Canyon. A dark brown mud plaster, not more

[1]Note that the junction of this tributary and Capulin Canyon is located near an archeological site. The well-developed tributary channel, however, should serve to deflect any future debris flows south of the site.

than 1-cm thick and containing abundant charcoal fragments, was observed on light-colored pumice outcrops lining the channel. The upper mud line could be found approximately 2 m above the channel bottom and a 1.5-m high mud splash line was observed on a tree located on the right channel bank. The debris-flow plaster was not continuous as it had apparently been preferentially washed off smooth rock surfaces by subsequent flood waters. The tributary where this debris flow occurred drains a considerable area off the south flank of Boundary Peak. Presumably, the proportion of material transported from the hillslopes relative to the surface water flow was sufficient to form a very dilute debris flow. No evidence of this debris-flow deposit could be found along Capulin Creek itself, presumably due to dilution by the high flood waters. The adjacent tributary to the south showed only signs of surface water flooding. Note that this debris flow occurred sometime after the June, 1996 visit, as no deposits were observed in the tributary at that time.

In conclusion, while Spittler and others, (1994) identified loose, friable bedrock units and cohesionless soils as factors that contribute to the formation of debris flows, observations made at Bandelier would suggest that these factors resulted in the generation of only minor debris-flow activity. The materials that did appear to be susceptible to debris flow, however, were the colluvium weathered from the sandstones and siltstones of the Gallesteo formation and the Sante Fe Group, as well as the lahar and debris-flow deposits of the Cochiti Formation.

Hillslope Geometry, Smoothness, and Vegetative Cover

Long, smooth and regular slopes can allow for the generation of significant surface overland flow. The longer and steeper the slope, the higher energy the flows; high energy flows can lead to the erosion of material from the hillslopes. Removal of the vegetation results in decreased rainfall interception and infiltration, resulting in increased surface runoff, which can also result in accelerated erosion of hillslopes.

Two types of hillslopes were observed in the drainage: long, smooth, and covered by the El Cajete pumice; and generally steeper, rock-mantled slopes. Both types of slopes were denuded of ground-covering vegetation in the areas of high fire intensity. The steeper slopes in the drainage are very rocky, in places 80% covered by boulders up to 50 cm in diameter. We observed that on 45% slopes mantled with a significant proportion of cobbles

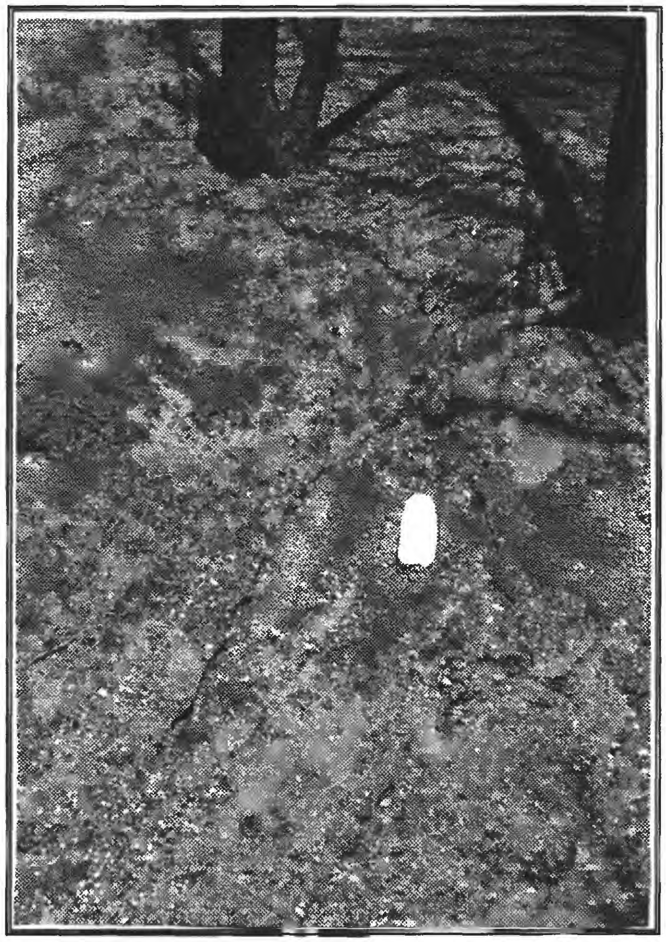

Figure 5. Photograph of rills developed on hillslope following June 26, 1996, rainstorm. Rills were up to 4 cm deep, and 20 cm wide, with generally flat bottoms. Water bottle in center of photgraph is 20-cm long.

and boulders, concentrated flow, and thus rilling, occurred only in the small patches where the rocky cover was absent. However, on the south side of Boundary Peak, on 55% slopes and where the rainfall was apparently intense, enough surface overland flow was generated to move the cobbles on the rocky surface short distances. At this site, all the ash and charcoal smaller than approximately 4 cm, and in places up to 3 cm of mineral soil, was removed. In addition, at another site with only 5% coverage of cobbles up to 20 cm in diameter, approximately 80% of the ash and pumice layer was removed by rilling and sheetwash. Thus the cobbles and boulders effectively protect the burned hillslopes from surface erosion as long as the slope is not too steep, or the rainfall not too intense.

The long, smooth slopes that are present due to the mantling of the El Cajete pumice showed abundant rilling where the low-density pumice fragments, ash, charcoal, and pine needles were rafted along the surface of water flows and deposited as levees lining the paths of the flows. That the low-density materials were rafted along the surface of the flows, rather than being incorporated into a slurry, might have prevented the erosion commonly associated with the passage of debris flows.

Dry-Ravel Concentrations

Dry-ravel deposits are formed by the particle-by-particle transport of material downslope due to gravity. This process has been observed on steep slopes both following, and during fires, where loose, noncohesive 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 (for example, Florsheim, and others 1991; Wells, 1987). Cannon and others, (1995) also described aprons of dry-ravel material mantling hillslopes and lining channels; these deposits were subsequently eroded in a high intensity rainfall event, resulting in destructive debris flows.

Very few accumulations of dry-ravel deposits were observed in the Capulin Creek drainage. Some dry-ravel material was observed along trails, where small, 0.3 meter 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%. No accumulations of dry-ravel materials were observed in tributaries to Capulin Creek, nor were significant accumulations observed on hillsides.

Figure 6. Photograph of debris flow generated on hillslopes during the June 26, 1996, rainstorm. The path of the flow is lined by levees up to 15-cm high. The levees consist of pine needles, pumice and charcoal fragments, and some silty matrix. Note that the flow was deflected around the burnt log in the center of the photograph.

Hydrophobic Soils

Even under unburned conditions, organic substances leached from plant litter can induce a non-wettable condition in sands and coarse-grained soils, and microbial by-products may coat mineral soil particles (DeBano, 1980). Non-wettable soil is particularly common in chaparral communities, in part because of the high resin content of the organic litter. Under unburned conditions, the non-wettable substances generally do not form a continuous layer because rodent, worm, insect, and root activity continuously disrupts the soil-column structure, and forms conduits for water to enter (Spittler, 1996). When a high-temperature fire sweeps through an area, however, the existing organic water-repellent materials volatilize. These materials then condense on mineral soil particles and produce an extremely water-repellent layer (Wells, 1987). This layer can affect the erosion potential of a site by increasing surface runoff (Wells, 1987).

The assessment of the development of a hydrophobic layer in the soil in Bandelier National Monument involved digging a small pit with clean, inclined sides. Pits were, in general, about 10 cm deep, with one side inclined at about 3:1. Water from a squirt bottle was dripped along the incline. Hydrophobicity was identified if the water beaded on the surface and did not infiltrate for at least 1 minute. Where hydrophobic material was found, its lateral extent was evaluated by dripping more water on either side within in the pit. In addition, a minimum of three other nearby pits were dug to determine if the layer was laterally continuous.

Hydrophobic soils were observed at only 4 of the 15 test sites in Bandelier, 3 of which were located in the areas of highest intensity fire. The hydrophobicity was extremely localized within the soils, and was nowhere laterally continuous. For example, at site 5 (fig. 3), a hydrophobic, 4-cm thick, light tan, dry silt loam was observed beneath 3 cm of black ash and pumice and 3 cm of slightly moist brown silt loam. This layer was not continuous within the pit, and just one of three additional soil pits dug nearby showed only patchy hydrophobicity. Similar conditions were observed at the other three sites. Note also that additional sites in high burn intensity areas did not exhibit any hydrophobicity.

In one location the material exposed in the base of the rills formed by the June rainfall exhibited some hydrophobicity, but this was not observed at any other site.

Condition of Riparian Vegetation

A map of fire intensity generated by the U.S Forest Service from 1:12,000-scale aerial photography taken after the fire and limited field checking was used to assess the condition of the riparian vegetation. A portion of this map is shown in figure 2. Areas mapped as high fire intensity are characterized by essentially 100% tree mortality and total consumption of tree needles and ground cover. Moderate fire intensity is characterized by 80% to 100% 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% tree mortality, and duff and older needle cast remain intact. Note that a considerable gap between the light and moderate designations in percent tree mortality. This is due to 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. Of further note, in aerial photographs crown-fire conditions appear as very high intensity burn, 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. It is, however, the best tool available.

The Forest Service map of fire intensity shows a 0.8-km-long reach of moderate intensity burn with a few patches of high intensity at the very head of Capulin Canyon. Immediately upstream from the edge of figure 2 (and thus not shown on the figure), a 1.1-km-long reach of moderate intensity burn is mapped adjacent to a 1.1-km-long section of high burn intensity. This is the only extensive zone of riparian vegetation that experienced high fire intensity. The map also shows an approximately 5-km-long reach of Capulin Creek extending downstream from the edge of the map in figure 2 to the Base Camp that experienced light fire intensity. An additional 1-km-long reach of light fire intensity was mapped 1.6 km downstream from the Base Camp.

Over a total length of approximately 20 km, approximately 6% of the riparian vegetation in Capulin Canyon experienced high fire intensity, 10% experienced moderate intensity, and 30% was impacted by light intensity burn. The riparian vegetation in the two ephemeral drainages that head on the south side of Boundary Peak and join Capulin Creek just upstream from Painted Cave was not impacted by the fire. In these areas, as well as the unburned length of Capulin Creek, the vegetation lining the creek continues to intercept rainfall and absorb raindrop impact, mulch the ground surface, and supply structural support of loose, surficial material and reinforcement of the deeper soil by roots.

Condition of Fibrous Root Mat

Destroying the fibrous root mat beneath the surface reduces the soil cohesion and can thus result in accelerated erosion by surface overland flow. The root mat was observed in July to be intact even in areas of high fire intensity. In some locations, the root mat appeared to control the depth of the rills that formed as a result of the June 26 rainfall. Note that in areas where the vegetation was killed by the fire, the root mat will eventually decompose, and the cohesion element lent to the soil will be lost.

Continuity of Burn Mosaic

The continuity of the burned mosaic influences the area of hillslope upon which erosion can potentially occur. An spatially extensive high-intensity-burned area will produce considerably more material that an area that has been spottily burned by a low intensity fire. The map of fire intensity generated by the U.S Forest Service from 1:12,000-scale aerial photography taken after the burn and some field checking was used to assess the continuity of the burn mosaic.

For the entire Dome fire, 1281 ha, or 19% of the total burned area of 6684 ha was mapped as high intensity burn, 1411 ha, or 21% was mapped as moderate intensity burn, 1159 ha, or 17% as light. The remaining 2,832 ha, or 42%, are mapped as no burn or low intensity. The distribution of burn intensities for the Dome fire indicates a rather spotty burn mosaic, although at this time there is no method to quantitatively determine how continuous the burn mosaic must be in order to generate debris flows.

EVIDENCE OF PAST DEBRIS-FLOW ACTIVITY

The fact that some debris-flow activity occurred during the summer monsoon season indicates that conditions do exist in Capulin Canyon that can produce debris flow. The scale of these two events was, however, very small, and it remains to determine if Capulin Canyon is susceptible to large-scale, highly destructive debris-flow events, and if so, if fires played any part in their initiation. The Capulin Creek drainage and its tributaries from the western margin of the map in figure 3 to just below Painted Cave were thus examined for evidence of large-scale past debris-flow activity. Although no definitive evidence of recent, pre-fire debris-flow activity was observed, and most of the high-energy deposits in the canyon, of which there are many, appear to be unequivocally those of dilute stream flow (that is abundant open framework and imbricated boulder and cobble bars that contain very little matrix, or well-sorted deposits of boulders and cobbles in a sandy matrix) (fig. 7), some possible debris-flow deposits were detected. At location D on figure 3, a large lobe of material approximately 2 m high and at least 5 m wide consisting of boulders and cobbles up to 1 m in diameter in an abundant silty matrix nearly fills the canyon bottom. The grain-size distribution of the matrix material is presently being determined. The right margin of the deposit, located 10 m from the hillside, is very distinct and slopes steeply (41 degrees) up to a gently undulating surface. Numerous Ponderosa pine are growing on the deposit surface. The deposit rests on a 3 degree slope. The leading edge of the lobe (or the snout) is considerably less distinct than the right margin as it appears to have failed by a series of slumping events following deposition. If this is indeed a lobe of debris-flow material, the leading edge would have been greater than 2 m thick and with a very steep slope, and could have failed easily after deposition. The left side of the deposit has been eroded by Capulin Creek and thus the flow margin is not discernible. No evidence that could indicate the age of this deposit was observed, nor were any indications of its relation to the fire history in the canyon.

Alluvial fans that have formed at the junctions of some tributaries with Capulin Canyon were examined for evidence of possible debris-flow activity. A small fan has formed at the mouth of the small tributary drainage immediately down channel from location D in figure 3, and the morphology of a deposit located on the right channel bank suggests the possibility of a set of nested debris flow levees. The deposits contain boulders as much as 0.5 m in diameter in abundant matrix material. The grain-size distribution of this material is presently being determined. The nested morphology may also be a result of incision into the fan by the tributary stream. In addition, the two major tributaries that join Capulin Creek near Painted Cave (fig. 3) have deposited a significant amount of material at the

Figure 7. Photograph of typical high-energy streamflow deposits in Capulin Canyon. The deposits consist of boulders in a loose, sandy matrix. Note that the incision to bedrock occurred during the June 26, 1996, rainfall event.

juncture. Stream cuts into these fans show thick, poorly sorted, and boulder-rich deposits that could possibly be those of debris flow. However, the difficulties in determining debris-flow origin of older deposits makes this judgment rather uncertain.

No other indications of historic debris-flow activity were observed in the section of the canyon examined.

Some indication of the historic response of the watershed to fire events was discovered in an incision into a fan surface of the tributary labeled E in figure 3. This stream cut exhibited a stratigraphy similar to the sheetflood sediments deposited on the flood plain of Capulin Creek itself during June flooding–lenses of primarily sandy matrix containing some cobbles and pebbles, resting on silty sands. Two buried soils were observed separating packets of these units, and the presence of abundant charcoal fragments and ash within these soils indicates that fires have occurred in the watershed in the past. C-14 dates of 1650-1950 A.D., and 1280-1630 A.D. were obtained from charcoal in the upper, and lower soils, respectively. The internal stratigraphy of the fan, however, did not indicate the occurrence of debris flows following these fires, and the fan surface is covered with abundant openwork boulder and cobble berms, again made up of clast-supported and imbricated materials.

Of further interest is the response in canyons north of Capulin Canyon following the 1977 LaMesa fire. This fire is reported to have been the largest and most intense fire to burn in the Jemez Mountains this century (Allen, and others, 1996). Unexceptional summer thunderstorms resulted in large flood events in Frijoles

Canyon, but debris flows were not described (White, 1981). This fire was reported to have been more intense, and produced a less spotty burn mosaic than the Dome fire (C. Allen, personal commun., 1996).

The results of this examination indicate that while there has been significant high-energy flooding in Capulin Canyon the past, large-scale debris-flow does not appear to have been particularly widespread. The evidence observed in the canyon would seem to indicate that the watershed response to fires or to severe meteorological events in the past has been primarily as flooding, but not definitively debris flow. This response might, however, be due to the less intense and extensive character of fires in the past.

DEBRIS-FLOW POTENTIAL

Based on the following observations, the potential for significant debris- and hyperconcentrated-flow activity in Capulin Canyon itself as a result of the Dome fire is determined to be low.

Even though evidence of the occurrence of fires in the past was observed in Capulin Canyon, evidence of resultant widespread debris- and hyperconcentrated-flow activity was not detected. However, the preponderance of high-energy streamflow deposits in the canyon indicates that the prevailing hazard is that of flooding with considerable sediment bulking.

The June 26, 1996 thunderstorm produced abundant surface overland flow and rilling, and transported low-density pumice, charcoal, ash and some mineral soil from the hillslopes as non-erosive, and small-scale debris flows. Runoff from this event also transported cobble and boulder-sized material short distances in some locations. Deposits from only two debris flows of significant volume were observed resulting from the entire summer thunderstorm season.

Evaluation of the geologic and geomorphic factors identified as contributing to post-fire debris-flow activity does not indicate a major propensity for debris-flow activity. Note that the relative influence of each of these factors is not known, and methods for evaluating quantitatively the influence of these factors do not exist at this time. These factors were evaluated qualitatively for this report.

- Although the El Cajete Pumice does result in loose, friable material potentially available for mobilization into debris flow, and the soils are, in general, noncohesive, observations following the summer of 1996 monsoon season indicated the potential for only minor debris-and hyperconcentrated-flow activity. The hillside response to the June, 1996 thunderstorm was surface overland flow and resultant rilling that transported pumice, ash, charcoal, pine needles, and some mineral soil down the hillslopes and draws as non-erosive and small-scale, debris flows. Material from the lahar and debris-flow deposits of the Cochiti Formation and possibly local areas of non-indurated sandstones and siltstones within the Sante Fe Group, however, supplied material to a very fluid debris flow.
- Although long, smooth and regular slopes, denuded of ground-covering vegetation, and covered with the friable El Cajete pumice are present in the area, these slopes produced only small-scale and non-erosive debris flows during the June 26 rainstorm. These hillslopes are generally inclined at less than 65%.
- No significant concentrations of dry-ravel materials were observed in the watershed.
- A continuous water-repellant layer within the soil was not observed. Only a spotty occurrence of hydrophobic soils was detected.
- The riparian vegetation along Capulin Creek remains, for the most part, intact.
- The fibrous root mat remains intact, even in areas of high intensity fire, and appears to control the maximum depth of rill development in some places.
- Of the 6684 ha burned in Bandelier National Monument, 19% exhibit evidence of high fire intensity, 21% show moderate fire intensity, and 17% show low fire intensity. The remaining 42% shows no burn or low intensity. This distribution of burn indicates a rather spotty burn mosaic, however, at this time there is no method to quantitatively determine how continuous the burn mosaic must be in order to generate debris flows.

A moderate potential for debris and hyperconcentrated flow, however, does appear to exist for the two major tributary drainages that join Capulin Canyon near Painted Cave. These two tributaries show possible sedimentological evidence for past-debris flow activity, and a very fluid debris flow occurred in the northern tributary in the summer of 1996.

RECOMMENDATIONS

Based on the definition of a moderate potential for debris and hyperconcentrated flow for the two major tributaries to Capulin Canyon, we recommend that recreational activity downstream from these tributaries be restricted for at least one year. Assessment of the state of vegetation recovery on the hillslopes in the headwaters of the tributaries should continue, as should monitoring of hillslope response to summer thunderstorms. Once vegetation is sufficiently reestablished such that summer thunderstorms no longer produce abundant surface overland flow, the hazard will be mitigated. Note that such mitigation occurred within two years in the steep drainages of Storm King Mountain, near Glenwood Springs, Colorado, that were burned by the 1994 South Creek fire.

In Capulin Canyon itself, however, the remaining prevalent hazard is that of flooding with considerable sediment bulking. Most of the movement of material from the hillslopes following the Dome fire occurred during the first significant thunderstorm of the season, perhaps due to compaction of the soil surfaces by raindrop impact, as suggested by Meyer, and others (1995). Response to later thunderstorm events was dominated by high-energy dilute stream flows and considerable incision and movement of material in the main channel. Further, stratigraphic evidence in the canyon indicated that the watershed response to fires and severe meteorological events in the past has been primarily as flooding, but not definitively debris flow. The report prepared by Jack Veenhuis of the U.S. Geological Survey, Water Resources Division for the Monument should address the issues associated with flood hazards in Capulin Canyon.

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APPENDIX A-: HILLSLOPE CONDITION

Site Number: 3
Fire Intensity: moderate
Slope: 58%
Rock Cover: 20 to 90%
Needle Cast: sparse
Ash depth, color, and moisture: 0-3 cm, dry
Soil and Moisture: 3+ cm, clayey silt, moist
Hydrophobicity: none
Root mat condition: not observed
Distance from Boundary Peak trail head: 2012 m
Effect of June 26, 1996 storm: some rilling in open areas, length controlled by occurrence of boulder patches, rills only in areas without stone cover.

Site Number: 4
Fire Intensity: high
Slope: 19%
Rock Cover: not observed
Needle Cast: sparse
Ash depth, color, and moisture: 0-3 cm, black, moist only at surface
Soil and Moisture: 3+ cm silty sand, slightly moist
Hydrophobicity: none
Root mat condition: not observed
Distance from Boundary Peak trail head: 1525 m
Effect of June 26, 1996 storm: no rilling or sheetwash.

Site Number: 5
Fire Intensity: high (4-cm diameter tree branches consumed)
Slope: 18%
Rock Cover: pumice blanket
Needle Cast: none
Ash depth, color, and moisture: 0-3 cm, black ash and pumice, dry
Soil and Moisture: 3-6 cm, brown silt, slightly moist; 6-10, cm light tan, dry, hydrophobic silt; 10+ cm brown, no hydrophobic silt.
Hydrophobicity: in 4-cm thick light tan silt, not observed in three nearby pits. Spotty hydrophobicity observed in base of rills.
Root mat condition: not observed
Distance from Boundary Peak trail head: 1250 m
Effect of June 26, 1996 storm: abundant rills average 20-cm wide, 3-cm deep through pumice and ash layer.
Conclusions: Most gentle slopes with rilling yet observed. Hydrophobicity allowed for formation of rills on gentle slopes.

Site Number: 6
Fire Intensity: high (3-cm diameter limbs gone)
Slope: 38%
Rock Cover: pumice layer
Needle Cast: none
Ash depth, color, and moisture: 0-3 cm, black ash, charcoal, and burned pumice, dry
Soil and Moisture: 3-11 cm light brown silt with pumice fragments, dry; 11+ cm light tan silt with pumice fragments, dry
Hydrophobicity: upper light brown silt is strongly hydrophobic
Root Mat Condition: intact
Distance to Boundary Peak trail head: 1036 m
Effect of June 26, 1996 storm: some rills on slope, approx. 12-cm wide and 2-cm deep. No hydrophobicity at base of rills.

Site Number: 7
Fire Intensity: high
Slope: 53%
Rock Cover: 90% coverage with up to 25-cm diameter cobbles
Needle Cast: very sparse
Ash depth, color, and moisture: not observed
Soil and Moisture: not observed
Hydrophobicity: none
Root mat condition: not observed
Distance to Boundary Peak trail head: 945 m
Effect of June 26, 1996 storm: surface overland flow (sheetwash) has removed all ash and charcoal fragments less than 1-cm diameter.

Site Number: 8
Fire Intensity: low (needles and small branches remain on trees)
Slope: 44%
Rock Cover: 30% coverage, up to 20-cm diameters cobbles
Needle Cast: moderate
Ash depth, color, and moisture: 0-2 cm, dry
Soil and Moisture: +2 cm of silt with pumice fragments
Hydrophobicity: none
Root mat condition: not observed
Distance to Boundary Peak trail head: 884 m
Effect of June 26, 1996 storm: some sheetwash to move needles slightly, but not sufficient to move large quantities of material.

Site Number: 9
Fire Intensity: high
Slope: 53%
Rock Cover: approx. 5% coverage with up to 20-cm diameter cobbles
Needle Cast: sparse
Ash depth, color, and moisture: 0-3 cm, black ash, charcoal and burned pumice
Soil and Moisture: +3 cm silt with pumice fragments, damp
Hydrophobicity: none
Root mat condition: not observed
Distance to Boundary Peak trail head: 884 m
Effect of June 26, 1996 storm: approx. 80% of ash and pumice layer removed by rilling and surface overland flow. Rills average 2-cm deep.
Conclusions: Much more material removed from this site than adjacent site 8. The differences being less surface coverage by cobbles and more intense burn at this site.

Site Number: 10
Fire Intensity: moderate (needles and small branches removed)
Slope: 38%
Rock Cover:
Needle Cast: none
Ash depth, color, and moisture: 0-2 cm, ash, charcoal and burned pumice
Soil and Moisture: 2+ cm light brown silt with pumice fragments, moist
Hydrophobicity: none
Root mat condition: intact
Distance to Boundary Peak trail head: 945 m
Effect of June 26, 1996 storm: abundant rilling approx. 2-cm deep. Approx 60% blackened pumice and 100% litter removed.

Site Number: 13
Fire Intensity: low (some needles left on trees)
Slope: 30%
Rock Cover: none
Needle Cast: moderate
Ash depth, color, and moisture: 0-2 cm ash and burned pumice, dry
Soil and Moisture: 2-4 cm tan silt with pumice fragments, dry; 4+ cm light brown silt and pumice fragments, moist.
Hydrophobicity: upper tan silt hyydrophobic in places
Root mat Condition: some intact
Distance to Boundary Peak trail head: 3048 m
Effect of June 27, 1996, storm: only sign of surface runoff is one rill, 5 cm wide, and not hydrophoic at base.

Site Number: 15
Fire Intensity: high
Slope: 42%
Rock Cover: none
Needle Cast: none
Ash depth, color, and moisture: 0-3 cm ash, charcoal, burned pumice, dry
Soil and Moisture: 3-5 cm silt with pumice fragments, dry; 5+cm silt with pumice fragments, dry
Hydrophobicity: spotty in upper silt layer
Root mat condition: some intact
Distance to Boundary Peak trail head: 1981 m
Effect of June 26, 1996 storm: abundant rills, 5-cm wide, not hydrophobic in base.

Site Number: 16
Fire Intensity: high
Slope: 44%
Rock Cover: approx. 80% coverage by up to 30-cm diameter cobbles
Needle Cast:
Ash depth, color, and moisture: 0-4 cm light brown silt with few particles of charcoal on surface, dry
Soil and Moisture: 4+ brown silt, moist
Hydrophobicity: none
Root mat condition: intact, and controls depth of surface erosion
Distance to Boundary Peak trail head:1859 m
Effect of June 26, 1996 storm: Surface overland flow that flushed ash and charcoal off slope, leaving only charcoal fragments greater than 2-cm.

Site Number: 17
Fire Intensity: high
Slope: 55%
Rock Cover: approx. 80% coverage with up to 50-cm diameter cobbles
Needle Cast: none
Ash depth, color, and moisture: 0-1 cm, gray ash, dry
Soil and Moisture: 1+ cm brown silt, moist
Hydrophobicity: none
Root mat condition: intact
Distance to Boundary Peak trail head: 274 m
Effect of June 26, 1996 storm: abundant surface overland flow has moved cobbles up to 50-cm diameter downslope.

Site Number: 18
Fire Intensity: high
Slope: 34%
Rock Cover: approx. 90% coverage with up to 50-cm diameter cobbles
Needle Cast: not observed
Ash depth, color, and moisture: 0-1 cm, black ash and charcoal, dry
Soil and Moisture: 1+ cm tan silt, dry
Hydrophobicity: none
Root mat condition: intact
Distance to Boundary Peak trailhead: 0 m
Effect of June 26, 1996 storm: ash and charcoal has been flushed by surface overland flow. No rill or channel development. No movement of rocks.

Site Number: 19
Fire Intensity: high
Slope: 27%
Rock Cover:
Needle Cast: none
Ash depth, color, and moisture: 0-2 cm black ash, charcoal, and burned pumice, dry
Soil and Moisture: 2-6 cm tan silt with pumice fragments, dry; 6+ cm moist brown silt with pumice fragments, moist
Hydrophobicity: none
Root mat condition: intact
Distance to Boundary Peak trail head: 0 m
Effect of June 26, 1996 storm: some rills 20-cm wide and 3-cm deep, no hydrophobicity in base. No clear levees on rills, formed by eroding through layer of charcoal and ash.
Samples: BD-2 surface ash and pumice; BD-3 silt below ash, 0-3 cm, abundant root material; BD-4 silt from 3+ cm

Site Number: 20
Fire Intensity: moderate
Slope: 44%
Rock Cover:
Needle Cast: none
Ash depth, color, and moisture: 0-5 cm black ash, charcoal, and partially burned needle fragments, dry
Soil and Moisture: 5+ cm brown silt, moist
Hydrophobicity: none
Root mat condition: not observed
Distance to Boundary Peak trail head: -274 m
Effect of June 26, 1996 storm: abundant rilling through thick ash layer. Rills 5-cm wide and 4-cm deep. Levees line rills where slope gentles. No hydrophobicity in base of rills.