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# Preliminary Evaluation of the Fire-Related Debris Flows on Storm King Mountain, Glenwood Springs, Colorado

by

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# PRELIMINARY EVALUATION OF THE FIRE-RELATED DEBRIS FLOWS ON STORM KING MOUNTAIN, GLENWOOD SPRINGS, COLORADO

## ABSTRACT

The South Canyon Fire of July 1994 burned 2,000 acres of pinyon-juniper and mountain shrub vegetative communities on Storm King Mountain near Glenwood Springs, Colorado. On the night of September 1, 1994 at approximately 10:30 pm, in response to a torrential downpour, a wall of mud, rocks and burned trees came crashing down onto Interstate I-70 in four places. Throughout the night and early morning hours material continued to flow out of the canyons, inundating sections of a 3-mile length of Interstate I-70 under tons of rocks and mud. Although the burned area was seeded in November of 1994, the potential for continuing and destructive debris-flow activity still remains.

The objective of this study is to describe the September 1994 events and to provide a preliminary definition of existing potential hazards in the event of rainstorms of similar intensity to the September storm or during a protracted snow melt in the spring. Detailed mapping from 1:8000-scale aerial photographs taken on November 10, 1994, coupled with extensive field observations and measurements show that the net result of the September rainstorm was to flush dry-ravel deposits from the side channels, transport loose, larger material from the main channels, and precipitate the erosion of unconsolidated, burned surficial soil from the hillsides. This material was mobilized into a combination of debris- and hyperconcentrated flow. The flows inundated approximately 35 acres along I-70 with roughly 91,000 $yds^3$ of material. Flow velocities from 10 to 28 ft/sec are calculated, with discharges between 1000 and 4000 $ft^3$/sec. Approximately 15% of the loose, unconsolidated soil on the hillsides was removed to a depth of 1.5 inches by rilling and sheet wash. Three existing potential geologic hazards are identified on Storm King Mountain: continued debris-flow activity resulting from accelerated incision and entrainment of channel alluvium by high-volume surface-water flows, mobilization of colluvial material on the channel side slopes and valley-fill material in the canyons by downcutting, and erosional destabilization of deep-seated landslide deposits. Finally, steps to evaluate the potential impact of the first, and most likely, hazard, as well as steps to assess the potential of the occurrence of the following two, less likely, hazards are described.

## INTRODUCTION

The South Canyon Fire of July 1994 burned 2,000 acres of pinyon-juniper and mountain shrub vegetative communities on Storm King Mountain near Glenwood Springs, Colorado (Figures 1 and 2). In the days following the fire, abundant ash and loose mineral soil was transported downslope and accumulated in drainages and on side slopes. Torrential rains the night of September 1, 1994 mobilized this loose, unconsolidated material, loose material stored in the canyons over the years, and burned soil remaining on the hillsides, into debris flows. Throughout the night, material from these flows inundated sections of a 3-mile length of Interstate I-70 under tons of rocks and mud (Plate 1). Miraculously, although 30 vehicles and their drivers were engulfed by the flows, and in some cases, pushed into the Colorado River, no deaths, and only minor injuries resulted from this cataclysm. Even though the burned area was reseeded in November of 1994 with grass mixtures (M. McGuire, Bureau of Land Management, personal communication, 1995), the potential for continuing and destructive debris-flow activity still remains.

The objective of this study is to provide a preliminary definition of existing potential hazards in the event of rainstorms of similar intensity to the September storm and during a protracted snow melt in the spring.

### Approach

To properly evaluate the fire-debris flow hazard, and to implement emergency erosion and debris flow control work to mitigate the risk, it is necessary to understand the relations between the post-fire physical characteristics of the Storm King Mountain watershed and sediment-transport activity. At the onset, I engage in a general discussion of the nature of fire-related sedimentation events; this includes descriptions of the sediment-water flow continuum, and the role of vegetation in slope stability. Then, moving specifically to Storm King mountain, the geologic setting and the physical configuration of the watershed are described. Field observations by Colorado Geological Survey and Bureau of Land Management personnel are then used to describe the conditions in the watershed following the fire and preceding the debris flows. The September, 1994 events are then described and evaluated using a number of different techniques. Detailed examination of aerial photographs of the Storm King mountain watershed taken on November 10, 1994 at a scale of 1:8000, coupled with extensive field observations and measurements, were used to generate a map of the September events. The volume of material deposited at the mouths of the canyons in the watershed was estimated from this map and from field measurements. Field observations and measurements were used to evaluate the dominant mechanisms for mobilization of sediment from the burned basins, to characterize the flow processes, and to calculate the velocities and discharges of the flows themselves. Laboratory testing was used to characterize the physical properties of the soils on the hillsides, and the material involved in the flows. Finally, a synthesis of the information gleaned from the above analyses allows for discussion of a number of different scenarios for the remaining hazards. Recommendations are proposed to evaluate the potential severity of these hazards.

## GENERAL NATURE OF FIRE-RELATED SEDIMENTATION EVENTS

Large fire-related sedimentation events are generally initiated by storm precipitation. 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 (e.g. Kotok and Kraebel, 1935; Rowe et al., 1949, 1954).

### The Sediment-Water Flow Continuum

Fire-related sedimentation events may feature a wide variety of sediment concentrations and particle-size distributions, both spatially and temporally. Sediment from a number of different sources may be incorporated into the flow as it progresses down a hillside or channel, or the flow may be diluted with the addition of more water from side channels. In addition, as a storm develops, and the amount of runoff changes, the amount of sediment entrained in the flow may also change. The particle-size distribution and concentration of sediment in a slurry have large effects on flow behavior because of particle frictional interactions, collisions, and interlocking (Rodine and Johnson, 1976; Major and Pierson, 1992). The mineralogy and dispersion of clays in flows is also significant, because electrostatic attractions between clay particles may add strength to the slurry. Hampton (1972), described concentrations of smectitic clays as low as 3% as having a measurable effect on flow properties of slurries.

Pierson and Costa (1987) distinguished four types of flow based on sediment concentration and rheology, each of which are described below, and represent segments of the sediment-water flow continuum (i.e., a continuous range of properties).

o normal or dilute streamflow,
o hyperconcentrated flow,
o slurry, or debris flow,
o granular flow.

**Dilute Streamflow.** Flows in which the sediment load has no effect on flow behavior, or imparts no yield strength to the flow, are considered as normal streamflow (Pierson and Costa, 1987). Turbulence is the primary mechanism for sediment support 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.

**Hyperconcentrated flow.** Sediment-water flows in which the concentration, size distribution, and/or composition of the entrained sediment lead to a measurable yield strength have been defined as hyperconcentrated flow (Pierson and Costa, 1987). Intermediate ranges of sediment concentration and low to moderate clay contents result in generally low yield strengths. Smith and Lowe (1991) recommend that hyperconcentrated flow be used to refer to non-Newtonian flows with little or no strength that produce deposits that are intermediate in nature between streamflow and debris-flow deposits. Deposition occurs by particles dropping out of the flow as individual grains, and the remaining fluid continues to move; hyperconcentrated flow thus results in deposits with the particles in contact with each other (i.e. clast supported). Hyperconcentrated-flow deposits also show some sorting and gradation, depending on the velocity and depth of flow at the time of deposition.

**Slurry or debris flow.** Slurry flow is characterized by a substantial yield strength and plastic behavior, yet the fluid retains at least partially liquid properties (i.e. it will spontaneously assume the shape of its container) (Meyer, 1993). The onset of slurry flow in sediment-water mixtures is defined by Pierson and Costa (1987) to occur at the point where yield strength increases rapidly with increasing sediment concentration, probably due to internal friction that arises from interlocking of grains. In hyperconcentrated flows, particles are deposited as individual grains from suspension, and the remaining fluid continues to move; in debris flow, the sediment-water mixture flows as a single phase, and only the very largest particles may fall out of suspension. Deposition occurs essentially as a freezing in place of this single-phase mixture, and results in sharp, well-defined flow boundaries with significant relief. Levees lining the flow path and lobes of material at the path terminus are characteristic of this flow process. Deposits may contain gravel-sized, or larger, particles which are supported in a fine-grained matrix.

A large number of terms have been used for the processes and deposits of slurry flow, including debris flow, mudflow, and debris torrent. In this paper, we'll refer to the results of such a process as debris flow.

**Granular flow.** Granular flow occurs at high ranges of sediment concentration, where the mass loses it ability to liquify, and frictional and collisional particle interactions dominate the flow behavior (Pierson and Costa, 1987). At the lower end of this range, granular flows may have similar field characteristics to high-strength slurry flows; the upper end of the range extends to flows with no water, requiring steep slopes or high inertia for movement. In the upper end of the range, dry ravel, the particle-by-particle transport of material downslope due to gravity, can occur. This process has been described on steep slopes following a fire, where loose, noncohesive material was formerly anchored by vegetation. Dry ravel has been described as an important post-fire process in southern California, where the channels are loaded with sediment, increasing available sediment for large events (e.g. Florsheim, et al., 1991; Scott and Williams, 1978; Wells, 1981, 1987).

Debris avalanches are very rapid or extremely rapid inertial granular flows, most often generated by the *en masse* failure of sizeable masses of material (Pierson and Costa, 1987). This type of mass movement has been linked to fires in the humid conifer forests of the Cascade Range, where failures commonly involve all or part of a thick, commonly water-saturated colluvial and soil mantle overlying bedrock (Swanson and Dyrness, 1975). These failures probably occur due to decay of tree roots and resulting loss of anchoring effects (Meyer, 1993).

## The Role of Vegetation in Slope Stability and Erosion

In a watershed, vegetation provides five major physical functions that help control soil erosion during rainfall events (Spittler, in press):

o Interception of rainfall, which extends the time for water to reach the ground surface and absorbs raindrop impact energy.
o Mulching of the ground surface to provide temporary water storage and slow release, slope roughness, and energy absorption.
o Structural support of loose, surficial material.
o Reinforcement of the deeper soil by roots, which increases the natural slope stability.
o Maintains conditions necessary for soil micro-organisms that provide soil structure.

On unburned slopes, live vegetation and vegetative litter intercept and slowly transmit precipitation to the soil. During normal rainfall events, the volume of rainfall that infiltrates into the soil is generally high, so that little surface flow occurs. Water from the surface soil percolates to the ground water table and migrates down gradient in slope-forming materials. Rainfall may ultimately emerge as surface flow from streams and stream channels. Water flows slowly through the soil, often traveling a few meters or less per day. This reduces the size of flood peaks and allows streams to continue to run significantly beyond individual storms.

When a watershed is burned a number of possible hydrologic and geomorphic changes occur, including (modified from Swanson, 1981):

- o Enhanced wind erosion.
- o Increased rates of dry ravel of loose material.
- o Decreased rainfall interception and infiltration, resulting in increased surface runoff.
- o Increased rainsplash, rill, and sheetwash erosion.

All of these processes result in destabilization and accelerated erosion of slopes. Enhanced wind erosion and increased rates of dry ravel of loose material occurred on Storm King Mountain in the time following the fire and up to the September rain storm. In the days following the fire, residents of Glenwood Springs reported seeing huge clouds of dust flying above the mountain; presumably the loose, friable and virtually unprotected burned mineral soil and ash were being transported by wind and dry ravel and deposited on the hillsides and in the side drainages. Further, decreased rainfall interception and infiltration and increased rainsplash, rill, and sheetwash erosion occurred during the September storm.

Following a fire, instead of the volume of rain water being routed through the hydrologic system over a period of days to months as soil water and ground water, it may force its way through the system over a period of several hours as surface flow or runoff. Greatly increased surface runoff is expected from intensely burned slopes primarily due to the lack of rainfall interception by vegetation (Spittler, in press). This causes the infiltration rate of the soil to be rapidly exceeded in brief, intense storms. In addition, the volume and velocity of the surface runoff can increase rapidly due to the lack of impedance by vegetation and litter (Wells, 1981, 1987); such high-discharge flows will result in the formation of gullies or rills on hillsides. The erodibility of a soil can be considered to be a function of the dispersivity of the clays present. Dispersivity is defined as the degree to which clay particles repel each other, and results in the disintegration of the clay structure, and thus erosion. The presence of ash in a soil, in some cases, may increase its dispersivity (Durgin, 1985). Wells (1987) describes a process where the excess water that cannot penetrate into the soil saturates only the most surficial material which may then fail as very small-scale debris flows or grain flows. This then leads to the formation of gullies and rills on a hillside. In addition, the gullies and rills provide an efficient means for transporting surface runoff and sediment to the stream channels. Peak flows in the channel may occur with less of a lag time than those observed in unburned watersheds, and flood peaks are often much higher and more capable of eroding sediment stored in the channel. Any loose, permeable material in the channel can easily be entrained by the increased surface flow, and channel incision can also occur. Finally, the size of storms necessary to surpass the critical stream power required to mobilize sediment stored in the channel is reduced. This is a consequence of the increased peak flow of streams in burned watersheds caused by rapid runoff (Spittler, in press).

## GEOLOGIC SETTING

The boundary of the area burned in the South Canyon fire, visible in the 1:8000-scale aerial photographs, is shown on Plate 1, a topographic map of Storm King Mountain. The area is underlain by Permian- and Pennsylvanian-aged Maroon Formation (Fairer et al. 1993). This formation is principally bright reddish orange and reddish brown conglomerate, conglomeratic sandstone, arkosic sandstone with interbeds of siltstone, mudstone, claystone and shale, and minor thin beds of limestone. From the highway to approximately 2000 feet to the north, the beds dip steeply to the southwest at between 35 to 50 degrees. Continuing to the north, the beds then flatten to nearly horizontal due to either to faulting or folding, depending on the location. The bedding steepens again on the upper flanks of Storm King Mountain.

The Maroon Formation weathers rapidly to a silty-sand matrix colluvium, and this material has a history of producing debris flows in the Glenwood Springs area (e.g. Mears 1977; Morris, et al., 1982). These debris flows differ from those that occurred in September on Storm King mountain in that they were more viscous, had a lower water content, were slower moving, and contained more large material. Evidence that more viscous flows occurred in the past can be observed in the canyons of Storm King Mountain.

Two extensive, deep-seated landslides are also mapped by Fairer, et al. (1993) and Soule and Stover (1985) on the flanks of Storm King Mountain. Our own photographic analysis indicates that these two landslides could be considered as one large landslide that covers the mid-slope flank of the mountain (Plate 1). This large landslide comprises an area of approximately 580 acres. Fairer, et al. (1993) assigned a Holocene to late-Pleistocene age to the deposits, described them as chiefly unsorted and unstratified rock debris characterized by hummocky topography, and suggested a maximum thickness of possibly 150 feet.

The maps by Fairer, et al. (1993) and Soule and Stover (1985) also show wedges of unsorted, clast-supported colluvium that may be as much as 15-ft thick located adjacent to the stream channel in drainage B. Field examination of the watershed and our own photographic analysis indicates the extent of these unconsolidated materials is significantly greater than previously mapped; a thick wedge of deeply dissected alluvium and colluvium fill the valley associated with drainage B, while nearly all of the side slopes of the other drainages are mantled with a thick deposit of colluvium.

Thus a preliminary examination of the pre-fire setting suggests that even without the fire, three geologic hazards are evident on Storm King Mountain; debris flow, mobilization of the colluvial and alluvial material by downcutting, and destabilization of the deep-seated landslide deposits, also by erosion. Debris flow is an ongoing process on Storm King Mountain, as evidenced by remnants of recent debris-flow deposits observed in the channels and reports of their periodic occurrence. However, without the exacerbating effects of the fire, the probability of the mobilization of the colluvial and alluvial materials and destabilization of the deep-seated landslide deposits is minimal.

## Watershed Configuration

The Storm King Mountain watershed is characterized by an average gradient of 30%, with some hillsides, particularly in the lower portion, having gradients greater than 70%. The terrain mapped as landslide deposit has an average gradient of 30%. Soils in the lower third to half of the burn are described in a Bureau of Land Management memo from M. McGuire, Soil, Water and Air Lead, to M. Mottice, Area Manager, as very shallow, recent, poorly developed, with a high percentage of rock, and supporting a sparse pinyon-juniper vegetative community. These soils are classified under the Unified Soil Classification System (Craig, 1987) as either a silty sand or an inorganic silt, silty or clayey fine sand, with slight plasticity (Table 1). The grain-size distribution of this material is shown in Figure 3A. The Bureau of Land Management memo further describes the upper watershed soil as a stony loam which supports a mountain shrub vegetative community.

**Table 1. Physical properties and classification of materials.**

| Sample | Description | LL | PL | Unified Soil Classification |
|---|---|---|---|---|
| ST-3 | in place, unburned soil | 32.0% | 26.1% | ML |
| 11-A | in place, unburned soil | ----- | ----- | SM |
| 10A,B | in place, burned soil | ----- | ----- | SM* |
| P-2 | dry ravel | ----- | ----- | SM* |
| ST-1 | dry ravel | 20.0% | nonplastic | SM |
| ST-2 | slurry | 29.0% | 27.0% | SM |
| USGS-12 | slurry | 32.1% | 31.7% | SM |
| GS-17 | slurry | 28.1% | nonplastic | SM |
| ST-4 | slurry | 27.2% | 26.9% | GM |
| GS-19A | slurry | ----- | ----- | GM* |

*assume PI<4%

The watershed can be divided into seven major drainages, labeled as A through G on Plate 1, all of which are direct tributaries of the Colorado River. These drainages typically have short, steep stream channels and precipitous side slopes. This topographic configuration is conducive to a rapid concentration of runoff and, when combined with intense rains, is a primary cause of high peak discharge and erosion rates (Rowe et al, 1954). In addition, two watershed front areas (H and I) are delineated on Plate 1. The areas of each drainage and watershed front, and the percentage of the drainage or front burned, are tabulated in Table 2.

**Table 2. Areas of major drainages, burned area, and percentage of drainage burned, within the Storm King Mountain Watershed.**

| Drainage | Area | Burned Area | Percent Burned |
|---|---|---|---|
| A | 496 acres | 23 acres | 5% |
| B | 555 acres | 513 acres | 92% |
| C | 568 acres | 562 acres | 99% |
| D | 186 acres | 177 acres | 95% |
| E | 127 acres | 73 acres | 57% |
| F | 562 acres | 328 acres | 58% |
| G | 99 acres | 79 acres | 80% |
| H | 153 acres | 126 acres | 82% |
| I | 174 acres | 0 acres | 0% |

## THE POST-FIRE, PRE-DEBRIS FLOW SETTING

The South Canyon fire burned approximately 2000 acres of pinyon-juniper and mountain shrub vegetative communities (Plate 1 and Figure 2). The most intensely burned area extends from roughly 0.5 mile up the mountain side to near the summit of the mountain, and is characterized by the complete burning of large branches and many major tree trunks, completely burned brush and grass, and the presence of both dark and white ash (Figure 4). Some sandstone outcrops were fractured by the intense thermal stresses. The burnt soil is loose and friable, and approximately 2 to 4 inches in depth (Figure 5). Two samples of burnt soil (taken from the same location but at depths of 0-1 inch and 1-4 inches) were classified as silty sand (Table 1). The grain-size distribution of the burned soil is essentially the same as that for unburned soil (Figure 3A), indicating no discernable alteration in grain-size distribution occurs with burning. The average dry density of three samples of burned soil is 0.026 $lb/in^3$.

Around the margins of the heat of the fire was less intense; within this zone some leaves are left on trees, branches are only partially burned, and scattered clumps of grass with some short stubble remain. Approximately 0.25 to 1.0 inch of charcoal on top of 0.5 to 1.5 inches of loose, friable, burned soil are present.

The development of a few-centimeter thick water-repellant layer in the soil formed by the condensation of hydrophobic organic compounds upon burning and vaporization of vegetation and litter is often described as the result of a fire, and can effect the erosion potential of a site by increasing surface runoff (Wells, 1987). Hydrophobic soils were observed in the burned area and obvious hydrophobic characteristics were observed to a depth of five inches in laboratory samples of burned soil; water stood on the samples for at least four hours before sinking in. Note however, that other researchers have stated that such a layer can, in fact, be more common in unburned sites than burned, and thus a water-repellant layer is not necessary for the development of a major surface runoff event following a fire (e.g. Meyer, 1993).

In the days following the fire, residents of Glenwood Springs reported seeing huge clouds of white dust flying above the mountain; presumably the loose, friable and virtually unprotected burned mineral soil and ash on the hillsides were being transported by wind and deposited in the side drainages. The processes of dry ravel also resulted in the downslope transport of material. Accumulations of loose, silty sand material and ash up to 3 ft deep along the sides of most side drainages were observed (Figures 6 and 7, Table 1). This material is well sorted, and is devoid of the >0.5mm fraction seen in the in place soils (Figures 3A, B). A void ratio of approximately 0.33 was obtained for a sample of this material by determining the amount of water added to a known volume of material at saturation. Aprons of this loose material were also observed on many side slopes (Figure 8). Further, larger material in the form of loose boulders, cobbles and channel alluvium has been deposited in the channel over the years by either gravity-driven or stream and debris-flow processes (Figure 7). The material in the channel was available for entrainment by channel runoff during the storm, and the material on the side slopes was susceptible to erosion and transport by surface flow.

**SEPTEMBER, 1994 EVENT**

On the night of September 1, 1994 at approximately 10:30 pm, in response to a torrential downpour, a wall of mud, rocks and burned trees came crashing down onto Interstate I-70 in four places. Thirty cars traveling on the highway at the time were engulfed by the mud, but luckily only minor injuries were reported. According to Colorado Department of Transportation personnel, material continued to flow out of the canyons throughout the night of September 1 and the early morning hours of September 2.

Mud and debris issuing from the mouth of drainage B overtopped the Jersey barriers that divide the west- and east-bound lanes of the interstate and continued into the Colorado River, where it was deposited as a fan that blocked nearly half of the river (Plate 1, Figure 9). Material from drainage B also traveled westward along I-70, again overtopping the Jersey barriers into the east-bound lanes, and finally stopped at mouth of drainage A (Figures 10 and 11, Plate 1). The coarsest material in the flow was deposited at the mouth of the canyon, while the more fluid material continued over the interstate (Figure 12). Sample ST-2, collected from a terrace surface near the canyon mouth, was classified as a silty sand (Table 1) and its grain-size distribution is shown in Figure 3C. Sample GS-19A, collected from the fan deposited at the mouth of the canyon, shows a considerably greater coarse fraction, and is classified as a silty, sandy gravel (Table 1, Figure 3C).

Material from drainage C traveled down the I-70 access ramps, under the overpass, and continued to the Colorado River (Plate 1, Figure 13). The access roads were buried by up to 5 feet of mud, boulders, and debris, with an average depth 2 feet. An average density of $0.055 lb/in^3$ (1.53 times higher than that of water at $0.036 lb/in^3$), and a water content of 53% by weight was determined for these materials by Brain Menounos of the University of Colorado from samples taken on September 4, 1994 beneath the overpass. Material collected from the fan deposited at the canyon mouth (Sample GS-17) is classified as a silty sand (Table 1); the gradation curve for the sample is shown in Figure 3C. Sample USGS-12 was taken at the head of a slight draw on the canyon sidewall of drainage C, as the first appearance of debris-flow deposits, and is also classified as a silty sand, and its particle-size curve differs from that of sample GS-17 in that it has slightly more fine materials (Figure 3C).

Material issuing from the mouth of drainages F and G also covered the interstate with layer of mud and debris from a few inches thick to 0.5-feet thick.

Deposition of material also occurred at the bases of the two watershed fronts (H and I, Plate 1). Figure 14 shows that material that was deposited in the west-bound lane and along the interstate at the base of watershed front I.

Interstate I-70 was closed until 3 pm September 2 when one lane in each direction was opened. Approximately 14,900 vehicles use I-70 on a typical day.

Material was deposited at the mouths of every major drainage whose upper reaches were burned (Plate 1). Calculations of the areas inundated by the flow events are tabulated in Table 3, along with the approximate volume of material deposited at the canyon mouths, calculated by assuming an average depth for each deposit. A total area of approximately 35 acres was inundated.

**Table 3. Area inundated, average depth, and volume of material deposited at each canyon mouth.**

| Drainage | Deposit Area (acres) | Average Depth (ft) | Deposit Volume ($yd^3$) |
|---|---|---|---|
| B | 8.5 | 2.0 | 27,400 |
| C,D | 15.9 | 2.0 | 51,400 |
| E | 1.1 | 1.0 | 1,800 |
| F | 5.8 | 0.6 | 5,600 |
| G | 1.7 | 0.5 | 1,400 |
| H | 1.1 | 1.0 | 1,800 |
| I | 1.1 | 1.0 | 1,800 |
| | | **TOTAL:** | 91,300 $yds^3$ |

The estimated volumes of deposits are conservative in that an average depth of deposits over the road and ground surface was used; the depth of material deposited in the basins at the mouths of the canyons is not taken into account.

## Rainfall Conditions

Unfortunately, only daily rainfall totals recorded at a site approximately 2 miles from Storm King Mountain are available; the rainfall total for Friday, September 2 of 0.67 inches was recorded at the corner of 13th and Grand Avenues in Glenwood Springs. Eyewitness accounts suggest that rainfall conditions on the west end of Glenwood Springs (and closer to Storm King Mountain) were more severe than are indicated by this total. A motorist described the rain as "...so hard you almost couldn't see. It came down like a monsoon". The first and strongest pulse of intense rainfall was reported to have occurred between 8 and 9 pm, another pulse of intense rainfall occurred at 10:30, and rain was still falling heavily at 11pm.

The recurrence interval for the 24-hour rainfall total reported for this storm is not long, indicating that the 24-total was not an unusual event (N. Doeskin, State Climatologist, personal communication, 1995). Observations that this amount of rainfall fell in a very short time period, however, would suggest a less frequent recurrence of short duration, intense rainfall. The lack of detail of the recording station, or site-specific data for Storm King Mountain, precludes this determination, however.

## The Mobilization of Sediment from Burned Basins

Principal mechanisms for the mobilization of sediment from Storm King Mountain include particle-scale, grain-by-grain failure of surficial material leading to the formation of rills and gullies, the entrainment of the loose, dry ravel material in the side channels and colluvium and alluvium in the main channels by surface runoff. These processes in the burned basins caused sediment concentrations to progressively increase and produced debris-flow conditions.

Wells (1987) suggests that saturation of a thin layer of surficial soil during an intense rainfall event may result in the formation of either small-scale granular or debris flows. Continued and sequential small-scale failures lead to the formation and of rills and gullies.

On Storm King Mountain, the formation of rills and gullies was observed in both the inplace, burned mineral soil and in the aprons of dry ravel material on the side slopes leading to drainages (Figure 15). Rills started up high on the slopes and their relative density, depth, and width increased with distance down slope. Formation of rills and gullies served to contribute loose mineral soil from the hillsides into the channels, as well as to provide efficient transportation routes for surface runoff. This is a self-perpetuating process; as the flow volume increases, more material is entrained, and the rills and gullies deepen and widen.

Field estimates made following the September events suggest that during the September storm on Storm King Mountain, approximately 15% of the burned mineral soil was removed to an approximate average depth of 1.5 inches by rill and gully formation. Note that the degree of rill and gully formation on Storm King Mountain is considerably less than that observed in burned watersheds in Yellowstone National Park (Meyer, 1993), and near San Luis Obispo, California (S. Ellen, U.S. Geological Survey, personal communication, 1994).

The more predominant sediment-transporting mechanism acting on Storm King Mountain was progressive sediment bulking of the surface runoff. The abundant loose, friable material blown and transported into the side channels by wind and dry ravel in the days following the fire was incorporated into the surface flow as it progressed downchannel. In addition, the material deposited and stored in the stream channels from years of smaller flooding and debris-flow events was incorporated into the flows. Detailed observations high on the hillside in drainage C indicated that at a point 300 ft below the ridgecrest, sufficient loose material had been entrained by the surface flow to give debris-flow qualities to the deposits.

The widespread occurrence of the process of debris avalanche as sources for debris flow, described previously, is precluded by the observation of the lack of numerous or widespread scarps or depressions at the head of drainages that experienced flow events on Storm King Mountain. A few landslide scarps are noted on Plate 1, but most of these contributed little volume of material to the prevalent process. The lack of debris avalanche scars observed in the burned area of Storm King Mountain is in keeping with the general observation that debris avalanches are less likely to occur in burned areas than in unburned ones. For example, Morton (1989) mapped eight times the number of debris flows on unburned slopes than occurred on burned slopes in the San Timoteo Badlands of southern California. This phenomenon is explained by increased surface runoff following a fire, so that failure triggered by infiltration is reduced.

The net result of the September rainstorm was to flush most of the dry-ravel deposits from the side channels, transport the loose, larger material from the main channels, and precipitate the erosion of loose surficial soil from the hillsides.

## Flow Dynamics

In general, the flows show an interesting combination of both debris- and hyperconcentrated-flow processes. As the flows traveled down the canyons, and particularly at the mouths of the canyons where material cascaded over high sandstone cliffs, they can be considered as hyperconcentrated. Figure 16 shows the deposits left by the passage of a flow through drainage C. At the margins of the flow path, the material deposited was very thin, indicating a high water content. In addition, as shown in Figure 17, the loose, friable mineral soil and ash that the flow traveled over was not disturbed, indicating the low strength of the flowing material. Within the channel, deposits of large boulders in a muddy matrix indicated a much stronger slurry that would approach the debris-flow behavior end of the sediment-water flow continuum (Figure 18). A cross-section through the flowing material would thus show a downward gradation from a very fluid, low strength slurry at the top, to a much higher strength slurry at the base. This gradation (representing a non-single phase fluid) is shown by the particle-size distribution for the slurry materials in Figure 3C, and is a diagnostic feature of hyperconcentrated flow. The deposits at the mouths of the canyons also show characteristics typical of hyperconcentrated flows. Figure 19 is a photograph of a cut made into the deposits at the base of drainage C and shows an approximately 1-foot thick layer of well-sorted, fine-grained material that grades downward into clast-supported, gravel- and boulder-size material at the base, another characteristic of hyperconcentrated flow. In this setting, most of the coarser-grained material settled out of suspension, and the interstitial fluid, consisting primarily of fine-grained silts and clays held in suspension, then continued to travel over the interstate and into the Colorado River as a single-phase, but low strength, hyperconcentrated flow.

Approximate velocities of the flows in drainages B, C, and F at the locations of the transects shown on Plate 1 were calculated using a technique proposed by Johnson, (1984). This technique is based on the observation that lateral deposits are commonly higher on the outsides of bends than on the insides. In this approach the velocity of the flow is calculated as a function of the degree of runup around a curve β, the channel gradient λ, and the radius of curvature of the path R, where

$$V=\sqrt{gR\cos\lambda\tan\beta}$$

This approach is based on the assumption that the material in the flow behaves as a perfect fluid, and is thus a reasonable approximation for the low-strength phase of the Storm King Mountain flows.

Approximate calculated velocities, the cross-sectional area of the flow at that location, and the calculated peak discharge are tabulated in Table 4. Note that the discharge calculated must be considered as the peak because the upper-most margins of the deposits (used in calculating cross-section areas) are those left during peak flows. Work by Rowe et al., (1954) indicated that peak discharge was the best indicator of watershed performance and was particularly sensitive to fire effects.

**Table 4. Calculated velocities, cross-sectional areas, and peak discharges of the flows for given drainages.**

| Transect | Drainage | Velocity (ft/sec) | Area ($ft^2$) | Discharge ($ft^3$/sec) |
|---|---|---|---|---|
| 1 | B | 22 | 187 | 4000 |
| 2 | B | 10 | 110 | 1000 |
| 3 | B | 15 | 189 | 2810 |
| 4 | B | 19 | --- | --- |
| 5 | C | 28 | 92 | 2600 |
| 6 | C | 10 | 110 | 1100 |
| 7 | C | 19 | 78 | 1500 |
| 8 | F | 20 | --- | --- |

Note that the values for Transects 6 and 7 were supplied by Brian Menounos, University of Colorado.

Although the velocities and discharges given in Table 4 are only approximate, the range of velocities reported is within the range of those reported by Mears (1977) for debris flows triggered by intense rainstorms in Glenwood Springs. The range of discharges reported here is nearly twice those reported by Mears (1977), perhaps due to the fact that these were fire-related events, with substantially more material available for incorporation into the flows. In addition, the difference of 3000 $ft^3$/sec calculated between transects 1 and 2 in drainage B occurs over a distance of only 200 ft; the only explanation for this difference being the degree of accuracy in determining the variables used in calculating the velocity. These values thus must be viewed as approximate ranges.

## REMAINING HAZARDS AND STEPS NECESSARY TO EVALUATE THEIR IMPACT

A number of different scenarios exist for the hazards posed by the current conditions at Storm King Mountain. These are discussed below in order of perceived probability of occurrence. In addition, steps to evaluate the potential impact of the first, and most likely, hazard (debris flows from the mobilization of channel alluvium and hillside materials), are described. Further, steps to assess the potential for the occurrence of the following two, less likely, hazards (debris flows from the mobilization of the colluvial wedge and reactivation or headward erosion of the old landslide deposits), are outlined.

### Debris Flows from Mobilization of Channel Alluvium and Hillside Materials

Although the net result of the September rainstorm in the burned drainages on Storm King Mountain was to remove the most easily eroded material from the channels and hillsides, a considerable hazard from such intense rainfall events still remains. In the months following the September events, considerable incision into the channel alluvium was observed, in some places up to 8 ft. Incision and entrainment of channel alluvium has been cited by several investigators as a debris-flow sediment source (e.g., Beaty, 1963; Scott, 1971), and abundant evidence for bulking of flood discharges with channel alluvium and subsequent transformation to debris-flow conditions was observed in lahar events following the 1980 Mount St. Helens eruptions (Scott, 1988). More specifically, work by Florsheim et al. (1991) in a southern California watershed that experienced a wildfire shows that the initial sedimentation events involving the dry ravel material in the channels was followed the next year by debris flows containing material that was eroded from the channel itself.

In addition, there is still abundant loose material left on the hillsides that, given another intense storm, could be delivered into the channels and then mobilize into debris or hyperconcentrated flows.

Considerable rainfall and resulting surface flow would be necessary to mobilize hyperconcentrated or debris flows from the existing channel alluvium, and the volume of material that would be involved in such an event, or that would reach the canyon mouths in any given rainfall event, is unknown at this time. Further, the volume of material that would be eroded from the hillsides and transferred to the canyon mouths by debris flow in any given storm is also unknown.

The following steps are recommended to fully assess the impact of this hazard:

1) Determine the volume of material available for mobilization in the channels and hillsides.

2) Characterize the erosion susceptibility of the materials in the channels and on the hillsides relative to rainfall events of varying intensities and durations. Determine where within the topography failure is likely to occur and at what rates.

3) Develop a model for debris-flow processes that can be used to simulate debris-flow travel through a digital elevation model of the area. Start with existing sediment routing models (e.g. McEwen, 1989; O'Brien, 1985), and modify to reflect the factors evaluated above. Such a model could potentially predict paths and flow rates within channels in the watershed.

**Debris Flows from Mobilization of Colluvial Wedge**

A further hazard exists from incision into channel alluvium in the form of the destabilization of the colluvial wedges located in drainage B. If sufficient channel downcutting occurs, and the entire mass fails catastrophically into the channel, approximately 403,000 $yd^3$ of material would be available to be mobilized from drainage A and 323,000 $yd^3$ of material from drainage B.

Again, at this time it is not known how much of the wedges would fail, or how much of the material would be mobilized by high surface flows, how much of this material would then reach the canyon mouth, or under what rainfall conditions this would occur.

The following steps are recommended to evaluate the potential for the occurrence and the impact of this hazard:

1) Determine rates of channel incision under different rainfall and surface flow conditions. If incision is proceeding at unprecedented rates, then the following procedures are recommended in order to asses the impact of this hazard.

2) Determine both the failure susceptibility of the colluvial wedges and the erosion susceptibility of the materials once deposited in the channel, again relative to rainfall events of varying intensities and durations. This information could then be incorporated into the model for debris flow described above to determine flow rates and volumes within the channel and at the canyon mouths.

**Reactivation or Headward Erosion into Old Landslide Deposits**

Some possibility exists that the removal of the vegetation by the fire may result in the destabilization of the old landslide deposits. Destabilization could occur in response to two processes: the headward erosion of the canyons at the base of the landslide, and dissection of the surface of the landslide deposits by deepening gullies. Examination of the aerial photographs indicates that a few steep drainages are superimposed on the lower reaches of the landslide deposits. Some drainage continues from the landslide deposits down into the heads of the canyons. If accelerated erosion in a very intense and long duration storm or storms should occur, the headwalls of these canyons could continue to retreat upslope, leading to the destabilization of the landslide mass by removal of downslope support. In addition, if the conditions of increased surface flow, brought about by the removal of vegetation, were to result in the formation of numerous very deep gullies into the surface of the landslide deposits, the breakup of the landslide mass and its eventual destabilization by removal of lateral support might occur. It is unlikely that the entire mass of the landslide deposits would be destabilized at once, and the time frame and rainfall conditions under which this process would occur are unknown. It is further not known if such a destabilization would result in the mobilization of the material into debris flows, or as translational failure of the smaller, broken up blocks. And again, it is not known how much material from such a failure would reach the canyon mouths.

The following steps are recommended to evaluate the potential for the occurrence of this hazard and to preliminarily appraise its impact:

1) Determine both the rates of headward erosion of the canyons into the foot of the old landslide deposits and rates of gully incision into the surface under varying rainfall conditions. If either of these two processes appear to be proceeding at unprecedented rates, the following steps are recommended:

2) Carefully map and determine the complete aerial extent of the landslide deposits and the depth to the failure surface.

3) Determine the location and volume of unstable blocks through careful and detailed evaluation of movement kinematics. Asses the stability of these blocks in terms of both failure and mobilization mechanisms.

4) If analyses indicate the unstable blocks may mobilize into debris flows, evaluate flow behavior and travel-distance potential using the model for debris-flow processes described above.

Note that careful and detailed field mapping on accurate large-scale maps is essential to all of the above objectives.

## SUGGESTIONS FOR IMMEDIATE RESPONSE

We suggest the following actions as an immediate response to the potential hazards described above. Note that these actions do not mitigate the hazards, and the steps outlined above are necessary to properly evaluate their potential impact.

Monitor conditions at Storm King Mountain throughout the spring snowmelt and thunderstorm season for a number of years. Repeated field examination is necessary to determine if headward erosion of steep canyons into the old landslide deposits is occurring, if gullies are forming and deepening on the surface of the landslide deposits at unprecedented rates, and if the colluvial deposits are being undercut.

Install an automated weather station on Storm King Mountain to track approaching storms. The station needs to be able to detect storms of the appropriate scale. It will also be necessary to define those weather conditions that present a hazard in order for a warning to be issued. Weather information for the September event was insufficient to draw any conclusions from, but ongoing observations of the occurrence of sedimentation events following storms could eventually lead to the qualitative definition of a rainfall threshold for hazardous conditions.

Consider installing an early-warning device across susceptible canyons. The motion of a large flow could trigger the device, allowing either warning signs to be activated, or the interstate to be closed.

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Wells, W.G., 1987, The effects of fire on the generation of debris flows in southern California: in, Costa, J.E., and Wieczorek, G.F., eds, Geological Society of America, Reviews in Engineering Geology, vol.7, pp.105-114. Figure 2. Storm King Mountain after the burn. View is from west to east. Photograph by Pat Rogers, Colorado Geological Survey.

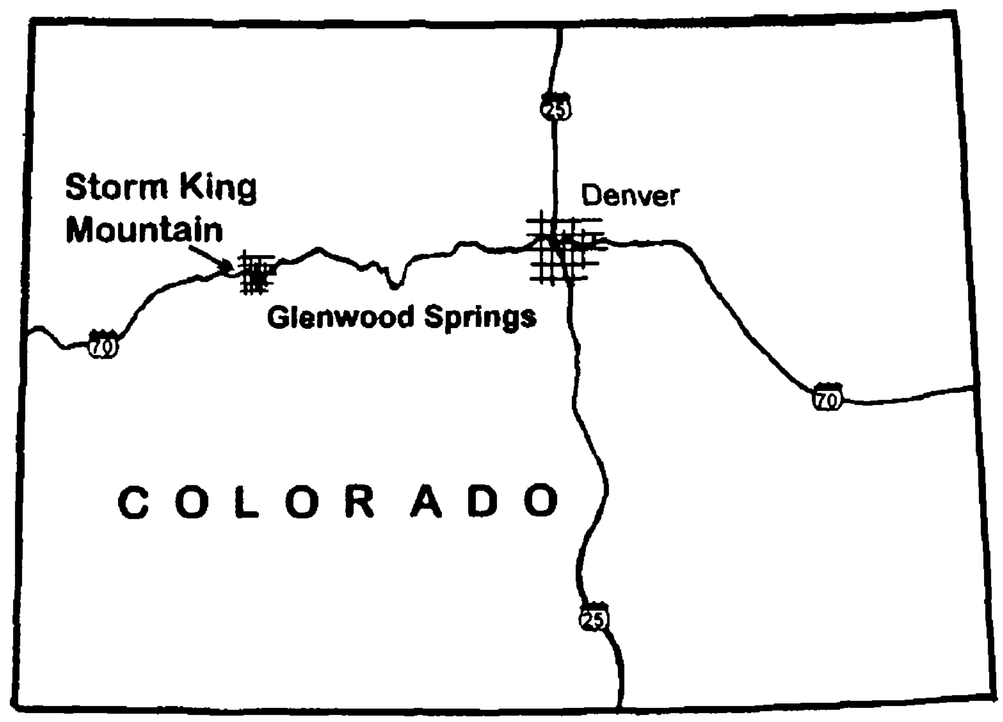


**Figure 1.** Location map of study area.

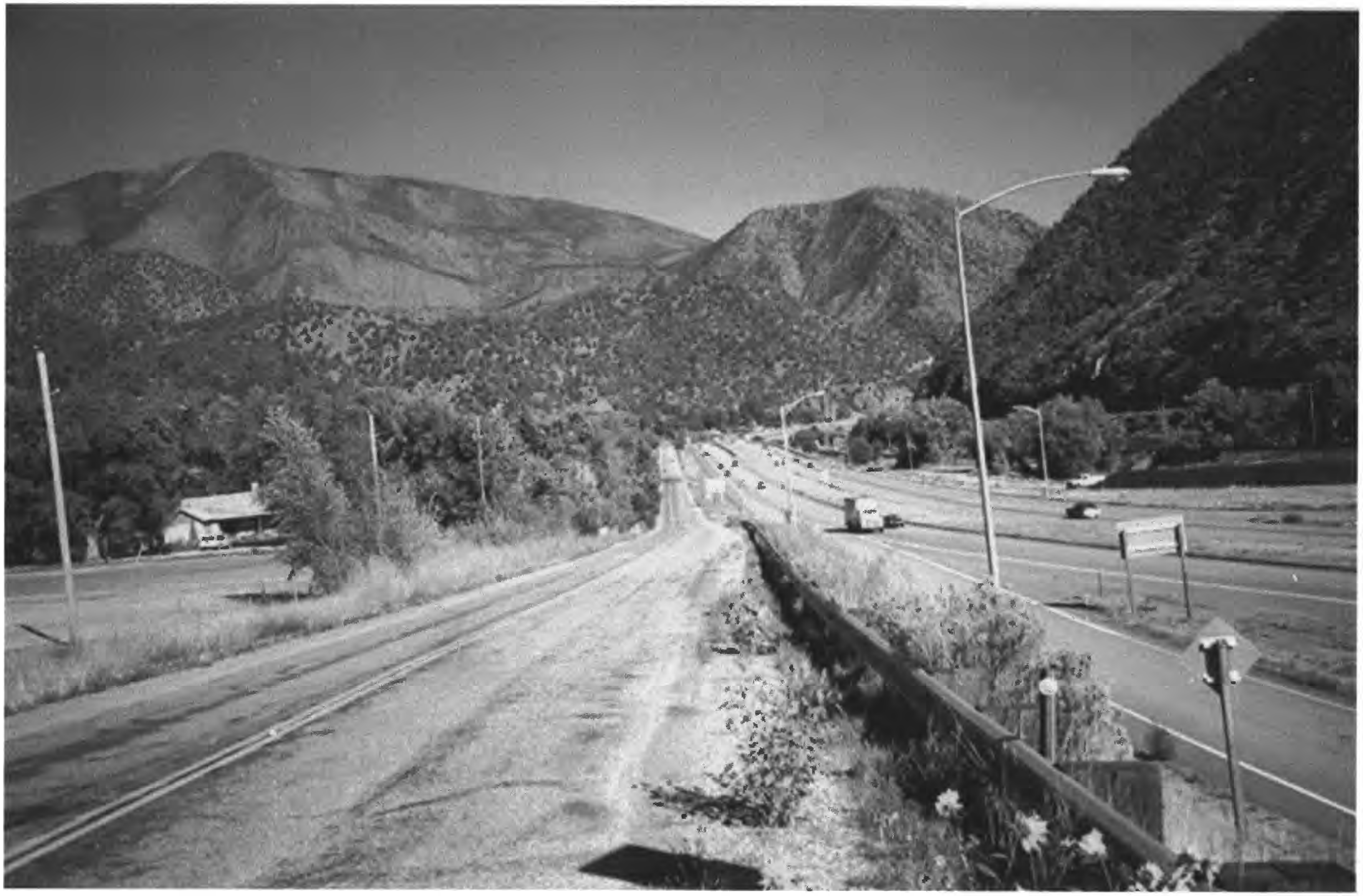

**Figure 2.** Storm King Mountain after the burn. View is from west to east. Photograph by Pat Rogers, Colorado Geological Survey.

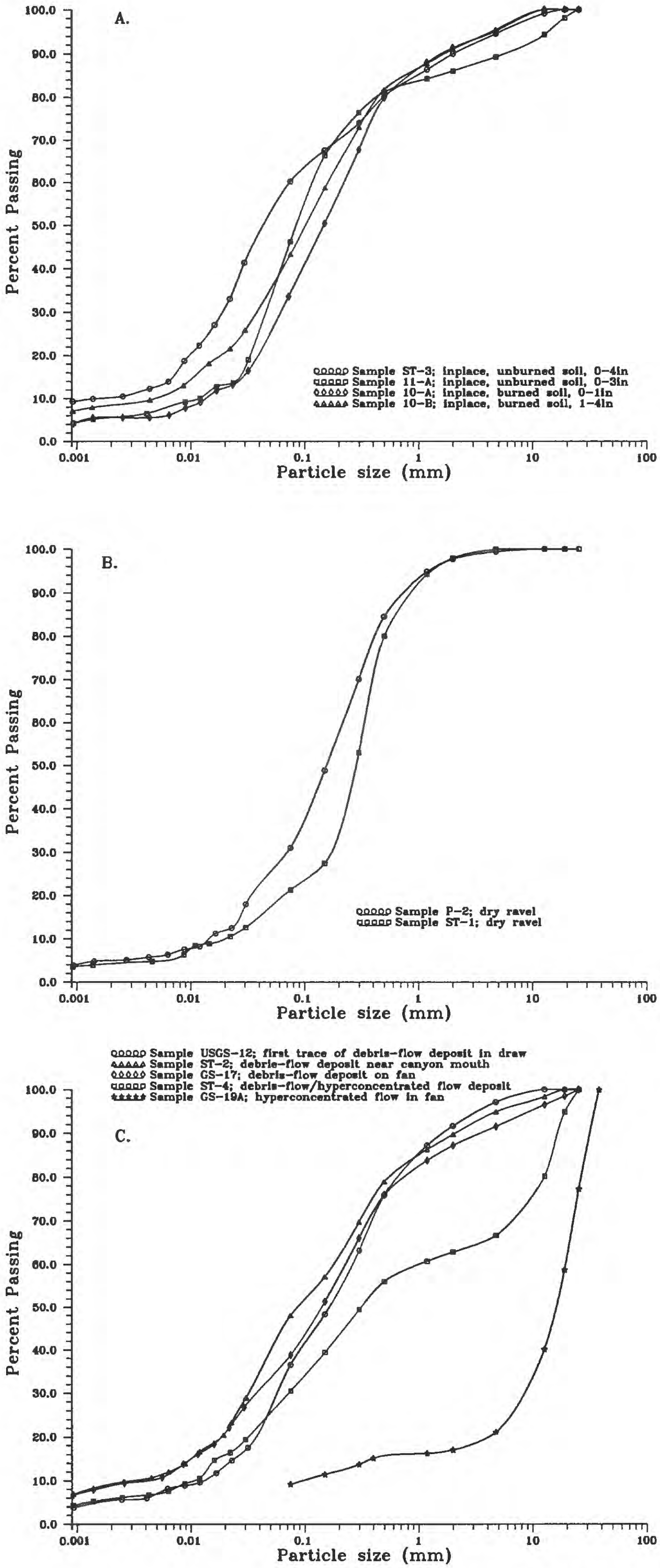


**Figure 3.** Grain-size distribution curves for: A. inplace burned and unburned soils, B. dry ravel material, and C. slurry.

**Figure 4.** Area of intense burn showing degree of destruction of vegetation, and loose surficial soil and white ash in foreground. Photograph by Roger Pihl, Colorado Geological Survey.

**Figure 5.** Close up view of loose surficial soil and ash. Loose material is approximately 2 inches thick. Photograph by Roger Pihl, Colorado Geological Survey.

**Figure 6.** Photograph of loose, fine-grained material transported by dry ravel and wind and deposited in side channels. Deposits, which may be up to 3 feet thick, supplied material for debris flow events in September. Photograph by Roger Pihl, Colorado Geological Survey.

**Figure 7.** View down channel C before flows. Note small apron of loose dry ravel material deposited along margins of channel and the larger loose boulders; both materials were available for entrainment by the September flow events. Photograph by Roger Pihl, Colorado Geological Survey.

**Figure 8.** Phogotgraph of dry ravel material deposited as apron on hillside. Photograph by Susan Cannon, U.S. Geological Survey.

**Figure 9.** Photograph of deposits at drainage B showing fan of material deposited in the Colorado River. Photograph taken on September 2, 1994 by Bob Elderkin, Bureau of Land Management.

**Figure 10.** Photograph of material from drainage B showing extent of deposits westward along I-70. Photograph taken on September 2, 1994 by Bob Elderkin, Bureau of Land Management.

**Figure 11.** Photograph showing extent and character of material from drainage B deposited along I-70. Material traveled westward from drainage B to the mouth of drainage B. Note the fluid character of the deposits as they engulf the wheels of the fron-end loader. Photograph taken on September 2, 1994 by Bob Elderkin, Bureau of Land Management.

**Figure 12.** Photograph of path and deposits from flow down drainage B. Note deposit of larger-sized material right at mouth of the canyon and the more fluid character of the material that traveled down I-70. Photograph taken on September 2, 1994 by Bob Elderkin, Bureau of Land Management.

**Figure 13.** Photograph of deposits from drainage C. Material exited the canyon, traveled down the acess road, under the I-70 overpass, and downslope to the Colorado River. Photograph taken on September 2, 1994 by Bob Elderkin, Bureau of Land Management.

**Figure 14.** Material deposited at base of drainage I. Bridge over Colorado River at South Canyon Creek is visible in distance. Photograph by Roger Pihl, Colorado Geological Survey.

**Figure 15.** Photograph of rills and gullies on a blanket of loose, dry ravel material deposited on hillside. Rills and gullies also formed in burned surficial soil on hillsides. The average depth of rills on hillsides is estimated to be 1.5 inches, and the process removed approximately 15% of loose surficial material. Photograph by Roger Pihl, Colorado Geological Survey.

**Figure 16.** Deposits left in path of debris flow in drainage C. Material was deposited as a thin veneer of mud, and was particularly thin at margins of deposit. Photograph by Roger Pihl, Colorado Geological Survey.

**Figure 17.** Thin deposit of debris flow overlying very loose, friable ash and burned mineral soil. Undisturbed character of underlying material illustrates the low strength of the material deposited on top. Photograph by Susan Cannon, U.S. Geological Survey.

**Figure 18.** Material deposited near axis of flow in drainage C. This material was more viscous, indicating a higher strength than the material deposited at the margins of the flow. Photograph by Susan Cannon, U.S. Geological Survey.

**Figure 19.** Cut in hyperconcentrated flow deposits at mouth of drainage C showing fine-grained, well-sorted material on top grading into gravel-sized, clast-supported material at a depth of approximately one foot. Photograph by Susan Cannon, U.S. Geological Survey.