DEBRIS-FLOW RESPONSE OF BASINS BURNED BY THE 2002 COAL SEAM AND MISSIONARY RIDGE FIRES, COLORADO

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Key Terms: Debris flow, Wildfire, Rainfall thresholds, Hazard assessments

ABSTRACT

Debris flows can be one of the most hazardous consequences of rainfall on recently burned hillslopes. Understanding the conditions under which debris flows can occur, and characterization of the magnitude of the debris-flow response are critical elements in post-fire hazard assessments. In this study, we document the debris-flow response of basins burned by the 2002 Coal Seam and Missionary Ridge Fires. The Coal Seam Fire burned 12,229 acres in the steep terrain immediately west of Glenwood Springs and the Missionary Ridge Fire burned 72,962 acres just north of Durango. Eyewitness and newspaper accounts of the rainfall-induced runoff events, measurements of channel cross sections, maps of burn severity, and networks of tipping-bucket rain gages are used to develop estimates of the peak discharges of the debris flows and to define the conditions that resulted in the debris flows.

Debris flows were produced from basins underlain by interbedded sandstones, siltstones and conglomerates, and from basins underlain by gneissic quartz monzonite and quartzite. Debris-flow producing basins ranged in size from 0.01 to 8.24 mi^2, had average gradients between 26 and 94 percent, and relief ratios between 16 and 73 percent. Basins burned at moderate and high severities over more than 50 percent of their areas were susceptible to debris-flow activity. Nearly 70 percent of the debris-flow generating storms were of durations equal to or less than two hours, and 93 percent of the storms had recurrence intervals of less than or equal to 2 years. The average intensities of the debris-flow triggering storms ranged between 0.04 and 0.67 in/hr, with 10-minute peak intensities up to 2.46 in/hr. Estimates of debris-flow peak discharges between 315 and 5581 ft^3/s were obtained using indirect methods, and values of peak discharge

per unit area ranged between $1.0x10^{-5}$ and $1.2x10^{-3}$ ft/s. Debris flows with the highest values of peak discharge per unit area occurred in response to storms with average intensities greater than about 0.4 in/hr and with 10-minute peak intensities greater than about 2.0 in/hr. And last, a rainfall intensity-duration threshold for post-wildfire debris flow activity of the form $I = 0.25D^{-0.5}$, where I = rainfall intensity (in in/hr) and D = the duration of that intensity (in hrs) is defined.

INTRODUCTION AND APPROACH

The fire season of 2002 was extremely active in Colorado. More than 619,000 acres (247,600 ha) were burned by approximately 4600 fires throughout the state (U.S.D.A. Forest Service 2003, National Interagency Fire Coordination Center 2003). Some of the most extensive fire activity included the 137,800-acre (55,120-ha) Hayman Fire, the 12,229-acre (4892-ha) Coal Seam Fire, and the 72,962-acre (29,185-ha) Missionary Ridge Fire (Figure 1).

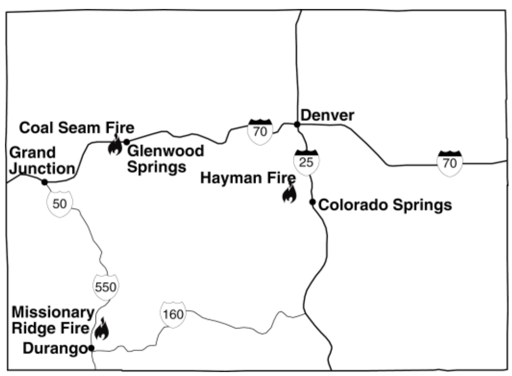


Figure 1. Map showing locations of Hayman, Coal Seam, and Missionary Ridge Fires of 2002 in Colorado.

Wildfire can have profound effects on a watershed. Consumption of the rainfall-intercepting canopy and of the soil-mantling litter and duff, intensive drying of the soil, combustion of soil-binding organic matter, and the enhancement or formation of water-repellent soils can result in decreased rainfall infiltration into the soil and subsequent significantly increased overland flow and runoff in channels (e.g., Doerr et al. 2000, Martin & Moody 2001, Moody & Martin 2001). Removal of obstructions by wildfire can enhance the erosive power of overland flow, resulting in accelerated erosion of material from hillslopes (Meyer 2002). Increased runoff can also erode significant volumes of material from channels, the net result being the transport and deposition of large volumes of sediment both within and down-channel from the burned area.

Debris flows are frequently produced in response to convective thunderstorm activity over basins burned by wildfire (Parrett 1987, Meyer & Wells 1997, Cannon 2001), as well as in response to winter frontal storms (Morton 1989, Cannon 2000). Debris flows pose a hazard distinct from other sediment-laden flows because of their unique destructive power; debris flows can occur with little warning, can exert great impulsive loads on objects in their paths, and even small debris flows can strip vegetation, block drainage ways, damage structures, and endanger human life. For example, a summer thunderstorm triggered debris flows from the steep basins burned by the 1994 South Canyon Fire on Storm King Mountain, Colorado (Figure 2A) (Kirkham et al. 2000, Cannon et al. 2001). This event inundated nearly 2 miles (3 km) of Interstate 70 with tons of rocks, mud and debris. Thirty vehicles and their occupants were engulfed in the flows, and in two cases, were pushed into the Colorado River. Although some travelers were seriously injured, no deaths resulted from this event. The similarities between the landscapes and geologic materials affected by the Coal Seam and Missionary Ridge Fires and those burned by the South Canyon Fire indicate the potential for a similar runoff response.

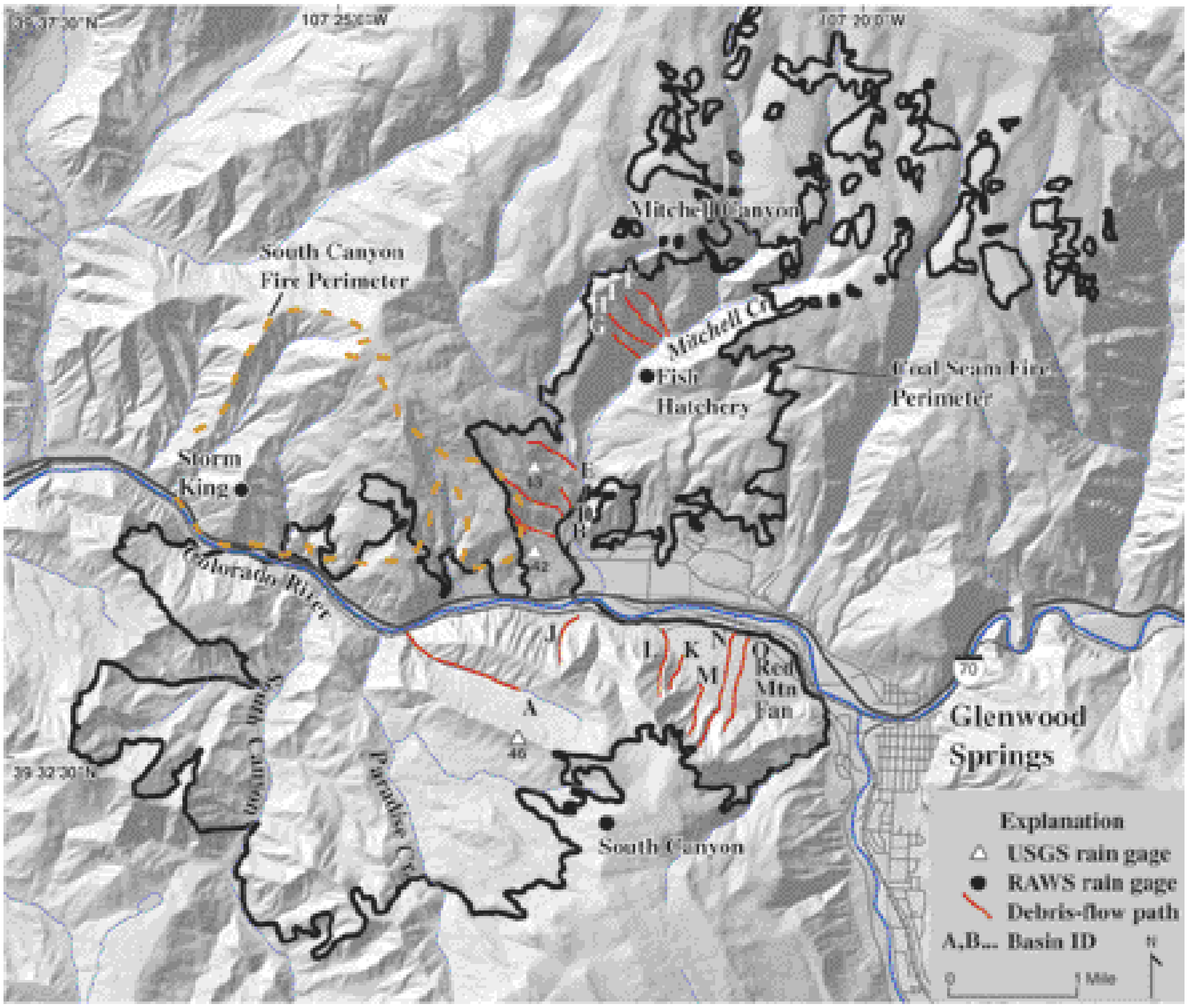


Figure 2A. Shaded relief image showing perimeter of Coal Seam and South Canyon Fires, locations of rain gages, and paths of debris flows generated in response to the August 5, 2002 storm.

The purpose of this report is to document the conditions that resulted in a debris-flow response from basins burned by the Coal Seam and Missionary Ridge Fires. Shortly after each fire was extinguished and before any rainstorms had impacted the area, networks of tipping bucket rain gages were installed, and a series of cross sections was installed in representative basins. After each significant rainfall event, we used field observations to document which basins produced debris flows, sediment-laden floods, and which showed no response. Surveys of channel cross sections made after event-producing storms were used to obtain indirect measurements of peak discharges of the debris flows. By documenting the basin characteristics and burn extent of the debris-flow producing basins, as well as the rainfall conditions that impacted the basins, we are able to define the conditions that lead specifically to the generation of post-wildfire debris flows. Estimates of the peak discharge of debris-flow events are used to define relations between the magnitude of the debris-flow response, storm rainfall triggers and basin area. In addition, a comparison of the rainfall conditions in storms that produced debris flows with those that produced sediment-laden floods or showed no response is used to define the threshold rainfall conditions for the production of fire-related debris flows from similar terrains.

SETTINGS

The Coal Seam Fire burned immediately west of Glenwood Springs, Colorado, and impacted the hillslopes and canyons on both the north and south sides of the Colorado River (Figure 2A). The fire burned through piñon-juniper woodlands, mountain shrublands, and aspen, Douglas fir, and spruce-fir forests. Most of the burned area is characterized by high relief, steep slopes, and tightly confined canyons. Channel gradients range between 20 and 65 percent. The northern-most portion of the burned area is a high elevation, relatively flat plateau known as the Flat Tops. Hillslope gradients range from nearly flat within the Flat Tops to greater than 80 percent within the Mitchell Creek and South Canyon watersheds and on Red Mountain (Figure 2A). The burned area ranges in elevation from approximately 5,720 ft (1787 m) along the Colorado River to 10,400 ft (3250 m) in the Flat Tops.

The area burned by the Coal Seam Fire is underlain primarily by the Pennsylvanian and Permian Maroon formation (consisting of interbedded sandstones, siltstones and conglomerates), a Proterozoic gneissic quartz monzonite, and the upper Cambrian Sawatch quartzite (Kirkham et al. 1997). Smaller extents of dolomite, dolomitic sandstone, shale and limestone have also been mapped in the upper reaches of the basins. A fault that trends east to west just north of the Glenwood Springs Fish Hatchery (Figure 2A) separates the Maroon formation from the quartz monzonite and quartzite. Soils developed on these units are generally shallow, poorly developed and with a high percentage of rock (Cannon et al. 1998). Five samples of the materials that mantle hillslopes underlain by the Maroon Formation are classified as silty sands (SM), and two samples from the quartz monzonites are classified as well-graded sands (SW). Immediately after the fire, the hillslope-mantling soils were observed to be very dry, and even a gentle wind entrained ash and fine sand. Accumulations of loose, unconsolidated dry-ravel deposits up to 1-m thick were observed in many of the tributary drainages to Mitchell Creek, South Canyon, and Basin A; these basins are underlain by the Maroon Formation (Figure 2A). Dry ravel is process frequently observed both during and after fires wherein soils dried during the passage of the fire experience particle-by-particle transport of material downslope by gravity. Dry ravel has been described as an important post-fire process in southern California where channels are loaded with sediment, increasing available sediment for transport in large runoff events (e.g., Wells, 1981). In addition, extensive talus deposits mantle the hillslopes underlain by the metamorphic rock types in tributaries to Mitchell Creek.

The steep channels that drain Red Mountain and the tributary canyons within the Mitchell Creek watershed show evidence of Holocene-to-recent debris-flow activity (Kirkham et al. 1997). These debris flows are most commonly produced from the Maroon formation. An extensive alluvial fan has formed at the base of Red Mountain, and smaller fans are common at the tributary junctions in Mitchell Canyon.

Glenwood Springs has a semi-arid climate with low humidity throughout the year (Interagency Burned Area Emergency Response Team 2002). Average high temperatures in the valley bottoms range from 30 to 40 degrees F. in winter to 80 to 90 degrees F. in the summer months. Average annual precipitation in the valley is between 15 and 17 in (381 to 432 mm), and up to 38 in (965 mm) at higher elevations. Precipitation usually falls during two periods – either as winter frontal storms, or summer convective thunderstorms. The thunderstorms are characterized by localized, short duration rainfall.

The Missionary Ridge Fire burned north and northeast of the city of Durango, Colorado, and included portions of the Animas, Florida and Los Pinos River Valleys (Figure 2B). The fire burned Ponderosa pine, mixed conifer, aspen and spruce-fir forests at elevations ranging from approximately 6500 ft (2030 m) along the Animas Valley to approximately 11,400 ft (3560 m) in the northern portion of the fire. Most of the burned area is characterized by steep hillslopes and canyons with gradients between 14 and 30 percent.

The lower Permian Cutler Formation underlies most of the area burned by the Missionary Ridge Fire, and is comprised of interbedded sandstones, siltstones and conglomerates (Carroll, et al. 1997, Carroll, et al. 1998, Carroll, et al. 1999, Gonzales, et al. 2002). The Hermosa, Molas, Junction Creek, Wanakah, Entrada, Dolores and Morrison Formations, which consist of interbedded sandstones, shales, limestones and conglomerates, and the underlying, older Eolus Granite have also been mapped within the burned area. In addition, extensive deposits of Quaternary glacial and colluvial deposits are mapped in many of the tributary drainages to the Animas, Florida, and Los Pinos Rivers. Soils within the burned area are most commonly alfisols – a forest soil with an illuviated clay horizon (Burned Area Emergency Response Team 2002). Although dry-ravel deposits were observed in some basins, they were not as extensive or as thick as those observed in the basins burned by the Coal Seam Fire.

Landslide and debris-flow activity is common in the area (Burned Area Emergency Response Team 2002). Debris flows are frequently generated from the Cutler Formation and Eolus Granite, and with less frequency from the Hermosa and Morrison Formations. Active, large alluvial fans have developed at the mouths of tributaries to the Animas River along the mountain front and to a lesser extent on other areas.

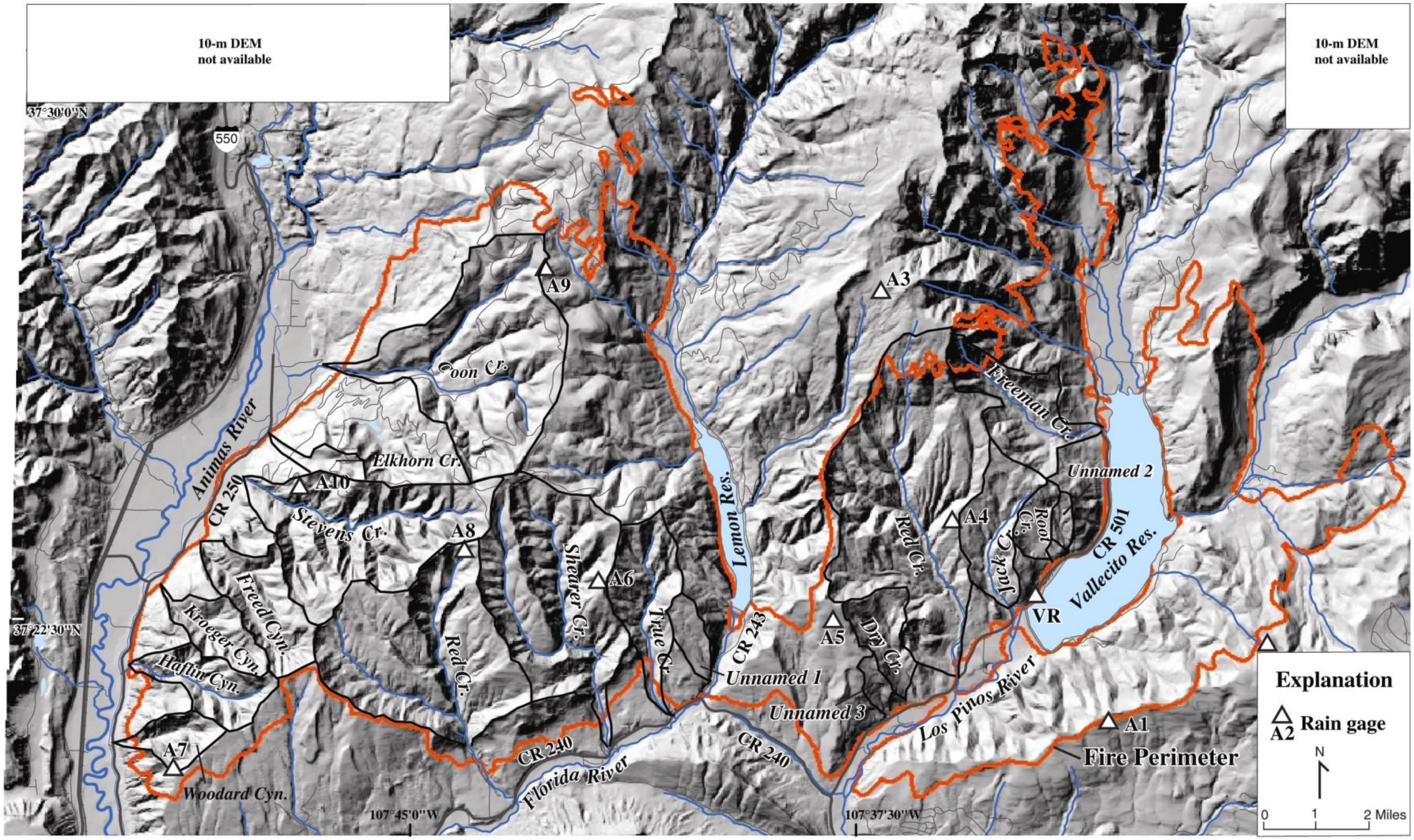


Figure 2B. Shaded relief image showing perimeter of Missionary Ridge Fire and locations of rain gages.

The area around Durango has a semi-arid climate with generally warm summers and cold winters. Annual precipitation in Durango is 18.6 in (472 mm), and winter snowfall totals average about 70 in (1778 mm) (Burned Area Emergency Response Team 2002). Forty-two percent of the precipitation in Durango falls between August and October during the summer-fall monsoon season. The monsoon season is characterized by severe, but locally variable and short-lived, thunderstorms.

METHODS

To document the debris-flow response of the Missionary Ridge and Coal Seam Fires, we utilized a network of tipping-bucket rain gages installed within the burned areas shortly after each fire was extinguished and before any rainstorms had impacted the areas. Twelve tipping-bucket rain gages were installed by the U.S. Geological Survey Water Resources Division in the area burned by the Missionary Ridge Fire as part of the post-fire Burned Area Emergency Rehabilitation monitoring program (Burned Area Emergency Response Team 2002) (Figure 2A). Data from these gages are available on the web at: http://co.water.usgs.gov/fires/missionridge. We installed three tipping-bucket rain gages in the area burned by the Coal Seam Fire (Figure 2B). The rain gages recorded the date and time of each 0.01-inch accumulation of rainfall, and from these data, we extracted measures of storm duration, total storm rainfall, average storm intensity, and peak 10-, 15-, 30- and 60-minute intensities. In addition, four Remote Access Weather Stations (RAWS) installed and maintained by the U.S.D.A. Forest Service and Bureau of Land Management within the Coal Seam Fire were used to supplement the information recorded by the tipping bucket rain gages (Figure 2A). Although these weather stations recorded rainfall totals (in addition to other weather data) at 10-minute intervals, some data were available only at 1-hour intervals.

After each significant rainfall event, we used field observations, police dispatch records, newspaper accounts, and observations from eye witnesses to document which basins produced debris flows, sediment-laden floods, and which showed no response. We defined threshold rainfall conditions that can result in fire-related debris-flow activity by comparing measures of rainfall intensities and durations recorded by gages located within 1 mi (1.6 km) of debris-flow producing basins with the those measures recorded by gages within 1 mi (1.6 km) of basins that produced only sediment-laden floods or showed no response. The threshold is defined by visually distinguishing those rainfall intensities and durations that occurred during the debris-flow producing storms.

Surveys of channel cross sections installed in basins in both fires either prior to any significant rainfall accumulations, or immediately after event-producing storms, were used to obtain indirect measurements of peak discharges of the debris flows. The cross-sectional areas defined by the passage of each of the debris flows were measured at either two or three locations near the mouths of eight basins in the Coal Seam Fire and ten basins in the Missionary Ridge Fire. Estimates of peak discharges of the debris-flow events were obtained using a slight variation of the velocity-area method described by O'Connor et al. (2001) wherein the product of the average of the two or three channel cross-sectional areas at peak stage and an estimate of flow velocity is calculated. Maximum flow stage was determined by the highest evidence of inundation at the cross section, with either a prominent muddy veneer or levees. The cross-sectional areas were measured by installing two pieces of steel rebar perpendicular to the channel with markings to indicate a level line, stretching a tape measure across the channel from the right to left banks, anchoring it at the level lines on the rebar, and recording the depth to the channel bed at 0.5-m intervals. In an effort to obtain velocities at a conveyance reach, the cross sections were located on fairly straight reaches of channel with constant gradients that showed little evidence of either erosion or deposition, other than the muddy veneer or the levees. For the debris flows that originated from basins underlain by sedimentary rock types, the average debris-flow velocity was assumed to be 16 ft/s (5 m/s). Debris flows that originated from the gneissic quartz monzonite and quartzite in the Coal Seam Fire appeared to be more viscous, and thus slower-moving, and we assumed an average velocity of 10 ft/s (3 m/s) for these flows. The assumed velocity of 16 ft/s (5 m/s) is based on an average of eight velocities calculated using the super-elevation method for debris flows generated from basins burned by the 1994 South Canyon Fire (Cannon et al. 1998). This average velocity is well within the range of 10 to 19 ft/s (3 to 6 m/s) found for debris flows in alpine environments by O'Connor et al. (2001). Although the critical-flow indirect method might provide a better measure of peak discharge of debris flows than the velocity-area method (O'Connor et al. 2001), no sites suitable for this approach could be located, and the values presented here should be viewed at best as estimates.

Basins within the burned areas were delineated using 10-m Digital Elevation Models (DEMs) and the watershed delineation tools in Arc 8.2. Measures of basin area, average basin gradient, and the relief ratio for each basin were then obtained from the DEM. Average basin gradient was calculated as the average of the gradient of each of the grid cells within the basin. The relief ratio was measured as the elevation change from the basin mouth to the drainage divide divided by the length of the longest channel extended to the drainage divide.

The area of each basin burned at varying severities was extracted from maps of burn severity generated using the Normalized Burn Ratio (NBR), a method that utilizes Landsat Thematic Mapper data (Key & Benson 2000). Burn severity is a relative measure of the effects of fire on soil hydrologic function (U.S. Department of the Interior, 2001). Areas classified as high burn severity generally exhibit complete consumption of the forest litter and duff, evidence of heating of the soil surface, and combustion of all fine fuels in the canopy. Areas burned at moderate severity can be characterized by the consumption of litter and duff in discontinuous patches, and leaves or needles, although scorched, may remain on trees. Areas of low burn severity may show charring of the relatively intact litter and duff, intact fine roots within the soils, and very little effect of fire on the canopy.

In this paper, we first describe the response of the burned basins in each of the fires to the summer of 2002 rainfall. We then present the conditions in the debris-flow producing basins, including lithology, basin area and gradient, and burn severity, followed by our estimates of debris-flow peak discharge. We next describe the rainfall conditions that resulted in debris-flow activity, and examine relations between these peak discharges, basin area, and debris-flow producing rainfall intensities. And last, we define the threshold rainfall conditions that resulted in the generation of debris flows from the burned basins.

SUMMER OF 2002 RESPONSE

In the following section, we have compiled a summary of the erosional response of individual burned basins in both fires to the 2002 summer monsoon season. We describe which basins showed a debris-flow response, and which produced sediment-laden floods. Those basins not mentioned in the summary either showed no response, or we have no record. Where available, we include information about the character of the debris-flow deposits, the channels through which the debris flows passed, and the timing of the events. Storm rainfall characteristics recorded from rain gages located within 1 mi (1.6 km) of the responding basin are shown in Tables 1A and B, and the estimates of debris-flow peak discharges that we were able to obtain are shown in Tables 2A and B. This compilation depended on field notes, notes of eyewitness interviews, and reviews of newspaper accounts. We apologize if we have missed or misrepresented events.

Coal Seam Fire

August 5, 2002 - Debris flows were first produced from basins burned by the Coal Seam Fire in response to the first heavy rain fall of the monsoon season. Field reconnaissance immediately following the event indicated that at least 15 basins produced debris flows in response to this storm (Figure 2A). The road along Mitchell Creek was blocked with an estimated several hundred cubic meters of debris-flow material in numerous places, and a 6-ft (2-m) diameter culvert was completely blocked by debris produced from Basin A. The debris flows spread over the fan surfaces, leaving deposits approximately 1 ft (0.3 m) thick that consisted of isolated clasts up to 1.5 ft (0.5 m) in diameter in abundant mud and ash (Figures 3A and B). The channels of Basins B, C, and D were flushed of the pre-existing dry-ravel deposits and eroded as much as about 2 ft (0.6 m) in depth, exposing bedrock in many places along their lengths. Debris flows were also produced from basins above the Fish Hatchery (Figure 4), from basins that supply the Red Mountain fan (Figure 5), and from Basin A. The debris flows produced from the basins above the Fish Hatchery deposited levees up to 2.0 ft (0.6 m) high lining the channels and lobes of material up to 5 ft (1.6 m) high at the flow terminus. The debris-flow materials consisted primarily of gravel and cobbles in a muddy matrix.

This storm dropped between 0.16 and 0.67 inches (4 and 17 mm) of rain on the burned area between 8:50 and 10:00 p.m., and most of this rain fell in just 10 minutes (Table 1A). The sheriff's dispatch records reported that at 9:05 p.m. a car was trapped by a debris flow flowing out of Basin B, just 5 minutes after the onset of the storm, as recorded by Rain Gage 43 (Figure 2A). In contrast, a train was reported stuck in mud flowing out of Basin A at 9:42 p.m., nearly an hour after the storm started.

Sept. 7, 2002 – Basins F, G, H, and I in the upper Mitchell Creek watershed produced debris flows consisting of up to gravel-sized material in a muddy matrix. The deposits left by these events appeared to have had higher water contents, relative to sediment loads, than the earlier flows.

Figures 3A and B. Photographs of A) debris-flow paths and B) deposits produced during August 5, 2002 storm from Basins B and C, Coal Seam Fire.

A.

B.

Figure 4. Debris-flow deposit produced during August 5, 2002, storm from Basin H, Coal Seam Fire.

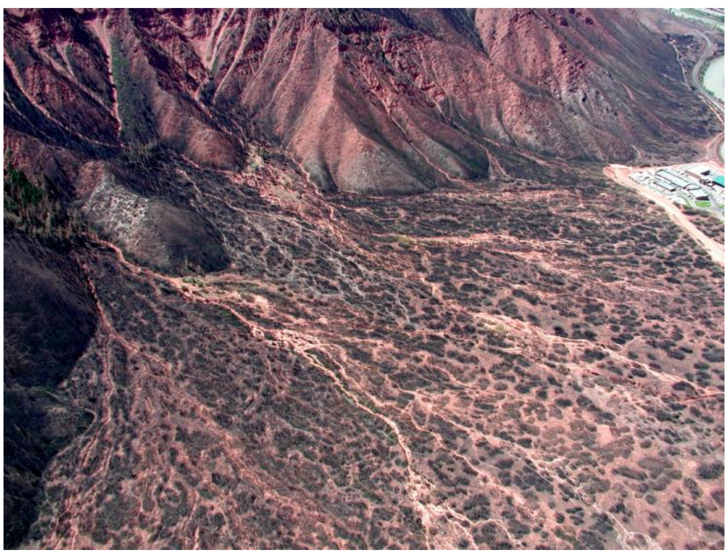


Figure 5. Debris-flow paths (lighter colored material) from the August 5, 2002, storm on the Red Mountain Fan. Buildings in upper right for scale.

Sept. 11, 2002 - Basins F, G, H, and I in the upper Mitchell Creek watershed again produced debris flows. A witness reported hearing two roars during the storm, indicating that there were either two pulses of debris flow in one basin or multiple basins producing debris flows at different times. During this storm, Mitchell Creek was observed to be heavily sediment-laden and boulders up to 15 in (40 cm) in diameter were transported downstream. No flooding or

debris flows were reported or observed in any other of the burned basins, although they received somewhat more rainfall than the debris-flow producing basins.
Sept. 12, 2002 - A basin located on the Eastern flank of Red Mountain flooded and made newspaper headlines in Denver, Colorado. This flood flowed through a residential area and many basements were flooded with water and mud.

Sept. 17, 2002 – Debris flows were again produced from basins F, G, H, and I above the Fish Hatchery in Mitchell Creek.

Oct. 2-3, 2002 – Debris flows were again observed emanating from basins F, G, H, and I above the Fish Hatchery, and Basins B and C showed evidence of the passage of sediment-laden floods. Up to 3.3 ft (1.0 m) of incision was measured at the mouth of Basin C, and up to 2.3 ft (0.7 m) at the mouth of Basin B. These events occurred in response to a storm that lasted more than 10 hrs with an average intensity of 0.09 in/hr (2 mm/hr) (Table 1A). Although several short bursts of heavy rainfall within this storm with peak intensities between 0.11 and 0.60 in/hr (3 to 15 mm/hr) were recorded, the time of occurrence of the debris flows within the storm is not known with sufficient accuracy to link their occurrence to high intensity rainfall.

Missionary Ridge Fire

July 11, 2002 – The first storm to impact the area burned by the Missionary Ridge Fire was a localized thunderstorm that impacted the area south of the Vallecito Reservoir dam. The Durango Herald (2002) reported that La Plata County Road (LPCR) 501 and a softball field were flooded with ash and mud flushed from the hillslopes. This storm occurred before the rain-gage network had been installed; thus no record is available.

July 22, 2000 – This storm similarly resulted in a flush of ash and mud from the burned hillslopes near Vallecito Reservoir. LPCR 501 was closed between the Vallecito Reservoir dam and the intersection of LPCR 240 (Figure 2B) in order to clear ash, mud, debris, and a 400 lb (180 kg) boulder that was moved by the flood waters (Durango Herald, 7/23/2002). Red Creek also showed significant flood activity.

July 23, 2002 – The first significant storm of the season impacted the Florida River basin. Debris flows were produced from an unnamed basin just below Lemon Reservoir (Unnamed Basin 1, Figure 2B), and significant sediment-laden floods were produced from Dry, Shearer and True Creeks. At least five vehicles, four containing people, were swept off LPCR 240 by the advancing water (Durango Herald, 2002). The debris flow from Unnamed Basin 1 crossed LPCR 243, blocked a driveway, and damaged a guardrail on a bridge. Material consisting of ash, fine-grained sand, gravel, and clasts up to 3 ft (1 m) in diameter was deposited up to 4 ft (1.2 m) deep on the road. This storm also resulted in sediment-laden floods that crossed LPCR 501 along Vallecito Reservoir in several places.

August 3, 2002 - This storm resulted in the generation of debris flows from many basins within the Los Pinos River drainage and along LPCR 240 (Figure 2B). A debris flow was produced from Freeman Creek at about 12:15 pm. Material up to 6 ft (2m) in diameter was moved in this event, and passage of the flow resulted in nearly 5 ft (1.5 m) of incision of the channel bed.

Debris flows crossed LPCR 501 in several places between Freeman Creek and Unnamed Basin 2 (Figure 2B). Root Creek also produced a debris flow that deposited material approximately 10 ft (3 m) deep including boulders up to 6 ft (2 m) in diameter at the junction with LPCR 501. Debris flows also crossed LPCR 240 in several places.

August 5, 2002 – Debris flows were again reported to have been produced from Unnamed Basin 1. Materials up to 4 ft (1.2 m) in diameter in abundant muddy matrix crossed CR 243. Sediment-laden streamflow events occurred along LPCR 501 near Vallecito Reservoir.

August 8, 2002 – This storm brought more rain to the Florida and Los Pinos River basins. Unnamed Basin 2 produced a debris flow that deposited ash, mud, and debris in a business located across LPCR 501. This event moved material up to 3 ft (1 m) in diameter across the road. Sediment-laden streamflow was produced from many of the smaller drainages north of Unnamed Basin 2, and flooding in Freeman Creek led to additional incision in the channel bed. Unnamed Basin 3 produced a debris flow that deposited levees approximately 3 ft (1 m) high that lined the channel; material up to 3 ft (1 m) in diameter was transported in a muddy matrix by this event. Adjacent Dry Creek showed evidence of sediment-laden streamflow. Root Creek also experienced another debris flow, and a sediment-laden flood was produced by Elkhorn Canyon along the Animas River. Material from the Elkhorn Canyon event covered LPCR 250 with about 1 ft (0.3 m) of ash and mud.

August 20, 2002 – This storm resulted in the generation of sediment-laden floods from Freeman and Dry Creeks, as well as from Unnamed Basin 3.

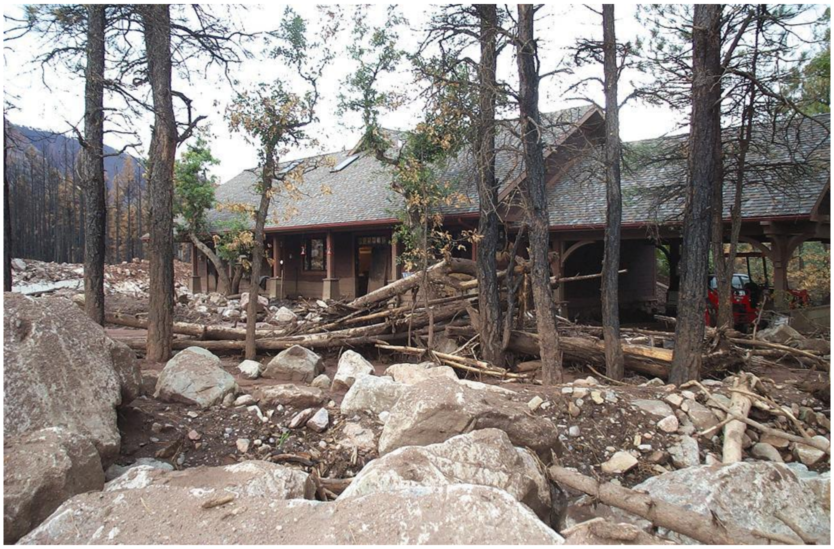
August 21, 2002 – An apparently localized storm resulted in the production of another debris flow from Root Creek, and light flooding in adjacent drainages. Passage of the flow resulted in approximately 3 ft (1 m) of channel incision, and significant deposition along the channel banks. Material up to 3 ft (1 m) in diameter was transported by this event. Deposits from sediment-laden floods were also observed at the mouth of Freeman Creek.

August 29, 2002 – A localized rainstorm triggered debris flows from Haflin and Kroeger Canyons in the Animas Valley. The flows carried material no greater than 3 ft (1 m) in diameter in a muddy matrix.

September 7, 2002 – This was the first big storm to impact the basins that drain into the Animas River. Debris flows were produced from Coon Creek, Stevens Creek, Freed Canyon, and Woodard Canyon. These events blocked CR 250 in three places with several feet of debris. The event on Stevens Creek covered approximately one-quarter of the fan area with deposits up to 5 ft (1.5 m) deep in places, and inundated a home that prior to the event was at least 200 ft (62 m) from the active channel with tons of rock and mud (Figures 6A and B). This event moved material up to 8 ft (2.5 m) in diameter in a muddy matrix. Evidence on the fan surface suggests that channels were blocked by large boulders and diverted many times during the event. Upstream from the fan, the channels showed up to 8 ft (2.5 m) of incision into extensive valley-fill deposits. The debris flow produced from Freed Canyon moved materials up to 6 ft (2 m) in diameter in a muddy matrix. The high mud line produced from this event was measured 12 ft (4 m) above the post-event channel base, and up to 6 ft (2 m) above the original bank levels. The area downstream from the waterfall at the head of the fan was heavily scoured in this event. Deposition by the debris flow in Coon Creek resulted in the shifting of the channel bed to the north by about 10 ft (3 m). Material from this event consisted of up to cobble-sized material in a muddy matrix. In addition to these events, sediment-laden floods near Red, Shearer, and True Creeks blocked CR 240.

September 10-12, 2002 – This storm had the longest duration of any that occurred during the 2002 monsoon season. The storm started on the evening of September 10 and continued into the early morning hours of September 12th. Debris flows were again produced from Coon and Stevens Creeks, and Woodard Canyon, but these were smaller discharge events carrying smaller (up to cobble-sized) material than those of September 7. Deposition by debris flow on Coon Creek filled in the channel, and shifted the channel back to the south. Soil slip scars that formed during this storm were observed in the upper reaches of Stevens Creek. These scars were relatively small – at most 100 ft^2 (10 m^2) in area. Material from these scars mobilized into debris flows that traveled a few hundreds of feet down the hillslopes on which they originated. Evidence of flooding was observed in Haflin, Freed and Kroeger Canyons. Debris flows were also produced from Root Creek near Vallecito Reservoir and from Unnamed Basin 1 near Lemon Reservoir. Sediment laden floods also resulted in the closure of LPCR 501 at Jack and Dry Creeks near Vallecito Reservoir.

A.

 B.

Figures 6A and B. Photographs of A) debris-flow path near apex of Stevens Creek Fan, and B) debris-flow deposits on fan, Missionary Ridge Fire. Debris flows occurred during September 7, 2002, storm.

September 20, 2002 – A storm focused on the southern end of the Animas Valley front produced debris flows from Haflin and Kroeger Canyons and from Stevens Creek. These events carried materials only up to about 1.5 ft (0.5 m) in diameter, a significant decrease from previous events. These events appear to have been triggered by a fairly localized storm, indicated by rain gages A7 and A12 (those located nearest to the canyons), which did not record any rainfall on this date.

October 2, 2002 – The last of the monsoon storms to impact the area produced sediment-laden floods on Coon Creek. These events reworked the existing deposits and scoured the south side of the channel.

DEBRIS-FLOW PRODUCING BASINS

In this section we document some of the conditions that produced debris flows in response to the summer 2002 rainfall. The parameters we examine include lithology, basin area, average basin gradient and relief ratio, and burn extent. Other conditions may certainly affect debris-flow occurrence from recently burned basins; here we examine these parameters as possible first-order effects.

Lithology

Most of the debris flows observed in the two burned areas were produced from basins underlain by the interbedded sandstones, siltstones, and conglomerates of the Maroon and Cutler Formations (Tables 3A and B). These formations are also the most extensive in the two burned areas; thus, this result was not unexpected. However, debris flows were also produced from basins underlain by quartz monzonites and quartzites in the Coal Seam Fire, and from other sedimentary units in the Missionary Ridge Fires. Samples of the materials that mantle hillslopes underlain by the Maroon Formation are classified as silty sands (SM), and materials from the quartz monzonites are classified as well-graded sands (SW).

The availability of readily entrained materials mantling hillslopes and infilling channels appears to affect how frequently debris flows are produced. Although the Cutler and Maroon Formations are lithologically similar, multiple debris flows were produced throughout the monsoon season from basins underlain by the Cutler Formation (Missionary Ridge Fire), while basins underlain by the Maroon formation (Coal Seam Fire) produced only one large debris-flow event. Later storms with similar or greater intensities to the debris-flow producing storm impacted the area burned by the Coal Seam Fire, so this difference cannot be attributed to meteorological vagaries. Rather, field observations in the basins burned by the Coal Seam Fire prior to the onset of summer thunderstorms indicated that although an abundance of dry-ravel deposits lined the channels, bedrock was usually less than about 2 ft (0.6 m) below the channel surface. Repeat surveys of a series of cross sections installed along the length of three channels indicated that most of the material incorporated into the debris flows was the channel-lining deposits, but significant channel incision did not occur (Gartner et al. in prep.). In this case, sufficient material to generate repeat debris flows was not available. In contrast, geologic mapping and field observations in the area burned by the Missionary Ridge Fire showed thick colluvial and glacial fills within many of the basins (Carroll et al. 1997, Carroll et al. 1998, Carroll et al. 1999, Gonzales et al. 2002). Field observations of up to 8 ft (2.5 m) of incision into these deposits, and a lack of significant hillslope erosion suggest that most materials in the Missionary Ridge debris flows originated from these deposits and that these deposits provided an ample material source for repeat debris-flow activity. In addition, the extensive talus deposits that mantle the hillslopes underlain by metamorphic materials in the Coal Seam Fire provided an abundant source of materials for repeat debris-flow activity. This finding indicates that debris-flow susceptibility cannot be simply evaluated in terms of underlying bedrock lithology or soils; understanding and characterization of the availability of readily eroded material is also necessary in a comprehensive hazard assessment.

Basin Area and Gradient

Debris flows were produced from basins with broad ranges in area, average gradient, and relief ratio. Those basins that produced debris flows burned by the Coal Seam Fire were between 0.01 and 0.83 mi^2 (0.03 and 2.15 km^2) in area, ranged in average gradient between 46 and 94 percent, and had relief ratios between 24 and 73 percent (Table 3A). Debris-flow producing basins in the Missionary Ridge Fire ranged in area between 0.25 and 8.24 mi^2 (0.64 and 21.34 km^2), in average gradient between 26 and 58 percent, and in relief ratio between 16 and 30 percent (Table 3B).

Basin area/relief ratio threshold – Measures of the areas and relief ratios of the debris-flow producing basins within the Coal Seam and Missionary Ridge Fires, combined with those measured from other basins throughout the western U.S. that also produced debris flows (Cannon 2001), are used to define the basin conditions most likely to produce debris flows

(Figure 7). Basins with areas and relief ratios that fall above the threshold line shown in Figure 7 are those most likely to produce post-wildfire debris flows, given sufficient rainfall.

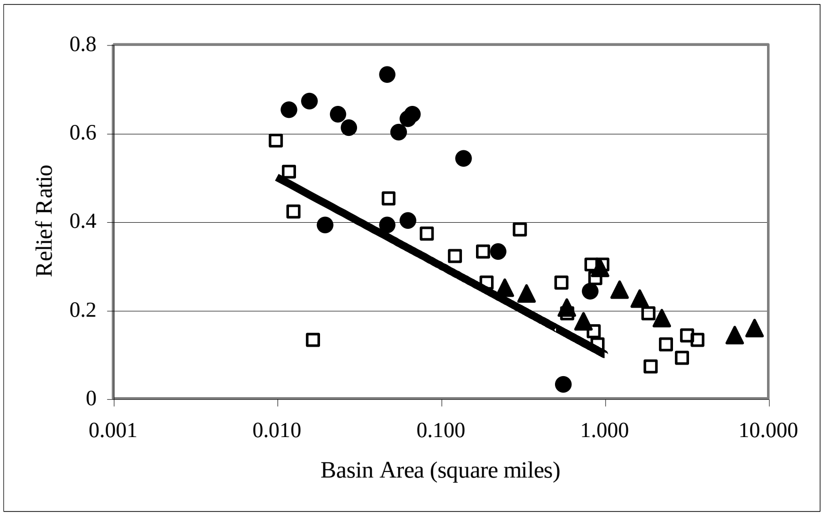


Figure 7. Basin area and relief ratios measured for basins that produced debris flows from the Coal Seam Fire (filled circles), the Missionary Ridge Fire (filled triangles), and fires located throughout the western U.S. (Cannon, 2001) (open squares). Solid black line defines threshold conditions for most basin areas and relief ratios known to have produced debris flows, given sufficient rainfall.

Burn Severity

Debris flows were produced from basins with as little as 3 percent of the area burned at high severity in the Coal Seam Fire, and from basins with as little as 22 percent of the area burned at high severity in the Missionary Ridge Fire (Tables 3A and B). Thus, debris flows can be produced from basins that have experienced very little high-severity fire. However, if we look at the combination of areas burned at high and moderate severities within a basin, we see that between 54 and 100 percent of the areas of the debris-flow producing basins were burned at this combination (Tables 3A and B). This suggests that a threshold value of around 50 percent of the basin area burned at high and moderate severities might be a good indicator of post-fire debris-flow susceptibility, again given sufficient rainfall.

PEAK DISCHARGE ESTIMATES

Peak discharge estimates measured for debris-flow events generated from basins burned by the Coal Seam Fire ranged between 347 and 781 ft^3/s (10 and 22 m^3/s) (Table 2A), and those estimated for the debris flows generated from the basins burned by the Missionary Ridge Fire were considerably higher, ranging between 293 and 5581 ft^3/s (9 and 167 m^3/s) (Table 2B). Normalizing the estimated peak discharges for the Coal Seam Fire by basin area results in values between $2x10^{-5}$ and $1.24x10^{-3}$ ft/s ($6.5x10^{-6}$ and $3.8x10^{-4}$ m/s) (Table 2A); these values are generally higher than those calculated for the Missionary Ridge Fire, which are between $1.0x10^{-5}$ and $1.5x10^{-4}$ ft/s ($2.0x10^{-6}$ and $4.4x10^{-5}$ m/s) (Table 2B).

DEBRIS-FLOW TRIGGERING STORMS

Nearly 70 percent of the storms that generated debris flows from the basins burned by the Coal Seam and Missionary Ridge Fires were of durations equal to or less than two hours, and ranged in intensities between 0.04 and 0.67 in/hr (1.0 and 16.5 mm/hr) (Tables 1A and B, Figure 8). With the exceptions of the October 2-3, 2002 storm recorded by the Rain Gage 43 in the Coal Seam Fire (recurrence interval of 5 yrs), and the July 7, 2002 storm recorded by gage A6 in the Missionary Ridge Fire (recurrence interval of 10 years), (Miller et al. 1976), all of the debris-flow triggering storms had recurrence intervals of less than or equal to two years (Tables 1A and B). Some eyewitnesses reported that the debris flows occurred in response to periods of high-intensity rainfall during the storm. The 10-minute peak intensities recorded near the debris-flow producing basins varied over an order of magnitude, and ranged between 0.24 and 2.46 in/hr (6.3 and 62.5 mm/hr) (Tables 1A and B).

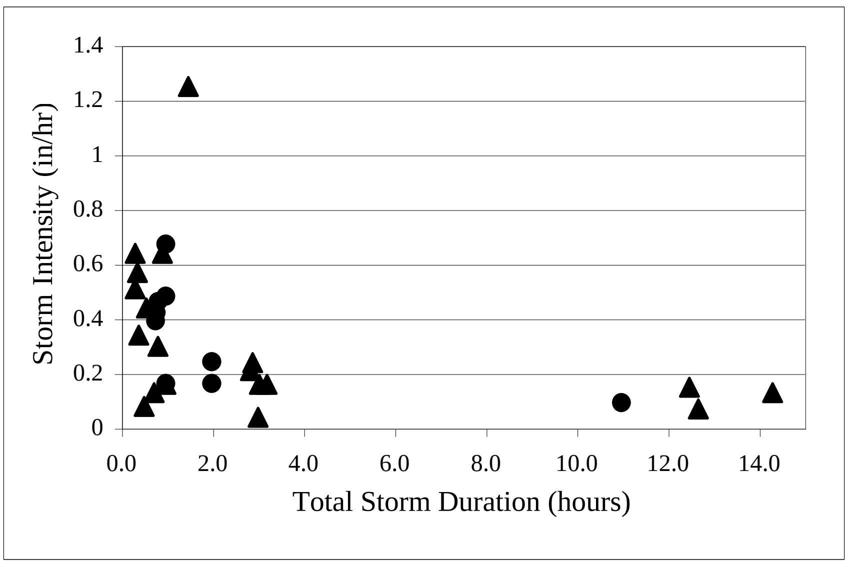
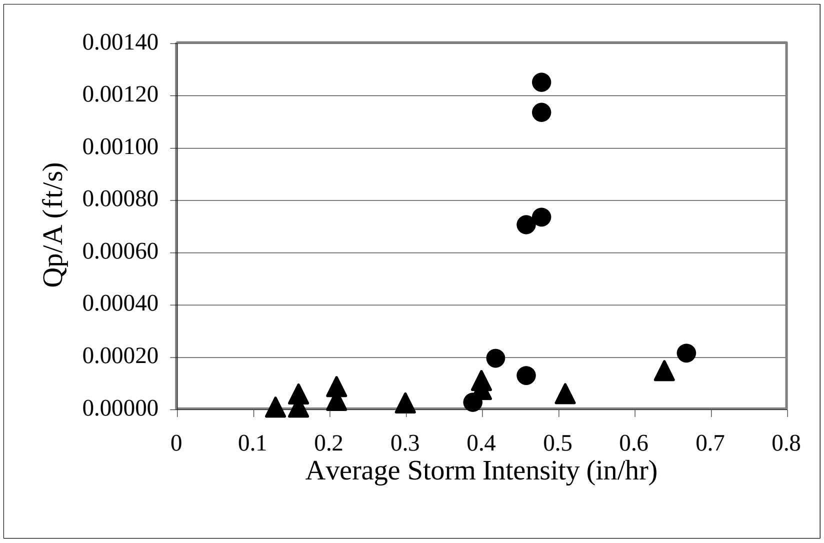


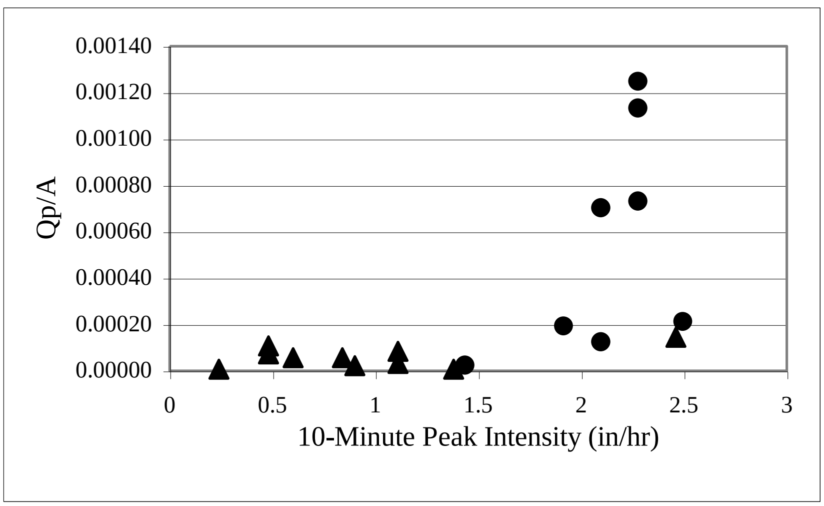
Figure 8. Average storm intensity and duration of debris-flow producing storms. Circles are measurements from storms that triggered debris flows from basins burned by the Coal Seam Fire and triangles are measurements from storms that triggered debris flows from basins burned by the Missionary Ridge Fire.

Peak Discharge, Basin Area and Rainfall Intensity

Relations between the magnitudes of the debris-flow response, basin area, and storm rainfall triggers are shown in Figures 9A and B. The debris flows with the highest values of peak discharge normalized by basin area, and thus the most potentially destructive, occurred in response to storms with average intensities greater than about 0.4 in/hr (10 mm/hr) and 10-minute peak intensities greater than about 2.0 in/hr (50 mm/hr).



A.



B.

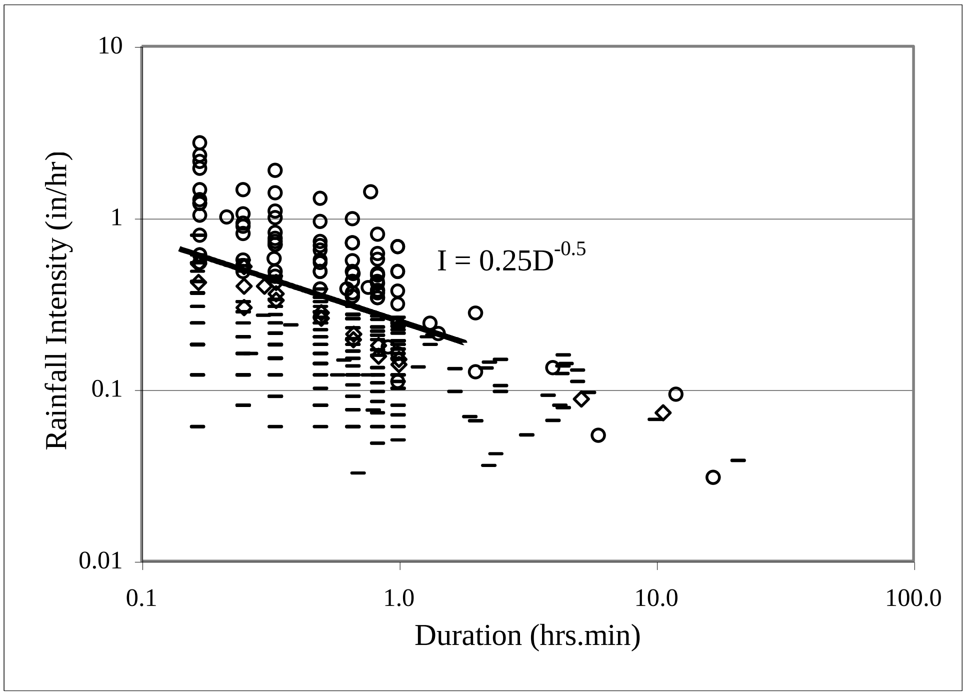
Figures 9A and B. Relations between estimates of debris-flow peak discharge normalized by basin area and (A) average storm intensity, and (B) 10-minute peak intensity for the Coal Seam Fire (circles) and the Missionary Ridge Fire (triangles).

RAINFALL INTENSITY-DURATION THRESHOLD FOR POST-FIRE DEBRIS-FLOW ACTIVITY

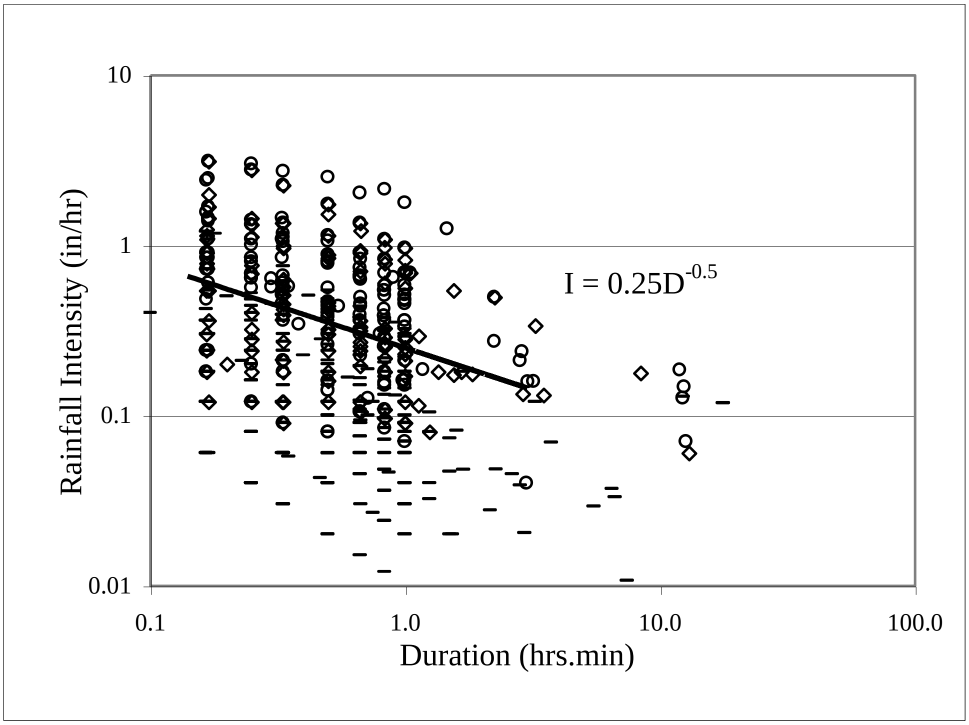
Although a number of workers have described the triggering of fire-related debris flows in response to high intensity rainfall (e.g., Cleveland 1977, Wells 1981, Parrett 1987, Booker 1998, Cannon et al. 1998), little work has been done to define the threshold rainfall conditions that result in debris flows. Such a threshold is a useful tool in issuing warnings and planning for emergency response. A rainfall intensity-duration threshold for the production of debris flows from basins burned by the Coal Seam and Missionary Ridge Fires in the form:

$$I = 0.25D^{-0.5} \qquad (1)$$

where I = rainfall intensity (in in/hr) and D = duration of that intensity (in hours) can be defined (Figures 10A and B).



A.



B.

Figures 10A and B. Rainfall intensity-duration thresholds for the generation of fire-related debris flows from the (A) Coal Seam and (B) Missionary Ridge Fires. Open circles represent measures of storm rainfall from gages near basins that produced debris flows; diamonds represent measures of storm rainfall from gages near basins that produced sediment-laden flows; and dashes represent measures of storm rainfall from gages near basins that showed no response.

Note that the threshold line for the Coal Seam Fire is best defined for durations less than about 2 hrs, while the threshold for the Missionary Ridge fire is fairly well defined for durations up to about 8 hrs. This difference in thresholds could reflect the shorter times to concentration that characterize the generally smaller and steeper debris-flow producing basins of the Coal Seam Fire (Chow et al. 1988). In addition, the rainfall conditions that result in debris-flow activity from recently burned basins are attained at durations at least an order of magnitude less that those described for the generation of debris flows in unburned settings, and at significantly greater intensities. This difference may be attributed to a difference in initiation mechanism. Many workers (e.g., Wells 1981, Parrett 1987, Meyer & Wells 1997, Cannon 2001, Cannon et al. 2001) have found that most debris flows generated from recently burned basins are generated through a process of progressive bulking of storm runoff with materials eroded from hillslopes and channels. In contrast, debris flows in unburned settings are usually found to initiate through the failure of a discrete landslide on the hillslope, which then mobilizes into a debris flow. The difference between the runoff-dominated processes found in burned areas and the infiltration-dominated processes on unburned hillslopes may account for the wide variation in rainfall threshold conditions.

The threshold presented here can provide the basis for warning systems and planning for emergency response in similar settings. That is, for basins that are underlain by similar rock types, have average gradients between 25 and 95 percent and areas less than about 10 mi^2 (25 km^2), are more than 50 percent burned at high and moderate burn severities, and experience summer convective rainstorms.

SUMMARY AND CONCLUSIONS

In this paper we have focused on defining the conditions under which debris flows can occur, and characterizing the magnitude of this response, from the 2002 Coal Seam and Missionary Ridge Fires in Colorado. These are critical elements in post-fire hazard assessments, emergency-response planning, and in the design of mitigation structures.

By documenting the basin area and gradient, and burn extent of the debris-flow producing basins, as well as the rainfall conditions that impacted the basins, we define some of the conditions that lead specifically to the generation of post-wildfire debris flows. Debris flows were produced from basins underlain by interbedded sandstones, siltstones and conglomerates and mantled with SM soils, and from basins underlain by gneissic quartz monzonite and quartzite with SW soils. An abundance of readily entrained materials mantling hillslopes and infilling channels resulted in debris-flow activity throughout the monsoon season. Debris-flow producing basins ranged in size from 0.01 to 8.24 mi^2 (0.03 to 21 km^2), had average gradients between 26 and 94 percent and relief ratios between 16 and 73 percent. A basin area/relief ratio threshold defines the basin morphologic conditions known to have produced post-fire debris flows, given sufficient rainfall. Basins burned at moderate and high severities over more than 50 percent of their areas were susceptible to debris-flow activity. Nearly 70 percent of the debris-flow generating storms were of durations equal to or less than 2 hrs, and 93 percent of these had recurrence intervals of less than or equal to 2 yrs. The average intensities of the debris-flow triggering storms ranged between 0.04 and 0.67 in/hr, (1.0 and 17.0 mm/hr) with 10-minute peak intensities up to 2.46 in/hr (62.5 mm/hr). The conditions described here are likely to produce debris flows from recently burned basins in the future.

Estimates of the peak discharge of debris-flow events are used to define relations between the magnitude of the debris-flow response, storm rainfall triggers, and basin area. Estimates of debris-flow peak discharges between 315 and 5581 ft^3/s (9 and 167 m^3/s) were obtained using indirect methods, and values for peak discharge per unit area ranged between 1.0×10^{-5} and 1.2×10^{-3} ft/s (2.0×10^{-6} and 3.8×10^{-4} m/s). Peak-discharge-per-unit-area values were generally higher for the Coal Seam Fire than for the Missionary Ridge Fire. Debris-flow events with the highest values of peak discharge per unit area, and thus potentially the most destructive, occurred in response to storms with average intensities greater than about 0.4 in/hr (10 mm/hr) and with 10-minute peak intensities greater than about 2.0 in/hr (50 mm/hr).

And last, a rainfall intensity-duration threshold for post-wildfire debris flow activity of the form $I = 0.25D^{-0.5}$, where I = rainfall intensity (in in/hr) and D = the duration of that intensity (in hrs) is defined. Such a threshold is a useful tool in issuing warnings and planning for emergency response for basins underlain by similar materials, of similar sizes and gradients, and burned extents that experience convective thunderstorms.

Conditions other than those examined here may certainly affect debris-flow occurrence from recently burned basins. Further work is focusing on evaluating the combined effects of a number of variables on debris-flow susceptibility and the magnitude of the response.

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Table 1A. Storm rainfall characteristics and related erosional response of basins within 1 mi (1.6 km) of each rain gage, Coal Seam Fire

Rain gage	Storm Date	Total storm rainfall (inches)	Storm duration (hr:min)	Average storm intensity (in/hr)	Storm recurrence (years)	10-Minute peak intensity (in/hr)	Response of basins located near gage
*Fish Hatchery	8/5/2002	0.48	1:00	0.48	<2	2.28	Debris flow
*Mitchell Creek	8/5/2002	0.31	0:50	0.37	<2	1.20	No response
*South Canyon	8/5/2002	0.67	1:00	0.67	2	1.80	Debris flow
*Storm King	8/5/2002	0.16	1:00	0.16	<2	0.52	No response
**42	8/5/2002	0.35	0:47	0.42	<2	1.92	Debris flow
**43	8/5/2002	0.38	0:50	0.46	<2	2.10	Debris flow
**46	8/5/2002	0.29	0:46	0.39	<2	1.44	Debris flow
*Fish Hatchery	9/7/2002	0.49	2:00	0.24	<2	n/a	Debris flow
*Mitchell Creek	9/7/2002	0.55	2:00	0.28	<2	0.78	No response
**42	9/7/2002	0.30	1:26	0.21	<2	0.60	No response
**43	9/7/2002	0.51	0:47	0.65	2	1.20	No response
**46	9/7/2002	0.32	1:20	0.24	<2	0.54	No response
*Fish Hatchery	9/11/2002	0.16	1:00	0.16	<2	n/a	Debris flow
*Mitchell Creek	9/11/2002	0.25	2:00	0.13	<2	n/a	No response
**42	9/11/2002	0.20	0:13	1.00	<2	1.02	No response
**43	9/11/2002	0.24	0:38	0.38	<2	1.26	No response
**46	9/11/2002	0.08	0:18	0.27	<2	0.42	No response
*Fish Hatchery	9/12/2002	0.09	1:00	0.09	<2	n/a	No response
*Mitchell Creek	9/12/2002	0.27	4:00	0.07	<2	n/a	No response
**Basin C	9/12/2002	0.04	0:20	0.12	<2	0.18	No response
**Basin B	9/12/2002	0.07	0:35	0.12	<2	0.24	No response
**Basin A	9/12/2002	0.12	0:18	0.40	<2	0.54	Sediment-laden flood
*Fish Hatchery	9/17/2002	0.31	2:00	0.16	<2	n/a	Debris flow
*Mitchell Creek	9/17/2002	0.34	2:00	0.17	<2	n/a	No response
**42	9/17/2002	0.22	1:41	0.13	<2	0.36	No response
**43	9/17/2002	0.26	1:18	0.20	<2	0.54	No response
**46	9/17/2002	0.28	1:22	0.20	<2	0.36	No response
*Fish Hatchery	10/2-3/2002	0.99	11:00	0.09	2	n/a	Debris flow
*Mitchell Creek	10/2-3/2002	0.32	6:00	0.05	<2	n/a	No response
**42	10/2-3/2002	0.85	9:24	0.09	2	0.48	Sediment-laden flood
**43	10/2-3/2002	1.09	9:15	0.12	5	0.60	Sediment-laden flood
**46	10/2-3/2002	0.78	10:39	0.07	<2	0.54	No response

*Remote Access Weather Station (RAWS) installed and maintained by U.S.D.A. Forest Service and the Bureau of Land Management.
**Gage installed by USGS

Table 1B. Storm rainfall characteristics and related erosional response of basins within 1 mi (1.6 km) of rain gages, Missionary Ridge Fire

Rain gage	Storm date	Total storm rainfall (inches)	Storm duration (hr:min)	Average storm intensity (in/hr)	Storm recurrence (years)	10-Minute peak intensity (in/hr)	Response of basins located near gage
A3	7/22/02	1.49	8:24	0.18	<2	1.24	Sediment-laden flood
A4	7/22/02	0.46	3:29	0.13	<2	1.08	Ash/Mud flow
A5	7/22/02	1.09	3:14	0.34	2	1.98	Ash/Mud flow
A6	7/22/02	0.16	5:31	0.03	<2	0.18	No response
A8	7/22/02	0.06	2:57	0.02	<2	0.06	No response
A12	7/22/02	0.39	3:15	0.12	<2	0.36	No response
A3	7/23/02	0.13	0:28	0.28	<2	0.42	No response
A4	7/23/02	0.40	2:54	0.13	<2	0.56	Sediment-laden flood
A5	7/23/02	0.50	3:12	0.16	<2	0.84	Debris flow
A6	7/23/02	1.87	1:28	1.25	10	2.40	Debris flow/Flood
A8	7/23/02	0.09	0:30	0.18	<2	0.36	Sediment-laden flood
A12	7/23/02	0.72	1:03	0.69	<2	1.44	Sediment-laden flood
A3	8/3/02	0.12	3:00	0.04	<2	0.24	Debris flow
A4	8/3/02	0.13	0:23	0.34	<2	0.48	Debris flow
A5	8/3/02	0.58	0:54	0.64	<2	2.46	Debris flow
A6	8/3/02	0.04	0:30	0.08	<2	0.18	Debris flow
A6	8/5/02	0.24	0:33	0.44	<2	1.08	Debris flow
A4	8/8/02	0.20	0:21	0.57	<2	0.90	Debris flow
A5	8/8/02	0.18	0:18	0.64	<2	0.84	Debris flow
A10	8/8/02	0.24	1:21	0.18	<2	0.45	Sediment-laden flood
A3	8/20/02	0.33	1:07	0.29	<2	1.14	Sediment-laden flood
A4	8/20/02	0.26	1:33	0.17	<2	0.78	Sediment-laden flood
A5	8/20/02	0.32	1:50	0.17	<2	0.90	Sediment-laden flood
A3	8/21/02	0.13	1:07	0.11	<2	0.24	Sediment-laden flood
A4	8/21/02	0.04	0:12	0.20	<2	0.18	Debris flow/Flood
A5	8/29/02	0.32	0:55	0.35	<2	1.20	No response
A6	8/29/02	0.14	0:43	0.19	<2	0.72	No response
A7	8/29/02	0.09	0:43	0.13	<2	0.24	Debris flow
A10	8/29/02	0.24	0:48	0.30	<2	0.90	Debris flow
A6	9/7/02	0.61	2:15	0.27	<2	0.72	Debris flow
A7	9/7/02	0.17	0:18	0.51	<2	0.60	Debris flow
A8	9/7/02	0.67	2:53	0.24	<2	1.56	Debris flow
A9	9/7/02	0.48	3:02	0.16	<2	1.38	Debris flow
A10	9/7/02	0.60	2:50	0.21	<2	1.11	Debris flow
A12	9/7/02	1.11	2:15	0.49	2	3.11	Sediment-laden flood

Table 1 B, continued.

Rain gage	Storm date	Total storm rainfall (inches)	Storm duration (hr:min)	Average storm intensity (in/hr)	Storm recurrence (years)	10-Minute peak intensity (in/hr)	Response of basins located near gage
A4	9/10/02	0.30	1:42	0.18	<2	0.54	Sediment-laden flood
A5	9/10/02	0.81	1:33	0.54	<2	1.68	Sediment-laden flood
A4	9/11/02	1.44	13:15	0.11	<2	0.30	Debris flow
A6	9/11/02	0.22	1:11	0.16	<2	0.72	Debris flow
A7	9/11/02	0.16	0:59	0.16	<2	0.72	Debris flow
A8	9/11/02	1.84	12:28	0.15	2	0.72	Debris flow
A9	9/11/02	0.89	12:40	0.07	<2	0.24	Debris flow
A10	9/11/02	1.82	14:18	0.13	2	0.60	Debris flow
A7, A10	9/20/02	--	--	--	--	--	Debris flow (no rainfall recorded)
A8	10/2/02	0.78	13:00	0.06	<2	0.27	Sediment-laden flood
A9	10/2/02	0.10	1:15	0.08	<2	0.12	Sediment-laden flood

Table 2A. Peak discharge estimates and peak discharge estimates normalized by basin area for debris flows generated from basins burned by Coal Seam Fire

Basin	Event date	Average cross-sectional area (ft^2)	Peak discharge (ft^3/s)	Peak discharge/basin area (ft/s)
A	8/05/02	30.8	493*	0.00002
B	8/05/02	48.8	781*	0.00012
C	8/05/02	19.7	315*	0.00019
D	8/05/02	24.4	390*	0.00070
F	8/05/02	63.0	630**	0.00113
G	8/05/02	40.6	406**	0.00730
H	8/05/02	24.0	240**	0.00124
M	8/05/02	21.8	349*	0.00021

*Calculated as Q = VA, with average velocity assumed to be 16 ft/s (5 m/s)
**Calculated as Q = VA, with average velocity assumed to be 10 ft/s (3 m/s)

Table 2B. Peak discharge estimates and peak discharge estimates normalized by basin area for debris flows generated from basins burned by Missionary Ridge Fire.

Basin	Event date	Average cross-sectional area (ft^2)	Peak discharge (ft^3/s)*	Peak discharge/basin area (ft/s)
Root	8/8/02	95.1	1522	0.00007
Root	8/21/02	109.4	1750	0.00008
Unnamed 2	8/8/02	46.8	748	0.00110
Haflin	8/29/02	18.3	293	0.00001
Freed	9/7/02	328.3	5253	0.00008
Stevens	9/7/02	348.8	5581	0.00003
Kroeger	8/29/02	47.3	757	0.00002
Coon	9/7/02	93.4	1494	0.00001
Woodard	9/7/02	93.4	1494	0.00006
Unnamed 3	8/8/02	83.5	1336	0.00015
Unnamed 1	8/5/02	57.5	920	0.00006
Unnamed 1	9/5/02	54.8	877	0.00005
Unnamed 1	9/10-12/02	37.6	602	0.00004

*Calculated as Q = VA, with average velocity assumed to be 16 ft/s (5 m/s)

Table 3A. Characteristics of debris-flow producing basins within the Coal Seam Fire.

Basin	Area (mi^2)	Average gradient (%)	Relief ratio (%)	Geologic unit	Percent basin unburned	Percent basin burned at low severity	Percent basin burned at moderate severity	Percent basin burned at high severity	Percent basin burned at moderate and high severities
A	0.81	51	24	1	0	1	38	61	99
B	0.22	53	33	1	17	3	46	35	81
C	0.06	55	40	1	6	3	62	29	91
D	0.02	49	39	1	2	10	45	43	98
E	0.05	46	39	2	0	8	57	25	82
F	0.02	74	64	2	0	1	96	3	99
G	0.02	71	67	2	0	0	89	11	100
H	0.01	69	65	2	0	0	96	4	100
I	0.03	64	61	2	0	1	80	19	99
J	0.05	84	73	1	0	0	17	83	100
K	0.57	52	30	1	42	4	8	46	54
L	0.14	60	54	1	2	11	46	41	87
M	0.06	87	63	1	6	13	26	55	81
N	0.07	88	64	1	3	12	26	58	84
O	0.06	94	60	1	12	25	19	44	63

1. Maroon Formation: interbedded sandstones, shales, siltstones and conglomerates (Kirkham et al., 1997)
2. Sawatch Quartzite and Gneissic quartz monzonite of Mitchell Creek (Kirkham et al, 1997)

Table 3B. Characteristics of debris-flow producing basins within the Missionary Ridge Fire.

Basin	Area (mi^2)	Average gradient (%)	Relief ratio (%)	Geologic units	Percent basin unburned	Percent basin burned at low severity	Percent basin burned at moderate severity	Percent basin burned at high severity	Percent basin burned at moderate and high severities
Root	0.73	32	17	1	0	1	29	69	98
Unnamed 2	0.24	39	25	1	0	6	56	39	95
Haflin	1.60	56	23	1, 2	4	11	34	51	85
Freed	2.18	53	18	1, 2	1	4	43	53	96
Stevens	6.08	52	14	1, 2, 3	2	12	50	35	85
Kroeger	1.21	53	25	1, 2	1	9	65	25	90
Coon	8.04	37	16	1, 2, 3	4	18	33	45	78
Woodard	0.92	58	30	1, 2	8	19	51	22	73
Unnamed 3	0.33	30	24	2	0	14	57	28	85
Unnamed 1	0.57	26	21	4	0	6	46	48	94

1. Cutler Formation: interbedded sandstones, shales, siltstones and conglomerates
2. Junction Creek, Wanakah, Entrada, and Dolores Formations: sandstone, with some shale and siltstone
3. Hermosa and Molas Formations: shale, limestone and sandstone
4. Morrison Formation: claystone, siltstone mudstone and sandstone