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Storm rainfall conditions for floods and debris flows from recently burned areas in southwestern Colorado and southern California

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Abstract

Debris flows generated during rain storms on recently burned areas have destroyed lives and property throughout the Western U.S. Field evidence indicate that unlike landslide-triggered debris flows, these events have no identifiable initiation source and can occur with little or no antecedent moisture. Using rain gage and response data from five fires in Colorado and southern California, we document the rainfall conditions that have triggered post-fire debris flows and develop empirical rainfall intensity–duration thresholds for the occurrence of debris flows and floods following wildfires in these settings. This information can provide guidance for warning systems and planning for emergency response in similar settings.

Debris flows were produced from 25 recently burned basins in Colorado in response to 13 short-duration, high-intensity convective storms. Debris flows were triggered after as little as six to 10 min of storm rainfall. About 80% of the storms that generated debris flows lasted less than 3 h, with most of the rain falling in less than 1 h. The storms triggering debris flows ranged in average intensity between 1.0 and 32.0 mm/h, and had recurrence intervals of two years or less. Threshold rainfall conditions for floods and debris flows sufficiently large to pose threats to life and property from recently burned areas in south-central, and southwestern, Colorado are defined by: $I=6.5D^{-0.7}$ and $I=9.5D^{-0.7}$, respectively, where I=rainfall intensity (in mm/h) and D=duration (in hours).

Debris flows were generated from 68 recently burned areas in southern California in response to long-duration frontal storms. The flows occurred after as little as two hours, and up to 16 h, of low-intensity (2–10 mm/h) rainfall. The storms lasted between 5.5 and 33 h, with average intensities between 1.3 and 20.4 mm/h, and had recurrence intervals of two years or less. Threshold rainfall conditions for life- and property-threatening floods and debris flows during the first winter season following fires in Ventura County, and in the San Bernardino, San Gabriel and San Jacinto Mountains of southern California are defined by $I=12.5D^{-0.4}$, and $I=7.2D^{-0.4}$, respectively. A threshold defined for flood and debris-flow conditions following a year of vegetative recovery and sediment removal for the San Bernardino, San Gabriel and San Jacinto Mountains of $I=14.0D^{-0.5}$ is approximately 25 mm/h higher than that developed for the first year following fires.

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The thresholds defined here are significantly lower than most identified for unburned settings, perhaps because of the difference between extremely rapid, runoff-dominated processes acting in burned areas and longer-term, infiltration-dominated processes on unburned hillslopes.

Keywords: Debris flow; Rainfall intensity–duration thresholds; Wildfire; Warning systems

1. Introduction

Debris flows and sediment-laden floods have been produced from basins burned by wildfire in response to short-duration, convective thunderstorms in the inter-mountain west (e.g., Parrett, 1987; Meyer and Wells, 1997; Cannon, 2001; Parrett et al., 2003; Cannon and Gartner, 2005), and to longer duration winter frontal storms in southern California (e.g., Scott, 1971; Scott and Williams, 1978; Wells, 1987; Morton, 1989; Booker, 1998). In both settings, the great majority of the debris flows were generated through erosion and entrainment of material by surface runoff from hillslopes and channels, rather than failure of discrete landslides (Parrett, 1987; Meyer and Wells, 1997; Cannon et al., 2001a,b). The goals of this paper are to 1) document the conditions of the storm rainfall that triggered debris flows through this process from basins burned by fires in south-central Colorado and southern California, and 2) to use this information to define the threshold rainfall intensity–duration conditions that can result in the production of post-fire debris flows and floods that pose significant hazards to life and property in these settings. Identification of measures of storm rainfall that are reliable predictors of destructive flood or debris flow response is critical for issuing warnings and planning for emergency response (e.g., Keefer et al., 1987; Wilson et al., 1993; Mills, 2002; NOAA-USGS Task Force, 2005; Baum et al., 2005).

2. Previous work

2.1. Post-fire debris flow initiation processes

Field and aerial photographic observations from 210 recently burned basins throughout the western U. S. indicated that the great majority of debris flows that occur within the first two years following wildfires in response to short-recurrence interval storms are generated through the process of progressive entrainment of material eroded from hillslopes and channels by surface runoff, rather than by infiltration-triggered landsliding, as is common in unburned settings (Cannon and Gartner, 2005). Meyer and Wells (1997) titled the process 'progressive sediment bulking' and describe it as starting with runoff high on hillslopes, which converges and concentrates within hollows and in low-order channels. Concentrated surficial runoff results in considerable erosion, often to bedrock, and the transport of material down slope. Evidence of debris flow can occur well down the drainage network. Meyer and Wells (1997) and Cannon et al. (2001a,b) suggest that the transition to debris flow occurs when sufficient material has been entrained, relative to the volume of runoff, to impart debris flow characteristics to the flow. Cannon et al. (2003b) identified the location of this transition within a drainage network in terms of a threshold contributing area, its gradient, and the underlying materials.

2.2. Rainfall thresholds

Empirically-derived rainfall intensity–duration thresholds have been widely used to identify rainfall conditions that will lead to the initiation of landslides from unburned hillslopes (see a world-wide compilation of local, regional and global thresholds by Guzzetti et al. (in press); http://rainfallthresholds.irpi.cnr.it/). In these cases, the thresholds identify the rainfall conditions that result in a destabilizing pore-pressure response at depth that is a function of the hydraulic properties of the hillslope material, its initial moisture content, and the intensity and duration of rainfall (Godt et al., 2006). Thresholds developed for unburned hillslopes, however, are not appropriate to the processes that are prevalent in recently burned basins, where the need exists for definition of the rainfall conditions that lead to concentrated surficial runoff and erosion of channel material. Coe et al. (2008-this volume), developed a rainfall threshold for the initiation of debris flows through a process similar to that outlined above for an unburned setting in central Colorado. We are not aware of similar efforts to systematically define the rainfall threshold conditions that lead to the generation of debris flows from recently burned areas.

Work in recently burned areas, however, has focused on identifying rainfall conditions that will lead to significant runoff and sedimentation events, but not specifically debris flows. Measurements of the peak discharge response of recently burned basins in Colorado, South Dakota and New Mexico by Moody and Martin (2001), indicated that 30 min peak rainfall intensities greater than about 10 mm/h resulted in significant increases in runoff. Similarly, comparison of measurements of hillslope sediment-runoff concentrations and rates of rainfall in a volcanic terrain by Cannon et al. (2001a,b) indicated that 30 min peak rainfall intensities greater than about 20 mm/h resulted in significant sediment movement in this setting.

In unburned settings, a number of different methods for characterizing storm rainfall and for selecting the location of the threshold line have been used to define rainfall intensity–duration thresholds. Storm rainfall conditions have been characterized simply by the total storm average intensity and duration, and the threshold conditions for debris flows are defined either by a line that defines the lower limit of the data (e.g., Caine, 1980; Godt et al., 2006), or when the data allows, by a line that separates rainfall totals from storms that produced debris flows from those that did not (e.g., Larsen and Simon, 1993). Working with the assumption that most debris flows are the result of some combination of rainfall intensity and duration within a storm, rather than the total storm rainfall, some workers have examined within-storm rainfall conditions. Rainfall has been characterized by the intensities and durations of periods of intense rainfall (bursts) that are separated by periods with no, or minimal, rainfall (Coe et al., 2008-this volume; Cannon and Ellen, 1988), or by the intensities and durations of combinations of bursts (e.g., Cannon and Ellen, 1988). Wieczorek and Sarmiento (1988) also compiled measures of rainfall intensities within a storm for a given set of durations, including 2.5, 5, 6.5, 7.5 and 10.25 h. A single storm is, thus, characterized by many different measures of storm rainfall, rather than as a single value. With this data, threshold lines are located using one of three approaches: 1) defining the lower limit of conditions within storms known to produce debris flows (e.g. Coe et al., 2008-this volume), which identifies the lowest, or most conservative, rainfall conditions for the initiation of debris flows; 2) separating conditions in storms that produced debris flows from those that did not, if the data allows (e.g. Wieczorek and Sarmiento, 1988); or 3) or defining the upper limit of conditions in storms known not to have produced debris flows (e.g., Cannon and Ellen, 1988). In this last approach, the threshold is defined by measures of storm rainfall that are unique to the storms producing debris flows. This approach is based on the reasoning that of the many different measures of rainfall compiled for each storm it is not known which most strongly correspond to the occurrence of debris flows, but it is assumed that some do not; those conditions that occurred during storms that did not produce debris flows are not likely to result in debris flows. An advantage of the second two approaches over the first in the definition of thresholds for use in warning systems is that they define less conservative conditions, and can thus reduce the number of false alarms issued.

3. Approach

For this study, we evaluated the rainfall and debris-flow response in five recent fires; the Coal Seam and Missionary Ridge Fires that burned in the summer of 2002 in south-central Colorado (Figs. 1, 2, and 3), and the Piru, Old, and Grand Prix Fires that burned in the fall of 2003 in southern California (Figs. 1, 4, and 5). Shortly after each fire was extinguished and before any rainstorms had impacted the area, networks of tipping-bucket rain gages were installed throughout the burned areas (Table 1). After each significant rainfall, we documented which basins produced debris flows, sediment-laden floods, and which showed no response. By documenting the rainfall conditions for these events, we define the ranges of total rainfall, durations, average intensities, and recurrence intervals of storms that lead specifically to the generation of post-wildfire debris flows. In addition, comparisons of the rainfall conditions in storms that produced debris flows with those that produced sediment-laden floods or showed a negligible response are used to define rainfall intensity–duration thresholds for the production of post-fire debris flows and floods in each of these settings. We develop thresholds for the first year after a fire for the south-central Colorado and southern California settings, and following one year of vegetative recovery and sediment movement in southern California. Where available, information on the known times of debris flows or floods within a storm, and characterization of the rainfall conditions leading up to these events, are used to better define triggering conditions and to verify the thresholds.

In unburned settings, characterization of the occurrence of debris flows often requires identification of an antecedent rainfall threshold, which defines an accumulation of rainfall during the preceding season, in addition to a storm-specific intensity–duration threshold (Wieczorek and Glade, 2005; Wilson, 2000). In recently burned areas, where debris flows are most likely to be

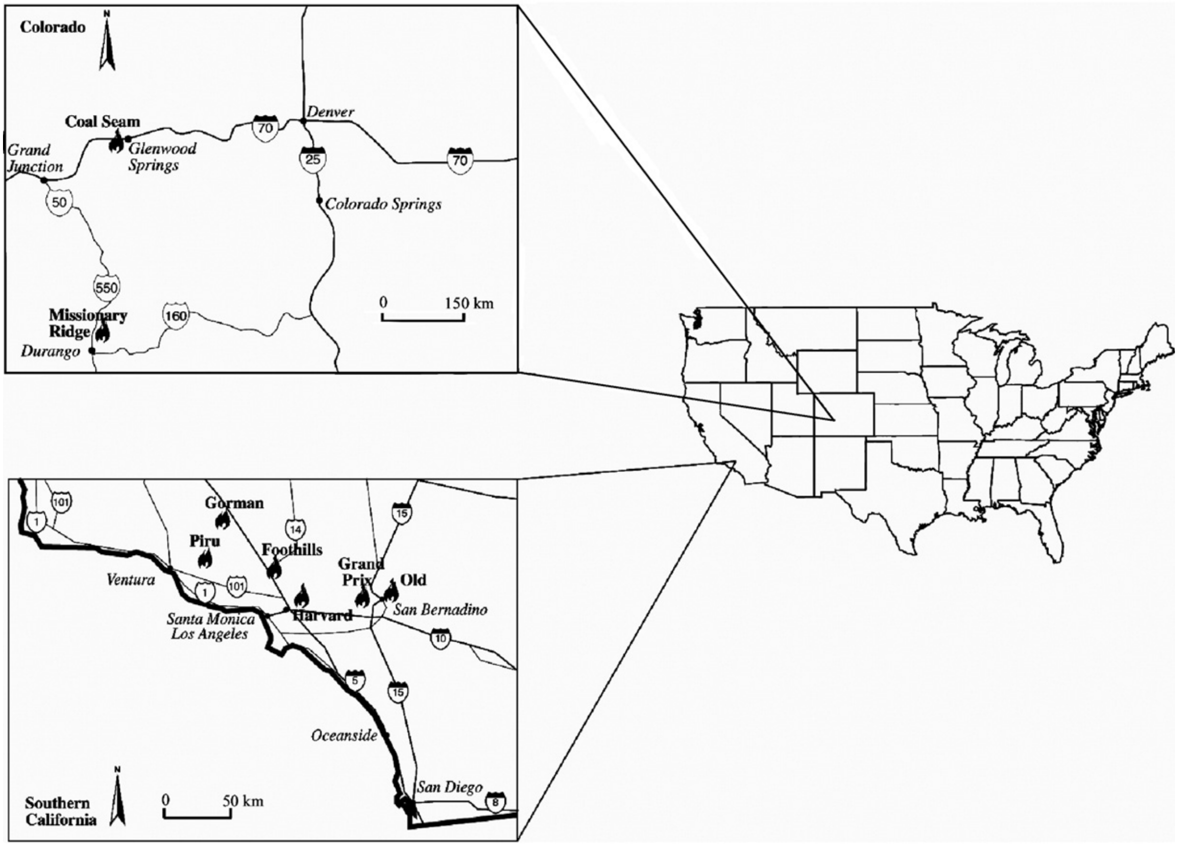

Fig. 1. Maps showing locations of fires in the study.

initiated through runoff-dominated processes rather than from infiltration-triggered landslides, the largest and most extensive debris flows generally occur in response to the first significant storm to impact an area, when antecedent soil moisture accumulations would be negligible (Cannon and Gartner, 2005). In addition, because most of the sediment contributed to post-fire debris flows is eroded from channels (Santi et al., 2008-this volume), rather than through shallow landsliding associated with transient pore pressure changes, the definition of antecedent rainfall conditions may not as critical for debris-flow initiation in burned landscapes as it is in undisturbed settings. Therefore, we have assumed that rainfall intensity–duration thresholds alone can be considered sufficient to provide an initial assessment of the rainfall conditions that result in debris flows from recently burned areas. Further study is necessary to quantify the effect of antecedent soil moisture in burned areas.

3.1. Data collection

Rainfall that impacted burned basins was documented by networks of tipping-bucket rain gages installed within the burned areas shortly after each fire was extinguished and before any rainstorms. Twelve tipping-bucket rain gages were installed by the U.S. Geological Survey in the area burned by the Missionary Ridge Fire as part of the Rapid Deployment Data Collection Network (Teller, 2003) (Table 1; Fig. 3). We installed three tipping-bucket rain gages in the area burned by the Coal Seam Fire (Table 1; Fig. 2), and four Remote Access Weather Stations (RAWS) installed and maintained by the USDA Forest Service and Bureau of Land Management were used to supplement this information. Although the RAWS stations recorded rainfall totals at 10-minute intervals, some data were available only at 1-hour intervals. The Grand Prix and Old Fires benefited from an existing ALERT network of 16 rain gages operated by the San Bernardino Flood Control Distinct (Table 1; Fig. 5). We augmented this network with an additional 19 gages for a total of 35. We also installed 11 gages in the Piru Fire (Table 1; Fig. 4). Although not all gages operated during all storms, rain gages were generally located within approximately 1.5 km of basins whose response was monitored. Data were stored on internal data loggers and periodically downloaded.

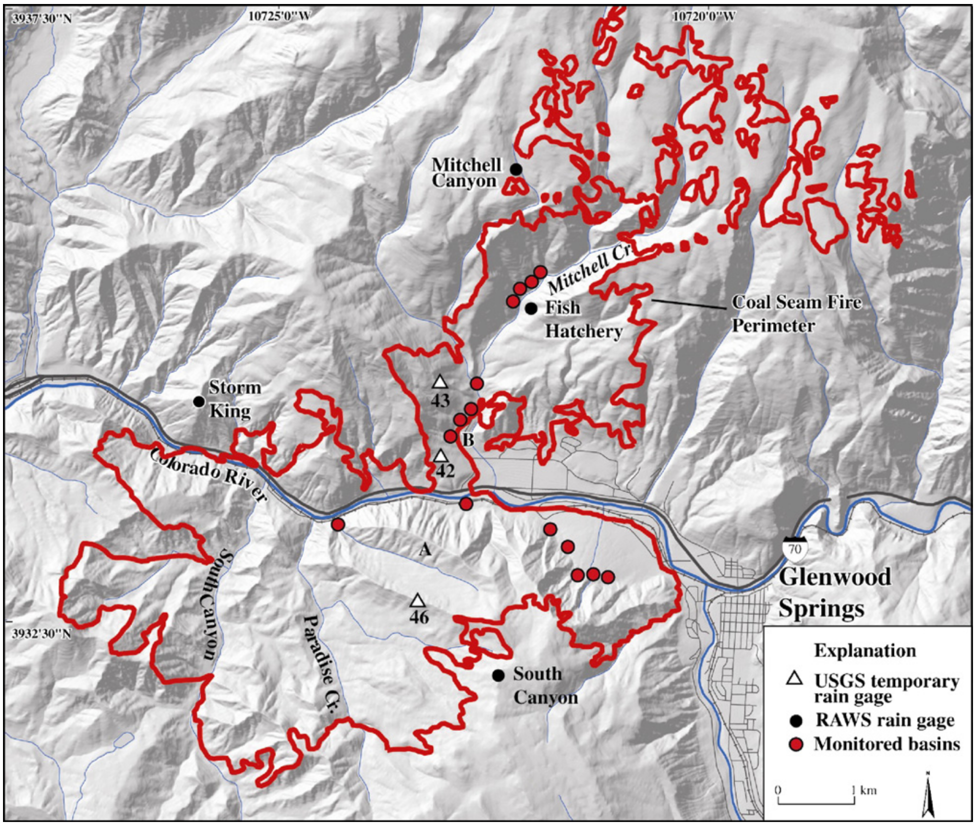

Fig. 2. Map of area burned by the 2002 Coal Seam Fire in south-central Colorado, locations of rain gages, and outlets of monitored basins.

The tipping-bucket rain gages record the date and time of each 0.25 mm accumulation of rainfall. From these data and for each storm of interest, we computed measures of storm duration, total storm rainfall, average storm intensity (total storm rainfall divided by the duration), and peak 10-, 15- and 30-minute and 1-, 3-, 6-, 12-and 18-hour intensities (where appropriate) within a storm. Thus, each storm is characterized by as many as 11 measures, including up to eight measures of peak intensity for given durations. Peak intensities were not computed for given durations longer than that of the storm.

Field observations made after each significant rainfall identified which basins produced debris flows or sediment-laden floods that could pose a significant hazard to life and property, and which basins showed a negligible hydrologic response, using sedimentologic and physical criteria described in Pierson (2005). We characterized the peak flow process for each storm at the basin mouth, as this is where any impact would most likely occur.

To document the storm rainfall conditions that have triggered debris flows from recently burned areas, we examined measures of total storm rainfall, storm duration and average storm intensity from rain gages located within 1.5 km of basins that produced debris flows. We also determined the recurrence interval of each storm from hydrologic atlases of the areas (Miller et al., 1973; Bonnin et al., 2006). Because some eyewitnesses reported that the debris flows occurred in response to periods of high-intensity rainfall during the storm, we also examined the range of 10-minute peak intensities for the Coal Seam and Missionary Ridge Fires and of the 30-minute peak intensities for the Piru, Old and Grand Prix Fires.

If the times of events within a storm are known, those measures of rainfall that lead up to the event can provide a more specific measure of the triggering conditions than does total storm rainfall. To this end, we compiled available information on the known times of debris flow and floods from police dispatch records, stream gage records, newspaper accounts, and observations from eyewitnesses. We then documented the measures of storm rainfall leading up to these events.

To define rainfall intensity–duration thresholds for each of the burned areas, we compared measures of peak

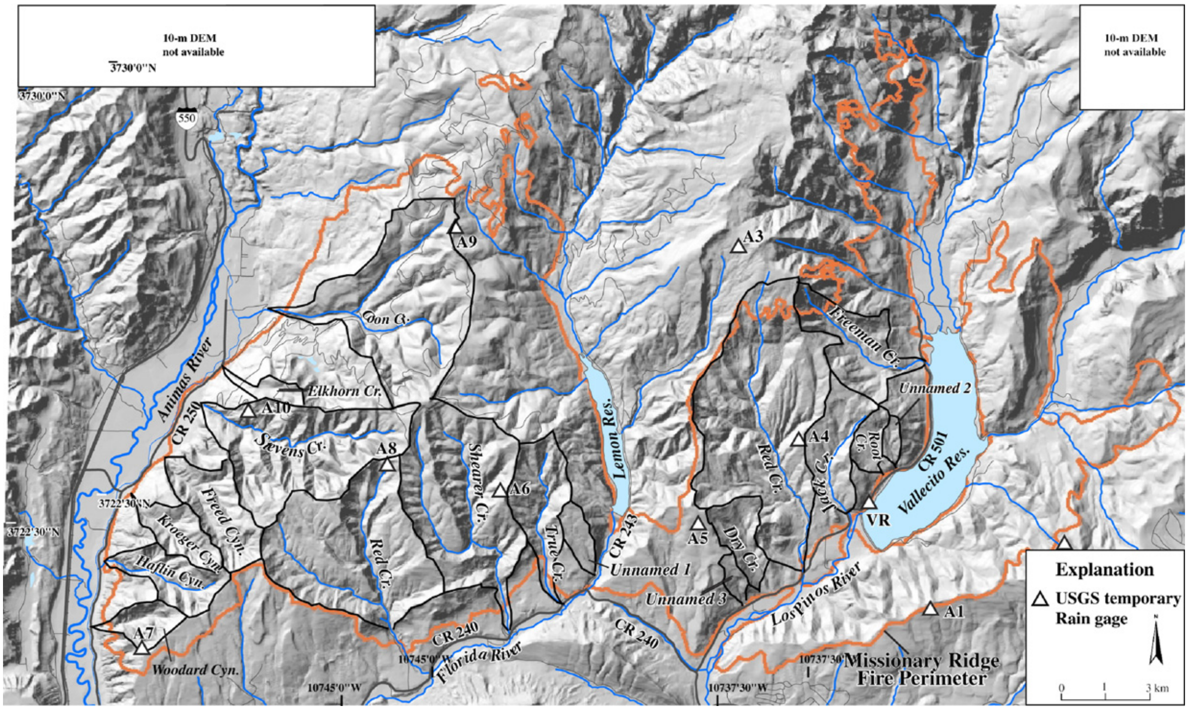

Fig. 3. Map of area burned by the 2002 Missionary Ridge Fire in southwest Colorado, locations of rain gages, and outlines of monitored basins.

storm rainfall of different durations recorded by gages located within 1.5 km of basins that produced either debris flow, sediment-laden flood, or showed a negligible response. We first examined the data to determine if it was possible to visually distinguish rainfall conditions that resulted in debris flow from those that produced sediment-laden floods or a negligible response. For each setting, we then defined the rainfall thresholds as the upper limit of conditions in storms known not to have produced debris flows or floods. This threshold identifies those combinations of rainfall intensities and durations that were unique to the debris-flow and flood-producing storms (i.e. those conditions that did not occur in storms that showed a negligible response). We selected this approach for defining the threshold line (see Previous Work) so that the thresholds could be effectively incorporated into a system for issuing warnings for events that pose significant hazards to life and property (e.g. NOAA-USGS Task Force, 2005), rather than simply identifying the onset of any small, short-recurrence interval rainfall. Because each storm is represented by several rainfall intensities at different durations, some measurements from debris-flow producing storms are expected to fall below the threshold line, and in the field occupied by measurements from storms that showed a negligible response. We determined, however, that for each storm that produced debris flows, some measures of storm rainfall were located above the threshold line. Measures of storm rainfall that lead up to the known times of debris flow and floods were then used to verify, or if necessary, to modify, the positions of the thresholds.

4. Settings

4.1. Coal Seam Fire, Colorado

The Coal Seam Fire burned 4941 hectares immediately west of Glenwood Springs, Colorado during early June of 2002. The fire jumped a four-lane highway and the Colorado River, burning the hillslopes and canyons on both sides of the river (Fig. 2). The fire burned through piñon–juniper woodlands, mountain shrublands, and aspen, Douglas fir, and spruce–fir forests. Approximately 75% of the area was burned at high and moderate burn severity (USDA Forest Service, 2002a). The monitored basins are characterized by steep slopes and small, tightly confined canyons (Fig. 2 and Table 1). The burned area ranges in elevation from approximately 1787 m along the Colorado River, up to 3250 m.

The area burned by the Coal Seam Fire is underlain primarily by interbedded sandstones, siltstones and conglomerates, gneissic quartz monzonite, and quartzite

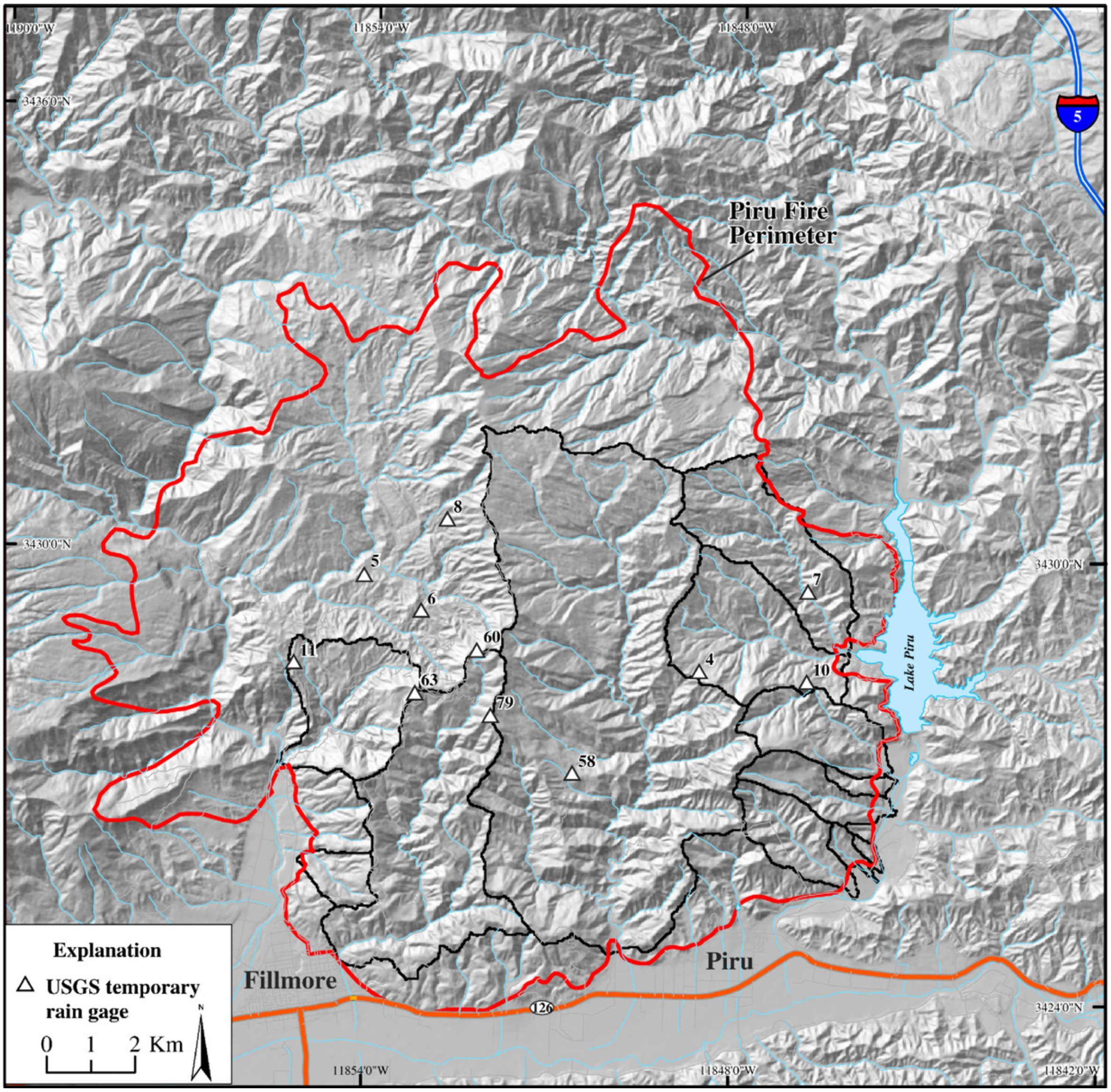

Fig. 4. Map of area burned by the 2003 Piru Fire in southern California, locations of rain gages, and outlines of monitored basins.

(Kirkham et al., 1997). Smaller extents of dolomite, dolomitic sandstone, shale and limestone occur in the upper reaches of the basins. Soils are generally shallow, poorly developed and with a high percentage of rock (Cannon et al., 1998). 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, all basins that are underlain by the sedimentary rock units (Fig. 2). Dry ravel is a process frequently observed during and after fires wherein soils dried during the passage of the fire experience particle-by-particle transport of material downslope by gravity (Swanson, 1981). Dry ravel has been described as an important post-fire process in southern California, by which channels are loaded with sediment available for transport in large runoff events (e.g., Wells, 1981). Extensive dry-ravel deposits were also observed lining channels prior to the debris flows that occurred following the South Canyon Fire near Glenwood Springs, CO in 1994 (Cannon et al., 1998). Tributaries to Mitchell Creek also contain extensive talus deposits that mantle the hillslopes underlain by the metamorphic rock types.

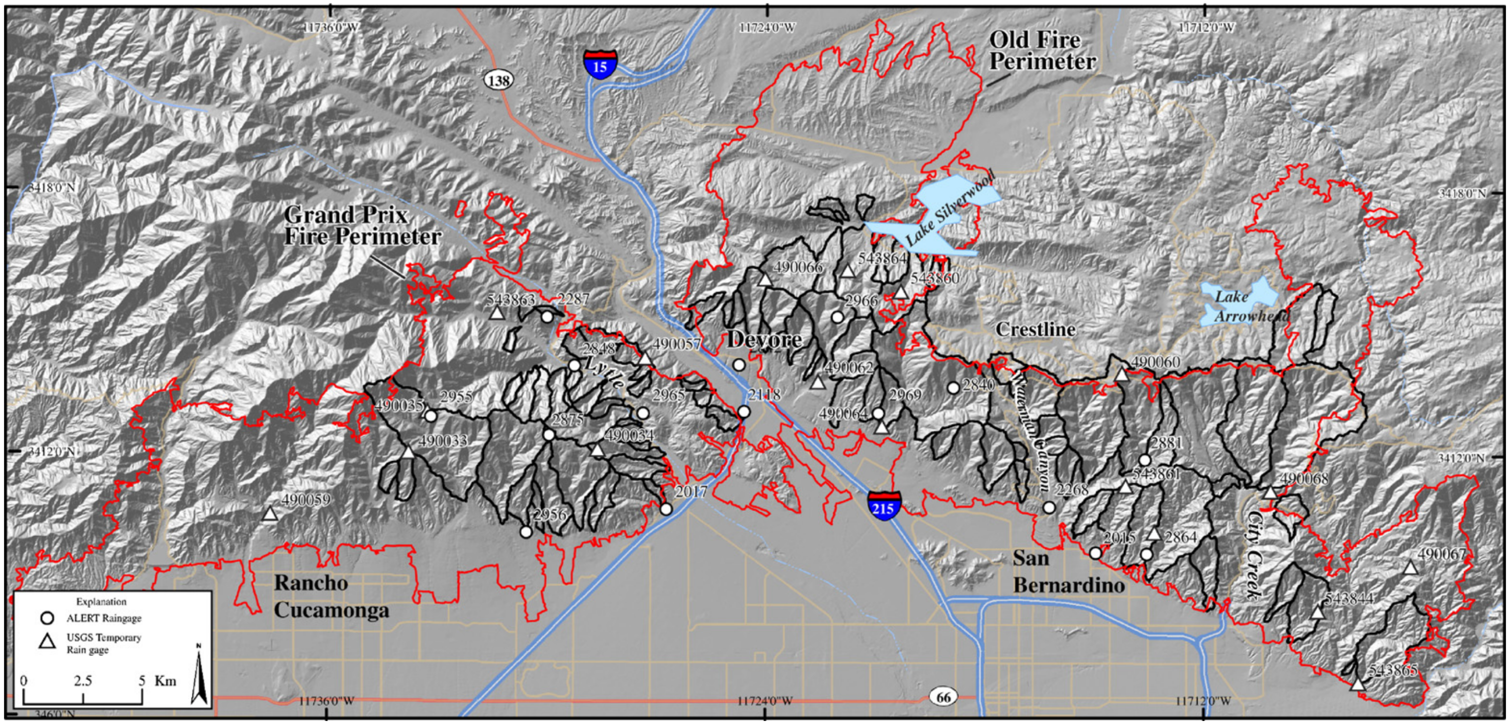

Fig. 5. Map of areas burned by the 2003 Old and Grand Prix Fires in southern California, locations of rain gages, and outlines of monitored basins.

Table 1
Ranges of characteristics of basins within the Coal Seam, Missionary Ridge, Piru, Old and Grand Prix Fires where storm response is known

Fire	Range of basin areas (km^2)	Range of average basin gradients (%)	Range of basin ruggedness [a]	Percent high and moderate severity (%)	Number of monitored basins	Number of rain gages
Coal Seam [b]	0.03 to 2.1	46 to 94	0.2 to 3.4	75	15	7
Missionary Ridge [b]	0.8 to 20.8	26 to 58	0.2 to 1.6	61	17	13
Piru	0.3 to 61.0	40 to 55	0.2 to 0.5	50	13	11
Old, Grand Prix	0.2 to 4.6	33 to 82	0.2 to 1.1	60, 80	87	35

[a] Calculated as elevation change in basin divided by square root of basin area (Melton, 1965).
[b] From Cannon et al. (2003a,b).

Glenwood Springs has a semi-arid climate with low humidity throughout the year (USDA Forest Service, 2002a). The USDA Forest Service report describes average high temperatures in the valley bottoms ranging from − 1 to 4 °C in winter to 27 to 32 °C in the summer months, and average annual precipitation in the valley ranging between 381 and 432 mm, and up to 965 mm at higher elevations. Precipitation usually falls during two periods — either as winter frontal storms, or as summer convective thunderstorms. The thunderstorms are characterized by intense, localized, short-duration rainfall.

4.2. Missionary Ridge Fire, Colorado

The Missionary Ridge Fire burned 28,524 ha north and northeast of the city of Durango, Colorado during June and July of 2002, and included portions of the Animas, Florida and Los Pinos River Valleys (Fig. 3). The fire burned Ponderosa pine, mixed conifer, aspen and spruce–fir forests at elevations ranging from approximately 2030 m along the Animas Valley to 3560 m in the northern portion of the fire. Approximately 61% of the area was burned at moderate and high severities (USDA Forest Service, 2002b). The monitored basins are somewhat larger than those in the Coal Seam Fire, with gentler hillslope gradients and lower ruggedness values (Table 1).

Interbedded sandstones, siltstones and conglomerates underlie most of the area burned by the fire (Carroll et al., 1997, 1998, 1999; Gonzales et al., 2002). Formations of interbedded sandstones, shales, limestones and conglomerates, and underlying, older granite also occur within the burned area. In addition, extensive 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 (USDA Forest Service, 2002b). 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.

The area around Durango has a semi-arid climate with generally warm summers and cold winters. Annual precipitation in Durango is 472 mm, and winter snowfall totals average about 1778 mm (USDA Forest Service, 2002b). Forty-two percent of the precipitation in Durango falls between August and October during the summer–fall monsoon season. The monsoon season is

Table 2A
Characteristics of storm rainfall from rain gages located within 1.5 km of basins that produced debris flows in the Coal Seam Fire, south-central Colorado

Rain gage	Storm date	Total storm rainfall (mm)	Storm duration (h:min)	Average storm intensity (mm/h)	Storm recurrence (years)	10-minute peak intensity (mm/h)
Fish hatchery	8/5/2002	12.19	1:00	12.19	< 2	57.94
South Canyon	8/5/2002	17.02	1:00	17.02	2	45.72
543842	8/5/2002	8.89	0:47	11.35	< 2	48.77
543843	8/5/2002	9.65	0:50	11.58	< 2	53.36
543846	8/5/2002	7.37	0:46	9.61	< 2	36.59
Fish hatchery	9/7/2002	12.45	2:00	6.23	< 2	n/a
Mitchell Creek	9/7/2002	13.97	2:00	6.99	< 2	19.87
Fish hatchery	9/11/2002	4.06	1:00	4.06	< 2	n/a
Fish hatchery	9/17/2002	7.87	2:00	3.94	<2	n/a
Fish hatchery	10/2–3/2002	25.15	11:00	2.29	2	n/a

Table 2B
Characteristics of storm rainfall from rain gages located within 1.5 km of basins that produced debris flows in the Missionary Ridge Fire, south-central Colorado

Rain gage	Storm date	Total storm rainfall (mm)	Storm duration (h:min)	Average storm intensity (mm/h)	Storm recurrence (years)	10-minute peak intensity (mm/h)
A4	7/22/2002	11.68	3:29	3.35	< 2	27.4
A5	7/22/2002	27.69	3:14	8.56	2	50.3
A5	7/23/2002	12.70	3:12	3.97	< 2	21.3
A6	7/23/2002	47.50	1:28	32.39	10	61.0
A3	8/3/2002	3.05	3:00	1.02	< 2	6.1
A4	8/3/2002	3.30	0:23	8.61	< 2	12.2
A5	8/3/2002	14.73	0:54	16.37	< 2	62.5
A6	8/3/2002	1.02	0:30	2.04	< 2	4.6
A6	8/5/2002	6.10	0:33	11.09	< 2	27.4
A4	8/8/2002	5.08	0:21	14.51	< 2	22.9
A5	8/8/2002	4.57	0:18	15.24	< 2	21.3
A4	8/21/2002	1.02	0:12	5.10	< 2	4.6
A7	8/29/2002	2.29	0:43	3.20	< 2	6.1
A10	8/29/2002	6.10	0:48	7.63	< 2	22.9
A6	9/7/2002	15.49	2:15	6.88	< 2	42.7
A7	9/7/2002	4.32	0:18	14.40	< 2	15.2
A8	9/7/2002	17.02	2:53	5.90	< 2	39.6
A9	9/7/2002	12.19	3:02	4.02	< 2	35.1
A10	9/7/2002	15.24	2:50	5.38	< 2	28.2

characterized by severe, but locally variable and short-lived, thunderstorms.

4.3. Piru Fire, Southern California

During October 2003, the Piru Fire burned a total of 25,886 hectares in the Topatopa Mountains north and east of the town of Fillmore in Ventura County, southern California, and impacted the Sespe, Hopper, and Piru Creek watersheds that feed into Santa Clara River (Rust, 2003) (Fig. 4). Approximately 50% of the area was burned at high and moderate severities. The Piru Fire is located in the Transverse Ranges Geomorphic Province (California Geological Survey, 2002), and is underlain by claystones, shales and sandstones (State of California, 1969). Most soils in this area are moderately deep to shallow loams to sandy loams with half having rock fragments and the other half having minimal rock fragments (Rust, 2003). Some deep to very deep soils are located on old landslide deposits. The monitored basins range in area between 0.25 and 61 km^2, with average hillslope gradients between 40 and 55% (Table 1). Vegetation includes grasslands and coastal sage scrub chaparral. The Topatopa Mountains experience a Mediterranean climate that provides an average annual precipitation of between 635 and 890 mm, most of it

Table 3
Conditions of storm rainfall leading up to debris flows for which the time of occurrence is known from the Coal Seam, Old, Grand Prix, Harvard, Gorman and Foothills Fires

Fire name and year	Reported debris-flow event	Storm date	Storm duration preceding event (h:min)	Storm rainfall intensity preceding event (mm/h)
Coal Seam, 2002	Car impacted at Basin B	5 Aug 2002	0:10	50
			0:6	75
Coal Seam, 2002	Train derailed at Basin A	5 Aug 2002	0:48	10
Old, 2003	Truck trapped in Devore	25 Dec 2003	11:00	6.5
Old, 2003	Deaths in Waterman Canyon	25 Dec 2003	16:45	2.3
Old, 2003	Stream gage record at City Creek	25 Dec 2003	2:45	3.6
Grand Prix, 2003	Cars trapped at Lytle Creek	25 Dec 2003	13:45	3.2
Harvard, 2005	Mud out of Wildwood Canyon	17 Oct 2005	2:0	5.5
Harvard, 2005	Mud out of Wildwood Canyon	17 Oct 2005	3:0	6.3
Gorman, 2005	Mud and debris on freeway	17 Oct 2005	3:6	10.3
Foothills, 2004	Mud in mobile home park	17 Oct 2005	3:30	7.8

Table 4
Characteristics of December 25, 2003 storm rainfall from rain gages located within 1.5 km of basins that produced debris flows in the Old and Grand Prix Fires, southern California

Rain gage	Total storm rainfall (mm)	Storm duration (h:min)	Average storm intensity (mm/h)	Peak 30-minute intensity (mm/h)	Storm recurrence (years)
33 [a]	47.0	18:52	2.5	11.68	< 2
34 [a]	173.7	29:45	5.8	32.00	2
35 [a]	86.4	13:38	6.3	22.86	< 2
57 [a]	136.7	25:22	5.4	28.45	2
59 [a]	92.5	26:21	3.5	20.32	< 2
60 [a]	100.8	28:06	3.6	22.86	< 2
62 [a]	82.8	23:20	3.5	14.73	< 2
64 [a]	68.8	23:50	2.9	14.73	< 2
66 [a]	128.5	27:57	4.6	28.45	< 2
67 [a]	17.8	11:00	1.6	5.59	< 2
68 [a]	30.5	24:03	1.3	10.16	< 2
44 [a]	19.6	4:35	4.3	9.14	< 2
45 [a]	27.4	5:25	5.1	10.16	< 2
860 [a]	179.6	29:08	6.2	29.46	2–5
861 [a]	39.6	11:10	3.5	19.81	< 2
863 [a]	151.1	12:28	12.1	37.08	2
864 [a]	136.7	29:09	4.7	24.89	2
865 [a]	18.0	4:27	4.1	11.68	< 2
2015 [b]	57.9	11:48	4.9	24.89	< 2
2017 [b]	54.1	25:02	2.2	10.16	< 2
2118 [b]	107.7	24:00	4.5	20.83	2
2268 [b]	61.2	14:09	4.3	16.26	< 2
2287 [b]	142.0	14:15	10.0	28.45	2
2840 [b]	119.6	5:52	20.4	50.29	2
2842 [b]	148.3	23:45	6.2	22.35	2
2848 [b]	147.1	24:25	6.0	28.45	2
2864 [b]	30.5	6:40	4.6	12.19	< 2
2875 [b]	51.8	26:49	1.9	10.16	< 2
2881 [b]	89.2	11:39	7.7	32.00	< 2
2955 [b]	34.0	11:13	3.0	8.13	< 2
2956 [b]	120.1	25:52	4.6	29.97	< 2
2965 [b]	67.1	9:23	7.1	16.26	< 2
2966 [b]	80.0	24:37	3.3	18.29	< 2
2969 [b]	41.7	19:45	2.1	12.19	< 2

[a] USGS rain gage.
[b] San Bernardino Flood Control District ALERT rain gage.

occurring during the winter as long-duration, low-intensity storms (California Geological Survey, 2002).

4.4. Old and Grand Prix Fires, Southern California

The Old and Grand Prix Fires burned approximately 57,000 ha in the Santa Ana and Mojave River basins in southern California during October of 2003 (Biddinger et al., 2003) (Fig. 5). Approximately 60% of the Grand Prix and 80% of the Old Fire are mapped as high and moderate burn severity (Biddinger et al., 2003). The fires are located in the Transverse Ranges and the Mojave Desert Geomorphic Provinces (California Geological Survey, 2002), and span elevations from 490 to 2775 m. The fires burned basins in the San Gabriel and San Bernardino Mountain Ranges that are characterized by high relief, steep hillslopes, and tightly confined, steep canyons (Table 1). The mountains are composed of a complex assembly of various rock types

Table 5
Characteristics of October 20, 2004 storm rainfall from gages located within 1.5 km of basins that produced debris flows in the Old and Grand Prix Fires, southern California

Rain gage	Total storm rainfall (mm)	Storm duration (h:min)	Average storm intensity (mm/h)	Peak 30-minute intensity (mm/h)	Storm recurrence (years)
33	100.8	31:03	3.2	12.1	< 1
34	209.3	33:30	6.2	40. 6	< 1
35	75.9	22:30	3.4	9.1	< 1
66	62.0	8:14	7.5	20.6	< 1
862	130.0	27:20	4.8	32.5	< 1

including easily weathered, extensively faulted, coarse crystalline igneous and metamorphic rocks and a small area of sedimentary rocks (Bortugno and Spittler, 1998; Scott and Williams, 1978). Soils are, for the most part, shallow, rocky, sandy loams, less than 1 m in thickness, and show little evidence of profile development (Wells, 1981). Vegetation includes grasslands on lower slopes, coastal sage scrub and chaparral in the front county, mixed conifer forest at higher elevations, and desert scrub chaparral in the area burned in the Mojave Desert. The San Gabriel and San Bernardino Mountains experience a Mediterranean climate characterized by hot, dry summers and cool, wet winters and an average annual precipitation of between 50 and 890 mm, most of it occurring during the winter as long-duration, low-intensity storms (California Geological Survey, 2002).

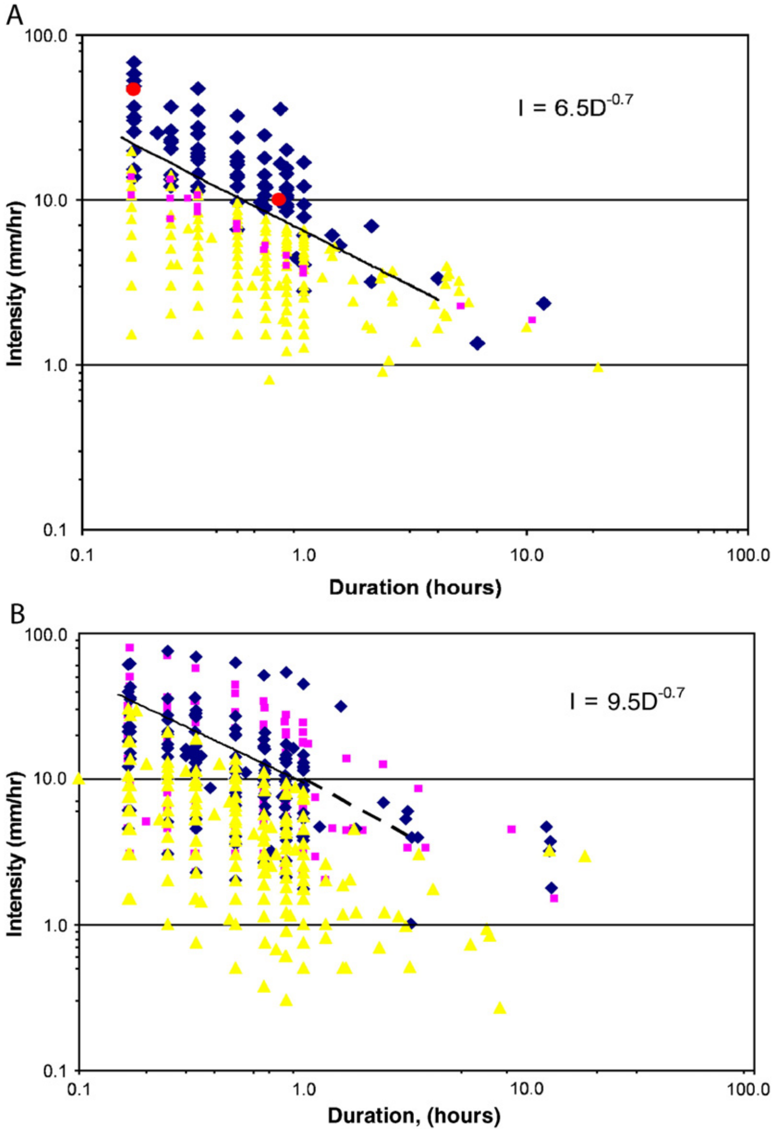

Fig. 6. Rainfall intensity–duration thresholds for the generation of fire-related debris flows from the (A) Coal Seam and (B) Missionary Ridge Fires in Colorado. Blue diamonds represent measures of storm rainfall from rain gages near basins that produced debris flows; pink squares represent measures of storm rainfall from gages near basins that produced sediment-laden flows and yellow triangles represent measures of storm rainfall from gages near basins that showed a minimal or no response. Each storm is represented by several data points representing peak intensities of different durations within the storm. Measurements from different storms can occupy the same location, but at least one measure of storm rainfall from the debris flow and flood-producing storms lies above the threshold line. Red dots on (A) indicate rainfall conditions preceding known times of the occurrence of a debris flow. Threshold line on (B) is dashed where placement is less certain.

The portion of the fire in the Mojave Desert Province has an annual average precipitation of 380 to 635 mm (California Geological Survey, 2002).

5. Storms triggering debris flows

5.1. South-central and southwest Colorado

During the first summer following the fires, five convective thunderstorms triggered debris flows from 15 basins burned by the Coal Seam Fire, and eight storms resulted in debris flows from 10 basins within the Missionary Ridge area (Tables 2A and B). The storms were extremely localized, as evidenced by the variable responses of the rain gages and basins to storms throughout the summer. About 80% of the storms that generated debris flows from the burned basins were of durations equal to or less than 3 h, with most of the rain falling in less than 1 h. Records from rain gages near basins that produced debris flows indicate that the storms that triggered debris flows ranged in average intensity between 1.0 and 32.0 mm/h. With the exception of the July 23, 2002 storm recorded by gage A6 in the Missionary Ridge Fire (recurrence interval of 10 years (Miller et al., 1973)), all of the storms triggering debris flows had recurrence intervals of less than or equal to two years. Some eyewitnesses reported that the debris flows occurred in response to periods of high-intensity rainfall during storms. The 10-minute peak intensities recorded near the debris-flow producing basins varied over an order of magnitude, between 6.3 and 62.5 mm/h.

Although information on the rainfall conditions leading up to the generation of debris flows within a storm can provide a more specific measure of the triggering event than does total storm rainfall, we were able to locate only two timed reports for debris flow in the Coal Seam area and none for the Missionary Ridge area (Table 3). At 9:05 pm on August 5, 2002 a car was trapped by a debris flow produced from a 0.6 km^2 tributary to Mitchell Creek in the Coal Seam Fire (B on Fig. 2). In this same storm, a train was engulfed by mud flowing out of a 2.1 km^2 basin at 9:42 pm (A on Fig. 2). Comparison of this information with adjacent rain gage records indicates that in this setting, debris flows can be produced from recently burned basins in response to as little as six to 10 min of storm rainfall.

5.2. Southern California — First winter following the fire

A winter frontal storm on December 25, 2003 that lasted for many hours produced debris flows from at

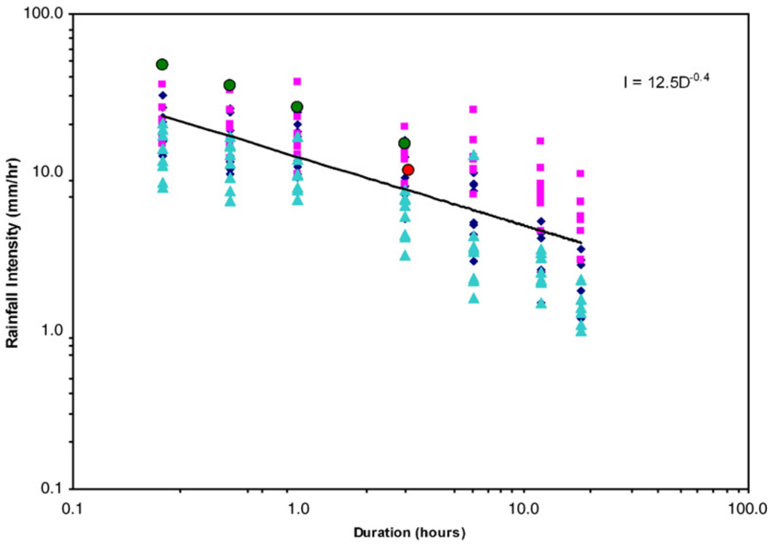

Fig. 7. Rainfall intensity–duration thresholds for the generation of fire-related debris flows from the Piru Fire in southern California. Blue diamonds represent measures of storm rainfall from rain gages near basins that produced debris flows in response to the December 25, 2003 storm; pink squares represent measures of storm rainfall from gages near basins that produced debris flows and floods in response to the February 25, 2004 storm; light blue triangles represent measures of storm rainfall from gages near basins that showed a minimal response to the February 2, 2004 storm. Each storm is represented by several data points representing peak intensities of different durations within the storm. Measurements from different storms can occupy the same location, but at least one measure of storm rainfall from storms that produced debris flows and floods lies above the threshold line. Red dot indicates the average storm intensity leading up to known time of a debris flow from the 2005 Gorman Fire in response to a storm on October 17, 2005, and green dots are the peak intensities preceding the event.

least 68 of the basins burned by the Old and Grand Prix Fires in southern California. Records from the rain gages located near basins that produced debris flows indicate that the storm started with very low intensities, and intensities gradually increased over a period of between 5.5 and 30 h, depending on the gage location (Table 4). The average storm intensities recorded near the debris-flow producing basins ranged between 1.3 and 20.4 mm/h, and the 30-minute peak intensities varied between 8.0 and 37.1 mm/h. These are not unusual meteorological events. Only one gage (number 860) showed a recurrence of five years, while the remaining gages recorded two-year or less than two-year storms (Bonnin et al., 2006).

Information on the timing of debris flows within storms that could be related to a nearby rain gage record for some basins within the Old and Grand Prix Fires, and from the nearby 2005 Harvard Fire, indicate that the debris flows occurred following as little as 2 h, and up to 16 h, of low-intensity (2–10 mm/h) rainfall (Table 3).

5.3. Southern California — Second year following the fire

A storm on October 20, 2004 produced debris flows from six of the monitored basins in the Old and Grand Prix Fires. Sediment-laden floods were produced from the remaining monitored basins. Gages located near the basins that produced debris flows during this storm indicated that the storm lasted between eight and 33 h at average intensities of between 3.2 and 7.5 mm/h (Table 5). Peak 30-minute intensities ranged between 9.1 and 40.6 mm/h. This storm had a less than one year recurrence interval (Bonnin et al., 2006).

Debris flows were reported in response to a storm on October 17, 2005 that impacted the 2004 Foothills Fire following 3.5 h of rain at intensities of 7.8 mm/h (Table 3).

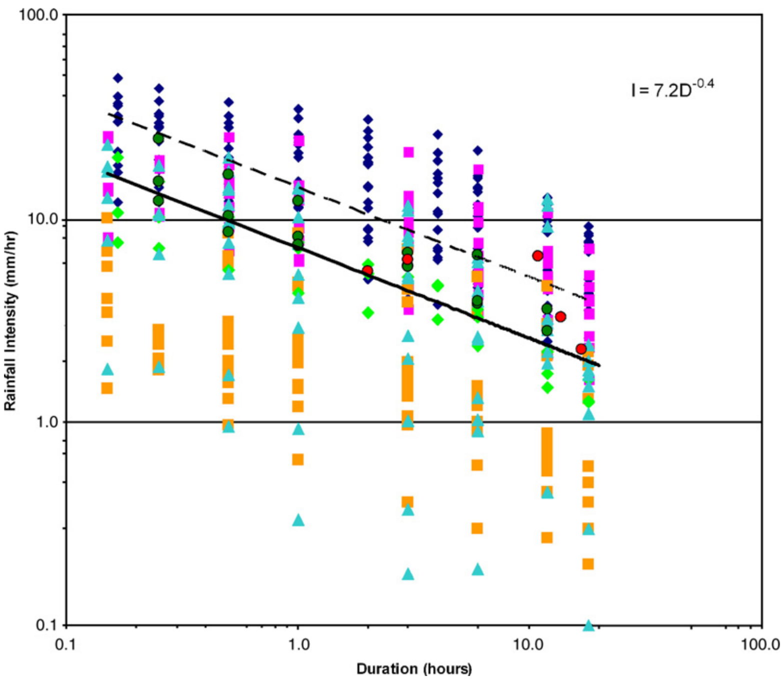

Fig. 8. Rainfall intensity–duration thresholds for the generation of fire-related debris flows from the Old and Grand Prix Fires in southern California. Blue diamonds represent measures of storm rainfall from rain gages near basins that produced debris flows in response to the December 25, 2003 storm; pink squares represent measures of storm rainfall from gages near basins that produced sediment-laden floods in response to the February 22, 2004 storm; light green diamonds, orange squares, and light blue triangles are measures of storm rainfall from gages near basins that showed a minimal response to storms on December 25, 2003, January 2, 2004 and February 2, 2004, respectively. Each storm is represented by several data points representing peak intensities of different durations within the storm. Measurements from different storms can occupy the same location, but at least one measure of storm rainfall from storms that produced debris flows and floods lies above the threshold line. Red dots indicate the average storm intensities leading up to the known times of the occurrence of debris flow in the Old and Grand Prix Fires during the December 25, 2003 storm, as well as events triggered on October 17, 2004 in the Harvard Fire. Green dots indicate measures of peak storm rainfall of varying durations preceding these events. The dashed line represents the threshold defined only as conditions unique to the storms that produced debris flows, while the solid line is the threshold defined by also taking onto account the rainfall conditions leading up known times of debris flows.

6. Rainfall thresholds for south-central and southwest Colorado

With the dataset developed here, it is not possible to distinguish storm rainfall conditions measured from gages located near basins that produced debris flows from those measured from gages located near basins that produced sediment-laden floods or near basins that showed a negligible response in either the Coal Seam Fire or the Missionary Ridge Fire (Fig. 6A and B). It is possible, however, to define thresholds that separate storm conditions measured near basins that triggered either debris flows or sediment-laden floods from storm conditions that produced a negligible response. For the Coal Seam Fire, the storm rainfall intensity–duration threshold that defines the rainfall conditions unique to the debris-flow and flood-producing storms is:

$$I = 6.5D^{-0.7}, \tag{1}$$

where I = rainfall intensity (in mm/h) and D = duration of that intensity (in hours). The filled red circles, Fig. 6A, show the rainfall conditions leading up to the two known times of occurrence of debris flows from basins burned by the Coal Seam Fire. These points fall above, and close to the threshold, indicating that the position of the threshold adequately represents those rainfall conditions that can potentially result in significant post-fire debris-flow and flood activity.

The threshold is best defined for durations of less than 1 h, but delineates a range of rainfall combinations, from high-intensity, short-duration (20 mm/h for 10 min or, 3.4 mm total) to lower-intensity, longer-duration (3 mm/h for 3 h, or 9 mm total), any of which can result in the triggering of debris flows and floods.

For the Missionary Ridge Fire, a rainfall intensity–duration threshold for the production of the combination of debris flows and floods of the form

$$I = 9.5D^{-0.7} \tag{2}$$

is identified (Fig. 6B). This threshold is best defined for rainfall durations less than 1 h and defines a range of conditions that can result in floods and debris flows between 30 mm/h for 10 min (for a total of 5 mm) and 4 mm/h for 3 h (for a total of 12 mm).

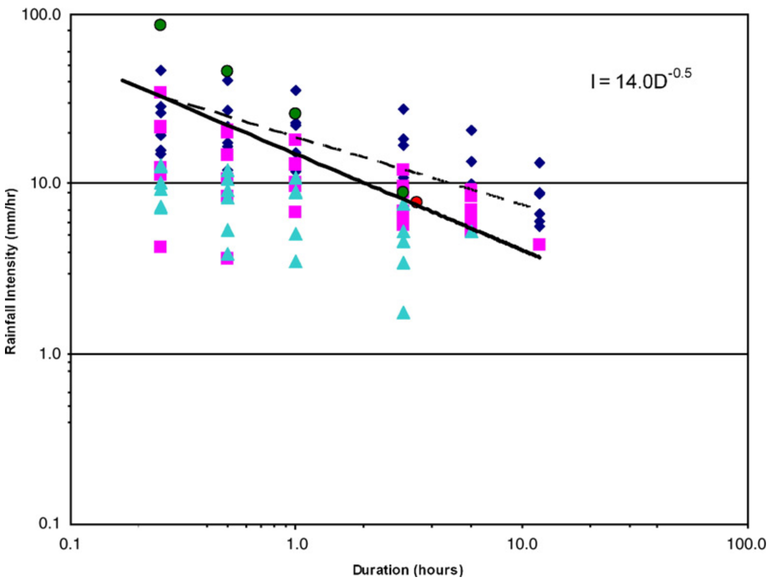

Fig. 9. Rainfall intensity–duration thresholds for the generation of fire-related debris flows from Old and Grand Prix Fires in southern California following one year of recovery. Blue diamonds represent measures of storm rainfall from rain gages near basins that produced debris flows in response to the October 20, 2004 storm; pink squares and light blue triangles represent measures of storm rainfall from gages near basins that showed a minimal response to the October 27, 2004 and November 21, 2004 storms, respectively. The red dot shows the average storm rainfall intensity that preceded the report of debris flow from the 2004 Foothills Fire in response to the October 17, 2005 storm, and the green dots show the peak intensities the preceded the event. The dashed line represents the threshold defined only as conditions unique to the debris-flow producing storms, while the solid line is the threshold defined by also taking onto account the rainfall conditions leading up known times of debris flows.

7. Rainfall thresholds for southern California

7.1. First winter immediately following the fire

In the case of the Piru and Old and Grand Prix Fires, it was not possible to distinguish the rainfall conditions near basins that produced debris flows from those that generated sediment-laden floods or that showed a negligible response (Figs. 7 8 and 9). For the Piru Fire, however, it is possible to identify a rainfall intensity–duration threshold for the production of either debris flows or floods as a line of the form

$$I = 12.5D^{-0.4} \quad (3)$$

(Fig. 7). This threshold is well defined out to 20-hour durations, and defines a range of rainfall conditions between 25 mm/h for 10 min and 4 mm/h for 20 h that can result in post-fire debris flows and floods during the first winter season following a fire. This threshold line can also be represented as ranging between 4 mm of rain in 10 min to 80 mm in 20 h. The recurrence interval for these values range between less than one year and 2 years (Bonnin et al., 2006).

The red dot on Fig. 7 shows the average rainfall intensity that preceded a report of mud and debris on the freeway below the Gorman Fire (located approximately 15 km northeast of the Piru Fire), and the green dots are measures of peak rainfall for different durations preceding the report. These points fall well above the threshold line and indicate that the threshold placement is adequate. The very short-recurrence interval of the values that define the threshold indicate that its placement is even somewhat conservative. The location of the Gorman Fire nearby the Piru Fire, but not immediately adjacent indicates that this threshold is appropriate for use beyond the immediate Piru Fire area.

The rainfall intensity–duration threshold that defines the conditions that are unique to storms that produced debris flows and floods in the Old and Grand Prix Fire is identified in Fig. 8. Because of data variability, considerably more subjectivity occurs in locating this threshold line than with those in Figs. 6 and 7. Comparison of the threshold with measures of average rainfall intensities and peak rainfall of varying durations that preceded events with known times of occurrence (red and green dots in Fig. 8) indicates that it would be

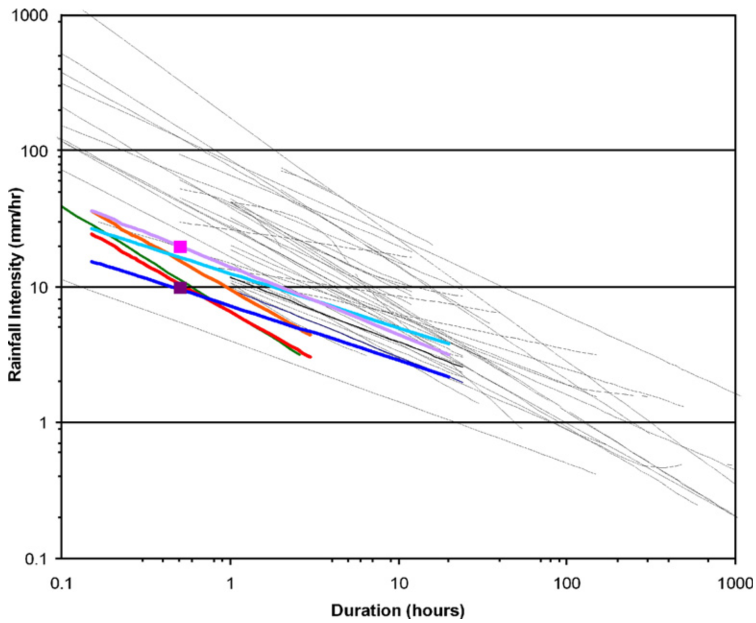

Fig. 10. Comparison of thresholds developed here (Old and Grand Prix Fire — dark blue line; Coal Seam Fire — red line; Missionary Ridge Fire — orange line; Piru Fire — light blue line; second winter following fire — violet line) with those of Coe et al. (2007-this volume), for the initiation of debris flows from unburned setting in central Colorado (green line); Moody and Martin (2001), for increased runoff from burned basins in Colorado, South Dakota and New Mexico (purple square); Cannon et al. (2003a,b), for increased sediment movement from burned volcanic terrain in New Mexico (pink square); and a compilation of worldwide, regional, and local thresholds by Guzzetti et al. (in press); http://rainfallthresholds.irpi.cnr.it/) (gray lines).

preferable to define a lower limit of potential conditions that trigger debris flows and floods of the form:

$$I = 7.2D^{-0.4}. \quad (4)$$

This threshold defines a range of rainfall conditions between 15 mm/h for 10 min (25 mm total) and 2 mm/h for 20 h (40 mm total) that can result in post-fire debris flows and floods during the first winter season to impact an area. These values all have a less than one year recurrence (Bonnin et al., 2006), and, thus, represent a conservative result.

7.2. Second winter following the fire

Recovery of vegetation and removal of material from hillslopes and channels during runoff can affect rainfall threshold conditions. The rainfall intensity–duration threshold that defines the conditions that are unique to the storms that produce debris flows and floods after one year of recovery in the Old and Grand Prix Fire is shown in Fig. 9. The measures of peak rainfall intensity up to 1 h in duration that lead up to a reported event from the 2004 Foothills Fire (Table 3) lie above this line, however, while the 3-hour peak intensity and the average storm rainfall up to the event are below the line (red and green dots in Fig. 9). This placement indicates that it would be preferable to define a lower limit of potential conditions triggering debris flows and floods of the form:

$$I = 14.0D^{-0.5} \quad (5)$$

(Fig. 9). Most of the gages recorded less than 18 h of rainfall for the longest of the storms used in generating the threshold (October 20, 2004), and the threshold can only be reliably drawn to about a 12-hour duration. Most recurrence intervals of the threshold rainfall conditions are less than one year (Bonnin et al., 2006).

8. Discussion

8.1. Threshold definition

Comparison of the thresholds developed here with the known times of occurrence of events within storms indicate that, in the cases of the Coal Seam and Piru Fires, the approach of defining the rainfall conditions that are unique to storms that produced debris flows and floods identifies measures that are reliable predictors of flood or debris-flow response in these settings. In the case of the Old and Grand Prix Fires, however, similar analyses indicated that it was necessary to relocate the threshold lines at slightly lower values of rainfall intensity and duration. These evaluations point to the importance of including information on the times of occurrence within storms in the identification of threshold conditions. The low (two year to less than one year) recurrence intervals of the rainfall conditions defined by the thresholds using this approach indicate that the alternative method of defining the thresholds by the lower limit of the storm conditions producing debris flows would result in the identification of extremely low rainfall values that could occur in nearly any storm, and would, thus, have limited utility in warning systems and emergency-response planning.

8.2. Threshold comparisons

Comparison of the threshold lines for the Missionary Ridge and Coal Seam Fires indicates that intensities up to 10 mm/h greater than those that occurred in the Coal Seam Fire are necessary to trigger debris flows and floods in the Missionary Ridge setting (Fig. 10). The difference is greatest for the shorter durations, decreases over time, and becomes negligible after about two hours. Similarly, the rainfall threshold defined for the Old and Grand Prix Fires is approximately 10 mm/h lower than that developed for the Piru Fire at the shorter durations, and this difference becomes negligible after about 10 h. These differences in thresholds might reflect the shorter times necessary to generate runoff from the smaller and steeper basins of the Coal Seam, Old and Grand Prix Fires (Chow et al., 1988).

The rainfall threshold conditions identified for flood and debris-flow triggering events after one year of vegetation recovery and sediment removal are approximately 25 mm/h higher for the shorter durations than those identified for the first rainy season after a fire (Fig. 10). The difference between the thresholds decreases with longer durations, and becomes essentially negligible after about 10 h.

The threshold developed for southwest and south-central Colorado are nearly identical than those developed for steep, unburned basins in central Colorado by Coe et al. (2008-this volume) (Fig. 10). The slight difference may reflect uncertainty in threshold placement because of the vagaries of rainfall measurements in rugged, mountainous settings, and the resemblance may reflect the lack of vegetation in both settings as well as the similarity in processes.

The threshold rainfall value defined by Moody and Martin (2001), as resulting in significant runoff response from recently burned basins (10 mm/h for 30 min), is very close to the values proposed here for 30-minute durations for the Coal Seam, Old and Grand Prix Fires (Fig. 10). The threshold value proposed by Cannon et al. (2003a,b), for increased sediment movement (20 mm/h for 30 min), is more similar to the threshold proposed here for the Piru and Missionary Ridge burned areas, indicating potential regional differences in such thresholds (Fig. 10).

The rainfall thresholds developed here for the occurrence of debris flows and floods following wildfires were compared to a compilation of local, regional and global thresholds for debris-flow activity from unburned basins by Guzzetti et al. (in press) (Fig. 10). Although the thresholds defined here follow the same general trend of a power law decrease in intensity with duration, they are among the lowest, in terms of both intensity and duration. Only one of the thresholds in Guzzetti et al. (in press), the North Shore Mountains, Vancouver, British Columbia (Jakob and Weatherly, 2003), falls below the thresholds defined here. In this case, debris flows were preceded by several weeks of accumulated rainfall. The difference between the processes found in burned areas, where runoff and sediment entrainment can be nearly instantaneous, and the longer-timeframe, infiltration-dominated processes on unburned hillslopes may account for these differences.

8.3. Use of rainfall thresholds

The thresholds presented here can provide guidance for rudimentary warning systems and planning for emergency response to significant runoff in similar settings. By comparing precipitation forecasts and measurements made during storms with the appropriate threshold lines, decisions on warning and emergency response can be made. As a storm develops, it is important to compile measurements of peak intensities of different durations (as was done for the definition of the thresholds) as well as cumulative storm rainfall intensities and durations. Each rainfall measurement should be compared with the thresholds. When *any* combination of rainfall intensity and duration approaches or exceeds the threshold line, debris flows and flooding that pose significant risks to life and property become likely. Less destructive debris flows and floods can be expected before storm rainfall reaches the thresholds.

The threshold derived for the Coal Seam and Missionary Ridge Fires can be used to identify when destructive post-fire floods and debris flows are possible during the first rainy season, and would apply to recently-burned basins in south-central, and southwest Colorado that have similar soil, burn severity and basin characteristics (see Table 1 and Settings section). Similarly, the threshold developed for the Piru Fire can be used to identify when post-fire debris flows and floods might occur in response to the first winter of frontal storms in areas with similar characteristics; that is, for basins of comparable sizes and gradients in interior Ventura County. The thresholds developed for the Old and Grand Prix Fires for the first and second winters following fires can be useful for identifying the rainfall conditions in winter storms that could result in post-fire debris flows and floods for the San Bernardino, San Gabriel, San Jacinto Mountains in southern California.

The thresholds defined for the two southern California settings are presently being used as guidance for the NOAA-USGS Demonstration Flash-Flood and Debris-Flow Early-Warning System in southern California (Cannon, 2005).

9. Conclusions

In this paper we documented the rainfall conditions that have triggered post-fire debris flows, developed rainfall intensity–duration thresholds for destructive debris flows and floods following wildfires in south-central and southwest Colorado and parts of southern California, and tested and modified these thresholds using information on the rainfall conditions leading up to the reported times of specific events. Debris flows that initiate through the process of progressive sediment bulking have occurred after as little as six to 10 min of rainfall during short-duration (less than 3 h), high-intensity convective storms and after up to 16 h of rainfall during long-duration (up to 30 h), lower-intensity frontal storms. The thresholds defined here are among the lowest, in terms of intensity and duration, of thresholds developed for unburned settings throughout the world, reflecting significant differences in processes on burned and unburned hillslopes. Differences between the debris-flow triggering conditions and rainfall intensity–duration thresholds in Colorado and Southern California reflect local differences in basin sizes and gradients; smaller, steeper basins generated floods and debris flows in response to lower rainfall totals and intensities over shorter time periods.

Based on the assumption that rainfall characteristics are the primary drivers of a post-wildfire runoff response, the thresholds presented here can provide guidance for rudimentary warning systems and planning for emergency response in similar settings. A warning system based solely on rainfall thresholds, however, is not able to provide information on specific areas that are likely to experience post-fire floods and debris flows, the size of potential events, or the areas likely to be inundated. A comprehensive warning system should be linked with information on the areas likely to generate, and to be impacted by, such events. In addition, in this analysis we characterized rainfall within storms as simply by the intensity of a range of different durations, but have not accounted for the effect that changing conditions during a storm might have on triggering debris flows and floods. For example, we have not quantified the effect of a gradual increase in precipitation over a long time period or the effect of a short burst of higher intensity rainfall late in a storm. Additional work is necessary to identify rainfall triggers from such storms. Further, debris flow and flood are physically distinct processes, and should require separate tools for assessment. In this analysis we were not able to distinguish those rainfall conditions that resulted in debris flows from those that produced floods indicates that a more detailed analysis may be required. Although the assumption of rainfall dominance is reasonable as a first approximation, other factors certainly affect runoff processes from burned areas. These include the distribution of burn severity, material properties, basin and channel gradients, and the availability of material for entrainment. Work is underway to quantify the combined effect of these factors on the probability and magnitude of post fires.

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References

Baum, R.L., Godt, J.W., Harp, E.L., McKenna, J.P., McMullen, S.R., 2005. Early warning of landslides for rail traffic between Seattle and Everett, Washington, USA. Proceedings of the 2005 International Conference on Landslide Risk Management/18th Annual Vancouver Geotechnical Society Symposium, May 31 to June 3, 2005 Vancouver, British Columbia. Balkema, Canada.

Biddinger, T., Gallegos, A.J., Janeki, A., TenPas, J., Weaver, R., 2003, BAER watershed assessment report, 2003 Grand Prix and Old Fire, San Bernardino National Forest, unpublished report.

Bonnin, G.M., Martin, D., Lin, B., Parzybok, T., Yekta, M., Riley, D., 2006. Precipitation-Frequency Atlas of the United States: NOAA Atlas 14, Volume 1, Version 4. NOAA, National Weather Service, Silver Spring, Maryland.

Booker, F.A., 1998, Landscape and management response to wildfires in California: MSc thesis, University of California, Berkeley.

Bortugno, E.J., Spittler, T.E., 1998, Geologic map of the San Bernardino Quadrangle, 1:250,000: California Division of Mines and Geology, Regional Geologic Map Series, San Bernardino Quadrangle, Map No 3A.

California Geological Survey, 2002. California Geomorphic Provinces, Note 36. 4 pp.

Caine, N., 1980. The rainfall intensity–duration control of shallow landslides and debris flows. Geografiska Annaler 62A, 23–27.

Cannon, S.H., 2001. Debris-flow generation from recently burned watersheds. Environmental and Engineering Geoscience 7, 321–341.

Cannon, S.H., 2005. A NOAA-USGS Demonstration Flash-Flood and Debris-Flow Early-Warning System: U.S. Geological Survey Fact Sheet 2005–3104. http://pubs.usgs.gov/fs/2005/3104/.

Cannon, S.H., Ellen, S.D., 1988. Rainfall that resulted in abundant debris-flow activity during the storm of January 3–5, 1982, in the San Francisco Bay region, California: U.S. Geological Survey Professional Paper 1434, 27–33.

Cannon, S.H., Gartner, J.E., 2005, Wildfire-related debris flow from a hazards perspective: Chapter 15 *in:* Jakob, M. and Hungr, O. eds., Debris flow hazards and related phenomena: Praxis, Springer, Berlin, Heidelberg, p. 363–385.

Cannon, S.H., Powers, P.S., Savage, W.Z., 1998. Fire-related hyperconcentrated and debris flows on Storm King Mountain, Glenwood Springs, Colorado, USA. Environmental Geology 35 (2–3), 210–218.

Cannon, S.H., Bigio, E.R., Mine, E., 2001a. A process for fire-related debris-flow initiation, Cerro Grande Fire, New Mexico. Hydrological Processes 15 (15), 3011–3023.

Cannon, S.H., Kirkham, R.M., Parise, M., 2001b. Wildfire-related debris-flow initiation processes, Storm King Mountain, Colorado. Geomorphology 39, 171–188.

Cannon, S.H., Gartner, J.E., Holland-Sears, A., Thurston, B.M., Gleason, J.A., 2003a. Debris-flow response of basins burned by the 2002 Coal Seam and Missionary Ridge fires, Colorado. In: Boyer, D.D., Santi, P.M., Rogers, W.P. (Eds.), Engineering Geology in Colorado—Contributions, Trends, and Case Histories: AEG Special Publication 15. Colorado Geological Survey Special Publication, vol. 55. 31 pp., on CD-ROM.

Cannon, S.H., Gartner, J.E., Parrett, C., Parise, M., 2003b. Wildfire-related debris flow generation through episodic progressive sediment bulking processes, western U.S.A. In: Rickenmann, D., Chen, C.L. (Eds.), Debris-Flow Hazards Mitigation — Mechanics, Prediction, and Assessment, Proceedings of the Third International Conference on Debris-Flow Hazards Mitigation, Davos, Switzerland, 10–12 September 2003. A.A. Balkema, Rotterdam, pp. 71–82.

Carroll, C.J., Kirkham, R.M., Wracher, A., 1997. Geologic map of the Rules Hill quadrangle, La Plata County, Colorado — description of map units, economic geology and references. Colorado Geological Survey Open-file Report 97-1.

Carroll, C.J., Kirkham, R.M., Wilson, S.C., 1998. Geologic map of the Ludwig Mountain quadrangle, La Plata County, Colorado — description of map units, economic geology, fracture data and references. Colorado Geological Survey Open-file Report 98-2.

Carroll, C.J., Gillam, M.L., Ruf, J.C., Loseke, T.D., Kirkham, R.M., 1999. Geologic map of the Durango East quadrangle, La Plata County, Colorado — description of map units, fracture data and analysis, economic geology and references. Colorado Geological Survey Open-file Report 99-6.

Chow, V.T., Maidment, D.R., Mays, C.H., 1988. Applied Hydrology. McGraw Hill Book Company, New York, NY. 680 pp.

Coe, J.A., Kinner, D.A., Godt, J.W., 2008. Initiation conditions for debris flows generated by runoff at Chalk Cliffs, Central Colorado, USA:. Geomorphology 96, 270–297 (this volume). doi:10.1016/j.geomorph.2007.03.017.

Guzzetti, F., Peruccacci, S., Rossi, M., Stark, C.P., in press, Rainfall thresholds for the initiation of landslides. Meteorology and Atmospheric Physics.

Godt, J.W., Baum, R.L., Chleborad, A.F., 2006. Rainfall characteristics for shallow landsliding in Seattle, Washington, USA. Earth Surface Processes and Landforms 31, 97–110.

Gonzales, D.A., Stahr, D.W., Kirkham, R.M., 2002. Geologic map of the Hermosa quadrangle, La Plata County, Colorado. Colorado Geological Survey Open-file Report 02-1.

Jakob, M., Weatherly, H., 2003. A hydroclimatic threshold for landslide initiation in the North Shore Mountains of Vancouver, British Columbia. Geomorphology 54, 137–156.

Keefer, D.K., Wilson, R.C., Mark, R.K, Brabb III, E.E., Ellen, S.D., Harp, E.L., Wieczorek, G.F., Alger, C.S., Zatkin, R.S., 1987. Real-time landslide warning during heavy rainfall. Science 238 (13), 921–925.

Kirkham, R.M., Streufert, R.K., Cappa, J.A., 1997. Geologic map of the Glenwood Springs Quadrangle, Garfield County, Colorado — description of map units, economic geology, geochemical analyses, and references. Colorado Geological Survey Map Series 31.

Larsen, M.C., Simon, A., 1993. A rainfall intensity–duration threshold for landslides in a humid–tropical environment, Puerto Rico. Geografiska Annaler 75A 1–2, 13–23.

Melton, M.A., 1965. The geomorphic and paleoclimatic significance of alluvial deposits in southern Arizona. Journal of Geology 73, 1–38.

Meyer, G.A., Wells, S.G., 1997. Fire-related sedimentation events on alluvial fans, Yellowstone National Park, USA. Journal of Sedimentary Research 67 (5), 776–791.

Miller, J.F., Frederick, R.H., and Tracey, R.J., 1973, Precipitation-frequency atlas of the western United States, NOAA Atlas 2, vol. 3-Colorado: U.S. Department of Commerce, National Oceanic and Atmospheric Administration, National Weather Service, Silver Spring, MD.

Mills, K.A., 2002. Oregon's debris flow warning system. Geological Society of America Abstracts with Programs 34 (5), 25.

Moody, J.A., Martin, D.A., 2001. Post-fire, rainfall intensity-peak discharge relations for three mountainous watersheds in the western USA. Hydrological Processes 15, 2981–2993.

Morton, D.M., 1989. Distribution and frequency of storm-generated soil slips on burned and unburned slopes, San Timoteo Badlands, southern California. In: Sadler, P.M., Morton, D.M. (Eds.), Landslides in a Semi-Arid Environment with Emphasis on the Inland Valleys of Southern California. Publications of the Inland Geological Society, vol. 2, pp. 279–284.

NOAA-USGS Task Force, 2005. NOAA-USGS debris-flow warning system — final report. U.S. Geological Survey Circular, vol. 1283. 47 pp.

Parrett, C., 1987. Fire-related debris flows in the Beaver Creek drainage, Lewis and Clark County, Montana. U.S. Geological Survey Water-Supply Paper 2330, 57–67.

Parrett, C., Cannon, S.H., Pierce, K.L., 2003. Wildfire-related floods and debris flows in Montana in 2001. U.S. Geological Survey Water-Resources Investigations Report 03-4319.

Pierson, T.C., 2005. Distinguishing between debris flows and flows from field evidence in small watersheds. U.S. Geological Survey Fact Sheet 2004–3142.

Rust, B., 2003, Soil Resource Assessment, Piru Fire, Los Padres National Forest, unpublished report.

Santi, P.M., deWolfe, V.G., Higgins, J.D., Cannon, S.H., Gartner, J.E., 2008. Sources of debris flow material in burned areas:. Geomorphology 96, 310–321 (this volume). doi:10.1016/j.geomorph.2007.02.022.

Scott, K.M., 1971. Origin and sedimentology of 1969 debris flows near Glendora, California. California: U.S, Geological Survey Professional Paper 750-C, pp. C242–C247.

Scott, K.M., Williams, R.P., 1978. Erosion and sediment yields in the Transverse Ranges, southern California. U.S. Geological Survey Professional Paper 1030. 38 pp.

State of California, 1969, Geologic map of California, Olaf P. Jenkins edition, Los Angeles sheet, compiled by Charles W. Jennings and Rudolph G. Strand: Department of Conservation, Division of Mines and Geology, 1:250,000 scale.

Swanson, F.J., 1981. Fire and geomorphic processes. In: Mooney, H.A., Bonniksen, T.H., Christensen, N.L., Lotan, J.E., Reiners, W.A. (Eds.), Fire Regimes and Ecosystem Properties. USDA Forest Service General Technical Report WO-26, pp. 401–420.

Teller, R.W., 2003. Rapid-deployment Data-collection Networks for Wildland Fire Applications: U.S. Geological Survey Fact Sheet FS-036-03. http://pubs.usgs.gov/fs/fs03603/fs03603.html.

USDA Forest Service, 2002a, Burned area emergency stabilization and rehabilitation plan, Coal Seam Fire: U.S. Department of Agriculture, PSICC, June 2002 Hydrology Report, unpublished report.

USDA Forest Service, 2002b, Burned area emergency stabilization and rehabilitation plan, Missionary Ridge and Valley fires: U.S. Department of Agriculture, July 2002 Hydrology Report, unpublished report.

Wells, W.G., 1981. Some effects of brushfires on erosion processes in coastal Southern California. Erosion and Sediment Transport in Pacific Rim Steeplands. Christchurch, New Zealand, International Association of Hydrological Science, 132, pp. 305–342.

Wells, W.G., 1987. The effects of fire on the generation of debris flows in southern California. In: Costa, J.E, Wieczorek, G.F. (Eds.), Debris Flows/Avalanches, Process, Recognition, and Mitigation. Geological Society of America Reviews in Engineering Geology, vol. 7, pp. 105–114.

Wieczorek, G.F., Sarmiento, 1988. Rainfall, peizometric levels, and debris flows near La Honda, California in storms between 1975 and 1983. In: Ellen, S.D., Wieczorek, G.F. (Eds.), Landslides, Floods, and Marine Effects of the Storm of January 3–5, 1982, in the San Francisco Bay Region, California. U.S. Geological Survey Professional Paper, 1434, pp. 43–62.

Wieczorek, G.F., Glade, T., 2005, Climatic factors influencing the occurrence of debris flows, *in:* Hungr, O. and Jacob, M. eds., Debris flow hazards and related phenomena: Praxis, Springer, Berlin, Heidelberg, p.325–362.

Wilson, R.C., 2000. Climatic variations in rainfall thresholds for debris-flow activity. In: Claps, P., Siccardi, F. (Eds.), Mediterranean Storms, Proceedings of the European Geophysical Union Plinius Conference on Mediterranean Storms, Maratea, Italy, pp. 415–424.

Wilson, R.C., Mark, R.K., Barbato, G., 1993. Operation of a real-time warning system for debris flows in the San Francisco Bay Area, California. In: Shen, H.W., Su, S.T., Wen, F. (Eds.), Hydraulic Engineering '93: Proceedings of the 1993 Conference, San Francisco, Calif., July 25–30, 1993, vol. 2. Hydraulics Division, American Society of Civil Engineers, pp. 1908–1913.