M. Jakob and O. Hungr (eds), *Debris-flow Hazards and Related Phenomena*: Praxis. Springer Berlin Heidelberg 2005.

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Wildfire-related debris flow from a hazards perspective

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15.1 INTRODUCTION

Wildland fire can have profound effects on the hydrologic response of 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 change the infiltration characteristics and erodibility of the soil, leading to decreased rainfall infiltration, subsequent significantly increased overland flow and runoff in channels, and movement of soil (e.g., Swanson, 1981; Spittler, 1995; Doerr *et al.,* 2000; Martin and Moody, 2001; Moody and Martin, 2001b; Wondzell and King, 2003). Unit-area peak discharges measured following wildfire have shown between 1.45- and 870-fold increases over pre-fire rates (Moody and Martin, 2001a). Removal of obstructions by wildfire through consumption of vegetation can also enhance the erosive power of overland flow, resulting in accelerated erosion of material from hillslopes (Meyer, 2002). Increased runoff can erode significant volumes of material from channels, either by bank failure or channel bed erosion. Over longer time periods, decreased rates of evapotranspiration caused by vegetation mortality and decay of root structure may result in increased soil moisture and the loss of soil cohesion (Klock and Helvey, 1976; Swanson, 1981; Schmidt *et al*., 2001). Rainfall on burned watersheds thus has a high potential to transport and deposit large volumes of sediment both within and down-channel from the burned area.

Debris flows can be one of the most hazardous consequences of rainfall on burned hillslopes (e.g., Parrett, 1987; Morton, 1989; Meyer and Wells, 1997; Cannon, 2001) (Fig. 15.1A,B). They 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 by impact and erosion, and endanger human life. The deaths of sixteen people during the Christmas Day 2003 storm that impacted recently-burned hillslopes in southern California highlight the most drastic consequences of post-wildfire debris flows (Los Angeles Times, 2003). In addition to the lives lost, US$9.5 million were spent to remove the 4.1 million cubic meters of material deposited in debris retention basins following this event. Understanding the processes that result in fire-related debris flows, the conditions under which they occur, and their size and frequency of occurrence are critical elements in effective post-fire hazard assessments.

The objective of this chapter is to provide an overview of the current understanding of post-wildfire debris-flow processes and their occurrence. We examine the physical processes by which post-wildfire debris flows initiate in different settings, over varying time scales, and in response to variable storm rainfall conditions. We describe the lithologic, soil, basin-configuration, and burn-severity conditions known to have produced debris flows following wildfire, and examine relations between the magnitude of debris-flow response and storm-rainfall conditions, lithology, basin gradient, and burn severity conditions. This chapter is intended as a review and synthesis of the published literature; in-depth examination of specific issues is available from the literature citations in this chapter.

In addition to specific findings reviewed in this chapter, we use here data from two compilations: Gartner *et al.* (2004), and Gartner *et al.* (in press). Gartner *et al.* (2004) assembled published data on the magnitude of post-fire debris-flow events from 95 basins throughout the western U.S., and from our own monitoring efforts (Fig. 15.2). This database includes estimates of debris-flow volume or peak discharge; the area, relief ratio, and the percent burned of each debris-flow producing basin; the lithology underlying the basin; and the reported storm rainfall conditions that triggered the event. Further, Gartner *et al.* (in press) compiled data from the literature and from our own monitoring efforts on debris-flow initiation process; basin area, average gradient; area of basin burned at high, moderate, and low severities; underlying rock type; grain-size distribution of burned hillslope-mantling materials; triggering storm rainfall total, duration, average intensity, and, where available, the peak intensities of different durations. Although this compilation consists of data for 210-debris-flow producing basins located throughout the western U.S. (Fig. 15.2), because of differences in data reporting, not every parameter is characterized for every basin.

These data compilations allow for the unique opportunity to examine issues related to the generation of post-wildfire debris flows across a variety of environments and under a variety of conditions, and to move from a qualitative conception of the controls on post-fire debris-flow generation to the definition of specific conditions that result in their occurrence.

15.2 FIRE-RELATED DEBRIS-FLOW INITIATION PROCESSES

Two primary processes for the initiation of fire-related debris flows have been identified in the literature: runoff-dominated erosion by surface overland flow, and infiltration-triggered failure and mobilization of a discrete landslide mass.

Figure 15.1 (a) Photograph of debris-flow path and (b) deposits generated from a burned basin following the 2002 Coal Seam Fire in Colorado. Pickup truck towing trailer in lower left of (a) for scale.
Photographs by Andrea Holland-Sears, USDA Forest Service.

Fig. 15.2. Map showing locations of documented fire-related debris-flow events in the western U.S. Data for more than one basin exists at most locations. Yellow dots signify locations of basins for which data on either debris-flow volume or peak discharge exist (Gartner *et al*., 2004); both red and yellow dots show locations of debris-flow producing basins included in Gartner *et al*. (in press); green dots show additional debris-flow locations reported in the literature.

15.2.1 Runoff-dominated erosion by surface overland flow

The process

Debris-flow initiation in recently burned areas is most frequently attributed to significantly increased rates of rainfall runoff. Johnson (1984), Wells (1987), Spittler (1995) and Cannon *et al.* (2001a; 2003b) traced debris-flow deposits upslope through small gullies into a series of rills, and concluded that the debris flows initiated high on the hillslopes from material eroded by surface runoff. Wells (1987) described debris flows initiating as miniature soil slips in a saturated layer of soil a few millimeters thick above a subsurface water-repellent zone, and Gabet (2003) continued this characterization by modeling shallow failure along the lengths of hillslopes. Cannon *et al.* (2001a; 2003b) did not observe the presence of miniature soil slips at the rill heads as the source of the debris flows; rather, they described a progressive entrainment of hillslope materials into runoff that resulted in debris-flow conditions with travel down slope. Note that these small, hillslope-generated debris flows do not necessarily evolve into more destructive debris flows once they travel into channels (Cannon *et al*., 2003b)

Meyer and Wells (1997) and Cannon *et al.* (2001b) describe a somewhat different process focused within channels. These workers also observed that runoff high on hillslopes resulted in the generation of rills. However, convergence and concentration of flow within hollows[1] and in low-order channels resulted in considerable erosion, often to bedrock, and the transport of material down slope. Debris-flow deposits in the form of levees and lobes consisting of poorly-sorted, unstratified deposits with a fine-grained, consolidated matrix, and muddy veneers, first occurred well down the drainage network (Fig. 15.3). Meyer and Wells (1997) concluded that debris flows initiated through progressive bulking of surface runoff with sediment entrained by rill erosion in steep, upper-basin slopes and from deep incision as the flows progressed down channels. Parrett (1987) and Cannon *et al.* (2001b) also noted the lack of landslide scars in a burned area that experienced debris flows and suggested a similar mechanism. Scott (1971), Parrett (1987) and Meyer and Wells (1997) emphasize that sediment input from hillslope rilling, as well as material entrained by extensive channel incision are important in the bulking process that led to the formation of debris flows. The sheer volume of material that is often excavated from the drainage network, however, suggests that a large proportion of the material within the debris flows originated from this source.

Cannon *et al.* (2001b; 2003b) further examined the process of progressive sediment bulking in burned areas using detailed field mapping of transitions from debris floods (see Chapter 2, this volume) to debris flow within channels. This work identified a threshold

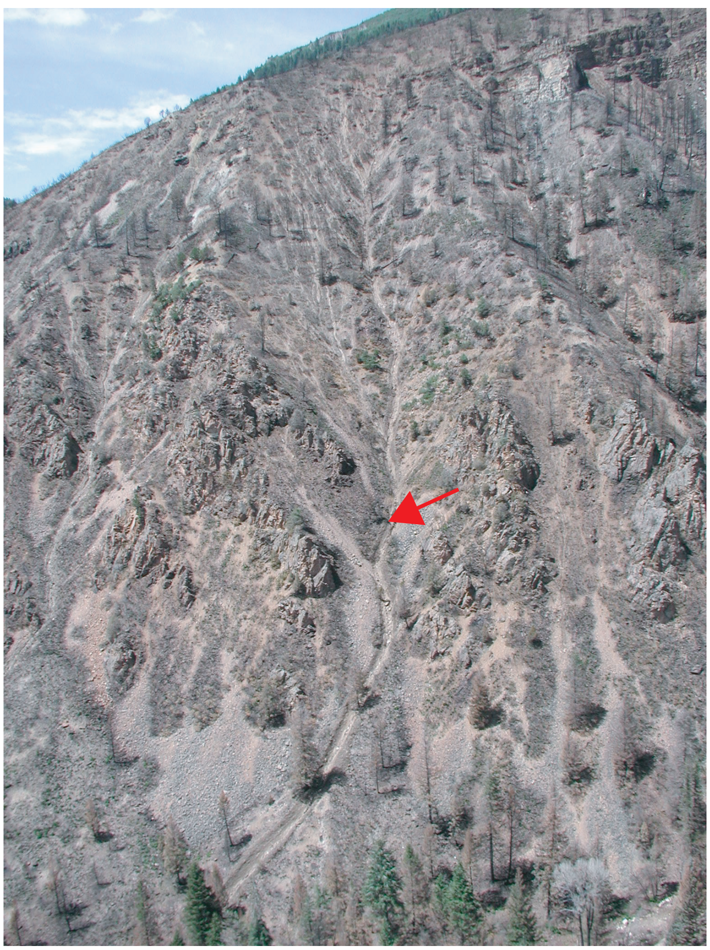


Fig. 15.3. Photograph of debris-flow path generated through process of progressive bulking of runoff with sediment eroded from hillslopes and channels in 2002 Coal Seam Fire in Colorado. Levees consisting of poorly sorted, unstratified and matrix-supported material, and mud coatings persisted down channel from point indicated by arrow. Photograph by Andrea Holland-Sears, USDA Forest Service.

[1] As described by Hack (1965) and Reneau and Dietrich (1987), unchannelized areas on hillslopes in which the contours are concave outward away from the ridge, and that occur in the valley axis upslope from the stream head.

location within channels where sufficient eroded material is incorporated, relative to the volume of surface runoff, to generate debris flows that persist down the length of the channel. Above this location in a given basin, the attainment of debris-flow conditions can be transitory; variations in sorting and grain-size distributions in the deposits indicate that the flow fluctuates between debris flow and more dilute flows before persistent debris-flow conditions are achieved. Cannon *et al.* (2003b) attributes the fluctuation in deposit character to an episodic sediment input to the flows, and demonstrates that these episodic fluxes increase in volume with travel down channels. The episodic sediment contributions appear to be necessary in order to entrain sufficient material, relative to the amount of runoff, to impart debris-flow characteristics to the flow. Although Tognacca and Bezzola (1997), Tognacca *et al.* (2000), and Istanbulluoglu *et al.* (2003), describe possible theoretical frameworks and experimental and field work that characterize the erosive processes that can result in channel erosion on steep hillslopes, they do not specifically address the critical transition from sediment-laden water flow to debris flows. This is an important consideration in burned areas because given sufficient rainfall, although channel incision can occur in nearly every basin, debris flows are not necessarily generated from all incised channels.

As a variation on the process described above, debris flows have also been generated from burned basins in response to increased runoff by water cascading over a steep, bedrock cliff and incorporating material from a readily erodible bed (Larsen, 2003). Johnson and Rodine (1984) described this process in unburned terrain as the "firehose" effect.

Note that although this paper focuses exclusively on debris flows generated from burned basins, debris flows generated through what appear to be a similar process have also been described on unburned, yet primarily unvegetated, hillslopes (e.g. Scott and Williams, 1978; Johnson and Rodine, 1984; Davies *et al.,* 1992; Coe *et al.,* 2003). Gostner *et al*. (2003) outline a methodology for debris-flow hazard assessment that integrates the transition from clear water flow to debris flow in steep, unburned channels. See also Chapter 7 in this volume.

Settings and abundances

The runoff-dominated process for generating wildfire-related debris flows described above is the most frequently reported in the literature; 76% of the 210 basins documented as having produced debris flows showed this process (Gartner *et al.,* (in press) (Fig. 15.4). Runoff-initiated debris flows have been observed in a variety of environments, including the northern Rocky Mountains of the U.S. (Klock and Helvey, 1976; Meyer and Wells, 1997; Parrett *et al.,* 2003), and British Columbia (Timothy Smith, Westrek Geotechnical Services, written communication, 2004), the central and southern Rocky Mountains (Cannon *et al.,* 2001a,b; Meyer *et al.,* 2001), the Uinta mountains (Larsen, 2003) and the Wasatch Front (McDonald and Giraud, 2002) of Utah, northeastern Oregon (William Russell, Oregon State University, written communication, 2003), the Huachuca Mountains of southeastern Arizona (Wohl and Pearthree, 1991), the Mazatzal Mountains of south-central Arizona (Anne Yoberg, Arizona Geological Survey, written communication, 2004), southern California (Doehring, 1969; Wells, 1981, 1987; Morton, 1989; Booker, 1998; Cannon, 2001), and the Big Sur coast of California (Cleveland, 1973; Johnson, 1984) (Fig. 15.2). Debris flows generated through this process have also been described in the Alps of Switzerland (Conedera *et al.,* 2003).

Post-wildfire debris flows generated through runoff bulking have not been reported in the Coastal and Cascade Mountains of the Pacific Northwest (Wondzell and King, 2003. Swanson (1981) and Beschta (1990) suggest that these areas are characterized by long-

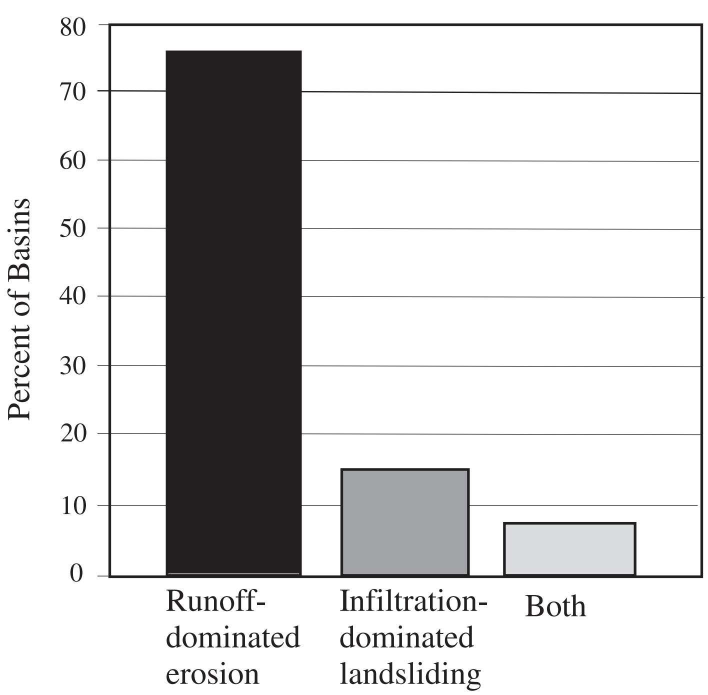


Fig. 15.4. Frequency of debris-flow initiation processes for 210 debris-flow producing basins from data in Garter and Cannon (2004).

duration, low-intensity rainfall, so that infiltration rates are seldom exceeded, even after intense wildfires. Wondzell and King (2003) further propose that rapid recovery of fire-caused reductions in infiltration rates, high antecedent soil moisture, and rapid rates of vegetation regrowth after fires in these regions might explain the absence of overland flow.

Rainfall conditions and time frames

Debris flows generated through runoff-dominated processes are most frequently produced in response to high-intensity, short-duration storms, and all events reported in the literature occurred within two years of the fire (Gartner *et al.,* in press). Both winter frontal storms and summer monsoon thunderstorms have triggered debris flows by this process. Debris flows have occurred in response to storms with durations as short as 18 minutes (Cannon *et al.,* 2003a), and during 10-day long, more than 100-year recurrence storms (Scott, 1971) (Fig. 15.5 filled circles). However, most debris-flow producing storms are between about 30 minutes and 24 hours in duration (Fig. 15.5). Although debris flows have been reported in response to average storm rainfall intensities of more than 100 mm/hr (Klock and Helvey 1976), most debris-flow producing storm rainfall intensities are greater than about 4 mm/hr.

The rainfall conditions leading up to debris-flow generation within a storm are a more specific measure of the triggering event than the total storm rainfall. For the few cases where the times of debris-flow occurrence within a storm are known, we can see that debris flows have occurred after as little as 6 minutes of rainfall at intensities of 95 mm/hr (Cannon *et al.,* 2003a), and up to 5 hours of rainfall at intensities of 6 mm/hr (Gartner *et al.,* in press) (Fig. 15.5 open circles).

By comparing the rainfall conditions in storms that produced debris flows from recently burned basins with those that produced sediment-laden floods or showed no response, and defining those conditions that are unique to debris-flow producing storms, Cannon *et al*. (2003a) defined threshold rainfall intensity-duration conditions for runoff-dominated debris flows in the form:

$$I = 7.0D^{-0.6} \tag{15.1}$$

where I = rainfall intensity (in mm/hr) and D = duration of that intensity (in hours) (Fig. 15.6). This threshold is a useful tool for issuing warnings and planning for emergency response in mid-latitude, temperate climate settings with steep, recently burned basins underlain by sedimentary rocks and with thin colluvial covers that experience convective thunderstorms. Additional thresholds are necessary for different environments and storm conditions.

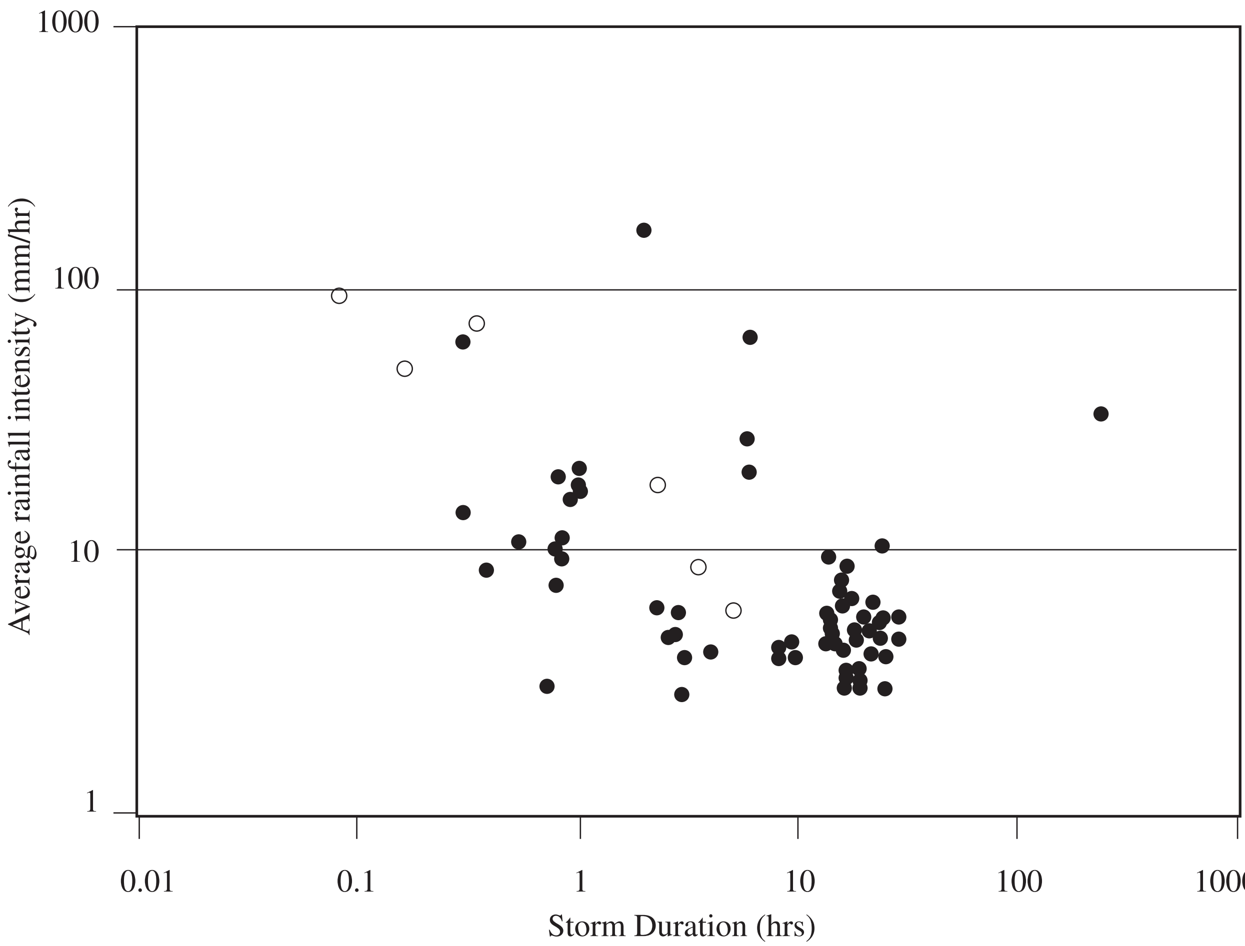


Fig. 15.5 Average storm rainfall intensity and duration for debris-flow producing storms (filled circles) Data from Gartner *et al*. (in press). Open circles show storm rainfall intensities and durations leading up to debris-flow events in Colorado and southern California where time of occurrence is known.

Note that the rainfall conditions that trigger fire-related debris flows defined here 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 lower intensities (e.g., Campbell, 1974; Caine, 1980; Larsen and Simon, 1993). This difference can likely be attributed to the difference in infiltration- and runoff-initiation mechanisms.

How frequently will debris flows be produced from burned basins? Work by Cannon (2001) and Cannon *et al.* (2003a) demonstrated that basins with thin colluvial covers and minimal channel-fill deposits produced debris flows only in response to the first significant rainfall of the season, reflecting a supply-limited setting (e.g. Bovis and Jakob, 1999). In contrast, basins with thick accumulations of colluvium in the channels, and those mantled with thick talus deposits, produced repeated debris-flow events throughout the two summer monsoon seasons following the fire.

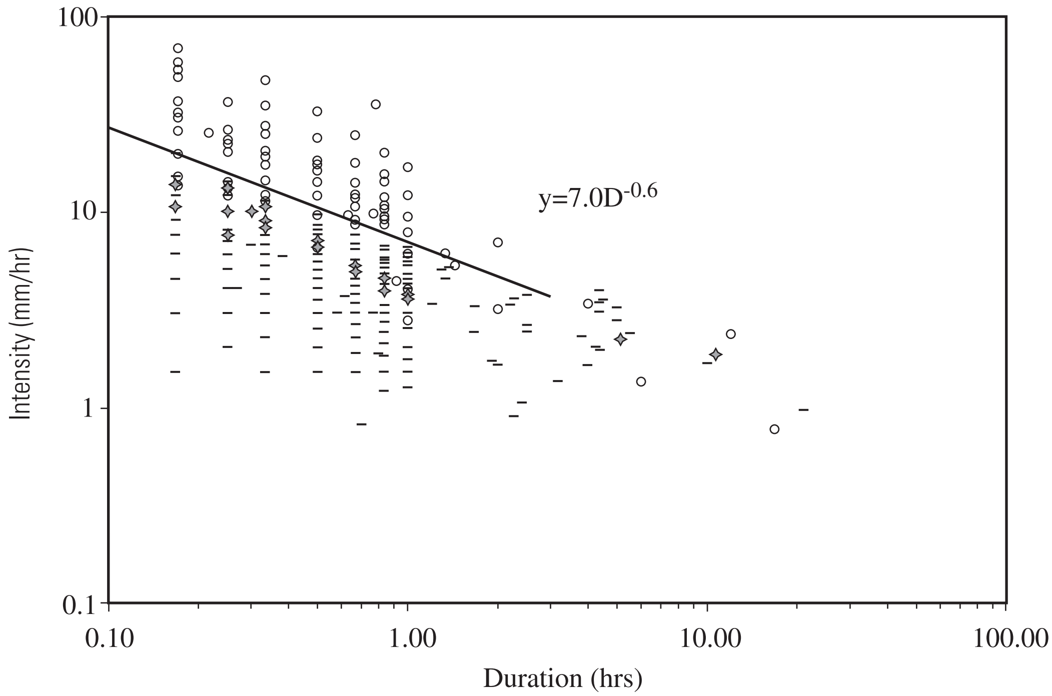


Fig. 15.6. Rainfall intensity-duration threshold for the generation of fire-related debris flows from recently burned, steep basins underlain by sedimentary rocks from Cannon *et al.* (2003a). Open circles represent measures of storm rainfall from gages within 1 km of basins that produced debris flows; diamonds represent measures of storm rainfall from gages within 1 km of basins that produced sediment-laden flows; and dashes represent measures of storm rainfall from gages within 1 km of basins that showed no response.

15.2.2 Infiltration-dominated landslide failure and mobilization

The process

Debris-flow initiation by failure of discrete landslide masses on hillslopes has been documented in wildfire-affected watersheds. The landslide failures observed in burned areas can range in thickness from a few tens of centimeters to more than 6 meters, and generally involve the soil and colluvium-mantled hillslopes; the failures mobilize into the muddy slurries characteristic of debris flow (Fig. 15.7).

Landslides occur if shear stresses (driving forces) equal or exceed the shear strength (resisting forces) (see Chapter 4, this volume). Shear stresses are imparted by the mass of the soil and gravity. Shear strength consists of the combined resistance to movement provided by friction on the shear surface and the cohesion of the mineral soil and plant roots. The balance between driving and resisting forces depends primarily on slope steepness, pore-water pressure, and the thickness and physical characteristics of the hillslope-mantling materials.

In order to attribute landslide activity to wildfires, it is necessary to consider the possible changes imparted by the fire to this balance of forces. Although three possible wildfire-related landslide-triggering effects have been proposed in the literature, there is little well-controlled data available on this subject. Increases in soil moisture after fires were measured by Klock and Helvey (1976) and Helvey (1980), who attributed these to reduced interception and transpiration rates caused by vegetation consumption and mortality. These workers postulated that the increases in soil moisture (and attendant increases in pore pressures) could promote shallow landslide failure. Although Klock and Helvey (1976) and Helvey (1980) documented the occurrence of landslides that mobilized into debris flows at their study site, the role of the increased soil moisture in the landslide failure was postulated. Wildfire-induced tree mortality can also lead to the decay of regolith-anchoring roots, and Swanson (1981) proposed that this could result in decreased soil cohesion and the increased

Fig. 15.7. Photograph of landslide scar on hillslopes burned by 2002 Missionary Ridge Fire in Colorado. Material from scar mobilized into a debris flow and traveled only a short distance down slope.

probability of landsliding. Although the impact of logging and associated increased soil moisture and root decay rates on slope stability has been extensively studied (see Chapter 16, this volume), a comparable body of definitive work on the impact of wildfire does not exist. As an example, Megahan (1983) measured increased pore pressures and attendant rates of subsurface flow in a watershed that had experienced both clearcutting and wildfire, but did not detect these responses in a watershed that was burned by wildfire alone. Some physical evidence specific to wildfires that supports root-decay promoted failure is provided by DeGraff (1997), who demonstrated that the character of the sheared roots exposed along the slip plane in a shallow landslide scar within an area burned by wildfire 10 years previously demonstrated failure of decaying, rather than live, material. And last, Wondzell and King (2003) suggest that increased peak flows that occur after fire can contribute to accelerated bank erosion, with a concurrent increase in rate of bank-side failure. Booker (1998) also describes such a process following fires in southern California.

Settings and abundances

The process of generation of debris flows exclusively by failure of discrete landslides on hillslopes has been documented in burned areas in a number of different settings, including southern California (Scott, 1971; Morton, 1989; Menitove, 1999; and Cannon 2001), the Sierra Nevada of California (DeGraff, 1997), central Idaho (Megahan *et al.,* 1978; Meyer *et al.*, 2001; Shaub, 2001), and north central Washington (Klock and Helvey, 1976; Helvey, 1980). Debris-flow deposits assumed to have originated from landslides related to forest-fire activity have been described in the Oregon Coast Range by May and Gresswell (2003) and in east-central British Columbia by Sanborn *et al.* (2002).

Of the 210 basins included in Gartner *et al.* (in press), only 33 (16%) were characterized by observations of debris flows originating exclusively from landslide failures (Fig. 15.4). These data came from reports of just four events, two in southern California following winter storms that impacted basins burned by fires the previous summer (Morton, 1989; Cannon, 2001), one in the Sierra Nevada of California 10 years after the fire (DeGraff, 1997), and one in response to a greater than 100-year recurrence prolonged rainstorm that culminated in a rain-on-snow event and triggered widespread flooding and landsliding throughout the northwestern U.S. (Meyer *et al.,* 2001; Schuab, 2001).

Note that Scott (1971), Klock and Helvey (1976), Cannon (2001), and Cannon *et al.* (2001b; 2003a) described evidence of both runoff- <u>and</u> infiltration-triggered debris-flow initiation processes within individual burned basins; these events account for 8% of the sample of 210 burned basins (Fig. 15.4). Importantly, Cannon *et al.* (2001b) found that when this was the case, considerably more material was contributed to the debris flows from hillslope runoff and channel erosion than from the landslide scars.

Rainfall conditions and timeframes

Debris flows generated from landslide failure in burned areas most frequently occur in response to prolonged periods of storm rainfall, usually of a week or more in duration, or prolonged rainfall in combination with rapid snowmelt or rain-on-snow events. Landslides have been documented as occurring during the first rainy season immediately after the fire (e.g. Morton, 1989; Cannon, 2001; Cannon *et al*., 2001a,b; 2003a), one to two years after the fire (Scott, 1971; Klock and Helvey, 1976; Meyer *et al.,* 2001), and up to 10 years (DeGraff, 1997), or even 30 years (May and Gresswell, 2003) after the fire. Note that it is important to establish if landslide failure can indeed be attributed to fire, and not simply to extreme meteorological events which would have triggered failures even without the effect of the fire. This is particularly important for failures that occur after significant time periods.

Although we found no reported instances of fire-related debris-flow activity triggered by spring snowmelt alone, Gray and Megahan (1981), Meyer *et al.* (2001), and Schuab (2001), described debris flows generated from burned watersheds in response to rain-on-snowmelt events.

15.3 FIRE-RELATED DEBRIS-FLOW SUSCEPTIBILITY

Numerous studies have documented an increased occurrence of debris flows following wildfire (e.g., Parrett, 1987; Morton, 1989; Meyer and Wells, 1997; Cannon *et al*., 2003a). However, in a study of the response of 95 recently burned basins to storm rainfall, Cannon (2001) found that not all basins that experience heavy rainfall produced debris flows; only about 40% showed evidence of debris flow. The remainder of the basins showed either a sediment-laden flood response, or no response. The fact that not all burned basins produce debris flows suggests the existence of a set of geologic, geomorphic, and rainfall conditions that may indicate a susceptibility specifically to debris-flow activity following wildfires.

In the following section we describe conditions in basins known to have produced fire-related debris flows, with the expectation that debris flows can be produced in the future from basins with similar conditions. The parameters we consider include bedrock lithology, surficial materials, basin area, average basin gradient, burn extent and severity, and water repellent soils. Other conditions may certainly affect debris-flow occurrence from burned basins; here we consider these parameters as possible first-order effects that can be readily characterized within the relatively short timeframes necessary for hazard assessments.

15.3.1 Bedrock Lithology and Surficial Materials

Basins underlain by some rock types appear to be more likely to produce debris flows than others following wildfires. More than 70% of the 160 basins that generated debris flows through runoff-dominated surface erosion included in Gartner *et al*. (2004) are underlain by metamorphic and sedimentary rock types, in nearly equal proportions (Fig. 15.8). Significantly smaller numbers of debris flows have been generated from basins underlain by volcanic, granitic, and mixed lithologies through this process. More than 90% of the basins that produced debris flows through the mobilization of discrete landslides were underlain by decomposed granite, although some landslide-triggered debris flows have also been documented in sedimentary terrains (Fig. 15.8). The basins that produced debris flows through the combination of mobilization of infiltration-triggered landslides and runoff-dominated progressive sediment bulking were underlain in nearly equal proportions by granitic and sedimentary materials. Post-fire landslide activity has not yet been documented in metamorphic or volcanic terrains. Note that Spittler (1995) further suggests that the presence of highly-fractured, hard bedrock may affect debris-flow generation.

An abundance of loose, unconsolidated materials lining channels and mantling hillslopes is thought to play a role in post-fire debris-flow generation. Doehring (1969), Wells (1987), Spittler (1995), Booker (1998), Menitove (1999), and Cannon (2001b) emphasized

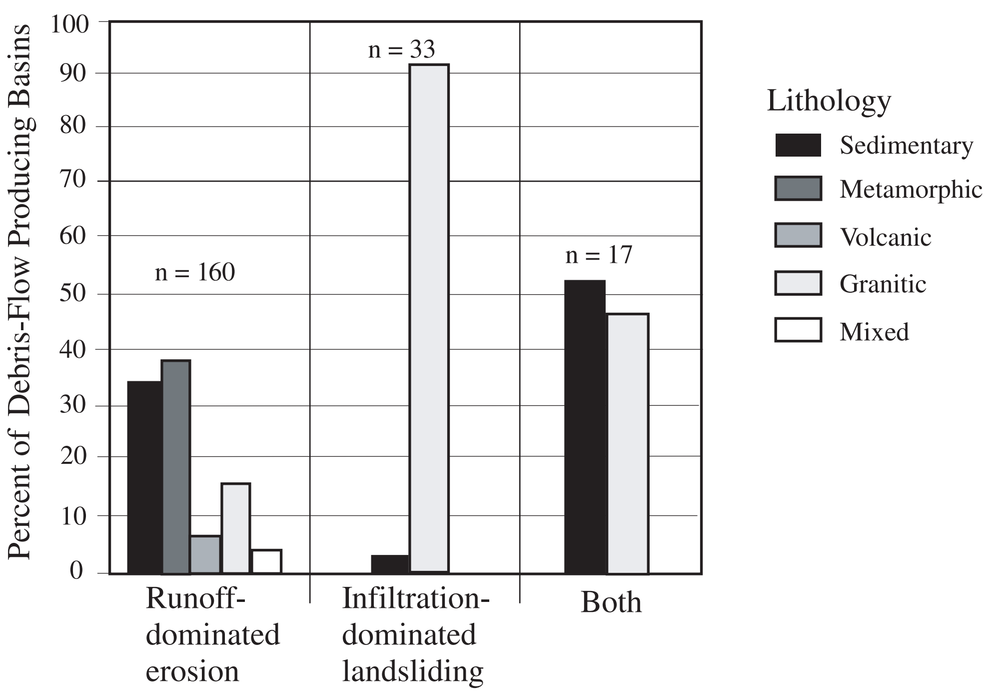


Fig. 15.8. Frequency of lithologies identified by initiation process underlying 210 debris-flow producing basins included in Gartner *et al.* (in press).

the importance of dry-ravel[2] deposits that are stored in channels and incorporated into the passing debris flows. Further, Cannon *et al.* (2003a) documented fire-related debris-flow occurrence in a setting with extensive glacial deposits mantling hillslopes and infilling channels. The observation that debris flows have been generated from hillslopes and channels that do not show extensive dry-ravel deposits indicates that the presence of dry-ravel material is not a pre-requisite for debris-flow generation in all settings, and suggests perhaps that its presence may affect the magnitude of the event, rather than susceptibility. At any rate, characterization of the availability of readily eroded material is a necessary element in a comprehensive hazard assessment.

The physical properties of surficial materials may certainly influence debris-flow generation from burned basins. Cannon *et al.* (2004) found that the sorting of the grain-size distribution of samples of burned surficial soils, soil permeability and percent organic matter of unburned soils were significant factors in distinguishing debris-flow producing basins from those that showed a different response. However, Cannon (2001), found no significant differences in the proportions of fine materials or dispersion ratios of samples collected from debris-flow producing basins and those that did not. The necessity of additional work to determine the soil properties that best indicate a propensity toward debris-flow production is clear, as is the need to put this understanding in a physical context.

15.3.2 Basin Area and Average Gradient

Fire-related debris flows can be produced from basins with broad ranges in area and average gradient (Gartner *et al.,* in press). Debris-flow producing basins range in area from 0.02 km^2 up to 25 km^2; the average basin area of 2.5 km^2 and median of 0.65 km^2 indicates that most debris-flow producing basins are the lower-order tributaries (Fig. 15.9). The basins ranged in average gradient between 14 and

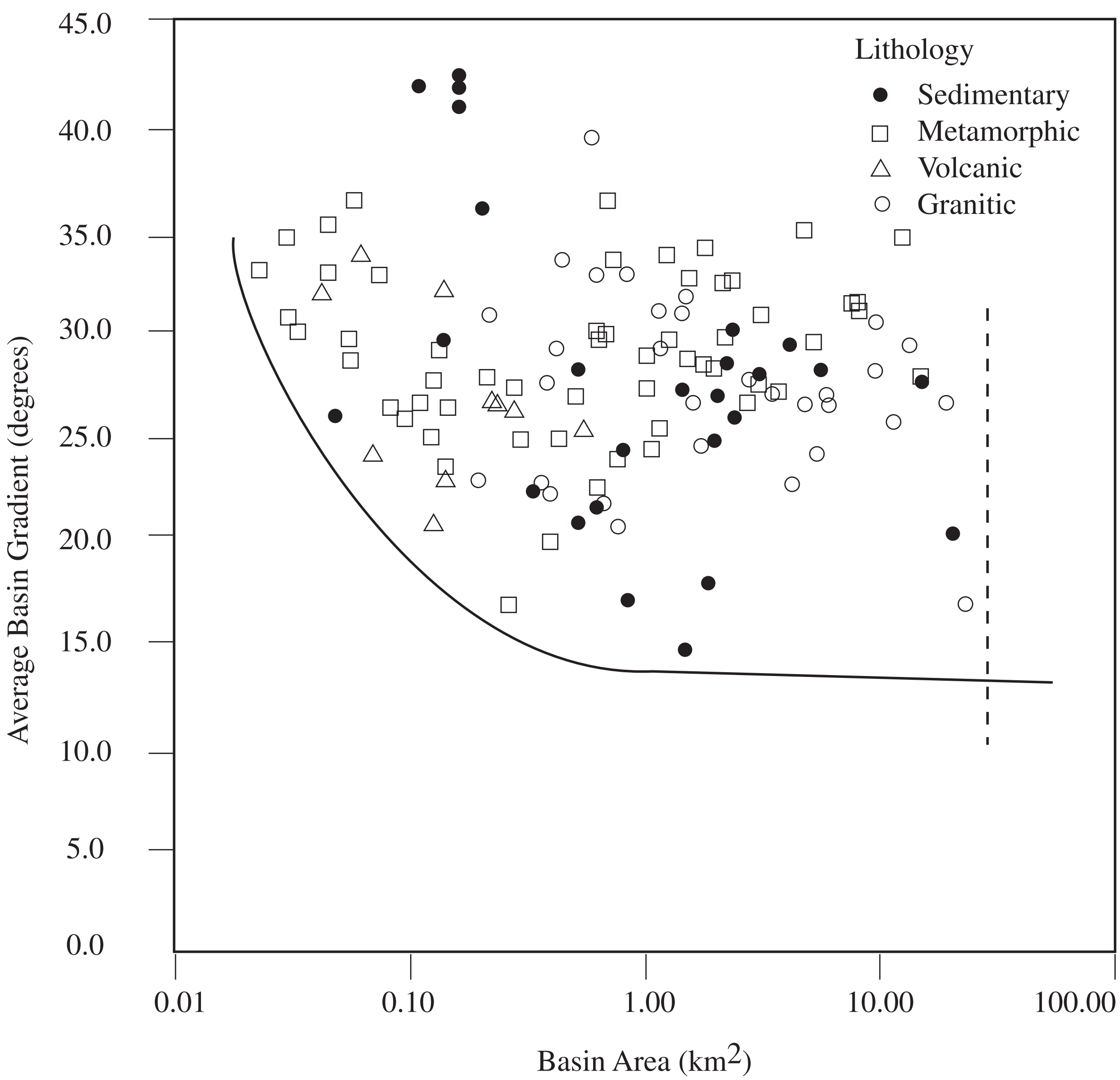


Fig. 15.9. Relations between basin area and average basin gradient, relative to lithology, of basins reported to have produced fire-related debris flows. Heavy line indicates threshold conditions, above which, runoff-initiated debris flows can be expected. Dashed vertical line emphasizes that debris flows were not observed beyond the outlets of basins larger than about 25 km^2.

[2] Dry ravel is the process of rapid, downhill movement of individual regolith and organic particles solely under the influence of gravity, and without the effect of water (Swanson, 1981). This process occurs in response to drying of the soil and combustion of soil-binding organisms and has been observed occurring both during and after the passage of the fire.

42 degrees (Fig. 15.9). Importantly, debris flows were not observed at the outlets of basins larger than about 25 km^2; although debris flows may have been generated in the lower order drainages of such basins, they were not of sufficient size or energy to travel the entire length of the basin.

Threshold conditions for basin area and average gradient combinations that are most likely to produce runoff-initiated debris flows are shown as the heavy line in Fig. 15.9. Basins with areas and average gradients that fall above this line are those most likely to produce this type of debris flow, given, of course, sufficient rainfall and readily erodible material. The data in Gartner *et al*. (in press) are not sufficient to delineate such thresholds for landslide-initiated debris flows.

The basin area and gradient characteristics of fire-related debris-flow producing basins do not appear to vary significantly with rock type (Fig. 15.9), although debris-flow generating basins underlain by volcanic rock types might be considered to be somewhat smaller than those underlain by granites. Debris-flow producing basins underlain by metamorphic and sedimentary materials show wide variations in both area and average gradient.

15.3.3 Burn Extent and Severity

Burn severity is a qualitative description of the effects of fire on soil hydrologic function (Miller, 1994). Areas classified as high burn severity generally exhibit complete consumption of the forest litter and duff, and combustion of all fine fuels in the canopy. A deep ash layer may be present, and the top layer of the mineral soil may be changed in color due to significant soil heating where large diameter fuels were consumed. The layer below may be blackened from charring of organic matter in the soil. 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. Foliage and twigs are consumed, and some heating of the mineral soils may occur if the soil organic layer was thin. Areas of low burn severity may show charring of the relatively intact litter and duff, consumption of small diameter wood debris, intact fine roots within the soils, and very little effect of fire on the canopy. Essentially no soil heating occurs in this case.

Although debris flows have been produced from basins that have experienced very little, or even no, high-severity fire (Fig. 15.10A), the area of a basin burned at a combination of high and moderate severities strongly influences debris-flow occurrence (Fig. 15.10B); most (91%) of the fire-related debris flows included in Gartner *et al.* (in press) were produced from basins with more than 65% of their areas burned at a combination of high and moderate severities (Fig. 15.10B). Further, using logistic regression statistical analyses, Cannon *et al.* (2004) found that the area of a basin burned at a combination of both high and moderate severity best separated debris-flow producing basins from those that showed a different response. Work by Agee (1973) and Neary *et al*. (1999) demonstrates that the removal of the soil-mantling litter and duff by fire is the indicator of burn severity that most closely affects rates of post-fire runoff and erosion; the fact that the litter and duff consumption is part of both the high and moderate burn severity classification provides a physical basis for this finding.

15.3.4 Water Repellent Soils

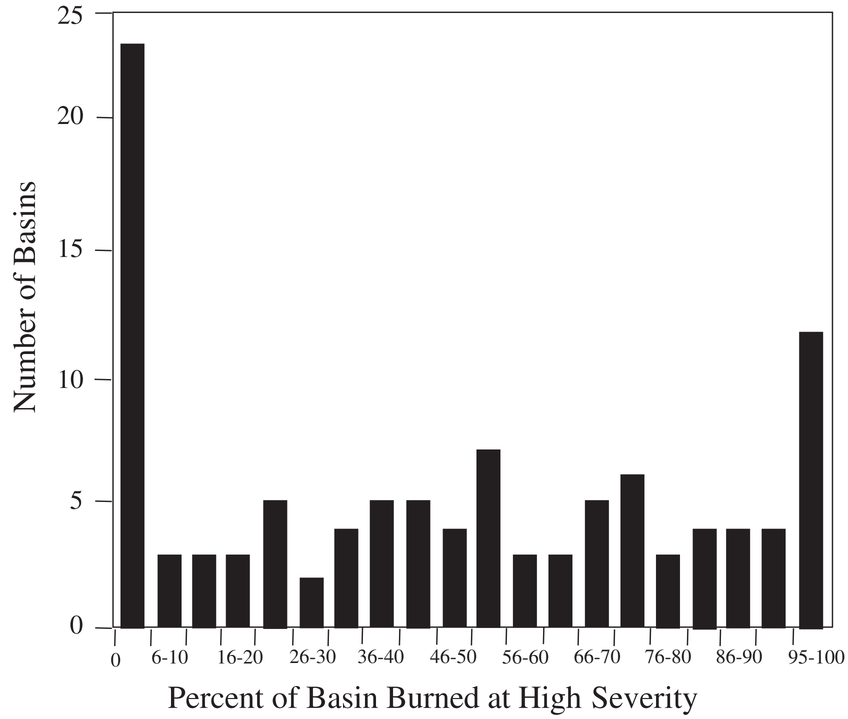
Although increased rates of runoff and erosion after wildfires are frequently attributed to the enhancement or development of water-repellent soils with the passage of the fire (e.g. Doerr *et al.,* 2000; Shakesby *et al*., 2000; Letey, 2001), and this increased runoff and erosion is generally assumed to influence debris-flow generation (e.g. Spittler, 1995), the role of this phenomenon relative to debris-flow occurrence has not been extensively examined. Wells (1981) and Gabet (2003) described debris-flow initiation as failure of a few millimeter-thick saturated layer of soil above a subsurface water-repellent zone. However, in an evaluation of the response of 95 recently burned basins, Cannon (2001) found that debris flows that originated within low-order channels were more likely to be generated from basins without water-repellent soils than from basins with water repellency. The lack of detectable water repellency in debris-flow producing basins led Meyer and Wells (1997) and Cannon (2001) to conclude that the properties of the bare, burned soils alone are sufficient to result in runoff sufficient to generate debris flows. These results indicate the necessity of additional work to evaluate the physical effects of this phenomenon on the generation of debris flows.

15.4 MAGNITUDE OF DEBRIS-FLOW RESPONSE

Obtaining measurements of the magnitude of the debris-flow response to fire is one of the most challenging efforts in characterizing the effects of rainfall on a basin, and the most important parameter in a hazard assessment. Debris-flow magnitude is generally characterized as either peak discharge or volume. The 61 peak discharge estimates reported from runoff-dominated debris flows included in Gartner *et al.* (2004) vary from 2 to 240 m^3/s (Fig. 15.11). The 34 reported volumes range from as little as 600 m^3 (Wells, 1981) to 300,000 m^3 (Wells, 1987).

The dominance of runoff processes over infiltration processes in recently burned basins indicates that methodologies developed for unburned basins to map landslide potential (Chapter 4, this volume) may be appropriate only in limited settings. As an alternative, relations traditionally defined between peak discharges of floods, basin characteristics, and storm rainfall can be useful in predicting the magnitude of potential debris-flow response from burned basins. The relations described below can be used to prioritize mitigation efforts in burned basins, to aid in the design of mitigation structures, and to guide decisions for warning, evacuation, shelter, and escape routes.

A



B

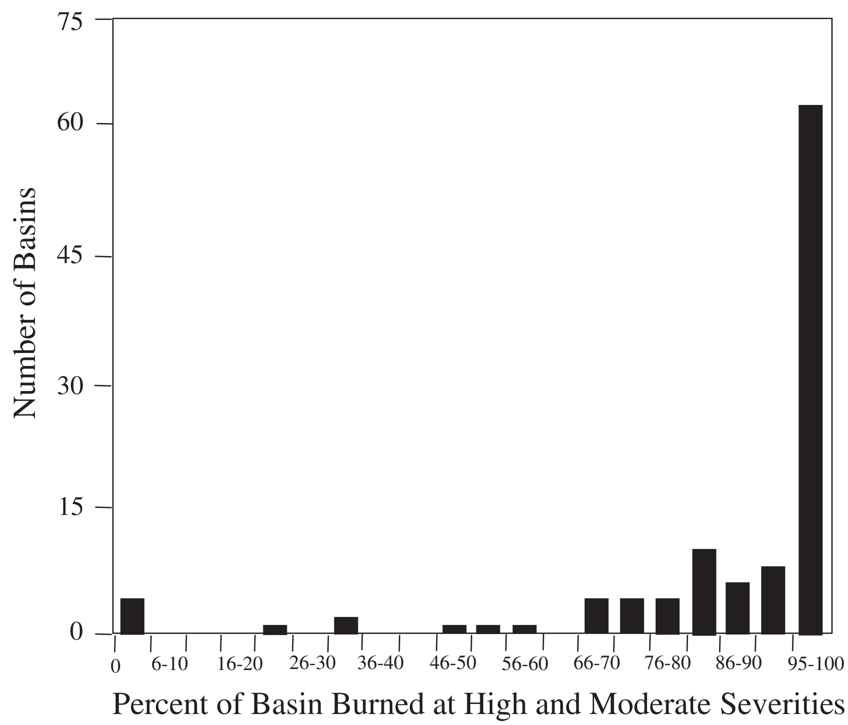


Fig. 15.10. A, Frequency distributions of percent of basin area burned at high severity, and B, at moderate and high severities for 108 debris-flow producing basins included in Gartner *et al*. (in press).

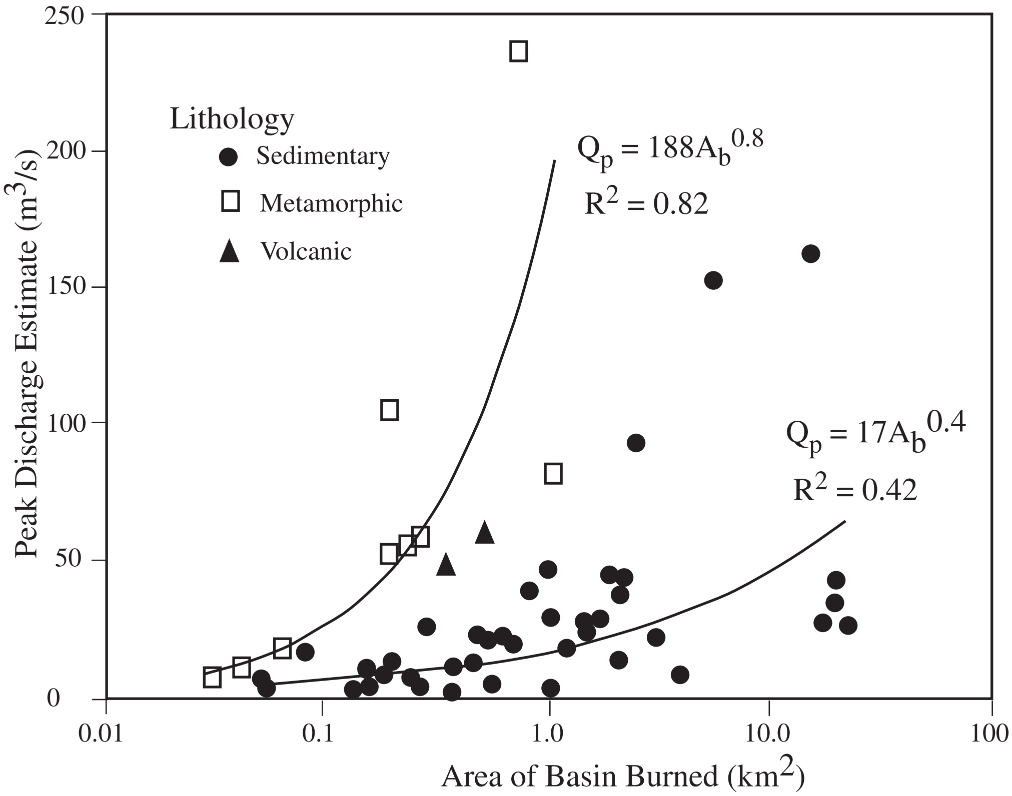


Fig. 15.11. Relation between peak debris-flow discharge estimates (Q_p) and area of basins burned at high and moderate severities (A_b), identified by lithology. Data from Gartner *et al.* (2004).

15.4.1 Relations Between Peak Discharge, Area of Basin Burned, and Lithology

Fig. 15.11 shows the estimates of peak discharge compiled by Gartner *et al*. (2004) as a function of the area of the basins burned at high and moderate severities. When the data points are distinguished by lithology, peak discharge and burned area of basins underlain by metamorphic rock types are strongly related by the power law:

$$Qp = 188A_b^{0.8} \tag{15.2}$$

where Qp is the estimate of peak discharge in m^3/s and A_b is the area burned. Due to the asymptotic form of the relation, this relation is probably most appropriate for basins less than about 1.0 km^2 in area. The relation is not as robust for basins underlain by sedimentary rock types, where

$$Qp = 17A_b^{0.4}. \tag{15.3}$$

The data are not sufficient to define such relation for basins underlain by volcanic or granitic lithologies, or using the measured volumes (a preferred measure of debris-flow magnitude) as the dependent variable. Note that these relations are based on the assumption that the bedrock lithology reflects some unknown quality of the erodibility, and thus propensity for debris-flow production, of the surficial materials.

15.4.2 Relations Between Peak Discharge, Area of Basin Burned, Average Basin Gradient and Storm Rainfall

Using data from Gartner *et al*. (2004) and multi-variate statistical analyses, Cannon *et al.* (2004), found that the peak discharge of debris flows issuing from the outlet of recently-burned basins could be estimated by the following relation:

$$Qp = 171 + 0.552(\theta) + 2.84(\log A_b) + 3.6\ (I). \tag{15.4}$$

where Qp is the debris flow peak discharge (in m^3/s), θ is the average basin gradient (in percent), A_b is the area of the basin burned at all severities, (in m^2), and I is the average storm rainfall intensity (in mm/hr). This relation has an adjusted R^2 of 0.67 for this dataset. Although volume may be a preferred measure of debris-flow magnitude, it was not possible to develop similar relations for this measure with the available dataset (Cannon *et al.,* 2004).

15.5 SUMMARY AND CONCLUSIONS

Data compiled from studies of debris-flow processes following wildfires throughout the western U.S. can answer some of the questions fundamental to post-fire hazard assessments - what, where, why, when, how big, and how often? Not all elements of all questions have satisfactory answers, but what follows is what can be gleaned from the preceding pages.

What and why? Fire-related debris flows have been found to initiate through two primary processes: runoff-dominated erosion by surface overland flow, and infiltration-triggered failure of a discrete landslide mass. Runoff-dominated processes are by far the most prevalent (76% of a sample of 210 basins), and occur in response to decreased infiltration and attendant increased runoff and erosion brought about by the immediate effects of the fires. Infiltration-triggered landslide activity is frequently attributed to both increased soil moisture brought about by vegetation-mortality-induced reduced transpiration rates, and root decay associated with decreases in soil cohesion.

Where? Debris flows that initiate through runoff-dominated erosion have been documented throughout the intermountain west and southern California. Basins underlain with sedimentary and metamorphic rock types with more than about 65% of their areas burned at a combination of high and moderate severities, and with areas and average gradients that fall above the threshold shown in Fig. 15.9 are those most likely to produce this type of debris flow.

Debris flows generated through mobilization of infiltration-triggered landslides have been documented in southern California, the Sierra Nevada of California, Washington, Idaho, and Colorado, and in basins underlain by sedimentary and granitic rock types.

When? Runoff-initiated debris flows are produced in response to storms that occur up to two years after the fire, and often in response to the first significant rainfall of the storm season. They occur most frequently in response to storms with average intensities greater than about 4 mm/hr and between 30 minutes and 24 hours in duration. However, debris flows have occurred within a storm after as little as 6 minutes of rainfall at intensities of 95 mm/hr.

Threshold rainfall intensity-duration conditions in the form $I = 7.0D^{-0.6}$, where I = rainfall intensity (in mm/hr) and D = duration of that intensity (in hours), can be used to determine the conditions under which to expect runoff-initiated debris flows in steep, recently burned basins underlain by sedimentary rock types and with thin colluvial covers that experience convective storms and are located in temperate climate mid-latitudes.

Debris flows generated through mobilization of landslides can occur during the first rainy season immediately after the fire, and up to about 10 years after the fire. These events generally occur in response to prolonged rainfall events, and in some cases, considerably more material is contributed to the debris flows from hillslope runoff and channel erosion than from the landslide scars. The most extensive landslide events have occurred in response to week long, or multi-week storms, or prolonged rainfall in combination with rapid snowmelt or rain-on-snow events. Although these events might be among the most destructive, they occur in response to infrequent meteorologic events.

How big? Reported peak discharge estimates for runoff-initiated debris-flow events vary between 2 and 240 m^3/s and reported volumes range from as little as 600 m^3 to 300,000 m^3. Relations between peak discharge estimates and area of the basin burned at high and moderate severities for basins underlain by metamorphic rock types are defined by $Qp = 188A_b^{0.8}$, and in sedimentary rock types by $Qp = 17A_b^{0.48}$, where Qp is the estimate of peak discharge in m^3/s and A_b is the area burned in m^2. Peak discharge for a given storm event can be estimated using the relation: $Qp = 171 + 0.552(\theta) + 2.84(\log A_b) + 3.6(I)$, where θ is the average basin gradient (in percent), A_b is the area of the basin burned at all severities, (in m^2), and I is the average storm rainfall intensity (in mm/hr). It was not possible to develop similar relations for volume with the available dataset.

How often? Basins with thin colluvial covers and minimal channel-fill deposits generally produce debris flows only in response to the first significant rainfall of the season. Basins with thick channel-fill deposits, and those mantled with thick accumulations of talus, frequently produce numerous debris flows throughout the rainy season.

In the absence of similar data in other settings throughout the world, the relations developed here may be appropriate for preliminary hazard assessments. However, we would expect that local conditions strongly affect debris-flow occurrence, and collection and analysis of site-specific data can only help but to improve such assessments.

15.5.1 Future Research Needs

Neither the progressive sediment bulking or shallow landsliding process for debris-flow generation described in this chapter is well understood in the context of burned areas. The mechanics of generation of debris flow through progressive sediment bulking, with a focus on the transition from water flow to debris flow, can benefit from examination through a combination of theoretical, experimental, and field work Although possible wildfire-related landslide-triggering effects have been proposed in the literature, there is little well-controlled data available on this subject. Quantitative examination of the effects of decreased transpiration, root decay, and revegetation following fires is necessary to define the role of post-fire landsliding in the generation of debris flows. It will be necessary to determine if landslide activity over long time frames can indeed be attributed to wildfires, or simply extreme meteorologic events.

The discussion of post-fire debris-flow susceptibility presented above has focused on examining the univariate effects of a limited number of parameters, while susceptibility is a multi-variate issue, and factors other than those examined here may well affect debris-flow occurrence. Further work is necessary to identify those conditions that best separate debris-flow producing basins from those that do not produce debris flows, and to develop relations that characterize the combined effects of these variables on debris-flow susceptibility. Variations in storm-rainfall patterns, material properties, and other effects will most certainly require that these relations be region specific. For example, the fire and debris-flow response history of basins that burn frequently may be an important factor in debris-flow susceptibility in southern California, where fires are a frequent occurrence.

To develop relations that better characterize post-fire debris-flow susceptibility, the physical role of water-repellency in the generation of post-fire debris flows needs to be better understood. Further, most fires show an extremely patchy mosaic of burn severity, and little attention has focused on examining the effects of variations within the spatial distribution of the fire within a basin on debris-flow generation. And last, there is a need to identify specifically those soil properties that indicate propensity to debris-flow production, and put this understanding in a physical framework.

Because measures of debris-flow volume are preferable to those of peak discharge for quantifying debris-flow magnitude, we suggest that such measures be systematically collected and cataloged so that relations between volume and burned area, basin gradient, rainfall intensity, and other controlling variables can be developed.

Definition of rainfall conditions that can potentially lead to post-wildfire debris flows is a critical element in any hazard assessment, and there is a need for definition of such conditions in settings other than that described here. Collection and analysis of information of the times of debris-flow occurrences within a storm will provide an invaluable addition to such an analysis.

Finally, definition of the locations and potential volumes of sediment sources within burned areas is a critical element in hazard assessments. This requires the development of rigorous methodologies for characterizing the amount of material stored in channels and available from hillslopes in order to define the magnitude of the potential hazards posed by post-wildfire debris flow.

We are in just the first stages of understanding the effects of wildfire on debris flow processes. The extensive recent fires in western North America can provide significant opportunities to move beyond the empirical evaluations presented here to develop an improved understanding of the physical controls on this hazardous phenomenon, and to develop useful and appropriate tools and methodologies for characterizing the hazards.

15.6 REFERENCES

Agee, J. K. (1973) *Prescribed fire effects on physical and hydrologic properties of mixed-conifer forest floor and soil.* University of California Resources Center, Davis, California, Contribution Report No. 143, 57 pp.

Beschta, R. L. (1990) Effects of fire on water quantity and quality. In: Walsad, J. S., Radosevich, S. R. and Sandberg, D. V. (eds), *Natural and prescribed fire in the Pacific Northwest Forests.* Oregon State University Press, pp. 219-231.

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

Bovis, M. J. and Jakob, M. (1999) The role of debris supply conditions in predicting debris flow activity. *Earth Surface Processes and Landforms*, **24**, 1039-1054.

Caine, N. (1980) The rainfall intensity-duration control of shallow landslides and debris flows: *Geografisk Annaler*, **62A**, pp. 23-37.

Campbell, R. H. (1974) Soil slips, debris flows, and rainstorms in the Santa Monica Mountains and vicinity, southern California. U.S. Geological Survey Professional Paper 851.

Cannon, S. H. (2001) Debris-flow generation from recently burned watersheds. *Environmental & Engineering Geoscience* **7**, 321-341.

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

Cannon, S. H., Kirkham, R. M. and 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. and 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. and Rogers, W.P. (eds), *Engineering Geology in Colorado–Contributions, Trends, and Case Histories,* AEG Special Publication 14, on CD-ROM.

Cannon, S. H., Gartner, J. E., Parrett, C. and Parise, M. (2003b) Wildfire-related debris flow generation through episodic progressive sediment bulking processes, western U.S.A. In: Rickenmann D., and Chen C.L. (eds) *Proceedings of 3rd International Conference on Debris-Flow Hazards Mitigation- Mechanics, Prediction, and Assessment, September 10-12, 2003, Davos, Switzerland,* p. 71-82.

Cannon, S. H., Michael, J. A., Gartner, J. E. and Gleason, J. A. (2003c) Assessment of potential debris flow peak discharges from basins burned by the 2002 Missionary Ridge Fire, Colorado. *U.S. Geological Survey Open-File Report 03-332.*

Cannon, S.H., Gartner, J.E., Rupert, M.G., and Michael, J.A., 2004, Emergency assessment of debris-flow hazards from basins burned by the Cedar and Paradise Fires of 2003, southern California: U.S. Geological Survey Open-File Report 04-1011.

Cleveland, G. B. (1973) Fire + rain = mudflows, Big Sur. *California Geology* **26**, 127-15.

Coe, J. A., Godt, J. W., Parise, M. and Moscariello, A. (2003) Estimating debris-flow probability using fan stratigraphy, historic records, and drainage-basin morphology, Interstate 70 highway corridor, central Colorado, USA. *Proceedings of 3rd International Conference on Debris-Flow Hazards Mitigation- Mechanics, Prediction, and Assessment, September 10-12, 2003, Davos, Switzerland,* pp. 1085-1096.

Conedera, M., Peter, L., Marxer, P., Forster, F., Rickenmann, D., and Re, L. (2003) Consequences of forest fires on the hydrogeological response of mountain catchments – a case study of the Riale Buffaga, Ticino, Switzerland. *Earth Surface Processes and Landforms* **28**, 117-129.

Davies, T. R., Phillips, C. J., Pearce, A. J. and Zhang, X. B. (1992) Debris flow behavior – an integrated overview. *Erosion, Debris flows, and Environment in Mountain Regions* (Proceedings of the Chengdu Symposium, July 1992), IAHS Publ. no. 209.

DeGraff, J. V. (1997*) Geologic investigation of the Pilot Ridge debris flow, Groveland Range District, Stanislaus National Forest.* USDA Forest Service, 20 pp.

Doehring, D. O. (1969) The effect of fire on geomorphic processes in the San Gabriel Mountains, California. *Contributions to Geology*, **7**, 43-65.

Doerr, S. H., Shakesby, R. A. and Walsh, R. P. D. (2000) Soil water repellency – its causes, characteristics and hydro-geomorphological significance. *Earth-Science Reviews* **51**, 33-65.

Gabet, E. J. (2003) Post-fire thin debris flows- sediment transport and numerical modeling. *Earth Surface Processes and Landforms* **28**, 1341-1348.

Gartner, J. E., Bigio, E. R. and Cannon, S. H. (2004) *Compilation of post-wildfire runoff-event data from the Western United States*. U.S. Geological Survey Open-File Report 2004-1085.

Gartner, J. E., Cannon, S. H., Bigio, E. R., Davis, N. K., McDonald, C., Pierce, K. L., Rupert, M. G. (in press) *Compilation of basin morphology, burn severity, soils and rock type, erosive response, debris-flow initiation process, and event-triggering rainfall for 599 recently burned basins in the western U. S.* U.S. Geological Survey Open-File Report.

Gostner, W., Bezzola, G. R., Schatzmann, M and Minor, H. E. (2003) Integral analysis of debris flow in Alpine torrent- the case study of Tschengls. In: Rickenmann D., and Chen C.L. (eds) *Proceedings of 3rd International Conference on Debris-Flow Hazards Mitigation- Mechanics, Prediction, and Assessment, September 10-12, 2003, Davos, Switzerland,* pp. 1129-1140.

Gray, D. H. and Megahan, W. F. (1981) *Forest vegetation removal and slope stability in the Idaho batholith.* USDA-Forest Service Research Paper INT-271, 23 pp.

Hack, J. T. (1965) *Geomorphology of the Shenandoah Valley, Virginia and West Virginia, and origin or the residual ore deposits*. U.S. Geological Survey Professional paper 484.

Helvey, J. A. (1980) Effects of a north central Washington wildfire on runoff and sediment production. *Water Resources Bulletin* **16**, 627-634.

Istanbulluoglu, E. D. G., Tarbotton, R. T., Pack, R. T. and Luce, C.H. (2003) A sediment transport model for incision of gullies on steep topography. *Water Resources Research* **39**, 1103.

Johnson, A. M., with contributions by Rodine, J. R. (1984) Debris flow. In: Brunsden D. and Prior, D. B. (eds), Slope Instability, John Wiley and Sons, New York, pp. 257-361.

Klock, G. O. and Helvey, J. D. (1976) Debris flows following wildfire in North Central Washington. *Proceedings of the Third Federal Inter-Agency Sedimentation Conference, March 22025, 1976, Denver, CO pp. 91-98.*

Larsen, I. J., (2003) From the rim to the river – the geomorphology of debris flows in the Green River Canyons of Dinosaur National Monument, Colorado and Utah: M.S. Thesis, Utah State Unveristy, Logan UT, 196 pp.

Larson, M. C. and Simon, A. (1993) A rainfall intensity-duration threshold for landslides in a humid-tropical environment, Puerto Rico. *Geografiska Annaler*, **75A**, pp. 13-23.

Letey, J. (2001) Causes and consequences of fire-induced soil water repellency. *Hydrological Processes* **15**, 2867-2875.

Los Angeles Times (2004) *Flash floods wash away lives, dreams*. Chong, J., Renaud, J., Ailsworth, E., Jan 3, 2004, p. B.1.

Martin, D. A. and Moody, J .A. (2001) Comparison of soil infiltration rates in burned and unburned mountainous watersheds. *Hydrological Processes* **15**, 2893-2903.

McDonald, G. N. and Giraud, R. E. (2002) *September 12, 2002, fire-related debris flows east of Santiaquin and Spring Lake, Utah County, Utah*. Utah Geological Survey Technical Report 02-09, 15 pp.

May, C. L. and Gresswell, R. E. (2003) Processes and rates of sediment and wood accumulation in headwater streams of the Oregon Coast Range, USA. *Earth Surface Processes and Landforms* **28**, 409-424.

Megahan, W. F. (1983) Hydrologic effects of clearcutting and wildfire on steep granitic slopes in Idaho. *Water Resources Research* **19**, 811-819.

Megahan, W. F., Day, N. F. and Bliss, T.M. (1978) Landslide occurrence in the western and central Northern Rocky Mountain physiographic province in Idaho. *Proceedings 5th North American Soils Conference, Fort Collins, CO.* pp. 116-139.

Menitove, A. (1999) Wildfire related debris-flow susceptibility in the Santa Monica Mountians, Los Angeles and Ventura Counties, California. MSc thesis, Colorado School of Mines, Golden, Colorado.

Meyer, G. A. (2002) Fire in western conifer forests – geomorphic and ecologic processes and climatic drivers. *Geological Society of America Abstracts with Programs* **34**, p. 46.

Meyer, G. A., Pierce, J. L., Wood, S. L. and Jull, A. J. T. (2001) Fire, storms and erosional events in the Idaho Batholith. *Hydrological Processes* **15**, 3025-3038.

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

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

Moody, J. A. and Martin, D. A. (2001b) Initial hydrologic and geomorphic response following a wildfire in the Colorado Front Range, *Earth Surface Processes and Landforms*, **26**, 1049-1070.

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. and 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.

Miller, M. (1994) *Fire behavior and characteristics.* Chapter II in Fire Effects Guide, National Wildfire Coordinating Group.

Neary, D. G., Klopatek, C. C., DeBano, L. F. and Ffolliott, P. F. (1999) Fire effects on belowground sustainability: a review and synthesis. *Forest Ecology and Management* **122**, 51-71.

O'Loughlin, C. L. (1974) The effect of timber removal on the stability of forest soils. *New Zealand Journal of Hydrology* **13**, 121-123.

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, pp. 57-67.

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

Reneau, S. L. and Dietrich, W. E. (1987) The importance of hollows in debris flow studies; examples from Marin County. In: Costa, J.E. and Wieczorek, G. F. (eds), *Debris flows/avalanches: process, recognition, and mitigation.* Geological Society of America Reviews in Engineering Geology, v VII, p. 165- 180.

Sanborn, P. Jull, T. J., Hawkes, B. (2002) Holocene fire history and slope processes in an inland temperate rainforest, east-central British Columbia, Canada. *Geological Society of America Abstracts with Programs* **34**, p. 319

Schmidt, K. M., Roering, J. J., Stock, J. D., Dietrich, W. E., Montgomery, D. R. and Schuab, T. (2001) The variability of root cohesion as an influence on shallow landslide susceptibility in the Oregon Coast Range. *Canadian Geotechnical Journal* **38**, 995-1024.

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

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

Shakesby, R. A., Doerr, S. H. and Walsh, R. P. D. (2000) The erosional impact of soil hydrophobicity – current problems and future research directions. *Journal of Hydrology* **231-232**, 178-191.

Shaub, S. (2001) Landslides and wildfire – an example from the Boise National Forest. MSc thesis, Boise State University, Idaho.

Spittler, T. E. (1995) Fire and the debris flow potential of winter storms. In: Keeley, J. E., and Scott, T. (eds), *Brushfires in California Wildlands: Ecology and Resource Management.* International Association of Wildland Fire, Fairfield WA, p. 113- 120.

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

Swanston, D. N. (1975) *Slope stability problems associated with timber harvesting in mountainous regions of the western United States.* USDA Forest Service General Technical Report PNW-21, 14 pp.

Tognacca, C. and Bezzola, G. R. (1997) Debris-flow initiation by channel-bed failure. In: Chen, C. L. (ed), *Debris-Flow Hazards Mitigation: Mechanics, Prediction, and Assessment*, *Proceedings for the first international conference, San Francisco, CA*, *August 7-9, 1997,* ASCE, American Society of Civil Engineers, pp. 44-53.

Tognacca, C., Bezzola, G. R. and Minor, H. E. (2000) Threshold criterion for debris-flow initiation due to channel bed failure. In: Wieczorek, G. F. and Nasser, N. D. (eds), *Debris-Flow Hazards Mitigation: Mechanics, Prediction, and Assessment,* Balkema, Rotterdam. pp. 89-97.

Wells, W. G., II. (1981) Some effects of brushfires on erosion processes in coastal Southern California. In: *Erosion and Sediment Transport in Pacific Rim Steeplands*, Christchurch, New Zealand, International Association of Hydrological Science, **132**, 305-342.

Wells, W. G., II. (1987) The effects of fire on the generation of debris flows in southern California. In: Costa, J. E.,and Wieczorek, G. F. (eds), *Debris Flows/Avalanches – Process, Recognition, and Mitigation.* Reviews in Engineering Geology, Vol. VII, pp. 105-113.

Wohl, E. E. and Pearthree, P. P. (1991) Debris flows geomorphic agents in the Huachuca Mountains of southeastern Arizona. *Geomorphology* **4**, 273-292.

Wondzell. S. M. and King, J. G. (2003) Post-fire erosional processes in the Pacific Northwest and Rocky Mountain Regions. *Forest Ecology and Management* **178,** 75-87.

Ziemer, R. R. (1981) Roots and the stability of forested slopes. *International Association of Hydrologic Science*, **132**, 343-357.