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Rainfall intensity limitation and sediment supply independence of post-wildfire debris flows in the western U.S.

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Abstract

This work explores two hypotheses related to post-wildfire debris flows: first, that they are rainstorm-intensity limited and not rainstorm-volume limited, and second, that they are not sediment-supply limited. The first hypothesis suggests that it is common to generate more than enough water to account for the volume in the debris flow, but to actually produce a debris flow the water must be delivered in sufficiently large doses. This is demonstrated by a dataset of 44 debris flows from eight burned areas in California, Colorado, and Utah. Assuming that a debris flow is composed of 30% water and 70% solids, these events were generated during rainstorms that produced an average of 17 times as much water as necessary to develop a debris flow. Even when infiltration is accounted for, the rainstorms still generated an overabundance of water. Intensity-dependence is also shown by a number of cases where the exact timing of debris flows can be pinpointed and are contemporaneous with high intensity bursts of rainfall. The hypothesis is also supported by rainfall intensity-duration thresholds where high volume storms without high intensity bursts do not generate debris flows. The second hypothesis, that of sediment-supply independence, is supported by data indicating the dramatic increase in volume of flows that occur directly after wildfire, as opposed to flows in unburned terrain. Also, repeated flows within short time intervals are only possible with an abundance of channel sediment, dry ravel, and bank failure material that can be mobilized, and field observations confirm these sediment sources, even directly after a debris-flow event.

Keywords: water; intensity; sediment; balance

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1. Introduction

Because debris flows are usually triggered by rainfall events, there is often an implicit assumption that their generation is rainfall-limited. Along the same lines, the scouring of debris-flow channels during the event may be interpreted to limit the supply of sediment for future flows in the same channel. The purpose of this study is to demonstrate that neither of these limitations applies to post-wildfire debris flows in particular settings, such as the Western United States. Rainfall is still necessary, and sediment must be available to be mobilized into the flow, but the thresholds can be shown to be quite low, which is why post-wildfire debris flows are common, they are larger than flows in unburned areas, and they can occur repeatedly in the same channels. Rainfall limitations are explored through water-balance calculations to demonstrate how rainstorms are partitioned into debris flows, infiltration, and runoff. Sediment supply is investigated through volume comparisons of burned and unburned source areas, field measurement of sediment sources, and records of repeated flows.

2. Data sources

Our data for rainfall limitation can be found in Gartner (2005); however, portions of the data set are also available in Cannon et al. (2008) and Cannon et al. (2003). The data set contains field measurements from 44 drainage basins with post-wildfire debris flows, including debris-flow volume, basin area, aerial extent of burn severity, total rainfall,

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rainfall duration, and storm rainfall intensity. The total rainfall amount (mm) for each basin was estimated using inverse distance weighting techniques based on the values of proximal rain gauges (Gartner, 2005). The basins were burned in eight different wildfires in Colorado, California, and Utah. The average size of the study basins is approximately 1 km^2, however, basin area ranged from 0.01 km^2 to 4.1 km^2. Topography ranges from steep, rugged slopes to more gentle gradients (Cannon et al. 2008). Vegetation consists of juniper, shrublands, aspen, fir, grasslands, conifers, and chaparral (Cannon et al., 2008). The climate in the western United States is characterized by very dry, semi-arid periods followed by episodic intense rainfall. Summers are hot and dry, winters are cool and potentially wet (Moody and Martin, 2001; Cannon et al. 2008). The Colorado basins consist of sedimentary interbedded sandstone, siltstone, and conglomerate; the California basins consist of coarse crystalline igneous rocks (Cannon et al. 2008); and the Utah basins consist generally of "quartzite, sandstone, siltstone, schist, gneiss, and amphibolite" intruded by dikes and overlain by limestone and shale (McDonald and Giraud, 2002).

The data for sediment supply can be found in Santi et al. (2008) and Santi and Morandi (2013), consisting of debris-flow volume measurements with associated measurements of in-channel, sheetwash, and rill contributions for the Santi et al. (2008) dataset. The study basins are located primarily in Colorado, California, and Utah, although Santi and Morandi (2013) also include data for comparison from Italy, British Columbia (Canada), Washington state (USA), and several other Western U.S. states.

3. Conceptual model

The analysis of rainfall limitations is done through a water balance calculation, where each drainage basin is idealized as a two-layer system, with ash overlying the soil column (this is a common simplification, used for example in Moody et al., 2009; Woods and Balfour, 2012; and Bodi et al., 2011). Kinner and Moody (2010) suggest the two-layer system exists because of the capillary barrier effect. This effect occurs because ash has much higher hydraulic conductivity and infiltration capacity than the underlying soil (Moody et al., 2009; Gabet and Bookter, 2011; Bodi et al., 2011). Kinner and Moody (2010) note this barrier effect is most enhanced under dry conditions. This model was also confirmed by Ebel et al. (2012), who measured soil water content profiles at a recently burned site and found that almost no water infiltrated below the ash layer.

Because of the high initial infiltration capacity of the ash, we have assumed that 100% of the rainfall will infiltrate the ash layer until it reaches saturation, and any additional rainfall will run off. This is a "fill and spill" infiltration model, where the capacity is not time variant, rather than a Hortonian model that includes time-variable infiltration (Gabet and Bookter, 2011). The effects of evaporation and transpiration were not included due to the short duration of each rainfall event.

Topography plays a significant role in runoff generation, and is undoubtedly a factor for the study basins, which generally have greater than 30-50% slope (Gartner 2005). As a conservative approach, however, the model used in this study does not include the effects of topography, so the actual runoff is expected to be larger than the calculated runoff.

Based on this model, the water balance equation, where each value is a volume over the entire drainage basin, is:

$$\textit{Rainfall} = \textit{Debris flow water content} + \textit{Ash infiltration} + \textit{Unburned soil infiltration} + \textit{Overland flow} \quad (1)$$

Each of these parameters is described in detail below. For some less-constrained input variables, a range of values is given so that both high overland flow and low overland flow end members can be calculated.

Rainfall is calculated as the total storm rainfall (measured in proximal rain gauges) multiplied by the drainage basin area.

Debris-flow water content can be calculated under the assumption that a debris flow, by definition, contains approximately 20-40% water (Pierson and Costa 1987, Phillips and Davies 1991). If the material contains less than 20% water, then it is a form of rigid mass wasting; if it is above 40% water, it is termed "hyper-concentrated flow" (Phillips and Davies, 1991). Therefore, for the data used in this study, water content of the debris flow is calculated as 20% (high overland flow end member) or 40% (low overland flow end member) of the total volume of the debris-flow deposit.

Ash infiltration is calculated as the product of ash porosity, ash thickness, and burned area within each basin. While ash porosity has been measured as high as 67% (Woods and Balfour 2010) to 83% (Cerda and Doerr 2008), this is immediately post-wildfire, and the ash quickly compresses to a lower porosity. We have used a range of 20-30%

porosity (representing high and low overland flow end members, respectively), which matches observations of other researchers and is close to and slightly larger than field capacity of 0.12-0.24 measured by Ebel (2013).

Ash thickness of 10 mm was assumed, based on similar field thickness measurements by Kinner and Moody (2012) and Ebel et al. (2012). The 10 mm assumption is also in agreement with the values used for controlled ash placement in test plots by Gabet and Sternberg (2008), Woods and Balfour (2010), and Bodi et al. (2011). Ash may be thicker than 10 mm after wildfire in more heavily forested areas, such as the pine and juniper areas in Colorado and Utah, but the low tree density and patchy vegetation may result in a lower average thickness, so the assumption of 10 mm is considered reasonable.

The ash infiltration calculation also assumes that ash is present over the entire burned portion of the basin, and ash is not present in the unburned portion. There are possibly burned areas with insignificant ash thickness that are not accounted for in our calculation.

Unburned soil infiltration is expected in unburned portions of the basin. We estimated this infiltration using USDA Natural Resources Conservation Service (NRCS) runoff curves (USDA, 1986). For this calculation, the following assumptions were made:

- Antecedent Moisture Condition II (this is average soil moisture. AMC I – dry soil – may apply directly following the wildfire, but general conditions were assumed to better match with AMC II),
- Hydrologic Soil Groups B, C, and D (representing a range of soil types from fine to sandy textures and slow to high infiltration rates), and
- Hydrologic Condition Poor to Fair (poor is <30% ground cover and fair is 30-70% ground cover).

For Colorado and Utah, these conditions produce a range of Runoff Curve Numbers, CN, from 71-93. For California the CN range is 67-89. Runoff Curve Numbers may be converted to potential maximum retention, S (in inches), with the equation (from Chow et al., 1988):

$$S = 1000/CN - 10 \tag{2}$$

S may then be used to calculate expected runoff, P_e, with the equation (from Chow et al., 1988):

$$P_e = (P - 0.2S)^2 / (P + 0.8S) \tag{3}$$

Where P is cumulative rainfall in inches.

While the range of S values (calculated from CN) is given for statewide location, the P_e values are calculated for each basin depending on the cumulative rainfall measured in that basin or in nearby rain gauges.

Overland flow is calculated from Equation 1 as the difference in the measured rainfall and the calculated infiltration. A range of values is presented, with both low and high overland flow estimations.

4. Results of water balance calculation

Figures 1 and 2 show the final water balance calculation for each basin, where each component (debris flow, infiltration, and overland flow) is represented as a percentage of the total rainfall on the basin. The Low Overland Flow Calculation (Figure 1) assumes the maximum infiltration values for both burned and unburned areas and assumes debris-flow water content of 40%. The High Overland Flow Calculation (Figure 2) assumes minimum infiltration values and debris-flow water content of 20%.

There is excess rainfall in the form of overland flow runoff for all basins except four in Figure 1 (Haflin, Basin 23, Root Creek, and Coal Seam G) and except for one in Figure 2 (Basin 23). Most basins show a significant excess of water, with substantial overland flow. The amount of overland flow is highest for the California basins (Janet Creek J3 through El Capitan II, which are shown on the right side of these graphs).

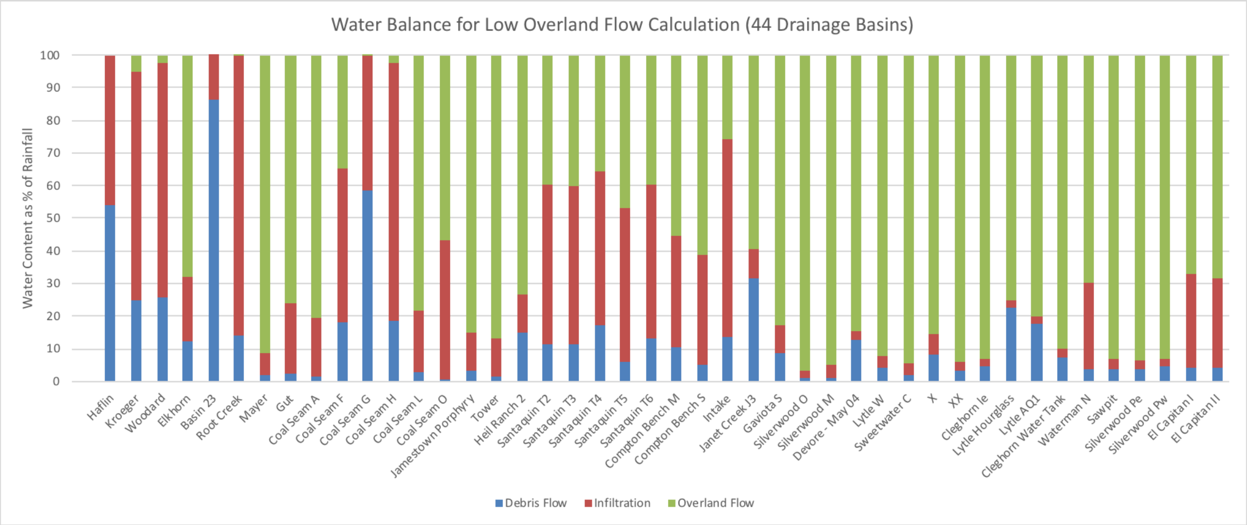

Fig. 1. Results of water balance calculation for Low Overland Flow assumptions.

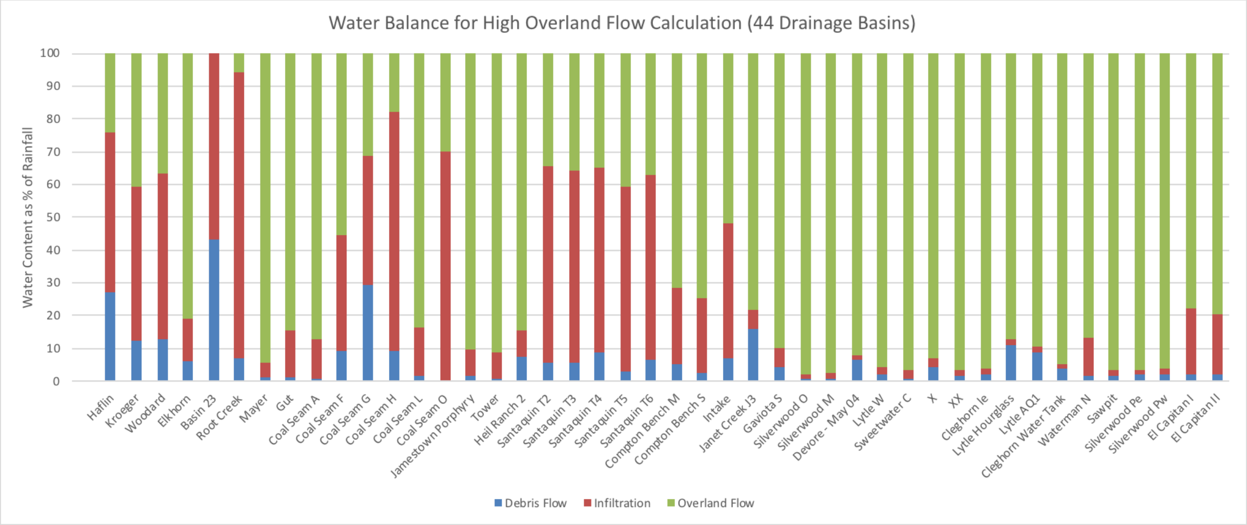

Fig. 2. Results of water balance calculation for High Overland Flow assumptions.

The amount of water incorporated into the debris flows is much less than the amount available in each rainstorm. Assuming an average proportion of water in the debris flow (30%, which is mid-range of the low and high values of 20% and 40% used in the calculation), only a median of 5.9% of the rainstorm water is incorporated into debris flows, with the remainder either infiltrating or exiting as overland flow. This is 1/17th of the available water, and this small fraction verifies that the debris flows are not rainstorm volume limited. The amount of water in debris flows is shown on Figure 3.

5. Rainfall intensity limitations

While rainfall volume can be shown not to limit debris-flow occurrence, a dependence on rainfall intensity can also be demonstrated. Figure 4, from Friedman and Santi (this volume) and Friedman (2012), shows the close time proximity between rainfall intensity bursts (zones of increased slope on the rain gauge cumulative rainfall curves) and the pressure spikes recorded in the nearby pressure transducers. In this study, pressure transducers were drilled into bedrock in the drainage channel to measure debris flows overriding them, and rain gauges were placed within tens of meters of the pressure transducers (Basin 24) or were in adjacent canyons (Basin 16, located 1.1 km from the Basin 32 pressure transducer). These data show debris-flow response within a few minutes of rainfall intensity bursts. Similar short lag times have been measured by other researchers as well (e.g., Coe et al., 2008).

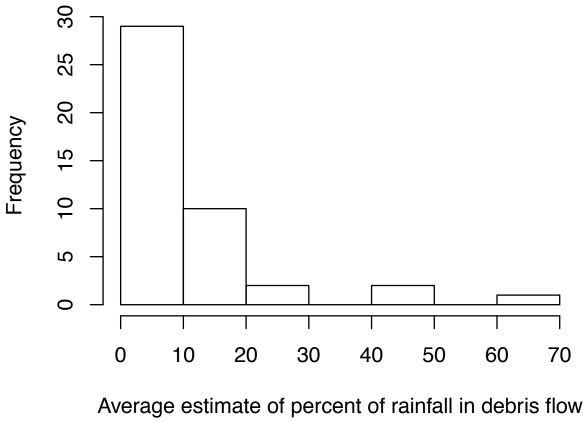

Fig. 3. Histogram of percent of storm rainfall incorporated into debris flow for each watershed, assuming the debris flow is composed of 70% solids and 30% water. In very few cases does the debris flow entrain more than 20% of the available water.

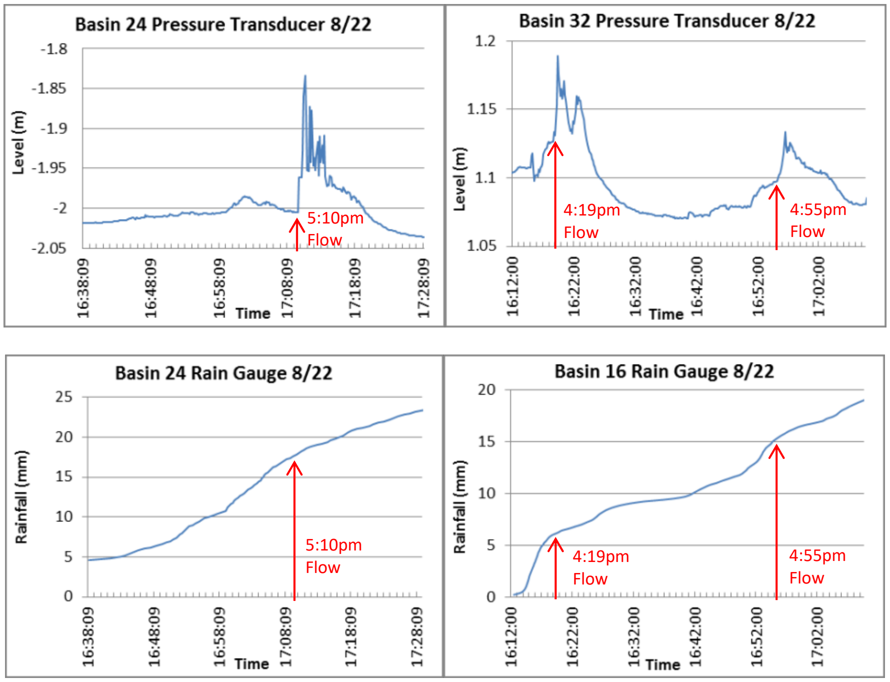

Fig. 4. Example of short lag time between rainstorm intensity burst (zones of increased slope of the cumulative rainfall curves shown in blue on the bottom graphs) and debris-flow generation (spikes on the pressure transducers shown in blue on the upper graphs). Note that the rain gauge for Basin 24 was located within meters of the pressure transducer, but the rain gauge in Basin 16 was located 1.1 km from the pressure transducer in Basin 32.

Rainfall intensity dependence for debris-flow initiation has also been well established through rainfall intensity-duration threshold graphs, where local data can be used to construct thresholds dividing storms that produce debris flows from those that do not. An example is shown on Figure 5, which summarizes the thresholds from numerous locations (with those from burned areas shown in color). It is possible to have rainstorms that generate large amounts of total amounts of water (long duration storms) that do not have sufficient intensity to trigger debris flows.

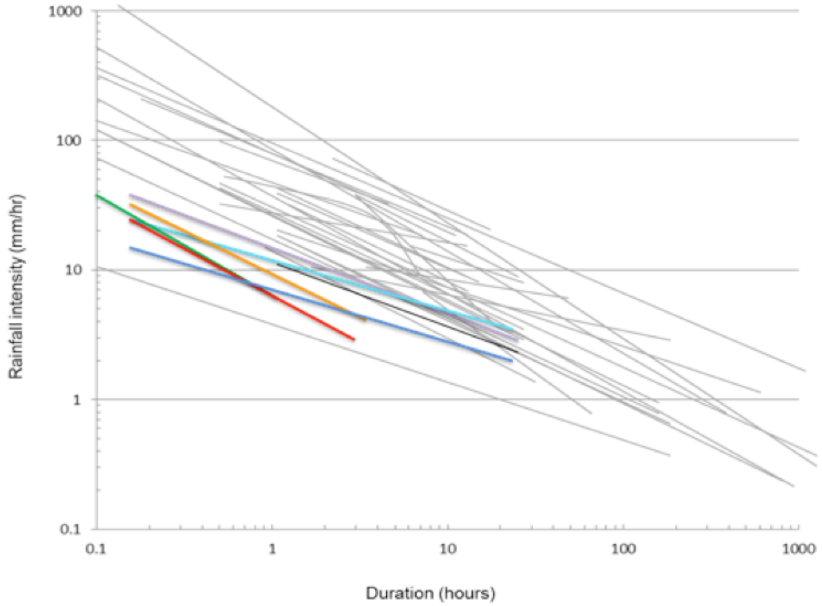

Fig. 5. Compilation of measured intensity-duration thresholds for debris-flow generation at various unburned (gray lines) and burned (colored lines) locations (from Cannon and DeGraff, 2009). Burned areas have lower threshold storms to trigger debris flows, but for all cases it is possible to have long duration storms producing large cumulative rainfall that do not generate debris flows because of low rainfall intensity.

6. Sediment supply independence

Three lines of evidence demonstrate that post-wildfire debris flows are not sediment supply limited. The first is the multi-fold increase in volume of debris flows following wildfire. Santi and Morandi (2012) compared the volumes of debris produced from a large dataset of western US debris flows, including 274 events from recently burned areas (within one year), 162 events from recovering basins (one to ten years after wildfire), and 216 events from areas that are unburned or fully recovered (ten years after wildfire). They showed that the area yield rate (debris-flow volume divided by basin area) was doubled for burned areas. When they used cluster analysis to subdivide the data into areas of similar basin size, channel length, and channel gradient, they showed that burned areas had an even higher difference in debris-flow volume, ranging from 2.7 to 5.4 times the volumes produced by unburned areas.

The amount of sediment produced by these debris flows is substantial, and it has been shown that the majority of it comes from channel scour as water moves down-canyon. Santi et al. (2008) measured incremental debris production from the channel and surrounding hillside for sections of the drainage channel extending from zero-order channels near the top of the drainage basin to the canyon mouth of the at the bottom of the basin. An example of their data is shown on Figure 6. Based on data from 46 debris flows, they showed that hillslope and rill erosion accounted for an average of only 3% of the final debris volume, but channel scour accounted for nearly the entire remainder of the volume. Sediment in the channel accumulates through normal weathering and sedimentation processes, strongly supplemented during and after the fire by dry ravel (Swanson, 1981; Wells, 1987; Florsheim et al., 1991; Schmidt et al., 2011). This produces a sediment-filled channel with ample material to be incorporated into a debris flow by channel scour. In some cases, a debris flow may scour to bedrock, but at many locations sediment remains in the channel (Figure 7) and may be incorporated into subsequent flows. Furthermore, post-debris flow channel banks are over-steepened from scour, and these banks frequently fail, recharging the sediment supply for future flows (Figure 8).

Finally, multiple debris-flow events have been observed in the same canyon over short time frames indicating that the supply of sediment is not easily exhausted. For example, Gartner, et al. (2004) provides a database of post-wildfire debris flow and flood events in the Western US, noting at least eight locations where repeated debris flows occur in the same drainage basin within days to months of each other. Cannon and Gartner (2005) note that "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 … frequently produce numerous debris flows throughout the rainy season."

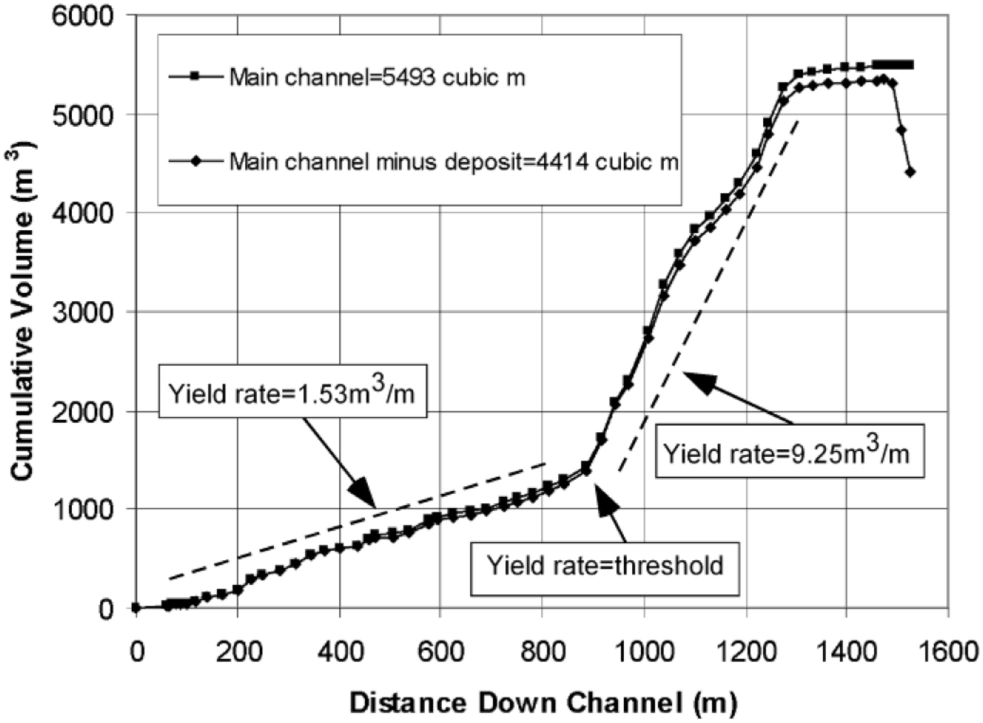

Fig. 6. Measurement of incremental debris production using multiple channel cross-sections (from Santi et al., 2008). Channel yield rate, calculated as the volume of debris produced per unit channel length, is the slope of the graph at any point.

Fig. 7. Channel scour from a debris flow, with remaining sediment that can be incorporated into successive debris flows.

Fig. 8. Failure of channel banks that have been over-steepened by recent debris-flow scour. This process quickly adds new sediment to the channel that can be incorporated into successive debris flows (photograph by Rich Giraud, Utah Geological Survey).

7. Conclusions

Using conservative assumptions for infiltration and debris-flow water content, there is excess water from rainfall in nearly every analyzed drainage basin that produces significant overland flow runoff during debris-flow generating storms. This means that for post-wildfire settings, at least in the Western US and perhaps other semi-arid mountainous or Mediterranean climates, debris flows are not rainfall volume limited. The model for debris-flow generation then becomes a system where there is ample surface water flow both before and after the debris flow, and that the debris flow is triggered not by reaching a threshold total water volume or saturation, but by reaching a threshold rainfall intensity. The limiting factor for triggering debris-flow behavior of the fluid runoff is the dynamics of the pulse of water and entrained sediment. Furthermore, the supply of sediment in drainage channels is substantial, producing much larger debris flows than pre-fire, and the supply of sediment is capable of producing repeat events in the same channel, at least until vegetation recovers enough to temper the overland flow or until smaller rainstorms move sediment through the system by fluvial transport.

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