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Frequency–magnitude distribution of debris flows compiled from global data, and comparison with post-fire debris flows in the western U.S.

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Abstract

Forecasting debris flow hazard is challenging due to the episodic occurrence of debris flows in response to stochastic precipitation and, in some areas, wildfires. In order to facilitate hazard assessment, we have gathered available records of debris flow volumes into the first comprehensive global catalog of debris flows (n = 988). We also present results of field collection of recent debris flows (n = 77) in the northern Rocky Mountains, where debris flow frequency increases following wildfire. As a first step in parameterizing hazard models, we use frequency–magnitude distributions and empirical cumulative distribution functions (ECDFs) to compare volumes of post-fire debris flows to non-fire-related debris flows. The ECDF of post-fire debris flow volumes is significantly different (at 95% confidence) from that of non-fire-related debris flows, suggesting that the post-fire distribution is composed of a higher proportion of small events than that of non-fire-related debris flows. The slope of the frequency–magnitude distribution of post-fire debris flows is steeper than that of non-fire-related debris flows,
corroborating evidence that small post-fire debris flows occur with a higher relative frequency than non-fire-related debris flows. Taken together, the statistical analyses suggest that post-fire debris flows come from a different population than non-fire-related debris flows, and their hazard must be modeled separately. We propose two possible non-exclusive explanations for the fact that the post-fire environment produces a higher proportion of small debris flows: 1) following fires, smaller storms or effective drainage areas can trigger debris flows due to increased runoff and/or decreases in root strength, resulting in smaller volumes and increased probability of failure, and 2) fire increases the probability and frequency of debris flows, causing their distribution to shift toward smaller events due to limitations in sediment supply.

Keywords: Debris flow; Frequency; Magnitude; Fire

1. Introduction

The majority of sediment transport in mountainous areas is caused by episodic events such as debris flows (Dietrich and Dunne, 1978). Debris flows move sediments ranging in size from mud to boulders several meters in diameter, and introduce them to stream channels, where this sudden influx of material can alter stream courses and morphology (Costa, 1988; Benda et al., 2003; Ritter et al., 2006; Hoffmann and Gabet, 2007) and increase habitat heterogeneity (Rieman and Clayton, 1997; Benda and Sias, 2003). As human infrastructure expands further into mountainous landscapes (Theobald and Romme, 2007), management of debris flow hazards becomes an increasingly important issue. In the drier climates of the western U.S., where debris flows often follow wildfire, this problem is of particular concern (Cannon et al., 2010).
Debris flows initiate through a variety of mechanisms. Landslides triggered during rainstorms by increases in pore pressure can mobilize into debris flows (Iverson et al., 1997; Gabet and Mudd, 2006). Debris flows can also form through the progressive bulking of surface runoff as it entrains sediment while flowing downslope (Van Steijn, 1999; Cannon et al., 2001, 2003). The “firehose effect” refers to an initiation mechanism whereby a focused turbulent water flow mobilizes an accumulation of rocks (Helsen et al., 2002; Larsen et al., 2006; Conway et al., 2010). Dry rock and soil falling into a stream, instantaneously increasing its sediment concentration, can initiate a debris flow, an initiation mechanism we refer to as “rockfall” (Jakob and Friele, 2010). Although these mechanisms refer to separate triggering events, it is important to recognize that debris flows may exhibit a combination of these different behaviors. For example, landslide-initiated debris flows often continue to entrain sediment as they move downslope, growing in volume (Hungr and Evans, 2004; Iverson et al., 2011; Mangeney, 2011). In addition, the generation of runoff in progressively bulked debris flows may initially be due to the failure of a thin layer of ash or soil on the order of 1–2 cm thick (Gabet, 2003a; Gabet and Sternberg, 2008).

During the past few decades, evidence has emerged that wildfire increases debris flow occurrence (Hyde et al., 2007; Gartner et al., 2008; Cannon et al., 2010). Immediately after a fire, the role of overland flow during rainstorms may become magnified due to loss of vegetation (Wondzell and King, 2003; Parise and Cannon, 2012) as well as changes in soil properties and sediment supply (Woods et al., 2007; Gabet and Sternberg, 2008; Moody and Ebel, 2012). As surface vegetation recovers, occurrence of runoff-initiated debris flows decreases (Wondzell and King, 2003). However, loss of root strength from tree mortality affects deeper soil levels, and may increase susceptibility to landslide-initiated debris flows, which have been documented as
soon as the first intense rain following fire (Cannon et al., 2001) or as long as several decades later (Benda and Dunne, 1997; May and Gresswell, 2003).

Given the role that fires play in increasing a landscape’s susceptibility to debris flows, a key question to be answered is whether fire-related debris flows are fundamentally different from non-fire-related debris flows, particularly with respect to volume, a critical factor from the perspective of natural hazards. Frequency–magnitude (FM) distributions quantify the relative probability of events of various sizes, and thus provide a means for evaluating stochastic natural hazards (Hungr et al., 2008; Finney et al., 2011; Thompson et al., 2011). For many types of natural hazards, small events occur exponentially more frequently than large events, with FM distributions for earthquakes, landslides, debris flows, and wildfires following a power-law distribution (Malamud and Turcotte, 1999; Helsen et al., 2002; Hungr et al., 2008; Jakob and Friele, 2010; Thompson et al., 2011). FM distributions have been used to parameterize local models for non-fire-related debris flow hazard, but parameters vary from region to region, necessitating extensive data collection (Moon et al., 2005; Hungr et al., 2008; Conway et al., 2010; Jakob and Friele, 2010). If the parameters of the global post-fire FM distribution are statistically equivalent to those of the global non-fire-related FM distribution, then the two groups can be regarded as coming from the same population, and predictive models can take advantage of the larger sample size created by combining the two groups. However, if the parameters of the post-fire FM distribution are different from the parameters of the non-fire-related FM distribution, then the two groups come from different populations, and must be assessed separately.

As a first step toward characterizing debris flow hazard and risk, and in light of the fact that FM distributions require a large number of events for parameterization, we have compiled a
global catalog of debris flows, which we augmented via field collection. We use several statistical techniques to compare the samples of post-fire and non-fire-related debris flows to determine whether they come from different populations. Sufficient attribute data were present for an initial analysis of the relationship of initiation mechanism (runoff versus landslide) with volume of debris flows.

2. Methods

2.1. Data acquisition

2.1.1. Catalog of previously researched events

Observations of individual debris flows were compiled into a global catalog from original field observations, unpublished raw observations from other researchers (Sue Cannon, Oldrich Hungr, and Dieter Rickenmann), and previously published studies (Sharp and Nobles, 1953; Doehring, 1968; Scott, 1971; Cleveland, 1973; Morton and Campbell, 1974; Klock and Helvey, 1976; Plafker and Ericksen, 1978; Fairchild and Wigmosta, 1983; Wells, 1987; Wieczorek et al., 1988; Cannon, 1989; Slosson et al., 1989; Pierson et al., 1990; Rickenmann and Zimmermann, 1993; Thurber Engineering and Golder Associates, 1993; McNeeley and Atkinson, 1996; DeGraff, 1997; Vallance and Scott, 1997; Booker, 1998; Cannon et al., 1998; Cenderelli and Kite, 1998; Iverson et al., 1998; Van Steijn, 1999; Meyer et al., 2001; Helsen et al., 2002; Marchi et al., 2002; McDonald and Giraud, 2002; Clague et al., 2003; Conedera et al., 2003; Gartner et al., 2004; Gartner, 2005; Stock and Dietrich, 2006; Gabet and Bookter, 2008; Griswold and Iverson, 2008; Hungr et al., 2008; Santi et al., 2008; Conway et al., 2010; Stoffel, 2010).
In order to be included in this catalog, an estimate of the volume of material transported by the debris flow was required. Volume is the most common parameter chosen to represent magnitude of debris flows (Van Steijn, 1996), and is directly related to the amount of material displaced by the event, as opposed to planimetric area, which may or may not be constrained by topography. Volume estimates were made using several different methods: 1) estimation from the dimensions of the deposit, based on excavation, ground-penetrating radar, and/or GPS (as in some of our field measurements, as well as Cannon et al., 1998; Stock and Dietrich, 2006; Bothe, 2009; Jakob and Friele, 2010; Stoffel, 2010), 2) measurement of the amount of material displaced from gully by a series of cross-sections over the length of downcutting (Cannon, 1989; Van Steijn, 1999; Gartner, 2005; Gabet and Bookter, 2008; Santi et al., 2008), 3) instrument measurement of flow velocity and cross-sectional area of channel (Marchi et al., 2002; Jakob and Friele, 2010), 4) estimates of scarp volume from aerial photos (Cannon, 1989), and 5) amount of material removed by cleanup crews (Cannon, personal communication). Each measurement method has associated error, but we were unable to estimate these errors in either sign or magnitude, and accepted the estimates of previous work as being the best available. Since most measurement methods were used in the samples of both post-fire and non-fire-related debris flows, their effect can be expected to be similar in both samples. Volume was the only required attribute for inclusion in the catalog, but we have included several additional attributes in the catalog when available (e.g. planimetric area of deposit, event date, location, origin/cause, volume measurement methodology, source of debris flow information, whether the debris flow was post-fire, and the name of the associated fire event where applicable).
2.1.2. Field collection

While records of debris flows are rare, records of post-fire debris flows are even more sparse, with the volumes of only 97 events reported in the literature. Because FM distributions require a large number of events for parameterization, additional field collection of post-fire debris flow magnitudes was necessary for this study. We mapped debris flow fan inundation areas in recently burned areas in the Bitterroot, Sapphire, White Cloud, Smoky, and Sawtooth Mountains of Montana and Idaho (Fig. 1). We visited sites as soon after the event as possible, a period which varied from as short as three months to as long as eight years for events that occurred before this study was undertaken. At debris flow sites, we also collected data regarding initiation mechanisms (referenced in the catalog under the “Origin” field). Lithology of debris flow deposits varied by mountain range: in the Bitterroot and Smoky Mountains, primarily granite; in the Sapphires, primarily granite and metagranite; and in the Sawtooths, primarily porphyritic andesite and quartzite.

Field mapping employed kinematic GPS using a Trimble Juno SB. Specifically, we walked the perimeter of each deposit with the GPS unit in the record mode. Perimeter files were corrected using the nearest base station. In order to check the fidelity of debris flow fan areas generated by this method, we selected a subset of four fans in Sleeping Child Creek, and measured these using a series of transects and a tape measure. Area estimates using the two methods were within 10% of each other, except in one case where the transect method missed a narrow lobe of the fan. Santi et al. (2008) cite the expected error when measuring debris flow volumes via GPS as −27% to +37%, but our accuracy appeared to be much higher, perhaps due to improvements in GPS technology. We concluded that the kinematic GPS method was more accurate as well as more efficient than the transect method, and also had the advantage of producing georeferenced polygons which could be used in a GIS for further analysis.
For our field data, conversion of planimetric fan area to debris flow volumes followed Bothe (2009). The gravelly composition of the fans in Laird Creek permitted excavation of the fan material and direct location of the depth at which the new deposit was underlain by a thin organic horizon and older more weathered material. By digging in a number of locations interspersed on the fan, Bothe (2009) produced a mean estimate of depth for five of the fans in Laird Creek where we collected perimeter data; planimetric areas of each fan were multiplied by the mean depth estimate for that fan to produce volume estimates. These average depth estimates ranged from 0.14–0.34 m, with a watershed mean of 0.24 m. For fans in Laird Creek that lacked a direct measurement, the mean depth estimate of 0.24 m was used to produce volume estimates. This coefficient was also used for similar deposits in Warm Springs Creek (fan deposits consisted of primarily gravelly material and were generally not constrained by topography). In Sleeping Child Creek, digging was not possible due to the prevalence of cobble and boulder-sized clasts in the fan deposits, and deposits appeared to be thicker, perhaps due to a more viscous slurry and/or confinement by the narrow valley. Here, we used linear regression of our planimetric area measurements against lower-bound volume estimates produced by measurements of gully morphology by Gabet and Bookter (2008) for the same gullies \((m = 0.6, n = 6, R^2 = 0.55)\). The lower-bound estimate was chosen since it is likely that some material was lost into Sleeping Child Creek during the debris flow event, meaning the fan deposit is smaller than the material displaced from the gully. For deposits in Sleeping Child Creek, planimetric area was thus multiplied by 0.6 m to produce a volume estimate. Notably, this coefficient is almost identical to that produced by linear regression of area and volume figures presented by Cannon et al. (1998) for debris flows following a fire on Storm King Mountain in Colorado. This coefficient was also applied to debris flow fan areas in Rooks Creek, Fourth of July Creek, Rye
Creek, Two Bear Creek, and the Sawtooths, where the clast size distribution of the deposits was similar to that of Sleeping Child Creek and/or debris flows tended to be constrained by narrow valley topography.

Comparing our estimates of volume derived by direct measurements of thickness and area for five debris flows in Laird Creek with volume estimates derived from our model using 0.24 m thickness, errors varied from as low as 1 m$^3$ to as high as 641 m$^3$ (1% to 79%). We expect similar error rates where this model was used, in the remainder of Laird Creek and Warm Springs Creek, with an additional up to 10% estimated error resulting from kinematic GPS measurements of areas. Error rates are difficult to estimate for the other watersheds, where we were not able to collect direct measurements of debris flow thickness. Such uncertainty in volume measurements does not affect FM distributions greatly, since measurements are grouped into bins; for this study, bin sizes were 10,000 m$^3$, and multiplying most debris flow volumes collected for this study by ±79% would not change the subsequent bin assignment, since most volumes are less than 300 m$^3$. In addition, unless this method systematically over- or under-estimated volumes, the net effect of error on the slope of the FM distribution would be small.

2.2. Statistical methods

In order to compare the distribution of post-fire debris flow volumes with that of non-fire-related debris flows, we divided events into two categories: those that occurred in recently-burned areas and those that did not. Volume data were explored graphically, using boxplots and regional groupings.
For both categories, debris flow $FM$ distributions were compiled from the catalog. Robust regression was performed on the data in log-log space, using the Kendall’s Tau statistic, which is more robust to outliers than traditional linear regression methods and does not assume normality of residuals (Sen, 1968). We used the median volume for each frequency as the dependent variable as in Finney et al. (2011), which reduced the disproportionate effect of the rarest largest events on the slope coefficient, and produced a better fit with more frequently occurring event sizes. The slope parameter quantifies the ratio of small to large debris flows (Finney et al., 2011), and thus is the parameter of interest in this project. The intercept parameter is of little interest in this study, since it is strongly influenced by sample size; larger $y$ values are generated by larger sample sizes. To evaluate the similarity of the slope parameter of the post-fire debris flow $FM$ distribution to that of non-fire-related debris flows, we calculated a 95% confidence interval around the slope parameters.

In addition, the empirical cumulative distribution functions (ECDFs) of volume for post-fire and non-fire-related debris flows were compared. We computed the nonparametric test statistic $D$, the maximum separation distance between the two distributions. As $D$ increases, so does the likelihood that the two distributions are different. The Kolmogorov–Smirnov test was used to determine the likelihood that the ECDF of post-fire debris flows is different from that of non-fire-related debris flows, based upon $D$.

3. Results

3.1. Field collection
In the field, we collected volume measurements of recent debris flows in 77 zero-order drainages at the sites shown in Fig. 1 and Table 1. Of these debris flows, only three were not related to wildfires. Debris flows occurred in clusters in several watersheds; these clusters appear to be due to the conjunction of two events: a wildfire of moderate to high severity and a localized rainstorm. The upper third of zero-order watersheds that produced debris flows generally had experienced high tree mortality following wildfire, likely resulting in increased overland flow during storms. From observations of rejuvenated rill networks and available rainfall records, we determined that all 74 post-fire debris flow events were initiated by intense precipitation within 1–2 years of a wildfire, which led to overland flow, rilling, and mobilization of material in the gully, in other words, runoff initiation. Physical evidence for runoff initiation consisted of a sudden transition from rill to a gully head with abrupt downcutting, as well as the absence of a discrete scarp (Fig. 2). Data were insufficient to reconstruct rainfall that initiated some debris flows, but where precipitation data were available from a nearby station, recurrence intervals for storms related to these debris flows had a less than 2- to 25-year recurrence interval (Parrett et al., 2004).

Recent deposits are visibly less weathered than the paleofan, and lack lichen and vegetative cover. It is possible that several recent debris flows have occurred in an individual gully, and are superposed. We were not able to differentiate multiple recent debris flow deposits from pulses within a single debris flow, and found evidence of multiple surges in the form of lobes perched atop the main deposit. At Sleeping Child Creek, we concluded that in some cases tributary gullies failed after the main gully, but during the same storm. It was not possible, however, to determine whether the time interval between failures was seconds, minutes, or hours. Superposition of recent debris flow deposits is a potential source of error in the catalog as
a whole. It is uncertain whether errors of this type would occur with the same frequency in the post-fire and non-fire-related populations. We assume here that each recent deposit was generated during a single storm. The combined volume at the end of the storm is arguably the best estimation of hazard and impact to highly valued resources, and might still be considered a single “event” since it was generated during a single storm.

A debris flow site typical of our study area is shown in Fig. 3: a rejuvenated gully leading to a poorly-sorted non-stratified deposit, often with levees present. Deposits consisted of a sandy matrix, with clasts ranging from sand to cobble or boulder (Fig. 4). Some valley floors, such as Rye Creek of the Sapphire Mountains and nearby Laird Creek in the southern Bitterroot Mountains, are formed entirely from a sequence of alternating debris flow fans and paleofans (Fig. 5).

3.2. Statistical analyses of debris flow volumes in the catalog

The 77 debris flows measured during this study were combined with those from the literature to form a catalog of 988 events. The catalog can be accessed through Pangaea at http://doi.pangaea.de/10.1594/PANGAEA.783654. Fig. 6 shows the geographical distribution of debris flows by nation. Canada, France, Switzerland, and the USA are the only nations to have over 50 records of debris flow volumes. No records are present in the catalog for Asia, Africa, or Australia, which of course does not suggest that these areas do not experience debris flows, only that debris flow volume data have not been published or not accessible to us partly because of linguistic barriers. Even with our effort to augment the sample of post-fire debris flows via field collection, it was smaller than that of non-fire-related debris flows ($n = 264$ vs. $n = 724$). Given
the limitations of this dataset, statistical analyses in this manuscript must therefore be considered a first step toward hazard and risk modeling of debris flows, and understanding of differences and similarities in the size distributions of post-fire and non-fire-related debris flows.

Debris flow volumes in the catalog spanned 10 orders of magnitude. Volumes in the same region are generally more similar to one another than to volumes at other locations, but volumes vary as much as four orders of magnitude even within the same location (Table 2; Fig. 7). This regional similarity may be a result of the topography (e.g. difference in elevation from ridge to valley floor, slope, and/or basin length), geology, disturbance history (e.g. fire-prone versus non-fire-prone ecosystem), and/or climate (e.g. size of the characteristic storm of the area, temperature ranges). The Wasatch is the only region with a number of both post-fire and non-fire-related debris flows recorded, and there the median post-fire debris flow is larger than the median non-fire-related debris flow. However, we lack information on basin geometry, storm rainfall that precipitated these debris flows, geology, etc. at these Wasatch sites, and cannot attribute this difference to recent burning.

The global size distributions of post-fire debris flows and non-fire-related debris flows showed some notable differences. The median volume of post-fire debris flows was smaller than that of non-fire-related debris flows, with the largest of the latter in the catalog being three orders of magnitude larger than the largest post-fire debris flow (Fig. 8, Table 3). To test whether the lack of large events among post-fire debris flows could be a result of the smaller sample size, since large events are extremely rare, we took a random sample from the non-fire-related debris flows of the number as the post-fire debris flow sample \((n = 264)\), and compared the size of the largest events. In 98 of 100 samples, the largest non-fire-related debris flow was still larger than
the largest post-fire debris flow, suggesting that catalog completeness is not the source of differences in the size distribution.

The slope of the $FM$ distribution of post-fire debris flows is steeper than that of non-fire-related debris flows (Fig. 9, Table 3). The 95% confidence intervals around the two slope parameters do not overlap, signifying that the two parameters are significantly different (Fig. 10), and meaning that the ratio of large to small debris flows is different for the two categories, with a higher proportion of small events occurring in the post-fire debris flow sample.

Another method for comparing two distributions is to plot the ECDFs. The ECDF of post-fire debris flows generally plots to the left of the ECDF of non-fire-related debris flows (Fig. 11), signifying that post-fire debris flows tend to consist of more smaller volumes. The maximum separation between the two distributions, or $D$, was equal to 0.1. The Kolmogorov–Smirnov test was used to test the hypothesis that post-fire debris flows tend to be smaller, yielding a p-value of 0.02. This means that the likelihood of a separation distance that is large or larger occurring by chance in a random sample, if indeed the two distributions are from the same population, is approximately 1 in 50. This result constitutes strong evidence that the distribution of post-fire debris flow volumes is composed of smaller values than that of non-fire-related debris flows.

Initiation mechanism was reported for 422 debris flows in the catalog, or 43%. Of those debris flows, runoff is the most common initiation mechanism for both non-fire-related ($n = 199$, or 63%) and post-fire debris flows ($n = 90$, or 87%). Landslides are the second most common initiation mechanism in both groups, with 90 non-fire-related debris flows (28%) and 14 post-fire events (13%) initiating this way. Of non-fire related debris flows, 15 (5%) are known to have initiated through the firehose effect and 14 (4%) through rockfall. This result is consistent with previous studies, which observed that the most prevalent initiation mechanism for post-fire
debris flows in the U.S. Interior West is runoff (Spittler, 1995; Hyde et al., 2007; Santi et al., 2008).

Runoff-initiated debris flows tended to be larger and less variable in volume than those initiating through landslides (Fig. 12). The median volume of runoff-initiated debris flows was 1951 m$^3$, in contrast to 279 m$^3$ for those that initiated through landslides. The largest volumes for runoff-initiated debris flows were recorded by Van Steijn (1999) in the French Alps ($n = 198$); debris flows in the Alps tend to have larger volumes than most other areas (Fig. 7). When runoff-initiated debris flows are further grouped into post-fire and non-fire-related events, post-fire events are smaller (Fig. 13). These results demonstrate that initiating mechanism does not account for the differences in volumes between post-fire and non-fire-related samples.

In summary, these statistical analyses indicate differences in magnitudes of post-fire and non-fire-related debris flows, independent of initiation mechanism. The ECDF of volumes of post-fire debris flows differs from that of non-fire-related debris flows, as does the slope of the $FM$ distribution, indicating that small debris flows occur more frequently in the post-fire sample.

4. Discussion

Two major contributions of this manuscript are: 1) compilation of the first global catalog of debris flows, and 2) statistical analyses suggesting that the size distributions of post-fire and non-fire-related debris flows are different. However, these efforts constitute only a first step toward hazard and risk modeling at global scales due to the low number of debris flow volumes compiled from the literature and lack of attribute data on many important drivers of debris flow volume (e.g. topography, climate, weather, and geology). We see an analogy between debris flow and earthquake catalogs. Prior to the 1950s, the seismograph network was small;
correspondingly, records of earthquakes were relatively few, and it was thus difficult to characterize earthquake risk. For the past several decades, the seismograph network has been extensive enough to capture all earthquakes globally, resulting in sufficient records to parameterize the $FM$ distribution of earthquakes at the global scale. The state of the current debris flow catalog, particularly that in English, is not dissimilar to that of earthquakes in the 1950s. Despite the small number of records of debris flow magnitudes, it is evident that moderate- and high-severity wildfire increases the probability of debris flows by increasing their frequency through a suite of changes in vegetation, soil characteristics, and sediment supply. By removing vegetation, adding ash, and producing changes in the soil surface, fires decrease the stability of zero-order watershed systems and make them more prone to debris flow activity. As evidence, we rely on our field observations as well as previous research demonstrating that relatively small storms (e.g. with a 2-year return interval; Parrett et al., 2004; Cannon et al., 2010) can provoke debris flows in recently burned basins while nearby unburned basins do not experience debris flow activity.

However, post-fire debris flows tend to be smaller. We expect that in most fire-prone environments, sediment transport is supply-limited. Once fire removes vegetation, dry ravel can dramatically accelerate, moving material into gullies, where it can be mobilized by overland flow when a storm occurs (Bennett, 1982, as cited in Wondzell and King, 2003). Sediments that were stable when retained by live and dead vegetation now roll downhill under the influence of gravity (Gabet, 2003b). Once in the gully, gravel, cobbles, and boulders can be mobilized by a slurry of overland flow during fairly short-return-interval (~2 yrs) storms. Once the gully is empty and sediments have been mobilized, repeat debris flows at the same site are unlikely in the short term (unless additional side channels fail during future storms).
This change in frequency and magnitude relations in the post-fire regime can be attributed to either or both of the two components prerequisite to the generation of runoff-initiated debris flows: overland flow and fine-grained sediment. Both components increase in the post-fire environment. More overland flow occurs during intense storms due to: 1) decreased rainfall interception by vegetation, resulting from mortality of the overstory and consumption of live and dead vegetation by fire, with removal of vegetation increasing with fire severity (Wondzell and King, 2003; Campbell et al., 2007; Parise and Cannon, 2012); 2) surface roughness may decrease due to consumption of litter and duff layers, removing impediments to runoff (Lavee et al., 1995); 3) where ash overlays coarse soils, infiltration is reduced due to the small grain size of the ash particles (Gabet and Sternberg, 2008; Woods and Balfour, 2010; Gabet and Bookter, 2011); and 4) extent of hydrophobic soil and/or hyperdryness sometimes increase following fires, although their spatial pattern is generally discontinuous enough to allow infiltration (Woods et al., 2007; Moody and Ebel, 2012). Availability of fine-grained sediments increases following fire due to several factors: 1) vegetation has been converted to ash, which is abundant following high-severity fire (Gabet and Sternberg, 2008); 2) consumption of litter and duff exposes underlying soil; and 3) fire can break down soil aggregates (Spittler, 1995; Wondzell and King, 2003; Roering and Gerber, 2005); 4) pH of debris flow fluid can be increased by ash, which can cause dispersion of clay compounds and thus facilitate their entrainment (Gabet and Bookter, 2011). In addition, the bulk density and viscosity of runoff can be increased by the incorporation of ash (Burns, 2007; Gabet and Sternberg, 2008), which enables it to entrain more sediment and prevents positive pore pressures from dissipating. These changes allow runoff-initiated post-fire debris flows to occur in smaller zero-order drainage
basins during smaller precipitation events than in unburned environments, increasing the proportion of small debris flows following fires.

Changes in the post-fire environment also increase initiation of debris flows by landsliding in some areas, due to increased soil saturation and decreased strength of regolith. However, these factors also apply to debris flow initiation by landslides. Soil saturation during long-duration low-intensity storms can increase following fires, especially those of moderate/high severity due to: 1) mortality of trees, shrubs, and herbaceous plants leads to decreased evapotranspiration, increasing soil moisture and decreasing the amount of infiltration necessary for saturation (Swanson, 1981; Wondzell and King, 2003); and 2) interception by canopy, understory, litter and duff layers is reduced (Dunne and Leopold, 1978 as cited in Gabet and Sternberg, 2008), making more water available for infiltration. A second factor is that the strength of the regolith is reduced due to vegetation mortality, causing a loss of root strength. We hypothesize that because debris flows can occur in response to smaller perturbations (e.g. smaller storms) due to changes in the post-fire environment or in smaller hollows where elevated subsurface flow is concentrated, the frequency of small debris flows increases after fires.

In the catalog as well as our field research, all post-fire debris flows in the U.S. Interior West were initiated by runoff within 0-5 years of fire, while post-fire debris flows near the U.S. West Coast initiated by either landslides or runoff. This pattern is likely due to characteristics of precipitation: in the Interior West, summer convective storms are common, and can generate high enough precipitation rates to produce overland flow (Wondzell and King, 2003). Summer convective storms can occur near the West Coast as well. Although long-duration low-intensity storms that can produce saturation-induced debris flows are not common in the Interior West, they do occur on the West Coast.
The level and patterning of fire severity within a watershed adds a source of variability to the magnitude of debris flows generated therein. For most post-fire debris flows in the Northern Rockies, the majority of material comes from rilling of hillslopes (Cannon et al., 2001) or gullies (Parrett et al., 2004; Santi et al., 2008), rather than soil-slip scars, so we expect that the location of rill and gully rejuvenation is important in determining debris flow volume, with more material available for entrainment if the debris flow initiates higher in the watershed. Where more material is removed in the upper reaches of a catchment by high severity fire, we expect that gully rejuvenation will occur higher in the watershed, increasing the runout length, and the amount of material entrained.

This study entails large formal and informal uncertainties driven largely by the small sample size. However, we do not expect that uncertainty in debris flow volume estimation significantly affects our results, since $FM$ distributions are fairly robust to such uncertainty, due to binning of observations. Augmentation of the catalog will require further data collection or cooperation of additional researchers. While literature review supports the conclusion that this catalog is currently the most complete record of debris flow magnitudes, it is only marginally sufficient for parameterizing $FM$ distributions. For example, if we omit debris flows that followed the Station Fire ($n = 94$) from our analysis, then the confidence intervals of the slope parameters of the two $FM$ distributions overlap. Given the limited sample size and the lack of attribute data on topography, precipitation, time since last debris flow, sediment generation rates, and fire severity, we could not examine the interaction of these driving factors in producing predictions of debris flow volume. We also noted that some geographic areas were better-represented than others in our catalog; despite efforts to contact researchers, we were not able to obtain data for debris flows in Asia, Australia, or Africa, partly because of linguistic barriers.
Some geographic areas were represented only by post-fire or non-fire-related debris flows, but not both, e.g. all debris flows except three in the Rockies and Southern California are post-fire, while all debris flows in Hawaii, British Columbia, and the Alps are non-fire-related, with the exception of one post-fire debris flow recorded by Conedera et al. (2003).

Despite inherent error and challenges presented by small sample sizes, the catalog and associated statistical analyses provide a first step in global hazard modeling of debris flows. As a possible starting point for future research, we propose two alternate and non-exclusive hypotheses to explain why post-fire debris flows tend to be smaller than non-fire-related debris flows. First, smaller storms or effective drainage areas can trigger debris flows because of the increased generation of overland flow, in the case of runoff-initiated debris flows, or decreases in root cohesion, in the case of landslide-initiated debris flows. These changes result in a higher probability of failure and smaller debris flow volumes. Second, debris flow volumes in most environments are limited by the supply of available loose material; we expect that fire increases the probability and frequency of debris flows, causing post-fire debris flows to be smaller because less sediment is available in each event.

5. Conclusions

Based on our catalog of 988 events, post-fire debris flows tend to be smaller than non-fire-related debris flows. For post-fire debris flows, the slope of the $FM$ distribution is steeper, meaning that the ratio of small to large events is higher than in unburned areas, indicating that small debris flows occur with higher proportional frequency. Fire produces a number of changes in vegetation and soil characteristics that increase overland flow, available sediment, and soil
moisture, as well as decreasing the strength of the regolith; we propose that these changes increase the proportional frequency of small debris flows, and produce debris flows in small zero-order drainage basins not susceptible to debris flows under unburned conditions. In regions where sediment transport is supply-limited, wildfire provokes smaller debris flows by increasing their probability and frequency. Models for hazard prediction of post-fire debris flows therefore should be parameterized separately from non-fire-related debris flows, and will likely include different predictor variables.

Acknowledgements

This study was funded in part by a Geological Society of America Graduate Student Research Grant and a University of Montana Transboundary Research Award to Karin Riley. This work was also funded in part by the U.S. Forest Service’s Rocky Mountain Research Station and Western Wildland Environmental Threat Center. We are grateful for intrepid off-trail field help at the mercy of wasps and bears, from Davis Bothe, Esther Bowlin, Brian Elling, Dan Hoffmann, Morgan Hyde, Chuck Irestone, Jack Kehoe, Solmaz Mohadjer, and Warren Roe. We appreciate collaboration with Sue Cannon, Anna Klene, and Henk van Steijn throughout this project, as well as constructive review of this manuscript by Isaac Grenfell. Sue Cannon, Oldrich Hungr, Dieter Rickenmann, and Henk van Steijn generously provided extensive unpublished datasets that are included in the catalog.
References


Table captions

Table 1. Sites where debris flow data were collected in the field for this study. Likely dates of debris flows were based on: 1) US Geological Survey precipitation stations, as reported by Parrett et al. (2004), or 2) local newspaper reports (Wutz, 2010), as indicated by superscripts. Peak 5-minute precipitation intensity and recurrence interval were derived from precipitation data in Parrett et al (2004). Three-hour total precipitation was recorded by nearby NEXRAD stations. Initiation mechanism was based on field observations during this study.

Table 2. Location name, code, description, source literature, number of debris flows, and whether debris flows were post-fire, for locations in Fig. 7. “This study” means debris flow data were collected for this study.

Table 3. Selected statistics for post-fire and non-fire-related debris flow volumes. Volumes are in m$^3$. 
Figure captions

Fig. 1. Field sites for debris flow fan dimensions collected for this study. Mountain ranges where debris flows were mapped during this study are shown in gray and Italic, with the total number of debris flows occurring in that mountain range noted. Clusters of debris flows occurred in some watersheds, and these are titled in black, with the number of debris flows in that watershed given. Note that the number of debris flows occurring in a watershed is also included in the total amount for the corresponding mountain range; for example, all debris flows mapped in the Bitterroot Mountains (\( n=18 \)) occurred in Laird Creek (\( n=18 \)). Clusters of debris flows were likely produced by the conjunction of a recent high severity burn and intense localized rainfall. Relevant fire perimeters are shown in orange.

Fig. 2. Abrupt transition from rill to gully head as physical evidence for runoff initiation. Note abrupt downcutting on the order of 0.8 m. Gully head is finger-shaped. Scarp indicating landsliding is absent.

Fig. 3. Post-fire debris flow in the Fourth of July Creek drainage in the White Cloud Mountains. Note the rejuvenated gully in the background, and the levees at lower left and middle right.

Fig. 4. Detail of fan deposit in Rye Creek in the Sapphire Mountains of Montana, representing a typical deposit for the region. Note size distribution of clasts, from cobble to sand.

Fig. 5. Photograph showing topography typical of the Sapphire and southern Bitterroot Mountains, where a cluster of debris flows occurred following the extensive fires of 2000. Three paleofan perimeters are roughly outlined in yellow. One of the recent debris flows entered the backyard of the house shown in this photo, which is built atop a much larger paleofan. A second fan is visible at right. From the vantage point of this photo, taken from atop a third debris flow fan, it is evident that alternating debris flow fan/paleofan deposits define the topography of the valley floor as well as the course of Laird Creek (stream course shown in blue). Debris flow events occurred following the fires of 2000 atop each of these three paleofans, but fan boundaries were already obscured by regrowth of vegetation by the time this photo was taken in 2008.

Fig. 6. Geographical distribution of debris flows in our catalog, by nation.

Fig. 7. Debris flow volumes, grouped by location. Only locations with more than five debris flows are shown in this figure. Specific locations were known for some debris flows (e.g. Sleeping Child Creek), while only general locations were known for others (e.g. Switzerland). The highest degree of specificity was retained in this graph, resulting in some groupings being broader geographically than others. Post-fire debris flows are plotted in red. Location codes identify these debris flows in the catalog.

Fig. 8. Boxplots of volumes of post-fire and non-fire-related debris flows.

Fig. 9. Frequency–magnitude distribution of post-fire and non-fire-related debris flows.
Fig. 10. 95% confidence interval of slope parameters of the frequency–magnitude distribution for post-fire and non-fire-related debris flows.

Fig. 11. Empirical cumulative distribution functions (ECDFs) of post-fire and non-fire-related debris flow volumes.

Fig. 12. Boxplots comparing the volume of debris flows initiating through landslides (“L”, $n = 104$) to those initiating through runoff (“RO”, $n = 383$).

Fig. 13. Boxplots comparing runoff-initiated debris flow volumes, for non-fire-related ($n = 199$) and post-fire events ($n = 184$).
Table 1.

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Figure 1
Figure 5
Figure 6
Figure 7
Figure 8
Figure 9
Figure 10
Figure 11
Figure 13