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Debris-flow volume quantile prediction from catchment morphometry

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ABSTRACT

Estimation of the volumes of potential future debris flows is a key factor in hazard assessment and mitigation. Worldwide, however, there are few catchments for which detailed volume-frequency information is available. We (1) reconstructed volume-frequency curves for 10 debris-flow catchments in Saline Valley, California (USA), from a large number of well-preserved, unmodified surficial flow deposits, and (2) assessed the correlations between lobe-volume quantiles and a set of morphometric catchment characteristics. We found statistically significant correlations between lobe-volume quantiles, including median and maximum, and catchment relief, length (planimetric distance from the fan apex to the most distant point along the watershed boundary), perimeter, and Melton ratio (relief divided by the square root of catchment area). These findings show that it may be possible to roughly estimate debris-flow lobe-volume quantiles from basic catchment characteristics that can be obtained from globally available elevation data. This may assist in design-volume estimation for debris-flow catchments where past flow volumes are otherwise unknown.

INTRODUCTION

Debris flows are dense masses of sediment and water that are common in mountainous terrain, and they can create low-gradient (<15°) sediment fans through repeated deposition over time. Such debris-flow fans are preferred locations for development in many mountainous regions (Jakob et al., 2005). Estimation of both past and potential future flow volumes on fan surfaces is critical for assessment of flow hazard and design of mitigation measures, because flow volume is a prime control on flow velocity, peak discharge, and inundation area (e.g., Iverson et al., 1998; Rickenmann, 1999; Griswold and Iverson, 2008). A global analysis of debris-flow hazards between 1950 and 2011 showed that the number of fatalities increases exponentially with flow volume (Dowling and Santi, 2014). Ideally, we should know the full flow volume–frequency distribution, because maximum volumes are relevant for hazard assessment, while median volumes are relevant for sediment budget estimation (Bovis and Jakob, 1999).

Worldwide, however, there are very few catchments for which detailed volume-frequency information is available (e.g., Jakob and Friele, 2010; Bennett et al., 2014). The debris-flow volume reaching a fan depends on the amount of sediment available and the potential of the flow to mobilize and transport this sediment, and it is thus a function of catchment morphometry, morphology, and geology as well as hydroclimatic conditions (e.g., Hungr et al., 1984; Bovis and Jakob, 1999). In most systems, debris, rather than water, availability is the dominant control on flow volume (e.g., Jakob and Bovis, 1996; Bovis and Jakob, 1999). Many researchers have therefore attempted to correlate debris-flow volume with morphometric catchment characteristics, predominantly catchment area and slope and channel length (e.g., Hungr et al., 1984; Jakob and Bovis, 1996; Marchi and D'Agostino, 2004; Ma et al., 2013). A major shortcoming of these correlations is that they are based on only one to a few debris flows per catchment, inhibiting estimation of key flow-volume quantiles such as the median and maximum. It has been difficult to overcome this issue because of both the brevity of observational records relative to typical debris-flow return periods and the difficulty of determining flow volume directly, even in well-instrumented catchments with frequent flows (Schürch et al., 2011).

Fan surfaces are a potential archive of volume information for a large number of flows (e.g., Jakob et al., 2016). Debris flows deposit sediment levees and lobes (e.g., Blair and McPherson, 2009), the dimensions of which may scale with the volume or peak discharge of the flow (Berti and Simoni, 2007). Unfortunately, debris-flow deposits are often reworked by postdepositional sediment transport processes or buried by subsequent flows, both of which obscure the original deposit dimensions and hinder volume estimation (e.g., Jakob and Bovis, 1996; Blair and McPherson, 2009; de Haas et al., 2014). In addition, large debris flows tend to spread out to form multiple lobe deposits, making it difficult to reconstruct the entire flow volume, especially if parts of the deposit are later reworked. As a result, the links between fan deposits, flow-volume quantiles, and the potential controls on flow volumes have not yet been comprehensively explored.

Here, we used the surfaces of 10 remarkably well-preserved debris-flow fans in Saline Valley, California (USA), which host numerous unmodified flow deposits, to (1) create lobe volume–frequency curves from hundreds of well-preserved surficial debris-flow deposits, and (2) assess the correlation between lobe-volume quantiles and a set of morphometric catchment characteristics, in order to explore and develop a method for debris-flow design-volume estimation.

STUDY AREA

Saline Valley is a closed extensional basin located at the boundary between the Mojave and Great Basin Deserts in southeastern California (Fig. 1). The southern and western valley margins host a series of well-exposed debris-flow fans that have developed in response to accommodation generation by slip on the Hunter Mountain and Saline Valley faults (Oswald and Wesnousky, 2002). We focused on 10 of those fans that preserve abundant debris-flow deposits with clear primary flow features and negligible secondary modification.

Eight fans, S01–S08, originated from the Nelson Range in the southern part of the valley (Fig. 1). The Nelson Range is underlain by the Early Jurassic Hunter Mountain quartz monzonite batholith (Oswald and Wesnousky, 2002). Fan S03 was fed by two subcatchments, each of which contributed sediment to a separate part of the fan surface. We treated those two subcatchments and their corresponding fan surfaces as individual systems in the analyses presented here.

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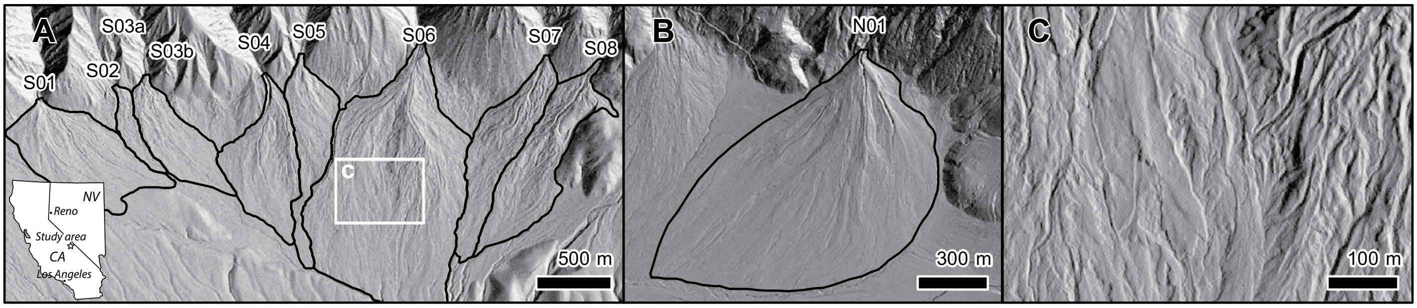

Figure 1. Debris-flow fans studied in this work. A: Fans S01–S08, on the southern margin of Saline Valley (California, USA). Fan apex of S05 is located at 6°34′28.85″N, 117°38′20.06″W. B: Fan N01, on the northern margin of Saline Valley. Fan apex is located at 36°49′31.66″N, 117°55′21.73″W. C: Detail of well-preserved debris-flow deposits on the surface of fan S06. NV—Nevada; CA—California.

A ninth debris-flow fan, N01, originated from the Inyo Mountains in the northern part of Saline Valley (Fig. 1). The catchment of this fan consists mostly of Paleozoic marble, quartzite, and chert with a small area of quartz monzonite in the catchment headwaters (Conrad and McKee, 1985).

Saline Valley is located in the rain shadow of the Sierra Nevada and Inyo Mountain ranges to the west, with mean annual precipitation of 100–200 mm (PRISM Climate Group, 2015). Historical records in nearby Owens Valley show that recent debris flows in the region have been predominantly triggered by high-intensity summer rainstorms (e.g., Beaty, 1963; Blair and McPherson, 1998).

DATA COLLECTION AND ANALYSIS

We estimated debris-flow lobe volumes from a gridded lidar data set with 0.5 m horizontal cell size (Fig. DR1 in the GSA Data Repository[1]), collected in April 2007 by the National Center for Airborne Laser Mapping (NCALM, University of Houston, Texas, USA). Debris-flow lobe deposits were manually identified and mapped using hillshade, curvature, and local slope maps (cf. Staley et al., 2006; Roering et al., 2013), cross-checked by field measurements in September 2017 (Fig. DR2). Lobe thickness, h (m), was measured by defining the maximum thickness of a lobe extracted from elevation cross- and long-profiles, assuming a planar bed underneath the lobe deposits (Fig. DR1). Lobe width, w (m), was defined as the maximum width of the lobe deposit. The cross-sectional area of each debris-flow lobe, A_l (m^2), was then calculated by assuming a trapezoidal cross section (cf. de Haas et al., 2015):

$$A_l = 0.75hw. \tag{1}$$

We assumed a conservative uncertainty on A_l of 50%, accounting for variation between triangular and rectangular cross sections and deviations from a planar bed. Iverson et al. (1998) and Griswold and Iverson (2008) showed that the cross-sectional area of a debris flow is a semi-empirical function of its total volume V (m^3):

$$A_l = \varepsilon V^{2/3}. \tag{2}$$

Based on 15 recent nonburied debris flows, we found $\varepsilon \approx 0.1$ for the Saline Valley fans ($R^2 = 0.82$; Fig. DR3), similar to the ε found by Griswold and Iverson (2008) for 50 nonvolcanic debris flows worldwide. The estimated debris-flow volumes are accurate within a factor 2 (Fig. DR3). For our calculation, we assumed $\varepsilon = 0.1 \pm 0.025$. We used Equation 2 to convert the measured cross-sectional areas to total lobe volumes, propagating the errors in A_l and ε.

Direct measurement of total flow volumes is generally not possible for all but the most recent flows due to burial by more recent deposits. For the same reason, we typically cannot identify whether individual flows deposited one or multiple lobes. Note that the volume of the largest debris flows, which are most likely to have formed multiple lobes, may thus have been underestimated (e.g., Blair and McPherson, 1998; de Haas et al., 2016, 2018).

We compared the inferred debris-flow lobe volumes to a wide range of morphometric catchment characteristics (Table 1). The lidar data set does not cover the full fan catchments, and therefore we used Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) Global Digital Elevation Model (GDEM) data to infer these catchment characteristics. This elevation data set is globally available and has a 30 m horizontal resolution, ensuring worldwide applicability but limiting our analysis to simple catchment characteristics. We assessed the correlations between catchment characteristics and the 25, 50, 75, and 99 percentiles and maximum lobe-volume quantiles through linear regression.

RESULTS

The number of individual debris-flow lobe deposits identified on the fans ranged from 84 on fan S03b to 851 on fan S06 (Fig. 2). The smallest reconstructed median debris-flow lobe volume, 140 ± 55 m^3, was found on fan S03b. The largest median lobe volume, 830 ± 330 m^3, was found on fan S04. The reconstructed maximum lobe volumes ranged from 4400 ± 1750 m^3 on fan S02 to 92,000 ± 37,000 m^3 on fan S07. The volume distribution curves highlight the variation in the lobe volumes on a single fan, which can vary by four orders of magnitude.

Overall, median lobe volume is the quantile that showed the best correlation with catchment characteristics (Fig. 3). Statistically significant correlations ($p < 0.05$) were found between median lobe volume and catchment area, relief, length, perimeter, and Melton ratio (Table DR1). The goodness-of-fit (R^2) of these correlations ranged between 0.39 and 0.51, where Melton ratio performed the best. Statistically significant relations were also found between maximum lobe volume and catchment relief, length, and perimeter, while the relation with Melton ratio was close to significant with $p = 0.07$. Catchment perimeter, length, relief, and Melton ratio generally showed statistically significant correlations with most other lobe-volume quantiles, and where correlations were statistically insignificant, the p values were nonetheless still typically smaller than 0.1.

We found no statistically significant correlations and poor goodness-of-fit values, generally below 0.20, between lobe-volume quantiles and mean catchment slope, relief ratio, form factor, elongation ratio, and circularity index (Table DR1).

TABLE 1. MORPHOMETRIC CATCHMENT CHARACTERISTICS

Catchment attribute	Dimensions	Symbol and definition
Area	m^2	A_c
Relief	m	H_c
Length	m	L_c
Perimeter	m	P_c
Mean slope	degrees	S_c
Melton ratio	–	$M_r = H_c/\sqrt{A_c}$
Relief ratio	–	$R_r = H_c/L_c$
Form factor	–	$F_f = (A_c/L_c)^2$
Elongation ratio	–	$E_r = (4A_c/\pi)/L_c$
Circularity index	–	$C_r = 4\pi A_c)/P_c$

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[1] GSA Data Repository item 2019278, supplemental Figures DR1–DR4 and Table DR1, is available online at http://www.geosociety.org/datarepository/2019/, or on request from editing@geosociety.org.

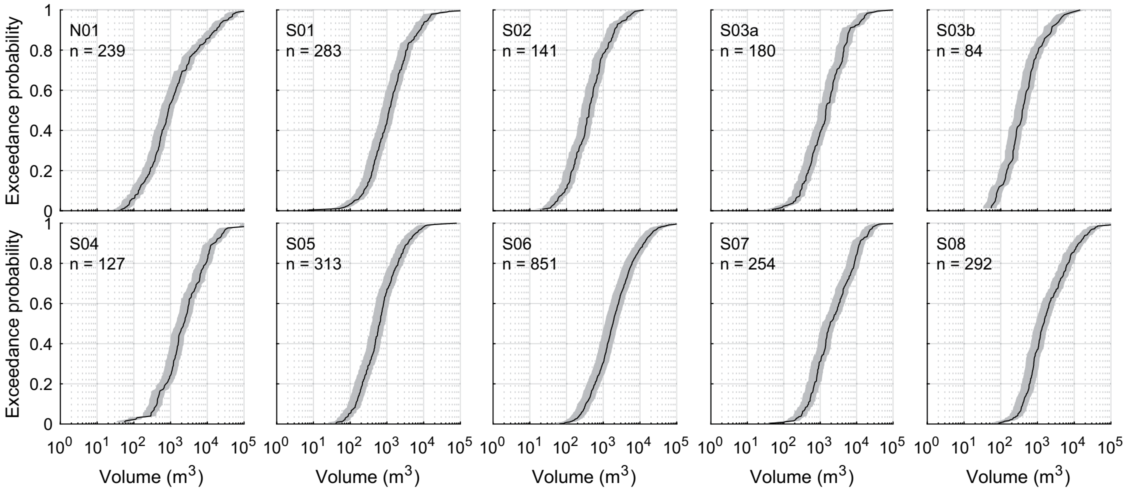

Figure 2. Cumulative lobe volume–frequency distributions for each studied fan in Saline Valley (California, USA). Gray bands indicate volume error range.

Our data set showed two outliers in the relationships between lobe volume and catchment area, relief, Melton ratio, perimeter, and length, corresponding to the two smallest watersheds, S02 and S03b (Fig. 3). These outliers had relatively small lobes, which for maximum volume were almost one order of magnitude lower than would be expected based on the correlations with catchment characteristics.

Based on our very limited sampling, differences in catchment lithology did not seem to affect the lobe volume–catchment characteristic relationships in our data set. The flow volumes on fan N01, with a catchment that consisted predominantly of metasedimentary rock, followed similar relationships with catchment characteristics as those fed from the quartz monzonite catchments (Fig. 3).

DISCUSSION

Our results show that, at least in climatically and tectonically similar areas, it may be possible to predict debris-flow lobe-volume quantiles, including median and maximum, based on catchment relief, perimeter, length, area, and Melton ratio. These findings may assist in debris-flow hazard assessment and mitigation where data on lobe or flow volumes are otherwise unknown, which holds true for the vast majority of catchments. Moreover, our findings may help to estimate sediment budgets where such data are otherwise unavailable (Bovis and Jakob, 1999). Although our data do not show how climatic and lithological conditions may affect lobe-volume quantiles, we suggest that, where the flow-volume distribution of a debris-flow system is known, flow-volume quantiles in neighboring catchments may be reasonably estimated based on a catchment relief, perimeter, length, area, or Melton-ratio correction.

Several studies have used catchment characteristics to discriminate between the likely predominance of debris-flow and streamflow sediment transport. In particular, catchment area (e.g., de Scally and Owens, 2004), length (e.g., Wilford et al., 2004), and Melton ratio (e.g., Bertrand et al., 2013) have demonstrated utility in discriminating the formative fan process. Not surprisingly, these are the same catchment characteristics as those found here to be capable of predicting debris-flow lobe-volume quantiles.

So why do these catchment characteristics determine process and lobe volume? Debris-flow volume is a function of two elements: (1) the volume of the initiating failure or failures, and (2) the volume changes, by entrainment and deposition, along the transport path (Jakob et al., 2005). In the simplest case, debris flows may initiate on the steep slopes of the upper catchment, after which they can grow in volume by eroding sediment while traversing through the catchment to finally deposit on the fan. As such, for a given initial failure volume, the flow volume entering a fan depends on the erosional potential of the debris flow and the amount of material available for entrainment (e.g., Jakob et al., 2005). The entrainment rate at the base of a debris flow likely increases with bed slope (e.g., Iverson and Ouyang, 2015), and therefore flow volume is likely to increase with catchment relief (Fig. 3). Similarly, traversal of larger distances by a debris flow through steep channels in a catchment results in larger potential for net entrainment (assuming that sufficient bed sediment exists and that its density and saturation are sufficient to promote entrainment; Iverson, 2012) and larger flow volume. This may explain the increasing flow-volume quantiles with catchment area, perimeter, and length (Fig. 3). One should note, however, that these effects are partly damped because the average catchment gradient decreases with catchment area. Similarly, catchment length, perimeter, and relief are strongly related and increase logarithmically with basin area, and the square-root of catchment area scales linearly with basin relief, which defines the Melton ratio ($R^2 > 0.9$: Fig. DR4).

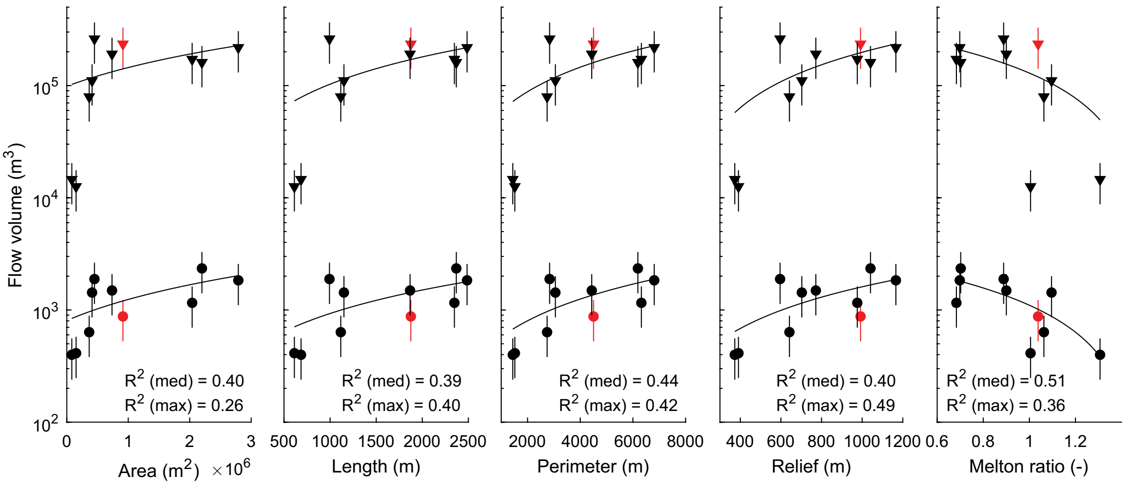

Figure 3. Catchment area, length, perimeter, relief, and Melton ratio plotted against median (med; circles) and maximum (max; triangles) debris-flow lobe volumes. Vertical lines indicate volume error range. Black symbols are from quartz monzonite catchments S01–S08; red symbols are from catchment N01 underlain by metasedimentary rock. Linear regression lines are shown for median and maximum lobe volumes.

It is important to remember that our estimated volumes are based on the cross-sectional areas of individual lobes and will therefore underestimate the volume of large flows that form multiple depositional lobes (e.g., Beaty, 1963; Blair and McPherson, 1998, 2009). Volume estimates for flows forming multiple lobes, however, are only possible by direct measurement or for the most recent events on a fan surface, which have not been buried by subsequent flows. As such, it is currently not possible to obtain large data sets of debris-flow volumes corrected for multiple lobe formation. It is important to realize, however, that for some hazard applications (such as damage to infrastructure), it is volume of sediment deposited at a point, rather than the total flow volume, that is most relevant. Our approach describes the probability to find a lobe of a given size on a debris-flow fan, but for hazard assessment and mitigation, it is also important to understand the frequency of such flows. To advance the novel catchment-morphometry–based method to estimate debris-flow quantiles presented here, future research should thus focus on direct estimation of flow volume–frequency distributions from a number of debris-flow catchments in diverse climatic and lithological settings.

CONCLUSIONS

We reconstructed debris-flow lobe-volume distributions from a large number of well-preserved flow deposits on 10 fans in Saline Valley, California, and we compared lobe-volume quantiles to a set of morphometric catchment characteristics. Our results show that, when controlled for climatic and tectonic setting, lobe-volume quantiles, including the 25, 50, and 75 percentiles and the maximum, depend on catchment area, length, perimeter, relief, and Melton ratio. This implies that simple catchment characteristics, which can be extracted from globally available elevation data sets, may be used to obtain rough estimates of minimum flow design volumes for sediment budgets as well as for hazard assessment and mitigation. While these relationships are promising, future research should focus on the generation of flow volume–frequency distributions from different climatic and lithological settings worldwide against which to test the wider application of these estimates.

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