A robust method to identify the occurrence of a runoff-generated debris flow

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Abstract. Debris flows generated by rainfall runoff can occur in rocky alpine landscapes and burned steeplands. Runoff-generated debris-flow events are commonly composed of a series of dense granular surge fronts separated by water-rich flows. Owing to this intra-event variability in flow composition and mechanics, post-event interpretations of preserved sedimentary deposits, or lack thereof, can result in a dizzying mix of interpretations that range from clearwater flow to debris flow. Accurate identification of the presence or absence of a debris flow during a runoff event is critical for building empirical models used to predict likelihood of debris-flow occurrence, rainfall thresholds, and flow properties. Here, we propose a simple, quantitative method to identify the occurrence of a runoff-generated debris flow, based on a dimensionless discharge Q_* calculated as the ratio of the peak event discharge Q_p to the theoretical maximum clearwater runoff rate Q_w. Using a preliminary compilation of Q_* values from floods and runoff-generated debris flows, we find 98% of floods have Q_* values < 1.6, whereas 91% of debris flows have Q_* values greater than 1.6. Estimating Q_* is typically straightforward as part of standard post-event reconnaissance if suitable rainfall estimates are available, and appears to be a robust indicator that runoff-generated debris flows traversed a particular portion of a valley network.

1 Introduction

In steep landscapes, a wide range of hydrologic responses can initiate during high-intensity rainfall and subsequent runoff. In some instances water flow transporting modest amounts of sediment is the result [1], whereas in others, large, destructive debris flows form with potentially devastating consequences for downstream communities, infrastructure, and ecosystems [2].

Although physics-based modelling of debris flows is rapidly progressing [3,4], empirical models still see widespread use for predicting likelihood and magnitude of potential debris flows, rainfall intensity-duration thresholds, as well as flow characteristics critical in designing effective debris-flow mitigation [5–8]. Central to such empirical models are accurate data sets depicting flow type (debris flow versus water flood), flow characteristics, as well as landscape and storm characteristics.

Unfortunately, accurate identification of flow type is often difficult and uncertain, particularly for debris flows generated by rainfall runoff. Runoff-generated debris-flow events are commonly composed of a series of dense, granular surge fronts separated by water-rich flows transporting sediment [9–11]. Owing to this intra-event variability in flow composition and dominant flow mechanics, post-event interpretations of preserved sedimentary deposits (such as lateral levees and matrix supported deposits without imbricated clasts [12]), or lack thereof, can result in various observers categorizing an event across the entire spectrum of flow types that range from clearwater flow to debris flow. Such misidentification of flow type and the unintentional mixing of different flow types within a data set has negative implications for the predictive capability of empirical models trained on these data sets.

To increase the accuracy of flow identification, particularly for the growing number of workers conducting rapid post-event reconnaissance, the debris-flow hazards community needs a simple, rapid, and objective metric for characterizing the observed flow type in a given channel. In this paper, we propose such a quantitative identifier of a runoff-generated debris flow, based on a dimensionless discharge Q_* calculated as the ratio of the peak event discharge Q_p at a particular location to the theoretical maximum clearwater discharge Q_w at the same point in the network.

2 A quantitative flow-type diagnostic based on dimensionless discharge

Rainfall runoff from steep, barren slopes can transform into a debris flow by variety of mechanisms [13–16]. Once a debris flow has formed, flow discharge increases not only from the volumetric bulking associated with high sediment concentrations (>50% by volume), but more importantly from a change in dominant flow mechanics that occurs in dense granular mixtures [17,18]. In particular, the frictional resistance to movement between solid particles markedly increases resistance to flow above the viscous resistance seen in water flows [17]. To overcome such large forces, steep and deep surge fronts develop. The net result is that debris flows can have peak discharges over 40 times larger than water flows at the same point in the network [19,20].

The proposed flow diagnostic based on debris flow discharge takes advantage of this striking amplification of peak flow discharge that occurs in dense granular mixtures [18,20]. Peak event discharge Q_p, however, can vary substantially over the travel path from small headwater drainages to larger mainstem valleys. Thus, we calculate a dimensionless peak discharge Q_* as the ratio of the peak event discharge Q_p to the theoretical maximum runoff rate of clearwater Q_w at the location of the discharge measurement, that is, $Q_* = Q_p/Q_w$. To estimate the maximum clearwater discharge, or the maximum rainwater input at the valley cross-section of interest, we assume that no rainfall infiltrates, and that it rapidly concentrates to produce a quasi-steady input of water with a discharge $Q_w = AI$, in which A is the upstream drainage area and I is the rainfall intensity. Here we use the peak rain intensity averaged over a 30-minute interval I_{30} as a compromise between short-timescales of concentration of rainfall runoff in small headwater basins and the availability of high temporal resolution rainfall measurements needed to calculate intensities over short durations.

The theoretical expectation is $Q_* < 1$ for a variety of floods with 1 being the theoretical maximum clearwater flood value achieved from an impermeable basin and $Q_* = 0$ indicating no runoff. For water floods a common interpretation of Q_* is as a runoff coefficient in the "rational method" of Chow [21], which commonly fall well below one in undisturbed landscapes and approach 0.1 in burned landscapes prone to rapid runoff [22,23]. For flows that entrain an equal volume of sediment for every unit volume of water (>50% sediment concentration by volume) and that maintain steady flow $Q_* = 2$. Thus, for debris flows that build and sustain steep and deep surge fronts we expect at very least $Q_* > 1$ but likely much greater than one.

3 Preliminary data set

For this work, we build off an initial compilation of dimensionless discharge measurements from post-fire floods and debris flows by Kean et al. (2016) [20] and add an additional 55 measurements from post-fire debris flows obtained around the western US. In total, this preliminary data set is composed of hundreds of floods and 101 debris flows. Flows were only included in the data set if flow type could be unequivocally identified from video footage, eyewitness accounts, or extensive rapid-response field surveys.

Debris-flow data from Kean et al. largely consist of measurements made using automated in situ sensor networks to constrain inundated cross-sectional area, average debris-flow surge velocity and local rainfall intensity, whereas the new measurements presented here were largely made during post-event reconnaissance at sites that had suitable rainfall data.

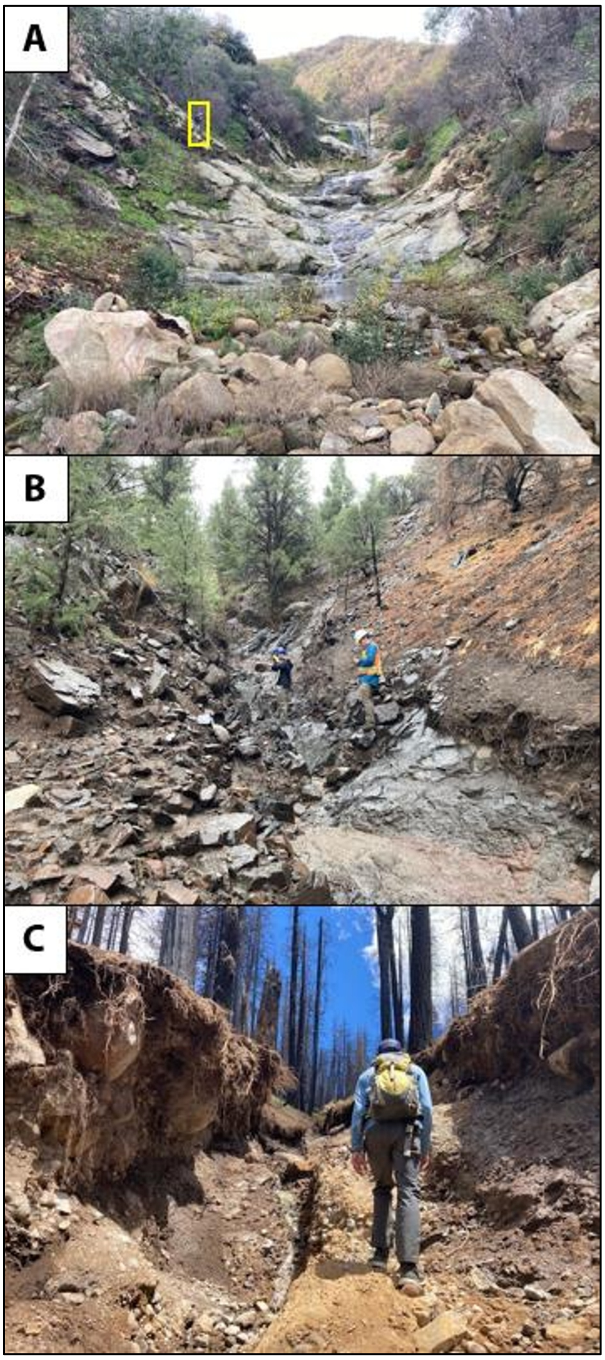

Fig. 1. Photographs of characteristic channel cross-sections following debris-flow events. A and B show suitable cross-sections with well-preserved peak flow depths and minimal channel incision during the event. Person for scale circled in A. C shows channel reach that was substantially eroded during the event. This reach would not be suitable owing to likely overestimate of inundated cross-sectional area.

To estimate peak discharge through post-event reconnaissance, we first found a suitable channel cross-section to measure inundated cross-sectional area. A suitable cross-section had clear evidence of peak flow depth in the form of pervasive erosion of the valley wall, destruction of valley wall vegetation, and/or preserved levees that could be tracked at a consistent level for tens of meters upstream and downstream and that lacked evidence of substantial vertical incision over the course of the event (Figure 1). These cross-section locations were commonly found in relatively straight valley reaches floored with resistant bedrock. Valley segments that had experienced substantial vertical incision were typically easy to identify by inset channels cut well below obvious rooting depths into colluvium. Once a suitable cross-section was identified, we then conducted a survey of the valley cross-section below peak flow depth markers using a laser rangefinder.

To estimate average flow velocity, we assumed Froude critical flow such that the cross-sectional average flow velocity $U = \sqrt{gh}$, in which g is the gravitational acceleration and h is the hydraulic radius of the inundated cross-section. Froude critical flow has been shown to be a reasonable approximation for flow velocity, even if typically an underestimate for debris flows [5,24].

To quantify the skill of Q_* as a flow-type diagnostic, we iterated through threshold values of Q_* used to separate floods from debris flows and computed a threat score,

$$Threat\ Score = \frac{TP}{TP+FP+FN} \qquad (1)$$

in which TP is the number of true positives, FP is the number of false positives, and FN is the number of false negatives produced by drawing the threshold at that particular Q_* value. The optimal Q_* value to separate debris flows from clearwater floods occurs at the maximum threat score.

4 Results

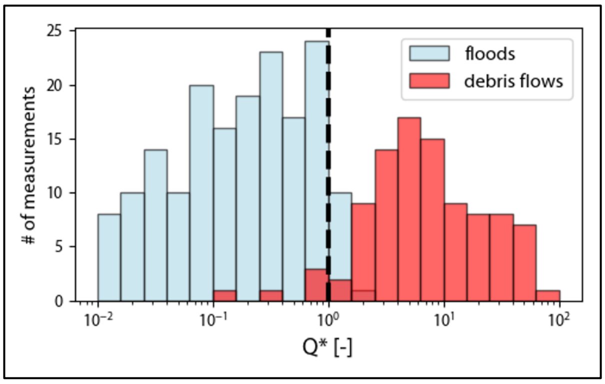

Fig. 2. Histograms of dimensionless discharge $\boldsymbol{Q}_*$ for floods (in blue) and debris flows (in red) largely do not overlap. Overlapping portions of the two histograms show as darker red. Heavy dashed black line marks $\boldsymbol{Q}_* = \mathbf{1}$, and shows the theoretical maximum clearwater runoff rate from an impermeable basin.

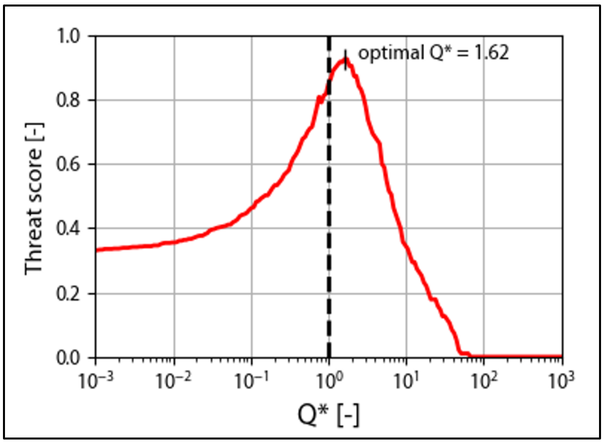

Fig. 3. Plot showing the threat score as a function of $\boldsymbol{Q}_*$ value used to separate floods from debris flows. The highest accuracy is obtained at $\boldsymbol{Q}_* = \mathbf{1.6}$. Heavy dashed black line marks $\boldsymbol{Q}_* = \mathbf{1}$, and shows the theoretical maximum clearwater runoff rate from an impermeable basin.

We find that the distributions of Q_* for floods and debris flows generally do not overlap (Figure 2). In this preliminary dataset, the median Q_* value for floods is 0.1, whereas for debris flows it is 6.5, highlighting that the median Q_* value of debris flows is almost 70 times larger than that of floods. Based on the threat score, the optimal Q_* value to separate these populations is 1.6. (Figure 3). We find that 93% of debris flows fall above $Q_* = 1$ and 91% of debris flows have $Q_* > 1.6$, whereas 93% of floods fall below $Q_* = 1$ and 98% of floods fall below $Q_* = 1.6$.

5 Discussion

Though the focus of this study is on field-based cross-sectional surveys, Q_* could also be estimated using remote methods such as drone-based structure-from-motion or lidar analysis. Such methods may prove useful in studies of how flow type evolves along the channel.

Although the diagnostic power of Q_* is strong and consistent with physics-based hypotheses, there are mechanisms which can increase the inferred Q_* value of a flow and that do not involve debris-flow mechanics. First, using a cross section that experienced substantial erosion during an event such that the maximum cross-sectional area of the flow is over estimated. Second, non-steady flow conditions. One notable phenomenon encountered in our field surveys was that of organic-rich flows that were extremely unsteady owing to the building and failure of dams composed largely of organics. These flows may be more common in burned areas where there is abundant loose woody material and charcoal strewn across the landscape. Flows which entrain this material may “lock up” through log jams and subsequently release water-rich surges with Q_* well above 1, creating trim lines that may mimic those of debris-flow surges, but which likely lack the large sediment concentrations of debris flows.

6 Conclusions

The simple quantitative definition of a runoff-generated debris flow in which debris flows have $Q_* > 1.6$ appears to be a robust and easy to estimate definition and should be useful for identifying flow type (flood versus debris flow) in rapid-response reconnaissance work. The definition is robust owing to the nearly 2 orders of magnitude that separate median Q_* values for floods and debris flows.

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