Exploring controls on debris-flow surge velocity and peak discharge at Chalk Cliffs, Colorado, USA

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Abstract

We present a series of debris-flow events and use combined sensor and video data to explore how sediment concentration and triggering rainfall intensity affect the velocity and discharge of debris-flow surges generated by surface-water runoff. We analyze an initial data set of 49 surges from four debris-flow events recorded by a monitoring system at Chalk Cliffs, Colorado, and compare measurements of surge height, velocity, peak discharge, triggering rainfall intensity, and qualitative estimates of sediment concentration. Measurements of sediment concentration and velocity were obtained using an automated camera system with a high resolution and frame rate. We find that the triggering rainfall intensity of the debris flows, which affects the sediment-to-water ratio, is a strong control on surge velocity and peak discharge. While surges with high and low sediment concentrations both exceed the peak discharge of water-only flow, fluid-rich surges generated by high rainfall intensities have much greater velocities and peak discharges than sediment-rich surges generated by lower rainfall intensities. These observations suggest that rainfall intensity may be an important predictive variable in empirical relationships for estimating the velocity and peak discharge of runoff-generated debris flows, which are common in alpine areas and burned steeplands.

Keywords: debris flow; monitoring; velocity; entrainment; flow depth

1. Introduction

Debris flows have long been recognized as a significant hazard in steep watersheds, and methods to estimate their velocity and peak discharge are needed for quantifying the risk to infrastructure (e.g., Hungr et al., 1984). Empirical relations derived from monitoring data and field and laboratory observations are frequently used to estimate the velocity and peak discharge of debris flows (e.g., Rickenmann, 1999). Observations of debris-flow properties have come from a diverse set of observations made worldwide (e.g., Pierson, 1985; Davies, 1990; Suwa et al., 1993; Iverson, 1997; H"arl"imann et al., 2003, Arattano and Marchi, 2005). Advancements in sensors and computing technologies have made it easier to monitor debris flows, and the number of sites making direct measurements of debris-flow dynamics is growing worldwide (e.g., Imaizumi et al., 2005; Huang et al., 2007; McCoy et al., 2010; Kean et al., 2011; Navratil et al., 2013; Comiti et al., 2014; H"arl"imann et al., 2014; Cui et al., 2018; Schimmel et al., 2018; and others in this volume). Even with this large body of existing knowledge, a broad spectrum of flow types exists due to differences in topography, triggering conditions, sediment availability, grain-size distribution, boundary conditions, and flow density. This variability makes it very difficult to predict debris-flow dynamics in a given watershed.

Monitoring debris-flow events with automated equipment can provide the information to define rainfall intensity-duration thresholds and relations between debris-flow velocity, flow depth, peak discharge, and volume. However, monitoring remains challenging and expensive due to the hazardous and destructive nature of debris flows. Even when the equipment is working, the complexity and variability of debris flows make interpreting instrumental data challenging. Auxiliary data from video recorded by automated systems can clarify the interpretation of debris-flow dynamics. For example, video can help differentiate debris flows from floods, and estimate sediment concentrations...
and grain sizes. Additionally, data extraction from video footage is becoming easier due to the advent of methods for image analysis, such as particle image velocimetry (PIV).

Here, we use observations of flow stage, rainfall intensity, and video recorded in a small basin in central Colorado (Fig. 1) to identify the controls on velocity and peak discharge of debris-flow surges triggered by surface-water runoff. Video is used to estimate both the sediment concentration and height (thickness) of the surges. This work is a first step towards a long-term goal of defining empirical relations for velocity and discharge for runoff-generated debris flows, which are common in alpine areas and burned steeplands.

Fig. 1. Instrumentation to measure debris-flow surge characteristics. (a) Detailed view of the monitoring system to measure debris-flow depth, rainfall, and ground vibrations; (b) Camera view of 42-m long reach used to measure surge velocity and sediment concentrations; and (c) Automated camera system used for the 42-m long reach.

2. Study site

The Chalk Cliffs is a natural laboratory to study debris flows, and a monitoring program for associated mass movement research was established in 2002 (Coe et al., 2008). The Chalk Cliffs are located at the base of Mt. Princeton in the Sawatch Range of the Rocky Mountains, in central Colorado. The cliffs are composed of highly fractured, hydrothermally altered quartz monzonite (Miller, 1999), which gives the Cliffs their characteristic look of white “chalk.” The average slope of the 42-m reach of channel by the upper monitoring station is 17° (Fig. 1). The drainage area above the station is 0.06 km². Bedrock with slopes greater than 25° is exposed in 60% of the entire Chalk Cliffs basin. Sparsely vegetated colluvium with slopes less than 25° covers the remaining area. The relatively large amount of exposed bedrock promotes rapid surface-water runoff during rainstorms that entrains channel sediment and initiates debris flows. An annual monsoon pattern of high-intensity summer thunderstorms and the substantial supply of sediment derived from the hydrothermally altered bedrock produce an average of about four debris flows per year.

Since 2002, a range of automated monitoring equipment has been added to study various aspects of debris-flow dynamics (e.g., McCoy et al. 2010, 2012, 2013; Kean et al., 2013, 2015). The components of the monitoring system are shown in Fig. 1. The primary data acquisition hub is located on a 6-m long aluminum truss bridge spanning the channel. The enclosure houses a datalogger, cellular modem, and power system. A laser stage gage, directed slope normally, and a pair of siphoning tipping-bucket rain gages are mounted on the bridge, approximately 3 m above the
approximate center of the channel. The datum of the stage gage is the elevation of the bedrock channel bed beneath the gage. Other instrumentation installed, but not included in this paper, includes geophones, force plate, rock temperature profilers, pyranometers, a close-up video camera, and a dedicated seismic logging system and geophones (see Michel et al., this volume, for a description of the debris-flow induced ground vibrations at the site). The wide-angle camera shown in Fig. 1c is triggered by a rainfall threshold, and its (cropped) field of view is shown in Fig. 1b.

Debris-flow surges at Chalk Cliffs can vary greatly in flow depth, frequency, sediment concentration, and flow velocity (Fig. 2). This variability is correlated with rainfall intensity, which affects the sediment-to-water ratio in the debris flow. Rainstorms with peak 5-minute rainfall intensity ($I_5$) less than ~30 mm/hr typically trigger a series of small, slow-moving, and sediment-rich debris-flow surges (Fig. 2a). These surges have a characteristic granular snout and more watery tail. Debris flows triggered by intermediate rainfall intensity (~30 < $I_5$ < ~80 mm/hr) also typically have a granular snout and watery tail but have higher water content and are thicker and faster moving than debris flows triggered at low rainfall intensity. High rainfall intensity ($I_5$ > ~80 mm/hr) triggers the largest and fastest moving debris flows at the site. Debris flows triggered by high rainfall intensity typically have fewer surges than debris flows triggered by lower rainfall intensities. Surges triggered by high rainfall intensity are typically followed by a sustained period of high, fast-velocity flow. In general, the grain size of the sediment in each Chalk Cliffs flow varies proportionally with the initiating rainfall intensity.

Sediment availability, which changes over the summer debris-flow season, also affects surge characteristics. Early season debris flows (May-June) typically have more sediment available in the channel than debris flows occurring later in the summer (Coe et al., 2008). During some years with frequent rainstorms, the material available for debris flows is flushed from the basin upstream of the station, resulting in late season water floods. When accumulated bed sediment is present, it not only provides more potential debris for entrainment, but the accumulated material changes channel geometry such that, in the case of v-shaped sections in bedrock, “flatter” flows are produced, as well as a lesser thickness for any given flow volume.

![Fig. 2. Representative examples of debris-flow surges with different sediment concentrations estimated qualitatively from video. (a) High-sediment (Low-water) concentration; (b) Intermediate-sediment concentration; and (c) Low-sediment (high-water) concentration. In general, sediment concentrations decrease with increasing rainfall intensity.](image)
Flow velocity was calculated by recording the travel time of a debris-flow surge between two known points whose along-flow travel distance was derived from a site survey. To minimize error, these points were chosen to be 42 m apart, and spanned a straight, relatively uniform reach of channel. Peak flow height was estimated at the bridge station located in the middle of the reach (Fig. 1b).

Sediment concentrations were determined qualitatively and assigned three different levels: high-sediment (low-water) concentration, intermediate, and low-sediment (high-water) concentration. These terms are used in a relative sense, as all the surge fronts recorded in this study have sediment concentrations high enough to be classified as debris flows. Furthermore, the flows characterized as low-sediment concentration have the largest volumes and carry the largest grains. The sediment concentration levels were determined based on inspection of video imagery (e.g., Fig. 2) and stage time series. For example, the presence of splashing in the video was used to identify fluid-rich flows. In addition, high-frequency variability in the laser stage measurements also indicated the flows had higher water content than the fluid-poor (high-sediment) surges, which did not exhibit high-frequency stage fluctuations (see also Kean et al., 2013).

We estimated peak-flow height (surge thickness) by differencing the elevation (stage) of the flow surface from the elevation of the base of the flow. The laser distance meter accurately measures the elevation of the flow surface; however, the base of the flow was estimated. The base of the flow does not always correspond to the elevation of the bedrock channel due to the periodic presence of bed sediment beneath the flow. The level of bed sediment changes with time due to erosion or deposition by flows. We estimated the base of flows in two ways based on erosional or depositional characteristics of each flow. Erosional flow events are characterized by high-velocity surges that progressively decrease in peak stages as bed material is entrained by the flow (Fig. 3a). For simplicity, we estimated the base of the erosional flows using the debris-flow entrainment rates measured at the site by McCoy et al. (2012), which found that dry beds erode at a rate of 0.035 m/s. Ground vibrations could also be used to estimate the base of the flow using a more complicated analysis (Kean et al., 2015). For depositional events, we used a combination of video and stage measurements to estimate the base of the flow (Fig. 3b). Video was used to identify times in between surges when there was negligible flow, and the stage at this time was used to represent the elevation of stationary bed sediment. We linearly interpolated an estimate of the base of the flow between times when the bed level could be identified from the video (Fig. 3b).

We calculated peak discharge for each surge by multiplying the measured surge velocity over the 42-m reach by the cross-sectional area of the surge at its peak height. The cross-sectional area was defined by (1) the elevation of the flow surface, (2) estimated base of the flow, and (3) a surveyed channel cross-section that defined the lateral boundaries of the flow when used with the elevation of the flow surface. To evaluate the amplification of surface-water discharge by debris-flow sediment, we used the runoff coefficient of the “rational method” to evaluate the ratio of peak discharge to the water discharge supplied by rainfall (e.g., Chow et al., 1988). This non-dimensional ratio is often used to evaluate the peak water discharge in small basins. The runoff coefficient is defined by the equation

\[ Q_p / (I_s A_b) \]

where \( Q_p \) is the peak discharge, \( I_s \) is peak 5-minute rainfall intensity, and \( A_b \) is the area of the basin (0.06 km²). The theoretical upper limit in the runoff coefficient for steady rainfall and water-only discharge is 1; however, the runoff coefficient for debris flows can greatly exceed 1 due to the addition of sediment and the unique flow dynamics of debris-flow surges, which amplify peak flows relative to water (Hung, 2000; Kean et al., 2016).

We estimated the volume of each debris-flow event (sediment and water) by integrating the discharge time series over the duration of the flow. We used the measured velocity of the surge front to represent the velocity of the complete surge (i.e., surge front and tail) and determined a time series of flow cross-sectional area using the same method to determine the cross-sectional area at the time of peak flow.
Fig. 3. Time series of flow stage (black), estimated base level of flow (red), 5-minute rainfall intensity (grey), cumulative rainfall (blue) for (a) an erosional debris-flow event on July 9, 2018 and (b) a depositional debris-flow event on July 11, 2017.

4. Results and Discussion

We examined an initial data set of four debris-flow events (including a total of 49 surge fronts) from 2017 and 2018 (Table 1) to identify possible controls on debris-flow surge velocity and peak discharge. Analysis of additional events recorded at the site is planned. Time series of two of the events are shown in Fig. 3. Both events were the first events of their respective season and flow over an initially sediment-covered bed. It is notable that a significant amount of material accumulated in the monitoring reach prior to the 2017 season (~1.6 m depth of sediment, Fig. 3b). Twelve of the 20 surge fronts, from July 11, 2017, were omitted from our results since an incised channel in the sediment redirected the surge fronts away from the stage sensor (i.e., camera footage indicated that the height measurements were unreliable). This accumulated material was entrained during a large event on July 14, 2017. The July 14, 2017 event is included in the results since it was uncommon to have rain from an extremely intense thunderstorm fall on such a large amount of accumulated sediment. Unfortunately, several of the surges overtopped the laser distance sensor and coated it in an opaque slurry of fine material. As a result, measurements of surge properties for this event are only available for the time when the laser was working, and the estimated total volume is a minimum. The fourth event analyzed occurred on August 14, 2018, on a bare bedrock channel. This event, which occurred late in the debris-flow season, was fluid rich and had few coarse-grained surge fronts. With the exception of the July 11, 2017 event, all of the analyzed debris flows were erosive.

Table 1. Summary of debris-flows properties from this study.

<table>
<thead>
<tr>
<th>Date</th>
<th>Volume (m$^3$)</th>
<th>$Q_{med}$ (m$^3$/s)</th>
<th>peak $I_5$ (mm/hr)</th>
<th># of surges</th>
<th>Cumulative rainfall (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>11 July 2017</td>
<td>420</td>
<td>4.2</td>
<td>30</td>
<td>20</td>
<td>14</td>
</tr>
<tr>
<td>14 July 2017</td>
<td>5,700</td>
<td>46</td>
<td>110</td>
<td>13</td>
<td>37</td>
</tr>
<tr>
<td>9 July 2018</td>
<td>330</td>
<td>3.8</td>
<td>67</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>14 Aug 2018</td>
<td>1,600</td>
<td>5.1</td>
<td>73</td>
<td>6</td>
<td>21</td>
</tr>
</tbody>
</table>
For the years that we included in this study (2017-2018), the first flows of the summer season (July 11, 2017, and July 9, 2018) were dominated by surge fronts with high-sediment concentrations, whereas later events in the season (July 14, 2017, and August 14, 2018) had more fluid-rich surges. The increased water content of the later season debris flows was likely because they were triggered by higher intensity rainstorms, and because there was less sediment available due to sediment export by the first flows of the season.

Measured surge velocity and peak discharge appear to be correlated with both peak rainfall intensity and sediment concentration (Fig. 4). High flow velocities and peak discharges are generally associated with high rainfall intensities and fluid-rich surges, whereas low flow velocities and peak discharges are associated with low rainfall intensities and high sediment concentration surges. Furthermore, the vertical clustering suggests that $v$ is independent of $h$ at a given $h$, with water content or sediment concentration having a strong influence.

In Figure 4, we compared the velocity and peak flow thickness data with two other relations sometimes used to estimate flow velocity: the critical Froude number and the Manning equation. Estimates of velocity based on a critical Froude number are used to estimate water velocity in steep channels (e.g., Grant, 1997) given by the equation $v = \sqrt{gh}$, where $v$ is velocity, $g$ is acceleration of gravity, and $h$ is peak flow thickness. Manning’s equation, which is also used to estimate turbulent water velocity, is given by the equation $v = (1/n)h^{2/3}s^{-1/2}$, where $n$ equals the roughness coefficient, and $S$ is the channel slope. Rickenmann (1999) showed that a Manning’s roughness coefficient of 0.1 provided a reasonable match to a variety of debris-flow observations. The fit of the data-derived best-fit line shown in Fig. 4a suggests the relationship between velocity and peak discharge at the Chalk Cliffs site falls in between these two estimates. Variability in the debris-flow observations may also be influenced by other factors, such as changing cross-sectional flow geometry as the result of variable bed sediment cover. Figure 4b indicates a correlation between peak discharge (a function of cross-sectional flow area) and surge thickness.

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**Fig. 4.** Relations between (a) peak flow thickness and flow velocity and (b) peak flow thickness and peak discharge. Data points are color coded by 5-minute rainfall intensity, and the symbols for each data point are classified according to three levels of sediment concentration. Mean translational velocity is the time taken by the flow front to move between two known locations.
The difference in the distributions in the runoff coefficient \( \left( \frac{Q_p}{I_5A} \right) \) for flows with low- and high-sediment concentrations further highlights the control of water content (and indirectly rainfall intensity) on the peak discharge of debris flows (Fig. 5). While the median of both distributions exceeds the theoretical limit of water flow, the runoff coefficient of low sediment concentration flows is multiple times greater than the runoff coefficient of high-sediment concentration flows.

![Histogram showing the frequency distribution of normalized peak discharge](image)

**Fig. 5.** A histogram showing the frequency distribution of normalized peak discharge (i.e., the runoff coefficient) for flow surges with low-, intermediate-, and high-sediment concentration. The light, dashed lines show the median coefficient values of the concentration groups.

### 5. Conclusion

We have presented a set of debris-flow height, velocity, qualitative sediment concentration, and rainfall intensities from the Chalk Cliffs debris-flow monitoring site. We have shown that these data can be used to improve, on a site-by-site basis, empirical debris-flow velocity-height relationships. Although these data can contribute to enhanced understanding of the debris-flow dynamics, the hazardous conditions of the monitored basin challenge system reliability, and the difficulties associated with accurate data interpretation benefit from validation and cross-correlation of multiple sensors—especially video.

These data have shown that empirical relationships for debris flows provide a fair approximation of debris-flow magnitudes. However, other factors not taken into account in this study, such as pre-event sediment availability and its moisture levels and grain size provide an additional opportunity for monitoring that could lead to more accurate debris-flow height and velocity predictions. Over time, as more debris-flow events are added to a database, we are
hopeful that new correlations considering bed sediment heights, and/or the integration of tiered rainfall thresholds, may serve to further refine the predictive ability and utility of existing empirical debris-flow relationships.

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