Evaluation of a method to calculate debris-flow volume based on observations of flow depth

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Abstract. The volume of a debris flow is a critical parameter in hazard analysis, yet accurate estimates of volume are often unavailable due to mixing with larger rivers at the downstream end of alluvial fans. We describe a method to calculate the volume of debris flows using flow depth data collected at a check dam, using a Manning friction relation to describe the velocity of the debris flow as a function of flow depth, and the geometry of the channel cross section. The method is evaluated using a published data set from the USGS debris-flow flume where event volume and stage information have been accurately measured, and results in volume estimates either somewhat smaller than or up to 50% larger than observed volumes. We further demonstrate the method to single-surge and a multiple-surge debris flows observed at Illgraben.

1 Introduction

Accurate estimates of debris-flow volume are necessary for many applications, including hazard analysis, interpreting recent events, evaluating the performance of mitigation structures, and a variety of applications in geomorphology (e.g. [1-6]). In many Alpine torrent channels, debris-flow deposits become mixed with flood flows when they enter larger river channels, thereby transporting sediment away from the depositional area. Further, uncertainties in the elevation of the ground surface before the event may introduce large errors into volume estimates. Consequently, it is difficult to accurately measure deposit volume. Many authors provide volume estimates without stating which methods were used to calculate the volume. Presumably, reported volume values are based on e.g. estimates of deposit thickness and aerial extent, or expert judgement.

Herein we describe and test a method to calculate event volume using flow depth data, a friction relation to describe the velocity of the debris flow as a function of flow depth, and the geometry of the channel cross section where depth is measured. We sum the discharge over the event duration to calculate the volume. To test the method, we use published data from the USGS debris-flow flume [7] where volume and depth have been accurately measured.

2 Methods

The method we use was briefly described in [1] to compare the amount of sediment exported from Illgraben catchment in comparison with measurements from sediment traps on hillslopes. No independent observations of debris-flow volume are available there due to mixing of debris flows sediment with flood flows in the Rhone River. The method has been in use since 2007 [2] to estimate volume and discharge for interpreting well-documented debris flows [1-6, 8-11]. The method has not yet been systematically tested at any field sites, mainly due to a lack of accurate independent volume estimates e.g. from measurements of sediment trapped in retention basins.

Observations of debris-flow velocity along an individual surge are uncommon [12-14] but it is clear on publicly-available videos of debris-flow surges that the velocity is largest at the front of the flow, and both depth and velocity decrease with distance upstream of the flow front. Many friction relations are available to describe how the depth-averaged flow velocity varies as a function of flow depth (e.g. [15]), however the Manning friction approach used herein has the advantage that it has been in widespread use for estimating flow velocity in sediment-laden floods as well as debris flows [16-18]. The Manning relation describes how the depth-averaged velocity V varies with the hydraulic radius R of the flow for steady-uniform flow in channel with slope S:

$$V = kR^{m}S^{1/2} \quad (1)$$

where: k = a friction coefficient assumed to be constant over the duration of the event, and m is the exponent on the hydraulic radius term, usually m=2/3. The friction coefficient in the case of debris flows is interpreted to include both friction arising at the interface of the debris flow and the channel bed, and the internal friction within the flow. The hydraulic radius R is the ratio of the area of the channel A and the wetted perimeter of the channel P (Fig. 1). For wide channels, or for when the sidewalls of the channel are much smoother than the channel bed (as in the USGS experiments [7] discussed below), it is reasonable to approximate $R \sim h$, where h is the flow

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https://doi.org/10.1051/e3sconf/202341502012

depth. Both A and P vary as a function of the flow depth, which at Illgraben is a trapezoidal cross-section (Fig. 1), at a distance 1 m upstream of the brink of a concrete check dam.

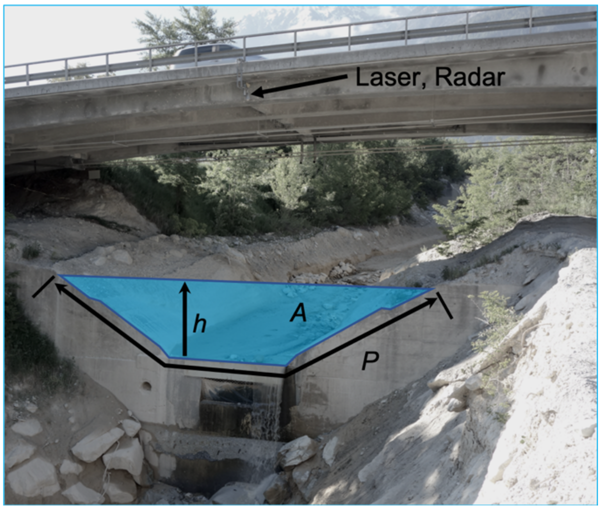

Fig. 1. Sketch of the measurement cross section at the check dam under the road bridge at Illgraben. The cross-sectional area A (blue shaded area) and wetted perimeter P are functions of the flow depth h which is determined using the distance from laser or radar sensors installed on the bridge (e.g. [2]); these sensors are aimed at the center of the force plate, which is 4 m wide, and 2 m long (in the flow direction).

The volumetric discharge Q (m^3/s) of the flow passing over the check dam is the product of the velocity and the cross-sectional area: $Q=VA$. The influence of channel width on discharge is taken into account using A. The total volume M (m^3) of the event is the sum of the discharge over the event:

$$M = \sum_{i=start}^{i=end} C_1 Q_i \Delta t \tag{2}$$

where: C_1 is a correction coefficient with a value close to or smaller than one to account for the fact that the velocity is not uniform at the cross-section, or more specifically because the flow, after the passage of the debris-flow front, tends to be slower at the edges than in the middle of the channel. Herein we use C_1=1 because this effect is most visible towards the tail of events when the corresponding discharges are relatively small.

2.1 Application to the USGS debris-flow flume

The debris-flow experiments results described by Iverson et al. [7] are useful for testing our procedure because the initial volume has been accurately measured, the time-series of flow depth information is available, and results are provided for two mixtures, a sand-gravel mixture (SG) and a sand-gravel-mud mixture (SGM) which is qualitatively similar to the sediment at Illgraben. The sizes of the flows are large, minimizing the influence of possible scale effects. Additionally, the results are reported for aggregated repeats of nearly identical simulations, minimizing any unique problems that may arise from using an individual experiment. Here, we use their results for the rough channel bed.

The python data analysis script we use to calculate the main event parameters V, Q, and M for Illgraben was modified for the geometry of the USGS channel. The front velocity was determined from the front trajectory plot (Fig. 9 in [7] and the friction coefficient k was back-calculated and used to compute the parameters. A timestep of 0.01 s was used, and we focus on results reported at 32 m downstream from the headbox (Fig. 2).

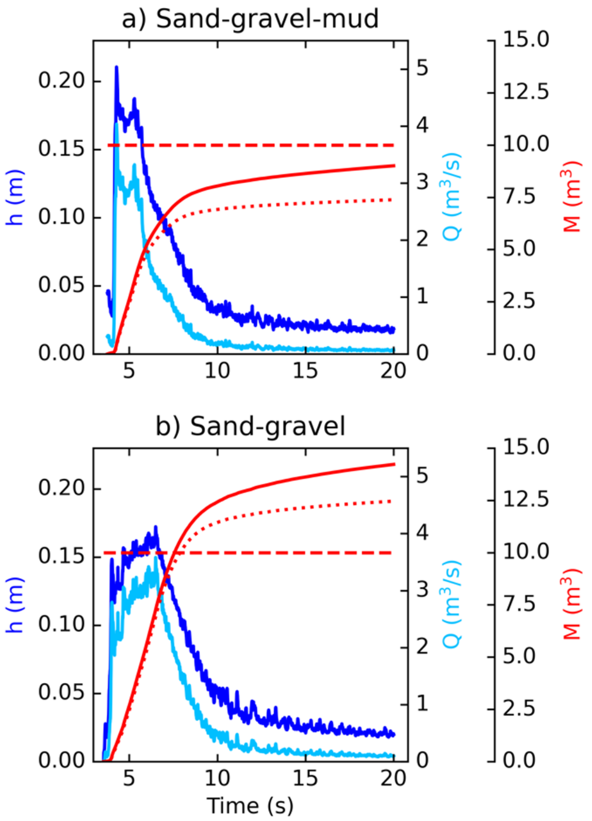

Fig. 2. Results for the USGS debris-flow flume at x=32m for calculated discharge (light blue lines), and cumulative event volume M (red) for flow depths h (dark blue) as reported in [7]. The initial volume of the flow is the horizontal red dashed line, and the cumulative volume is shown for Manning exponent m=2/3 (solid red line) and m=1 (red dotted line). Results are shown for the SGM (a) and SG (b) sediment mixtures.

2.2 Application to the Illgraben

Two large-volume events from Illgraben were selected, one debris flow one main surge (24 June 2021) and an event with semi-periodic roll waves (5 June 2022). For the 24 June 2021 event, the maximum measured front depth corresponds to the measured front velocity. For the 5 June 2022 event, the maximum flow depth and velocity are from the first surge, however the maximum flow depth was observed several minutes later in a subsequent surge. The front velocity was calculated as the travel time between two check dams along the channel, and the flow depth was taken from the laser depth sensor. These values were used to determine appropriate *k* values for the volume analysis described above.

The data (Fig. 3) are from the downstream end of the channel above the confluence with the Rhone River (the location of the force plate described elsewhere [2, 4], near the brink of the check dam (Fig. 1). At this location, data was collected at 2400 Hz and was exported as median values in bins of 1s duration.

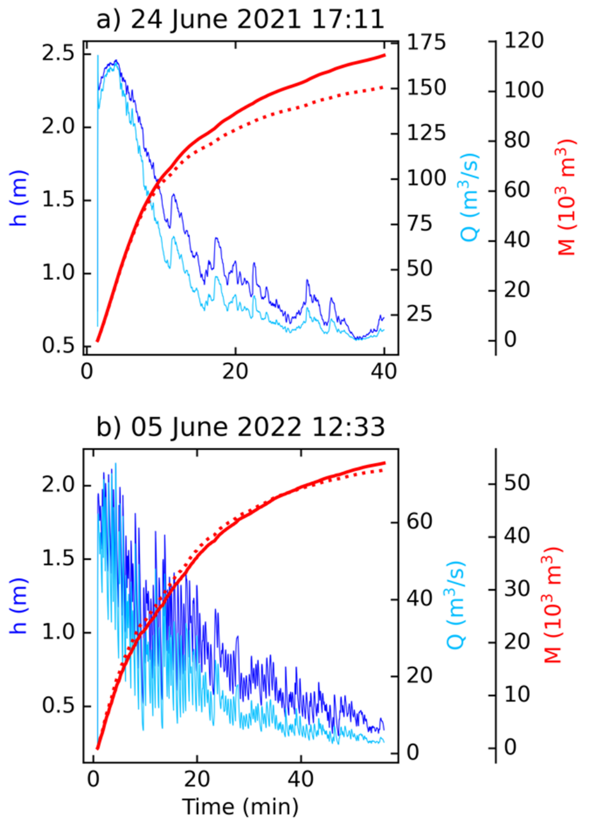

Fig. 3. Results from Illgraben torrent for debris flows with one main surge (a) and with many roll waves (b). The dark blue lines are measured flow depths *h*, the light blue lines are the calculated discharges *Q*, the solid red line is the running sum of event volume *M* for *m*=2/3, and the dashed red line is the *M* for *m*=1, as discussed in the text.

3 Results & Discussion

3.1 Results USGS debris-flow flume

The results from the USGS flume experiments (Fig. 2) are useful for testing our volume-calculation method, because both initial volume and accurate stage data are available. In the experiments, both the front velocity and thickness of the flow (Figs. 9 and 10 in [7], respectively) were approximately constant, indicating that the flow was not significantly accelerating as it moved down the channel, similar to flows observed at Illgraben. The results for the SGM mixture, which contains some muddy sediments, show promising results, with the measured volume asymptotically approaching the initial volume of 10 m^3. The SG mixture (without mud) shows poorer performance, over-predicting the volume by a factor of 1.4. While the results for the SGM experiments support our volume-estimation method, several factors may be able to account for the lack of good agreement for the SG sediment mixture.

Changes in bulk density can influence the volume. As the flow transitioned from rest in the head box to the channel, small changes in bulk density were reported (Fig. 19 in [7]). This indicates that calculating the mass of the flow, not volume, in comparison with the initial mass would provide a more accurate comparison.

Deposition within the surge, followed by re-entrainment at the tail of the event (especially in the SG rough bed experiments, may result in an apparent flow depth which is systematically too large, resulting in an over-estimation of debris-flow volume. We intend to test this idea by performing our calculations on the SG experiments which were performed on a smooth bed.

3.2 Results at Illgraben

The results at Illgraben for single-surge debris flows (Fig. 3a) and multi-surge events with large roll waves (Fig. 3b) indicate an increase in event volume up to nearly M=120,000 m^3 and M=52,000 m^3, respectively.

It it is not known if deposition occurs on the channel bed during an event, which could result in an over-estimate of the flow volume similar to what may be occurring at the USGS flume for the SG mixture, described above. Erosion (and a correspondingly larger discharge and volume) can be excluded due to the presence of the check dam and force plate at the measurement section.

Some evidence for deposition during the flow is provided by geophone measurements, (see [2, 4]) which show that the impulses (from impacting particles) on the bed remain fairly large near the flow front, and thereafter they decrease significantly. This may indicate that a layer of sediment has deposited on the force plate, although independent measurements of deposit thickness are not available. A more likely explanation for the decrease in impulses is that the grain size decreases (fewer particles create vibrations) and/or that the particles are being transported in a liquified flow after the front passes [2] and only rarely interact with the channel bed. We anticipate that the new results from 3D LiDAR scanning analysis [13, 14] will help constrain the problem.

The flow passing over the measurement section (Fig. 1) is influenced by the free-overfall for Froude numbers $F=V/(gh)^{1/2}<1$, where g is the gravitational acceleration. For $F<1$, we expect the free overfall to cause a small hydraulic drawdown, which causes the flow to accelerate near the overfall, thereby minimizing deposition at that cross section. However, the drawdown under these conditions also causes the flow surface to be somewhat lower than expected at the measuring distance 1 m upstream of the overfall. The consequence of this systematic error is that the depth, and therefore estimates of velocity, discharge, and volume are also somewhat underestimated. The concepts of hydraulic drawdown, or backwater effects, were elaborated for water flows in open channels (e.g. [16]). While we expect that results for surface drawdown for debris flows will be similar to water flows, debris flows are non-Newtonian fluids and some differences may arise. It is likely that measurements being collected by 3D LiDAR scanners [13, 14] will help us address this problem and allow us to correct for the drawdown in a procedure analogous to using the slope of the hydraulic grade, rather than the surface of the flow, as in open-channel flow [16].

3.3 Influence of exponent *m* on the results

Several factors may influence the accuracy of our predictions at both the USGS flume and Illgraben. First, observations of objects floating on the surface of the flow at Illgraben indicate that the surface velocity for a given depth decreases more rapidly than predicted using the Manning relation, assuming a constant vertical velocity profile. If the exponent on the hydraulic radius term m in Eq. 1 is increased, the velocity predicted for smaller flow depths will decrease, and estimates of discharge and volume will also consequently decrease.

There is some support for using a larger exponent m in gravel-bed rivers where the size of the particles is large compared with the flow depth [18]. While the equivalent roughness in debris flows is large (max. particle diameters can be as large as the depth of the flow), the use of a larger m has not yet, to the best of our knowledge, been evaluated for debris flows. Therefore, the results below for m=1 must be treated as speculative.

To illustrate the influence of a larger Manning exponent m, we examined all four events here using an exponent m=1 and determined the cumulative volume M (the dashed red lines on Figs. 2 and 3). For all cases, the value of friction coefficient k for the front of the flow was re-calculated using (1) with m=1.

The results for m=1 indicate that the total volume of the flow at the USGS flume is underestimated for the SGM case (Fig. 2a) and somewhat better predicted for the SG case (Fig 2b). At the Illgraben, the calculated volume is approximately 20% smaller for the single-surge event (Fig. 3a) and roughly similar for the event with roll waves. While these results are somewhat speculative, they illustrate some of the problems and assumptions inherent in calculating debris flow volume from only stage measurements: A fundamental assumption is that the flow friction is adequately described using the Manning equation, and furthermore, that the friction coefficient is constant along the entire duration of the debris flow. It is clear that particle grain size certainly varies in a debris flow, but the flowing bulk density remains somewhat constant over many reported events (e.g. [2, 4, 12]), so the sediment concentration is approximately constant. So, it may be reasonable to assume that the friction coefficient k may also be approximately constant over an event, however this is contradicted by Hungr [19] who suggested a longitudinal variation of flow friction related to sediment concentration. In spite of these shortcomings, analysis of the USGS data suggest that event volume estimated using the Manning relation and stage data at non-erodible cross sections may yield flow magnitude estimates M accurate to within 50%.

4 Conclusions

We described and tested a method for estimating the volume of a debris flow based on flow depth measurements collected from a check dam, combined with the Manning friction relation commonly used in river engineering. The results are sensitive to the calibration procedure, and result volumes estimated to within 50% based on comparisons with calculations made at the USGS debris-flow flume where both flow volume and flow depth measurements are available. Increasing the exponent on the hydraulic radius term in the Manning equation does not clearly increase the accuracy of the method.

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