Calculation of debris flow volumes from hydrographs

We estimate debris flow volumes from flow hydrographs of individual events, using the method in Schlunegger et al. (2009) to calibrate a simple Manning-type friction relation (Barnes, 1965). Estimates are made at two gauging stations, one in the catchment at check dam (CD) 9 and 10, and the second at the fan toe at CD28 and 29. At the upstream station, a geophone at CD9 (Figure DR1) records the passage of the flow front and triggers a radar sensor ~39 m downstream at CD10, which records the debris flow hydrograph. We estimate front velocity using the time difference between detection of the flow front at both stations and calibrate the Manning equation according to the procedure described below. At the downstream station (CD29), a laser and a radar unit record debris flow hydrographs. We estimate front velocity from the front arrival times at geophones mounted on CD28 and CD29, and calibrate the Manning equation as below. To quantify the uncertainty in the velocity estimate, we also calculate average debris flow velocities for the channel reaches CD1 to 9 and CD9 to 29 and the resulting flow volumes. Results for all flows are shown in Table DR1. Below we illustrate the volume calculations using data from the upper station at CD9/10 for event 9 on 1 July 2008 (Table DR1).

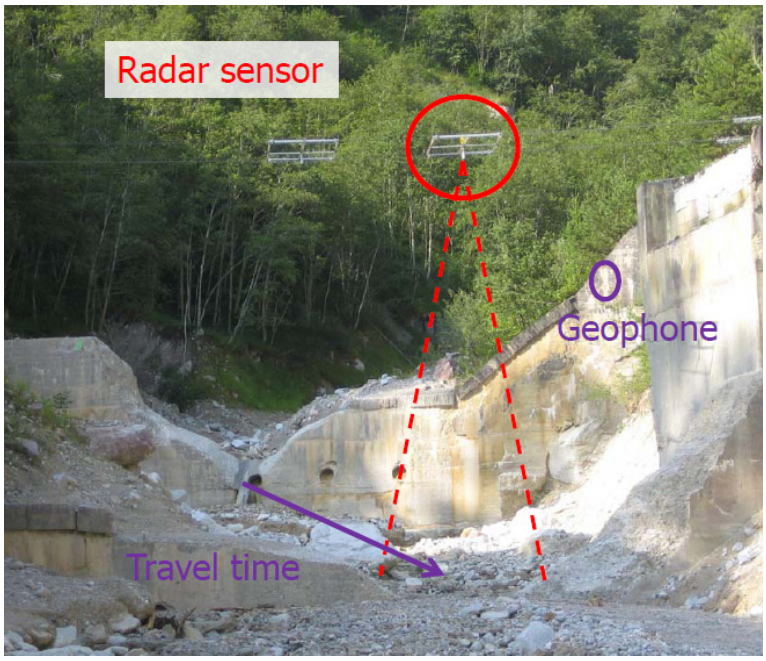

Figure DR1: Upper gauging station at CD9 and CD10. The distance between CD9, where the geophone is mounted, and CD10, where the radar is mounted, is 39 m (purple arrow). Channel slope is 10%.

The necessary calculation steps in detail are:

1. Estimate front velocity from travel time between CD9 and CD10:

$$u_{local} = \frac{\Delta l}{\Delta t} = \frac{39\ \mathrm{m}}{8\ \mathrm{s}} = 4.9\ \mathrm{m/s}$$

2. Measure front height from radar recordings (Figure DR2): $h_f = 4.5\ \mathrm{m}$

3. Estimate the hydraulic radius for the passage of the flow front based on a channel cross profile surveyed with a hand level on 25 May 2009: $h_r(h_f = 4.5\ \mathrm{m}) \approx 2.1$

4. Calculate the coefficient for the Manning friction relation using front velocity, hydraulic radius and channel slope:

$$k = \frac{u_{local}}{h_r^{2/3} \cdot S^{1/3}} = \frac{4.9\ \mathrm{m/s}}{(2.1\ \mathrm{m})^{2/3} \cdot 0.1^{\frac{1}{3}}} = 6.5\ \mathrm{m}^{1/3}/s$$

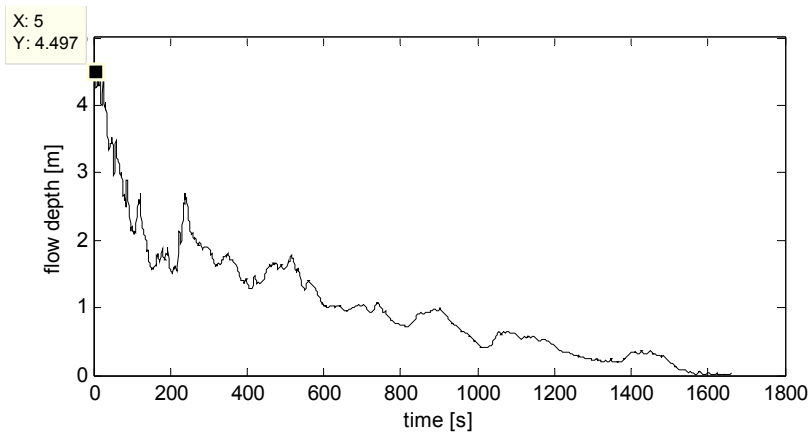

Figure DR2: Hydrograph of event 9 at CD10. Front height (see data tip) is 4.5 m measured 5 s after recording of the front at CD9.

5. Integrate along the hydrograph (Fig. DR2) to obtain the total flow volume. At every recording of flow depth, *h(t),* we calculate the corresponding hydraulic radius, $h_r(t)$, and then calculate the mean velocity, *u(t),* for each time step. We multiply the velocity with the flow cross section area, *A(t),* which is a function of flow stage, *h(t),* and the channel cross-sectional profile, to obtain discharge. The flow volume is the sum of the discharge time series, *Q(t),* over the duration of the event.

$$V = \sum_{t=0}^{t=t_{max}} Q(t) = \sum_{t=0}^{t=t_{max}} A(t)\, u(t) = \sum_{t=0}^{t=t_{max}} A(t)\, k\, h_r\,(t)^{2/3}\, S^{1/3} \approx 27'000\, m^3$$

In Table DR1 we show the calculated volumes at CD10 and at CD29 for all 14 events. For the analysis in the paper we use the volumes calculated according to the workflow detailed above.

As a check we have also calculated the average velocities between CD1 and CD9 and between CD9 and CD29 from front arrival times at CD1 and CD29 respectively. Then we calculated the friction coefficient (step 4 above) using these velocities and then integrated along the hydrograph to obtain flow volume (step 5 above, using same cross section geometry as in step 3). For five events (flows 2, 4, 8, 11 and 12) the average velocities are significantly lower and would, if used for the volume calculation, lead to substantially smaller volumes at CD10 (Table DR1). These events would change from being dominantly depositional to having no net volume change whilst traversing the fan. For all other events the dominant behaviour would not change. Therefore we conclude that the uncertainties in the local velocity estimate are small enough to warrant our analysis in the paper.

Table DR1: Database of debris flow velocities, front height and volumes. Channel slopes used for calculating k at the gauging stations are 0.1 (CD10) and 0.086 (CD29) respectively.

		gauging station at CD10 measured velocity **u**, front height $\mathbf{h_f}$ and calculated Strickler coefficient **k**, volume **V** and peak discharge **Q**													gauging station at CD29 measured velocity **u**, front height $\mathbf{h_f}$ and calculated Strickler coefficient **k**, volume **V** and peak discharge **Q**				
		Front height	based on travel time CD9–CD10				based on travel time CD1–CD9				based on travel time CD9–CD29				Front height	based on travel time CD27–CD29			
No.	**Date**	$\mathbf{h_f}$ m	$\mathbf{u_{local}}$ m s^{-1}	**k** m$^{2/3}$ s$^{-1/3}$	**V** m^3	**Q** m^3 s^{-1}	$\mathbf{u_{CD1-9}}$ m s^{-1}	**k** m$^{2/3}$ s$^{-1/3}$	**V** m^3	**Q** m^3 s^{-1}	$\mathbf{u_{CD9-29}}$ m s^{-1}	**k** m$^{2/3}$ s$^{-1/3}$	**V** m^3	**Q** m^3 s^{-1}	$\mathbf{h_f}$ m	$\mathbf{u_{27-29}}$ m s^{-1}	**k** m$^{2/3}$ s$^{-1/3}$	**V** m^3	**Q** m^3 s^{-1}
1	2007/05/28	1.6	7.8	17.6	27800	80	n/a	n/a	n/a	n/a	6.6	14.9	23500	70	1.5	6.6	21.5	18600	70
2*	2007/06/15	0.7	5.6	19.3	68800	130	0.7	2.4	8600	16	2.2	7.6	27200	50	3.8	2.5	5.3	10200	140
3	2007/07/01	2.0	3.3	6.3	9400	40	1.5	2.9	4400	17	n/a	n/a	n/a	n/a	n/a	n/a	n/a	0	0
4*	2007/07/21a	2.7	4.9	7.8	15600	90	1.0	1.6	3200	17	0.9	1.4	2900	15	1.0	0.4	1.7	4600	3
5	2007/07/21b	2.8	2.6	4.3	11700	60	10.8	17	48600	220	7.0	11	31000	140	1.9	6.8	20.2	67400	100
6	2007/08/08	0.5	3.9	16.7	28400	20	0.3	1.3	2200	2	n/a	n/a	n/a	n/a	n/a	n/a	n/a	0	0
7	2007/08/29	0.6	4.9	20.2	1600	7	0.5	2.1	200	1	n/a	n/a	n/a	n/a	n/a	n/a	n/a	0	0
8*	2008/06/16	1.3	3.9	10.5	15900	50	1.5	4.0	6100	20	2.1	5.4	8200	30	1.1	2.4	9.1	7700	17
9	2008/07/01	4.5	4.9	6.5	27000	200	7.6	10.1	41500	310	6.5	8.6	35500	270	2.2	5.3	14.4	60000	90
10	2008/08/19	1.0	4.3	12.6	4100	20	0.9	2.6	850	3	n/a	n/a	n/a	n/a	n/a	n/a	n/a	0	0
11*	2008/08/31	2.5	3.9	6.7	10600	60	n/a	n/a	n/a	n/a	2.6	4.4	7100	40	1.45	1.9	6.3	8200	19
12*	2009/07/17	1.8	4.3	9.1	7200	40	3.6	7.8	6100	40	n/a	n/a	n/a	n/a	n/a	n/a	n/a	0	0
13	2009/07/28	2.3	3.3	6.1	5300	40	5.4	9.8	8500	70	3.0	5.4	4700	40	1.0	2.2	9.1	13500	20
14	2009/08/09	2.3**	7.8	14.4	106300	630	5.9	10.9	80400	480	6.8	12.5	92700	550	2.6	5.9	15.1	56800	130

* Only for these events the use of alternative calculations for the flow volume have a significant effect on the fan-scale flow behaviour.

** A second surge with a front height of 5.2m arrived 17s after passage of the flow front.

n/a: debris flow not detected at CD1 (Events 1 and 11) or debris flow did not trigger lower gauging station due to full deposition on fan (Events 3, 6, 7, 10, 12).

Quantitative comparison of elevation change and flow depth

Here, we briefly explain the processing that lead to the visualization of our data in Fig. 3A. First we created the maps of elevation change (termed difference models) with a cell size of 0.2 x 0.2 m from subsequent surveys and the models of maximum flow depth for each event (as explained in the main text). Crucial here is that for each grid cell in the difference model there is a corresponding grid cell in the flow-depth model. We then produced a scatter plot of flow depth vs. elevation change combining all four events into one data set. Because of the large number of data points – as illustrated by the density plot (Fig. 3A and Fig. DR3) – the structure of the data is not immediately obvious. Therefore we subdivided the data in bins with a width of 0.5 m along the flow-depth axis (i.e. [0 m – 0.5 m[; [0.5 m – 1.0 m[… [3.0 m – 3.5 m]). We choose a bin width of 0.5 m, because this reflects our estimated uncertainty on the maximum flow depth. Any bin width smaller than 0.5 m would yield a percentile plot that over interprets the data. Next we calculated the corresponding elevation change value for the 1, 10, 25, 50, 75, 90 and 99 percentile based on the data in each bin. This gave the vertical position of the respective percentile line at the centre of each bin (0.25 m, 0.75 m, 1.25 m … 3.25 m) in Fig. 3A.

Density plots of erosion/deposition depth versus flow depth

In addition to the summary density and percentile plot shown in the main text (Figure 3) we show in Figure DR3 density and percentile plots for events 9, 11, 12 and 14 individually.

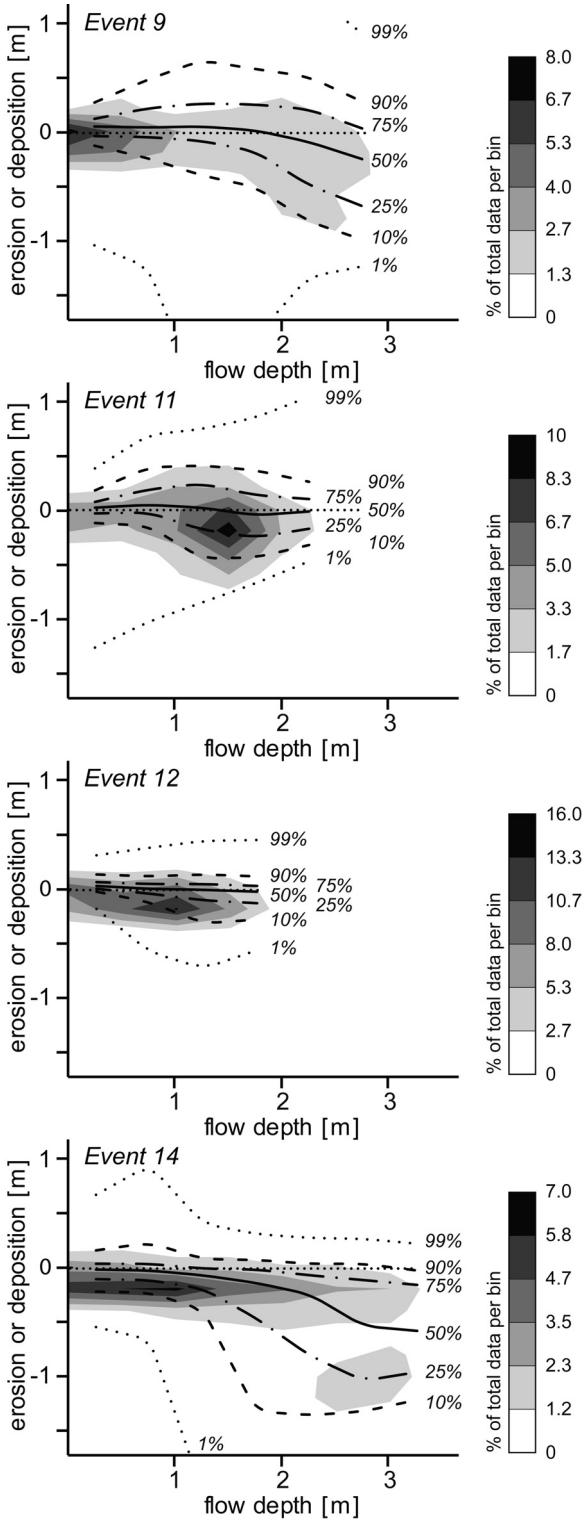

Figure DR3: Percentile and density plot of cell by cell (0.2 x 0.2 m) comparison of elevation change (erosion or deposition) from TLS vs. maximum flow depth as mapped in the field for individual events 9, 11, 12 and 14 (from top). Bin size for density plot is the same as in Figure DR4. The percentiles are calculated based on a bin width of 0.5 m of flow depth

References

Barnes, H.H., 1965, Roughness Characteristics of Natural Channels: Geological Survey (U.S.).

Schlunegger, F., Badoux, A., McArdell, B.W., Gwerder, C., Schnydrig, D., Rieke-Zapp, D., and Molnar, P., 2009, Limits of sediment transfer in an alpine debris-flow catchment, Illgraben, Switzerland: Quaternary Science Reviews, v. 28, no. 11, p. 1097–1105.