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Debris flow modeling at Meretschibach and Bondasca catchment, Switzerland: sensitivity testing of field data-based erosion model

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Abstract

Debris flow volumes can increase due to the incorporation of sediment into the flow as a consequence of channel-bed erosion along the flow path. This study describes a sensitivity analysis of the recently-introduced RAMMS debris flow entrainment algorithm which is intended to help solve problems related to predicting the runout of debris flows. The entrainment algorithm predicts the depth and rate of erosion as a function of basal shear stress based on an analysis of erosion measurements at the Illgraben catchment, Switzerland (Frank et al., 2015). Starting with a landslide-type initiation in the RAMMS model, the volume of entrained sediment was calculated for recent well-documented debris-flow events at the Bondasca and the Meretschibach catchments, Switzerland. The sensitivity to the initial landslide volume was investigated by systematically varying the initial landslide volume and comparing the resulting debris-flow volume with estimates from the field sites. In both cases, the friction coefficients in the RAMMS runout model were calibrated using the model where the entrainment module was inactivated. The results indicate that the entrainment model predicts plausible erosion volumes in comparison with field data. By including bulking due to entrainment in runout models, more realistic runout patterns are predicted in comparison to starting the model with the entire debris-flow volume (initial landslide plus entrained sediment). In particular, lateral bank overflow – not observed during this event – is prevented when using the sediment entrainment model, even in very steep (≈ 60–65 %) and narrow (4–6 m) torrent channels. Predicted sediment entrainment volumes are sensitive to the initial landslide volume, suggesting that the model may be useful for both reconstruction of historical events as well as the modeling of scenarios as part of a hazard analysis.

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1. Introduction

Sediment erosion caused by debris flows strongly influences the bulking behavior of debris-flows (Iverson, 1997). The entrainment of sediment along the channel has been observed to considerably increase the volume of debris flows at many different locations (e.g. Hungr et al., 2005; Scheuner et al., 2009; Iverson et al., 2010; Berger et al., 2010a; Berger et al., 2011; Schürch et al., 2011; Iverson et al., 2011, McCoy et al., 2012; Tobler et al., 2014; Frank et al., 2015). Two recent extreme examples from the central Swiss Alps in the last decade showed significant bulking along the flow path. In the Spreitgraben catchment (2009-2011), the overall multi-surge event volumes increased to about 90'000 to 130'000 m^3 – mainly due to erosion along the active channel on the fan (Tobler et al., 2014; Frank et al., 2015). At the Rotlauigraben catchment (2005), about 2/3 of the total volume of 550'000 m^3 was eroded from the debris-flow fan during a multiple-surge debris-flow event initiated by the failure of a glacier moraine during an intense rainfall event (Scheuner et al., 2009). Therefore, the debris-flow erosion and bulking process should be included in debris-flow runout models to increase the accuracy of runout predictions including the overall runout distance, location and amplitude of lateral bank overflow but also – importantly for hazard assessment – the flow and depositional pattern on the fan (Gamma, 2000; Scheuner et al., 2009; Hussin et al, 2012; Han et al., 2015; Frank et al., 2015).

However, models which include bulking by debris flows are relatively new and their performance for practical applications has not yet been systematically investigated. Most entrainment modeling studies focused on the field site where the erosion data for the underlying entrainment modeling concept was collected and/or exclusively dealt with a single model application field site to test their concept for entrainment modeling (e.g. Han et al., 2015; Frank et al., 2015). Herein we describe the systematic application of the new RAMMS entrainment/bulking model (Frank et al., 2015) for several recent events in the Swiss Alps.

Computational debris-flow runout models, which usually neglect erosion, are often used to assess runout distance and pattern (Crosta et al., 2003; D'Ambrosio et al., 2003; Medina et al., 2008; Hungr and McDougall, 2009; Christen et al., 2012) and are therefore useful for hazard analysis where predictions of flow intensity (e.g. the spatial distribution of flow depth and velocity) are required (e.g. Scheuner et al., 2011). Because the debris flow process often was observed to cause significant entrainment of sediment which can strongly influence the flow (e.g. Dietrich and Dunne, 1978; Suwa and Okuda, 1980; Gallino and Pierson, 1984; Hungr et al., 1984; Benda, 1990; Pierson et al., 1990; Meyer and Wells, 1997; Vallance and Scott, 1997; Berti et al., 1999; Cannon and Reneau, 2000; Fannin and Wise, 2001; May, 2002; Wang et al., 2003; Revellino et al., 2004; Scott et al., 2005; Godt and Coe, 2007; Breien et al., 2008; Gartner et al., 2008; Guthrie et al., 2010; Procter et al., 2010; Berger et al., 2010; Berger et al., 2011; Schürch et al., 2011; Iverson et al., 2011; McCoy et al., 2012; Tobler et al., 2014; Frank et al., 2015), the importance of including entrainment and bulking debris flow runout modeling would be appropriate. Processed-based entrainment rates using algorithms which consider the material properties of the debris flow bulk (Crosta et al., 2003; D'Ambrosio et al., 2003; Medina et al., 2008; Deubelbeiss and McArdell, 2012) as well as pre-specified entrainment rates which pre-define the absolute volume of eroded material (Beguería et al., 2009; Hungr and McDougall, 2009; Hussin et al., 2012) have been introduced in numerical runout models.

Recently, we introduced an erosion algorithm in the RAMMS debris flow runout model for the assessment of debris flow erosion and bulking (Frank et al., 2015). The erosion algorithm uses a relation between basal shear stress and erosion based on an analysis of data from the Illgraben catchment, Switzerland (Frank et al., 2015; Berger et al., 2011; Schürch et al., 2011). The entrainment model was used to predict the overall erosion pattern and erosion volume at the first site where it was tested, the Spreitgraben, Switzerland. However, secondary erosion processes such as bank collapse and small torrential flood events between the debris flow events increased the uncertainty in the evaluation of the model. As a consequence, additional sensitivity tests were not made. In this study we therefore focus on testing the sensitivity of the RAMMS debris flow and entrainment model by assessing the sensitivity of total event volume (initial landslide volume plus volume of eroded sediment) to initial flow volume. This is especially important in hazard analysis where landslide scenarios are considered to trigger debris flows. For this sensitivity analysis, we evaluated two Alpine catchments with diverse topography and recent well-documented debris flows with volumes up to a few 10,000 m^3: the Bondasca catchment in Southeastern Switzerland and the Meretschibach catchment in Southern Switzerland.

2. Erosion modeling study sites and available data

2.1. Meretschibach catchment, Switzerland

The Meretschibach catchment is located in Southern Switzerland, adjacent to and east of the Illgraben catchment (Figure 1). The catchment area is about 9.2 km^2 and ranges from the summit of the Bella Tola mountain (3,025 m a.s.l.) to the confluence with a drainage channel (619 m a.s.l.) following into the Rhone River. Debris flows in the Meretschibach currently originate mainly in the Bochtür subcatchment (1.42 km^2 area) which is covered mostly by steep debris slopes with hillslope angles on the talus deposits of up to 60%. Patches of forest are present below the treeline (2,200 m a.s.l.) and at the margins of the catchment, and largely contiguous forest is found along both sides of the channel below an elevation of 1,600 m. The Bochtür subcatchment is underlain by Triassic sericitized quartzite and white quartzites of the Bruneggjoch formation (Gabus et al. 2008). The surface has several terrace-like structures have been mapped as sacking-type features (Gabus et al., 2008) and are likely sources of landslides and rockfall.

Sediment deposits are abundant on the steep slopes of the catchment, originating from a variety of mass wasting processes. Field observations of rockfall, the presence of damaged trees, and unpublished records in the community forestry archives records indicate that rockfall is a dominant process for generating sediment. Observations in the source area also indicate that dry ravel of gravel and sand is also common in the summer months when the hillslopes are relatively dry. According to the event inventory debris flows occur mainly between April and October (Szymczak et al. 2010). Small debris flows start and deposit in the upper catchment, often depositing at an area of lower slope located an elevation of approximately 2,000 m a.s.l. Convective storms or long duration rainfall events have been observed to mobilize these sediment deposits and initiate debris flows.

Georadar profiles on the west side of the unforested part of the Bochtür subcatchment as well a airborne georadar measurements indicate that the sediment deposits are up to 5 m thick (Fankhauser et al., 2015), although independent observations of the spatial distribution of sediment thickness are not available. However extrapolation of that value to other parts of the catchment must be made with caution because the profiles were made on a talus deposit, which may be interpreted as a depositional area on the hillslope, that exhibits little geomorphic evidence of debris-flow activity.

In the years 2013 and 2014 several instruments and devices were installed in the catchment. In October 2013, a meteorological station was installed above the initiation zone to measure precipitation, temperature and snow height. Inexpensive wildlife-observation cameras recorded images every 15 minutes during daylight were positioned along the most active western channel to document the changes along the active channel. A debris flow monitoring station was installed on 23 July 2014 (Oggier et al. 2015a). It consisted of three geophones and a radar to measure the flow stage. The radar is triggered by the geophones or the meteorological station and provides detailed recordings of the debris flow hydrograph at a resolution of 1 Hz.

During summer 2014, three debris flows occurred. Because the monitoring station was installed after the first event (20 July 2014), no hydrograph data are available for this event. Precipitation and hydrograph data for the debris flow events on 28 and 29 July 2014 indicate that the debris flow event on 28 July was triggered due to convective storms with large rainfall intensity (up to 3.3 mm / 10 min) while the event 29 July 2014 initiated after a few hours of steady rainfall with moderate intensity (up to 1.5 mm / 10 min). The pictures from camera 4 (see Fig. 1 for the location) clearly showed that the initiation of the event on July 28 took place between 19:45 and 20:15 (UTC +2), corresponding with the hydrograph measured at the observation station.

To obtain additional information about the initial volume and the spatial distribution of erosion, the height models from 15 July and 28 October were compared. The digital elevation model of 17 July was the result of a photogrammetry flight by swisstopo. The second digital elevation model (28 October) – which is a surface model (including vegetation) – was taken with a drone (Oggier et al. 2015b). The results indicate that the volume of the events eroded at the open debris slopes of

Bochtür was between 800 and 1,200 m^3. Due to additional erosion downslope of the Bochtür subcatchment, the total volume of the debris flow events was between 8,000 and 10,000 m^3.

2.2. Bondasca catchment, Switzerland

The Bondasca catchment in south-eastern Switzerland is a tributary to the Bergell valley (Figure 2). The catchment area covers about 20.9 km^2 . The geology is dominated by the Tertiary intrusion of the Bergell granite. Originating from within the North wall of Pizzo Cengalo, a rock avalanche on 27 December 2011 deposited about 1.5 10^6 m^3 of sediments in the upper catchment with a runout of up to two kilometers from the rock wall. The deposits are up to 17 m thick and cover an area of about 0.760 km^2 while the hydrological sub-catchment is about 1.18 km^2 defined by the point where the channel leaves the rock avalanche deposits at the lower end of the deposit.

The sudden sediment input from the rock avalanche was followed by several debris flows in the summer of 2012 (5 and 14 July, 25 August, 24 September) whereof the two events in July evacuated about 90'000 m^3 of sediments from the rock avalanche deposit. The debris flows originated mainly just below a flat-shaped rock face. Some of the debris flow surges are thought to have been triggered due to water accumulation at the toe of the wall causing firehose-type debris flow initiation (Figure 3B and 5B) e.g. as described by Godt and Coe (2007). The slope of the channel on the rock avalanche deposit varies between approx. 32° (≈ 71 %) below the flat-shaped rock face and regularly decreases to 15° (≈ 33 %) at the lower end of the rock avalanche deposit.

3. Debris-flow entrainment modeling

The goal of this study is to evaluate the erosion algorithm implemented in the RAMMS debris flow model (version 1.6.25) which has been previously described by Frank et al. (2015). In particular, the sensitivity of the predicted erosion to the input parameters will be investigated, and the data sets described above provide a new basis for evaluating the model. The previous study (Frank et al., 2015) focused on demonstrating that more realistic runout results can be achieved when including sediment entrainment and bulking into the runout model. However that study also left many unanswered questions regarding the sensitivity of the model to input parameters, especially the initial landslide volume, which was not possible to assess in the previous study. Herein we focus on describing the sensitivity of the model to the initial landslide volume, using the two well-documented events described earlier in the paper.

Although the RAMMS model and the erosion algorithm have been published elsewhere, they will be briefly described below to provide the necessary background information for understanding the model. The underlying numerical formulas of shallow water equation and the Voellmy friction approach used in the RAMMS debris flow model are presented in detail in Christen et al. (2010); the field-data based empirical entrainment model is described in Frank et al. (2015).

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3.1. Computational debris-flow model RAMMS

The RAMMS debris-flow model is based on 2D depth-averaged shallow water equations for granular flows in three dimensions given by the coordinates of the topographic surface of the digital elevation model in a Cartesian coordinate system (x, y, z) and at time (t) (Bartelt et al., 1999; Christen et al., 2010). The mass balance equation incorporates the field variables flow height $H\,(x, y, t)$ and flow velocity $U\,(x, y, t)$ and is given by

$$\dot{Q}\,(x, y, t) = \partial_t H + \partial_x(HU_x) + \partial_y(HU_y)\,. \quad (1)$$

where $\dot{Q}\,(x, y, t)$ describes the mass production source term and U_x and U_y represent the depth-averaged velocities in horizontal directions x and y (Christen et al., 2010). The depth-averaged momentum balance equations account for the conservation of momentum in two directions x and y:

$$S_{g_x} - S_{f_x} = \partial_t(HU_x) + \partial_x\left(c_x H U^2{}_x + g_z k_{a/p}\frac{H^2}{2}\right) + \partial_y(HU_x U_y)\,, \quad (2)$$

$$S_{g_y} - S_{f_y} = \partial_t(HU_y) + \partial_x(HU_x U_y) + \partial_y\left(c_y H U^2{}_y + g_z k_{a/p}\frac{H^2}{2}\right). \quad (3)$$

where the earth pressure coefficient $k_{a/p}$ is normally set to 1 when running the standard Voellmy-Salm friction approach, c_x and c_y represent topographical coefficients determined from the digital elevation model, S_g is the effective gravitational acceleration, and S_f the frictional deceleration in directions x and y (Christen et al., 2010). The frictional deceleration S_f of the flow is determined using the Voellmy friction relation (Salm et al., 1990, and Salm, 1993) and specifies the Coulomb friction μ scaling with the normal stress and the turbulent friction ξ depending on the velocity squared (Christen et al., 2012; Bartelt et al., 2013):

$$S_f = \mu \cdot \rho \cdot Hg\cos(\phi) + \frac{\rho g U^2}{\xi} \quad (4)$$

where ρ is the mass density, g is the gravitational acceleration, ϕ is the slope angle (approximately similar to the internal friction angle of the material), and Hgcos(ϕ) is the normal stress on the overflowed surface. The tangent of the effective internal friction angle of the flow material can be defined for the resistance of the solid phase (the term containing μ) which extensivly controls deceleration behavior of a slower moving flow. On the other hand, the resistance of the viscous or turbulent fluid phase (the term including ξ) prevails for a quicker moving flow (Bartelt et al., 2013).

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3.2. Debris-flow entrainment model

The entrainment model was constructed using field data from the Illgraben catchment in Switzerland (Frank et al., 2015). The entrainment model describes the maximum erosion depth as a function of channel-bed shear stress and the vertical erosion rate of channel-bed sediment erosion. In detail, the model is based on the analysis of differential elevation models from pre- and post-event DTMs by Schürch et al. (2011b). This provides the depth of net erosion in a cell as a function of the local shear stress acting on the channel bed at the base of the flow. Similarly, the rate of erosion is constrained to be at the rate reported by Berger et al., 2011,using *in situ* erosion sensors, also at the Illgraben channel. In the analysis of Schürch et al (2011b), flow heights were determined using values interpolated between lateral levees after each event and the shear stress τ is approximated using the depth-slope product:

$$\tau = \rho g h S \tag{5}$$

where ρ is the bulk mass density of the flow, h is flow height, and S is the channel slope. An approximation of the typical potential erosion depth at the Illgraben follows the 50% percentile line fit to the distribution of elevation change for four debris flow events (Fig. 3a in Schürch et al., 2011b). The erosion algorithm implemented in the RAMMS entrainment model is defined by the maximum potential erosion depth e_m and a specific erosion rate. The relationship between the shear stress estimated and the measured erosion (Schürch et al., 2011b) is described as a linear function of shear stress using a proportionality factor $\frac{dz}{d\tau}$ (Eq. 2). The maximum potential erosion depth e_m is calculated using a critical shear stress τ_c (= 1 kPa) and the proportionality factor $\frac{dz}{d\tau}$ (= 0.1 m kPa^{-1}) as a function of basal shear stress τ:

$$e_m = \begin{cases} 0 \;\; for\, \tau < \tau_c \\ \frac{dz}{d\tau}(\tau - \tau_c) \;\; for\, \tau \geq \tau_c \end{cases} \tag{6}$$

The average rate of erosion recorded at the erosion sensor site during the Illgraben debris flow event of 1 July 2008 (Berger et al., 2011) is used to define a specific erosion rate $\frac{dz}{dt}$.

$$\frac{dz}{dt} = -0.025 \;\; for\, e_t \leq e_m \tag{7}$$

When the critical shear stress τ_c is exceeded, sediment can be entrained from the channel. Entrainment stops when the actual erosion depth e_t reaches the maximum potential erosion depth e_m (Eq. 2). Normally, the specific erosion rate is implemented using the default value $\frac{dz}{dt} = -0.025\ \mathrm{ms^{-1}}$ (Eq. 3) as presented in Frank et al. (2015). However, the model also allows to account for larger or smaller erosion scenarios by either doubling the rate or cutting it in half. In this study, we will use these variable erosion rates for testing the sensitivity of the model.

3.3. Erosion model setup

3.3.1. Topographic resolution

This study focuses on the evaluation of the sensitivity of the predicted (modeled) channel-bed erosion in relation to the initial volume (e.g. initial landslide size) and the comparison of the model results and the erosion pattern observed in the field. The ability to reproduce the observed erosion patterns highly depends on a realistic representation of the channel morphology where the channel is clearly visible in the DTM (Deubelbeiss et al., 2010 and 2011; Scheuner et al., 2011; Hohermuth and Graf, 2014) and the channel dimensions (e.g. cross-sectional area) in the DTM have to be similar to what is observed in the field (e.g. Frank et al., 2015). In this study, the initial topographic data available for the Meretschibach catchment (described above) are on a square grid of 0.5 m for a channel with a width of 2 to 4 m. At the Bondasca catchment data are available on a 2 m square grid for channel varying in width from about 5 to 20 m. Although a channel width to DTM grid spacing ratio of more than 5 to 10 would probably produce more accurate results, such data are generally unavailable and the increase in the time for a simulation would be impractical.

3.3.2. Erosion model starting condition: block release and input hydrograph

The type of initial release mechanism, lock release or input hydrograph, can be determined based on field observations, potential model constraints and previous modeling experience using the RAMMS debris flow model (Bartelt et al., 2013). Recent debris flow modeling studies (Deubelbeiss et al., 2010; Deubelbeiss et al., 2011; Han et al., 2015) summarized that debris flows in steep channels are mostly triggered by the sudden destabilization of material originating from lateral bank collapses or dam-type deposits located within the channel itself. Han et al. (2015) concluded that a hypothetical scenario such as the breaking of a dam – which they used to start their erosion model simulations – provides a stable and consistent release method. Deubelbeiss et al. (2010 and 2011), for a case study in the Swiss Alps, suggested that the block release method is most appropriate method for small to moderate initial volumes ranging from 1 m^3 up to 100 m^3 using the RAMMS debris flow model. The alternative release method using a discharge hydrograph seems to be more suitable for larger initial volumes (Deubelbeiss et al., 2010 and 2011) (> 100 m^3) which – in general – might be plausible for the larger channel of the Bondasca catchment.

The main problem with the block release is that the initial flow depth, width, or length of the initial landslide can be unrealistically large in comparison to field observations. Users have to resort to such large initial landslide volumes because most models do not allow for erosion along the

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channel path. The total debris flow volume, typically measured in the deposition zone, is often used as the initial landslide volume, thereby implicitly ignoring the possibility that channel-bed erosion and flow bulking occur (Frank et al., 2015). The input hydrograph starting condition in RAMMS was intended to help circumvent this problem by allowing users to specify an influx of debris as a function of time at a point lower in the watershed (e.g. just above the fan apex).

The block release volume is calculated by defining a specific block release height (with a precision of 1 cm) based on a pre-defined release area. The model assumes an instantaneous failure of the landslide. The initial landslide surface elevation is then set to the initial elevation of the land surface using an automatic procedure in RAMMS (the "subtract release from DTM" option in RAMMS introduced in version 1.6.45). The main advantage of this procedure is that it prevents unrealistic lateral spreading of the initial landslide mass in comparison with a landslide "block" situated on top of the land surface.

3.3.3. Specified erosion rates

As a basis for comparison of the sensitivity of the erosion algorithm, we hold constant the default erosion model coefficients (critical shear stress τ_c, potential erosion depth as a function of basal shear stress $\frac{dz}{d\tau}$, erosion rate $\frac{dz}{dt}$) described above. In the previous study (Frank et al., 2015) we demonstrated that an erosion rate of $\frac{dz}{dt}$ = 2.5 cm s^{-1} based on field data from the Illgraben catchment, Switzerland (Berger et al., 2011) produces plausible results for the much steeper Spreitgraben catchment. The catchments described in this paper are different in size and slope, so one might expect some variation in erosion rate. However, the erosion algorithm in RAMMS allows for rates up to $\frac{dz}{dt}$ = 5.0 cm s^{-1}), with an option to include a shape file describing where erosion may occur e.g. to account for engineering structures such as check dams or sills, or natural features such as bedrock, where significant erosion is not expected during one debris-flow event. For comparison we also used a rate of $\frac{dz}{dt}$ = 1.25 cm s^{-1} based on a lower rate from Berger et al. (2011).

4. Erosion and entrainment: observations and modeling results

4.1. Erosion patterns and entrainment model calibration

The observed erosion patterns are the basis for calibrating the RAMMS model coefficents, in particular the friction coefficients ξ and μ are systematically adjusted in successive model runs, until a satisfactory model result is achieved. The erosion pattern is derived by assessing the difference between the digital elevation models. In both study areas, a measured erosion pattern caused by one single debris flow event is not available. We therefore focus on the spatial

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distribution of erosion and deposition, instead of attempting to exactly predict the spatial change due to the debris flow process.

In the Meretschibach, the change in the DTM includes the erosion due to three debris flow events which appear to have originated on an open-slope talus deposit (Figure 3A). The location of the release area at the Meretschibach corresponds to the upper most visible erosion scar visible in the DTM analysis and as described above includes the erosion due to three debris flow events between July 17 to October 28, 2014 (Fig. 3A). Therefore, the release area was placed within the channel, where up to 2.5 meters of erosion was observed (upper end of the blue polygon at about 1750 m a.s.l. in Fig. 3A.). The location is just below a bedrock step intersecting the main channel at about 1800 m a.s.l. Further monitoring at the upper Bochtür subcatchment using interval cameras and conducting field observations on the site itself confirmed that at least some of the debris flows most likely initiated at this location.

We calibrated the RAMMS model using an initial block release volume of 10 m^3 which corresponds to the channel depth of 1-2 m and a width of 2-4 m at this location. To keep the initial volume within the channel and prevent unrealistic lateral outflow, no-flux boundaries were created at the lateral sides of the initial landslide block. Within the middle and lower channel sections (Fig. 3A, blue polygon), the observed runout and relative erosion patterns can be best reproduced using Voellmy friction parameters $\xi = 200$ ms^{-2} and $\mu = 0.6$ (Fig. 3B2). The modeled velocities of 6-9 ms^{-1} using $\xi = 200$ are plausible, although independent field data are not available for comparison. The parameter combination $\xi = 200$ ms^{-2} and $\mu = 0.7$ results in overbank flow along both sides of the middle channel, which was not observed in the field (Fig. 3C2). There were neither deposits outside of the channel nor were levees deposited along this entire channel reach (Fig. 3A, blue polygon). In contrast, the erosion pattern using $\xi = 200$ ms^{-2} and $\mu = 0.5$ resulted in an even distribution of erosion along the entire channel length, which is inconsistent with the field results which showed locations of deeper erosion depths (Fig. 3A). Within the normal range of the ξ parameter (Bartelt et al., 2013) the differences in flow and erosion patterns were small in comparison to those resulting from variations in μ, and are therefore not described herein. Hence, the further model runs were conducted using the best-fit parameters $\xi = 200$ ms^{-2} and $\mu = 0.6$ in the sensitivity analyses described in subsequent sections.

In the Bondasca catchment, the differential elevation model includes both the rock avalanche deposit (27 December 2011) and the erosion due to one debris-flow event (5 July 5, 2012) (Fig. 5). The upper end of channel erosion is located just below a planar outcrop of bedrock (Fig. 4B) corresponding to the likely location debris flow initiation zone (Fig. 5C). The surface runoff channels along the west side of the wall and runoff across the wall surface (Fig. 4B) converge on the sediments at the bottom of the rock wall (see pictures from 2014 in Fig. 5). This scenario suggests a firehose-type debris-flow initiation (e.g. Godt and Coe, 2007). Hence, this location was used for the runout modeling.

The observed erosion along the main debris flow channel (Fig. 5C) – resulting from the two debris flow events in July 2012 – were used to calibrate the RAMMS model within the upper two thirds of the study reach (Figure 4B, brown polygon) by varying the model parameters ξ and μ. The best fit was found with the parameter combination $\xi = 400$ ms^{-2} and $\mu = 0.3$. However, the observed elevation change also includes secondary processes such as lateral bank collapse and the deposits of debris-flow snouts and levees within the channel. Channel sections where the events eroded into the deposits present can also be identified by the stratigraphy in the field.

4.2. Entrainment modeling and runout patterns

The runout of a (landslide-type) block release of 10 m^3, neglecting erosion (Fig. 6A) results in maximum flow heights smaller than 0.5 m and the flow stops in the channel upstream of the deposition zone. By contrast, including debris-flow erosion (Fig. 6B) leads to a more realistic flow pattern consisting of flow within the channel reaching the deposition zone without any lateral outflow. For comparison, if the total event volume (≈ 1,555 m^3) is released as a landslide and the debris-flow is not allowed to erode the channel (Fig. 6C), the runout shows overbank flow along the upper channel reaches below the initiation area. The last scenario is a typical example of how debris-flow runout models are used when the total event volume is known. These results illustrate the ability of the runout model to better predict the erosion pattern if the channel-bed erosion and bulking process is included in the model.

4.3. Erosion model sensitivity testing

The results show that the total volume of eroded sediment, at both field sites, depends strongly on the initial landslide volume. At both the Meretschibach and the Bondasca catchments, there is a strong increase in the amount of sediment entrained and consequent increase in debris-flow volume (Fig. 7) for relatively small increases of the initial landslide volume. At the Meretschibach catchment, the erosion model – using the default maximum erosion rate $\frac{dz}{dt} = 2.5$ cm s^{-1}– shows the highest sensitivity to the total erosion volume between 2 and 3 m^3 of initial block release (e.g. initial landslide volume). Above 4-5 m^3 of initial block volume the increase of the total erosion volume within the erosion domain remains approximately constant. The cause for the rapid increase is related to the critical shear stress in the entrainment algorithm. Small initial landslides do not generate enough shear stress to initiate erosion, whereas larger landslides can cause erosion over the entire computational domain.

If we double the erosion rate to $\frac{dz}{dt} = 5.0$ cm s^{-1} based on field estimates reported by Frank et al., 2015 for the Spreitgraben catchment, a similar pattern is observed in the relationship between total erosion volume as a function of initial release volume. However the erosion volumes are 3 to 5 times larger than the ones resulting from the default erosion rate at the same initial release volume.

In contrast, implementing only half the default maximum erosion rate ($\frac{dz}{dt}$ = 1.25 cm s^{-1}) for low erosion scenarios decreases the sensitivity to initial volume in an analogous manner.

Similar trends in total erosion volume as a function of initial block release (landslide) volume are observed at the Bondasca catchment. However, the model only starts to predict significant erosion volumes for block releases exceeding 20 m^3, and the progressive increase in total erosion volume as a function of initial block release volume is somewhat less steep. For the default erosion rate $\frac{dz}{dt}$ = 2.5 cm s^{-1} (Frank et al., 2015), total erosion volumes increase most strongly between initial volumes of 20 to 100 m^3. The topography at the Bondasca catchment is somewhat less steep and more variable, which may help explain these differences. Doubling the default erosion rate at the Bondasca catchment results in the onset of erosion for initial volumes between 20 and 30 m^3. When reducing the default erosion rate to half of the default value, the erosion model depicts a somewhat less sensitive reaction of the erosion model than using the default rate.

5. Discussion

The total erosion volumes observed in the sensitivity tests (Fig. 7) indicate a strong sensitivity to block release volume (initial landslide volume) over a relatively narrow range of block release volumes. This result is based on the assumption that the entire landslide fails instantaneously and not progressively as a sequence of smaller landslides over a longer period of time. Information on the style of initial landslide failure are not available for either field site, therefore we focus the discussion on other factors related to the runout modeling. One striking difference between the two field sites is that the size of the block release necessary to cause significant erosion is an order of magnitude larger at the Bondasca site. The channel cross-sectional area where the flow travels and therefore where the erosion model is active is different at the two field sites. The Meretschibach is substantially steeper (50 to 65% vs. 15 to 35%). This results in larger shear stresses at the Meretschibach for the same initial landslide thickness, because the shear-stress varies as the product of initial release thickness, flow density, and channel slope. Other factors such as differences in channel-bed roughness may also be important, however the Voellmy friction relation within RAMMS does not explicitly consider channel-bed roughness.

In the RAMMS debris flow model, the development of the flow properties is controlled by the Voellmy friction parameters ξ and μ (described in section 3.1) where ξ is the dominant control over the flow velocities when the flow is moving rapidly and μ controls the runout distance. The ξ parameter was found in this study to have a relatively small influence over the flow behavior in comparison with the Coulomb friction term μ. The RAMMS manual (Bartelt et al., 2013) suggests using the tangent of the fan slope as first estimate to determine μ. As described in the calibration procedure (section 3.2), this corresponds to relative erosion patterns measured by differential DTM analysis. Hence, we conclude that the tangent of the channel slope can be used as a first approach to define parameter μ also for the erosion model, which was also found to be useful by Frank et al. (2015) in the first application of the model.

Morphological effects influence the erosional behavior of the field data based erosion model. The Bondasca channel is more variable in width and planform direction compared to the comparably uniform and straight Meretschibach channel. This difference will cause larger spatial variability in shear stress at Bondasca channel and therefore the channel will have a more variable onset of debris flow erosion along the length of the channel. In the Bondasca catchment, the channel where erosion takes place is significantly wider (4-10 m) than in the Meretschibach (1-3 m). On the one hand, the flow can laterally spread more often in Bondasca than in the Meretschibach, thereby locally reducing flow height, shear stresses and maximum potential erosion depth. On the other hand, once the critical shear stress is exceeded, the potential erosion depth tends to increase more rapidly in a narrow channel such as in the Meretschibach channel.

Another difference between the Meretschibach and the Bondasca channels is that the Bondasca channel bed has a rougher surface with more scours holes, and larger blocks within the channel which are similar in size to the nominal width of the channel. The model does not consider local variations in erodibility due to the presence of large blocks, so local scour patterns in the field around the large blocks are not present in the model results. Prancevic and Lamb, (2015a) suggested that in rough mountain channels the large particles can be interlocked and hence more stable. In contrast, local concentration of the flow between such large blocks may cause locally very large shear stresses and corresponding large erosion rates. However, we do not have enough information on the mobility of the large blocks, so this question cannot be addressed in more detail herein.

The current version of the RAMMS model with erosion (version 1.6.45) does not adjust the elevation of the bed when erosion occurs. The erosion can be subtracted from the initial DTM as a post-processing step within the user interface, e.g. for modeling subsequent surges. This issue was discussed at length by Frank et al (2015), and it can potentially complicate the interpretation of erosion patterns resulting from multiple debris flows. Insufficient field data are available to help constrain the events described herein.

Further assessment of the relation of the total erosion volumes depending on the initial volumes can be made by calculating a bulking factor. The bulking factor BF is the ratio between the total erosion volume V_{ero} to the initial volume V_{ini} :

$$\mathrm{BF} = V_{ero}/V_{ini} \tag{8}$$

At the Meretschibach channel, the bulking factor is ≈ 200 when the erosion model using the default erosion rate and an initial volume of 3 m^3 (Fig. 8). The BF reaches a peak $BF_p \approx 300$ at a release volume of 4 m^3. It then drops to a BF ≈ 30 for an initial volume of 100 m^3. The model simulations using the doubled default erosion rate show a bulking factor peak $BF_p \approx 1{,}800$ for an initial release volume of 2 m^3; half the default erosion rate shifts this peak to 50 m^3 for the initial volume but the corresponding peak bulking factor drops significantly down to ≈ 14.

The behavior of the bulking factor for the default erosion rate at the Bondasca catchment is relatively smooth when compared to that at the Meretschibach. A peak bulking factor can be identified somewhere between 200 and 500 m^3 but the value is lower in comparison (≈ 11) for the default erosion rate. The doubled rate leads to a peak bulking factor BF_p of ≈ 700 at a release volume of 30 m^3. That is still large compared to examples in the literature (BF from 10 to 50 reported by Berti et al., 1999 and Vandine and Bovis, 2002). Nevertheless, a several hundred fold increase of the debris flow volume due to bulking is plausible for extreme erosion cases. Larger erosion rates might be expected for pycroclastic deposits (not present in the catchments described herein) or due to the presence of very recent rock avalanche deposits which may contain firn-ice-debris mixtures (e.g. Spreitgraben, Tobler et al., 2014; Frank et al., 2015). Large erodibilities may be expected at the Bondasca catchment because the rock avalanche event occurred during winter and may have contained significant amount of snow.

Due to the very long (≈ 4 km) and flat (≈ 15%) channel section in the middle segment of the Bondasca catchment, the estimated deposition volumes (≈ 40,000 m^3) above the inlet of the Bondasca river in the central valley are highly influenced by further erosional and depositional processes along the channel.

6. Conclusion

Debris-flow runout predictions can be improved when considering the increase in flow volume along the flow path. Using a recently-introduced empirical erosion algorithm within the RAMMS 2D runout model (Frank et al., 2015) we illustrate that runout patterns at the Meretschibach and Bondasca catchments, in Switzerland, can be accurately modeled. When calibrated with field data, the model produces more realistic runout patterns compared to simulations which do not consider entrainment and bulking. In particular, we could show that even in very steep (≈ 60–65 %) and narrow (4–6 m) torrent channels, lateral overflow – not observed in the field case – is prevented when applying the entrainment model. However the model results can be quite sensitive to the volume of the initial block release in the model which corresponds to the initial landslide volume. The predicted erosion volumes are sensitive to the initial debris flow volume, with bulking factors approaching 2000 predicted by the model, depending on the scenario considered. However, the results are also sensitive to slope angle and channel morphology. The two field sites differ substantially: the Meretschibach catchment is very steep with a straight and narrow channel, whereas the Bondasca channel is less steep but morphologically more complex, yet the calibration procedure is the same as for the standard RAMMS model which does not include the entrainment process. The overall method presented herein is useful for case studies where sufficient data are available to constrain the model results. However, more case studies have to be conducted to develop a more comprehensive recommendation for modeling the runout of erosive debris flows in natural terrain.

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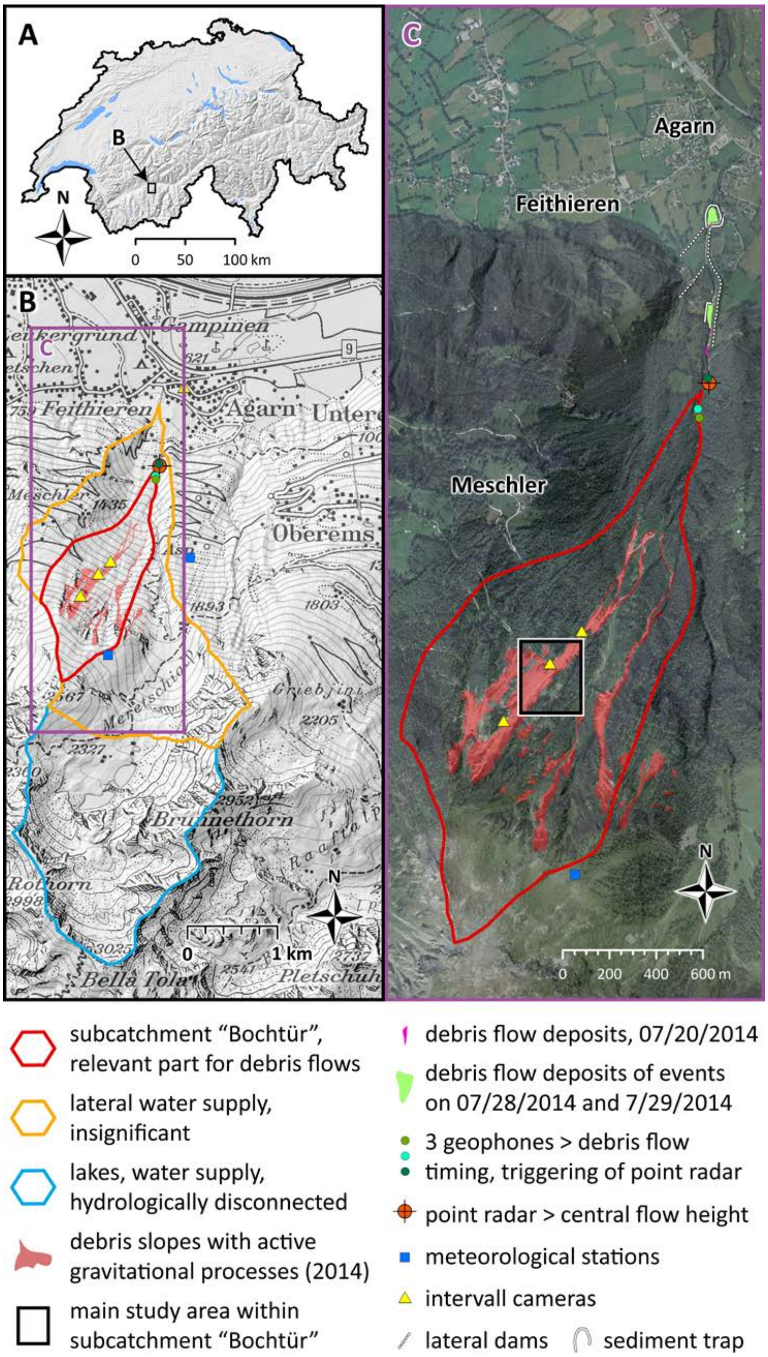

Figure 1. A. Location of the Meretschibach catchment in Southern Switzerland. **B.** Subcatchments of the Meretschibach and locations of the instrumentation site and data available for the erosion model analyses **C.** Initiation zone of the July 2014 events and camera positions. The main study

channel reach for the model testing is located in the middle part of "Bochtür" (black-white retangle), swissimage©2014, swisstopo (5704 000 000) (2014).

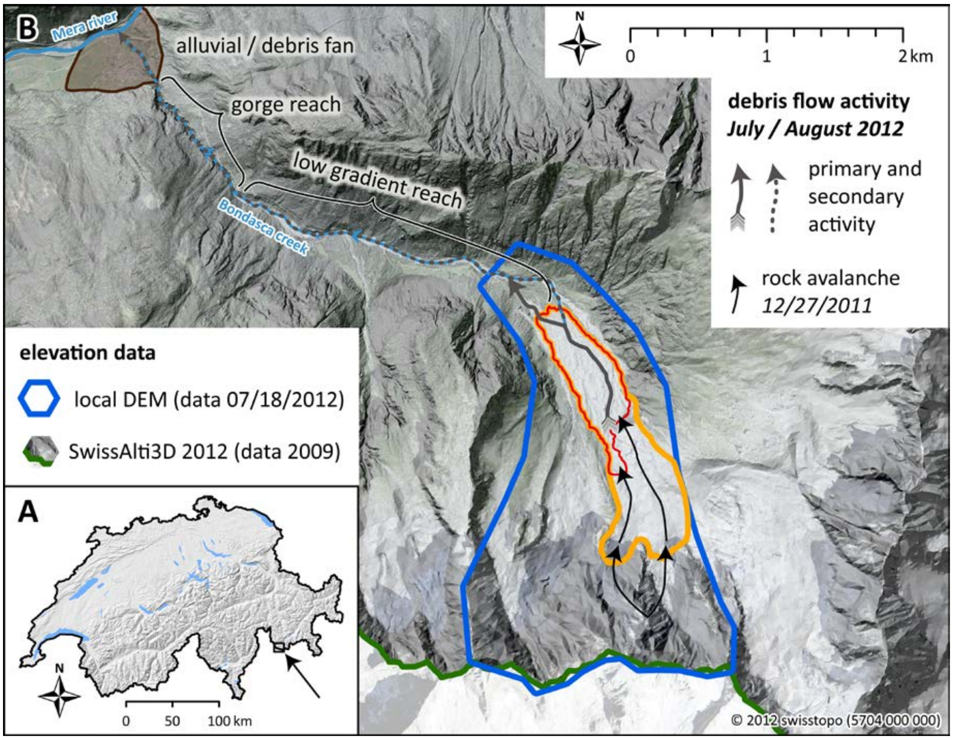

Figure 2. A. Location of the Bondasca catchment in south-eastern Switzerland close to the border to Italy. **B.** Perimeter of the 27 December 2011 rock avalanche deposit, including the main deposition area (yellow polygon) and the deposits lower-elevation deposits which have been partially exposed to erosion by debris flows in 2012 (red polygon). The 2012 post-event digital elevation model (lidar, blue polygon) is from 18 July 2012 (data courtesy of the Amt für Wald, Canton Graubünden). Pre-event digital elevation model (lidar) for 2009 is from the SwissAlti3D (version 2012) data set from swisstopo, ©2012, swisstopo (5704 000 000) . The grey solid arrow indicates the main debris-flow channel formed in 2012.

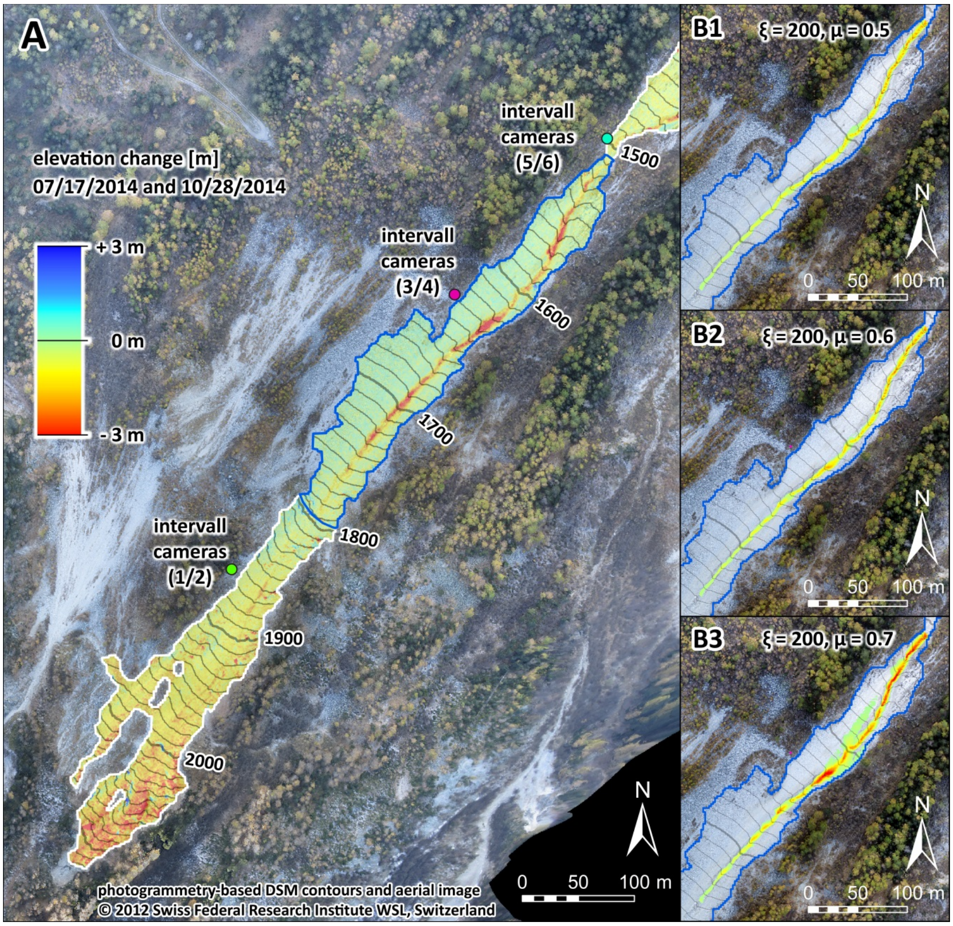

Figure 3. Calibration of modelled erosion patterns (**B1 to B3**) to the observed erosion depths (**A**) in the upper open debris slopes of the "Bochtür" catchment (Meretschibach) by varying values for the friction parameter μ. The blue polygon demarks the area where a differential DTM is available.

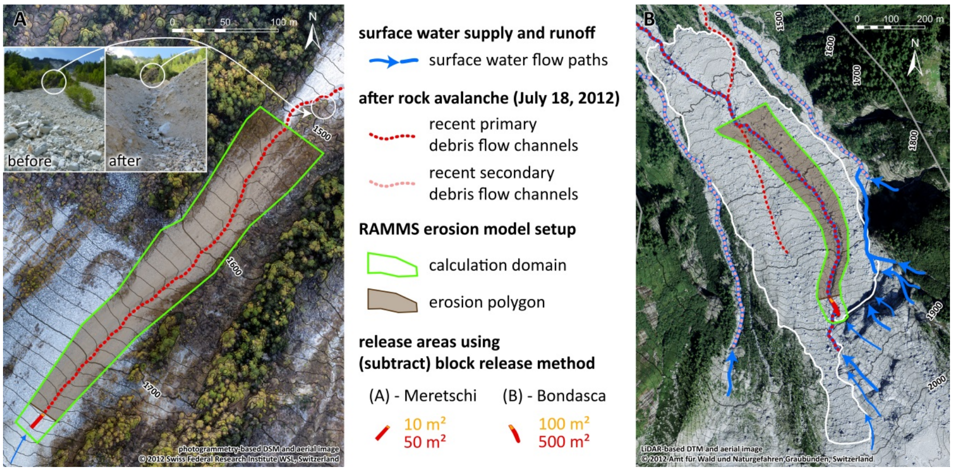

Figure 4. Erosion model configuration for the model simulations showing the initial block release areas in the Meretschibach catchment (**A**) and the Bondasca catchment, Switzerland (**B**). The hillslope is erodible within the brown shaded polygon.

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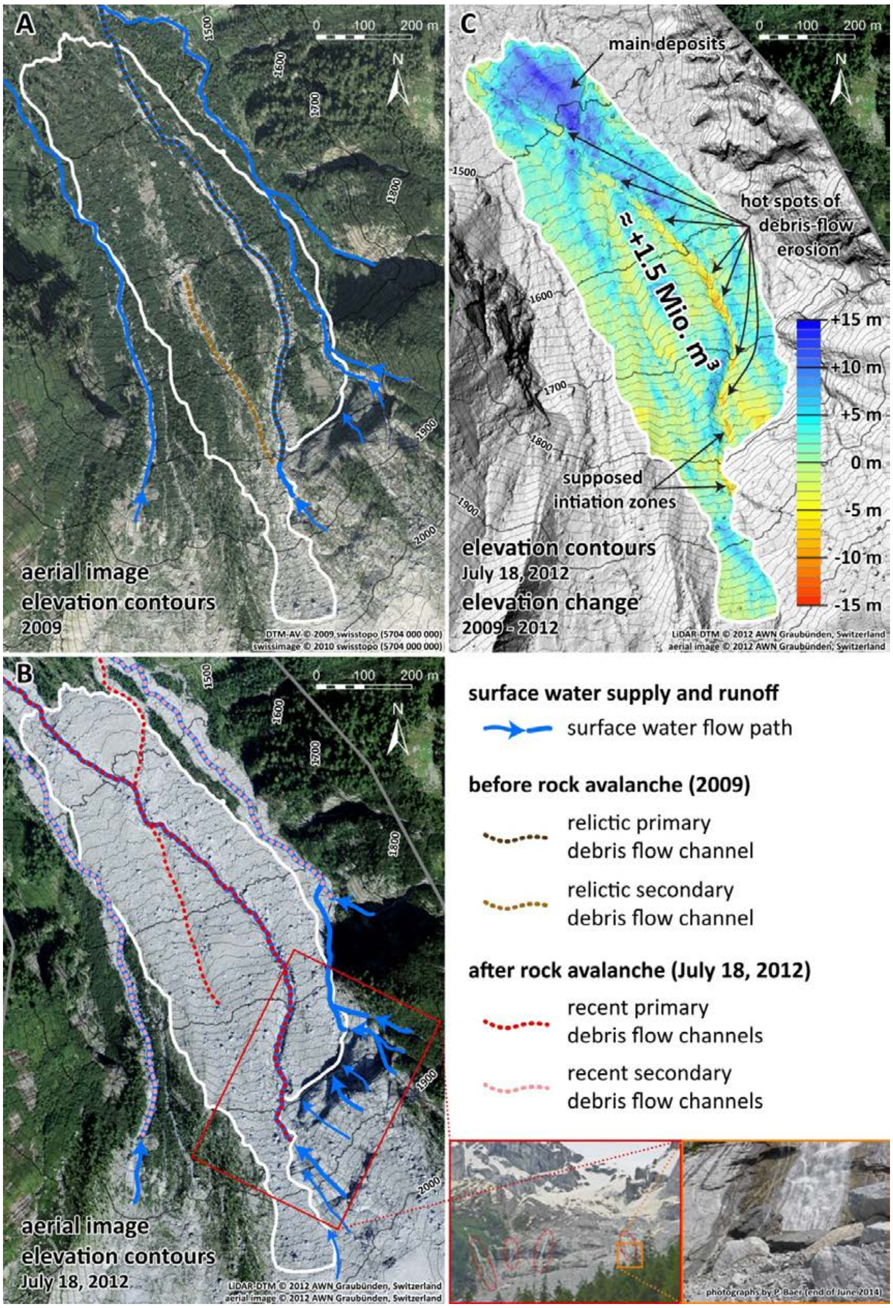

Figure 5. Overview of rock avalanche deposits, subsequently formed debris flow channels, and the resulting overall elevation change in the Bondasca catchment (A, B). The elevation change map 2009 to 2012 (C) includes both the rock avalanche (≈ 1.5 Mio m^3 on 27 Dec. 2011) and the first two debris flow events (5 and 14 July 2012).

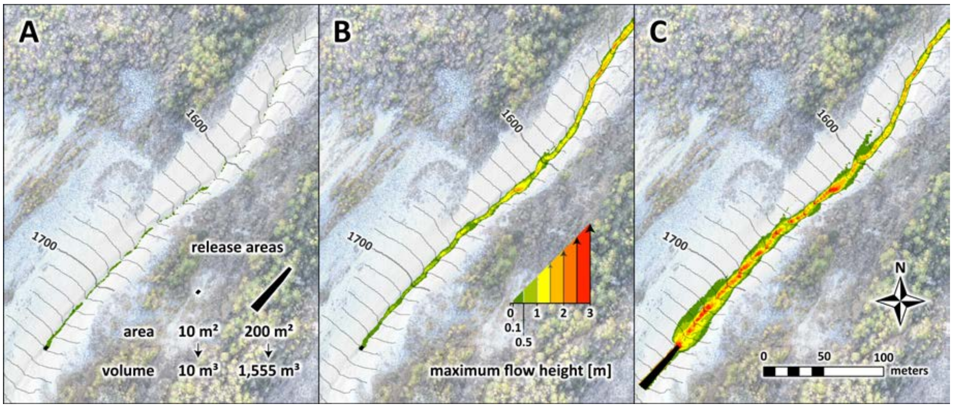

Figure 6. Comparison of runout patterns at "Bochtür" in the Meretschti catchment. The debris flow modeling is conducted using a (subtract) block release volume of (**A**) 10 m^3 and no-entrainment modeling, of (**B**) 10 m^3 and entrainment modeling as well as a total (subtract) block release volume of (**C**) 1,555 m^3 (sum of release and eroded volume from (**B**)) and no-entrainment modeling.

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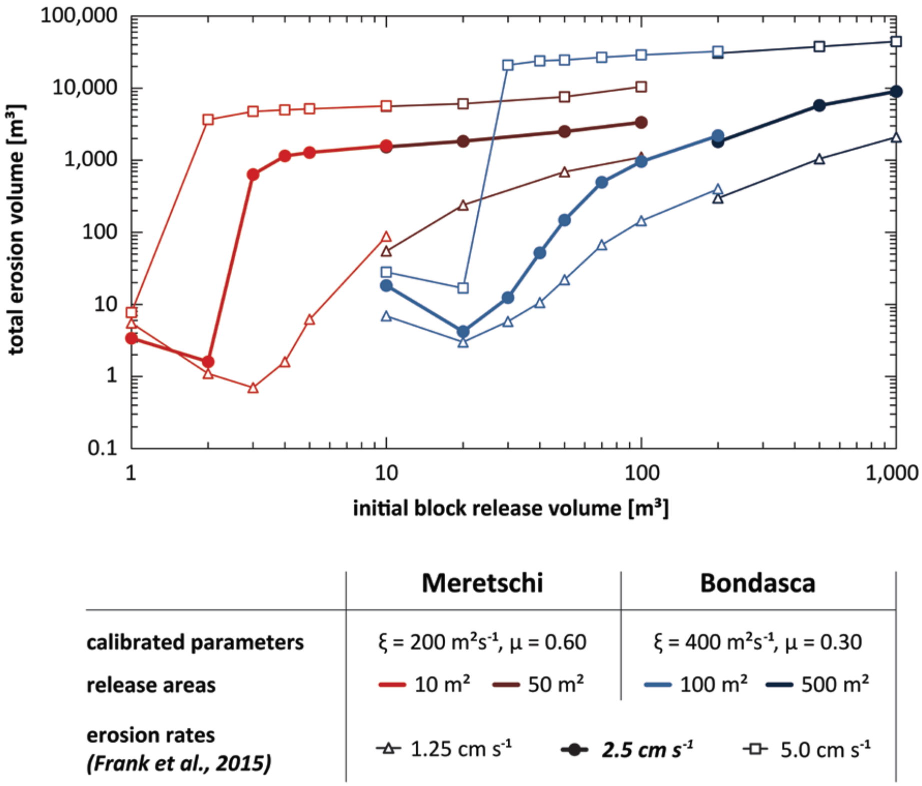

Figure 7. Sensitivity of modeled erosion volume to initial block release volume in the Meretschibach and in the Bondasca catchments.

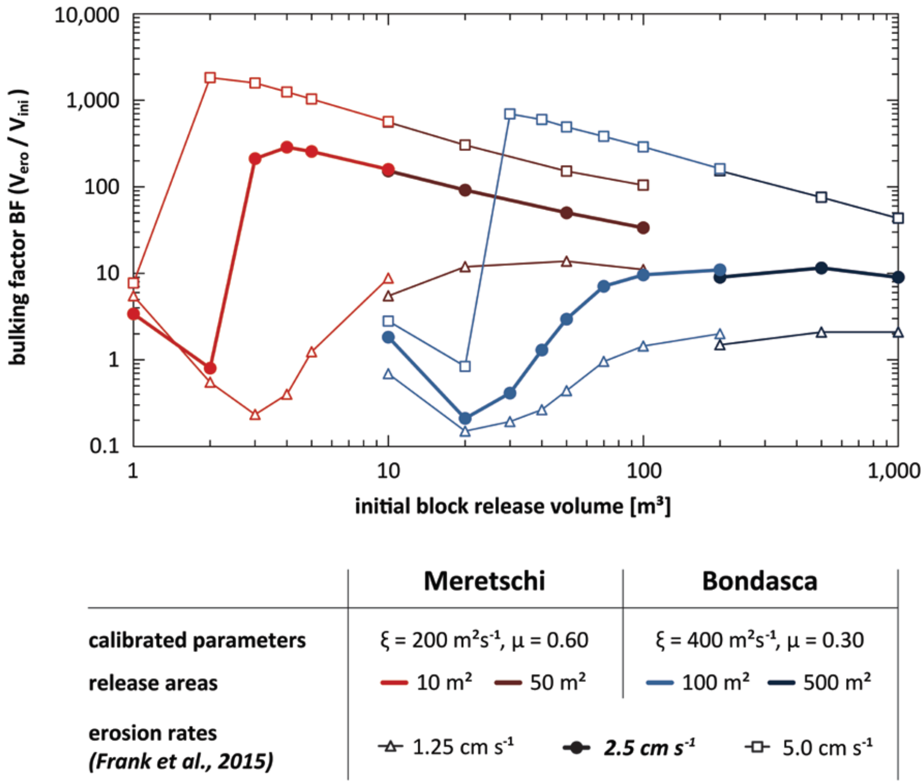

Figure 8. The bulking factor BF = V_{ero}/V_{ini} of the modeled total erosion volume V_{ero} [m^3] to initial block release volume V_{ini} [m^3] in the Meretschibach and Bondasca catchments.