Response file on **"Debris flow modeling at Meretschibach and Bondasca catchments, Switzerland: sensitivity testing of field data-based erosion model"** by F. Frank, B.W. McArdell, N. Oggier, P. Baer, M. Christen and A. Vieli

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Reviewer 1: Z. Han

Reviewer 2: Anonymous

Editor: M. Keiler

(A) Comments from referees/public

(B) Authors response

(C) Authors changes

General comment by the authors

In addition to the comments from the Editor and Reviewers, a few additional minor changes to the text have also been made for clarity. These changes are also visible in the document highlighting the changes made to the manuscript. A few formal errors (e.g. typos, etc.) were also fixed.

PLEASE NOTE: The page/line(s) references provided by **(A) reviewers and editor** and **(B) Response** still refer to first submission manuscript.

But <u>all</u> page/line(s) references given by the authors (**"(C) Changes"**) in this document refer to the new resubmission manuscript (which highlights track changes in RED and text moved in GREEN).

General comments by Reviewer 1

(A) Reviewer 1: This paper aims to simulate debris-flow process by considering bed erosion along the path. As erosion is a complex natural process and plays a very crucial role both in debris-flow dynamics, transportation, run out and deposition process, it is a very important research topic. To do so, this paper attempts to combine an empirical entrainment model which has been previously introduced by authors into the RAMMS model. The sensitivity of the developed model is tested by applying the model to two debris-flow events in Switzerland. The results show some interesting erosion and flow patterns.

(B) Response: We are grateful for the thorough reading of the manuscript and the helpful review, which we think will substantially improve the manuscript. We address both the general and specific comments below.

(C) Changes: Please see further general comments of Reviewer 1 below and "Specific comments".

(A) Reviewer 1: Generally, this is a straight-forward development of the RAMMS model for the simulating bed erosion in debris flows. The paper is well illustrative and authoritative. The authors build upon their previous work and extend the RAMMS model to the erosion simulation. It is a major contribution and is sound. However, in my opinion, the major limitation of this paper is that the described debris-flow entrainment model is rather sensitive to the empirical coefficients, and these coefficients are not well illustrated in the paper. Indeed, the authors show us a sensitivity analysis of erosion volume to the initial volume, erosion rate and calibrated parameters and in Fig.7. As they mention, the value of these parameters are suggested by the previous study in the same region, e.g., the erosion rate dz/dt = 2.5 cm/s. However, the rational range of these parameters may be different in other regions, there is a need to explain how to determine these parameters. The paper could be improved and made more accessible by further exploring these empirical parameters. I recommend this paper for publication after major revisions.

(B) Response: Yes, we agree that the results of the model are quite sensitive to the empirical coefficients and the initial conditions, which is the main focus of the manuscript. The uncertainties in the field data (e.g. initial flow volume, volume of eroded sediment, magnitude of erosion) are generally fairly large. It may be by chance that the same coefficients deliver plausible results at three different debris-flow sites in the Swiss Alps when in fact it may be possible to refine the coefficients in cases where more precise field data are available. For this reason, all of the coefficients can be adjusted when more or better results become available. We intend to edit the manuscript to make this point more clear. To further explore the influence of the parameter combinations, we also intend to highlight the inherent feedback in the model, whereby a rapid erosion rate results in an increase in flow depth leading to larger shear stresses and then to even larger potential erosion depths. This potentially explains the very rapid growth of debris flows, which is has been observed in some natural field cases and also in laboratory experiments involving realistic debris-flow sediments (e.g. Logan & Iverson, 2007, Video documentation of experiments at the USGS Debris-flow flume 1992-2006, U.S. Geological Survey Open-File Report 2007-1315).

(C) Changes: Editing of the manuscript was processed in sections 4.2. (page 12) and 5. (discussion, starting at page 14) to make the points mentioned above more clear. The reference list has been updated accordingly.

General comments by Reviewer 2

(A) Reviewer 2: The paper deals with bed entrainment for debris flows in Switzerland using numerical modelling. The topic is of interest for the Journal and the specific issues of this paper are relevant to scientists and practitioners. Some (mandatory) changes are required to improve the paper before acceptance. The list of specific comments and suggestions is given in the attached file.

(B) Response: We are grateful for the helpful specific comments, especially literature citations which were not cited in the last version of the manuscript. These comments should substantially improve the manuscript. Please see our responses to the specific suggestions below.

(C) Changes: Please see “Specific comments”.

Specific comments by Reviewer 1

(A) Reviewer 1: Page 6, 195-196. The authors mention that the slope angle φ in the deceleration term S_f is similar to the internal friction angle of the material. Does it mean that S_f will be the same when at a steep slope and a gentle slope? Please check it.

(B) Response: Yes, it is true that the slope angle is similar to the angle of internal friction at this slope. However we do not imply that the value of S_f in the Voellmy friction relation is the same as the value of internal friction in general. We intend to remove this comment to avoid confusion for readers, because the Voellmy friction angle is typically selected based on other criteria.

(C) Changes: The comment in parenthesis "(approximately similar to the internal friction angle of the material)" was removed (page 8, lines 208-209).

(A) Reviewer 1: Page 7, 221-222. The critical shear stress τ_c determines the maximum potential erosion depth e_m, the erosion will not be existed at the area where $\tau < \tau_c$. For this reason, the critical shear stress is a key parameter for controlling the shape of erosion area and erosion depth. But the authors superficially use an empirical value 1 kPa in the paper, and no sensitivity analysis is made. It seems that they could simply test and provide results on how sensitive the simulation is to the choice of the critical shear stress τ_c.

(B) Response: Yes, we did not include results for the sensitivity analysis regarding the value of the critical shear stress, because the influence is generally much smaller and the range of critical shear stress values is small. We disagree that our choice and use of 1 kPa is superficial, because this value based on indirect observations by Schürch et al. (2011, cited in the original manuscript) and it serves a general purpose of describing that torrent channel beds are typically not eroded by small debris flows. We do not know the precise value in the field at any field site however a value near 1 gives a good fit to the data set we used for that analysis. Using a Shields's criteria for critical shear stress from river engineering, we find a critical shear stress which is smaller than 1, depending on the grain size on the channel bed. We discussed the issue of different critical shear stresses in our first erosion model application at the Spreitgraben catchment (Frank et al., 2015). Therein, we described smaller debris flood events which produced about 4-5 kPa of shear stress but did not show any significant erosion in the channel bed, i.e. suggesting that the critical shear stress τ_c may be somewhat larger in the Spreitgraben than in the Illgraben channel.

We propose inserting a paragraph discussing this issue in more detail, especially noting that the value is close to zero, or could be set to zero if field evidence indicates that erosion is always expected. However we will gladly include such a plot as an additional figure if this is desired by the editorial staff.

(C) Changes: We performed additional model runs to assess the sensitivity of the model results to the critical shear stress value. We also changed the comparison from the *bulking factor* to *volume growth* (Hungr et al., 2005). For this assessment, we selected the Meretschibach catchment because it has a simple single-channel morphology channel geometry and therefore serves as a clear case for illustration. The results are presented in the new Figure 8. The former Figure 8 is now Figure 9 - which we also updated to show results as volume growth instead of using the bulking factor BF. The values for BF have all been recalculated as VG values and the manuscript has been updated accordingly. We added a short description of the results in section 4.3 (pages 13/14, lines 402-411)., introduced the VG equation (Eq. 8, moved to section 4.3, page 13, line 407), and now we discuss the results as presented in Fig. 8 in a new paragraph in the middle of the discussion section (page 16).

(A) Reviewer 1: Page 11, 360. The total erosion volume remains approximately constant when the initial volume exceeds a certain value. How to explain this phenomenon? Is this because the maximum erosion depth e_m is reached as controlled by the critical shear stress τ_c = 1 kPa? As such, it seems that the choice of τ_c as a model parameter should be discussed to a greater degree, especially if you want your method to be used more widely on debris flows of varying properties.

(B) Response: In fact, the volume continues to increase (the y-axis is a logarithmic scale). The maximum erosion depth e_m may be limiting – however e_m also increases due to increasing maximum flow heights (see also Fig. 3 in Frank et al., 2015) when systematically enlarging the initial release volumes in the sensitivity analysis. Again, the model is insensitive to the value of critical shear stress once that value is exceeded (please refer to our comment above).

(C) Changes: See changes as described in the comment above. We added the new Figure 8 (sensitivity analysis for τ_c). Changes were made in section 4.3 to describe the data presented in the new Figure 8 which we discuss in a new paragraph in the middle of our discussion (page 16).

(A) Reviewer 1: Page 12, 396-397. As I see in Fig.3, there is no significant difference of runout distance in B2 (μ=0.6) and B3 (μ=0.7). Please check the sentence “μ controls the runout distance”.

(B) Response: The sentence “μ controls the runout distance” is consistent with the Voellmy friction relation as used in runout models such as RAMMS. It is not a result from this present study. We will provide a suitable literature citation for that statement and adjust the wording to ensure that readers do not see this as a result of this project. Perhaps the problem lies in the illustration of the modeling results for three μ values. The calculation domain, where the software was used, was limited in spatial extent to the area where we have differential DTM data for comparison (e.g. the blue polygon in Fig. 3A), so we actually do not show the final runout distance. In the process of answering this comment, we noticed that the blue polygon is drawn inconsistently in figure 3B1-B3, but it is drawn correctly in Fig. 3A. We will also correct this error in the final manuscript.

(C) Changes: We now provide a literature citation “(Bartelt et al., 2013)” for the statement “μ controls the runout distance (page 14, line 429). We’ve also adjusted the wording in this paragraph of the discussion chapter to ensure that readers do not see this as a result of this project (page 14, lines 431-435). We also adapted the inconsistently drawn blue polygons in figure 3B1-B3 to be consistent with the correctly drawn blue polygon in Fig. 3A.

(A) Reviewer 1: Page 27, 675. The total erosion volume in both cases show an abrupt decrease, and then a significant increase with the initial release volume, i.e., 1-2 m^3 in Meretschi and 10-20 m^3 in Bondasca. Is there any rational explanation on it?

(B) Response: When comparing erosion depths as modeled using 10 vs. 20 m^3 as the initial volume in the Bondasca case e.g., we observed that the model run using 20 m^3 is large enough that part of the flow enters a secondary channel. The volume of the flow, then divided among two channels, causes a reduction in flow depth and a consequent decrease in shear stress, resulting in smaller erosion depths and therefore smaller erosion volumes. When using an initial volume of 10 m^3 then the flow fully stays in the main channel. We propose adding a small discussion paragraph explaining this issue.

(C) Changes: We added a brief discussion paragraph explaining this issue (page 17, lines 517-525).

Specific comments by Reviewer 2

(A) Reviewer 2: Page 1, lines 23-24.

why this choice. Basal friction and bed entrainment are interplaying in natural processes. Why separate calibration?

(B) Response: We decided to first calibrate the runout of the model based on the total volume of the event and the runout distance, and then work with smaller initial volumes, then including the erosion algorithm, to refine the results. Our goal was to avoid a time-intensive iterative procedure, especially for the benefit of practitioners who generally do not have time to go through a long calibration process. However the model could also be calibrated by starting with small landslide volumes, so this is just a statement of how we performed the calibration.

(C) Changes: We added a few words at this location in the abstract section to further clarify this (page 1, lines 24-27).

(A) Reviewer 2: Page 2, line 34.

you mean rheology?

(B) Response: This sentence would be better stated as follows: “Sediment erosion caused by debris flows causes flow bulking (in our case an increase in flow mass; Iverson 1997) which strongly influences the runout behavior of debris flows.” We suggest to change it to clarify this.

(C) Changes: We changed the first sentence of the “Introduction” chapter as suggested (page 3, lines 39-41).

(A) Reviewer 2: Page 2, line 38.

quote also works of:

- Cascini et al. (2106) Eng Geol
- Cuomo et al. (2016) Eng Geol
- Cuomo et al., (2014) Canadian Geotechnical Journal

where bed entrainment is discussed as far as its spatial-temporal variation, and its interplay with rheology

(B) Response: Thank you for pointing out this additional literature, which we did not initially consider for this manuscript. However our focus in not on the rheology of the flow or changes in the rheology as a consequence of entrainment. As stated in the manuscript, we use the Voellmy friction relation and we do not adjust the Voellmy friction coefficients as a function of flow properties. However we propose including this as a discussion point, where we will be able to cite some of these publications.

(C) Changes: We added this as a short discussion point and cite some of the publications in the paragraph which already described how morphological effects influence the erosional behavior of the model (page 15, lines 462-466). The reference list has been updated accordingly.

(A) Reviewer 2: Page 2, line 45. what is this? bed entrainment? you may also call erosion. But bulking process is hard to understand and not common in international literature.

(B) Response: The term “bulking” is commonly used in the literature to describe the increase in mass of a debris flow along the flow path ,e.g. see Iverson, R. M.: The Physics of Debris Flows, Reviews of Geophysics, 35, 245-296, 1997. doi: 10.1029/97RG00426, 1997, for a clear explanation in a paper which is very widely cited by debris-flow and landslide researchers throughout the world. A quick search on an academic search engine also indicates that “bulking” is commonly used in the debris-flow literature by authors from many countries outside of Switzerland, so we respectfully disagree with Reviewer 2 on this point. We realize that it may have other meanings in other academic disciplines, so we propose that we clarify the terms like this in the next version of the manuscript.

(C) Changes: Further clarification of the term *bulking* is made by "(in our case an increase in flow mass, e.g. Iverson, 1997)" in the first sentence of the Introduction section (page 3, lines 39-41). Additional definitions of the terms *erosion*, *entrainment* and *bulking* are given in the following sentences (page 4, lines 41-45). Throughout the rest of the manuscript, we made sure that we use those three defined terms consistently.

(A) Reviewer 2: Page 2, line 55.

is there any difference?

(B) Response: Erosion removes sediment from the channel bed, bulking describes the increase in size (mass) of the flow, so the two terms are closely related but not interchangeable. As stated above, we will, in the next version, provide definitions of the terms.

(C) Changes: These changes have been addressed in our response on line number 202 of this document.

(A) Reviewer 2: Page 2, lines 57-61.

there are cases where neglecting erosion one may obtain unsafe future scenarios, as bed entrainment change the propagation pattern, and thus influence the global behaviour of the landslide. This is especially true for debris avalanches (not channelised). However, also for debris flows, including the entrainment helps obtaining better model estimates. See, for instance Cascini et al. 2014 Geomorphology

(B) Response: Thank you for pointing out this paper, which we will consider citing for the next version of the paper. We agree that including entrainment may help users to obtain more accurate predictions.

(C) Changes: We cited Cascini et al. (2014) in the introduction section (page 4, line 77) and the reference list has been updated accordingly.

(A) Reviewer 2: Page 2, lines 73-74.

add models by Pastor et al.. You may find applications in previous works of Cuomo et al.

(B) Response: Thank you for pointing out these additional papers, which we will cite, if appropriate, in for the next version of the manuscript.

(C) Changes: We cited Pastor et al. (2009) there (page 4, line 75) and the reference list has been updated accordingly.

(A) Reviewer 2: Page 2, lines 76-79. Also line 165 (which does not have a comment, just a highlight).

are you using erosion, entrainment and bulking with the same content?

(B) Response: It is not clear to us if this comment is about the terminology or the differences in the bulk properties of the flow vs. the channel bed, so we will address both comments: (1). In our case, the bulking (increase in mass of the flow) produced by entrainment (the process described in the model which specifies how fast and where the additional sediment enters the debris flow) should be clear (also see our comments above regarding terminology). Net entrainment of sediment (erosion – deposition) results in net erosion of the channel bed (a decrease in the elevation of the channel bed), which can then be characterized in a spatial sense with a description of a pattern.

(2). Although it is possible to specify a different mass density for the sediment that is entrained from the channel bed, to a first approximation the mass densities of the two are similar, at least in torrents which experience frequent debris flows. In more detail, the degrees of sorting and ranges of grain sizes in both the flow deposits and the channel bed are fairly similar. However the model accounts for differing densities, if such values are available.

(C) Changes: These changes have been addressed in our response on line number 202 of this document.

(A) Reviewer 2: Page 6, line 192.

turbolent factor. And, it is does not depend on v^2. rephrase the whole sentence.

(B) Response: Thank you for pointing out that this is not clear to you, we propose that we re-write the sentence in question.

(C) Changes: By revisiting the referenced RAMMS papers (Christen et al., 2010; Christen et al., 2012; Bartelt et al., 2013), we re-wrote the entire sentence (page 7, line 202-206).

(A) Reviewer 2: Page 7, line 220. ??

(B) Response: Thank you for pointing out the error in the reference number of the equation, we will fix that in the next version of the manuscript (it should be Eq. 6).

(C) Changes: Error fixed at page 8, line 234.

(A) Reviewer 2: Page 7, line 221.

from where this value? / from where?

(B) Response: These values were described by Frank et al. (2015), however upon re-reading the paragraph above Equation 6, we realize that we should add more details in the next version of the manuscript. Additionally, we propose adding "Frank et al. (2015)" at the end of the sentence to make the origin more clear to the reader.

(C) Changes: We added the reference to our first entrainment model study "(Frank et al., 2015)" (where all details can be found) at the end of the two sentences to make the origin of the values and factors of the entrainment model more clear to the reader (page 8, line 232 and line 236). We also added a few words in this paragraph to give more details (page 8, line 232-236).

(A) Reviewer 2: Page 7, lines 229-230.

check numbering of eqs

(B) Response: Thank you for pointing out the error in the reference to the equation, we will correct and verify all equation numbers when preparing the next version of the manuscript.

(C) Changes: Error fixed at page 9, lines 243 and 244.

(A) Reviewer 2: Page 9, line 281. -2.5 ?

(B) Response: We agree with your suggestion we will also change the value to SI units, so -0.025 m/s, also for other occurrences of $\frac{dz}{dt}$ values in the manuscript.

(C) Changes: We changed the erosion rate values to SI units, so -0.025 m/s, for all other occurrences of $\frac{dz}{dt}$ values in the manuscript.

(A) Reviewer 2: Page 10, line 314.

how this was fixed?

(B) Response: The parameter ξ was determined by varying it within the range proposed by the developers of the RAMMS model (ξ = 100, 200, 400) and inspecting the results. The only realistic velocities (in the steep (≈60%) study reach of the Meretschibach channel) are obtained using ξ = 200 when combined with the variation of parameter μ (= 0.5, 0.6, 0.7). This is explained in the manuscript on page 10, lines 312-316. However to ensure that this is clear, we propose adding a sentence to clarify this procedure.

(C) Changes: We added a sentence (page 11, lines 331-333) to clarify the calibration and model set up procedure. We also updated the previous sentence in the manuscript (page 11, lines 327-329) to eliminate an inconsistency in how the model was actually applied in this case (e.g. it was correctly described in section 3.3.2. (page 10, lines 288-292) and in the caption of Fig. 6 on page 30, lines 794-797).

(A) Reviewer 2: Page 13, line 432.

Alternative, but related definition is that of Hungr, i.e. landslide growth rate = Vfinal / Vinitial

(B) Response: Thank you for pointing out Hungr's definition. We will verify which metric are used in the other papers which we reference, and for the next version of the manuscript we will choose the most suitable metric (as well as cite Hungr's landslide growth factor).

(C) Changes: We followed your suggestion for an alternative definition of the metrics and we now use Hungr's *volume growth* (VG) instead of the *bulking factor* (BF) (pages 13-14, lines 402-411 and new Figure 8). The VG values in the text were adjusted accordingly to Figure 9 (formerly Figure 8). However this change has not changed the interpretation of the results or the discussion thereof (pages 16-17).

Comments by the Editor (referencing comments from Reviewer 1 and 2)

(A) Editor: Reviewer 1, general comment: additionally, provide also a short review on theoretical concepts explaining this behavior and how it is related to your model

(B) Response and (C) Changes: As mentioned above in the response to the general comments by reviewer 1, we edited sections 4.2. (calibration, on pages 11 and 12) and 5. (discussion, starting at page 14) for clarity . In section 5 we also added a discussion about the inherent feedback of in our entrainment model and its relation to the similar observations in laboratory and field studies (page 17, lines 535-541). We added several new comments and references to related discussions in our previous manuscript where the model was introduced (Frank et al., 2015). Recent entrainment modeling papers (e.g. Cuomo et al., 2016) are now referenced (page 15, line 463) and discussed in relation to our empirical approach (these references were suggested in some specific comments by reviewer 2).

(A) Editor: Reviewer 1: Page 6, 195-196.: I think just deleting the sentence is not a good solution. You have to explain your choice for the parameter of internal friction, It seems that you did not used the typical criteria for Voellmy friction

(B) Response and (C) Changes: We have not measured angles of internal friction and we cannot back-up this statement with observations, so we think that it is appropriate to remove this sentence from the manuscript because it may be confusing to readers. We edited the manuscript to clarify that in fact our calibration procedure for the selection of μ does not differ significantly from that proposed in the standard RAMMS model (e.g. the typical criteria for Voellmy friction). To make this clear, we added a citation to Bartelt et al. (2013) and a clear statement on the calibration of runout using the RAMMS model with entrainment (pages 14-15, lines 431-450).

(A) Editor: Reviewer 1: Page 7, 221-222.: please add the suggested figure

(B) Response and (C) Changes: We added the suggested figure showing the model sensitivity to critical shear stress. It's now presented as the new Figure 8. The former Figure 8 is now Figure 9. The (new) Figure 9 was also adapted to show the *volume growth* instead of a *bulking factor*, as suggested by Reviewer 2. Please also see the more specific comments on the changes made (shown above in "**(C) Changes**" at page 4, lines 103 ff. in this document).

(A) Editor: Reviewer 2: Page 1, lines 23-24.: provide a better reasoning for your calibration procedure and highlighting also the pro and cons of the chosen procedure

(B) Response and (C) Changes: We added some additional explanation in the text (also summarized in the abstract, page 1, lines 24-27) to clarify our calibration procedure, e.g. in section 4.1 (page 11, lines 331-333). Also, we discuss the benefits and limiting factors in the discussion (section 5, page 15, lines 442-450). In the text we also refer to an extensive discussion of exactly this topic (page 14, lines 440-441), which was extensively described by Frank et al., (2015).

Debris flow modeling at Meretschibach and Bondasca catchment, Switzerland: sensitivity testing of field data-based ~~erosion~~ entrainment 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~~ model 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 (1) inactivated to find plausible values for general flow properties by adjusting both coefficients (ξ and μ) and then (2) activated to further refine coefficient μ which controls erosion (patterns).~~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~~ these events – 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.

1. Introduction

Sediment erosion caused by debris flows causes flow bulking (in our case an increase in flow mass, e.g. Iverson 1997) which strongly influences the runout strongly influences the bulking behavior of debris_-flows (Iverson, 1997). The term *erosion* can be defined as the process of removing sediment from the channel bed while sediment *entrainment* describes the procedure of incorporating the eroded sediment into the debris flow. The entrainment of eroded sediment along the channel has been observed to considerably increase the volume of debris flows (i.e. *bulking* process) 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 entrainment 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 entrainment 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 erosionentrainment, 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;

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Scott et al., 2005; Godt and Coe, 2007; Breien et al., 2008; Gartner et al., 2008; Pastor et al., 2009; 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; Cascini et al., 2014; 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~~ entrainment algorithm in the RAMMS debris flow ~~runout~~ model for the assessment of debris flow ~~erosion~~ entrainment and bulking (Frank et al., 2015). The ~~erosion~~ entrainment algorithm uses a relation between basal shear stress and erosion depth 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~~ 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~~ Entrainment 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~~Lucas et al., 2017), 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~~ debris-flow events on 28 and 29 July 2014 indicate that the ~~debris~~ 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-~~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~~planar 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~~ entrainment 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~~previously. Although the RAMMS debris model and the ~~erosion~~ entrainment 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).

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

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

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:

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

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

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 dry-Coulomb term (friction coefficient μ~~-~~) scaling with the normal stress and the *viscous or turbulent* friction (coefficient ξ) depending on the flow velocity U~~squared~~ (Christen et al., 2010; Christen et al., 2012; Bartelt et al., 2013):

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

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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 extensively controls deceleration behavior of a slower moving flow. ~~On the other hand, t~~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:

$$\tau = \rho g h S \qquad (5)$$

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-~~debris-flow events (Fig. 3a in Schürch et al., 2011b). The ~~erosion~~ entrainment algorithm implemented in the RAMMS ~~entrainment~~ debris flow model is defined by the maximum potential erosion depth e_m and a specific erosion rate $\frac{dz}{dt}$ (Frank et al., 2015). The relationship between the shear stress estimated (based on flow heights obserserved in the field) and the measured erosion depth (Schürch et al., 2011b) is described as a linear function of shear stress using a proportionality factor $\frac{dz}{d\tau}$ (Eq. ~~2~~6). The maximum potential erosion depth e_m (for each grid cell) 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 (Frank et al., 2015):

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

The average rate of erosion recorded at the erosion sensor site during the Illgraben ~~debris~~ 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~~6). Normally, the specific erosion rate is implemented using the default value $\frac{dz}{dt} = -0.025 \text{ ms}^{-1}$ (Eq. ~~3~~7) as presented in Frank et al. (2015). However, the model also allows to account for larger or smaller ~~erosion~~ entrainment 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~~ Entrainment 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~~ Entrainment model starting condition: block release and input hydrograph

The type of initial release mechanism, block release (e.g. landslide) 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~~ entrainment 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~~ using unrealistically large initial landslide volumes because most models do not allow for ~~erosion~~ entrainment along the 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 in this study) 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.

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3.3.3. Specified erosion rates

As a basis for comparison of the sensitivity of the ~~erosion~~ entrainment algorithm, we hold constant the default entrainment ~~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 $\frac{dz}{dt} = -0.025\ \mathrm{ms}^{-1}$ ~~$\frac{dz}{dt} = 2.5\ \mathrm{cm\ s}^{-1}$~~ 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 entrainment ~~erosion~~ algorithm in RAMMS allows for erosion rates up to $\frac{dz}{dt} = -0.05\ \mathrm{ms}^{-1}$ ~~$\frac{dz}{dt} = 5.0\ \mathrm{cm\ s}^{-1}$)~~, 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 $\frac{dz}{dt} = -0.0125\ \mathrm{ms}^{-1}$ ~~$\frac{dz}{dt} = 1.25\ \mathrm{cm\ s}^{-1}$~~ 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~~ debris-flow event is not available. We therefore focus on the spatial 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~~ 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~~ 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 method of subtracting the initial landslide block from the elevation model was applied. 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 ξ = 200 ms^{-2} and μ = 0.6 (Fig. 3B2). The parameter ξ was determined by varying it within the range proposed by the developers of the RAMMS model (ξ = 100, 200, 400) and inspecting the results (Bartelt et al., 2013). The modeled velocities of 6-9 ms^{-1} using ξ = 200 are plausible, although independent field data are not available for comparison. The parameter combination ξ = 200 ms^{-2} and μ = 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 n~~or ~~were~~ levees ~~deposited~~ accumulated outside of the channel along this entire channel reach (Fig. 3A, blue polygon). In contrast, the erosion pattern using ξ = 200 ms^{-2} and μ = 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 ξ = 200 ms^{-2} and μ = 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 as the initiation area for the runout modeling.

The observed erosion along the main debris flow channel (Fig. 5C) – resulting from the two ~~debris~~ debris-flow events in July 2012 – ~~were~~ was 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 ξ = 400 ms^{-2} and μ = 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 ($\approx$ 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~~illustrates again the problems associated with starting a runout model with the entire event volume assigned to the initial volume. These results illustrate the ability of the runout model to better predict the erosion pattern and runout 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 entrainment model – using the default maximum erosion rate $\frac{dz}{dt} = -0.025\ \mathrm{ms}^{-1}$ $\frac{dz}{dt} = 2.5\ \mathrm{cm\ s}^{-1}$ – 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 $\frac{dz}{dt} = -0.05\ \mathrm{ms}^{-1}$ $\frac{dz}{dt} = 5.0\ \mathrm{cm\ s}^{-1}$ 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 ($\frac{dz}{dt} = -0.0125\ \mathrm{ms}^{-1}$) ($\frac{dz}{dt} = 1.25\ \mathrm{cm\ s}^{-1}$) for low erosion entrainment 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 $\frac{dz}{dt} = -0.025\ \mathrm{ms}^{-1}$ $\frac{dz}{dt} = 2.5\ \mathrm{cm\ s}^{-1}$ (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 entrainment model than using the default rate.

Further assessment of the relation of the total erosion volumes depending on the initial volumes can be made by calculating a bulking factorgrowth rate (Hungr et al., 2005). We call it volume growth (VG) because we address an overall ratio for a specific channel section instead of a classic "yield rate" per running meter (Hungr et al., 2005): . The bulking factor BF is the ratio between the total erosion volume V_{ero} to the initial volume V_{ini} :

$$\mathrm{BFVG} = V_{final}/V_{ini} = (V_{ini} + V_{ero})/V_{ini} \qquad (8)$$

The volume growth (VG) is the ratio between the final debris flow volume V_{final} (consisting of the initial volume V_{ini} and the erosion volume V_{ero}) to the initial volume V_{ini}. We analysed the development of the volume growth (VG) to assess the sensitivity to various model parameters such as critical shear stress τ_c (Fig. 8) as well as erosion rate $\frac{dz}{dt}$ and initial volumes V_{ini} (Fig. 9).

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~~ entrainment 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 (Bartelt et al., 2013). 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. However, a calibration of the parameter ξ using an approximate discharge (block release volume or hydrograph implementation) and as observed at a particular channel section can help determine the most plausible ξ valaue within the ranges proposed by the developers of the RAMMS model (ξ = 100, 200, 400) (Bartelt et al., 2013). 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~~4.1), this corresponds to relative erosion patterns ~~measured~~ determined 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~~ entrainment model when applying to channel sections which exhibit a roughly constant channel slope.~~, which~~ This was also found to be useful by Frank et al. (2015) in the first application of the model.

For some field studies, applying this two-stage calibration method (inactive vs. active entrainment model) will benefit model users who previously conducted RAMMS runout modeling studies without entrainment. They can enhance their exisiting calibration procedure of parameter ξ and μ by mainly refining on parameter μ to reflect a documented, relative erosion pattern when activating the entrainment model. In that sense, this method might be primarily limited by the potential lack of field data (flow heights, discharge, erosion patterns) which were available in this study. However, more case studies are needed before we are able to draw any general conclusions regarding potential benefits and limits of this enhanced methodology for the RAMMS entrainment model application.

~~Morphological~~ In general, morphological effects influence the erosional behavior of the field data based ~~erosion~~ entrainment 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.

Other studies have adressed the spatio-temporal variation of bed entrainment interplaying with debris flow rheology (Cuomo et al., 2014; Cuomo et al., 2016). In RAMMS, we do not adjust the Voellmy friction coefficients as a function of flow properties because data to support the implementation of bed entrainment-flow properties interplay is not available for the catchments addressed herein (Meretschibach and Bondasca).

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 debris flow model with ~~erosion~~ entrainment (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}:~~

~~$$BF = V_{ero}/V_{ini} \qquad (8)$$~~

For the sensitivity assessment of volume growth (VG) to the critical shear stress τ_c, we selected the Meretschibach catchment because it has a simple single-channel morphology and therefore serves as a clear case for illustration (Fig. 8). Because the erosive channel reach addressed in our study shows steep slopes reaching 50 to 65 %, the resulting shear stresses are very high – even for very low flow heights and small initial volumes (1-10 m^3). This leads to a high model susceptibility to erosion (volumes) and volume growth when τ_c = 0 kPa which results in scenarios of a few cubic meters of initial volumes eroding some 1,000 to more than 10,000 cubic meters (Fig. 8). However the initial landslides observed at the Meretschibach were larger in volume, suggesting that a critical shear stress is appropriate. Small debris flows do not necessarily erode the channel bed, which has been observed in the field e.g. at the Illgraben (Schürch et al., 2011; Berger et al., 2010). The presence of a critical shear stress in steep channels is also supported by investigations of entrainment in torrential sediment transport (Lamb et al., 2008), although we are not aware of any systematic investigations of the critical shear stress for entrainment by landslides or debris flows.

The results show that when exceeding τ_c = 0.5 kPa, the volume growth remains steady within a value range of 20 to 60 for middle to larger initial volumes (≥ 10-50 m^3). Smaller initial volumes (≤ 5-10 m^3) show much more variation, i.e. are more sensitive to the critical shear stress. We conclude that a value of τ_c =1 kPa produces plausible results and we use that value for the other sensitivity tests in this study. However it may be possible to constrain this value at other field sites if small non-erosive debris flows can be identified and used to better constrain τ_c. The critical shear stress of τ_c = 1 kPa used herein will be applied for further sensitivity analysis.

The sensitivity to initial landslide volume is apparent at the Meretschibach. Using the default erosion rate and an initial volume of 3 m^3 , a volume growth of ≈ 200 is reached. A maximum of VG = 300 is observed for an initial release volume of 4 m^3. ~~At the Meretschibach channel, the bulking factor is 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 ≈ 300 at a release volume of 4 m^3.~~ It then drops to a ~~BF~~ VG ≈ 30 for an initial volume of 100 m^3. The model simulations using the doubled default erosion rate show a volume growth ~~bulking factor~~ peak VG_p ~~BF_p~~ ≈ 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~~volume growth peak drops significantly down to VG_p ≈ 14.

The behavior of the ~~bulking factor~~volume growth for the default erosion rate at the Bondasca catchment is relatively smooth when compared to that at the Meretschibach. But comparing erosion patterns as modeled using 10 vs. 20 m^3 as the initial volume in the Bondasca case e.g., we observed that the model run using 20 m^3 is large enough that part of the flow enters a secondary channel. The volume of the flow, then divided among two channels, causes a reduction in flow depth and a consequent decrease in shear stress, resulting in smaller erosion depths and therefore smaller erosion volumes – leading to lower volume growth approaching a value of 1 (VG ≈ 1.2) for V_{ini} = 20 m^3 compared to VG ≈ 3 for V_{ini} = 10 m^3. When using an initial volume of 10 m^3 then the flow remains entirely in the main channel. This may provide an explanation for the dip in the Bondasca volume growth between V_{ini} = 10 m^3 and V_{ini} = 20 m^3.

A volume growth peak ~~bulking factor~~ can be identified ~~somewhere~~ between 200 and 500 m^3 but the value is lower in comparison (≈ ~~11~~10-12.5) for the default erosion rate. The doubled rate leads to a volume growth peak ~~peak bulking factor~~ VG_p~~BF_p~~ of ≈ 700 at a release volume of 30 m^3. That is ~~still~~ large compared to examples in the literature (VG~~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~~ entrainment cases. Larger erosion rates might be expected for pyeroclastic 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). Such highly erosive events represent an inherent feedback in the entrainment process whereby a rapid (e.g. double) erosion rate results in a more rapid increase in flow depth leading to larger shear stresses and then to even larger potential erosion depths. This can potentially explain the very rapid growth of debris flows, which is has been observed in some natural field cases (e.g. Spreitgraben, Tobler et al., 2014; Frank et al., 2015) and also in laboratory experiments involving realistic debris-flow sediments (e.g. video documentation of experiments at the USGS Debris-flow flume 1992-2006, Logan & Iverson, 2007).

In addition, l~~L~~arge erodibilities may be expected at the Bondasca catchment because the rock avalanche event occurred during winter and may have contained significant amount of snow. However, d~~D~~ue 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~~ entrainment 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~~volume growth values 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~~ and 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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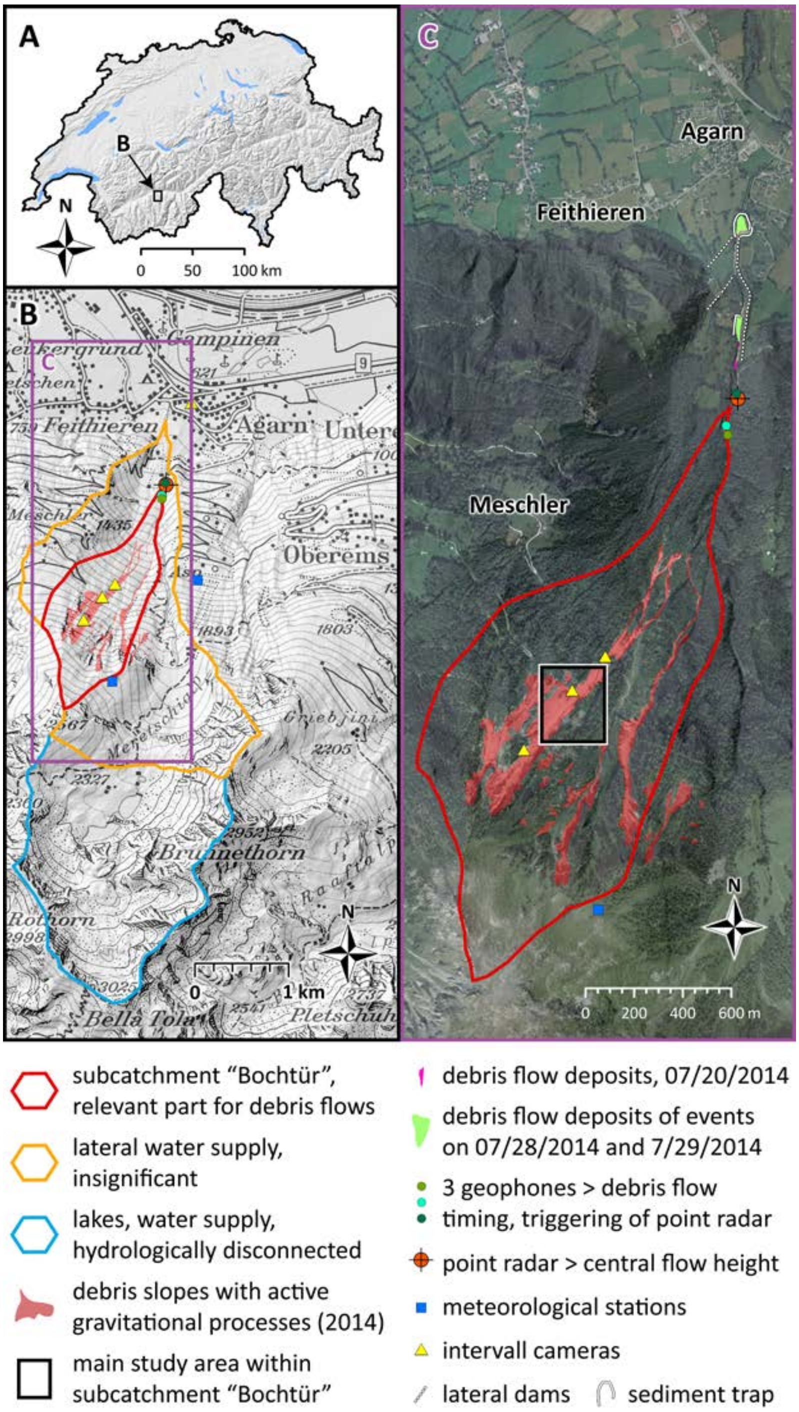

Figure 1. A. Location of the Meretschibach catchment in Southern Switzerland. **B.** Subcatchments of the Meretschibach and locations of the instrumentation site and data available for the erosion model analyses **C.** Initiation zone of the July 2014 events and camera positions. The main study

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

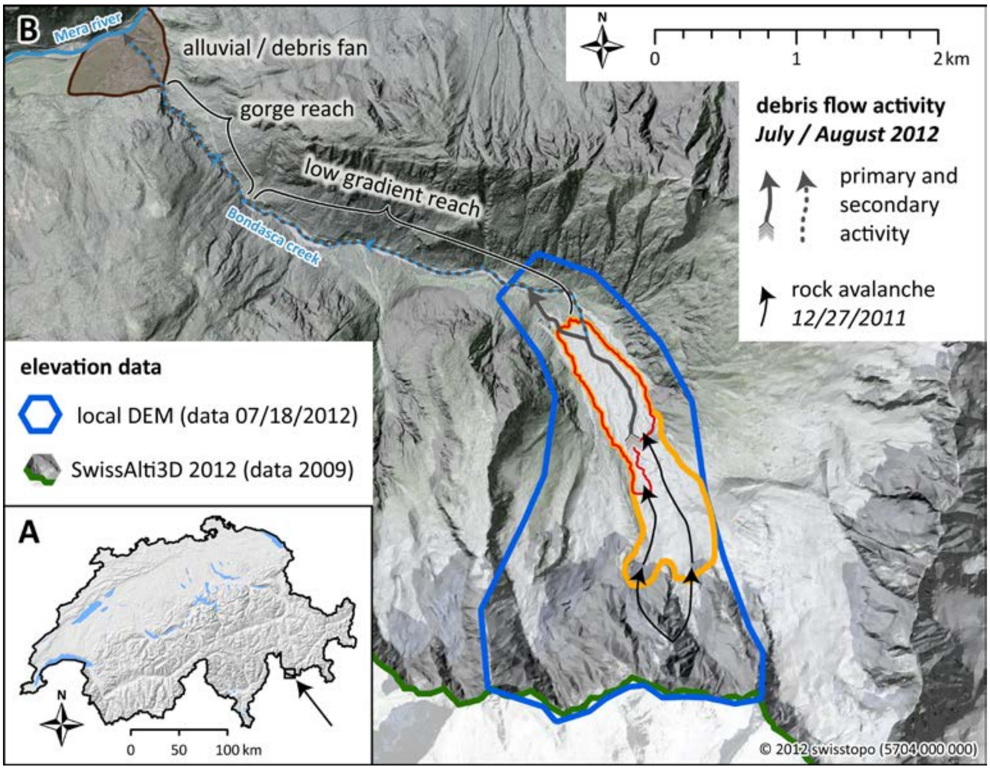

Figure 2. A. Location of the Bondasca catchment in south-eastern Switzerland close to the border to Italy. **B.** Perimeter of the 27 December 2011 rock avalanche deposit, including the main deposition area (yellow polygon) and the deposits lower-elevation deposits which have been partially exposed to 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.

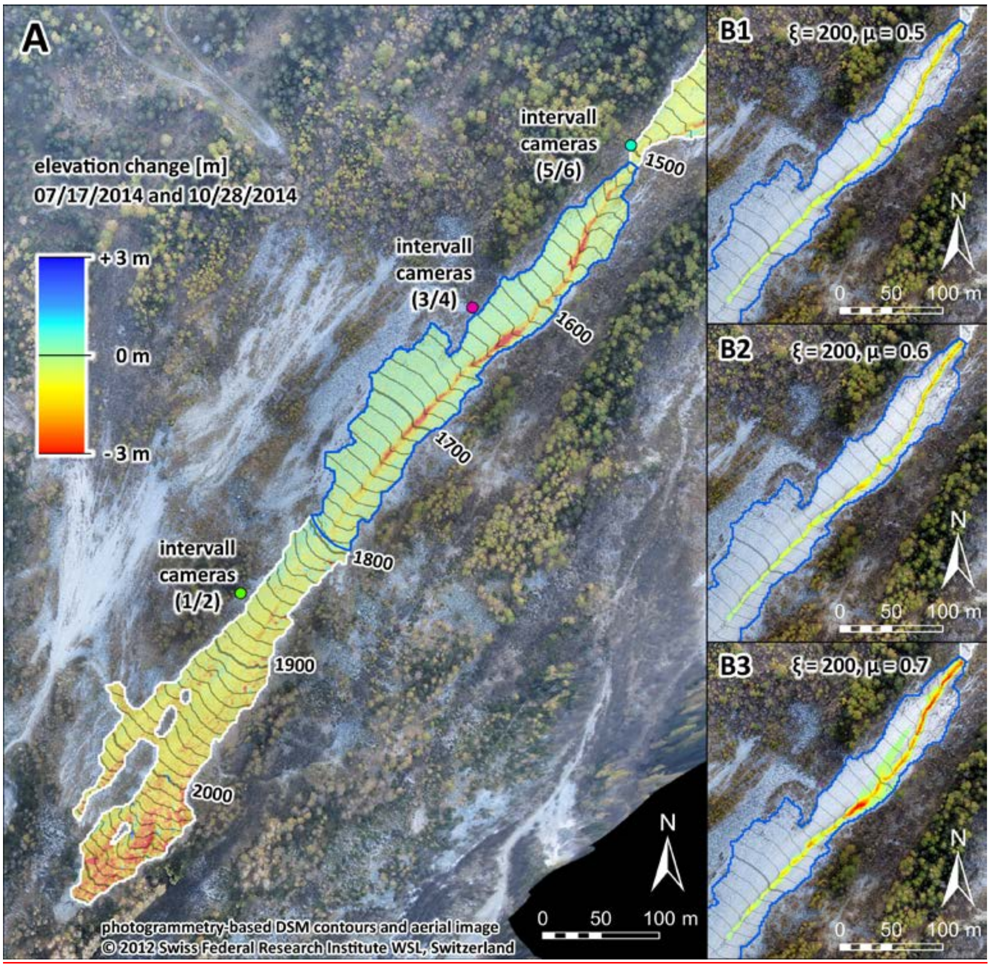

Figure 3. Calibration of modelled erosion patterns (**B1 to B3**) to the observed erosion depths (**A**) in the upper open debris slopes of the "Bochtür" catchment (Meretschibach) by varying values for the friction parameter μ. The blue polygon demarks the area where a differential DTM is available.

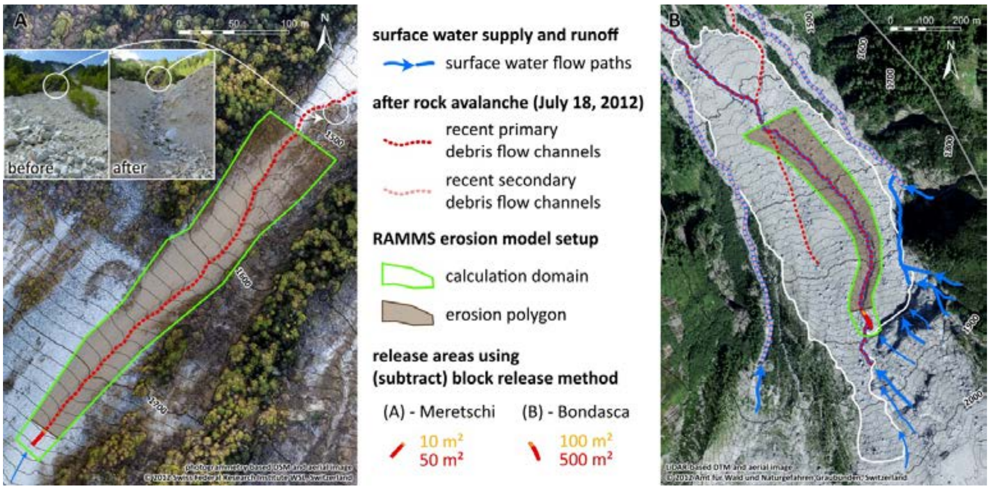

Figure 4. Erosion model configuration for the model simulations showing the initial block release areas in the Meretschibach catchment (**A**) and the Bondasca catchment, Switzerland (**B**). The hillslope is erodible within the brown shaded polygon.

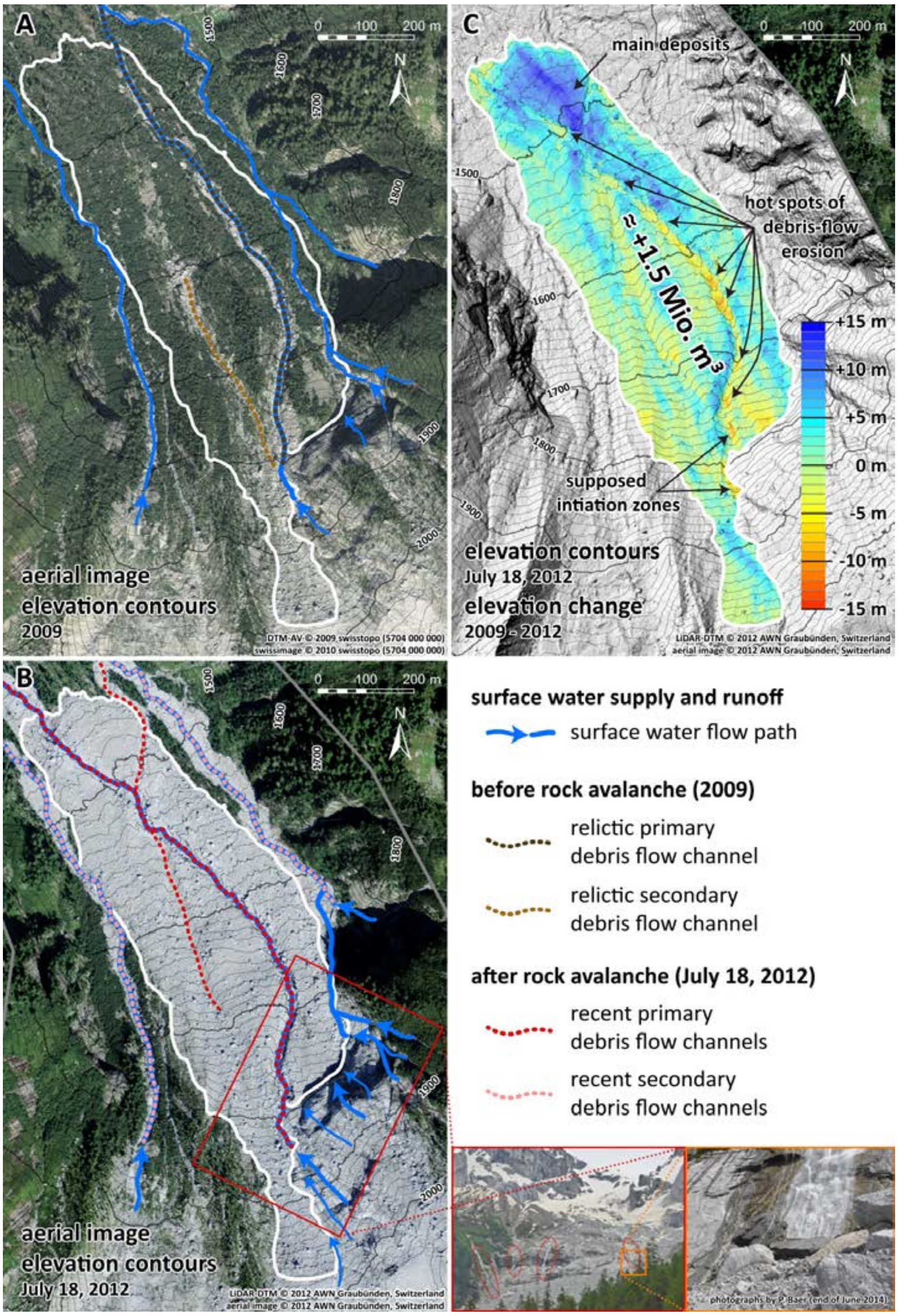

Figure 5. Overview of rock avalanche deposits, subsequently formed debris flow channels, and the resulting overall elevation change in the Bondasca catchment (A, B). The elevation change map 2009 to 2012 (C) includes both the rock avalanche (≈ 1.5 Mio m^3 on 27 Dec. 2011) and the first two debris debris-flow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

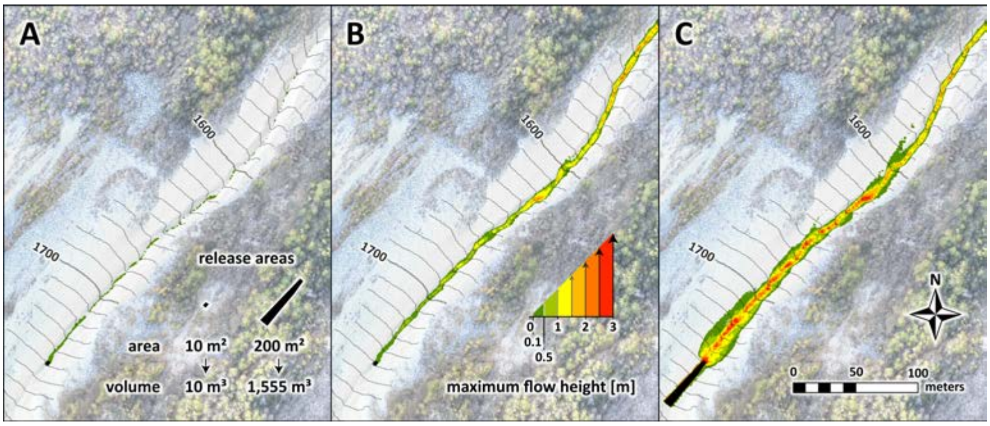

Figure 6. Comparison of runout patterns at "Bochtür" in the Meretschti catchment. The debris flow modeling is conducted using a (subtract) block release volume of (**A**) 10 m^3 and no-entrainment modeling, of (**B**) 10 m^3 and entrainment modeling as well as a total (subtract) block release volume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

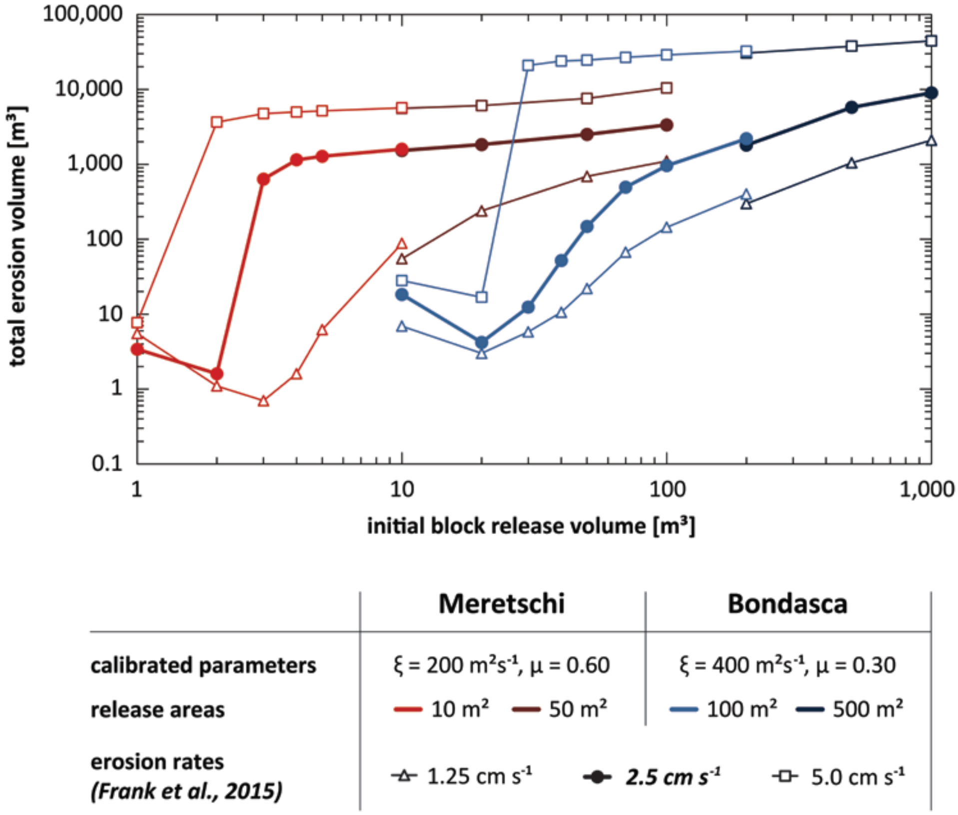

Figure 7. Sensitivity of modeled erosion volume to initial block release volume in the Meretschibach and in the Bondasca catchments.

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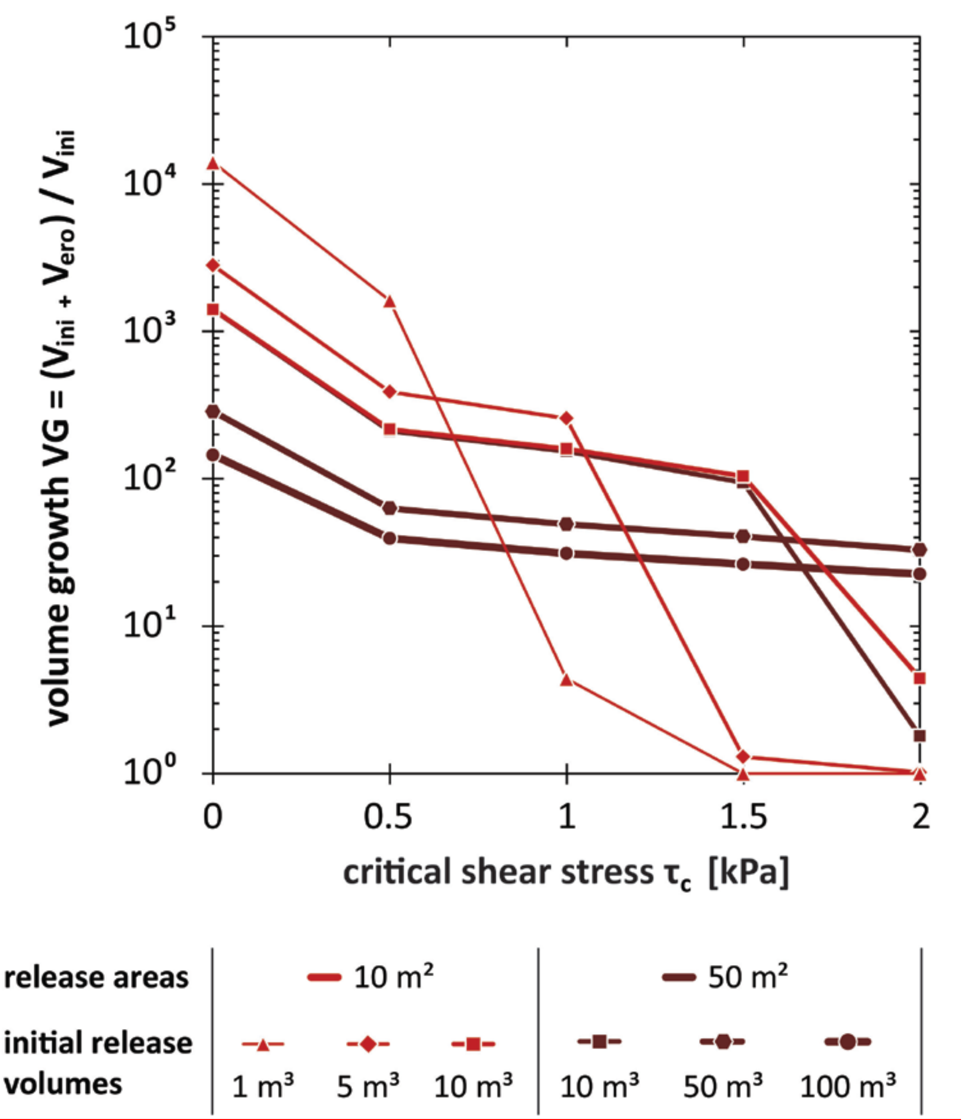

Figure 8. Sensitivity of the volume growth VG = (V_{ini} +V_{ero}) / V_{ini} to the critical shear stress τ_c depending on 5 different initial (block release) volumes V_{ini} as set up based on two release areas in the Meretschibach catchment.

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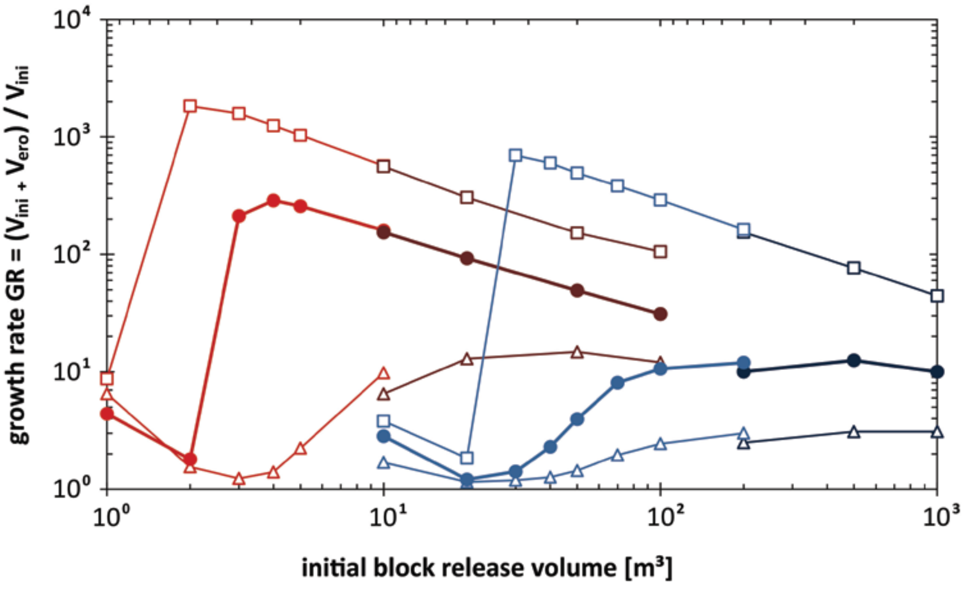

	Meretschi		Bondasca	
calibrated parameters	ξ = 200 m²s⁻¹, μ = 0.60		ξ = 400 m²s⁻¹, μ = 0.30	
release areas	10 m²	50 m²	100 m²	500 m²
erosion rates *(Frank et al., 2015)*	1.25 cm s⁻¹	***2.5 cm s⁻¹***		5.0 cm s⁻¹

Figure ~~8~~9. The ~~bulking factor BF~~volume growth VG = (V_{ini} +V_{ero}~~/~~) / V_{ini} consisting of the ~~modeled~~ sum of ~~total~~ the erosion volume V_{ero} [m^3] ~~to~~ and initial block release volume V_{ini} [m^3~~]~~] per initial block release volume V_{ini} [m^3] and adressing three different erosion rates ~~in~~ for the Meretschibach and Bondasca catchments.