

## Back-calculation of the 2017 Piz Cengalo-Bondo landslide cascade with r.avaflow

Martin Mergili, Michel Jaboyedoff, José Pullareello, Shiva P. Pudasaini

### Response to the comments of Referee #1

We would like to thank the reviewer for the constructive remarks. Below, we address each comment in full detail. Our response is written in blue colour. Changes in the manuscript are highlighted in yellow colour.

Dear authors. I appreciate your answer that has addressed all of my comments. I think that the paper now is clearer and that in this form is somewhat more interesting for the readers (a case study is always just a case study, the narration of the struggling with the modelling of a case study, with all the problems well addressed, is more interesting). I still have some comments, but they are minor ones.

#### Broad comments:

1) I still have some issues with the title, consider to incorporate “key challenges” – a form you use yourself in line 73 – in the title

We understand this point and have modified the title as follows: *Back-calculation of the 2017 Piz Cengalo-Bondo landslide cascade with r.avaflow: what we can do and what we can learn*

2) Even though it is good that you explicit the fact that  $\delta$  scales linearly with the solid fraction, you would agree with me that it is somewhat strange that the solid particles of your flow increase their friction angle along their path. Probably you also increase the fluid fraction and the “real, combined, effective  $\delta$ ” (the equivalent of a single phase model) is lower but if so I still believe that this should be explicated in the table with another column (either solid fraction or “effective  $\delta$ ”). Moreover, if in zone E the flow is so channelized how comes that no entrainment occurred (lateral instabilities for examples) when such a mass of solid and fluid material flowed in its path? Are zone D and E all composed by rocky outcrops (it does not seem so from the pictures)?

The reviewer raises an important issue here, which we have now clarified in the discussion (L427-433):

*“The higher values of  $\delta$  in the lower portion of the channel are based on the assumption that  $\delta$  of the solid material would somehow depend on the momentum or energy of the flow, which – due to the relatively low velocity – is much less in the zones D and, particularly, E. While this assumption, in our opinion, is justified by fluidization and lubrication effects often observed – or inferred – for very rapid mass flows, it remains hard to consider those effects by a well-justified numerical relationship. Until such a relationship (which definitely remains an important subject of future work) has been proposed, we rely on empirically-based zonations of friction parameters.”*

Providing values of “effective  $\delta$ ” in the table would be hard as the solid fraction changes dynamically.

Regarding the entrainment: indeed, the narrow gorge in zone E is incised in a bedrock swell (the outlet of the hanging valley of Pleistocene origin). In general, flow velocities and applied shear stresses are low in the zones D and, particularly, E, so that the assumption of no entrainment appears plausible.

3) Table 3. The threshold of 50% for empirical adequacy allows clearly a large space of wiggle room and it is maybe too generous. However the importance is that it is explicated in the text so the reader could weight better the results

Yes, we agree that the 50% are a rather “generous” margin. However, it has to be kept in mind that also the observations are uncertain, so that too narrow margins would be questionable. We have added the following sentence to the discussion (L439-440):

*“Also, the other reference data are not exact. Therefore, we allow a broad margin (50% deviation from the observation) for considering the model outcomes as empirically adequate.”*

### **Specific comments**

1) Line 57-61: this sentence is not clear and well articulated

Yes, we understand this point of criticism. Besides slightly changing the wording, we have converted the running text to a list, which hopefully improves the ease of reading (L59-68):

- (i) *model cascades, changing from one approach to the next at each process boundary (Schneider et al., 2014; Somos-Valenzuela et al., 2016). Each individual model is tailored for the corresponding process component;*
- (ii) *bulk mixture models or two- or even multi-phase flow models (Pitman and Le, 2005; Pudasaini, 2012; Iverson and George, 2014; Mergili et al., 2017; Pudasaini and Mergili, 2019). Two- or multi-phase flow models separately consider the solid and the fluid phase, but also phase interactions, and therefore allow to consider more complex process interactions such as the impact of a landslide on a lake or reservoir.*

*Worni et al. (2014) have highlighted the advantages of (ii) for considering also the process interactions and boundaries.*

2) Line 149: approximately

Thank You, corrected!

3) Line 387: please explicit what these “numerical issues related to the narrow gorge” are

We have clarified this issue as follows (L397-402):

*“... the steep walls of the gorge, in combination with the low number of raster cells representing the width of the flow, challenge the correct geometric representation of the flow in the topography-following coordinate system. Further, application of the NOC-TVD scheme results in numerical diffusion which becomes particularly evident in this situation. The introduction of adaptive meshes – which would help to locally increase the spatial resolution while maintaining the computational efficiency – could alleviate this type of issue in the future.”*

## Response to the comments of Referee #2 (Brian Mc Ardell)

We would like to thank the reviewer for the constructive remarks. Below, we address each comment in full detail. Our response is written in blue colour. Changes in the manuscript are highlighted in yellow colour.

The manuscript has been substantially improved from the last version. It describes the difficulties in modelling the Piz Cengalo-Bondo mass movement event cascade. I still have a few questions about the manuscript that I think should be considered before publication. I still think that the manuscript will be of interest to the readers of NHESS.

Lines 75-79: I'm not sure what the policy of NHESS is regarding repetition and word count, but lines 75—79 don't really add much to what has already been written in the previous page and therefore could be omitted. Instead, I would prefer more test to explain some novel aspects of your model, e.g. the nature of the coupling between the phases (another comment on that below).

We agree that there is not much new information in this paragraph. Its purpose is to lead over to the following sections and to facilitate following the storyline. We would therefore rather prefer to keep this piece of text.

Line 134: What is MNS? I presume that it's the French-language abbreviation of the English term DSM? Most readers won't be familiar with the French abbreviation. Additionally, why did you use the surface model from Swisstopo instead of the terrain model? The surface model would also include vegetation, so using a surface model from 2011 would have included about 6 years of vegetation growth for areas not modified by the 2011 event, and vegetation removed by the 2017 event would lead to systematic errors in your mass balance. Many trees which survived the 2011 rock avalanche were destroyed by the 2017 event, so this could easily lead to errors. I presume that this has been accounted for by the authors, however it may not be clear to readers.

MNS means “modèle numérique de surface” in French. Indeed, it is the equivalent term to “digital surface model”. DTM (en) = MNT (fr) and DSM (en) = MNS (fr). The term DEM may be used for different things, therefore we avoid this term in the revised manuscript and have replaced it by “DTM” throughout the manuscript. MNS was incorrect, MNT would have been correct, but we have removed the French terms anyway.

We compared the source area from the DTM (swisstopo, 2011) to the model we created by structure from motion (DSM, 2017) to assess the volume. At the top area the vegetation is not a problem, but the snow/glacier change between 2011 and 2017 affects the volume (this aspect is discussed at L143-144). The elevation map for the propagation modelling is the DTM from 2011, and not the DSM from 2017. The reason is, as highlighted by the reviewer, the vegetation, noise and artefacts in the DSM.

Section 3: Please include more details on how the fluid and solid phases are coupled. You gave carefully-worded explanations in the response to the reviews, and it would certainly be interesting for the reader to see the details of how the phases are coupled—even if only in plain text without equations. When looking at the video of the rock avalanche event and the videos of the various debris-flow surges in the village of Bondo, it is clear that phase separation is important, and this manuscript would be incomplete without at least some description of the coupling, as well as some description of the difference in travel speed of the two phases.

Yes, we agree with this suggestion and have added the following text to the section about `r.avaflow` (L203-207):

*“The solid and fluid phases have their own mass and momentum balance equations, so that they evolve as independent dynamical quantities while the phases are still coupled. This means that, in general, the solid and fluid velocities are different. However, the use of an enhanced drag model (Pudasaini, 2019) and the consideration of virtual mass forces ensure a strong coupling between the solid and the fluid phases in the mixture (Pudasaini, 2012; Pudasaini and Mergili, 2019).”*

Line 238 ff: The model has been tuned by adjusting the coefficients in six different regions of the runout zone. This strongly suggests that the model cannot be used for prediction without calibration. To help the reader understand how important the parameter tuning exercise is for applying the model, perhaps you could compare the results with results calibrated based only on an inspection of the aerial photographs, maps, and other materials prior to the 2017 event.

This is a very interesting idea, but we think that such an analysis could hardly be done at this point, particularly not within the scope of this publication. We would like to highlight two aspects:

- With the results of the calibration procedure with the 2017 event already available, it would be almost impossible to do such a parameterization in an unbiased way.
- The results would very much suffer from subjectivity of the parameterization. However, it could be a really useful future study to let a couple of scientists parameterize the model independently, based on pre-event data only (for this or another event), and then analyze the difference in the outcomes. However, this would be a separate study and would go beyond the scope of the present paper.

Section 5.1: Are the statistical metrics CSI and D2PC from Formetta et al., 2015? I haven't heard of these metrics before, or perhaps not with these names. This section is a bit confusing to read because the meaning of the statistical metrics and critical values of those parameters is only roughly explained.

These metrics have previously been used for slope stability analyses, before we introduced them into `r.avaflow`. The metrics are explained in detail in Formetta et al. (2015), Mergili et al. (2017) and also Mergili et al. (2018a), so that it does not appear necessary to reiterate everything in detail also in this publication.

Line 283: What is the justification of using a fluid with a density of  $1400 \text{ kg m}^{-3}$ ? Is this an empirical value or based on some physical assumptions? This value seems to be quite large, and appears to have

been arbitrarily defined. It is large enough that your solid concentrations will consequently appear to be quite small.

Fluid, in this case, is not pure water, but mud, i.e. a mixture of water and solid. In this case, we assume approx. 75% water ( $1000 \text{ kg/m}^3$ ) and 25% fine material ( $2700 \text{ kg/m}^3$ ) in the mud. This is a reasonable assumption from our point of view.

Line 328: Please explain what you mean by “leaks” or re-write the sentence to more clearly explain the effect.

We have replaced “leaks” with “releases material”.

Line 357 & 358. Please remove the sentence about this model being considered “best practice.” Given only one case study, with all of the tuning that went into reproducing the observations, and the other limitations described in the preceding paragraphs, this statement cannot be really taken seriously.

We do not agree with this statement, as it has to be distinguished between the model and the data. As is explained in the text of the revised manuscript, there is no other operational software available offering a comparable physical basis, and this is we refer to with that sentence. On the other hand, there is the parameterization which – in this point we completely agree – are uncertain, and we need more case studies like this one to build a set of guiding parameter values comparable to the one which exists, for example, for RAMMS, for “simpler” types of processes. This limitation is clearly stated in the discussion.

Line 362: Given what I’ve read of the Iverson & George model, it appears to also be useful for geophysical flows that would be comparable to the ones that you describe in the paper. I think that this statement in the paper is incorrect. I encourage you to focus on the advantages of your own model instead of highlighting possibly fictitious disadvantages of other models.

Based on the discussed literature, we have reformulated the corresponding part of the discussion accordingly (L375-381):

*“However, the Pudasaini (2012) model is better suited for the simulation of cascading mass flows for the following reasons: (i) solid and fluid velocities are considered separately which is important for complex, cascading mass flows; (ii) pore fluid diffusion is included, whereas the model of Iverson and George (2014) is limited to pore pressure advection and source terms associated with dilation; (iii) interfacial momentum transfers, such as the drag force, virtual mass force, and buoyancy between the solid and fluid phases are fully included; and (iv) viscous shear stress and dynamical coupling between the pore fluid pressure evolution and the bulk momentum equations are considered.”*

Line 400: The sediment leaving the area was of major interest to the communities downstream. This is part of the process cascade that would be relevant for hazard managers. If your model is capable of describing sediment transport (suspended and bedlam), then you may want to highlight that here but state that you did not focus on that aspect of the work.

We agree that also the lower part of the process would be interesting for hazard managers, but the focus of our work was the upper part. We have added the following sentence (L415-416): *“That lower part of the process chain was not subject of the present work.”*

Conclusions: This section is difficult to read: you may also want to include some more information about the case that you modelled in the paper and why: the conclusions should also contain a concise summary of the problem, the methods, results, and major discussions points.

This, in fact, is very true: for some reason, we have lost the beginning of the conclusions section. In the revised manuscript, we have added the following paragraph at the start of the conclusions (L456-462):

*“We have back-calculated the 2017 Piz Cengalo-Bondo landslide cascade in Switzerland, where an initial rock slide-rock fall of approximately 3 million m<sup>3</sup> entrained a glacier, continued as a rock avalanche, and finally converted into a series of debris flows reaching the village of Bondo at a total distance of 6.5 km. The water causing the transformation into a debris flow might have originated from entrained glacier ice or from water injected from the debris beneath the rock avalanche. Considering the event from its initiation to the first debris flow surge, we have evaluated the possibilities, but also the challenges in the simulation of such complex landslide events, employing the two-phase model of the software r.avaflow.”*

Table 1, Zone c: The exponent on the CE parameter is typeset as “-8-0”. Is this a typo?

Yes, thank You for reading so carefully. We have corrected this mistake; the correct exponent is -8.0.

# 1 **Back-calculation of the 2017 Piz Cengalo-Bondo landslide cas-** 2 **cade with r.avaflow: what we can do and what we can learn**

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## 13 **Abstract**

14 In the morning of 23 August 2017, around 3 million m<sup>3</sup> of granitoid rock broke off from the east face of  
15 Piz Cengalo, SE Switzerland. The initial rock slide-rock fall entrained 0.6 million m<sup>3</sup> of a glacier and  
16 continued as a rock(-ice) avalanche, before evolving into a channelized debris flow that reached the  
17 village of Bondo at a distance of 6.5 km after a couple of minutes. Subsequent debris flow surges fol-  
18 lowed in the next hours and days. The event resulted in eight fatalities along its path and severely dam-  
19 aged Bondo. The most likely candidates for the water causing the transformation of the rock avalanche  
20 into a long-runout debris flow are the entrained glacier ice and water originating from the debris be-  
21 neath the rock avalanche. In the present work we try to reconstruct conceptually and numerically the  
22 cascade from the initial rock slide-rock fall to the first debris flow surge and thereby consider two sce-  
23 narios in terms of qualitative conceptual process models: (i) entrainment of most of the glacier ice by the  
24 frontal part of the initial rock slide-rock fall and/or injection of water from the basal sediments due to  
25 sudden rise in pore pressure, leading to a frontal debris flow, with the rear part largely remaining dry  
26 and depositing mid-valley; and (ii) most of the entrained glacier ice remaining beneath/behind the  
27 frontal rock avalanche, and developing into an avalanching flow of ice and water, part of which overtops  
28 and partially entrains the rock avalanche deposit, resulting in a debris flow. Both scenarios can – with  
29 some limitations – be numerically reproduced with an enhanced version of the two-phase mass flow  
30 model (Pudasaini, 2012) implemented with the simulation software r.avaflow, based on plausible as-  
31 sumptions of the model parameters. However, these simulation results do not allow to conclude on  
32 which of the two scenarios is the more likely one. Future work will be directed towards the application

33 of a three-phase flow model (rock, ice, fluid) including phase transitions, in order to better represent the  
34 melting of glacier ice, and a more appropriate consideration of deposition of debris flow material along  
35 the channel.

36 Keywords: Debris flow, Entrainment, High-mountain process chain, Rock avalanche, Two-phase flow  
37 model, r.avaflow

## 38 **1 Introduction**

39 Landslides lead to substantial damages to life, property, and infrastructures every year. Whereas they  
40 have mostly local effects in hilly terrain, landslides in high-mountain areas, with elevation differences of  
41 thousands of metres over a few kilometres, may form the initial points of process chains which, due to  
42 their interactions with glacier ice, snow, lakes, or basal material, sometimes evolve into long-runout  
43 debris avalanches, debris flows or floods. Such complex landslide events may occur in remote areas, such  
44 as the 2012 Alpl rock-snow avalanche in Austria (Preh and Sausgruber, 2015) or the 2012 Santa Cruz  
45 multi-lake outburst event in Peru (Mergili et al., 2018a). If they reach inhabited areas, such events lead  
46 to major destruction even several kilometres away from the source and have led to major disasters in the  
47 past, such as the 1949 Khait rock avalanche-loess flow in Tajikistan (Evans et al., 2009b); the 1962 and  
48 1970 Huascarán rock fall-debris avalanche events in Peru (Evans et al., 2009a; Mergili et al., 2018b); the  
49 2002 Kolka-Karmadon ice-rock avalanche in Russia (Huggel et al., 2005); the 2012 Seti River debris  
50 flood in Nepal (Bhandari et al., 2012); or the 2017 Piz Cengalo-Bondo rock avalanche-debris flow event  
51 in Switzerland. The initial fall or slide sequences of such process chains are commonly related to a  
52 changing cryosphere such as glacial debuttreassing, the formation of hanging glaciers, or a changing per-  
53 mafrost regime (Harris et al., 2009; Krautblatter et al., 2013; Haeberli and Whiteman, 2014; Haeber-  
54 li et al., 2017).

55 Computer models assist risk managers in anticipating the impact areas, energies, and travel times of  
56 complex mass flows. Conventional single-phase flow models, considering a mixture of solid and fluid  
57 components (e.g. Voellmy, 1955; Savage and Hutter, 1989; Iverson, 1997; McDougall and Hungr, 2004;  
58 Christen et al., 2010), do not serve for such a purpose. Instead, simulations rely on

- 59 (i) model cascades, changing from one approach to the next at each process boundary (Schnei-  
60 der et al., 2014; Somos-Valenzuela et al., 2016). Each individual model is tailored for the cor-  
61 responding process component;
- 62 (ii) bulk mixture models or two- or even multi-phase flow models (Pitman and Le, 2005; Puda-  
63 saini, 2012; Iverson and George, 2014; Mergili et al., 2017; Pudasaini and Mergili, 2019).



Two- or multi-phase flow models separately consider the solid and the fluid phase, but also phase interactions, and therefore allow to consider more complex process interactions such as the impact of a landslide on a lake or reservoir.

Worni et al. (2014) have highlighted the advantages of (ii) for considering also the process interactions and boundaries.

The aim of the present work is to learn about our ability to reproduce sophisticated transformation mechanisms involved in complex, cascading landslide processes, with GIS-based tools. For this purpose, we apply the computational tool *r.avaflow* (Mergili et al., 2017), which employs an enhanced version of the Pudasaini (2012) two-phase flow model, to back-calculate the 2017 Piz Cengalo-Bondo landslide cascade in SE Switzerland, which was characterized by the transformation of a rock avalanche to a long-runout debris flow. We consider two scenarios in terms of hypothetical qualitative conceptual models of the physical transformation mechanisms. On this basis, we try to numerically reproduce these scenarios, satisfying the requirements of physical plausibility of the model parameters, and empirical adequacy in terms of correspondence of the results with the documented and inferred impact areas, volumes, velocities, and travel times. Based on the outcomes, we identify the key challenges to be addressed in future research.

Thereby we rely on the detailed description, documentation, and topographic reconstruction of this recent event. The event documentation, data used, and the conceptual models are outlined in Section 2. We briefly introduce the simulation framework *r.avaflow* (Section 3) and explain its parametrization and our simulation strategy (Section 4) before presenting (Section 5) and discussing (Section 6) the results obtained. Finally, we conclude with the key messages of the study (Section 7).

## 2 The 2017 Piz Cengalo-Bondo landslide cascade

### 2.1 Piz Cengalo and Val Bondasca

The Val Bondasca is a left tributary valley to the Val Bregaglia in the canton of Grisons in SE Switzerland (Fig. 1). The Bondasca stream joins the Mera River at the village of Bondo at 823 m asl. It drains part of the Bregaglia Range, built up by a mainly granitic intrusive body culminating at 3678 m asl. Piz Cengalo, with a summit elevation of 3368 m asl, is characterized by a steep, intensely fractured NE face which has repeatedly been the scene of landslides, and which is geomorphologically connected to the Val Bondasca through a steep glacier forefield. The glacier itself has largely retreated to the cirque beneath the rock wall.

94 On 27 December 2011, a rock avalanche with a volume of 1.5–2 million m<sup>3</sup> developed out of a rock top-  
95 pling from the NE face of Piz Cengalo, travelling for a distance of 1.5 km down to the uppermost part of  
96 the Val Bondasca (Haeberli et al., 2013; De Blasio and Crosta, 2016; Amann et al., 2018). This rock ava-  
97 lanche reached the main torrent channel. Erosion of the deposit thereafter resulted in increased debris  
98 flow activity (Frank et al., 2019). No entrainment of glacier ice was documented for this event. As blue  
99 ice had been observed directly at the scarp, the role of permafrost for the rock instability was discussed.  
100 An early warning system was installed and later extended (Steinacher et al., 2018). Displacements at the  
101 scarp area, measured by radar interferometry and laser scanning, were few centimetres per year between  
102 2012 and 2015, and accelerated in the following years. In early August 2017, increased rock fall activity  
103 and deformation rates alerted the authorities. A major rock fall event occurred on 21 August 2017  
104 (Amann et al., 2018).

## 105 **2.2 The event of 23 August 2017**

106 The complex landslide which occurred on 23 August 2017 was documented mainly by reports of the  
107 Swiss Federal Institute for Forest, Snow and Landscape Research (WSL), the Laboratory of Hydraulics,  
108 Hydrology and Glaciology (VAW) of the ETH Zurich, and the Amt für Wald und Naturgefahren (Office  
109 for Forest and Natural Hazards) of the canton of Grisons.

110 At 9:31 am local time, a volume of approx. 3 million m<sup>3</sup> detached from the NE face of Piz Cengalo, as  
111 indicated by WSL (2017), Amann et al. (2018), and the point cloud we obtained through structure from  
112 motion using pictures taken after the event. Documented by videos and by seismic records (Walter et al.,  
113 2018), it impacted the glacier beneath the rock face and entrained approx. 0.6 million m<sup>3</sup> of ice (VAW,  
114 2017; WSL, 2017), was sharply deflected at an opposite rock wall, and evolved into a rock(-ice) ava-  
115 lanche. Part of this avalanche immediately converted into a debris flow which flowed down the Val  
116 Bondasca. It was detected at 9:34 by the debris flow warning system which had been installed near the  
117 hamlet of Prä approx. 1 km upstream from Bondo. According to different sources, the debris flow surge  
118 arrived at Bondo between 9:42 (derived from WSL, 2017) and 9:48 (Amt für Wald und Naturgefahren,  
119 2017). The rather low velocity in the lower portion of the Val Bondasca is most likely a consequence of  
120 the narrow gorge topography, and of the viscous behaviour of this first surge. Whereas approx.  
121 540,000 m<sup>3</sup> of material were involved, only 50,000 m<sup>3</sup> arrived at Bondo immediately (data from the Can-  
122 ton of Grisons reported by WSL, 2017). The remaining material was partly remobilized by six further  
123 debris flow surges recorded during the same day, one on 25 August, and one – triggered by rainfall – on  
124 31 August 2017. All nine surges together deposited a volume of approx. 500,000–800,000 m<sup>3</sup> in the area  
125 of Bondo, less than half of which was captured by a retention basin (Bonanomi and Keiser, 2017).

126 The vertical profile of the main flow path is illustrated in Fig. 4. The total angle of reach of the process  
127 chain from the initial release down to the outlet of the Bondasca Valley was approx.  $17.4^\circ$ , computed  
128 from the travel distance of 7.0 km and the vertical drop of approx. 2.2 km. The initial landslide to the  
129 terminus of the rock avalanche showed an angle of reach of approx.  $25.8^\circ$ , derived from the travel dis-  
130 tance of 3.4 km and the vertical drop of 1.7 km. This value is higher than the  $22^\circ$  predicted by the equa-  
131 tion of Scheidegger (1973), probably due to the sharp deflection of the initial landslide. Following the  
132 concept of Nicoletti and Sorriso-Valvo (1991), the rock avalanche was characterized by channelling of  
133 the mass. Only a limited run-up was observed, probably due to the gentle horizontal curvature of the  
134 valley in that area (no orthogonal impact on the valley slope; Hewitt, 2002). There were eight fatalities,  
135 concerning hikers in the Val Bondasca, extensive damages to buildings and infrastructures, and evacua-  
136 tions for several weeks or even months.

### 137 2.3 Data and conceptual model

138 Reconstruction of the rock and glacier volumes involved in the event was based on an overlay of a 2011  
139 swisstopo Digital Terrain Model (DTM) (contract: swisstopo–DV084371), derived through airborne laser  
140 scanning in 2011 and available at a raster cell size of 2 m, and a Digital Surface Model (DSM) obtained  
141 through Structure from Motion (SfM) techniques after the 2017 event. This analysis resulted in a de-  
142 tached rock volume of 3.27 million  $\text{m}^3$ , which is slightly more than the value of 3.15 million  $\text{m}^3$  reported  
143 by Amann et al. (2018), and an entrained ice volume of 770,000  $\text{m}^3$  (Fig. 5). However, these volumes  
144 neglect smaller rock falls before and after the large 2017 event, and also glacial retreat. The 2011 event  
145 took place after the DTM had been acquired, but it released from an area above the 2017 scarp. The  
146 boundary between the 2011 and the 2017 scarps, however, is slightly uncertain, which explains the dis-  
147 crepancies between the different volume reconstructions. Assuming some minor entrainment of the  
148 glacier ice in 2011 and some glacial retreat, we arrive at an entrained ice volume of approximately  
149 600,000  $\text{m}^3$ , a value which is very well supported by VAW (2017).

150 There is still disagreement on the origin of the water having led to the debris flow, particularly to the  
151 first surge. Bonanomi and Keiser (2017) clearly mention meltwater from the entrained glacier ice as the  
152 main source, whereby much of the melting is assigned to impact, shearing and frictional heating directly  
153 at or after impact, as it is often the situation in rock-ice avalanches (Pudasaini and Krautblatter, 2014).  
154 WSL (2017) has shown, however, that the energy released was only sufficient to melt approximately half  
155 of the glacier ice. Water pockets in the glacier or a stationary water source along the path might have  
156 played an important role (Demmel, 2019). Walter et al. (2019) claim that much of the glacier ice was  
157 crushed, ejected and dispersed (Fig. 3b), whereas water injected into the rock avalanche due to pore

158 pressure rise in the basal sediments would have played a major role. In any case, the development of a  
159 debris flow from a landslide mass with an overall solid fraction of as high as  $\sim 0.85$  (considering the water  
160 equivalent of the glacier ice) requires some spatio-temporal differentiation of the water/ice content. We  
161 consider two qualitative conceptual models – or scenarios – possibly explaining such a differentiation:

162 S1 The initial rock slide-rock fall led to massive entrainment, fragmenting and melting of glacier  
163 ice, mixing of rock with some of the entrained ice and the meltwater, and injection of water  
164 from the basal sediments into the rock avalanche mass quickly upon impact due to overload-  
165 induced pore pressure rise. As a consequence, the front of the rock avalanche was characterized  
166 by a high content of ice and water, highly mobile, and therefore escaped as the first debris flow  
167 surge, whereas the less mobile rock avalanche behind – still with some water and ice in it – de-  
168 celerated and deposited mid-valley. The secondary debris flow surges occurred mainly due to  
169 backwater effects. This scenario largely follows the explanation of Walter et al. (2019) that the  
170 first debris flow surge was triggered at the front of the rock avalanche by overload and pore  
171 pressure rise, whereas the later surges overtopped the rock avalanche deposits, as indicated by  
172 the surficial scour patterns.

173 S2 The initial rock slide-rock fall impacted and entrained the glacier. Most of the entrained ice re-  
174 mained beneath and, after some initial sliding, developed into an avalanching flow of melting ice  
175 behind the rock avalanche. The rock avalanche decelerated and stopped mid-valley. Part of the  
176 avalanching flow overtopped and partly entrained the rock avalanche deposit – leaving behind  
177 the scour traces observed in the field – and evolved into the channelized debris flow which ar-  
178 rived at Bondo a couple of minutes later. The secondary debris flow surges started from the rock  
179 avalanche deposit due to melting and infiltration of the remaining ice, and due to backwater ef-  
180 fects. This scenario is similar to the theory developed at the WSL Institute for Snow and Ava-  
181 lanche Research (SLF), who also did a first simulation of the rock avalanche (WSL, 2017).

182 Fig. 6 illustrates the conceptual models attempting to explain the key mechanisms involved in the rock  
183 avalanche-debris flow transformation.

### 184 3 The simulation framework r.avaflow

185 r.avaflow represents a comprehensive GIS-based open source framework which can be applied for the  
186 simulation of various types of geomorphic mass flows. In contrast to most other mass flow simulation  
187 tools, r.avaflow utilizes a general two-phase-flow model describing the dynamics of the mixture of solid  
188 particles and viscous fluid and the strong interactions between these phases. It further considers erosion

189 and entrainment of surface material along the flow path. These features facilitate the simulation of cas-  
 190 cading landslide processes such as the 2017 Piz Cengalo-Bondo event. `ravaflow` is outlined in full detail  
 191 by Mergili and Pudasaini (2019). The code, a user manual, and a collection of test datasets are available  
 192 from Mergili (2019). Only those aspects directly relevant for the present work are described in this sec-  
 193 tion.

194 Essentially, the Pudasaini (2012) two-phase flow model is employed for computing the dynamics of mass  
 195 flows moving from a defined release area (solid and/or fluid heights are assigned to each raster cell) or  
 196 release hydrograph (at each time step, solid and/or fluid heights are added at a given profile, moving at a  
 197 given cross-profile velocity) down through a **DTM**. The spatio-temporal evolution of the flow is approx-  
 198 imated through depth-averaged solid and fluid mass and momentum balance equations (Pudasaini,  
 199 2012). This system of equations is solved through the TVD-NOC Scheme introduced by Nessyahu and  
 200 Tadmor (1990), adapting an approach presented by Tai et al. (2002) and Wang et al. (2004). The charac-  
 201 teristics of the simulated flow are governed by a set of flow parameters (some of them are shown in the  
 202 Tables 1 and 2).

203 The solid and fluid phases have their own mass and momentum balance equations, so that they evolve as  
 204 independent dynamical quantities while the phases are still coupled. This means that, in general, the  
 205 solid and fluid velocities are different. However, the use of an enhanced drag model (Pudasaini, 2019)  
 206 and the consideration of virtual mass forces ensure a strong coupling between the solid and the fluid  
 207 phases in the mixture (Pudasaini, 2012; Pudasaini and Mergili, 2019). Compared to the Pudasaini (2012)  
 208 model, some **further** extensions have been introduced which include (i) ambient drag or air resistance  
 209 (Kattel et al., 2016; Mergili et al., 2017); and (ii) fluid friction, governing the influence of basal surface  
 210 roughness on the fluid momentum (Mergili et al., 2018b). Both extensions rely on empirical coefficients,  
 211  $C_{AD}$  for the ambient drag and  $C_{FF}$  for the fluid friction. **Further, viscosity is computed according to an**  
 212 **improved concept.** As in Domnik et al. (2013) and Pudasaini and Mergili (2019), the fluid viscosity is  
 213 enhanced by the yield strength. Most importantly, the internal friction angle  $\varphi$  and the basal friction  
 214 angle  $\delta$  of the solid are scaled with the solid fraction in order to approximate effects of reduced interac-  
 215 tion between the solid particles and the basal surface in fluid-rich flows.

216 Entrainment is calculated through an empirical model. In contrast to Mergili et al. (2017), where an em-  
 217 pirical entrainment coefficient is multiplied with the momentum of the flow, here we multiply the en-  
 218 trainment coefficient  $C_E$  ( $\text{s kg}^{-1} \text{m}^{-1}$ ) with the kinetic energy of the flow:

$$219 \quad q_{E,s} = C_E |T_s + T_f| \alpha_{s,E}, \quad q_{E,f} = C_E |T_s + T_f| (1 - \alpha_{s,E}), \quad (1)$$

220 where  $q_{E,s}$  and  $q_{E,f}$  ( $\text{m s}^{-1}$ ) are the solid and fluid entrainment rates,  $T_s$  and  $T_f$  (J) are the kinetic energies of  
221 the solid and fluid fractions of the flow, and  $\alpha_{s,E}$  is the solid fraction of the entrainable material. Solid  
222 and fluid flow heights and momenta, and the change of the basal topography, are updated at each time  
223 step (see Mergili et al., 2017 for details).

224 As r.avaflow operates on the basis of GIS raster cells, its output essentially consists of raster maps –for all  
225 time steps and for the overall maximum – of solid and fluid flow heights, velocities, pressures, kinetic  
226 energies, and entrained heights. In addition, output hydrograph profiles may be defined at which solid  
227 and fluid heights, velocities, and discharges are provided at each time step.

## 228 **4 Parameterization of r.avaflow**

229 One set of simulations is performed for each of the Scenarios S1 and S2 (Fig. 6), considering the process  
230 chain from the release of the rock slide-rock fall to the arrival of the first debris flow surge at Bondo.  
231 Neither triggering of the event nor subsequent surges or distal debris floods beyond Bondo are consid-  
232 ered in this study. Equally, the dust cloud associated to the rock avalanche (WSL, 2017) is not the subject  
233 here. Initial sliding of the glacier beneath the rock avalanche, as assumed in Scenario S2, cannot directly  
234 be modelled. That would require a three-phase model, which is beyond the scope here. Instead, release  
235 of the glacier ice and meltwater is assumed in a separate simulation after the rock avalanche has passed  
236 over it. We consider this workaround an acceptable approximation of the postulated scenario (Sec-  
237 tion 6).

238 We use the 2011 swisstopo **DTM**, corrected for the rock slide-rock fall scarp and the entrained glacier  
239 ice by overlay with the 2017 SfM DSM (Section 2). The maps of release height and maximum entraina-  
240 ble height are derived from the difference between the 2011 swisstopo DTM and the 2017 SfM DSM  
241 (Fig. 5; Section 2). The release mass is considered completely solid, whereas the entrained glacier is as-  
242 sumed to contain some solid fraction (coarse till). The glacier ice is assumed to melt immediately on im-  
243 pact and is included in the fluid along with fine till. We note that the fluid phase does not represent  
244 pure water, but a mixture of water and fine particles (Table 2). The fraction of the glacier allowed to be  
245 incorporated in the process chain is empirically optimized (Table 3). Based on the same principle, the  
246 maximum depth of entrainment of fluid due to pore pressure overload in Scenario S1 is set to 25 cm,  
247 whereas the maximum depth of entrainment of the rock avalanche deposit in Scenario S2 is set to **1.5 m**.

248 The study area is divided into six zones A–F (Fig. 4 and Fig. 7; Table 1). Each of these zones represents  
249 an area with particular geomorphic characteristics and dominant process types, which can be translated  
250 into model parameters. Due to the impossibility to directly measure the key parameters in the field

(Mergili et al., 2018a, b), the parameters summarized in Table 1 and Table 2 are the result of an iterative optimization procedure, where multiple simulations with different parameter sets are performed in order to arrive at one “optimum” simulation for each scenario. It is thereby important to note that we largely derive one single set of optimized parameters, which is valid for both of the scenarios. Optimization criteria are (i) the empirical adequacy of the model results, and (ii) the physical plausibility of the parameters. Thereby, the empirical adequacy is quantified through comparison of the results with the documented impact area, the travel times to the output hydrograph profiles O2, O3, and O4 (Fig. 7), and the reported volumes (Amt für Wald und Naturgefahren, 2017; Bonanomi and Keiser, 2017; WSL, 2017). The physical plausibility of the model parameters is evaluated on the basis on the parameters suggested by Mergili et al. (2017) and on the findings of Mergili et al. (2018a, b). The values of the basal friction angle ( $\delta$ ), the ambient drag coefficient ( $C_{AD}$ ), the fluid friction coefficient ( $C_{FF}$ ), and the entrainment coefficient ( $C_E$ ) are differentiated between and within the zones (Table 1), whereas global values are defined for all the other parameters (Table 2). It is further important to note that  $\delta$  scales linearly with the solid fraction – this means that the values given in Table 1 only apply for 100% solid.

Durations of  $t = 1800$  s are considered for both scenarios. At this point of time, the first debris flow surge has largely passed and left the area of interest, except for some remaining tail of fluid material. Only heights  $\geq 0.25$  m are taken into account for the visualization and evaluation of the simulation results. A threshold of 0.001 m is used for the simulation itself, keeping the loss due to numerical diffusion within a range of  $<1$ –4% until the point when the flow first leaves the area of interest. Taking into account the size of the event, a cell size of 10 m is considered the best compromise between capturing a sufficient level of detail and ensuring an adequate computational efficiency, and is therefore applied for all simulations.

## 5 Simulation results

### 5.1 Scenario S1 – Frontal debris flow surge

Fig. 8 illustrates the distribution of the simulated maximum flow heights, maximum entrained heights, and deposition area after  $t = 1800$  s, when most of the initial debris flow surge has passed the confluence of the Bondasca stream and the Maira river. The comparison of observed and simulated impact areas results in a critical success index  $CSI = 0.558$ , a distance to perfect classification  $D2PC = 0.167$ , and a factor of conservativeness  $FoC = 1.455$ . These performance indicators are derived from the confusion matrix of true positives, true negatives, false positives, and false negatives.  $CSI$  and  $D2PC$  measure the correspondence of the observed and simulated impact areas. Both indicators can range between 0 and 1,

whereby values of *CSI* close to 1 and values of *D2PC* close to 0 point to a good correspondence. *FoC* indicates whether the observed impact areas are overestimated ( $FoC > 1$ ), or underestimated by the simulation ( $FoC < 1$ ). More details are provided by Formetta et al. (2015) and by Mergili et al. (2017, 2018a).

Interpreting these values as indicators for a reasonably good correspondence between simulation and observation in terms of impact area, we now consider the dimension of time, focussing on the output hydrographs OH1–OH4 (Fig. 9; see Fig. 7 and Fig. 8 for the location of the corresponding hydrograph profiles O1–O4). Much of the rock avalanche passes the profile O1 between  $t = 60$  s and  $t = 100$  s. OH2 (Fig. 9a; located in the upper portion of Val Bondasca) sets on before  $t = 140$  s and quickly reaches its peak, with a volumetric solid ratio of approx. 30% (maximum 900 m<sup>3</sup>/s of solid and 2,200 m<sup>3</sup>/s of fluid discharge). Thereafter, this first surge quickly tails off. The solid flow height, however, increases to around 3 m and remains so until the end of the simulation, whereas the fluid flow height slowly and steadily tails off. Until  $t = 1800$  s the profile O2 is passed by a total of 221,000 m<sup>3</sup> of solid and 308,000 m<sup>3</sup> of fluid material (the fluid representing a mixture of fine mud and water with a density of 1,400 kg m<sup>-3</sup>; see Table 2). The hydrograph profile O3 in Prä, approx. 1 km upstream of Bondo, is characterized by a surge starting before  $t = 280$  s and slowly tailing off afterwards. Discharge at the hydrograph OH4 (Fig. 9b; O4 is located at the outlet of the canyon to the debris fan of Bondo) starts at around  $t = 700$  s and reaches its peak of solid discharge at  $t = 1020$  s (167 m<sup>3</sup>/s). Solid discharge decreases thereafter, whereas the flow becomes fluid-dominated with a fluid peak of 202 m<sup>3</sup>/s at  $t = 1320$  s. The maximum total flow height simulated at O4 is 2.53 m. This site is passed by a total of 91,000 m<sup>3</sup> of solid and 175,000 m<sup>3</sup> of fluid material, according to the simulation – an overestimate, compared to the documentation (Table 3).

Fig. 10 illustrates the travel times and the frontal velocities of the rock avalanche and the initial debris flow. The initial surge reaches the hydrograph profile O3 – located 1 km upstream of Bondo – at  $t = 280$  s (Fig. 10a; Fig. 9c). This is in line with the documented arrival of the surge at the nearby monitoring station (Table 3). Also the simulated travel time to the profile O4 corresponds to the – though uncertain – documentation. The initial rock avalanche is characterized by frontal velocities >25 m/s, whereas the debris flow largely moves at 10–25 m/s. Velocities drop below 5 m/s in the lower part of the valley (Zone E) (Fig. 10b).

## 5.2 Scenario S2 – Debris flow surge by overtopping and entrainment of rock avalanche

Fig. 11 illustrates the distribution of the simulated maximum flow heights, maximum entrained heights, and deposition area after  $t = t_0 + 1740$  s, where  $t_0$  is the time between the release of the initial rock avalanche and the mobilization of the entrained glacier. The simulated impact and deposition areas of the



314 initial rock avalanche are also shown in Fig. 11. However, we now concentrate to the debris flow, trig-  
 315 gered by the **simulated** entrainment of 145,000 m<sup>3</sup> of solid material from the rock avalanche deposit.  
 316 Flow heights – as well as the hydrographs presented in Fig. 9c and d and the temporal patterns illustrat-  
 317 ed in Fig. 12 – only refer to the debris flow developing from the entrained glacier and the entrained rock  
 318 avalanche material. The confusion matrix of observed and simulated impact areas reveals partly different  
 319 patterns of performance than for the Scenario S1:  $CSI = 0.590$ ;  $D2PC = 0.289$ ; and  $FoC = 0.925$ . The lower  
 320  $FoC$  value and the lower performance in terms of  $D2PC$  reflect the missing initial rock avalanche in the  
 321 simulation results. The output hydrographs OH2 and OH4 differ from the hydrographs obtained  
 322 through the Scenario S1, but also show some similarities (Fig. 9c and d). Most of the flow passes through  
 323 the hydrograph profile O1 between  $t = t_0 + 40$  s and  $t_0 + 80$  s, and through O2 between  $t = t_0 + 100$  s and  
 324  $t_0 + 180$  s. The hydrograph OH2 is characterized by a short peak of 3,500 m<sup>3</sup>/s of solid and 4,500 m<sup>3</sup>/s of  
 325 fluid, with a volumetric solid fraction of 0.44 and quickly decreasing discharge afterwards (Fig. 9c). In  
 326 contrast to **the** Scenario S1, flow heights drop steadily, with values below 2 m from  $t = t_0 + 620$  s on-  
 327 wards. The hydrograph OH3 is characterized by a surge starting around  $t = t_0 + 240$  s. Discharge at the  
 328 hydrograph OH4 (Fig. 9d) sets on around  $t = t_0 + 600$  s, and the solid peak of 240 m<sup>3</sup>/s is simulated at  
 329 approx.  $t = t_0 + 780$  s. The delay of the peak of fluid discharge is more pronounced when compared to  
 330 Scenario S1 (310 m<sup>3</sup>/s at  $t = t_0 + 960$  s). Profile O4 is passed by a total of 65,000 m<sup>3</sup> of solid and  
 331 204,000 m<sup>3</sup> of fluid material. The volumetric solid fraction drops from above 0.60 at the very onset of the  
 332 hydrograph to around 0.10 (almost pure fluid) at the end. The maximum total flow height at O4 is 3.1 m.  
 333 Fig. 12 illustrates the travel times and the frontal velocities of the rock avalanche and the initial debris  
 334 flow. Assuming that  $t_0$  is in the range of some tens of seconds, the time of arrival of the surge at O3 is in  
 335 line with the documentation also for the Scenario S2 (Fig. 12a; Table 3). The frontal velocity patterns  
 336 along Val Bondasca are roughly in line with those derived in the Scenario S1 (Fig. 12b). However, the  
 337 scenarios differ among themselves in terms of the more pronounced, but shorter peaks of the hydro-  
 338 graphs in Scenario S2 (Fig. 9). This pattern is a consequence of the more sharply defined debris flow  
 339 surge. In Scenario S1, the front of the rock avalanche deposit constantly **releases material** into Val Bon-  
 340 dasca, providing supply for the debris flow also at later stages. In Scenario S2, entrainment of the rock  
 341 avalanche deposit occurs relatively quickly, without material supply afterwards. This type of behaviour  
 342 is strongly coupled to the value of  $C_E$  and the allowed height of entrainment chosen for the rock ava-  
 343 lanche deposit.

## 344 6 Discussion

345 Our simulation results reveal a reasonable degree of empirical adequacy and physical plausibility with  
346 regard to most of the reference observations. Having said that, we have also identified some important  
347 limitations which are now discussed in more detail. First of all, we are not able to decide on the more  
348 realistic of the two Scenarios S1 and S2. In general, the melting and mobilization of glacier ice upon rock  
349 slide-rock fall impact is hard to quantify from straightforward calculations of energy transformation, as  
350 Huggel et al. (2005) have demonstrated on the example of the 2002 Kolka-Karmadon event. In the pre-  
351 sent work, the assumed amount of melting (approximately half of the glacier ice) leading to the empiri-  
352 cally most adequate results corresponds well to the findings of WSL (2017), indicating a reasonable de-  
353 gree of plausibility. It remains equally difficult to quantify the amount of water injected into the rock  
354 avalanche by overload of the sediments and the resulting pore pressure rise (Walter et al., 2019). Con-  
355 firmation or rejection of conceptual models with regard to the physical mechanisms involved in specific  
356 cases would have to be based on better constrained initial conditions, and the availability of robust pa-  
357 rameter sets.

358 We note that with the approach chosen we are not able (i) to adequately simulate the transition from  
359 solid to fluid material; and (ii) to consider rock and ice separately with different material properties,  
360 which would require a three-phase model, not within the scope here. Therefore, entrained ice is consid-  
361 ered viscous fluid from the beginning. A physically better founded representation of the initial phase of  
362 the event would require an extension of the flow model employed. Such an extension could build on the  
363 rock-ice avalanche model introduced by Pudasaini and Krautblatter (2014). Also, the vertical patterns of  
364 the situation illustrated in Fig. 5 cannot be modelled with the present approach, which (i) does not con-  
365 sider melting of ice; and (ii) only allows one entrainable layer at each pixel. The assumption of fluid be-  
366 haviour of entrained glacier ice therefore represents a necessary simplification which is supported by  
367 observations (Fig. 3b), but neglects the likely presence of remaining ice in the basal part of the eroded  
368 glacier, which melted later and so contributed to the successive debris flow surges.

369 Still, we currently consider the Pudasaini (2012) model – and the extended multi-phase model (Puda-  
370 saini and Mergili, 2019) – best practice, even though other two-phase or bulk mixture models do exist.  
371 Most recently, Iverson and George (2014) presented an approach that has been solved with an open  
372 source software, called D-Claw (George and Iverson, 2014), and compared to large-scale experiments  
373 considering dense debris materials (Iverson et al., 2000; Iverson et al., 2010). The Iverson and George  
374 (2014) model can be useful for flow-type landslides, or bulk motion, where the solid particles and fluid  
375 molecules move together. However, the Pudasaini (2012) model is better suited for the simulation of

376 cascading mass flows for the following reasons: (i) solid and fluid velocities are considered separately  
377 which is important for complex, cascading mass flows; (ii) pore fluid diffusion is included, whereas the  
378 model of Iverson and George (2014) is limited to pore pressure advection and source terms associated  
379 with dilation; (iii) interfacial momentum transfers, such as the drag force, virtual mass force, and buoy-  
380 ancy between the solid and fluid phases are fully included; and (iv) viscous shear stress and dynamical  
381 coupling between the pore fluid pressure evolution and the bulk momentum equations are considered.

382 The initial rock slide-rock fall and the rock avalanche are simulated in a plausible way, at least with re-  
383 gard to the deposition area. Whereas the simulated deposition area is clearly defined in Scenario S2, this  
384 is to a lesser extent the case in Scenario S1, where the front of the rock avalanche directly transforms  
385 into a debris flow. Both scenarios seem to overestimate the time between release and deposition, com-  
386 pared to the seismic signals recorded – an issue also reported by WSL (2017) for their simulation. We  
387 observe a relatively gradual deceleration of the simulated avalanche, without clearly defined stopping  
388 and note that also in the Scenario S2, there is some diffusion after the considered time of 120 s, so that  
389 the definition of the simulated deposit is somehow arbitrary. The elaboration of well-suited stopping  
390 criteria, going beyond the very simple approach introduced by Mergili et al. (2017), remains a task for  
391 the future. However, as the rock avalanche has already been successfully back-calculated by WSL  
392 (2017), we focus on the first debris flow surge: the simulation input is optimized towards the back-  
393 calculation of the debris flow volumes entering the valley at the hydrograph profile O2 (Table 3). The  
394 travel times to the hydrograph profiles O3 and O4 are reproduced in a plausible way in both scenarios,  
395 and so are the impact areas (Figs. 8 and 11). Exceedance of the lateral limits in the lower zones is at-  
396 tributed to an overestimate of the debris flow volumes there, and to numerical issues related to the nar-  
397 row gorge: the steep walls of the gorge, in combination with the low number of raster cells representing  
398 the width of the flow, challenge the correct geometric representation of the flow in the topography-  
399 following coordinate system. Further, application of the NOC-TVD scheme results in numerical diffu-  
400 sion which becomes particularly evident in this situation. The introduction of adaptive meshes – which  
401 would help to locally increase the spatial resolution while maintaining the computational efficiency –  
402 could alleviate this type of issue in the future. The same is true for the fan of Bondo. The solid ratio of  
403 the debris flow in the simulations appears realistic, ranging around 40–45% in the upper part of the de-  
404bris flow path, and around 30–35% and lower (depending on the cut-off time of the hydrograph) in the  
405 lower part. This means that solid material tends to stop in the transit area rather than fluid material, as it  
406 can be expected. Nevertheless, the correct simulation of the deposition of debris flow material along Val  
407 Bondasca remains a major challenge (Table 3). Even though a considerable amount of effort was put in  
408 reproducing the much lower volumes reported in the vicinity of O4, the simulations result in an overes-

409 timate of the volumes passing through this hydrograph profile. This is most likely a consequence of the  
410 failure of r.avaflow to adequately reproduce the deposition pattern in the zones D and E. Whereas some  
411 material remains there at the end of the simulation, more work is necessary to appropriately understand  
412 the mechanisms of deposition in viscous debris flows (Pudasaini and Fischer, 2016b). Part of the discrep-  
413 ancy, however, might be explained by the fact that part of the fluid material – which does not only con-  
414 sist of pure water, but of a mixture of water and fine mud – left the area of interest in downstream direc-  
415 tion and was therefore not included in the reference measurements. That lower part of the process chain  
416 was not subject of the present work.

417 The simulation results are strongly influenced by the initial conditions and the model parameters. Pa-  
418 rameterization of both scenarios is complex and highly uncertain, particularly in terms of optimizing the  
419 volumes of entrained till and glacial meltwater, and injected pore water. In general, the parameter sets  
420 optimized to yield empirically adequate results are physically plausible. Reproducing the travel times to  
421 O4 in the present study requires the assumption of a low mobility of the flow in Zone E. This is achieved  
422 by increasing the friction (Table 1), accounting for the narrow flow channel, i.e. the interaction of the  
423 flow with the channel walls, which is not directly accounted for in r.avaflow. Still, the high values of  $\delta$   
424 given in Table 1 are not directly applied, as they scale with the solid fraction. This type of weighting has  
425 to be further scrutinized. We emphasize that also reasonable parameter sets are not necessarily physical-  
426 ly true, as the large number of parameters involved (Tables 1 and 2) creates a lot of space for equifinality  
427 issues (Beven et al., 1996). The higher values of  $\delta$  in the lower portion of the channel are based on the  
428 assumption that  $\delta$  of the solid material would somehow depend on the momentum or energy of the  
429 flow, which – due to the relatively low velocity – is much less in the zones D and, particularly, E. While  
430 this assumption, in our opinion, is justified by fluidization and lubrication effects often observed – or  
431 inferred – for very rapid mass flows, it remains hard to consider those effects by a well-justified numeri-  
432 cal relationship. Until such a relationship (which definitely remains an important subject of future  
433 work) has been proposed, we rely on empirically-based zonations of friction parameters.

434 We have further shown that the classical evaluation of empirical adequacy, by comparing observed and  
435 simulated impact areas, is insufficient in the case of complex mass flows: travel times, hydrographs, and  
436 volumes involved can provide important insight in addition to the quantitative performance indicators  
437 used, for example, in landslide susceptibility modelling (Formetta et al., 2015). Further, the delineation  
438 of the observed impact area is uncertain as the boundary of the event is not clearly defined particularly  
439 in Zone C. Also, the other reference data are not exact. Therefore, we allow a broad margin (50% devia-  
440 tion of the observation) for considering the model outcomes as empirically adequate.

441 The present work is seen as a further step towards a better understanding of the challenges and the pa-  
442 rameterization concerning the integrated simulation of complex mass flows. More case studies are neces-  
443 sary to derive guiding parameter sets facilitating predictive simulations of such events (Mergili et al.,  
444 2018a, b). A particular challenge of case studies consists in the parameter optimization procedure: in  
445 principle, automated methods do exist (e.g. Fischer, 2013). However, they have been developed for op-  
446 timizing globally defined parameters (which are constant over the entire study area) against runout  
447 length and impact area, and such tools do a very good job for exactly this purpose. However, they cannot  
448 directly deal with spatially variable parameters, as they are defined in the present work. With some  
449 modifications they might even serve for that – but the main issue is that optimization should also con-  
450 sider shapes and maximum values of hydrograph discharges, or travel times at different places of the  
451 path. It would be a huge effort to trim optimization algorithms to this purpose, and to make them effi-  
452 cient enough to prevent excessive computational times – we consider this as an important task for the  
453 future which is out of scope of the present work. Therefore, we have used a step-wise expert-based op-  
454 timization strategy.

## 455 7 Conclusions

456 We have back-calculated the 2017 Piz Cengalo-Bondo landslide cascade in Switzerland, where an initial  
457 rock slide-rock fall of approximately 3 million m<sup>3</sup> entrained a glacier, continued as a rock avalanche, and  
458 finally converted into a series of debris flows reaching the village of Bondo at a total distance of 6.5 km.  
459 The water causing the transformation into a debris flow might have originated from entrained glacier ice  
460 or from water injected from the debris beneath the rock avalanche. Considering the event from its initi-  
461 ation to the first debris flow surge, we have evaluated the possibilities, but also the challenges in the  
462 simulation of such complex landslide events, employing the two-phase model of the software r.avafLOW.

463 Both of the investigated Scenarios S1 (debris flow developing through injected water at the front of the  
464 rock avalanche) and S2 (debris flow developing through melted ice at the back of the rock avalanche,  
465 overtopping the deposit) lead to empirically reasonably adequate results, when back calculated with  
466 r.avafLOW using physically plausible model parameters. Based on the simulations performed in the pre-  
467 sent study, final conclusions on the more likely of the mechanisms sketched in Fig. 6 can therefore not  
468 be drawn purely based on the simulations. The observed jet of glacial meltwater (Fig. 3b) points towards  
469 Scenario S1. The observed scouring of the rock avalanche deposit, in contrast, rather points towards Sce-  
470 nario S2, but could also be associated to subsequent debris flow surges. Open questions include at least (i)  
471 the interaction between the initial rock slide-rock fall and the glacier; (ii) flow transformations in the  
472 lower portion of Zone C (Fig. 7), leading to the first debris flow surge; and (iii) the mechanisms of depo-

sition of 90% of the debris flow material along the flow channel in the Val Bondasca. Further research is therefore urgently needed to shed more light on this extraordinary landslide cascade in the Swiss Alps. In addition, improved simulation concepts are **required** to better capture the dynamics of complex landslides in glacierized environments: such would particularly have to include **a three-phase model**, where ice – and melting of ice – are considered in a more explicit way. Finally, more case studies of complex mass flows have to be performed in order to derive guiding parameter sets serving for predictive simulations.

## **Code availability**

The `r.avafLOW` code, including a detailed manual, is available for download at the `r.avafLOW` website (Mergili and Pudasaini, 2019).

## **Data availability**

The study is largely based on the 2011 swisstopo **Digital Terrain Model (DTM)** (contract: swisstopo–DV084371), and derivatives thereof. Unfortunately, the authors are not entitled to make these data publicly available.

## **Author contributions**

Martin Mergili (MM), Michel Jaboyedoff (MJ), José Pullarello (JP), Shiva P. Pudasaini (SP)

MM has contributed to the conceptualization and methodology of the research, designed the software, and performed the formal analysis, visualization, validation, and most of the writing of the original draft. MJ was involved in the conceptualization, investigation, and supervision as well as in the review and editing of the manuscript. JP has contributed to the investigation, visualization, and review & editing. SP has provided input in terms of methodology and review & editing of the manuscript.

## **Competing interests**

The authors declare that they have no conflict of interest.

## **Acknowledgements**

Shiva P. Pudasaini gratefully thanks the Herbette Foundation for providing financial support for his sabbatical visit to the University of Lausanne, Switzerland in the period April–June 2018, where this con-

499 tribution was triggered. Similarly, this work has been financially supported by the German Research  
500 Foundation (DFG) through the research project PU 386/5-1: “A novel and unified solution to multi-  
501 phase mass flows”. It strongly builds on the outcomes of the international cooperation project “A GIS  
502 simulation model for avalanche and debris flows (avaflow)” supported by the German Research Founda-  
503 tion (DFG, project number PU 386/3-1) and the Austrian Science Fund (FWF, project number I 1600-  
504 N30).

505 We would like to thank Brian McArdell and another anonymous reviewer for providing constructive  
506 comments and suggestions that helped to enhance the paper substantially, and are grateful to Sophia  
507 Demmel and Florian Amann for valuable discussions **as well as** to Matthias Benedikt for comprehensive  
508 technical assistance.

## 509 **References**

510 Amann, F., Kos, A., Phillips, M., and Kenner, R.: The Piz Cengalo Bergsturz and subsequent debris flows,  
511 *Geophys. Res. Abstr.*, 20, 14700, 2018.

512 Amt für Wald und Naturgefahren: Bondo: Chronologie der Ereignisse, 2 pp.,  
513 [https://www.gr.ch/DE/institutionen/verwaltung/bvfd/awn/dokumentenliste\\_afw/20170828\\_Chronologie](https://www.gr.ch/DE/institutionen/verwaltung/bvfd/awn/dokumentenliste_afw/20170828_Chronologie_Bondo_2017_12_13_dt.pdf)  
514 [\\_Bondo\\_2017\\_12\\_13\\_dt.pdf](https://www.gr.ch/DE/institutionen/verwaltung/bvfd/awn/dokumentenliste_afw/20170828_Chronologie_Bondo_2017_12_13_dt.pdf), accessed on 31 May 2019.

515 Beven, K.: Equifinality and Uncertainty in Geomorphological Modelling, in: *The Scientific Nature of*  
516 *Geomorphology: Proceedings of the 27th Binghamton Symposium in Geomorphology*, 27-29 September  
517 1996, John Wiley & Sons, 289–313, 1996.

518 Bonanomi, Y., and Keiser, M.: Bericht zum aktuellen Bergsturz am Piz Cengalo 2017, Bergeller Alpen im  
519 Engadin, 19. Geoforum Umhausen, 19.–20. Oktober 2017, 55–60, 2017.

520 Christen, M., Kowalski, J., and Bartelt, P.: RAMMS: Numerical simulation of dense snow avalanches in  
521 three-dimensional terrain, *Cold Reg. Sci. Technol.*, 63, 1–14,  
522 <https://doi.org/10.1016/j.coldregions.2010.04.005>, 2010.

523 De Blasio, F. V., and Crosta, G. B.: Extremely Energetic Rockfalls: Some preliminary estimates, in: *Land-*  
524 *slides and Engineered Slopes. Experience, Theory and Practice*, 759–764, CRC Press, 2016.

525 Demmel, S.: Water Balance in Val Bondasca. Initial hydrological conditions for debris flows triggered by  
526 the 2017 rock avalanche at Pizzo Cengalo. Master Thesis, ETH Zurich, 50 pp., 2019.

Domnik, B., Pudasaini, S. P., Katzenbach, R., and Miller, S. A.: Coupling of full two-dimensional and depth-averaged models for granular flows, *J. Non-Newtonian Fluid Mech.*, 201, 56–68, <https://doi.org/10.1016/j.jnnfm.2013.07.005>, 2013.

Evans, S. G., Bishop, N.F., Fidel Smoll, L., Valderrama Murillo, P., Delaney, K.B., and Oliver-Smith, A.: A re-examination of the mechanism and human impact of catastrophic mass flows originating on Nevado Huascarán, Cordillera Blanca, Peru in 1962 and 1970, *Eng. Geol.*, 108, 96–118, <https://doi.org/10.1016/j.enggeo.2009.06.020>, 2009.

Fischer, J.-T., Kowalski, J., and Pudasaini, S. P.: Topographic curvature effects in applied avalanche modeling, *Cold Reg. Sci. Technol.*, 74, 21–30, <https://doi.org/10.1016/j.coldregions.2012.01.005>, 2012.

Fischer, J.-T., Kofler, A., Fellin, W., Granig, M., and Kleemayr, K.: Multivariate parameter optimization for computational snow avalanche simulation in 3d terrain, *J. Glaciol.*, 61(229), 875–888, <https://doi.org/10.3189/2015JoG14J168>, 2015.

Formetta, G., Capparelli, G., and Versace, P.: Evaluating performances of simplified physically based models for landslide susceptibility, *Hydrol. Earth Syst. Sci. Discuss.*, 12, 13217–13256, <https://doi.org/10.5194/hessd-19-1-2015>, 2015.

Frank, F., Huggel, C., McArdell, B. W., and Vieli, A.: Landslides and increased debris-flow activity: a systematic comparison of six catchments in Switzerland. *Earth Surf. Proc. Landforms*, 44(3), 699–712, <https://doi.org/10.1002/esp.4524>, 2019.

George, D. L., and Iverson, R. M.: A depth-averaged debris-flow model that includes the effects of evolving dilatancy. II. Numerical predictions and experimental tests. *Proc. Royal Soc. A*, 470(2170), 20130820, <https://doi.org/10.1098/rspa.2013.0820>, 2014.

Haeberli, W.: Mountain permafrost—research frontiers and a special long-term challenge, *Cold Reg. Sci. Technol.*, 96, 71–76, <https://doi.org/10.1016/j.coldregions.2013.02.004>, 2013.

Haeberli, W., and Whiteman, C. (Eds.): *Snow and Ice-related Hazards, Risks and Disasters*, Elsevier, <https://doi.org/10.1016/B978-0-12-394849-6.00001-9>, 2014.

Haeberli, W., Schaub, Y., and Huggel, C.: Increasing risks related to landslides from degrading permafrost into new lakes in de-glaciating mountain ranges, *Geomorphology*, 293(B), 405–417, <https://doi.org/10.1016/j.geomorph.2016.02.009>, 2017.

Harris, C., Arenson, L. U., Christiansen, H. H., Etzelmüller, B., Frauenfelder, R., Gruber, S., Haeberli, W., Hauck, C., Hölzle, M., Humlum, O., Isaksen, K., Kääb, A., Kern-Lütschg, M. A., Lehning, M., Matsuoka, N., Murton, J. B., Nötzli, J., Phillips, M., Ross, N., Seppälä, M., Springman, S. M., and Vonder



558 Mühll, D.: Permafrost and climate in Europe: Monitoring and modelling thermal, geomorphological and  
559 geotechnical responses, *Earth-Sci. Rev.*, 92, 117–171, <https://doi.org/10.1016/j.earscirev.2008.12.002>,  
560 2009.

561 Hewitt, K.: Styles of rock-avalanche depositional complexes conditioned by very rugged terrain, Karako-  
562 ram Himalaya, Pakistan, *Rev. Eng. Geol.*, 15, 345–377, 2002.

563 Huggel, C., Zraggen-Oswald, S., Haeberli, W., Kääb, A., Polkvoj, A., Galushkin, I., and Evans, S.G.: The  
564 2002 rock/ice avalanche at Kolka/Karmadon, Russian Caucasus: assessment of extraordinary avalanche  
565 formation and mobility, and application of QuickBird satellite imagery, *Nat. Hazards Earth Syst. Sci.*, 5,  
566 173–187, <https://doi.org/10.5194/nhess-5-173-2005>, 2005.

567 Iverson, R. M.: The physics of debris flows, *Rev. Geophys.*, 35, 245–296,  
568 <https://doi.org/10.1029/97RG00426>, 1997.

569 Iverson, R. M., Reid, M. E., Iverson, N. R., LaHusen, R. G., Logan, M., Mann, J. E., and Brien, D. L.:  
570 Acute sensitivity of landslide rates to initial soil porosity, *Science*, 290, 513–516,  
571 <https://doi.org/10.1126/science.290.5491.513>, 2000.

572 Iverson, R. M., Logan, M., LaHusen, R. G., and Berti, M.: The perfect debris flow? aggregated results  
573 from 28 large-scale experiments, *J. Geophys. Res.*, 115, 1–29, <https://doi.org/10.1029/2009JF001514>, 2010.

574 Iverson, R. M., and George, D. L.: A depth-averaged debris-flow model that includes the effects of evol-  
575 ving dilatancy. I. Physical basis, *Proc. Royal Soc. A*, 470(2170), 20130819,  
576 <https://doi.org/10.1098/rspa.2013.0819>, 2014.

577 Kattel, P., Khattri, K. B., Pokhrel, P. R., Kafle, J., Tuladhar, B. M., and Pudasaini, S. P.: Simulating glacial  
578 lake outburst floods with a two-phase mass flow model, *Ann. Glaciol.*, 57(71), 349–358,  
579 <https://doi.org/10.3189/2016AoG71A039>, 2016.

580 Krautblatter, M., Funk, D., and Günzel, F. K.: Why permafrost rocks become unstable: a rock–ice-  
581 mechanical model in time and space, *Earth Surf. Process. Landf.*, 38, 876–887,  
582 <https://doi.org/10.1002/esp.3374>, 2013.

583 McDougall, S., and Hungr, O.: A Model for the Analysis of Rapid Landslide Motion across Three-  
584 Dimensional Terrain, *Can. Geotech. J.*, 41, 1084–1097, <https://doi.org/10.1139/t04-052>, 2004.

585 Mergili, M., Pudasaini, S. P.: r.avaflow – The open source mass flow simulation model,  
586 <https://www.avaflow.org/>, last access: 7 July 2019.

587 Mergili, M., Fischer, J.-T., Krenn, J., and Pudasaini, S. P.: r.avaflow v1, an advanced open source compu-  
 588 tational framework for the propagation and interaction of two-phase mass flows, *Geosci. Model Dev.*, 10,  
 589 553–569, <https://doi.org/10.5194/gmd-10-553-2017>, 2017.

590 Mergili, M., Emmer, A., Juřicová, A., Cochachin, A., Fischer, J.-T., Huggel, C., and Pudasaini, S.P.: How  
 591 well can we simulate complex hydro-geomorphic process chains? The 2012 multi-lake outburst flood in  
 592 the Santa Cruz Valley (Cordillera Blanca, Perú), *Earth Surf. Process. Landf.*, 43(7), 1373–1389,  
 593 <https://doi.org/10.1002/esp.4318>, 2018a.

594 Mergili, M., Frank, B., Fischer, J.-T., Huggel, C., and Pudasaini, S. P.: Computational experiments on the  
 595 1962 and 1970 landslide events at Huascarán (Peru) with r.avaflow: Lessons learned for predictive mass  
 596 flow simulations, *Geomorphology*, 322, 15–28, <https://doi.org/10.1016/j.geomorph.2018.08.032>, 2018b.

597 Nessyahu, H., and Tadmor, E.: Non-oscillatory central differencing for hyperbolic conservation laws, *J.*  
 598 *Comput. Phys.*, 87, 408–463, [https://doi.org/10.1016/0021-9991\(90\)90260-8](https://doi.org/10.1016/0021-9991(90)90260-8), 1990.

599 Nicoletti, G. P., and Sorriso-Valvo, M.: Geomorphic controls of the shape and mobility of rock ava-  
 600 lanches, *GSA Bull.*, 103(10), 1365–1373, [https://doi.org/10.1130/0016-](https://doi.org/10.1130/0016-7606(1991)103<1365:GCOTSA>2.3.CO;2)  
 601 [7606\(1991\)103<1365:GCOTSA>2.3.CO;2](https://doi.org/10.1130/0016-7606(1991)103<1365:GCOTSA>2.3.CO;2), 1991.

602 Pitman, E.B., and Le, L.: A two-fluid model for avalanche and debris flows. *Philos. Trans. R. Soc. A*, 363,  
 603 1573–1601, <https://doi.org/10.1098/rsta.2005.1596>, 2005.

604 Pudasaini, S. P.: A general two-phase debris flow model, *J. Geophys. Res. Earth Surf.*, 117, F03010,  
 605 <https://doi.org/10.1029/2011JF002186>, 2012.

606 Pudasaini, S. P.: A full description of generalized drag in mixture mass flows, *Engineering Geology*,  
 607 <https://doi.org/10.1016/j.enggeo.2019.105429>, 2019.

608 Pudasaini, S. P., and Krautblatter, M.: A two-phase mechanical model for rock-ice avalanches, *J. Ge-*  
 609 *ophys. Res. Earth Surf.*, 119, doi:10.1002/2014JF003183, 2014.

610 Pudasaini, S. P., and Fischer, J.-T.: A mechanical model for phase-separation in debris flow,  
 611 *arXiv:1610.03649*, 2016a.

612 Pudasaini, S.P., and Fischer, J.-T.: A mechanical erosion model for two-phase mass flows,  
 613 *arXiv:1610.01806*, 2016b.

614 Pudasaini, S.P., and Mergili, M.: A Multi-Phase Mass Flow Model, *J. Geophys. Res. Earth Surf.*,  
 615 *JGRF21102*, <https://doi.org/10.1029/2019JF005204>, 2019.

616 Preh, A., and Sausgruber, J. T.: The Extraordinary Rock-Snow Avalanche of Alpl, Tyrol, Austria. Is it  
 617 Possible to Predict the Runout by Means of Single-phase Voellmy- or Coulomb-Type Models?, in: Engi-  
 618 neering Geology for Society and Territory–Volume 2, edited by: Lollino, G. et al., Springer, Cham,  
 619 [https://doi.org/10.1007/978-3-319-09057-3\\_338](https://doi.org/10.1007/978-3-319-09057-3_338), 2015.

620 Saltelli, A., and Annoni, P.: How to avoid a perfunctory sensitivity analysis, *Environ. Model. Softw.*, 25,  
 621 1508–1517, <https://doi.org/10.1016/j.envsoft.2010.04.012>, 2010.

622 Savage, S. B., and Hutter, K.: The motion of a finite mass of granular material down a rough incline, *J.*  
 623 *Fluid Mech.*, 199, 177–215, <https://doi.org/10.1017/S0022112089000340>, 1989.

624 Scheidegger, A. E.: On the Prediction of the Reach and Velocity of Catastrophic Landslides, *Rock Mech.*,  
 625 5, 231–236, <https://doi.org/10.1007/BF01301796>, 1973.

626 Schneider, D., Huggel, C., Cochachin, A., Guillén, S., and García, J.: Mapping hazards from glacier lake  
 627 outburst floods based on modelling of process cascades at Lake 513, Carhuaz, Peru, *Adv. Geosci.*, 35,  
 628 145–155, <https://doi.org/10.5194/adgeo-35-145-2014>, 2014.

629 Somos-Valenzuela, M. A., Chisolm, R. E., Rivas, D. S., Portocarrero, C., and McKinney, D. C.: Modeling  
 630 a glacial lake outburst flood process chain: the case of Lake Palcacocha and Huaraz, Peru, *Hydrol. Earth*  
 631 *Syst. Sci.*, 20, 2519–2543, <https://doi.org/10.5194/hess-20-2519-2016>, 2016.

632 Steinacher, R., Kuster, C., Buchli, C., and Meier, L.: The Pizzo Cengalo and Val Bondasca events: From  
 633 early warnings to immediate alarms, *Geophys. Res. Abstr.* 20, 17536, 2018.

634 Tai, Y. C., Noelle, S., Gray, J. M. N. T., and Hutter, K.: Shock-capturing and front-tracking methods for  
 635 granular avalanches, *J. Comput. Phys.*, 175(1), 269–301, <https://doi.org/10.1006/jcph.2001.6946>, 2002.

636 VAW: Vadrec dal Cengal Ost: Veränderungen in Vergangenheit und Zukunft. Laboratory of Hydraulics,  
 637 Hydrology and Glaciology of the Swiss Federal Institute of Technology Zurich, 17 pp.,  
 638 [https://www.gr.ch/DE/institutionen/verwaltung/bvfd/awn/dokumentenliste\\_afw/Cengalo%20Gletschere](https://www.gr.ch/DE/institutionen/verwaltung/bvfd/awn/dokumentenliste_afw/Cengalo%20Gletschere)  
 639 [ntwicklung%20ETH\\_2nov\\_final.pdf](https://www.gr.ch/DE/institutionen/verwaltung/bvfd/awn/dokumentenliste_afw/Cengalo%20Gletschere), accessed on 31 May 2019, 2017.

640 Voellmy, A.: Über die Zerstörungskraft von Lawinen, *Schweizerische Bauzeitung*, 73, 159–162, 212–217,  
 641 246–249, 280–285, 1955.

642 Walter, F., Wenner, M., and Amann, F.: Seismic Analysis of the August 2017 Landslide on Piz Cengalo  
 643 (Switzerland), *Geophys. Res. Abstr.*, 20, 3163-1, 2018.

644 Walter, F., Amann, F., Kos, A., Kenner, R., Phillips, M., de Preux, A., Huss, M., Tognacca, C., Clinton, J.,  
645 Diehl, T., and Bonanomi, Y.: Direct observations of a three million cubic meter rock-slope collapse with  
646 almost immediate initiation of ensuing debris flows, *Earth Planet. Sci. Lett.*, submitted manuscript, 2019.

647 Wang, Y., Hutter, K., and Pudasaini, S. P.: The Savage-Hutter theory: A system of partial differential  
648 equations for avalanche flows of snow, debris, and mud, *ZAMM – J. Appl. Math. Mech.*, 84(8), 507–527,  
649 <https://doi.org/10.1002/zamm.200310123>, 2004.

650 Worni, R., Huggel, C., Clague, J. J., Schaub, Y., and Stoffel, M.: Coupling glacial lake impact, dam  
651 breach, and flood processes: A modeling perspective, *Geomorphology*, 224, 161–176,  
652 <https://doi.org/10.1016/j.geomorph.2014.06.031>, 2014.

653 WSL.: SLF Gutachten G2017.20: Modellierung des Cengalo Bergsturzes mit verschiedenen Rahmenbe-  
654 dingungen, Bondo, GR. WSL-Institut für Schnee- und Lawinenforschung SLF, 69 pp.,  
655 [https://www.gr.ch/DE/institutionen/verwaltung/bvfd/awn/dokumentenliste\\_afw/SLF\\_G2017\\_20\\_Modell](https://www.gr.ch/DE/institutionen/verwaltung/bvfd/awn/dokumentenliste_afw/SLF_G2017_20_Modellierung_Cengalo_Bergsturz_030418_A.pdf)  
656 [ierung\\_Cengalo\\_Bergsturz\\_030418\\_A.pdf](https://www.gr.ch/DE/institutionen/verwaltung/bvfd/awn/dokumentenliste_afw/SLF_G2017_20_Modellierung_Cengalo_Bergsturz_030418_A.pdf), accessed on 31 May 2019, 2017.

657

659 Table 1. Descriptions and optimized parameter values for each of the zones A–F (Fig. 4 and Fig. 7). The  
660 names of the model parameters are given in the text and in Table 2. The values provided in Table 2 are  
661 assigned to those parameters not shown. (S1) and (S2) refer to the corresponding scenarios. Explanations  
662 of the superscripts: <sup>1)</sup> Note that in all zones and in both of the scenarios S1 and S2,  $\delta$  is assumed to scale  
663 linearly with the solid fraction. This means that the values given only apply in case of 100% solid. <sup>2)</sup> This  
664 only applies to the initial landslide, which is assumed completely dry in Scenario S2. Due to the scaling  
665 of  $\delta$  with the solid fraction, a lower basal friction is required to obtain results similar to Scenario S1,  
666 where the rock avalanche contains some fluid. The same values of  $\delta$  as for Scenario S1 are applied for the  
667 debris flow in Scenario S2 throughout all zones. <sup>3)</sup> This volume is derived from our own reconstruction  
668 (Fig. 5). In contrast, WSL (2017) gives 3.1 million m<sup>3</sup>, and Amann et al. (2018) 3.15 million m<sup>3</sup>. <sup>4)</sup> In Sce-  
669 nario S2, the glacier is not directly entrained, but instead released behind the rock avalanche. In both  
670 scenarios, ice is considered to melt immediately on impact and included in the viscous fluid fraction. See  
671 text for more detailed explanations.

Zone	Description	Model parameters	Initial conditions
A	Rock zone – NE face of Piz Cengalo with rock slide-rock fall release area	$\delta = 20^\circ$ (S1) <sup>1)</sup> $\delta = 13^\circ$ (S2) <sup>2)</sup> $C_{AD} = 0.2$	Release volume: 3.2 million m <sup>3</sup> , 100 % solid <sup>3)</sup>
B	Glacier zone – Cirque glacier beneath zone A, entrainment of glacier ice <sup>1)</sup>	$\delta = 20^\circ$ (S1) $\delta = 13^\circ$ (S2) $C_E = 10^{-6.5}$	Entrainment of glacier ice and till (Table 3) <sup>4)</sup>
C	Slope zone – steep, partly debris-covered glacier forefield leading down to the Val Bondasca	$\delta = 20^\circ$ (S1) $\delta = 13^\circ$ (S2) $C_E = 10^{-6.5}$ (S1) $C_E = 10^{-8.0}$ (S2)	Entrainment of injected water in Scenario S1 Entrainment of rock avalanche deposit in Scenario S2
D	Upper Val Bondasca zone – clearly defined flow channel becoming narrower in downstream direction	$\delta = 20\text{--}45^\circ$	No entrainment allowed, increasing friction
E	Lower Val Bondasca zone – narrow gorge	$\delta = 45^\circ$ $C_{FF} = 0.5$	No entrainment allowed, high friction due to lateral confinement
F	Bondo zone – deposition of the debris flow on the cone of Bondo	$\delta = 20^\circ$	No entrainment allowed

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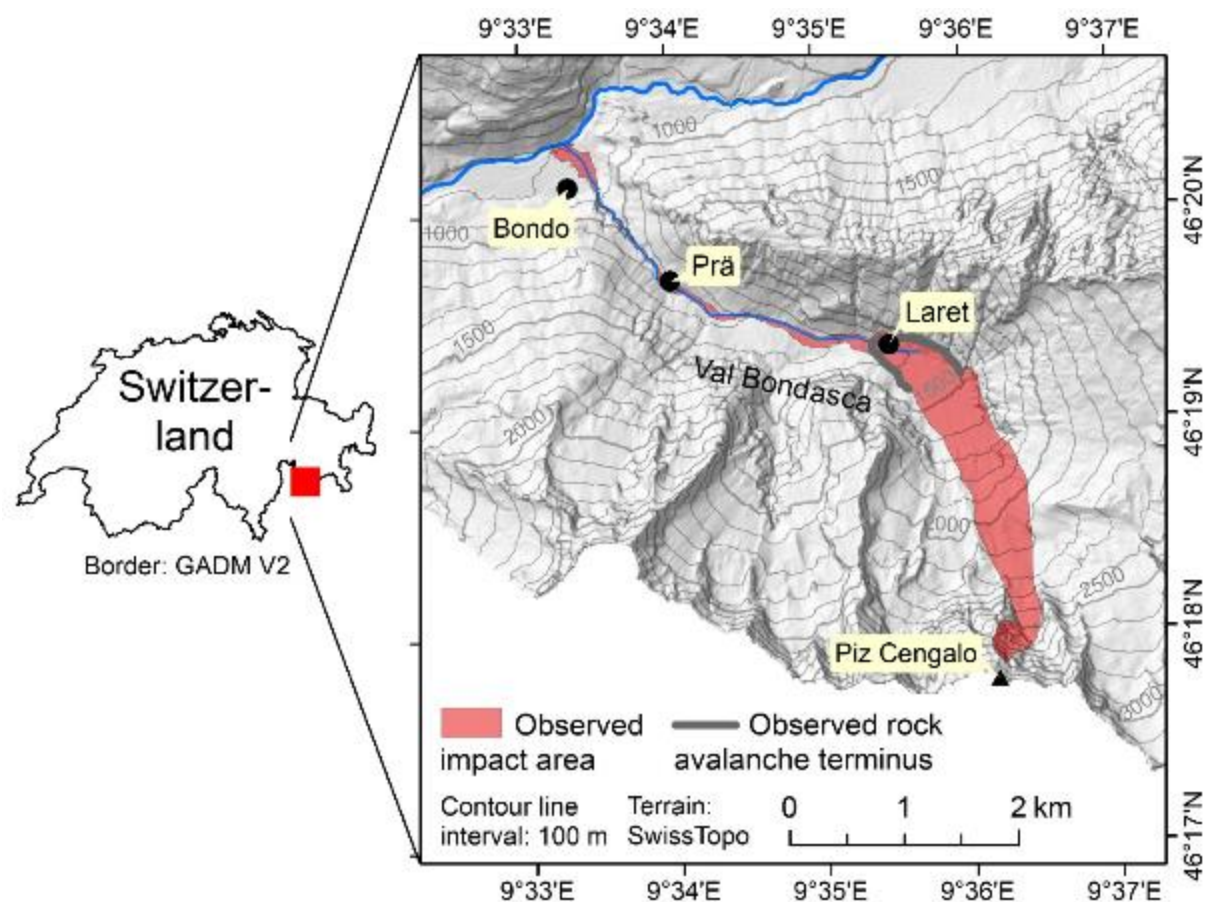
673 Table 2. Model parameters used for the simulations. Explanations of the superscripts: <sup>1)</sup> Fluid is here con-  
674 sidered as a mixture of water and fine particles. This explains the higher density, compared to pure wa-  
675 ter. <sup>2)</sup> The internal friction angle  $\varphi$  always has to be larger than or equal to the basal friction angle  $\delta$ .  
676 Therefore, in case of  $\delta > \varphi$ ,  $\varphi$  is increased accordingly.

Symbol	Parameter	Unit	Value
$\rho^S$	Solid material density (grain density)	kg m <sup>-3</sup>	2,700
$\rho^F$	Fluid material density	kg m <sup>-3</sup>	1,400 <sup>1)</sup>
$\varphi$	Internal friction angle	Degree	27 <sup>2)</sup>
$\delta$	Basal friction angle	Degree	Table 1
$\nu$	Kinematic viscosity of the fluid	m <sup>2</sup> s <sup>-1</sup>	10
$\tau_Y$	Yield strength of the fluid	Pa	10
$C_{AD}$	Ambient drag coefficient	–	0.04 (exceptions in Table 1)
$C_{FF}$	Fluid friction coefficient		0.0 (exceptions in Table 1)
$C_E$	Entrainment coefficient	–	Table 1

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Table 3. Selected output parameters of the simulations for the Scenarios S1 and S2 compared to the observed or documented parameter values. S = solid; F = fluid; fractions are expressed in terms of volume;  $t_0$  = time from the initial release to the release of the first debris flow surge. Reference values are extracted from Amt für Wald und Naturgefahren (2017a), Bonanomi and Keiser (2017), and WSL (2017). \*\*\* = empirically adequate (within the documented range of values); \*\* = empirically partly adequate (less than 50% away from the documented range of values); \* = empirically inadequate (at least 50% away from the documented range of values). The arithmetic means of minimum and maximum of each range are used for the calculations. Explanations of the superscripts: <sup>1)</sup> Not all the material entrained from the glacier was relevant for the first debris flow surge (Fig. 6), therefore lower volumes of entrained S (coarse till, in Scenario S2 also rock avalanche deposit) and F (molten ice and fine till, in Scenario S1 also pore water) yield the empirically most adequate results. The F volumes originating from the glacier in the simulations represent approximately half of the water equivalent of the entrained ice, corresponding well to the findings of WSL (2017). <sup>2)</sup> This value does not include the 145,000 m<sup>3</sup> of solid material remobilized through entrainment from the rock avalanche deposit in Scenario S2. <sup>3)</sup> WSL (2017) states that the rock avalanche came to rest approx. 60 s after release, whereas the seismic signals ceased 90 s after release. <sup>4)</sup> A certain time (here, we assume a maximum of 30 s) has to be allowed for the initial debris flow surge to reach O2, located slightly downstream of the front of the rock avalanche deposit. <sup>5)</sup> WSL (2017) gives a travel time of 3.5 minutes to Prä, roughly corresponding to the location of O3. It remains unclear whether this number refers to the release of the initial rock slide-rock fall or (more likely) to the start of the first debris flow surge. Bonanomi and Keiser (2017) give a travel time of roughly four minutes between the initial release and the arrival of the first surge at the sensor of Prä. <sup>6)</sup> Amt für Wald und Naturgefahren (2017) gives a time span of 17 minutes between the release of the initial rock slide-rock fall and the arrival of the first debris flow surge at the “bridge” in Bondo. However, it is not indicated to which bridge this number refers. WSL (2017), in contrast, give a travel time of 7–8 minutes from Prä to the “old bridge” in Bondo, which, in sum, results in a shorter total travel time as indicated in Amt für Wald und Naturgefahren (2017). Depending on the bridge, the reference location for these numbers might be downstream from O4. In the simulation, this hydrograph shows a slow onset – travel times refer to the point when 5% of the total peak discharge are reached.

Parameter	Documentation/Observation	Scenario S1	Scenario S2
Entrained ice (m <sup>3</sup> )	600,000 <sup>1)</sup>	–	–
Entrained S (m <sup>3</sup> )	–	60,000	60,000 <sup>2)</sup>
Entrained F (m <sup>3</sup> )	–	305,000	240,000
Duration of initial landslide (s)	60–90 <sup>3)</sup>	100–120**	100–120**
Travel time to O2 (s)	90–120 <sup>4)</sup>	140**	$t_0+120$ ***
Travel time to O3 (s)	210–300 <sup>5)</sup>	280***	$t_0+240$ ***
Travel time to O4 (s)	630–1020 <sup>6)</sup>	700***	$t_0+640$ ***
Debris flow volume at O2 (m <sup>3</sup> )	540,000	530,000** (43% S)	430,000** (45% S)
Debris flow volume at O4 (m <sup>3</sup> )	50,000	265,000* (34% S)	270,000* (24% S)



708  
709 Figure 1. Study area with the impact area of the 2017 Piz Cengalo-Bondo landslide cascade. The ob-  
710 served rock avalanche terminus was derived from WSL (2017).  
711





712  
713 Figure 2. Oblique view of the impact area of the event, orthophoto draped over the 2011 DTM. Data  
714 sources: swisstopo.  
715

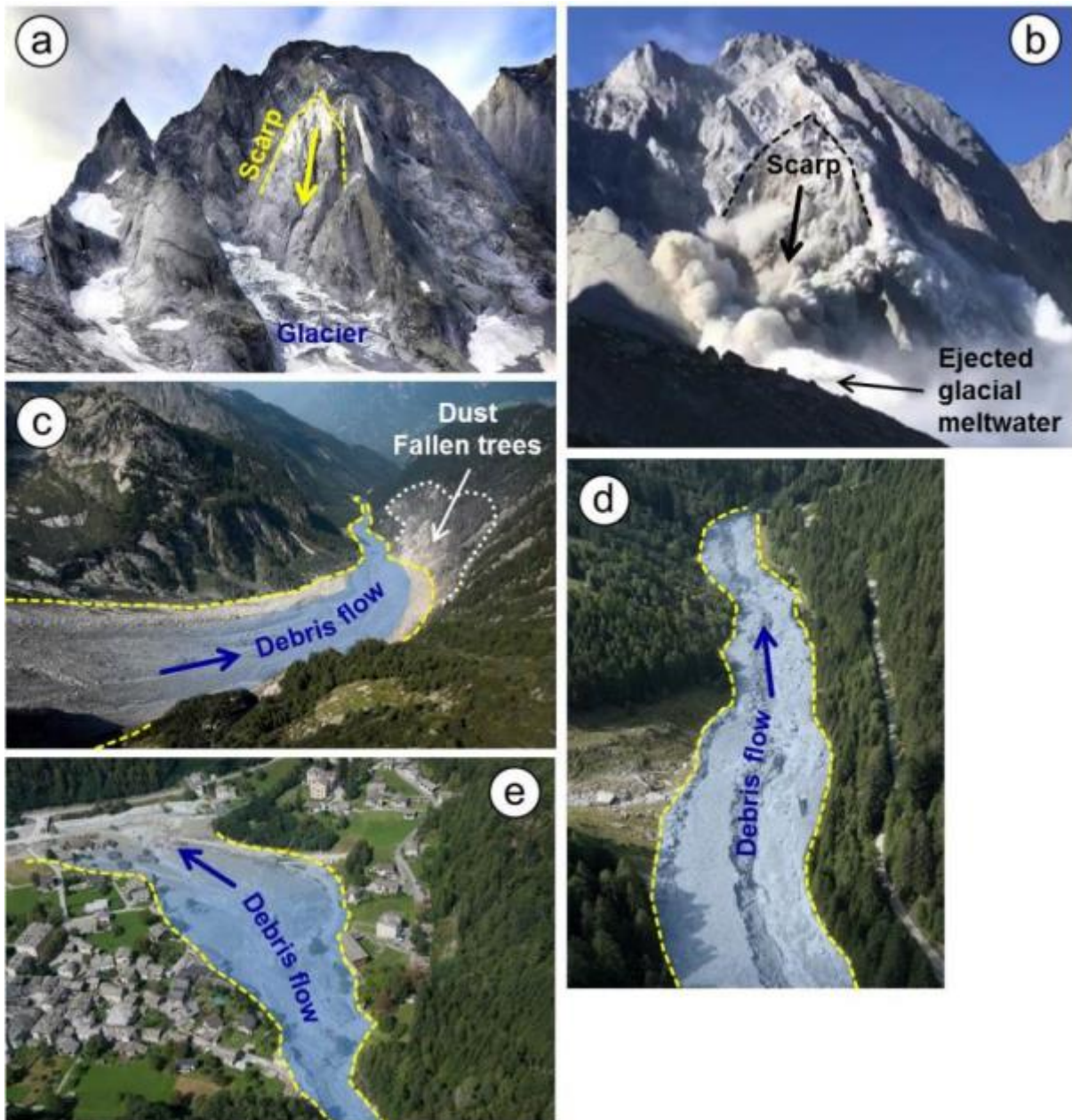


Figure 3. The 2017 Piz Cengalo-Bondo landslide cascade. (a) Scarp area on 20 September 2014. (b) Scarp area on 23 September 2017 at 9:30, 20 s after release, frame of a video taken from the Capanna di Sciora. Note the fountain of water and/or crushed ice at the front of the avalanche, most likely representing meltwater from the impacted glacier. (c) Upper part of the Val Bondasca, where the channelized debris flow developed. Note the zone of dust and pressure-induced damages to trees on the right side of the valley. (d) Traces of the debris flows in the Val Bondasca. (e) The debris cone of Bondo after the event. Image sources: Daniele Porro (a), Diego Salasc (b), VBS swisstopo Flugdienst (c)–(e).

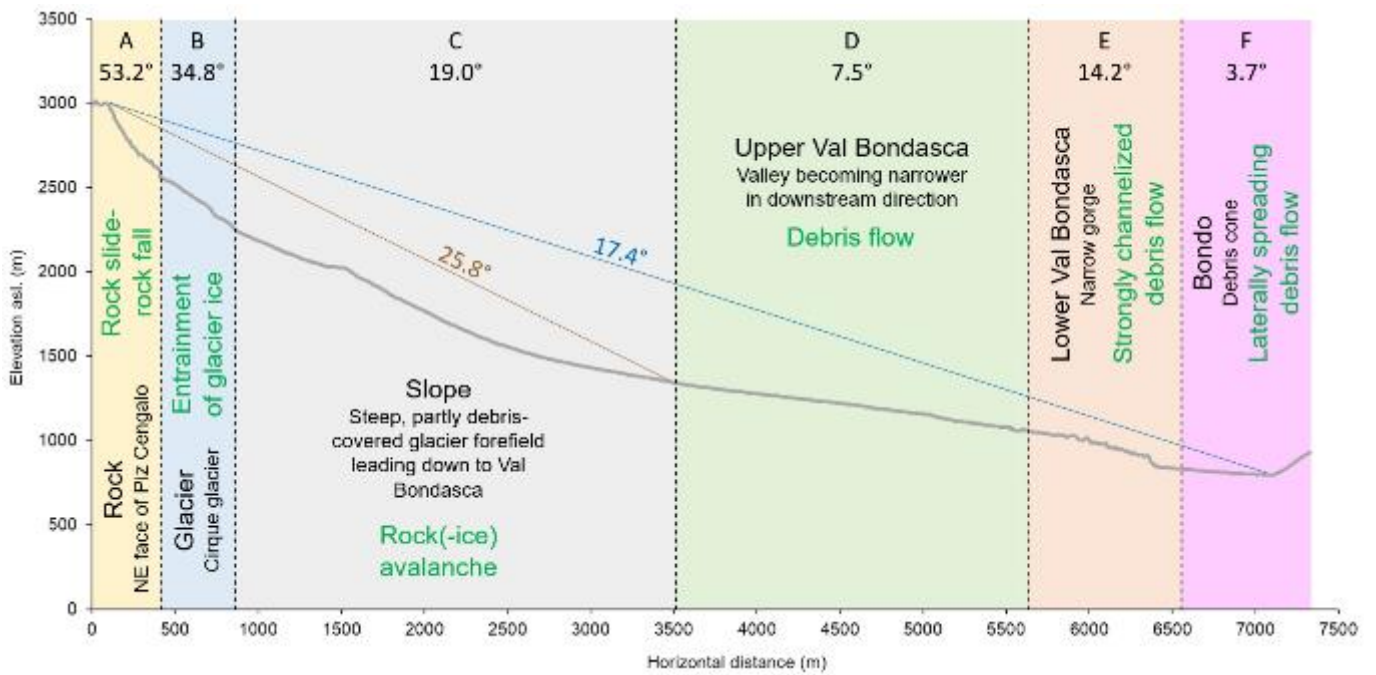


Figure 4. Profile along the main flow path of the Piz Cengalo-Bondo landslide cascade. The letters A–F indicate the individual zones (Table 1 and Fig. 7), whereas the associated numbers indicate the average angles of reach along the profile for each zone. The brown number and line show the angle of reach of the initial landslide (rock slide-rock fall and rock(-ice) avalanche), whereas the blue number and line show the angle of reach of the entire landslide cascade. The geomorphic characteristics of the zone (in black) are indicated along with the dominant process type (in green).



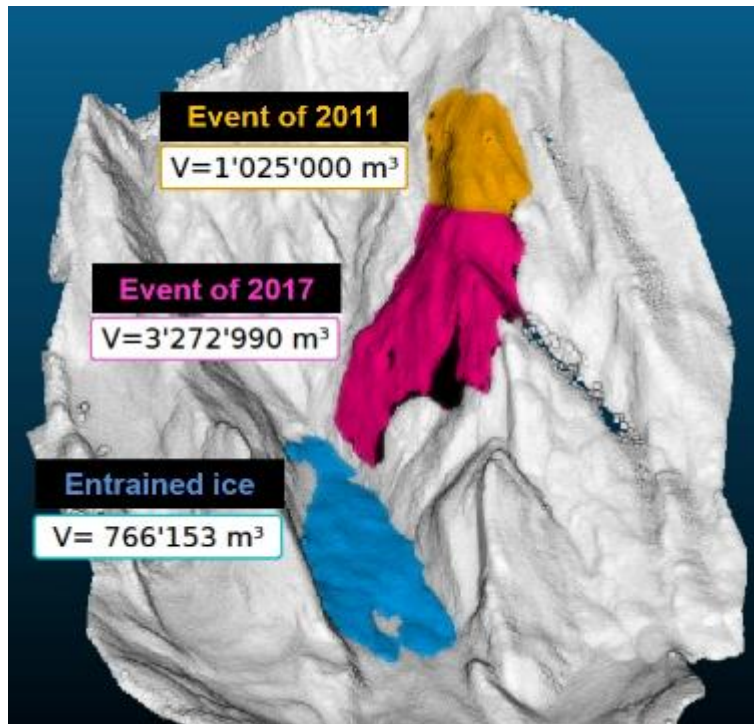


Figure 5. Reconstruction of the released rock volume and the entrained glacier volume in the 2017 Piz Cengalo-Bondo landslide cascade. Note that the boundary between the 2011 and 2017 release volumes is connected to some uncertainties, explaining the slight discrepancies among the reported volumes. The glacier volume shown is neither corrected for entrainment related to the 2011 event, nor for glacier retreat in the period 2011–2017.

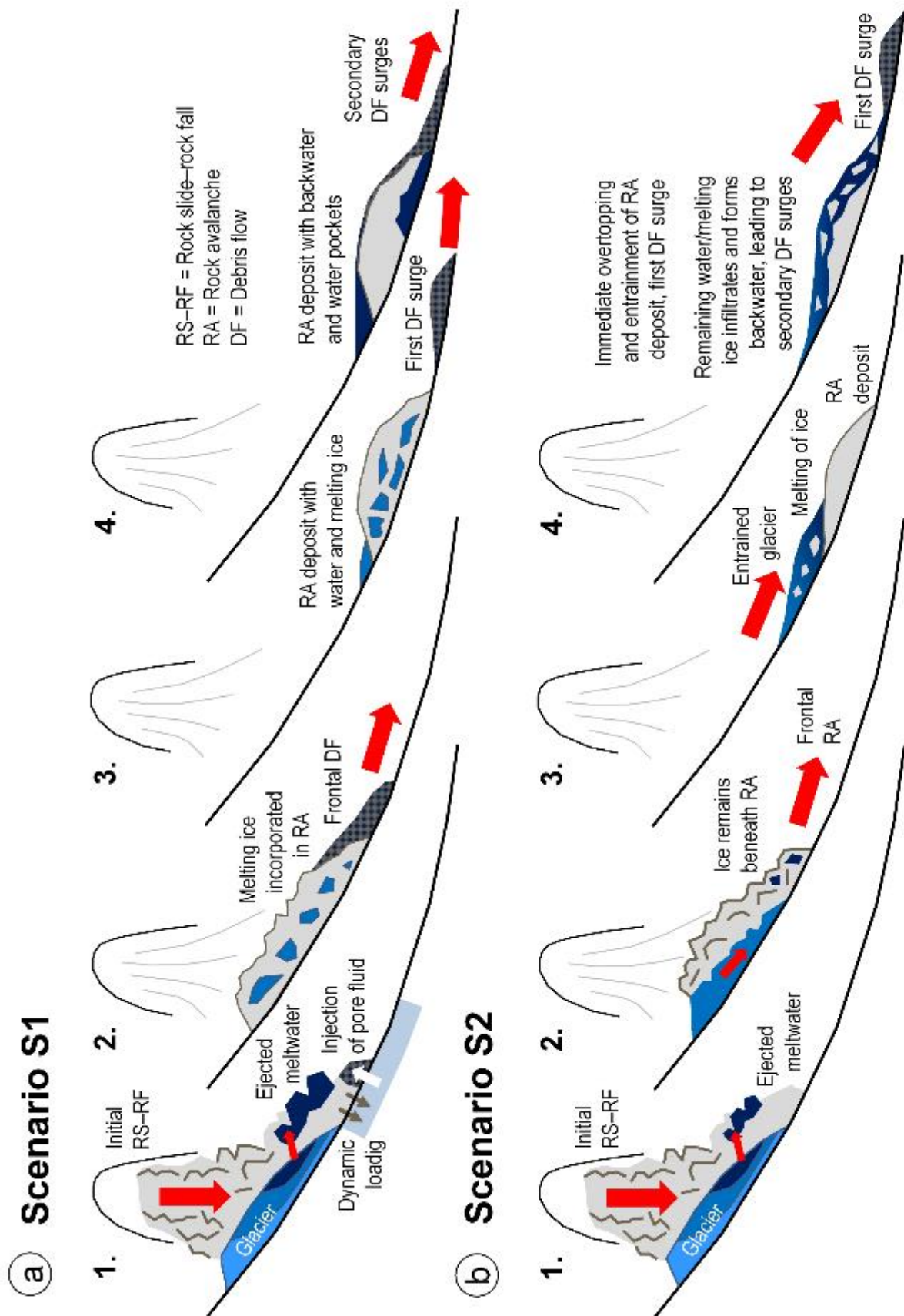


Figure 6. Qualitative conceptual models of the rock avalanche-debris flow transformation. (a) Scenario S1; (b) Scenario S2. See text for the detailed description of the two scenarios.

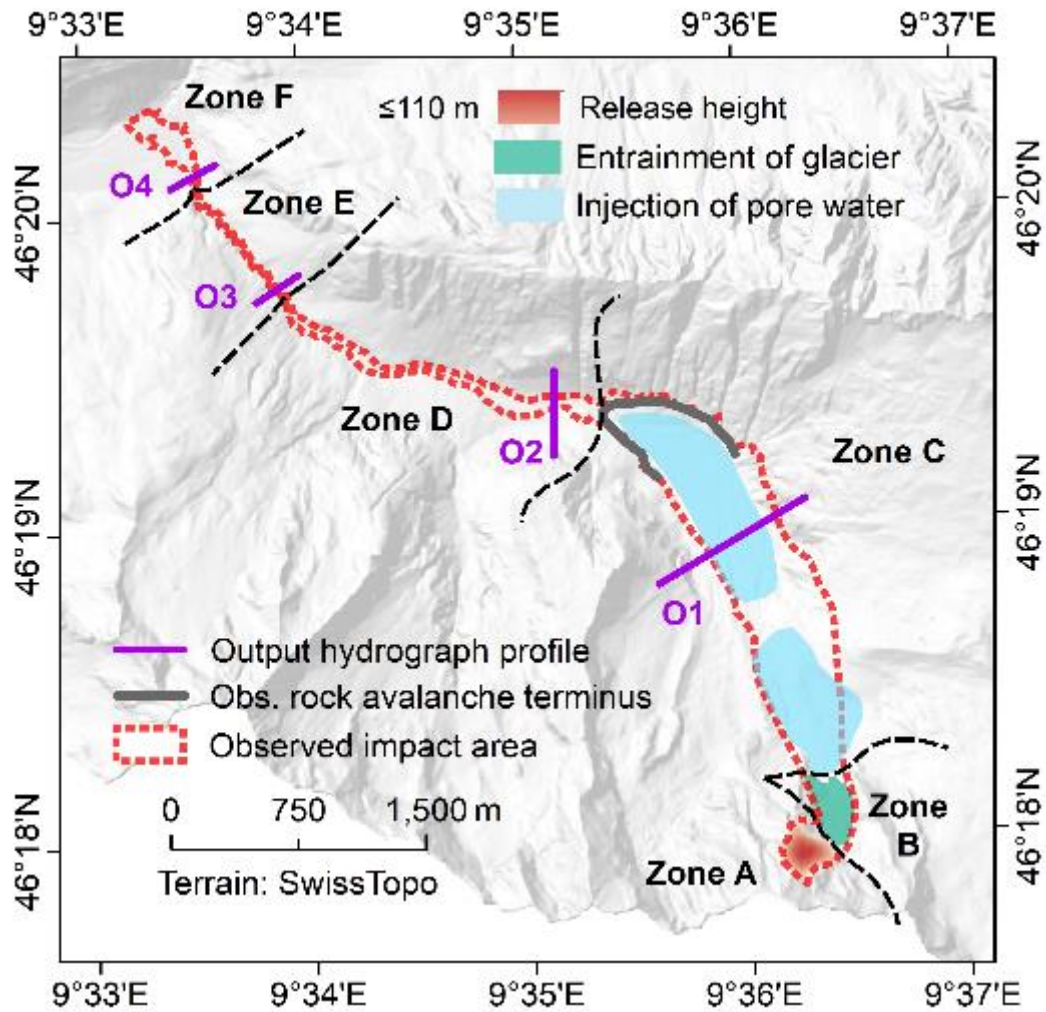


Figure 7. Overview of the heights and entrainment areas as well as the zonation performed as the basis for the simulation with r.avaflow. Injection of pore water only applies to the Scenario A. The zones A–F represent areas with largely homogeneous surface characteristics. The characteristics of the zones and the model parameters associated to each zone are summarized in Table 1 and Fig. 4. O1–O4 represent the output hydrograph profiles. The observed rock avalanche terminus was derived from WSL (2017).

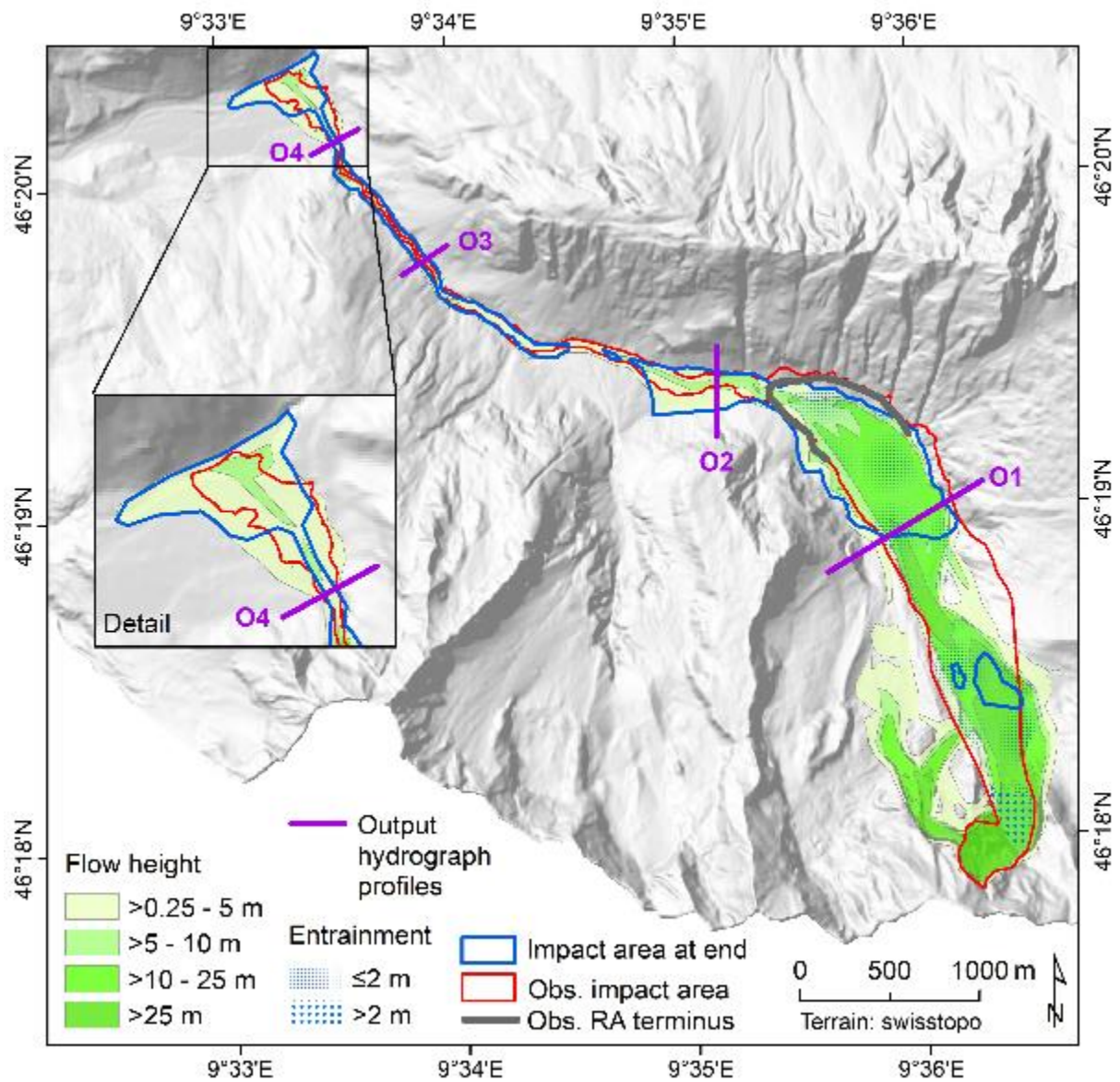


Figure 8. Maximum flow height and entrainment derived for Scenario S1. RA = rock avalanche; the observed RA terminus was derived from WSL (2017).



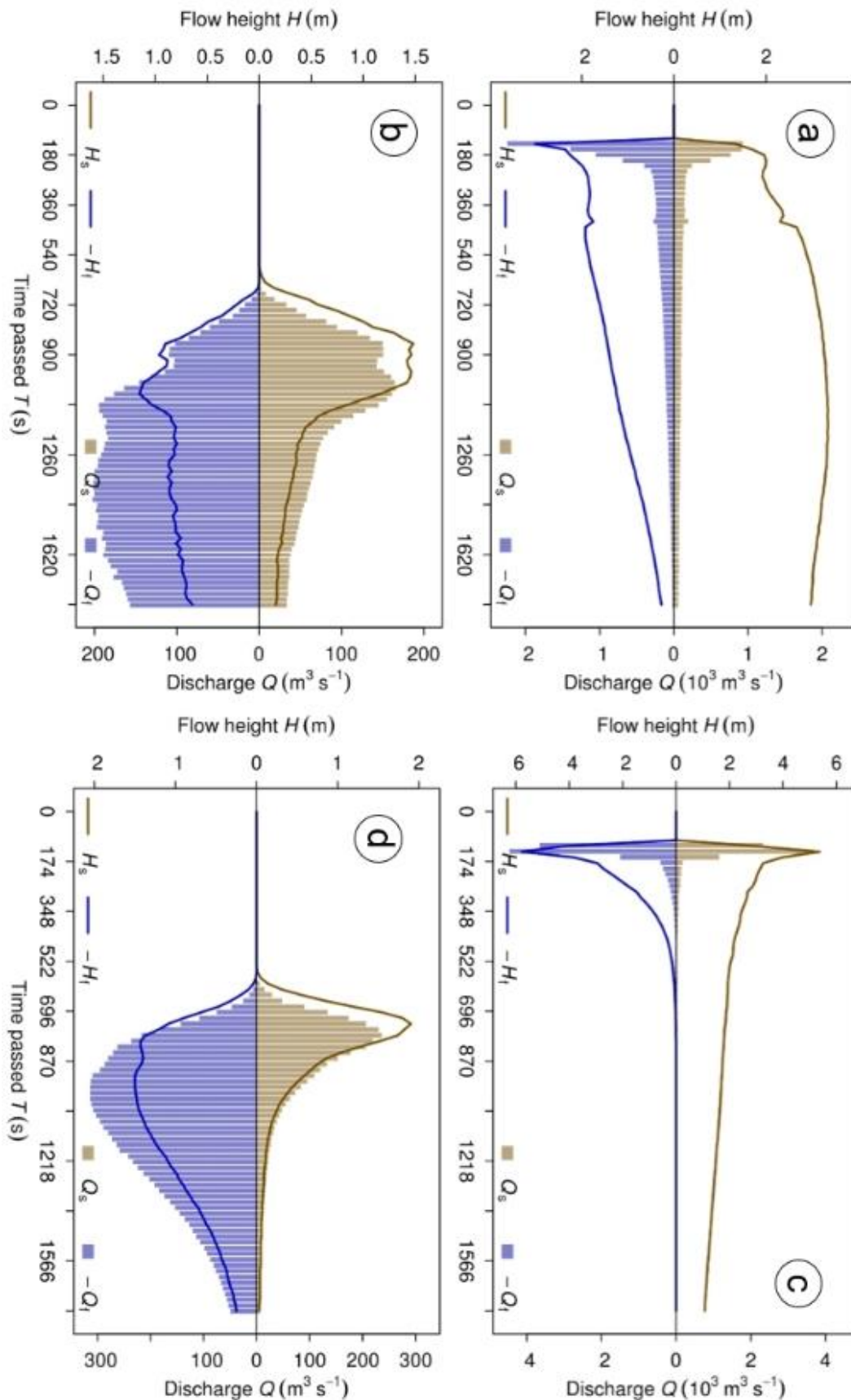


Figure 9. Output hydrographs OH2 and OH4 derived for the scenarios S1 and S2. (a) OH2 for Scenario S1. (b) OH4 for Scenario S1. (c) OH2 for Scenario S2. (d) OH4 for Scenario S2. See Fig. 7 and Fig. 8 for the locations of the hydrograph profiles O2 and O4.  $H_s$  = solid flow height;  $H_f$  = fluid flow height;  $Q_s$  = solid discharge;  $Q_f$  = fluid discharge.



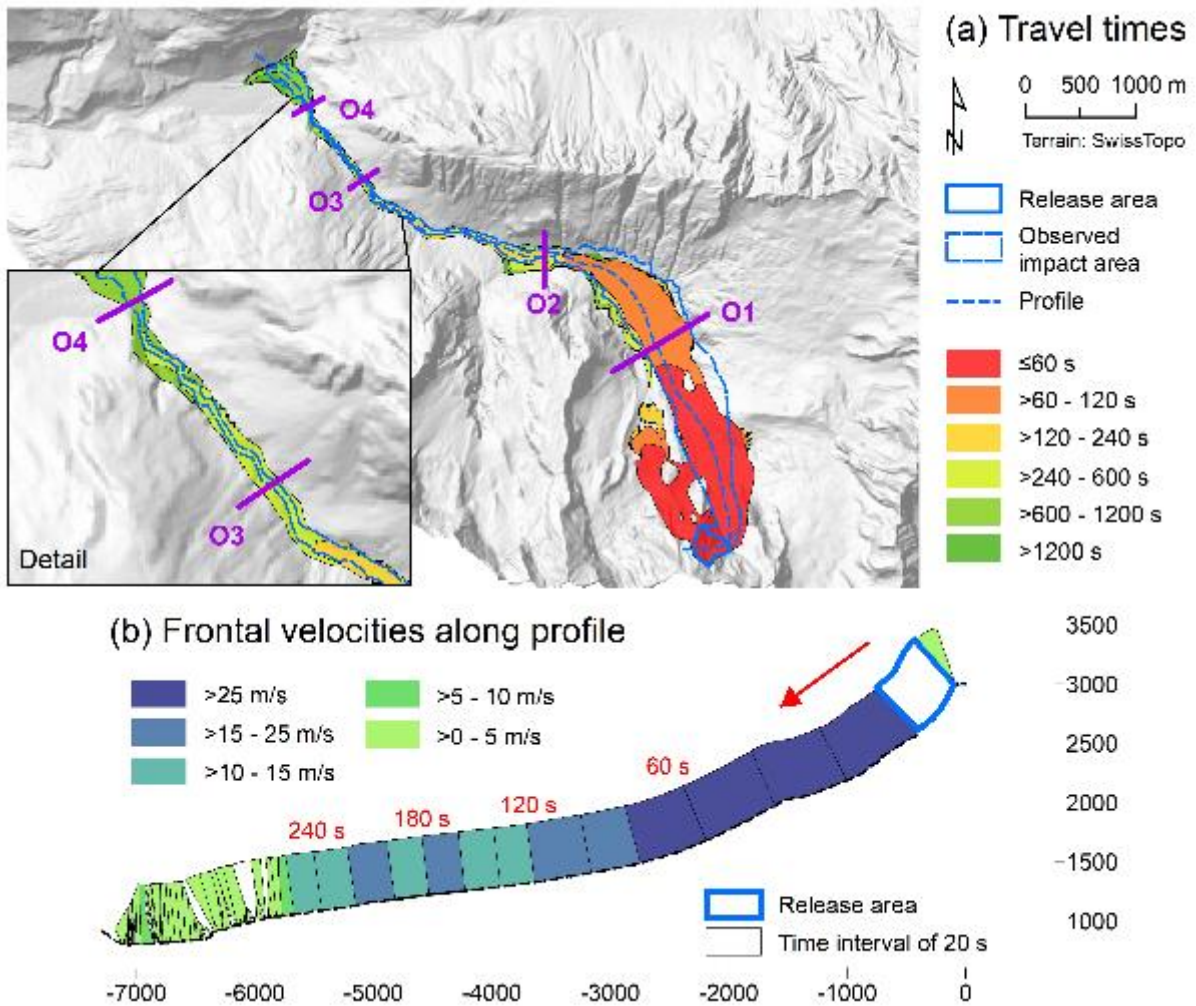


Figure 10. Spatio-temporal evolution and velocities of the event obtained for Scenario S1. (a) Travel times, starting from the release of the initial rock slide-rock fall. (b) Frontal velocities along the flow path, shown in steps of 20 s. Note that the height of the velocity graph does not scale with flow height. White areas indicate that there is no clear flow path.

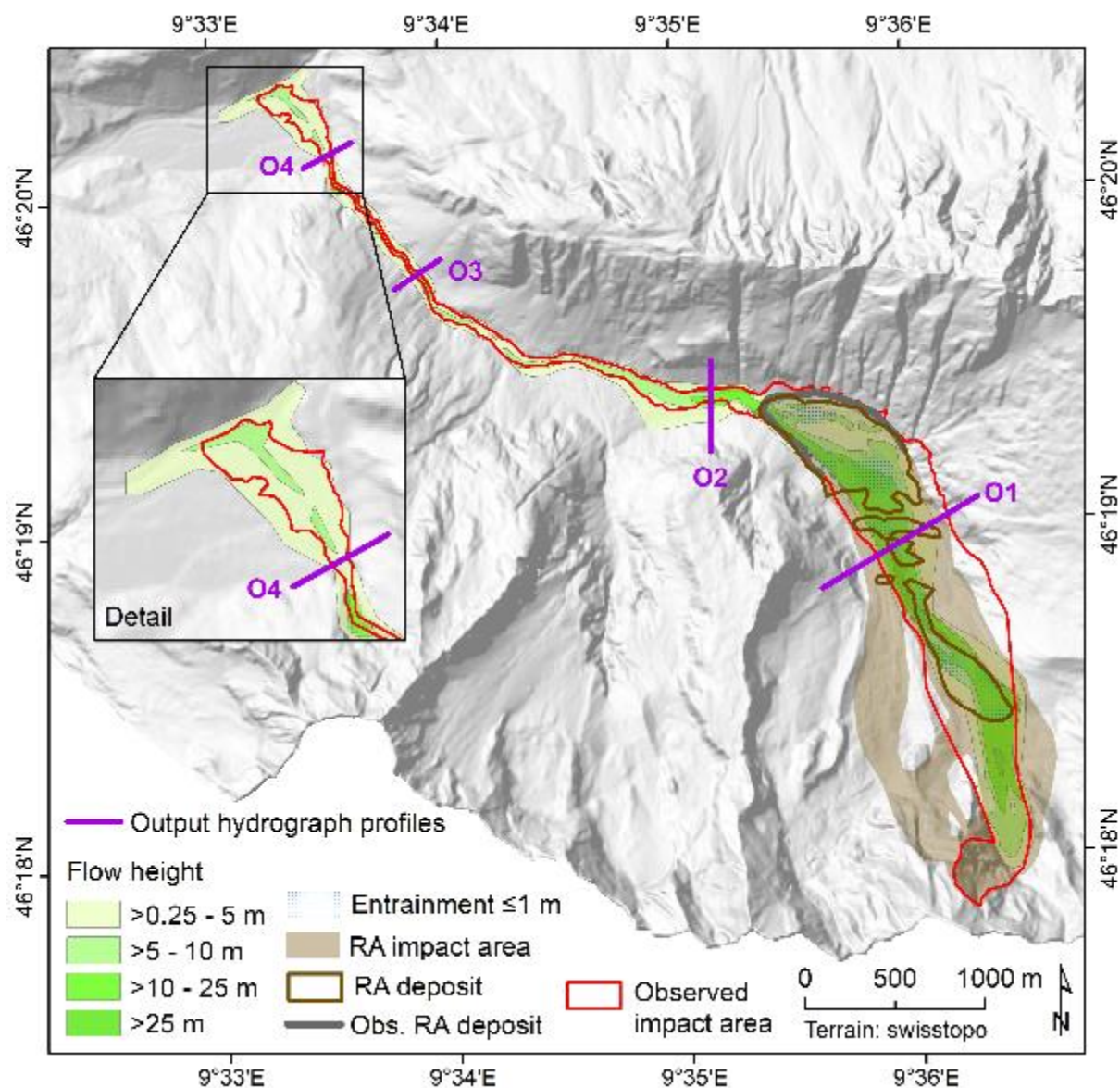


Figure 11. Maximum flow height and entrainment derived for Scenario S2. RA = rock avalanche; the observed RA terminus was derived from WSL (2017).

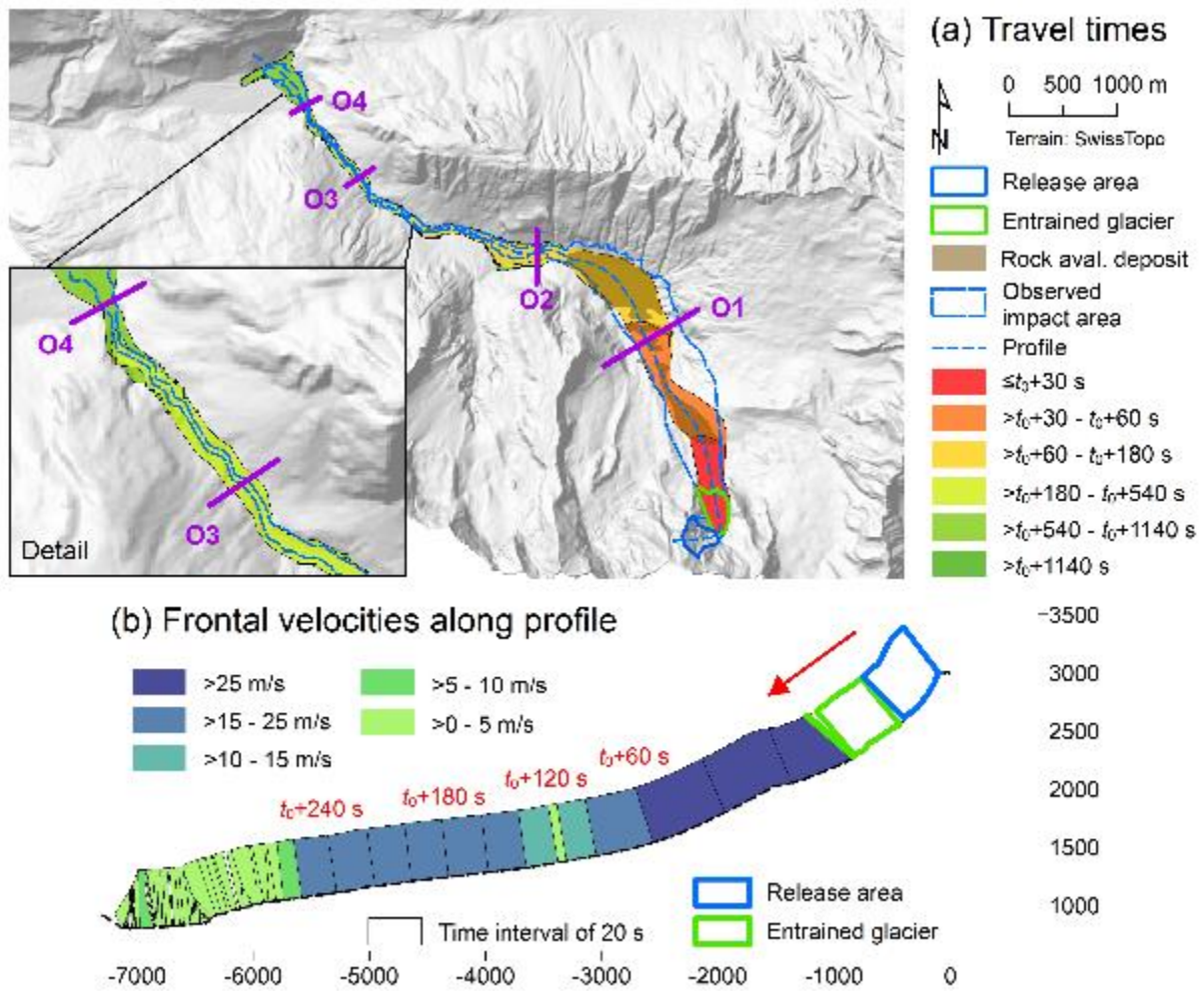


Figure 12. Spatio-temporal evolution and velocities of the event obtained for Scenario S2. (a) Travel times, starting from the release of the initial rock slide-rock fall. Thereby  $t_0$  (s) is the time between the release of the rock slide-rock fall and the mobilization of the entrained glacier. (b) Frontal velocities along the flow path, shown in steps of 20 s. Note that the height of the velocity graph does not scale with flow height. White areas indicate that there is no clear flow path.