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Entrainment maps considering hydrological conditions for mass movement runout modelling: application to debris-flow bulking at Pizzo Cengalo

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Abstract. Debris flows entrain sediments and water along their flow path and grow significantly in size. Because the entrainment process isn't well understood and data is rare, hazard and risk assessment with numerical models is challenging. It is known, however, that both for debris flows and rock avalanches, interstitial pore water in flow path substrate can cause increases in pore water pressures when overridden by the flow, which enhances erosion. The entrained water likely also plays a role in the process transition from rock avalanche to debris flow, like in the Pizzo Cengalo event in 2017. We present a framework for producing entrainment maps serving as an input for runout modelling, here illustrated using RAMMS. The entrainment maps consist of spatially-distributed entities with properties such as max erosion depth, and soil water content inferred from land cover and lithology maps. This study serves as a basis for producing duration curves of subsurface water available for entrainment and include it into the entrainment maps. Such hydrologically-informed entrainment maps will be useful to assess the probability of certain runout distances.

1 Introduction

Debris flows can significantly grow in size as material is entrained along their flow path (e.g., [1]). The flow may grow by entraining material from the bed or by bank collapse, but the exact mechanism and how it affects the flow is still debated [2]. Therefore, numerical modelling for hazard and risk assessment remains a challenging task. Models neglecting erosion may misestimate peak discharge, and the locations and extents of channel overtopping [3].

Theoretical work, large-scale laboratory experiments and field studies have shown the importance of the degree of water saturation for sediment entrainment [4]–[7]. All studies support the theory that positive pore pressures in the sediments being entrained aid in entraining material when basal sediments are overridden by the flow. Other types of landslides, such as rock avalanches, are also affected by the degree of saturation along the flow path as their mobility can be significantly higher when flowing over a saturated substrate [8].

In rare yet destructive cases, a process transition from rock avalanche to debris flow has been reported (e.g., [9–11]). At Pizzo Cengalo, Switzerland, two major rock avalanches occurred in December 2011 and August 2017. The earlier of the two deposited sediment in the upstream reaches of the Bondasca valley (Fig. 1). The later rock avalanche ($3x10^6$ m^3) entrained glacial ice and also sediments with interstitial water from the earlier deposits. This stored water likely played an important role in the process cascade [11]. In other cases, additionally the entrainment and melting of snow may be relevant for increasing saturation of the flow [9]. Therefore, to improve the hazard and risk assessment of mass movement runout, there is a need for an objective method to define numerous zones, each with homogeneous properties, to describe the entrainability of the sediment. To this end we produce "entrainment maps", which are characterized by static properties such as soil depth or hydraulic conductivity, but also by variables such as soil water content or snow water equivalent which can be predicted using hydrological models. We use publicly-available data on land cover and lithology to characterize the entrainment zones and determine entrainment hot spots. Hydrological modelling (e.g., [12]) will be used to assess probabilities of saturated conditions. The entrainment maps serve as inputs for runout modelling, herein with RAMMS, to constrain the entrainment with information on

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saturation, land cover and lithology. We test our framework at Pizzo Cengalo because it is well documented (see [11]–[13]).

2 Methods

The numerical model RAMMS [14] is used to compute the debris-flow runout. RAMMS treats the debris flow as a one-phase fluid and solves 2D depth-averaged equations for mass and momentum conservation. The Voellmy frictional relation is used herein. Hence, the two parameters for Coulomb friction (μ) and turbulent friction (ξ) need to be calibrated. The flow initiates either as single or multiple user-defined landslide releases or hydrographs. RAMMS has an erosion module which relates the maximum erosion depth to maximum shear stress [3]. The final erosion depth can be additionally constrained if e.g. the depth to bedrock is known. The terrain is not updated during the simulation. Although RAMMS also has a rock avalanche module, we focus on the debris-flow module and model two end-member scenarios of debris flow entrainment for a flow starting from the toe of the 2017 rock avalanche deposit.

We use publicly available data for Switzerland, provided by the Federal Office of Topography (swisstopo), to produce entrainment maps: a land cover map (LC) and a geo cover map (GC). LC divides surface features into 14 classes (e.g., forest, scree, glacier, bedrock, etc.) with an accuracy of <3 m and is updated every ~6 years. Hence, dynamic features such as glacier and forest outlines are accurately represented and pre- and post-conditions of rare events can be analysed (e.g., mass movement deposits). GC is not as accurate and uses smoothed outlines. However, it is based on the Geological Atlas of Switzerland [15] and provides information on the lithosphere (e.g., bedrock, mass movement deposit, alluvial deposit, etc.). We used QGIS to combine LC and GC. This helped to constrain e.g. the max erosion depth (Fig. 1). For example, the depth to bedrock must be shallower if GC is bedrock compared to a rock avalanche deposit. Furthermore, GC could potentially be used to roughly characterize soil water storage and soil hydraulic properties.

Simulations with RAMMS were made on a 2m grid, corresponding to the native resolution of the DTM, and within a small region constructed to have an aerial extent somewhat larger than that of the observed flow path (the computational domain; Fig. 1A). Because the details of the initial debris flow leaving the rock avalanche deposit are not well constrained, we iteratively tried several volumes until we converged on a plausible estimate of 50,000 m^3. The model was setup with an input hydrograph with a maximum discharge corresponding to the envelope curve for events of this volume [16]. Because the GC map is provisional, and to demonstrate the concept, we used the outline of the alluvial sediment at the valley bottom to set the extent of the erodible area (red polygon in Fig. 1A). Downstream of the erosion polygon, the flow enters a bedrock gorge before entering the village Bondo. We do not consider erosion within the gorge. Simulations were run for 3000 seconds (50 mins), corresponding to a moving momentum of ~10% of the maximum value.

We used two end-member scenarios to describe the erodibility of the alluvial sediment on the valley bottom: dry sediment and wet/loose saturated sediment as described in [17]. Experience from RAMMS users indicate that these end-member entrainment scenarios are generally useful at other field sites. However, additional research is being conducted in a parallel project to better constrain the erodibility of sediment related to the water content.

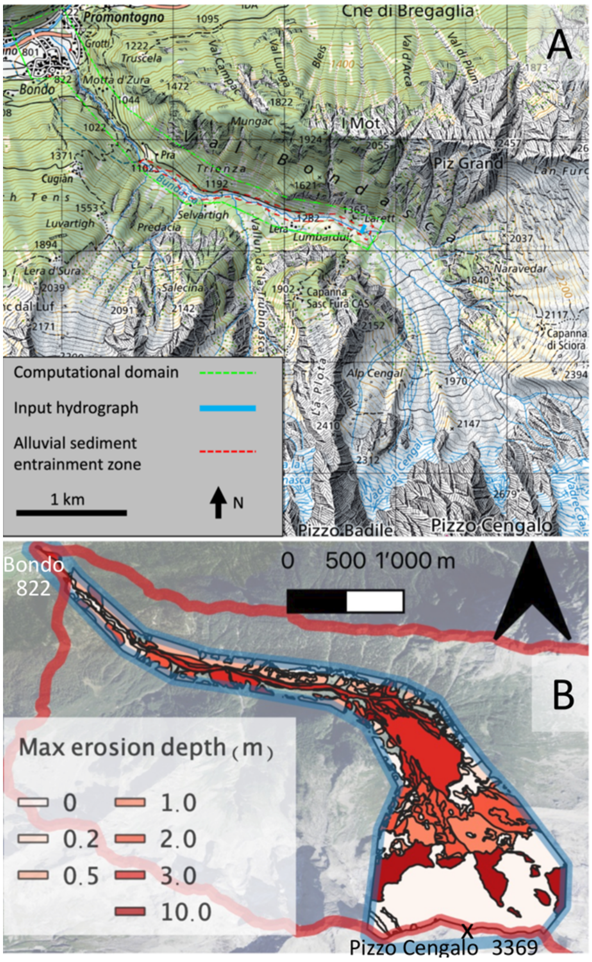

Fig. 1. Overview of the Bondasca basin spanning from Pizzo Cengalo to the village of Bondo. A) Modelling domain used for debris flow simulation with RAMMS with a hydrograph input at the toe of the 2017 rock avalanche deposit. B) Entrainment map with max erosion depth for mass movements in the Bondasca valley. These depths were inferred by using the combined LC/GC information. The red line shows the catchment outlines and the blue line the modelling domain which would be considered for a rock avalanche with a transition to a debris flow using RAMMS.

3 Results and Discussion

The scenario with saturated sediment eroded 3-4 m of the alluvial deposits along the flow path, while the unsaturated scenario typically eroded < 1 m (Fig. 2). The amount of additionally entrained material in the wet bed is significant and the provisional entrainment map confirms that these amounts of erosion are possible (Fig.

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1B). As seen in the downstream depositional area, the consequences of the two scenarios are also significantly different (Fig. 3). In the dry scenario, most sediments remain in the retention basin just upstream of the bridge at the basin outlet. In the wet scenario, however, the retention basin is smaller than the debris-flow volume and parts of the village are inundated.

These differences highlight the need of delineating areas of entrainment. Frank et al. [3] showed that such amounts of erosion are possible when the bed is exposed to the magnitude of maximum shear stress simulated here. However, to improve debris-flow hazard assessment, further developments need to be done to quantify probabilities of hydrological conditions enhancing such erosional events, i.e. the likelihood of high soil saturation. This will decrease the uncertainties in hazard assessment.

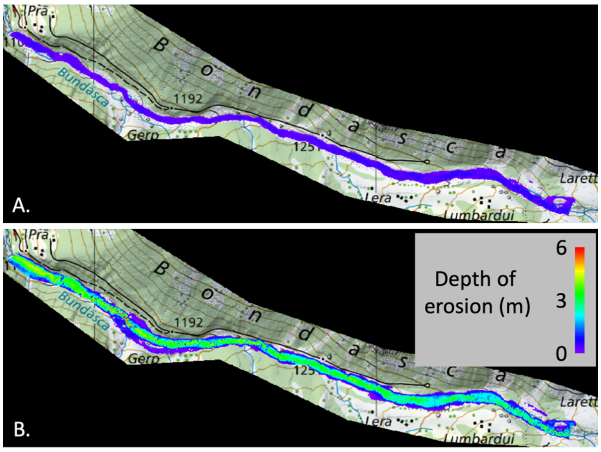

Fig. 2. Modelled erosion pattern for end-member entrainment scenarios: A) dry alluvial sediment, erosion depth up to 1.5 m; and B) wet alluvial sediment, with a maximum erosion depth up to 9.2 m.

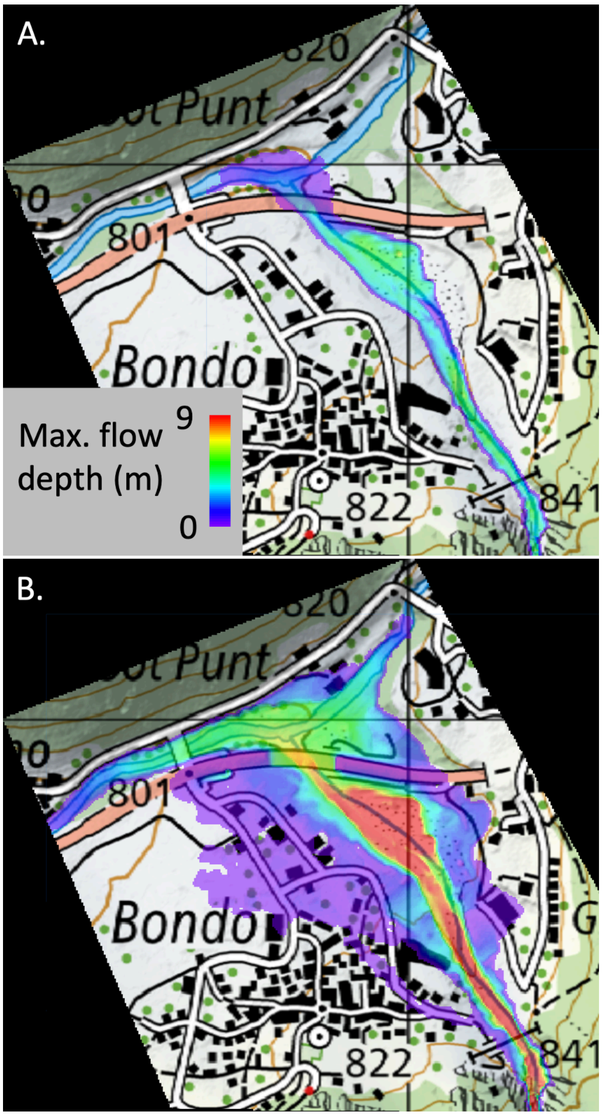

Fig. 3. Modelled maximum flow depth near Bondo village, for end-member entrainment scenarios: A) dry alluvial sediment; and B) wet alluvial sediment.

4 Conclusions and Outlook

We have presented a framework to include entrainment maps for more objectively constrained erosion in numerical runout modelling of mass movements. Because the work is ongoing and not yet incorporated into the RAMMS runout model, we illustrated two scenarios representing wet and dry conditions for debris flows initiating upstream of the village of Bondo. We have planned a series of next steps which include:

1. Fully developing the entrainment maps in a general way and then specifically into RAMMS.
2. Improving the empirical erosion-depth relation by studying a series of well-documented events with erosion data at Illgraben, Switzerland.
3. Setting up a hydrological model to obtain estimates of duration curves for soil water saturation and snow water equivalent (analogous to flow-duration curves for river discharge).
4. Applying the hydrologically-informed entrainment map concept to the village of Kandersteg, Switzerland, where citizens and infrastructure are threatened by a potential cascading process starting with a large landslide from Spitze Stei.
5. Exploring climate change impacts on the duration curves and therefore on the probabilities of certain runout distances.

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