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National-scale debris-flow hazard indication modelling for Swiss railway infrastructure

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Abstract. Debris flows are among the most destructive alpine hazards, threatening settlements and critical infrastructure with average annual damages in Switzerland of CHF 321 million. Hazard indication modelling of debris flows, among other hazards, offers the possibility to identify hazard hot spots at a regional and national scale. Additionally it lays the foundation for future scenario modelling. We present the Large-Scale Hazard Indication Modelling (LSHIM) framework for debris flows as commissioned by the Swiss federal railway (SBB) with guiding value return periods of 30, 100 and 300 years. For disposition, we combine high-resolution digital terrain models, climatic and geologic layers, and statistical modelling with a Random Forest approach. Disposition is cross-validated against the Swiss event database (StorMe) with an average accuracy of 81.4% and application results in 16,756 possible release areas. Dynamic runout is calculated with a tailored version of RAMMS::Debrisflow, where we define hydrograph volume from MeteoSchweiz-modelled extreme precipitation. Landscape erosivity is assessed by geology and geomorphology. Results indicate 74, 99 and 110 km of railway affected by debris flow hazard for a 30, 100 and 300 year return period, respectively. The highest intensity class shows the highest relative increase under greater return periods. This approach enables a large scale hazard indication assessment based on high-quality input data. The results are a valuable base for further planning and investigations that incorporate climate change. Limitations in the methodology lie in the static definition of release area and deterministic parameterization.

keywords: debris flow, large-scale, hazard indication modelling, hazard indication mapping

1 Introduction

Debris flows are a type of gravitational mass movements described in Iverson (2014) as "Water-laden masses of soil and fragmented rock that rush down mountainsides, funnel into stream channels and entrain objects in their paths." The moving mass goes through various physical stages (Klubertanz et al., 2009) and surging behavior (Schöffl et al., 2023) as it moves downstream until eventually depositing in lateral levees and a main depositional lobe (Iverson, 2014). A reaction of a channel

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to extreme precipitation varies on a continuous scale between clear-water flows, hyper-concentrated flow, debris floods and debris flows. Transition between these types can occur through bulking or dilution. Only debris flows have a concrete criteria in that sediment and water are thoroughly mixed (Church and Jakob, 2020). Despite this, debris flow risk management is fundamentally different from floods due to the different material composition, flow behavior and return interval (Davies et al., 2024). Therefore, it is important to make a distinction between the channel response types. Debris flows form a massive hazard throughout mountainous areas in the world due to their fast flow, long runout and poor predictability (Kumar et al., 2024). Three types of debris flow triggers are described in Qie et al. (2025) being 1) short convective storms, 2) long period of rain 3) outbursts from (glacial) lakes. These triggers lead to debris flows as either a cascading hazard (from lake outbursts or landslides on the channel bank) or by in channel mobilization of material as the other example (Hürlimann et al., 2003). Cryosphere debris flow are a special group as they are among the largest and most destructive debris flows in the alps (Chiarle et al., 2007). Debris flows originating in glaciated terrain tend to be less sensitive to precipitation intensity than debris flows lower, non-glaciated regions. The role of sediment processes and availability play a bigger role (Yu et al., 2021).

Debris flow events are among the most destructive gravitational events (Baggio et al., 2024) and can lead to substantial human and economic losses (e.g., Shah et al., 2025). In Switzerland, debris flows cause average annual losses of approximately CHF 321 million between 1972 and 2024 (Federal Office for the Environment FOEN, 2025). To (cost-)effectively prevent losses, a quantification of hazard is essential. Engineers rely on modelled maximum flow to plan protection measures for infrastructure assets (Kumar et al., 2024). On a global scale, debris flows are expected to become more common (Savina et al., 2020), therefore not only current but also future scenario modelling of debris flow hazard is essential. Debris flow hazard combined with exposure and vulnerability allows for quantitative risk calculations of which hazard modelling is an important building block. Risk calculations should guide planning of adaptation measures and determine acceptable vs. unacceptable risk spatially explicit (Davies et al., 2024). Debris flow initiation and runout is variable through various dimensions and highly dependent on a wide range of characteristics.

Debris flow susceptibility is a concept giving a relative quantification and/or classification of hazard for predefined areas (e.g., Melelli and Taramelli, 2004). From susceptibility, release areas or model start areas are defined, from which debris flow runout is simulated. In Scheidl et al. (2013) four types of debris flow runout models are mentioned. 1) expert-knowledge based on historic or geologic evidence 2) physically-based models 3) empirical (statistical) models and 4) statistical models with physical constraints (e.g. grfin tool, U.S. Geological Survey, 2025; Lee et al., 2025). Expert-knowledge and expert-knowledge based models, such as SEDEX, tend to perform well in local analyses (Kienholz et al., 2010). Empirical methods for debris flow extent and volume can give quick results (Gertsch and Kienholz, 2008), can be spatially explicit (e.g. TopFlowDF, Scheidl and Rickenmann, 2011) and are capable of capturing changing debris flow behavior through scenario modelling (Baggio et al., 2024). A good example of an empirical method are intensity duration curves for debris flows (e.g., Bernard et al., 2025; Dixit et al., 2024). For larger scales, empirical methods tend to become less reliable and require more complicated corrections (Cavagnaro et al., 2025). Additionally, scenario modelling is not always possible as well as spatially-explicit physical result.

Empirical models can be just as good as physically-based models in reproducing past events (Fan et al., 2017). Even as physical model use advances, Iverson (2014) states that empirical models will still have a place in hazard analysis due to their modest data requirement as well as probabilistic capabilities. A probabilistic approach to empirical models, such as DFP (Crescenzo et al., 2024) or MWR (Keck et al., 2024) tend to give good results, despite having a relatively simple statistical flow algorithm. Physically-based models pose an extra challenge as physical variables can not easily be acquired over large areas (Horton et al., 2013) and therefore empirical models had been preferred. For instance, oftentimes, in debris flow modelling, a correct estimation of material available for transport is more important than the estimation for precipitation and runoff modelling (Kienholz et al., 2010). Another example is the Voellmy approach to fluid behavior, which is widely used in physically based runout models (Bonomelli et al., 2024). This approach is still an approximation requiring parametrization of which the correct parametrization still plays an important role (Yang et al., 2025; Zhang et al., 2022; Graf et al., 2019). Davies et al. (2024) refers to the fact that physical variables will never be perfectly estimated in time and space facts as the 'imponderables' and necessitate the use of reference data from true events. Advances and case-studies have however enabled physical models, also over large areas (Graf et al., 2019). Advantages of physically-based models is easily acquiring results other than runout area that can be relevant in hazard/risk analysis, such as flow height, velocity and pressure.

Within the Swiss debris flow hazard modelling community, there are still a multitude of challenges in model choice, model application, model parametrization and model interpretation (Graf et al., 2019). For example, deterministic approaches of regional debris flow hazard analysis under scenarios tend to lead to an over-estimation of hazard (Delmonaco et al., 2003). Therefore in this paper, we aim to be as transparent as possible in our methodological choices, but also in our recommendations for interpretation of the hazard indication maps and well as the shortcomings related to our choices.

Recently, a Large-Scale Hazard Indication Modelling (LSHIM) methodology for snow avalanches in Switzerland has been developed (Bühler et al., 2022), using a tailored version of RAMMS::Avalanche (Christen et al., 2010) that has been applied for further studies in Switzerland (Ortner et al., 2023, 2025b) and in other regions (Sykes et al., 2022; Fischer et al., 2026). This is next to the NAKSIN approach from Norway (Issler et al., 2023), the only large scale hazard indication simulation approach applying sophisticated avalanche dynamic simulations according to our knowledge. In this manuscript, we aim to emulate this endeavor in developing and applying a LSHIM methodology for debris flow hazard (LSHIM-Debrisflow) and apply it to the Swiss federal railway (SBB) infrastructure. Features of LSHIM is the capability of scenario modelling as well as the delineation of release and runout areas. The aims are further developed as follows.

- Develop a national-scale debris-flow susceptibility model using a uniform statistical concept.
- Propagate susceptibility into physically-based runout simulations with RAMMS::LSHIM-Debrisflow (section 5.3) to derive hazard indication maps.
- Produce specific hazard indication maps for return periods of 30, 100 and 300 years suitable for subsequent risk modelling along the Swiss railway network.

Hazard indication and subsequent risk modelling enables adaptation planning. There's a multitude of possible adaptation measures to debris flow risk. Zimmermann (2004) mentions the establishment of a crisis management committee, evacuation plans, visual monitoring, sensor installation, regular surveys, rain gauge installation and structural measures. Which adaption measure to choose for specific railway infrastructure is outside of the scope of this research, but results presented here will provide a basic guidance to these decisions.

2 Study domain

We produce a national-scale debris flow hazard indication for the SBB whose network covers large parts of Switzerland. Switzerland is an alpine country (roughly 60 % of the area are covered by the Alps) with a well documented wide-spread activity of debris flows (Rickenmann and Zimmermann, 1993). Elevation ranges between 193 m in the canton of Ticino up to 4634 m at Dufourspitze in the canton of Valais. Out of the roughly 9.5 Million inhabitants, the large part is living in the large bowl between the Alps in the south and the Jura mountain range in the north. Switzerland has a temperate climate, but due to the large altitude differences, it can vary a lot (MeteoSwiss, 2026). In particular, heavy thunderstorms in summer with extreme precipitation peaks can trigger large debris flow events. Debris flows have been shown to occur not only in the alpine areas but also in the hilly lower elevated parts of the country (Hürlimann et al., 2015). The SBB is the largest railway company in Switzerland that operates fully electrified railway line and serves over 1 million passengers per day (Swiss Federal Railways (SBB), 2026). Total length of railway lines (excluding tunnels) is 5,397 km. This number measures individual railway tracks and does not aggregate parallel tracks. We do not aggregate tracks in the results of this research either. Debris flows have affected the railway infrastructure, for example at the Dornibach, Canton Uri, in 2005 after heavy rainfall (illustrations in appendix section B1). Such events have led to an ongoing process of increasing resilience at vulnerable sites.

To ensure adequate calculation domains along railway infrastructure, we adopt what are known as 'Bilanz-gebiete' (singular: Bilanz-gebiet) (Bühlmann and Schwanbeck, 2018), i.e. closed catchments of approximately similar size. These are our basic calculation tiles and we added contingency of a 2000 m buffer. Only debris flows that can reasonably threaten infrastructure are included in the runout calculations by an additional filter of 10 km flow distance from release area to railway infrastructure (excluding tunnels). This threshold comes from the maximum flow length of alpine debris flows as observed by Rickenmann and Scheidl (2010).

3 Swiss hazard and risk framework

We follow the method for hazard mapping in Switzerland, which has been in development since first avalanche hazard maps were issued in the 1960's. The method for avalanches is described in BFF and SLF (1984), for mass movement hazards in BAFU (2016) and for flood hazards, which include debris flows, in both Loat and Petrascheck (1997) and Loat (2010). The general procedure for risk assessment based on this methodological framework is described in Bründl et al. (2009). It's based

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Preprint. Discussion started: 19 August 2026

on the definition of the return period of initial conditions, which typically include a 30, 100 and 300 year return period and an additional overload scenario with a return period up to 1000 years.

For each of the return period scenarios, the physical impact of debris flows is characterized by the maximum flow height, which is considered the standard both in Switzerland SIA (2003), but also internationally (e.g., Hürlimann et al., 2006). Areas, where the maximum flow height d_{max} is below $0.5\,m$ are denoted as low intensity, as medium for $0.5\,m < d_{max} \leq 2\,m$, and as high for $d_{max} > 2\,m$. We comply with this concept and use the maximum flow height in three intensity classes (see section 5.6) as an indicator for the hazard.

Debris flow hazard in this paper is described with a hazard indication map with return periods of 30, 100 and 300 years. We omit a 1000 yr since no reliable precipitation data is available. Hazard indication maps are based exclusively on numerical modelling and do not include a detailed analysis of incident records and field surveys. They are suitable for indicating areas of hazard, but not as a basis for long term land-use planning. As our aim is to indicate hazard hot spots along the entire SBB rail network, we decided, for reasons of practicality, to elaborate hazard indication maps based on the current climate conditions as of 2025 along the railway infrastructure. Recently, probabilistic modelling of alpine mass movements has been introduced by Kleinn et al. (2024) for snow avalanches, as well as for rock fall and shallow landslides for the pilot region in Adelboden, Switzerland (Kleinn et al., 2025). Model results suggest a more differentiated picture than it is obtained with the deterministic approach based on three defined return periods of release conditions. However, due to requirements by the project partner in this study, we comply with the deterministic approach widely implemented in the Swiss natural hazard community.

4 Data

An overview of data sourced and applied in this research is given below. Full details, with references, is given in the appendix. All data processing is performed with Arcpy in the ArcGIS Pro environment (Esri, 2024).

4.1 Topography

Our basic DEM is the LiDAR-based SwissALTI3d (Federal Office of Topography swisstopo, 2024) at a 0.5 m resolution. We resample to 1 m and compute flow accumulation, slope, curvature and aspect as well as catchment delineation for the susceptibility analysis (section 5.2). In distributed runout modelling, DEM resolution plays an important role. In Stolz and Huggel (2008), a 25 m is considered to coarse for a typical debris flow channel in Switzerland making it unable to replicate the existing channel. A 4 m resolution is deemed sufficient. For computational reasons we settle on a 5 m resolution with cubic resampling.

https://doi.org/10.5194/egusphere-2026-4604
Preprint. Discussion started: 19 August 2026

4.2 Landscape data

The susceptibility analysis (section 5.2) takes into account the spatial distribution of binary forest cover data, vegetation height, various geological layers as well as geomorphological layers (see appendix Table A2).

4.3 Cryosphere

Current permafrost extent is extracted from PGIM (Kenner et al., 2019). All permafrost classes, whether continuous or discontinuous is treated as permafrost presence. SGI2016 (Linsbauer et al., 2021) provides a complete glacier inventory for Switzerland, which is treated as binary glacier presence map.

4.4 Extreme precipitation

Extreme precipitation, for application see section 5.4, at 1-hour duration at 30, 100 and 300 year return interval is sourced from the MeteoSchweiz spatial-covered intensity duration product (Fukutome et al., 2023). Surface area correction of extreme precipitation applies the methodology of Grebner et al. (1999).

4.5 Event inventory for model training

Debris flow propagation is a complex process and does not always have a clear initiation, transport and disposition area (e.g., Cannon et al., 2003; Simoni et al., 2020). For this reason we use the StorMe debris flow inventory polygon data (see Appendix Table A2) that identify process domains, rather than fixed points. Inventories of past events deal with biases and methodological inaccuracies, especially over larger areas. Additionally, we often do not know how exceptional recorded events are (Graf et al., 2019; Stoffel et al., 2005), but the StorMe inventory is the best reference data set to our knowledge. We have a total of 6351 debris flow polygons as well as 19,175 flood polygons, that are applied as explicit absence polygons.

5 Methods

The general workflow for the LSHIM debris flow framework with both susceptibility and runout is given in Fig. 1. Details for the analysis in the specific sections.

https://doi.org/10.5194/egusphere-2026-4604
Preprint. Discussion started: 19 August 2026

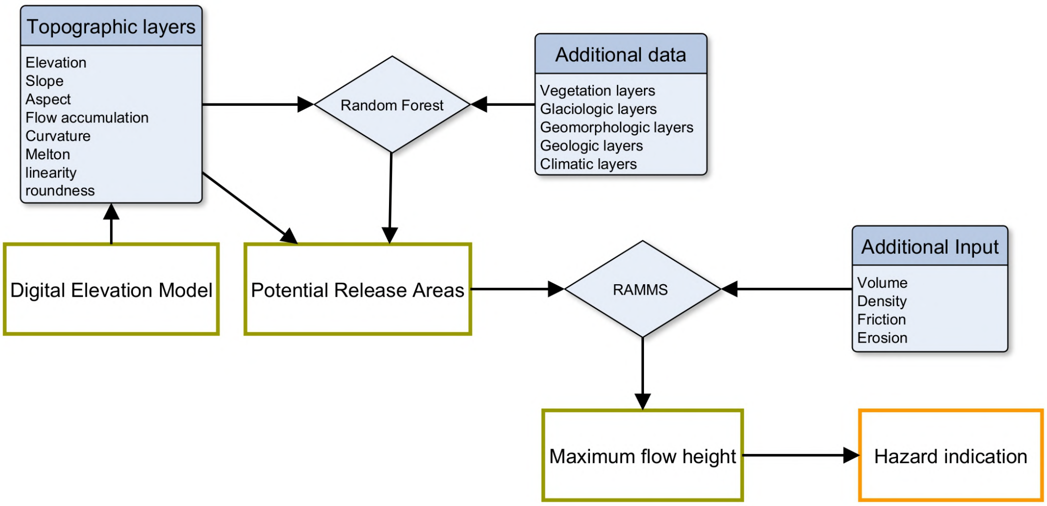

Figure 1. Flowchart of the general methodology for debris flow susceptibility and runout analysis.

5.1 Potential release areas

We focus on debris flow that originate from bulking. For this type the initiation should not be thought of as a specific point in a channel, but rather a zone where initiation varies due to local heterogeneity in extreme precipitation and sediment availability (Hürlimann et al., 2003; Yamanoi et al., 2025). Observations on release areas are slopes steeper than about 25 to 30 degrees (Iverson, 2014) and, based on California debris flows, flow accumulation between 0.2 and 1 km^2 (McGuire et al., 2023; Struble et al., 2023). Our methodology defines potential debris flow channel sections as sections, where the flow accumulation is between 0.1 and 2 km^2. The broad range is deliberate and anticipates subsequent filtering (section 5.2).

Specific release points in the susceptible channel, i.e. Potential release Areas (PRAs, singular: PRA), are a model necessity. We approximate the natural variation in initiation zones by allowing multiple PRAs to be defined along the length of a susceptible channel section. We place a point along the channel at a fixed interval (l = 750 m). In this research, we limit ourselves to a basic disposition, which is considered constant through time. This is opposed to variable disposition (Gertsch and Kienholz, 2008), which is closer to reality, but for computational efficiency, we decided on a general solution.

5.2 Susceptibility modelling

Statistical debris flow susceptibility analysis from a range of relevant landscape properties (topographical, hydrological, geological, vegetation) is a tried-and-tested method (e.g., Shen et al., 2017; Kim et al., 2016; Liu et al., 2025; Melelli and Taramelli, 2004; Morel et al., 2023; Napoli et al., 2023). Generally, a diverse set of properties increases accuracy (Kritikos and Davies, 2015), since many factors influence debris flow initiation (Marchi et al., 2019) or vary locally (Morel et al., 2023). For instance, the intuitive relationship between catchment area and debris flow occurrence is only very weak in a comparison of 809 debris flows in northeastern Italy, but multiple properties of specific stream sections and their catchments is a good predictor of debris flow initiation and even dimensions (Kienholz et al., 2010; Miller and Burnett, 2008). Using only raster properties does not do justice to the processes involved in debris flow generation, rather a focus should be on features (Liu et al., 2025; Melelli and Taramelli, 2004) or catchment-based properties (Lee et al., 2025).

In addition to properties from a potential discrete source point, we take into account properties of the channel and the catchment that flow into the source point. This gives a total of 41 properties that are displayed in Appendix Table A3. Reference PRAs are defined by overlap with the StorMe inventory (section 4.5) for debris flows (presence points, n = 2490) and floods (absence points, n = 814). Model training is performed on a range of selected possible models, these being: Random Forest (Breiman, 2001), Logistical regression (Harris, 2021), Catboost (Prokhorenkova et al., 2018), Naive Bayesian regression (Zhang, 2004), xgboost (Chen and Guestrin, 2016) and a simple neural network (Goodfellow et al., 2016). All models are applied using the python language; scikit package (Pedregosa et al., 2011). To select a model, we test all using the reference PRAs with a 10-fold cross validation.

5.3 Runout modelling with RAMMS

The RAMMS software has been used for modelling of gravitational processes in many studies worldwide (Kumar et al., 2024). Our version of RAMMS, RAMMS::LSHIM-Debrisflow, (RAMMS AG, 2024) (hereafter also referred to simply as RAMMS) is tailored for large-scale application to run simulations for groups of PRAs. RAMMS does a pre-run to narrow down the calculation domain. The pre-run resolution is 10 m. Results are then generated at a 5 m resolution. The initial domain is defined by a buffered (750 m) downstream line from the PRA. Upon reaching the first flat channel section (<4 deg for > 250 m), we define the assumed cone neck point and apply a 1750 m buffer.

5.4 Hydrograph volume and discharge parameterization

Correct estimates for hydrograph total volume and peak discharge is part of parameterization (RAMMS AG, 2024). It is important as both entrainment and eventual runout modelling are sensitive to hydrograph dimensions (Frank et al., 2017). In our one-phase approach, hydrograph volume (V_{total}) consists of a mixture of water and sediment. We relate the total water volume (V_{water}) to the catchment area ($A_{\text{catchment}}$) in m^2, a runoff coefficient (r unitless with a default value 0.1) and the 1-hour extreme precipitation (P_{1hour}) in m.

$$V_{\text{water}} = A_{\text{catchment}} \cdot P_{1\text{ hour}} \cdot r \quad (1)$$

https://doi.org/10.5194/egusphere-2026-4604
Preprint. Discussion started: 19 August 2026

Glacial presence in the catchment area of a stream slows the reaction time of the catchment to extreme precipitation (e.g., Klok et al., 2001) as the accumulation zone of glaciers work as a long-term buffer. The ablation zone displays quicker runoff (Jansson et al., 2003). We assume as general rule that 2/3 of the glacier is the accumulation zone, 1/3 is ablation zone. We compute the degree of glaciation in a PRA catchment and assume the glacier accumulation zone of a catchment has a runoff coefficient of 0.0. The ablation zone, as well as the non-glaciated part have the default value. The proportional average of the parts give an adjusted runoff coefficient.

We assume 1-hour is a representative approximation of the time to concentration for our catchment dimension. The order of magnitude is supported by the review paper by Beven (2020) and the 1-hour duration is convenient in terms of data availability. Applications in comparable research vary widely, with McGuire et al. (2024) using a 15 min. intensity or Rickenmann et al. (2008) using 72 hours. Both imply an assumption on the type of debris flow in their respective case studies. On a national scale, we want to include multiple types of debris flows through assumed density of the flow material in our one-phase approach. This is relevant for the hydrograph volume as well as debris flow pressure calculation in RAMMS. Using a factor to amplify discharge volume based on assumed debris flow type has been successfully applied in Cavagnaro et al. (2024). The range of observed debris flows in Switzerland is from smaller watery muddy debris flows to large granular debris flows (Davies, 1997). Predictions on which type of debris flow occurs when and where is still challenging (Graf et al., 2019). According to the SIA norm (SIA, 2003), density of Swiss debris flows varies between 1400 (fluid flows) and 2100 (granular flows) kg/m^3. We assume that the debris flow vs. flood probability (Section 5.2) correlates with the density of the debris flow according to equation 2 below.

$$\rho_{\text{debris flow}} = 1400 + (700 \cdot 2 \cdot (P_{\text{Debris flow}} - 0.5)) \tag{2}$$

The normalization with 0.5 is because $P_{\text{Debris flow}} < 0.5$ is not considered a debris flow. Hydrograph volume is attained by combining water volume and debris flow density through equation 3 below.

$$V_{\text{total}} = V_{\text{water}} \left(1 + \frac{\rho_{\text{debris flow}} - \rho_{\text{water}}}{\rho_{\text{sediment}} - \rho_{\text{debris flow}}}\right) \tag{3}$$

Here ρ_{water} is the water density at 1000 kg/m^3 and ρ_{sediment} is sediment density at 2500 kg/m^3. Maximum discharge in the hydrograph is related to total volume using the empirical relationship from Rickenmann (1999).

$$Q_{\text{max}} = 0.1 \cdot V_{\text{total}}^{\frac{5}{6}} \tag{4}$$

5.5 RAMMS parametrization

As with many other models, parametrization of processes is important. Flow direction and height is calculated by solving the shallow water equations (Bonomelli et al., 2024). Additionally the Voellmy approach, which simplifies friction behaviour,

https://doi.org/10.5194/egusphere-2026-4604
Preprint. Discussion started: 19 August 2026

governs flow behavior and runout extent (Salm, 1993). The basic equation with parameters is given below. The complete RAMMS approach which additionally includes yield-stress and curvature dependent contribution is described in RAMMS AG (2024).

$$S = \mu N + \frac{\rho g \|u\|^2}{\xi}, where N = \rho h g \cos\varphi \quad (5)$$

S is the basal shear stress [Pa], μ is the Coulomb friction coefficient, ξ is the turbulent (viscous) friction parameter [m/s^2]. Back-calculated μ has a value between 0.01 and 0.3, ξ between 100 and 1000 (Zimmermann et al., 2020). ρ is the bulk density of the flow [kg/m^3], g is the acceleration due to gravity [m/s^2], u is the depth-averaged velocity vector [m/s], h is flow height [m], φ is the slope angle $[deg]$. The Voellmy approach simplifies friction to two coefficients, namely μ and ξ. Of these, ξ governs flow behavior and μ, basal friction, governs stopping behavior of the debris flow (Naqvi et al., 2025; Rickenmann and Scheidl, 2023). The importance of correct parametrization of friction, especially μ is stressed in many projects (Scheidl et al., 2013; Kumar et al., 2024). In general, ξ has little influence on debris flow extent (Bolliger et al., 2024) and therefore we decide to parametrize the μ, defining a constant value for ξ (300 m/s^2). μ is approximated by the tangent of the angle of deposition (Bolliger et al., 2024), which is turn is approximated by the slope angle in 11'076 identified debris flow fans in swisstopo (2024a). The angle of disposition of material is dependent on local to regional geological properties. We aggregate deposition angle per Bilanz-gebiet. The 5th percentile of the slope angles of fans present within in the Bilanz-gebiet is chosen after visual inspection of results. To combat outliers, we only parametrize bilanz-gebiete if at least 10 fans are present. Secondly, we apply a moving window (d = 10 km) smoothing. This methodology results in the spatial distribution as given below in Fig. 2 which will serve as input to RAMMS.

Oftentimes the initial debris flow volume is small, but becomes multitudes larger (Shen et al. (2020) found 4 to 20 times larger) due to entrainment of material along the way down (Berger et al., 2011). This indicates that a good assessment of available material and entrainment capacity is absolutely necessary and needs to be applied in addition to the original hydrograph volume (Shen et al., 2020; Kienholz et al., 2010; Eu and Im, 2025). RAMMS includes a spatially explicit entrainment module, giving it an edge over many other runout models (Kumar et al., 2024). In Frank et al. (2017), it is noted that the entrainment module in RAMMS works well, but more case studies are needed. This research serves as a national-scale application.

Erosion is spatial-heterogeneously included in our RAMMS through explicit parametrization. We identify four erosion categories (High, medium, low and none) based on a decision scheme on TLM landcover (swisstopo, 2024b) and Geocover tectonic units (see Table 1 and Fig. 2). An intermediate step is applying the concept of Altschutt and Jungschutt (Gertsch and Kienholz, 2008) to Geocover units. Here, Altschutt comprises more weathered rock, which are therefore of higher erosive potential.

https://doi.org/10.5194/egusphere-2026-4604
Preprint. Discussion started: 19 August 2026

Table 1. Classification of TLM, Geocover, and erosion classes. “Altschutt" comprises rock debris that has undergone substantial weathering, whereas "Jungschutt" consists of fresh to only slightly weathered material. Note: The erosion class is reduced by one level within the *Kristallin* tectonic unit.

TLM class	Altschutt/Jungschutt	Erosion class
Rock	Altschutt	Low
Unconsolidated material	Altschutt	High
Other	Altschutt	Medium
Rock	Jungschutt	None
Unconsolidated material	Jungschutt	Medium
Other	Jungschutt	Low

Erosion classes are used to parametrize RAMMS through both physical erosion parameters (Table A4) and available sediment (table A5), which also is a function of return period.

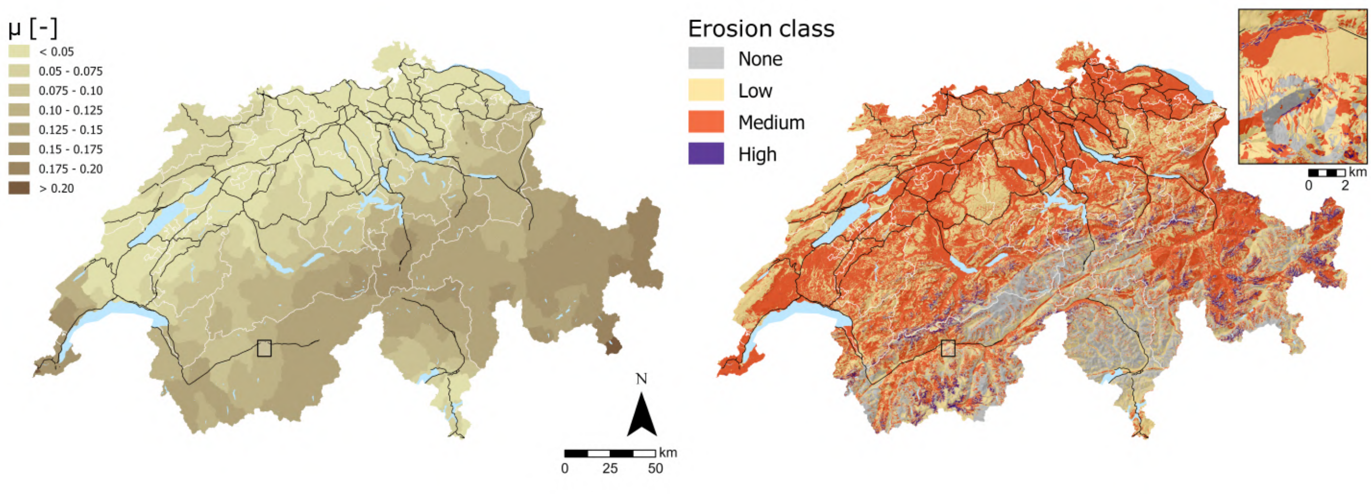

Figure 2. left: Spatial distribution of the Voellmy μ parameter over the bilanz-gebiete based on the slope angle of documented debris flow fans and a moving-window smoothing algorithm. right: Erosion classes for Switzerland based on the decision scheme in Table 1. TThe square indicates the extent of the detailed map of the Illgraben area (canton of Valais). SBB infrastructure is displayed in black, cantonal boundaries in white.

5.6 Hazard indication map generation

The output of RAMMS is a spatially explicit data set for each of the considered 30-, 100 and 300-year return period scenario including spatially explicit intensity information such flow height, flow velocity, flow pressure, flow momentum and erosion

https://doi.org/10.5194/egusphere-2026-4604
Preprint. Discussion started: 19 August 2026

(RAMMS AG, 2024), of which the maximum flow height was used to categorize intensity into the three intensity classes low, medium and high according to the method of hazard mapping (see section 3). Areas, in which the maximum flow height d_{max} is lower than 0.01 m were omitted in accordance with risk guidelines.

6 Results

6.1 Susceptibility model performance and predictors

Results on selected metrics of our susceptibility models are displayed in Table 2. Given the goal of planning measures and allocating resources, both false positives and false negatives are to be avoided in equal measure. For this reason accuracy and ROC-AUC are chosen as primary measures. The machine learning technique of Random Forest performs best on both measures and we apply it for further susceptibility analysis. It must be noted that between machine learning techniques differences are small and variation around the mean performance is greater than the difference between models, rendering any of these models a valid choice. Neural network and Support Vector Machine also perform well. Optimizing models is outside of the scope of this research, but given extensive calibration, we can see these models attaining similar performance to machine learning techniques. Naive Bayesian favors recall over discrimination ability, resulting in a skew with many false positives. The opposite is true for logistic regression, which has a conservative classification judging for low recall but high precision. This indicates debris flow susceptibility is not easily predicted by linear models and involves complex interactions that are better represented by any of the other models.

Table 2. Mean and standard deviation of performance metrics from a 10-fold cross validation of selected statistical models in predicting debris-flow disposition. All models use standard parametrization.

	Accuracy	**ROC-AUC**	**Precision**	**Recall**	**F1 score**
Random Forest	0.814 ± 0.016	0.866 ± 0.021	0.820 ± 0.014	0.967 ± 0.012	0.887 ± 0.009
XGBoost	0.812 ± 0.015	0.841 ± 0.022	0.837 ± 0.012	0.933 ± 0.015	0.882 ± 0.009
CatBoost	0.812 ± 0.014	0.833 ± 0.025	0.824 ± 0.009	0.954 ± 0.015	0.884 ± 0.009
Support Vector Machine	0.810 ± 0.013	0.825 ± 0.021	0.817 ± 0.010	0.963 ± 0.015	0.884 ± 0.008
Neural Network	0.802 ± 0.023	0.815 ± 0.029	0.859 ± 0.018	0.882 ± 0.019	0.870 ± 0.015
Naive Bayesian	0.778 ± 0.008	0.627 ± 0.041	0.788 ± 0.007	0.965 ± 0.008	0.867 ± 0.004
Logistic Regression	0.710 ± 0.032	0.784 ± 0.018	0.879 ± 0.010	0.713 ± 0.046	0.787 ± 0.029

Detailed information on the Random Forest relative attribute importance is given in Fig. 3 below. Most influence is exerted by attributes related to precipitation and topography with an additional role for geology, geomorphology and vegetation. Also the low magnitude of parameter influence suggest sufficient overlap and coverage by the attributes.

https://doi.org/10.5194/egusphere-2026-4604
Preprint. Discussion started: 19 August 2026

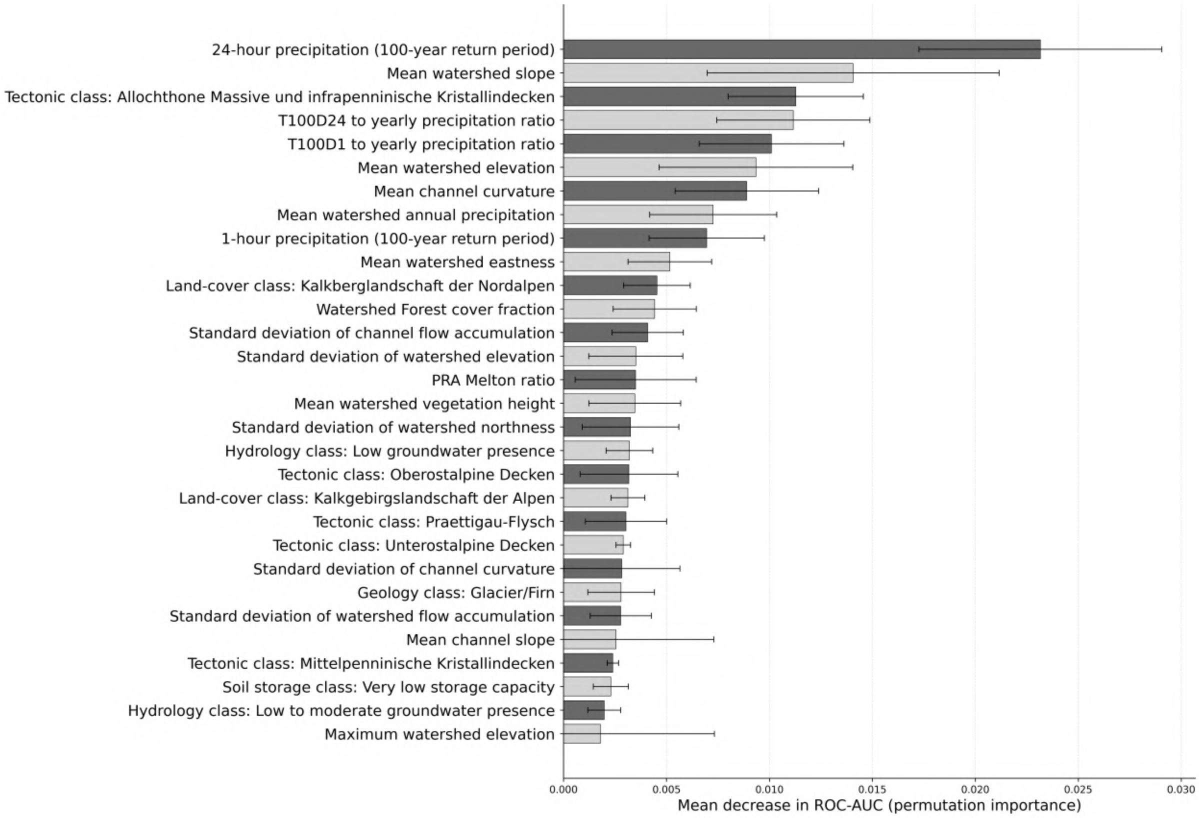

Figure 3. Random Forest mean input parameter importance quantified by mean decrease in ROC-AUC by removal of the target attribute. Only the 30 most important features are shown. Classified data applies the majority class in a PRA watershed.

A final Random Forest model is retrained on the entire reference dataset and applied to all PRAs with a generated debris flow probability per PRA ($P_{\text{Debris flow}}$) given in Fig. 4. The continuous probability is turned to discrete disposition by a threshold value with presence points (More likely debris flow prone than flood prone; $P_{\text{Debris flow}} > 50\%$) and absence points ($P_{\text{Debris flow}} < 50\%$). The initial 80,812 PRAs are filtered on the railway infrastructure resulting in a total of 16,756 PRAs for runout analysis.

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Preprint. Discussion started: 19 August 2026

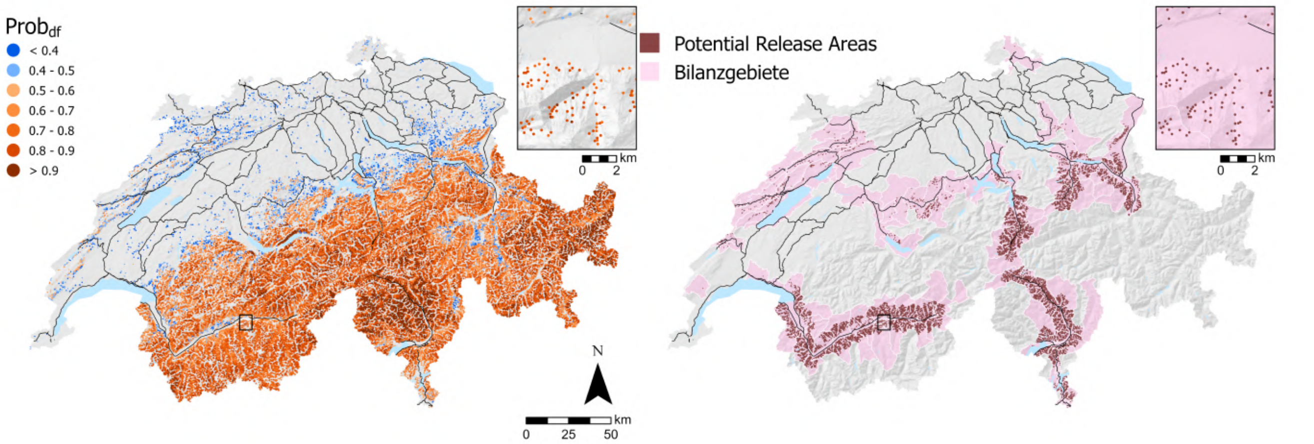

Figure 4. left) Debris flow disposition in hydrograph points displayed as Random Forest resulting probability for presence of debris flows. Right) 91 Bilanzgebiete and 16,756 debris flow Potential Release Areas within reach of SBB railway infrastructure included in RAMMS.

6.2 Runout modelling

Runout from PRAs, conditionally parametrized with precipitation and erosion capacity on a return period, is modelled dynamically with RAMMS. Given versatility and the physical basis of RAMMS, we model runout from PRAs at discrete timesteps with an explicitly distributed flow height, flow velocity and pressure (Fig. 5). Entrainment erosion is also explicitly computed every timestep. In the example, as with many debris flows, a multitude of mobilized material is generated through entrainment compared to the initial volume.

https://doi.org/10.5194/egusphere-2026-4604
Preprint. Discussion started: 19 August 2026

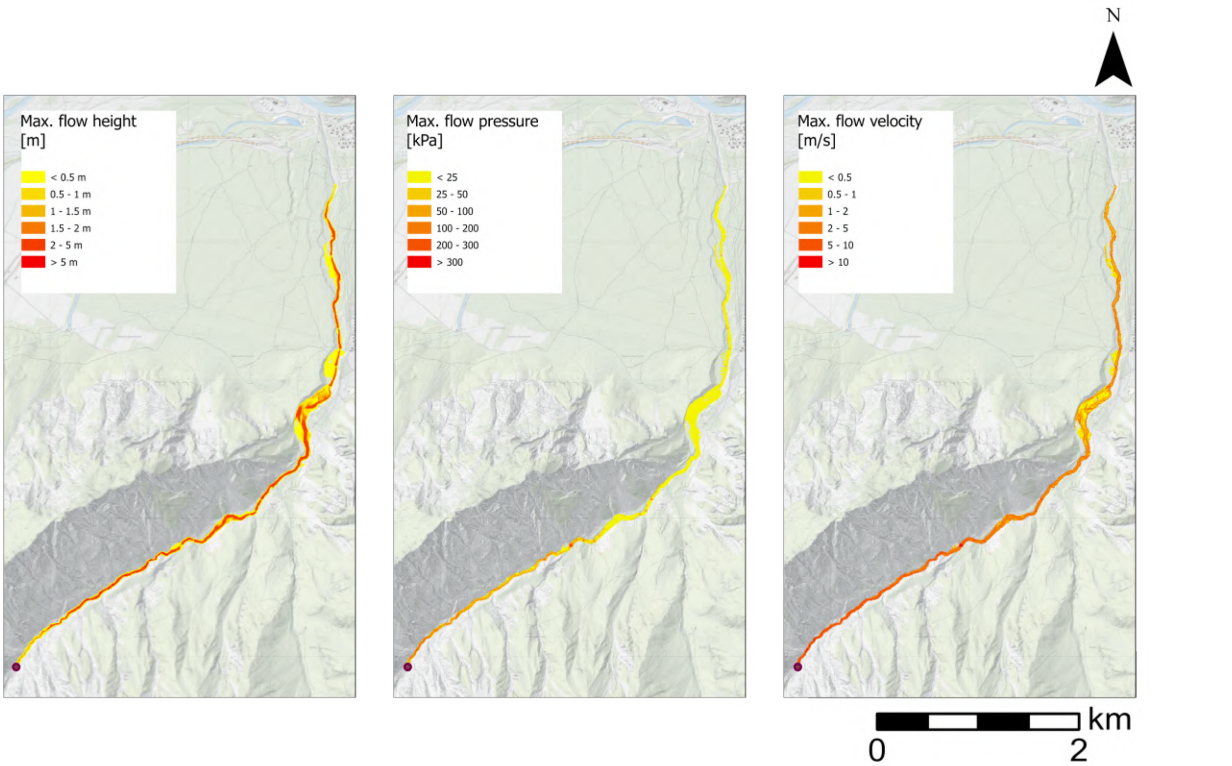

Figure 5. Example of RAMMS model results showing a debris flow from a single PRA (in purple) in the Illgraben catchment (Canton Valais) modelled under a 100-year return period. This debris flow has an initial volume, V_{total}, of 3,648 m^3. Assumed density, $\rho_{\text{debris flow}}$, is 1,761 kg/m^3. Total mobilized material volume is 75,713 m^3. Simulated time of the event is approximately 46 minutes. Through all timesteps on the left) the maximum flow height, middle) the maximum flow pressure and right) the maximum flow velocity.

As maximum flow height of a debris flow through all timesteps is the standard for Swiss debris flow risk analysis (section 5.6), we display this as a national scale with certain examples through the country and under specific return periods in Fig. 6. A benefit of using maximum flow height is that we incorporate overlapping paths of debris flows and implicitly choose the most hazardous. Details on selected study areas are given in Table 3.

https://doi.org/10.5194/egusphere-2026-4604
Preprint. Discussion started: 19 August 2026

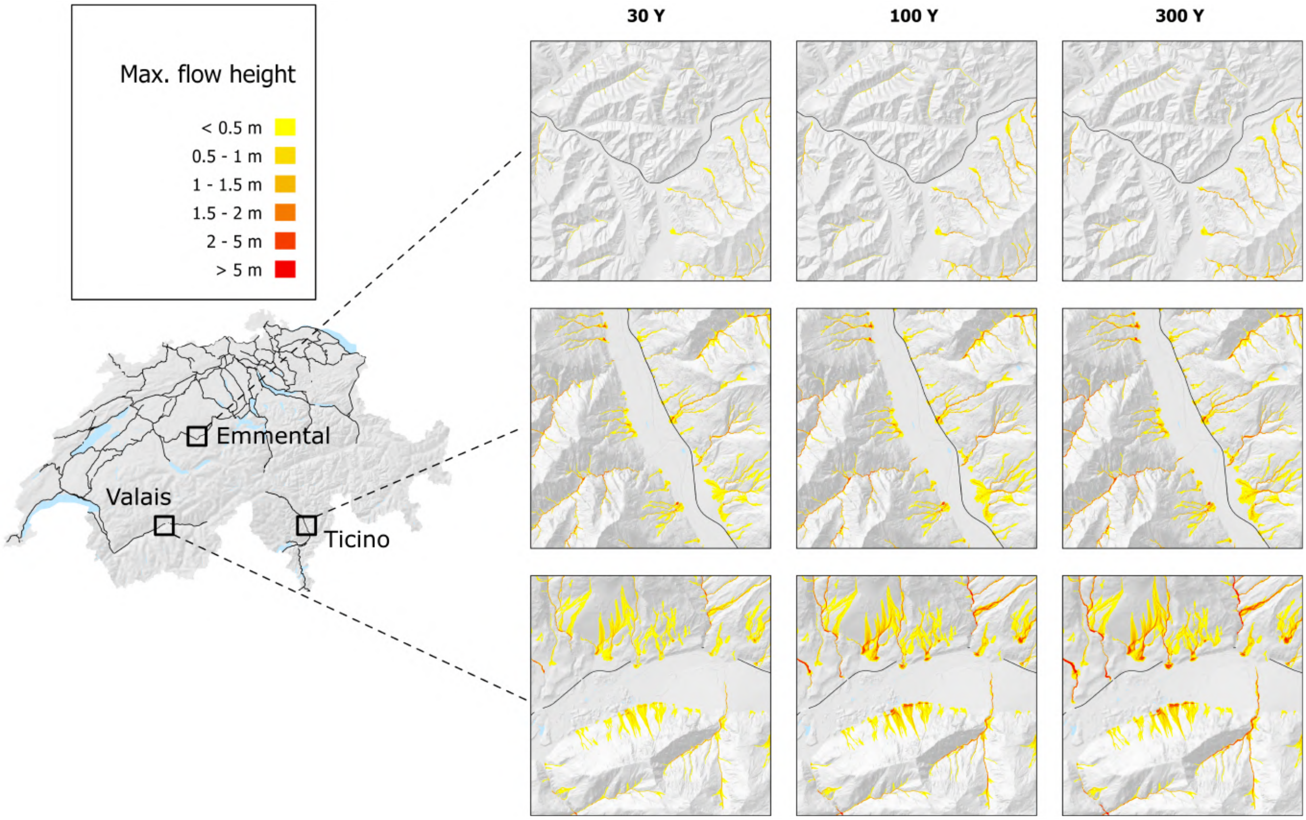

Figure 6. Debris flow maximum flow height for selected example areas along the SBB railway track (black lines) under a 30, 100 and 300 year return period. Upper rows give an example in Emmental in a pre-alpine area. Middle in Ticino in alpine but sediment-limited circumstances. Lower example for the Valais central valley, which is alpine with minor glacial and permafrost influence in the debris flow release areas.

https://doi.org/10.5194/egusphere-2026-4604
Preprint. Discussion started: 19 August 2026

Table 3. Summary statistics for three example areas. All areas are of identical size (110 km^2). Erosion gives the percentage of the area per class.

Environment		Emmental Pre-alpine	Ticino Sediment-limited	Valais Inner-alpine
PRAs	*No.*	57	367	326
Mean PRA altitude	*m a.s.l.*	1076	1124	1240
Mean debris flow bulk density	$kg\,m^{-3}$	1527	1974	1726
Mean μ	–	0.07	0.11	0.11
Mean 30-year 1-hour rainfall	*mm*	55	63	25
Mean 100-year 1-hour rainfall	*mm*	72	81	32
Mean 300-year 1-hour rainfall	*mm*	90	100	40
Erosion class No erosion	%	0	56	11
Erosion class Low	%	70	42	54
Erosion class Medium	%	30	2	34
Erosion class High	%	0	0	1

Fig. 6 shows a consistent increase in debris flow maximum flow height through all study areas under more extreme scenarios, which is directly related to the more extreme 1-hour precipitation. The difference is notably less pronounced in the sediment-limited area of Ticino. This is highlighted in the histogram of flow heights categories as given in Fig. 7 below.

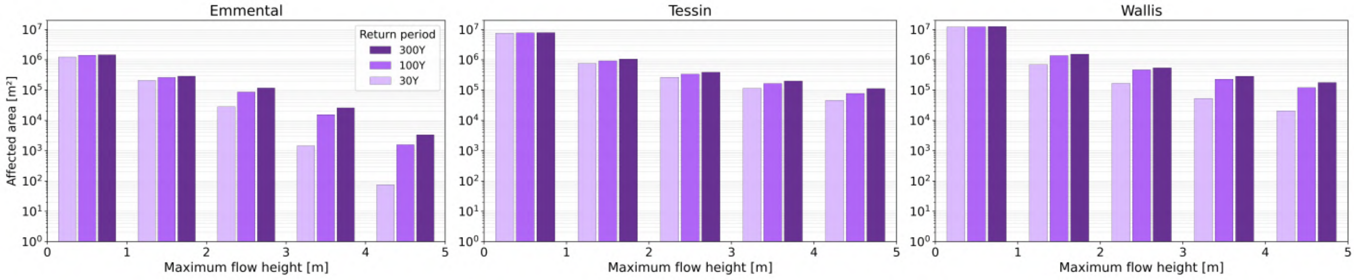

Figure 7. Histograms of affected area at 1-m interval of maximum flow height for three example areas from Fig. 6. Bars display the 30, 100 and 300 year return. Note the logarithmic scale.

https://doi.org/10.5194/egusphere-2026-4604
Preprint. Discussion started: 19 August 2026

The difference between example areas, shows the strong increase in affected area under the more extreme 300 year return scenario compared to the 30-year scenario and to a lesser degree the 100-year scenario. This also indicates that the extreme precipitation value works through the model architecture and increases affected area with more extreme scenarios.

6.3 Hazard indication mapping

Maximum flow height forms the basis for hazard indication mapping as described in section 5.6, which is displayed in conjunction with Fig. 6 in Fig. 8.

https://doi.org/10.5194/egusphere-2026-4604
Preprint. Discussion started: 19 August 2026

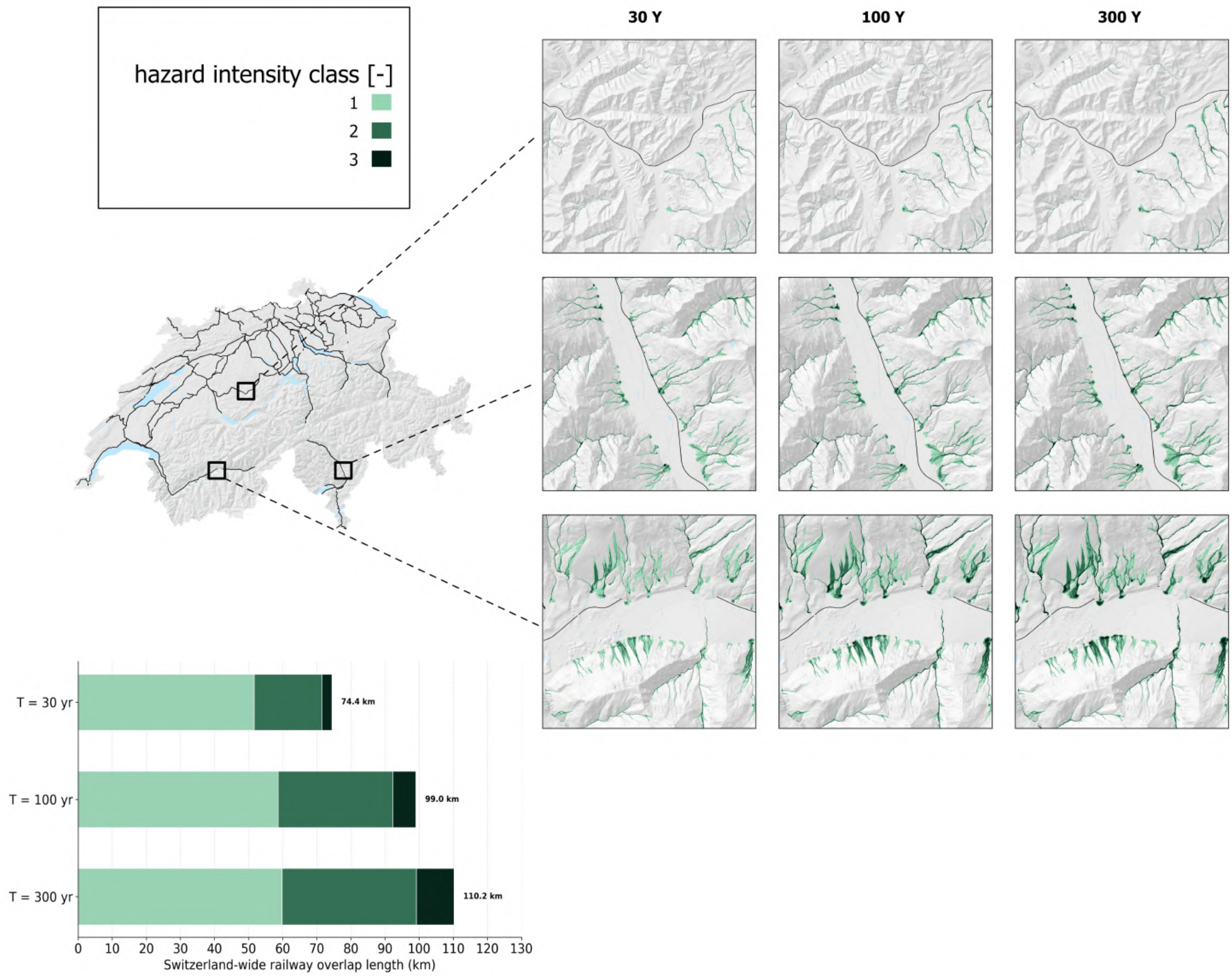

Figure 8. Left) Hazard indication national scale overview. Right) detailed view for selected areas. Below) Switzerland-wide length of affected railroad subdivided by category.

From Fig. 8 we conclude that the total length of affected SBB railroad increases significantly when comparing a 30-year return period with both a 100 (+33%) or 300-year (+48%) return period. This is in line with the maximum flow height results from Fig. 7. Interesting to note is that the absolute increase in the lower hazard category is modest. More significant increases are seen in affected railroad at second or third intensity. Compared to the entire railway infrastructure, approximately 2% of railway length is threatened by debris flows under the 300-year return period.

https://doi.org/10.5194/egusphere-2026-4604
Preprint. Discussion started: 19 August 2026

7 Discussion

7.1 Implications for railway hazard and risk management

Hazard and risk mapping over larger areas, such as regions or whole countries has gained increasing interest among natural hazard professionals in the last 20 years. It offers the possibility to get an overview about hazards in areas, where no other information such as hazard maps is available. Bühler et al. (2022) gives a brief overview on approaches since 2004 and presents a method for an automated hazard indication modelling of snow avalanches for the Canton of Grisons in Switzerland. This work represents the basis for the multi-hazard risk framework of Ortner et al. (2023), who simulated potential developments of avalanche risk to buildings driven by climate change in central Switzerland (Ortner et al., 2025b, a). Comparable and recent approaches are presented by Issler et al. (2023) for Norway and by Fischer et al. (2026) for Alaska.

Since then these approaches have been applied in large-scale modeling of rockfall (Bründl et al., 2025) and debris flow (this paper). For natural hazard professionals, responsible for the safety of public infrastructure such as the SBB, large-scale hazard and risk mapping offers the opportunity to identify areas with elevated hazard or risk and thereby information, where to prioritize mitigation measures in the future. The results, however, need to be validated and interpreted regarding the consequences of model assumptions and uncertainties.

7.2 Uncertainty and limitations

In our susceptibility analysis, a mean accuracy of 0.814 combined with the proclivity of Random Forest to overfitting, indicates not every Potential Release Area is correctly classified. Runout behavior of small and large debris flows is fundamentally different (Davies, 1997). Though we do a dimensioning of debris flows (section 5.4), the physical processes in multi-phased over-saturated fluids cannot be captured in our one-phase application of RAMMS. As a single-phase bulk-flow model, RAMMS cannot explicitly represent solid-fluid phase separation, dilution or transitions between debris-flow and debris-flood regimes. Consequently, highly fluid or rapidly transforming flows may not be reproduced adequately without case-specific calibration. Erosion parameterization is not constant and easy to be put in classes or return periods. It varies through time and also depends on debris flow characteristics as well as saturation degree (Roelofs et al., 2023). Case-studies have attempted statistical modelling of entrainment capacity (e.g., Abancó and Hürlimann, 2014), in a manner comparable to our susceptibility model. In scenario modelling and our physical approach, this was not feasible.

Due to its broad application and the relatively high DEM resolution (5 m), LSHIM of debris flows remains an automated hazard indication method. Detailed hazard maps at specific sites are as of now out of scope. Though numerical simulations are often preferred by stakeholders, there are no requirements for parametrization. This exposes concerns to the accuracy of these approaches (Graf et al., 2019). Also, despite this research having a large number of validation points and a well-setup calibration around these, still more events and over longer time-ranges could increase confidence in our susceptibility and therefore hazard

https://doi.org/10.5194/egusphere-2026-4604
Preprint. Discussion started: 19 August 2026

indication maps (Graf et al., 2019).

Deterministic scenario modeling fails to take feedback mechanisms and parameter inter-variability into account. For example, through time not every precipitation event with a specific return period is associated with a fixed sediment availability (Liu et al., 2025). This is well documented in the analysis of 61 debris flow torrents in Gertsch and Kienholz (2008) or in the margin of stability concept by Steger et al. (2024). This could lead to an overestimation of hazard (Liu et al., 2025). In general. it is important to also take into account the change in sediment budget, which can nullify a possible increased extreme precipitation (Frank et al., 2019). Also debris flow triggering is not guaranteed for comparable rainfall events (Baer et al., 2017; Gertsch and Kienholz, 2008). Despite this and in light of the hazard indication (requiring lower standards than full hazard maps) and the large-scale of the project, we think our scenarios provide a realistic indication for standardized scenarios of what planners can expect.

7.3 Future work

Large-scale debris flow modelling provides a solid basis for inter-comparison of debris flow hazard indication. Shortcomings, as mentioned in section 7.2, can be addressed by future studies. For instance, variable disposition on the basis of return periods can be incorporated. This could benefit from a validation not for all known events but by filtering events for known return periods. Lowering the threshold for $P_{\text{Debris flow}}$ could be applied under a more conservative modelling strategy, where false negatives are to be avoided at all costs. Better data availability on potential sediment entrainment as well as a stronger physical basis for its implementation could improve the quality of debris flow runout modelling. This may prove better than the current central focus on extreme precipitation and its return periods.

The method now has a strong deterministic character. We define clear release areas, parametrization and a restriction to 30, 100 and 300 year return periods. Continuous ensemble modelling in a probabilistic fashion (Kleinn et al., 2025) would better quantify uncertainty both in the susceptibility and runout modelling. Our methodology focuses on entrainment in the debris flow process where magnitude of the event strongly correlates with channel flow accumulation and sediment availability. In nature, large sediment pulses through landslides or releases of degrading permafrost can cause devastating debris flows (Stoffel and Huggel, 2012). Including this process, arguably in a robust probabilistic manner, would be a great improvement. By incorporation up-to-date weather forecasts near real-time modelling for decision making for the management of traffic routes could be aspired. First attempts to do so for snow avalanches have been made by Glaus et al. (2026).

8 Conclusions

This manuscript presents the first national-scale debris flow hazard indication modelling combining a comprehensive susceptibility and runout analysis. We define susceptible release areas in streams using a Random Forest, cross-validated the StorMe database, to an accuracy of 0.814 and ROC-AUC of 0.866. Topographic and precipitation attributes are shown to have the

https://doi.org/10.5194/egusphere-2026-4604
Preprint. Discussion started: 19 August 2026

highest predictive power. The debris flow dynamics simulation tool RAMMS::LSHIM-Debrisflow, with a spatially variable potential sediment and friction parametrization, is applied for runout modelling. Large differences can be observed across landscapes, with small fluid debris flow in pre-alpine areas, large granular debris flows in the alpine environment that accumulate a multitude of their mass from entrainment and areas with limited sediment availability that are smaller than could be concluded from topography. In total, we simulate 16,756 debris flows, that results in 74.4, 99.0 and 110.2 km of railway line affected by debris flow hazard for a 30, 100 and 300 year return period respectively. Subdivision in hazard intensity classes indicates the highest relative increase is in the highest intensity classes under more extreme return periods. This in turn indicates that debris flows under more extreme events tend to expand in flow height rather than spatial extent. The large-scale, but detailed site-specific maximum debris flow height, give unprecedented capacity to the Swiss federal railways to prioritize and plan adaptation measures. Limitations in our hazard assessment lie in the accuracy of the PRA definition and deterministic parametrization of erosion potential. These facts underline that this method is to be applied both on the large-scale and as hazard indication.

Code and data availability. Hazard indication maps as well as GIS workflow (python in ArcGIS pro) to produce these maps is not available given the commercial character of the project in which it was generated. Examples as used in this manuscript are avaialble upon request. Due to the sensitivity to hazard indication maps we like to state that example maps presented in this research do not give any guarantees. Local hazard should still be validated by experts.

Appendix A

A1 Topography

Table A1. Glossary of topographic data used in the susceptibility analysis. the base DEM also serves in the RAMMS runout calculations.

	Layer	Description	Resolution
1	Base DEM	swissALTI3D (https://www.swisstopo.admin.ch/en/height-model-swissalti3d)	0.5 m
2	Slope	Derived in ArcGIS Pro (3×3 window) from the base DEM	1 m
3	Northerness	Cosine of aspect; derived in ArcGIS Pro (3×3 window) from the base DEM	1 m
4	Easterness	Sine of aspect; derived in ArcGIS Pro (3×3 window) from the base DEM	1 m
5	Flow accumulation	D8 flow accumulation derived in ArcGIS Pro from the base DEM	1 m
6	Curvature	Derived in ArcGIS Pro (3×3 window) from the base DEM	10 m

https://doi.org/10.5194/egusphere-2026-4604
Preprint. Discussion started: 19 August 2026

A2 Spatial data

Table A2. Glossary of additional raster and vectordata, beside topographic, used in this project. A description and, when available, a link to the data source is provided. Layers 14 requires an area correction because extreme precipitation depth decreases over larger areas. The correction follows the method of Grebner et al. (1999).

	Layer	Description	Resolution
1	Vegetation height	Vegetation height model (LFI); https://www.lfi.ch/en/maps/vegetation-height-surface-model	1 m
2	Forest presence	Topographic Landscape Model – land cover forest; https://www.swisstopo.admin.ch/en/information-topographic-landscape-model	1 m
3	Permafrost	Permafrost and ground ice map; https://www.slf.ch/de/services-und-produkte/permafrost-und-bodeneiskarte/	10 m
4	Landscape typology	38 landscape-use types; https://www.are.admin.ch/are/de/home/agglomerationen-laendliche-raeume/grundlagen-und-daten/landschaftstypologie-schweiz.html	10 m
5	Rock cover	Topographic Landscape Model – land cover rock / loose rocks / other; https://www.swisstopo.admin.ch/en/information-topographic-landscape-model	10 m
6	Water storage capacity	Federal Office for Agriculture – six classes of available soil water; https://www.geocat.ch/geonetwork/srv/eng/catalog.search#/metadata/6caf4d0f-52da-433a-809f-92781316ad0e	10 m
7	Lithology	GeoCover geological vector database – attribute LITHOLOGY (rasterized); https://www.swisstopo.admin.ch/de/geologisches-modell-2d-geocover	10 m
8	Hydrogeology	GeoCover geological vector database – attribute HYDROGEO (rasterized); https://www.swisstopo.admin.ch/de/geologisches-modell-2d-geocover	10 m
9	Rock type	GeoCover geological vector database – attribute ROCK (rasterized); https://www.swisstopo.admin.ch/de/geologisches-modell-2d-geocover	10 m
10	Tectonic units	GeoCover geological vector database – attribute TECTONIC (rasterized); https://www.swisstopo.admin.ch/de/geologisches-modell-2d-geocover	10 m
11	Yearly precipitation	Climate normals precipitation 1991–2020 (MeteoSwiss); https://www.meteoswiss.admin.ch/climate/the-climate-of-switzerland/climate-normals.html	1000 m
12	1-hour and 24-hour extreme precipitation	MeteoSwiss extreme precipitation maps (1 h duration). Return periods of 30, 100, and 300 years are used in this study; (Fukutome et al., 2025); https://hydromaps.ch/#en/8/46.830/8.193/bl_hds	1000 m
13	Topographic Landscape Model (TLM)	Swiss Topographic Landscape Model (TLM) vector dataset from swisstopo.	-
14	Altschutt/Jungschutt	Attribute list from Geo7 engineering company applied to the GeoCover geological database	
15	StorMe debris flows	StorMe database – Wasser/Murgang category; features containing “Uebermuerung” in the description (total features: 6351); https://www.bafu.admin.ch/bafu/de/home/themen/naturgefahren/gefahrengrundlagen/schaeden/naturereigniskataster-StorMe.html	-
16	StorMe floods	StorMe database – Wasser/Murgang category; features containing “Ueberschwemmung” or “unspezifiziert” in the description (total features: 19175); https://www.bafu.admin.ch/bafu/de/home/themen/naturgefahren/gefahrengrundlagen/schaeden/naturereigniskataster-StorMe.html	-
17	SGI glacial extent	Swiss Glacier Inventory (SGI) glacier extent dataset.	-
18	GeoCover fans	Alluvial fan polygons derived from the GeoCover geological vector database.	-

https://doi.org/10.5194/egusphere-2026-4604
Preprint. Discussion started: 19 August 2026

A3 Hydrograph properties

A total of 36 statistical properties from 19 layers are assigned to the hydrograph points. Additionally 5 ratios are added giving a total of 41 properties. Ratios are added to enhance performance of statistical models. An overview is given in Table A3 below. Details on data origin are in section A1 and A2.

Table A3. Summary of spatial data layers and derived ratios used as hydrograph properties. CA = Catchment Area, STR = Streamsection, HY = Hydrograph point, MEAN = Mean value, MIN = Minimum value, MAX = Maximum value, RANGE = Range of values, STD = Standard deviation of values, PV = Point value, MAJ = Majority value. Note that for boolean raster (e.g. Forest presence, Permafrost) the mean value equals the percentage in the catchment area.

	Layer	Category	Statistical properties
1	DEM	Topography	**CA**: MEAN, MIN, MAX, RANGE, STD; **STR**: MEAN, MIN, MAX, RANGE, STD
2	Slope	Topography	**CA**: MEAN; **STR**: MEAN, STD
3	Northerness	Topography	**CA**: MEAN, STD
4	Easterness	Topography	**CA**: MEAN
5	Flow Accumulation	Topography	**CA**: MEAN, STD; **STR**: MEAN, STD; **HY**: PV
6	Curvature	Topography	**STR**: MEAN, STD
7	Vegetation height	Vegetation	**CA**: MEAN
8	Forest presence	Vegetation	**CA**: MEAN
9	Permafrost	Glaciology	**CA**: MEAN
10	Glacier presence	Glaciology	**CA**: MEAN
11	Landscape typology	Geomorphology	**CA**: MAJ
12	Land cover	Geomorphology	**CA**: MAJ
13	Water storage capacity	Geomorphology	**CA**: MAJ
14	Lithology	Geology	**CA**: MAJ
15	Hydrogeology	Geology	**CA**: MAJ
16	Rock type	Geology	**CA**: MAJ
17	Tectonic units	Geology	**CA**: MAJ
18	Extreme rainfall 1hr, T=100 yr	Climate	**CA**: MEAN
19	Extreme rainfall 24hr, T=100 yr	Climate	**CA**: MEAN
20	Yearly precipitation	Climate	**CA**: MEAN
Additional Ratios with description			
21	Stream linearity	–	Euclidean distance / length of the stream section
22	Catchment roundness	–	CA perimeter / CA area
23	Melton ratio	–	Elevation range / $\sqrt{\text{Flow Accumulation}}$
24	1 hr P ratio	–	Extreme rainfall 1 hr, T=100 yr / yearly precipitation
25	24 hr P ratio	–	Extreme rainfall 24 hr, T=100 yr / yearly precipitation

https://doi.org/10.5194/egusphere-2026-4604
Preprint. Discussion started: 19 August 2026

A4 Erosion parametrization

Table A4. RAMMS erosion parameters by erosion class.

Erosion class	**Erosion rate [m/s]**	**Potential erosion depth per unit basal shear stress [m/kPa]**	**Critical stress [kPa]**
High	0.05	0.20	0.5
Medium (default)	0.025	0.10	1.0
Low	0.0125	0.05	1.5
No erosion	0	0	1.5

https://doi.org/10.5194/egusphere-2026-4604
Preprint. Discussion started: 19 August 2026

Table A5. RAMMS potential erosion depth for different erosion classes and return periods.

Erosion class	Return period [yr]	Maximum erosion depth [m]
High	300	4.00
High	100	1.00
High	30	0.33
Medium	300	2.00
Medium	100	0.50
Medium	30	0.17
Low	300	1.00
Low	100	0.25
Low	30	0.08
No erosion	300	0.00
No erosion	100	0.00
No erosion	30	0.00

https://doi.org/10.5194/egusphere-2026-4604
Preprint. Discussion started: 19 August 2026

Appendix B

B1 Dornibach event

Figure B1. Illustrations from the Dornibach railway crossing in Canton Uri, Switzerland. Upper left is before the event. Other illustrations show the railway infrastructure after the event of August 24th, 2005.

420 *Author contributions.* FZ and MB conceived the study and developed the methodology. MB integrated our methods with Swiss hazard standards. YB provided expert input and feedback throughout the development of the study. FZ performed the data analysis and produced the figures. FZ wrote the manuscript with contributions to specific sections from all co-authors. All authors reviewed and approved the final manuscript.

https://doi.org/10.5194/egusphere-2026-4604
Preprint. Discussion started: 19 August 2026

Competing interests. One of the co-authors is in the editorial board of NHESS

Disclaimer. Generated hazard indication maps are guidelines and do not hold any judicial responsibility.

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Preprint. Discussion started: 19 August 2026

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