TOWARDS AN AUTOMATED AVALANCHE THALWEG ANALYSIS TO IDENTIFY AND COMPARE AVALANCHE TERRAIN

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ABSTRACT:

To reduce complexity of avalanche simulation outputs in three-dimensional terrain, individual avalanches can be represented by thalwegs. A thalweg describes avalanche properties and quantitative metrics along the main flow direction. Deriving such metrics at the regional scale requires an automated workflow. We present an automated, objective model-based approach for identifying two-dimensional thalweg representations of avalanches at the regional scale, extending an open-source model chain that delineates potential release areas and simulates their potential intensity and runout using AvaFrame::com4FlowPy. For each release area, the thalweg is computed as the flux-weighted (similar to mass-weighted) main flow direction, from which runout length and maximum impact pressure are derived. Applying this model chain with identical input parameters across four study areas, Davos (Switzerland), Livigno (Italy), Rogers Pass (Canada) and Sellrain (Austria), we compare the resulting distributions to characterize regional differences in avalanche release area, simulated runout length and impact pressure, which are translated to avalanche size. Results show that the terrain in Davos produces the smallest avalanches. 50% of release areas are assigned to dimension size 2, with a median release area of 2 600 m². For runout length and impact pressure, Rogers Pass has the largest proportion of avalanches assigned to size 5. Release area values are highest in Livigno across all percentiles, with a median of 4 200 m². Sellrain, while having the highest simulated avalanche density per unit area, shows the highest median impact pressure (56.3 kPa) among all study areas. These terrain-driven differences demonstrate the ability of the presented approach to objectively quantify and compare avalanche terrain across regions. Additionally, our results support the plausibility of the technical scheme for avalanche size classification used here, underlining its applicability for regional-scale avalanche terrain analysis.

KEYWORDS: Avalanche terrain identification, Avalanche size, Avalanche mobility, Automated model chain

1. INTRODUCTION

Comparative analyses of modeled and observed avalanches, at event, path or regional scales, typically rely on scalar or ordinal summary metrics (Fischer 2013). Deriving these metrics for large datasets requires an automated procedure. This study investigates an automated, objective model-based workflow for identifying thalwegs and extracting quantitative metrics along these thalwegs to compare regional-scale avalanche simulations across different study areas.

A thalweg describes properties along the main flow direction of a flow path in three-dimensional terrain. Two-dimensional representations, such as the altitude profile along the thalweg, simplify the representation of the three-dimensional avalanche properties. Additionally, single quantitative metrics, for example runout length, describing the flow path can be derived along the thalweg for statistical analyses of the underlying avalanche terrain or comparison of avalanche events or simulation outcomes. However, existing thalweg identification approaches are mainly limited to individual flow paths.

At regional scale, expert-based and automated workflows instead identify and classify avalanche terrain, for example the Avalanche Terrain Exposure Scale, Classified Avalanche Terrain and Avalanche Terrain Hazard maps (Schmudlach and Köhler 2016; Toft et al. 2024; Harvey et al. 2024; Statham and Campbell 2025). These approaches assign terrain to discrete classes, but do not derive quantitative flow path characteristics. Such classification maps have been compared across

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different study areas (Spannring 2024), but only at the level of discrete terrain classes rather than quantified avalanche characteristics. A consistent, objective thalweg representation extracted for many individual flow paths at the regional scale, enabling quantification of the avalanche terrain, has so far received little attention.

To address this gap, we present a regional-scale method for automated identification of two-dimensional thalwegs of avalanches. We extend an open-source model chain for avalanche terrain identification that delineates potential release areas (PRAs) from three-dimensional terrain and computes their potential intensity and runout (Veitinger et al. 2016; D'Amboise et al. 2022; Huber et al. 2023). From the resulting simulations, we derive scalar metrics along each thalweg, such as runout length and maximum impact pressure, which can be directly classified into avalanche size (CAA 2016; EAWS 2026; Fischer et al. 2026). Using this model chain, we identify and compare avalanche terrain in four study areas: Davos (Switzerland), Livigno (Italy), Rogers Pass (Canada) and Sellrain (Austria).

2. METHODS

The challenge addressed in this study is the automated thalweg identification for every flow path at the regional scale. We adapt and extend a model chain originally developed for the AutoATES workflow (Huber et al. 2023). The model chain enables fully automated thalweg identification, requiring a digital elevation model and a suitable parameterization as input, with optional forest information. The workflow is implemented in the open-source Avalanche-Terrain-Identification framework and is described in detail in its documentation (Hesselbach et al. 2026b).

2.1. Potential avalanche release and mobility simulation

PRAs are delineated and constrained based on terrain-derived characteristics, including slope, surface roughness and forest cover, using a fuzzy-logic approach (Veitinger et al. 2016).

For each delineated PRA, we compute the maximum potential intensity and runout using AvaFrame::com4FlowPy, an empirically motivated, open-source simulation tool for gravitational mass flows (D'Amboise et al. 2022; Oesterle et al. 2026). com4FlowPy estimates the routing and stopping behavior of avalanches based on an established travel-angle concept. It requires comparatively few input parameters, making it well suited for application across large and heterogeneous regions.

The parameterization is selected for each PRA to represent the maximum potential mobility, following an approach in which minimum runout angle and maximum velocity limit are assigned as a function of dimension size (McClung and Gauer 2018; Fischer et al. 2026). Larger release areas are thereby assigned parameter combinations corresponding to greater potential mobility. The equations for this parameterization can be found in Hesselbach et al. (2026b). Forest friction is additionally considered by locally increasing flow friction in forested areas, reducing simulated runout and intensity where dense forest cover is present, following Huber et al. (2024).

2.2. Automated thalweg identification

Within the runout simulation, the thalweg's location is computed along the main flow direction for each release area by averaging the respective flow quantities, weighted by the routing flux F. The routing flux is a com4FlowPy-specific parameter and can be interpreted as a proxy for mass. For a given quantity X, for example the x- and y-coordinates, the flux-weighted averaged values X_{coF} are computed as:

$$X_{coF} = \frac{\sum_{i=0}^{n} X_i \cdot F_i}{\sum_{i=0}^{n} F_i} \quad (1)$$

where index i represents all cells of one iteration step of the avalanche path simulation and n is the total number of cells within that step. This flux-weighted averaging is performed at every iteration of the simulation, yielding one representative thalweg location as the flux-weighted center position per iteration step. In a post-processing step, the thalweg is extended upslope and downslope beyond the simulated extent, following the respective upstream and downstream direction of the thalweg. Figure 1 shows the resulting thalweg's location for an example avalanche path, including the upslope and downslope extension.

Along each thalweg, we derive two scalar metrics: maximum impact pressure and runout length. The maximum energy line height, a direct com4FlowPy output, corresponds to the highest flux-weighted energy line height value along the thalweg, as obtained from Equation 1. The maximum impact pressure p is derived from the maximum flux-weighted energy line height, z^{vel}, following the relation $p = 2g\rho z^{vel}_{max}$, where g is gravitational acceleration and the assumed snow density is

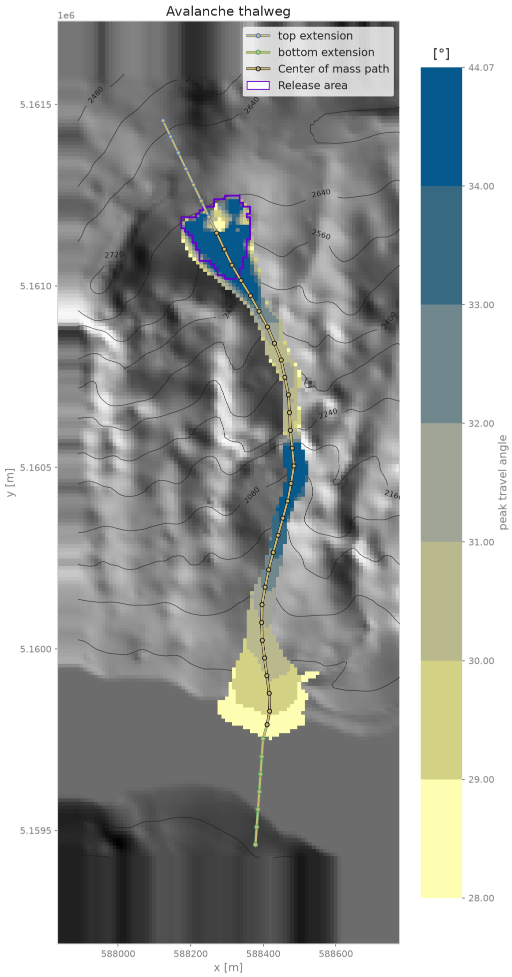

Figure 1: Location of the flux-weighted thalweg (center of mass path) with its upslope and downslope extensions, overlaid on the simulated peak travel angle of the flow path. The violet outline marks the release area boundary.

$\rho = 200$ kg m^{-3} for a dry flow regime. The runout length is defined as the horizontally projected distance between the start and end points of the derived thalweg coordinates, measured along the entire flow path.

These metrics are computed identically for every flow path across all four study areas, enabling both statistical analysis of avalanche terrain within a region and direct comparison between regions.

2.3. Avalanche size classification

Fischer et al. (2026) developed a technical and a communication scheme for avalanche size classification, harmonizing established classification schemes (e.g., CAA 2016; EAWS 2026). They distinguish between dimension size, runout size and destructive size: the technical scheme characterizes dimension size by release or deposition volume, runout size by runout length and destructive size by impact pressure. In this study, we derive dimension size from release area, assuming a constant release thickness of 1 m to convert release area into release volume. Runout size and destructive size are derived from the runout length and maximum impact pressure, respectively, as described in Section 2.2..

Each avalanche is thus classified along three independent size criteria, each describing the maximum possible event corresponding to the terrain potential or path size. Possible events may reach the path size potential under worst-case conditions or remain below in less critical scenarios, as addressed in Hesselbach et al. (2026a). We apply the technical scheme for assigning the size and report the corresponding communication scheme values in the figures for improved readability.

3. STUDY AREAS

We apply the presented method to four study areas spanning different Alpine and North American mountain environments: Davos (Switzerland), Livigno (Italy), Rogers Pass (Canada) and Sellrain (Austria). Figure 2 shows their locations and Table 1 their area, forested area and elevation range. The area of each region is approximately 100 km², with the exception of Davos, which is larger due to the broad, flat valley bottom.

For each region, a digital elevation model (DEM) and forest cover data serve as the primary inputs for the workflow.

Table 1: Overall area, forested area and elevation range of the study areas.

Study area	***Area [km²]***	***Forested area [km²]***	***Elevation range [m]***
Davos	156.0	38.5 (25%)	1034 - 2842
Livigno	101.8	11.9 (12%)	1781 - 3274
Rogers Pass	113.2	50.2 (44%)	892 - 2841
Sellrain	101.3	10.9 (11%)	1357 - 3087

4. RESULTS

4.1. Single avalanche: thalweg and derived characteristics

From an identified thalweg (Figure 1), we derive a simplified two-dimensional representation by plotting elevation against projected distance along the thalweg (Figure 3). This representation illustrates the runout length Δs and maximum flow velocity v_{max}, for the example flow path.

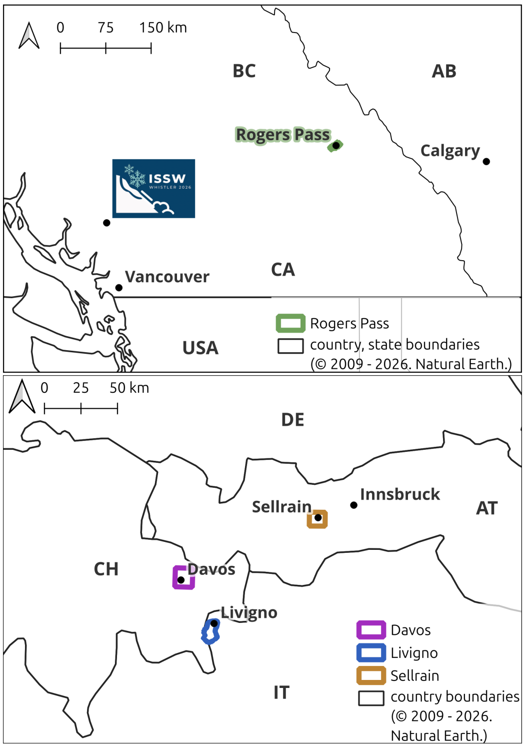

Figure 2: Overview maps showing the location of the Rogers Pass study area (upper panel) and the Davos, Livigno, and Sellrain study areas (lower panel).

Following Fischer et al. (2026), this avalanche is assigned to dimension size 4 (release area of 28,100 m²), runout size 4 (runout length of 1580.5 m) and destructive size 4 (maximum impact pressure of 440 kPa). This alignment across all criteria is not guaranteed for every avalanche, as the path size can differ for each criterion.

4.2. Regional comparison of avalanche terrain

Figure 4 shows the maximum flow velocity of all potential avalanches within an excerpt of the Sellrain study region, overlaid with the identified thalwegs as black lines.

Applying this thalweg approach across the four study regions allows regional comparison of release volume, runout length and impact pressure. Figure 5 shows the distributions of release area, simulated runout length and impact pressure for all thalwegs in the study regions Davos, Livigno, Rogers Pass and Sellrain (left to right). The quantities are classified into respective avalanche sizes following Fischer et al. (2026) (see Section 2.3.). The number of simulated avalanches per region ranges from 1 904 in Livigno to 2 999 in Davos, corresponding to a simulated avalanche density of 19 avalanches/km² in both Davos and

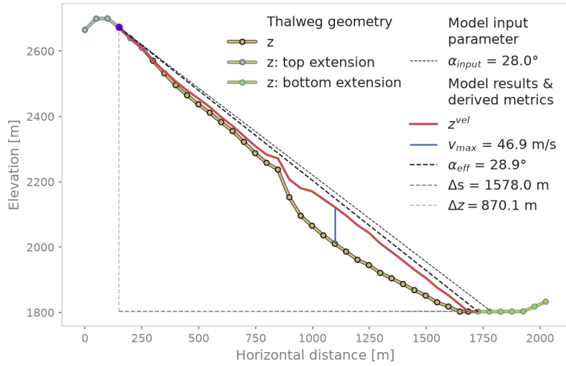

Figure 3: Two-dimensional representation of the elevation profile along the thalweg shown in Figure 1. Metrics such as the effective travel angle (black dashed line), maximum flow velocity (blue line) and runout length (gray dashed line) can be read from this representation.

Livigno, 21 avalanches/km² in Rogers Pass and 27 avalanches/km² in Sellrain.

The distribution of release area (upper panel of Figure 5) is similar for Livigno, Sellrain and Rogers Pass, with medians of 4 200 m², 3 800 m² and 3 500 m² (dimension size 3) and a 75th percentile of approximately size 3-4, so 25% of avalanches reach size 4 or larger. Davos has smaller release areas overall, with a median of 2 600 m² (dimension size 2-3). Maximum release area values correspond to size 5 in all regions, with the largest maxima in Livigno and the smallest in Davos. Across all percentiles, values are highest in Livigno and lowest in Davos.

The distribution of simulated runout length (middle panel of Figure 5) varies more strongly across regions, with medians ranging from 195 m in Davos (runout size 2) to 492 m in Sellrain (runout size 3). The 25th percentile corresponds to runout size 1 in Davos, and to size 2 in Livigno, Rogers Pass and Sellrain. Sellrain has the highest median, Rogers Pass the highest 75th percentile and Livigno the highest maximum.

The distribution of simulated maximum impact pressure (lower panel of Figure 5) is shifted to smaller destructive size classes overall compared to dimesion and runout size. Median impact pressure corresponds to destructive size 2 in Davos, Livigno and Rogers Pass (19.7 kPa, 29.3 kPa and 48.7 kPa, respectively) and to destructive size 2-3 in Sellrain (56.3 kPa). As with runout length, Sellrain has the highest median impact pressure, while Rogers Pass has the highest 75th percentile.

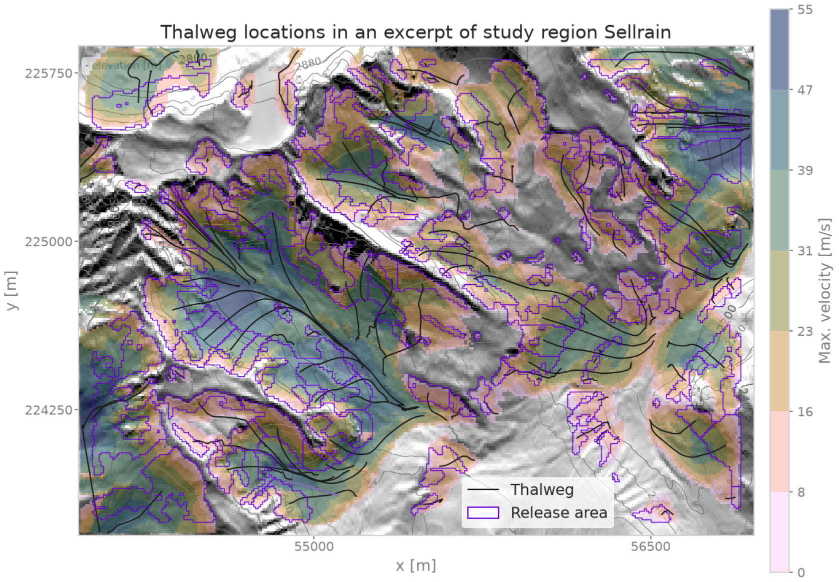

Figure 4: Automatically identified thalwegs (black lines) originating from mapped release areas (magenta outlines) across an excerpt of the Sellrain study area, shown with simulated maximum flow velocity.

4.3. Analysis of the avalanche sizes

Table 2 shows the median, 25th and 75th percentile of release area, runout length and impact pressure across all study areas, together with the relative proportion of avalanches per size class. Median of release area (3 300 m²) and runout length (351 m) correspond to size 3, while the median impact pressure (36.3 kPa) corresponds to size 2.

Since only release areas larger than 500 m² were considered, no avalanches are assigned to dimension size 1. Most avalanches are classified as dimension size 2 (42.4%), followed by dimension size 3 (33.8%). The distribution of runout size is similar, with 21.6% assigned to size 1 and 22.7% to size 2, together 44.3%, comparable to the proportion of dimension size 2. Notably, a larger proportion of avalanches is assigned to runout size 5 than to dimension size 5. In contrast, the distribution of destructive size is shifted towards smaller classes, with 37.6% and 21.1% assigned to size 1 and 2, respectively and only 14.9% assigned to size 4, compared to approximately 21% for both dimension size 4 and runout size 4.

Table 2: Median, 25th and 75th percentile of release area, runout length and impact pressure across all study areas, based on 10 034 simulated avalanches. And corresponding relative proportions of assigned size classes (dimension size, runout size and destructive size) are shown.

	Release area	***Runout length***	***Impact pressure***
Median	3 300 m²	351 m	36.6 kPa
25% perc.	1 200 m²	86 m	5.4 kPa
75% perc.	11 500 m²	931 m	114.7 kPa
Size 1	0%	21.6%	37.6%
Size 2	42.4%	22.7%	21.1%
Size 3	33.8%	29.5%	25.4%
Size 4	21.5%	20.5%	14.9%
Size 5	2.2%	5.7%	1.0%

5. DISCUSSION

Simulation results, such as impact pressure and runout length, reflect both the applied parameterization and the underlying terrain. And all processing steps of the presented model chain rely on simplified tools. In particular, the PRA segmentation, which determines the release area, has a high impact on further simulation results, since the parameterization depends on dimension size. As the same model chain is applied consistently across all regions, however, results remain comparable for a terrain analysis.

Furthermore, the parameterization does not account for regional differences in snow climate (e.g., maritime versus continental snowpack), which are known to influence release thickness and mobility (e.g., Schweizer et al. 2003). It is designed to represent the largest possible event, corresponding to the terrain's potential or path size. Smaller event sizes are not relevant for terrain identification, but are addressed in scenario-based simulations, e.g. in Hesselbach et al. (2026a).

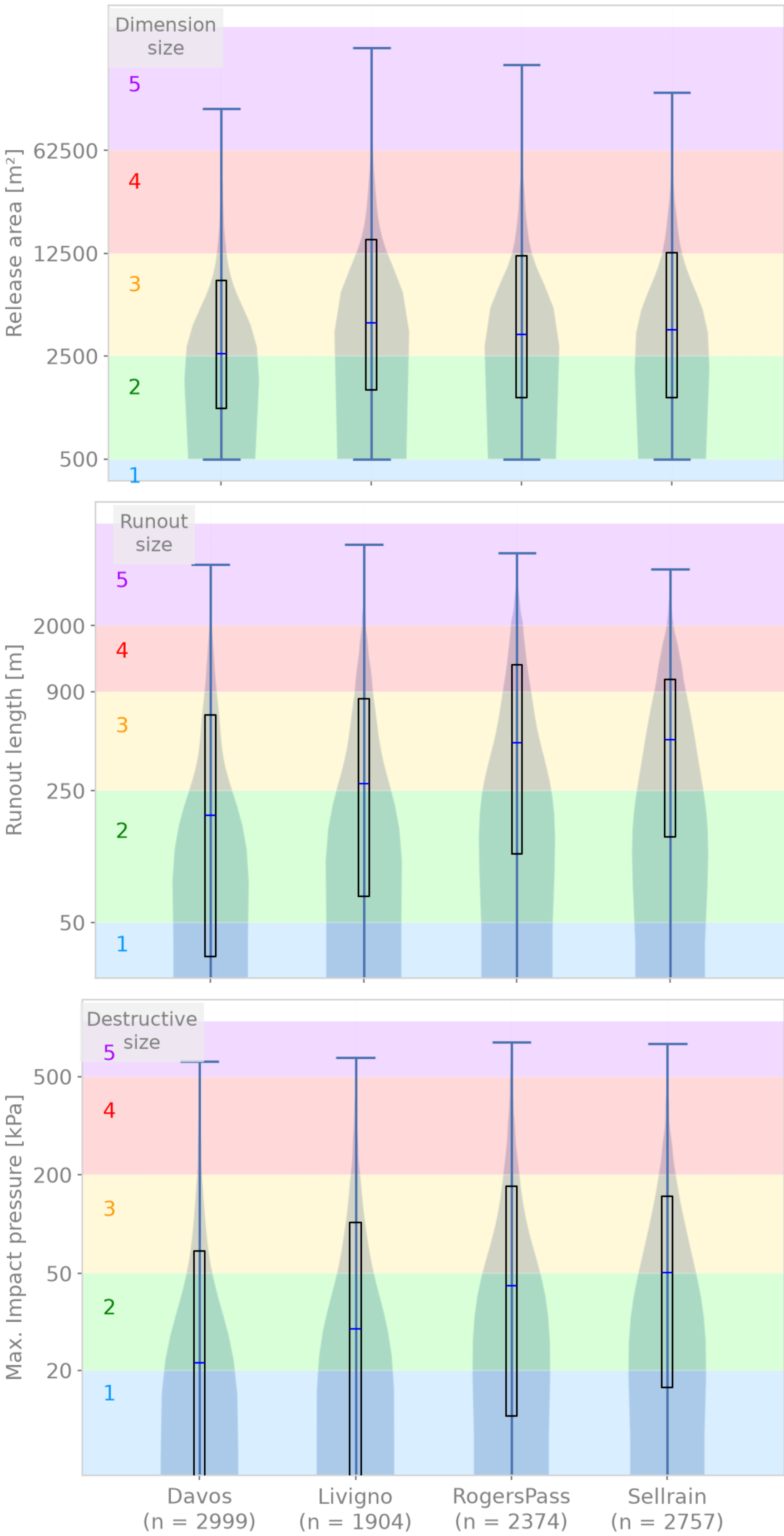

Figure 5: Distributions of release area, runout length and maximum impact pressure for all simulated thalwegs in each study region (Davos, Livigno, Rogers Pass, Sellrain). Boxplots indicate the 25th, 50th and 75th percentiles, the whiskers the minimum and maximum values. Background shading denotes the respective avalanche size following Fischer et al. (2026). n denotes the number of avalanches simulated per region. The y-axes are plotted on a logarithmic scale.

Release area, runout length and impact pressure show broadly similar patterns across regions, since the parameterization directly links release area to the minimum travel angle and maximum velocity limit (see Section 2.1.). Nonetheless, terrain-driven differences emerge, and an avalanche does not necessarily fall into the same size class across all criteria. This underscores the importance of distinguishing between avalanche size criteria (Fischer et al. 2026).

Across the four study areas, Davos produces the smallest avalanches, as its smaller release areas limit runout and impact pressure through the parameterization, additionally the high forest cover reduces runout and intensity. Rogers Pass, despite comparable forest cover and elevation range, produces markedly larger avalanches, particularly in the upper quartile, likely reflecting steep paths located above the forest line. Livigno and Sellrain are less forested and show similar release area distributions, yet Sellrain produces larger avalanches than Livigno in terms of runout length and impact pressure. Despite its lower elevation and higher forest cover, Rogers Pass shows release area, runout length and impact pressure distributions remarkably similar to those of Sellrain. Explaining these patterns in detail would require a closer terrain analysis. The contrast between Davos and Sellrain is consistent with Spannring (2024), a comparison of avalanche terrain classification maps (ATES and CAT) and a prior thalweg-based comparison between the two regions.

The similarity of size distributions within and across regions supports the plausibility of the technical scheme proposed by Fischer et al. (2026), particularly for dimension and runout size: as expected, avalanches predominate in classes 2 and 3, with few in class 5. And both criteria show a similar overall distribution shape. Destructive size, however, systematically tends toward smaller classes. This discrepancy may arise from limitations in how impact pressure, which characterizes destructive size, is computed: the parameterized maximum velocity limit directly constrains simulated impact pressure, and the assumed constant avalanche density fails to capture the higher pressures associated with denser, more destructive avalanches. Alternatively, it may reflect how destructive size itself is defined within the classification scheme. Some avalanches show a runout length of 0 m or an impact pressure of 0 kPa. This can occur where the slope angle of the terrain is lower than the minimum runout angle, so that release results only in a local collapse rather than in movement.

6. CONCLUSION AND OUTLOOK

We presented an automated, objective model-based approach for identifying two-dimensional thalweg representations of avalanches at regional scale, extending an open-source model chain. Applied consistently across the four study areas Sellrain, Davos, Livigno and Rogers Pass, the method enables reproducible extraction of quantitative avalanche metrics, including runout length and maximum impact pressure. Comparing the resulting distributions across regions allows us to characterize regional differences in release area, runout length and impact pressure. As identical parameterization was applied across all regions, differences can be attributed to terrain properties.

Overall, Davos has the largest proportion of avalanches assigned to size 1 and 2. For runout size and destructive size, Rogers Pass has the largest proportion of avalanches assigned to size 5. Release area values are highest in Livigno across all percentiles. Sellrain, while having the highest simulated avalanche density per unit area, shows the highest median runout length and maximum impact pressure among all study areas. Future regional comparisons would benefit from using larger study areas to better capture terrain diversity.

The presented approach relies on simplified models, which do not represent each avalanche path equally realistic in each criterion. As the workflow is modular, individual modules, such as PRA delineation or the simulation tool, could be substituted by alternative tools to address these limitations.

Analyses of identified thalwegs can serve as a diagnostic tool for the development and validation of simulation tools. Additionally, derived thalweg metrics offer potential for validating the applied parameterization, for instance, by comparing the simulated effective runout angle to the input runout angle. Beyond parameterization and model validation, these relations could support future comparisons between study regions and further underline the plausibility of the technical size classification scheme applied here (Fischer et al. 2026). To address regional differences in snow climate, the parameterization could be adapted region-specifically in future applications.

7. DATA AND CODE AVAILABILITY

Sellrain: DEM and DSM were obtained from the Open Government Data portal of the Province of Tyrol via the public Web Coverage Service (WCS), licensed under CC BY 4.0. Percentage canopy cover was derived following Hesselbach (2023) using the difference between DSM and DEM.

Davos: DEM and DSM were obtained from swissAlti3D, provided by the Swiss Federal Office of Topography (swisstopo). Forest information is derived using the same method as for Sellrain.

Livigno: The DEM was obtained from the freely available dataset provided by Regione Lombardia (Regione Lombardia 2015). The forest mask was generated using a proprietary Random Forest classification algorithm, developed by Alpsolut srl.

Rogers Pass: DEM is derived from LiDAR collected in 2015 by Parks Canada along the Trans-Canada Highway Corridor. This data is not available to the public, data requests should be directed to Glacier National Park. The forest canopy cover data is produced from multi-temporal Sentinel-2 imagery. This data is part of a forest mapping project (Sykes et al. 2026) and will be available through an Avalanche Canada data portal.

The code, its documentation and the used parameters can be found in the repositories in Hesselbach et al. (2026b) and Oesterle et al. (2026).

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