AVALANCHE SCENARIO MAPS: FROM TERRAIN IDENTIFICATION TO DECISION SUPPORT TOOL

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ABSTRACT:

Site-specific avalanche warning requires spatially explicit estimates of where avalanches may release, how they may propagate, and what size they may reach. These assessments are often made under time pressure and from heterogeneous or limited information. Avalanche scenario maps can support local decision-making by translating these assessments into a consistent spatial representation of expected avalanche activity and its potential interaction with exposed elements.

To address this need, we present a framework for translating an operational avalanche scenario into spatially explicit avalanche scenario maps by combining terrain potential with scenario-specific spatial and avalanche constraints. Terrain potential, derived through avalanche terrain identification, represents what the terrain can produce, while the avalanche scenario describes what is expected under prevailing conditions. A harmonized avalanche size interface links both components and enables spatial mapping of avalanche size.

The interface builds on the established EAWS, CAA and AAA classifications. Continuous size relationships retain compatibility with these five-class operational schemes while allowing model inputs and outputs to be expressed on the same scale. Simulation results can therefore be translated back into spatially mapped dimension, runout and destructive size.

The framework was developed and tested in two cross-border pilot regions and applied to selected scenarios across the EUREGIO Tyrol–South Tyrol–Trentino in the European Alps. Contrasting dry winter and wet spring scenarios demonstrate how the same terrain potential can result in spatially distinct avalanche scenario maps under different spatial and avalanche constraints. The resulting maps also allow scenarios to be compared in terms of affected area, characterized avalanche size and exposure of infrastructure. Developed iteratively with avalanche warning services and local avalanche commissions, the approach provides a basis for further integration into operational decision-support workflows.

KEYWORDS: Avalanche terrain identification, avalanche scenario maps, site-specific avalanche warning, avalanche size, avalanche simulation, decision support

1. INTRODUCTION

In site-specific avalanche warning, a key challenge is translating prevailing avalanche conditions into spatially explicit estimates of where avalanches are likely to release, how they may propagate, and what size they may reach in terms of dimension, runout and destructive potential. These assessments often have to be made under time pressure, based on heterogeneous and sometimes limited information ranging from regional weather and avalanche forecasts to local measurements, observations and expert judgment. Spatially explicit avalanche scenario maps can support local decision-making by translating these assessments into a consistent representation of expected avalanche activity and its potential interaction with exposed elements.

To address this need, we present a framework for translating an operational avalanche scenario into spatially explicit avalanche scenario maps by combining terrain potential with scenario-specific spatial and avalanche constraints. A harmonized avalanche size interface links both components and enables spatial mapping of avalanche size. We describe the conceptual workflow from terrain identification to scenario map generation and demonstrate its application for two contrasting avalanche scenarios. The workflow is implemented in the open-source Avalanche Terrain

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Identification (ATI) framework (Hesselbach et al. 2026).

2. CONCEPTUAL FRAMEWORK AND METHODS

The framework combines terrain potential derived through avalanche terrain identification with an operational avalanche scenario to generate spatially explicit avalanche scenario maps. The framework adopts established hazard-characterization descriptors from the Conceptual Model of Avalanche Hazard (CMAH) developed by Statham et al. (2018) and from the regional and site-specific warning frameworks of the European Avalanche Warning Services (EAWS 2022). The descriptors serve two main functions in the mapping framework: defining spatial constraints and avalanche constraints. Region, elevation and aspect define where avalanches are expected to release. Avalanche constraints are defined by expected avalanche size and flow regime. As an experimental extension, snowpack stability and its spatial frequency describe how critical and widespread instability is expected to be.

Avalanche size provides a common scale linking avalanche terrain identification, avalanche scenario, simulation and map representation. Following the concept described by Fischer et al. (2026), we distinguish between *path size*, the maximum avalanche size an individual path can produce as constrained by terrain, and *event size*, the maximum avalanche size expected under the assessed conditions. The established EAWS five-class avalanche size classification, based on the CAA system, provides the reference for the underlying absolute size scale (EAWS 2026; CAA 2016). The AAA relative-size scale complements this classification by expressing avalanche size relative to the maximum an individual path can produce. Reaching the full path potential, here represented by *path size*, corresponds to relative size R5, whereas avalanches below this potential correspond to lower relative-size classes (AAA 2016).

Fischer et al. (2026) harmonize these established classifications into a technical and communication framework distinguishing three size criteria: dimension, runout and destructive size. Several characteristics can be used to quantify each criterion; in the present workflow, release and deposition volume are used for dimension size, projected travel length for runout size, and maximum impact pressure for destructive size. The derived continuous technical relationships retain compatibility with the established five-class operational schemes while allowing model inputs and outputs to be expressed on the same size scale. This enables model results to be translated back into avalanche size and mapped spatially rather than presented as complex model outputs.

Figure 1 illustrates the application of the avalanche size framework along a schematic avalanche thalweg, from size-dependent model input to spatially mapped avalanche size. Dimension size derived from release volume provides the model parameterization, while simulated deposition volume, projected travel length and maximum impact pressure are translated into dimension, runout and destructive size. In Figure 1, progressively increasing *event sizes* from 1 to 5 are illustrated for a path with *path size* 5. Relative to the path potential, these simulations range from $1/5$ (R1) to the full path potential $5/5$ (R5).

Release and deposition volumes are approximated from their respective areas assuming a characteristic depth of 1 m. This simplifying assumption can be adapted to regional or elevation-dependent snow-climate conditions in the `ATI::mod2Mobility` implementation. Release volume defines the simulated dimension size, while deposition volume reflects changes in avalanche volume along the path, including entrainment. The *path size* limits the maximum simulated size. The presented framework is structured around three guiding questions:

What is possible?
The size-dependent avalanche potential of the terrain.

What is expected?
The avalanche activity expected under the operational avalanche scenario.

How to map?
The simulation outputs are translated into respective avalanche size criteria and represented on the avalanche scenario map (ASM).

2.1. What is possible?

We use the `ATI` model chain to characterize the size-dependent avalanche potential of the terrain. Potential release areas (PRAs) are delineated from a digital elevation model and derived terrain parameters using an adapted approach by Veitinger et al. (2016), including forest information following Schumacher et al. (2022). The PRAs are subsequently segmented into individual PRAs using watershed boundaries and four overlapping aspect sectors, each spanning three adjacent eighths

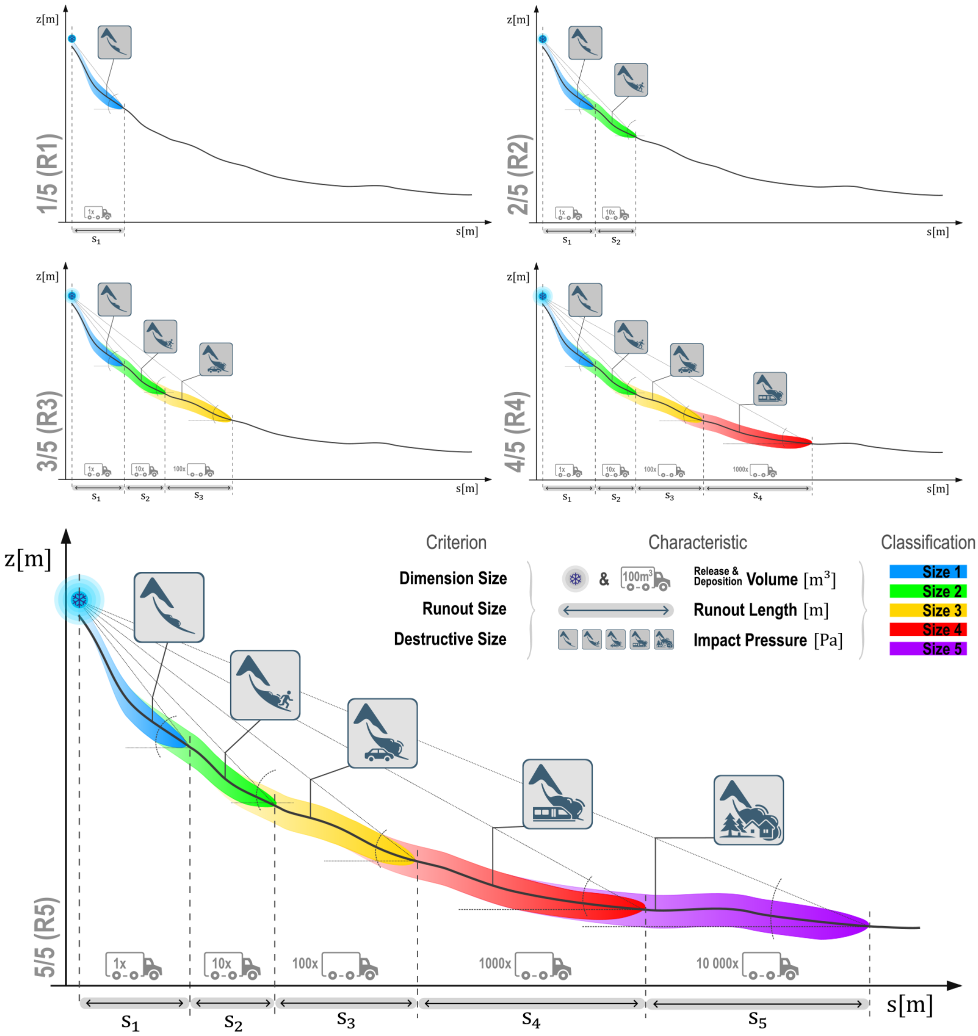

Figure 1: Application of the avalanche size framework along a schematic avalanche thalweg with *path size* 5. Increasing *event sizes* from 1 to 5 correspond to $1/5$ (R1) through $5/5$ (R5). Colored avalanche paths show runout size, arrows s_1 to s_5 projected travel length, pictograms destructive potential, and truck symbols the order-of-magnitude increase in avalanche volume. Size criteria and model parameterization follow Fischer et al. (2026).

of the compass (e.g. N = NW–N–NE), as implemented in `ATI::mod1Release`. For each PRA, the model chain estimates *path size* and simulates progressively increasing avalanche sizes up to this path-specific limit.

In the present implementation, *path size* is approximated from the dimension size characterized by the release volume of each PRA. This provides a simple path-specific upper limit for the size-dependent simulations, as illustrated in Figure 1. Alternatively, path potential can be characterized from simulated mobility along the full path using the same size framework, as demonstrated by Spannring et al. (2026) using runout length and impact pressure derived along avalanche thalwegs.

For progressively increasing dimension sizes up to this limit, size-dependent parameters controlling runout angle, maximum velocity and lateral spreading are derived for the cold flow regime following Fischer et al. (2026) and implemented in `ATI::mod2Mobility`. The parameter relationships are adapted for warm flow simulations to represent avalanche mobility expected for a wet snow avalanche problem. Avalanche propagation is simulated with the open-source `AvaFrame::com4FlowPy` model (D'Amboise et al. 2022; Oesterle et al. 2025). Mapping avalanche problems to either a cold or warm flow regime is a simplification of the present workflow.

2.2. *What is expected?*

The avalanche scenario describes what is expected under the prevailing conditions. It can be derived from the regional avalanche forecast or defined through expert judgment based on local observations. The regional bulletin provides operational context for site-specific assessment, while local information may be used to verify and refine the assessment (Statham et al. 2018; EAWS 2022).

For the mapping framework, the scenario descriptors are grouped according to their function:

(1) **Spatial constraints**
Where are avalanches expected to release?
Region, elevation and aspect identify the relevant PRAs.

(2) **Avalanche constraints**
What avalanche activity is expected?
The maximum expected avalanche size defines *event size*, while the prevailing avalanche problem determines the cold or warm flow regime.

2.3. How to map?

Map generation combines the terrain potential with the avalanche scenario. The spatial constraints first identify the relevant PRAs. For each path, *path size* defines the maximum avalanche size that can be parameterized. The *event size* defines the maximum size expected under the avalanche scenario. The selected parameterization is therefore capped by the *path size*. The assessed flow regime modifies the size-dependent parameterization to represent cold or warm flow conditions.

This interaction also connects absolute and relative avalanche size. Expressed relative to the path potential, an *event size* 4 on a path with *path size* 5 results in $4/5$ (R4), while an *event size* equal to or greater than *path size* reaches the full path potential (R5) (AAA 2016; Fischer et al. 2026).

Figure 2 illustrates the application of spatial and avalanche constraints for the dry winter and wet spring examples.

As an experimental extension, snowpack stability and its spatial frequency are used to determine how much of the maximum represented size is expected to be realized, based on descriptors underlying the EAWS matrix (EAWS 2022). Critical and widespread instability allows relative size to approach its upper limit, whereas greater stability or lower spatial frequency results in lower relative sizes.

The selected simulation outputs are subsequently translated into respective avalanche size criteria and mapped spatially on the ASM. Dimension size is characterized by deposition volume, runout size by projected travel length, and destructive size by maximum impact pressure.

3. APPLICATION AND RESULTS

The framework was developed and iteratively tested with avalanche commissions and avalanche warning services in two cross-border pilot regions: Brenner Pass (approximately 200 km^2) between Tyrol and South Tyrol, and Sella Pass (approximately 150 km^2) between South Tyrol and Trentino (Winkler et al. 2024). Following implementation in the pilot regions, selected scenarios were applied across the wider EUREGIO Tyrol–South Tyrol–Trentino in the European Alps. Across the EUREGIO-scale implementation, approximately 2.5 million avalanche simulations were precomputed to represent the underlying terrain potential.

The dry winter and wet spring scenarios in Figure 2 provide two illustrative examples of how different spatial and avalanche constraints act on the same underlying terrain potential. The dry winter scenario results in widespread simulated avalanche activity, while the wet spring scenario results in a smaller affected area.

Basic scenario statistics further illustrate the differences in the Brenner Pass pilot region. Within the 208.8 km^2 study area, the dry winter scenario includes 1,981 PRAs (24.1%) and results in a simulated affected area of 45.1 km^2 (21.6% of the study area). The wet spring scenario includes more PRAs (3,655; 44.4%) but results in a smaller affected area of 34.9 km^2 (16.7%). Motor road exposure also differs substantially between the scenarios, with 9.9 km within the affected area for the dry winter scenario compared with 0.5 km for the wet spring scenario. Of the exposed motor roads in the dry winter scenario, 6.1 km intersect areas with destructive size 3 or greater, whereas the exposed roads in the wet spring scenario remain below destructive size 2.

The two scenarios above represent simple examples with a single set of spatial and avalanche constraints. More complex operational situations can be represented by combining different scenario definitions across regions, elevation ranges and aspects. This allows different expected avalanche conditions, *event sizes* and flow regimes to be represented above and below an elevation threshold or in different parts of the region.

Figure 5 demonstrates such a composite scenario. In the northern part of the region, a high alpine dry-snow scenario with *event size* 4 is represented

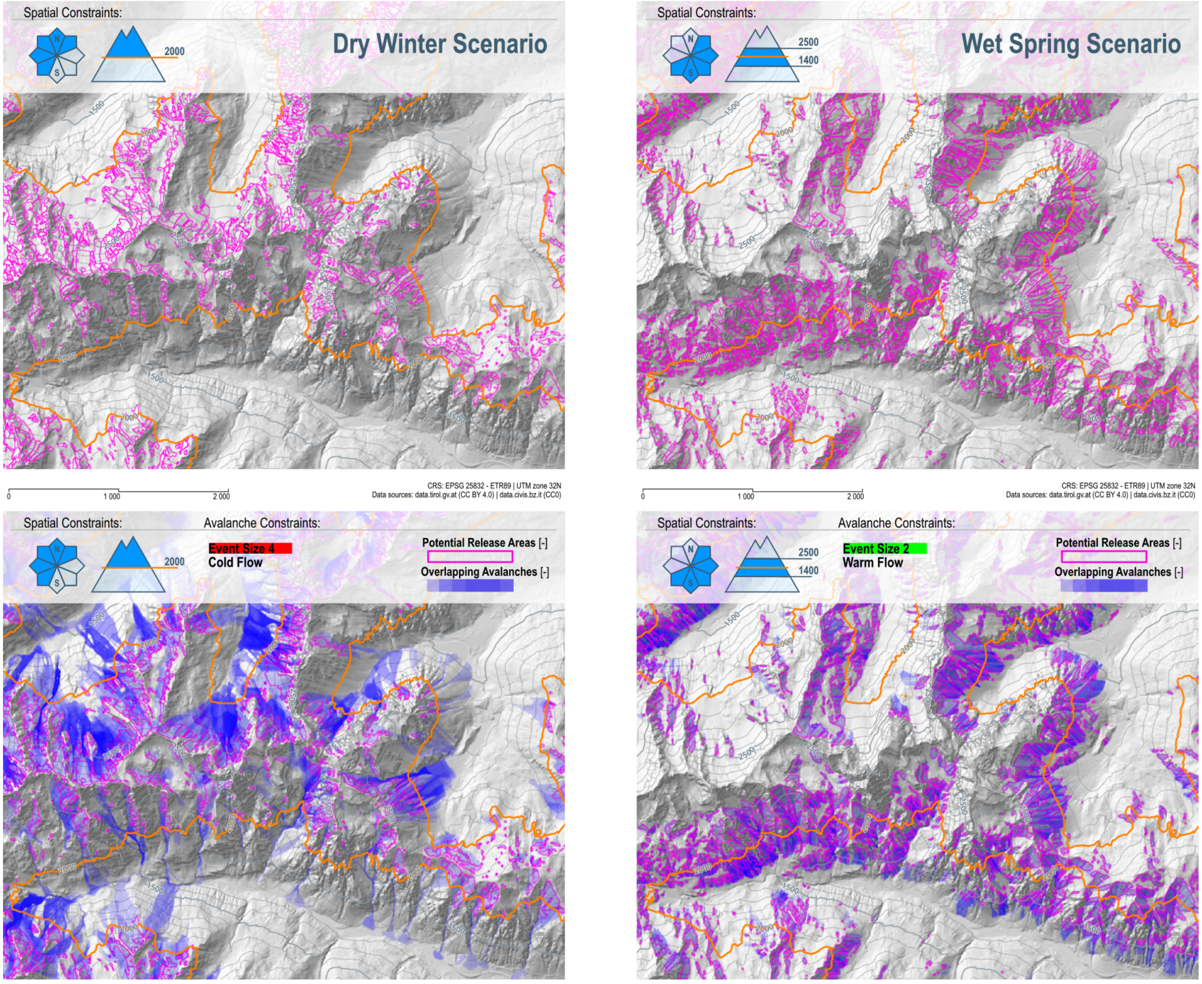

Figure 2: Application of spatial and avalanche constraints for two scenarios in a subsection of the Brenner Pass pilot region. Pink outlines indicate PRAs defined by the spatial constraints. The dry winter scenario applies *event size* 4 and a cold flow regime; the wet spring scenario applies *event size* 2 and a wet flow regime. Blue shading shows the simulated affected area, with darker shades indicating overlapping simulations. Elevation and aspect symbols inspired by `avalanche.report` (ALBINA project).

above 2200 m, while the southern part uses *event size* 3 above 2400 m. At lower elevations, warming is represented by wet snow scenarios with *event size* 2. Aspect constraints further differentiate the expected avalanche activity within each region and elevation range. Conceptually, this could represent a situation with a more widespread high alpine persistent weak layer problem in the north, a more spatially restricted persistent weak layer problem in the south, and increasing wet avalanche activity at different lower elevations in the north and south due to warming.

The framework was iteratively developed and applied in workshops with avalanche warning services and local avalanche commissions. The workshops focused on scenario interpretation, comparison with known avalanche paths, and the representation of avalanche size and affected areas. Feedback from practitioners was incorporated into the scenario logic and cartographic design (Winkler et al. 2024).

4. DISCUSSION

While Fischer et al. (2026) define and quantify the underlying avalanche size framework, the present work demonstrates how this framework can be carried through the model chain from size-dependent parameterization to simulation and to spatially mapped avalanche size. Avalanche size is derived continuously along the path and represented spatially on the ASM rather than assigned as a single value to each avalanche. This allows runout and destructive size to peak at different locations, reflecting where the avalanche stops and where its impact is greatest. Avalanche size can therefore serve as a common language linking terrain

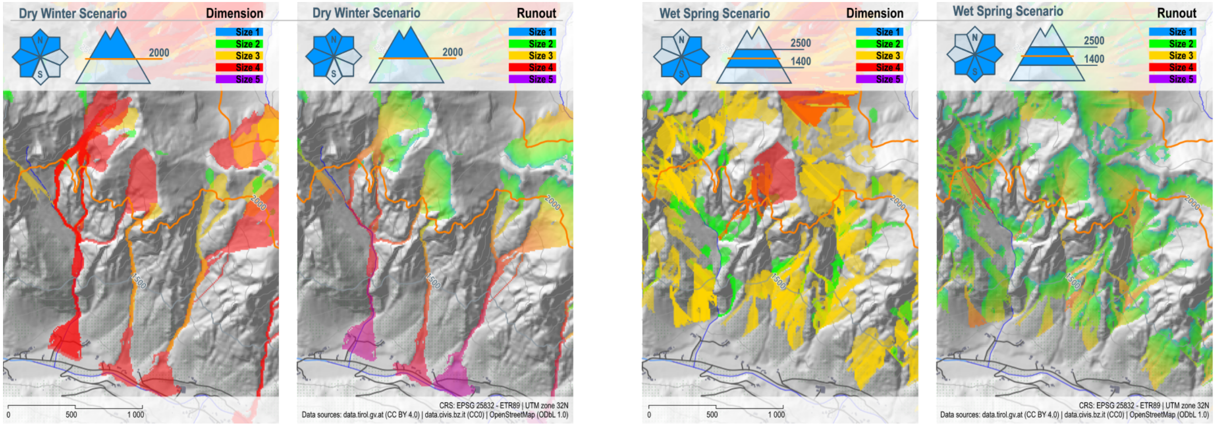

Figure 3: Spatially mapped dimension and runout size for the dry winter and wet spring scenarios in a subsection of the Brenner Pass pilot region. Dimension size is characterized by deposition volume and runout size by projected travel length. Elevation and aspect symbols inspired by `avalanche.report` (ALBINA project).

potential, avalanche scenario, simulation and map representation without implying a single unique size for the entire avalanche.

In the present implementation, *path size* is approximated from dimension size characterized by release volume. This provides a practical upper limit for size-dependent model parameterization, but does not fully characterize the mobility supported by the complete path. Downstream terrain can substantially influence avalanche mobility; Spannring et al. (2026) complement this approach by characterizing terrain-driven path potential from simulated runout length and maximum impact pressure along avalanche thalwegs.

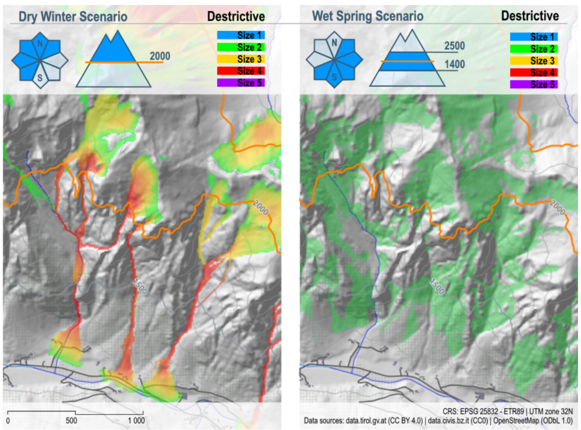

Figure 4: Spatially mapped destructive size for the dry winter and wet spring scenarios in a subsection of the Brenner Pass pilot region. Destructive size is characterized by maximum impact pressure. Elevation and aspect symbols inspired by `avalanche.report` (ALBINA project).

The avalanche scenario represents expected conditions rather than a deterministic prediction. Regional avalanche information provides an important starting point, but conditions at individual paths may differ and can be refined through local observations and expert judgment. The resulting ASMs are therefore intended to complement this assessment by making its spatial implications explicit, not to replace local decision-making. The workshops supported the practical interpretability and plausibility of the presented framework, but do not constitute quantitative validation. Systematic comparison with observed avalanche activity remains necessary (Winkler et al. 2024).

The basic statistics from the Brenner Pass pilot region also demonstrate how ASMs can support quantitative scenario comparison. Affected area, avalanche size and infrastructure exposure can be derived directly from the spatial outputs, making differences between operational scenarios explicit. These metrics describe the scenario representation and should not be interpreted as quantitative risk estimates.

Snowpack stability and its spatial frequency represent an additional challenge when moving from a regional assessment to individual avalanche paths. In the current framework, their influence on relative size is therefore treated as an experimental extension. Their strong spatial variability limits a direct path-specific interpretation (Schweizer et al. 2008). Future coupling with spatially distributed snowpack simulations could provide a more explicit representation of stability, weak layers and their spatial occurrence within the scenario definition.

Application in the pilot regions and transfer of selected scenarios to the wider EUREGIO demonstrate the technical scalability of the approach, but not yet full operational validity across the region. Further work requires region-wide parameterization and validation, broader scenario coverage and continued integration into operational workflows (Winkler et al. 2024).

The current implementation uses precomputed simulations to enable rapid scenario mapping, although precomputation is an implementation choice rather than a conceptual requirement. Beyond scenario-specific ASMs, the underlying terrain potential could also be communicated through simplified avalanche terrain maps as an accessible base product for training, mission preparation and rapid orientation. Such maps would provide an easy-to-interpret overview of where avalanche terrain exists and what it can potentially produce, complementing the situation-specific information provided by ASMs and serving a purpose comparable to the Avalanche Terrain Exposure Scale (Statham et al. 2006).

5. CONCLUSION

We present a framework for translating an operational avalanche scenario into spatially explicit avalanche scenario maps by combining terrain potential with scenario-specific spatial and avalanche constraints. Avalanche size provides the common interface between terrain potential, operational assessment, simulation and map representation. The distinction between *path size* and *event size* links the terrain-dependent upper limit of individual paths to the avalanche size expected under prevailing conditions.

The framework carries the harmonized size concept from size-dependent model parameterization through simulation and to spatially mapped avalanche size. Rather than assigning a single value to each avalanche, dimension, runout and destructive size can be derived continuously and represented spatially along the path. Application to contrasting dry winter and wet spring scenarios demonstrates how different expected conditions can be represented from the same underlying terrain potential. The resulting ASMs also allow scenarios to be compared quantitatively in terms of affected area, represented avalanche size and exposure of infrastructure.

Development and testing with avalanche warning services and local avalanche commissions provide a basis for further integration into operational decision-support workflows. Future work should focus on quantitative validation, improved characterization of path potential, integration of snowpack stability and its spatial variability, and broader regional scenario coverage. Simplified avalanche

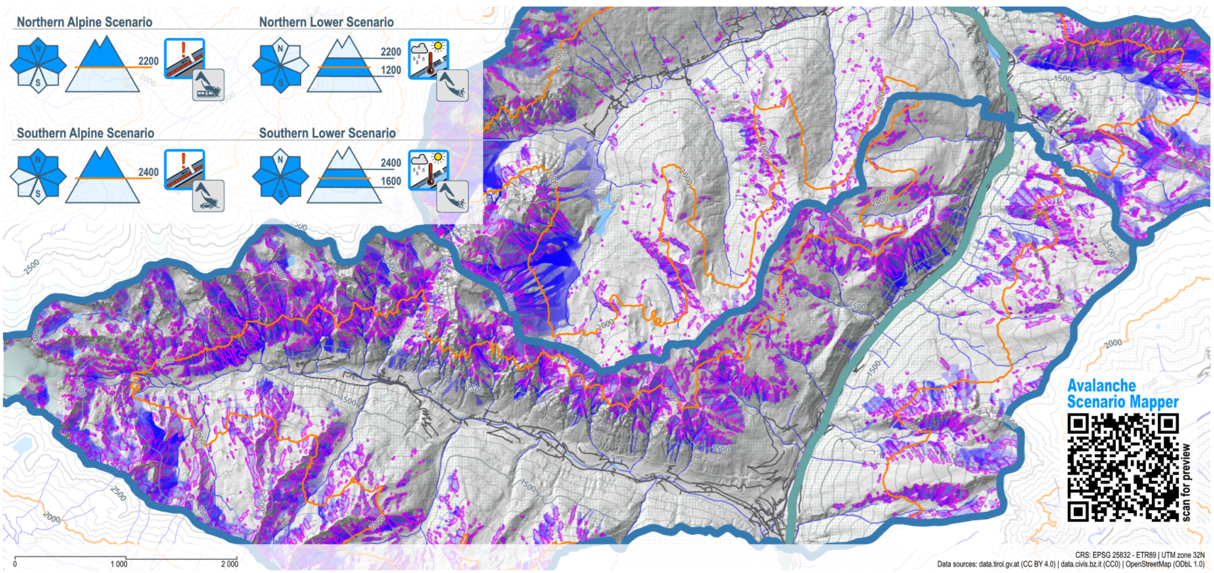

Figure 5: Example of a composite avalanche scenario across the Brenner Pass pilot region. Different spatial and avalanche constraints are combined for the northern and southern parts of the region and for different elevation ranges. The example represents higher dry snow avalanche activity in high alpine terrain and wet avalanche activity at lower elevations, demonstrating how several scenario definitions can be combined within one ASM. Elevation and aspect symbols inspired by `avalanche.report` (ALBINA project); avalanche problem icons from EAWS.

terrain maps may additionally provide an accessible scenario-independent product for training, mission preparation and rapid orientation.

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