A SPATIAL EXTRAPOLATION APPROACH TO SNOWPACK WEAK LAYER CRITICALITY ACROSS AVALANCHE RELEASE AREAS

Frédéric Pourraz[*1], Jill Chevalier[1], Alain Duclos[2,3], Gaëlle Bourgeois[4], Cédric Perillat-Merceroz[3]

[1]*LISTIC – University Savoie Mont Blanc, Annecy, France*
[2]*data-avalanche.org association, Aussois, France*
[3]*ALEA (Avalanches: Location, Research and Action), Aussois, France*
[4]*Department of Savoie – Natural Hazards Service, Chambéry, France*

ABSTRACT:

Winter road serviceability in Savoie (northern French Alps) is ensured by the Natural Hazards Service of the Department in collaboration with the consulting firm ALEA. Their operational feedback has enabled the identification and geolocation of 252 avalanche release areas and flow paths likely to impact the road network. These areas are subject to continuous monitoring throughout the winter season, based on the real-time evaluation of the five criteria of the **CRISTAL** framework.

This paper focuses specifically on the *“Weak layer criticality”* criterion, whose level is assessed using 2 main sources: observations of recent avalanche activity and performance of snowpack stability tests following the **ROMANsns** protocol, conducted several times per week all over the Savoie Department. However, this observation frequency does not allow full coverage of all 252 potential release areas. It is therefore necessary to extrapolate a criticality value for each site using data derived from spatially distant tests and/or observations. This extrapolation relies on a similarity computation incorporating various snow, meteorological, actinometric, and geospatial features. For some of these features, real-time observations and measures are insufficient; it is essential to model their temporal evolution from the beginning of the winter season. This approach makes it possible to assess whether snowpack stratigraphy across different sectors can be considered comparable. The resulting similarity is then used to estimate the *“Weak layer criticality”* criterion, at a given point in time, for each elevation band (at 100 m intervals) and for each aspect within the 252 studied areas. The **CRISTAL** method is subsequently applied to determine the required level of vigilance.

The objective of this approach is not to replace human expertise with digital tools, but to enhance it. In a context of high spatial and temporal variability in snowpack stratigraphy, this tool is intended to support experts in their decision-making or to alert them to potentially hazardous situations that they might not have identified as such. Ultimately, the goal is to promote more objective decision-making regarding operational measures to be implemented on the road network of the Savoie Department

KEYWORDS: Spatial extrapolation; Similarities; Snowpack criticality; Decision-making.

1. INTRODUCTION

Thanks to a fruitful collaboration between a research laboratory, a consulting firm, a collaborative association, and its own *”natural hazards”* department, the Savoie Department has become a driving force for innovation and improvement in avalanche danger forecasting adapted to the protection of its road network.

With a territory located predominantly in mountainous areas (nearly 1000 km of roads above 1000 m in elevation, including the sole access to some of the world’s most frequented winter sports resorts), the Savoie Department is fully confronted with the major safety issue of user exposure to avalanche risk.

Its forecasting system has naturally evolved in a multimodal way, with new equipment, new combinations of expertise, and new strategies. Indeed, beyond the massif-scale forecasting system provided by the Météo-France institution, the 252 sections of departmental road exposed to avalanches require forecasting at a local scale, in order to implement the most suitable risk reduction or elimination measures. This need is further heightened by the impact of climate change. While the well-known rise in the rain–snow line implies a significant decrease in snow depth below 2000 m in

* *Corresponding author address:*

Frédéric Pourraz
Lead partner of the Interreg ALCOTRA ***RESIL-AV*** *project*

LISTIC – University Savoie Mont Blanc
5 chemin de bellevue
74944 Annecy-le-Vieux
FRANCE

tel: +33 450 666 002
email: frederic.pourraz@univ-smb.fr

elevation, the impact is mainly qualitative above this threshold, where most large-scale avalanches liable to reach infrastructure originate. The evolution of the snowpack becomes more complex there, with abrupt cooling and warming events, melt episodes at unusual elevations, and occasionally very heavy precipitation.

On an operational level, the Savoie Department's information system relies on numerous sensor data sources (Bourgeois et al., 2026): EDF-DTG, ROMMA, Flowcapt, Arfang, and optical monitoring devices (Geoprevent, Skaping) (Barkat et al., 2024). It also relies on the ALEA consulting firm, which records recent avalanche observations daily in the data-avalanche.org association's database and carries out, over 2 days per week, snowpack stability tests for the Department, following the **ROMANsns** protocol (Pourraz et al., 2023b; Duclos et al., 2024). These tests are supplemented by two additional days in the neighboring Departments of Isère and Hautes-Alpes.

All of this data feeds daily into the **CRISTAL** decision-support approach (Pourraz et al., 2023a), enabling decisions to be made on tangible grounds and thereby limiting the influence of cognitive biases (McCammon, 2004). Initiated by the *"Obvious Clues Method"* (McCammon, 2006) and later taken up in the Avaluator (Haegeli and McCammon, 2006), the systematic evaluation of tangible, observable criteria emerged, as early as the 2000s (McCammon, 2000), as a necessity. This new paradigm was refined somewhat later with the *"Bounded Vigilance Model"* (McCammon, 2009), then taken up and expanded by data-avalanche.org (Duclos, 2012), whose primary objective is to avoid the surprise effect by characterizing 4 distinct vigilance modes.

These foundations of the **CRISTAL** approach have gained considerable maturity (Pourraz et al., 2023a), formalizing (see Figure 1) the systematic **evaluation** of 6 tangible criteria, the **analysis** of the required vigilance mode, and informed **decision-making** based on clear grounds that limit the influence of cognitive biases. This decision-making step applies both to backcountry users traveling on snow-covered terrain, and to road management (see Figure 1) and infrastructure management, targeting different types of action in each case.

In this paper, we will first present the approach adopted to continuously enhance and support the CRISTAL approach (see Section 2.). As the evaluation of the *"Temperature increase, snow thawing"* and *"New overloading"* criteria is already covered in another dedicated paper in this ISSW issue, we will focus specifically on the evaluation of the *"Weak layer criticality"* (i.e., presence and reactivity) criterion (see Section 3.). We will then discuss the final output and future perspectives (see Section 4.) before concluding (see Section 5.).

2. APPROACH

Initiated by a preliminary series of works (Pagnier et al., 2022; Pagnier, 2023), an expert system based on fuzzy subset theory (Zadeh, 1965) formalizes the rules for translating the 6 criteria of the **CRISTAL** approach into the 4 vigilance modes (Mauris et al., 2025b). This methodology thus relies on the field expertise, accumulated over many years, of ALEA and data-avalanche.org profes-

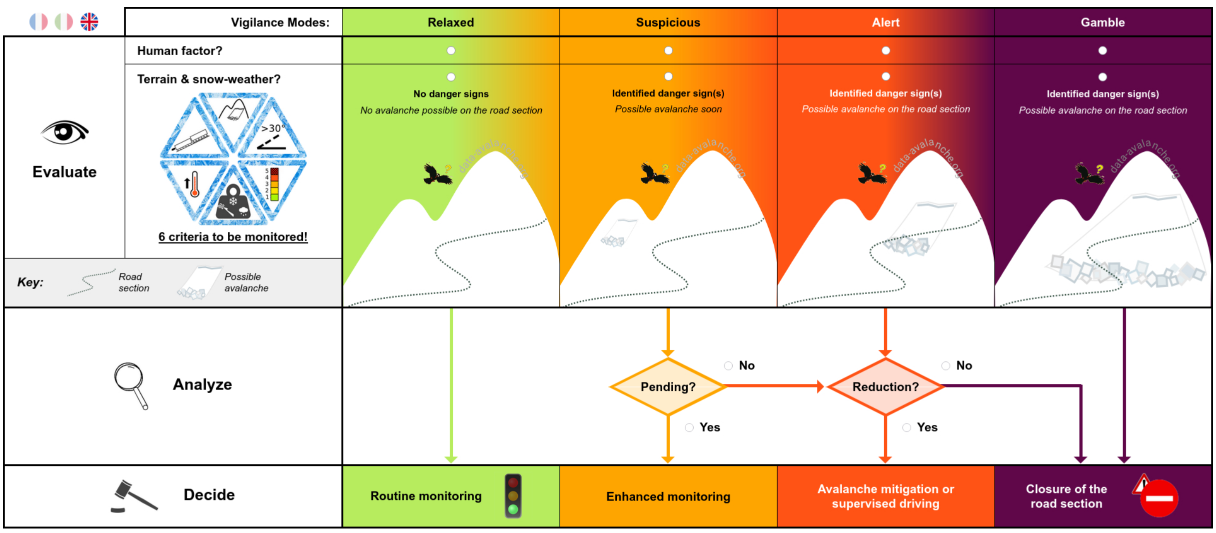

Figure 1: The **CRISTAL** decision-support framework, applied to winter road safety management.

sionals. The value of fuzzy logic is manifold:

- modeling expert knowledge and providing an easily understandable result;
- handling the notion of uncertainty that is induced by and inherent to the concept of risk;
- enabling a *"gray-box"* approach, in contrast to AI-based *"black-box"* approaches, and thereby preserving the explainability of the final result (Mauris et al., 2025a).

This last point is particularly important, as it allows for an objective justification of the final result, which can then more easily be accepted or challenged with reasoned argument by the decision-maker.

The preliminary step to this computation of the vigilance mode best suited to the situation is the evaluation of each of the system's 5 input criteria. The 6th criterion, the *"Danger level"*, refers to a careful reading of the avalanche danger assessment bulletin. It is therefore not considered a criterion in itself, but rather a means of partially assessing the other 5 criteria. It should also be noted that the *"Weak layer criticality"* criterion was previously referred to as *"Possible buried weak layer"* (Pourraz et al., 2023a) in the context of ski touring. In that context, the criterion referred to regular probing with a ski pole to assess the presence or absence of a weak layer along a route. In the context of the operational road management considered in this paper, the scope of this criterion is broader: stability tests provide a direct assessment of the reactivity of a weak layer (Duclos et al., 2024), in addition, of course, to its presence.

While the *"Temperature increase, snow thawing"* and *"New overloading"* criteria rely on the use of sensor-derived measurements, and the *"Slopes steeper than 30°"* criterion relies on the use of a DEM, the evaluation of the *"Recent avalanches observed"* and *"Weak layer criticality"* criteria requires a different approach. Indeed, the number of sensors deployed by the Savoie Department for monitoring the 252 zones, as well as the resolution of the IGN (French National Geographic Institute) DEM, allows for a relatively simple and precise computational process. Conversely, the recent avalanche observations recorded in the data-avalanche.org database cannot be exhaustive. Similarly, the few snowpack tests carried out each week by ALEA in the Savoie Department (4 to 6 tests across 2 different sectors) and in the neighboring Departments (also 4 to 6 tests across 2 different sectors) remain limited compared to the 252 zones to be assessed, distributed across the entire Department.

A relatively complex extrapolation process is therefore necessary, in order to obtain significant and operationally usable results.

The proposed approach consists of comparing the features of the zone where a snowpack stability test was performed with those of the 252 potential avalanche release areas in the Savoie Department, at a given point in time. The same principle applies in the case of an avalanche observation (features of the fracture zone). This comparison is carried out using a similarity computation, taking into account the following features:

- the elevation and aspects of the zones considered, extracted from a DEM with a 5-meter resolution;
- the accumulated rain and snow precipitation over the past hours and days, as well as since the beginning of the season, for each zone considered.

We acknowledge the limitations of the features currently considered and are working to incorporate additional features, which will be presented and discussed later in the paper (see Section 4.).

We therefore consider that the similarity, calculated on a scale from 0 to 1 as will be explained further on, makes it possible to weight the result of a snowpack test conducted in another sector of the Department, and thus to provide an assessment of the *"Weak layer criticality"* criterion for each of the 252 zones. The **CRISTAL** approach can then be implemented to determine the required vigilance mode and to make the resulting decisions.

Here again, we acknowledge that the similarity computation is not sufficient on its own. If the features of a monitored zone are 60% similar (i.e., a similarity value of 0.6) to those of a snowpack test zone, this similarity value alone does not indicate whether the monitored zone is more or less critical than the test zone. The monitored zone could be either 40% more critical or 40% less critical than the test zone. This limitation is currently being investigated and will be further discussed later in the paper (see Section 4.).

The objective here is to mimic what the Department's experts do on a daily basis, in order to reinforce their decisions or alert them to a potentially alarming situation that they might not have perceived as such.

Finally, this work is carried out as part of the Interreg ALCOTRA **RESIL-AV** project and therefore has a Franco-Italian scope. In addition to the

Savoie Department, this work will also be integrated into the information systems of the Italian regions of Valle d'Aosta and Piedmont. Among other things, this collaboration makes it possible to share sensor data, snowpack test results, and recent avalanche observations in neighboring sectors, in order to improve the granularity of the information sources.

3. EXTRAPOLATION OF THE WEAK LAYER CRITICALITY CRITERION

As mentioned previously, we will now detail the full approach for the *"Weak layer criticality"* criterion, the method being essentially identical for the *"Recent avalanches observed"* criterion.

This criterion assesses the presence or absence of a weak layer within the snowpack, as well as its reactivity/sensitivity, using the **ROMANsns** snowpack testing protocol, essentially based on a sequence of 2 CTs and one or more PSTs (Pourraz et al., 2023b; Duclos et al., 2024). At the end of these tests, the various measurements are aggregated into 4 distinct values (**Negative**, **Slight**, **Moderate**, and **Strong**) used to assess the criterion within the **CRISTAL** approach.

These are the values measured at a specific test zone, that we seek to weight using a similarity coefficient specific to each of the 252 zones of the Savoie Department. For example, if the test is rated **Moderate** and a particular zone has a similarity of 0.6, considering that this zone is more dangerous, its assessment will therefore be the fuzzy value: { 0.6_{Moderate} ; 0.4_{Strong} }.

Let us now detail this process.

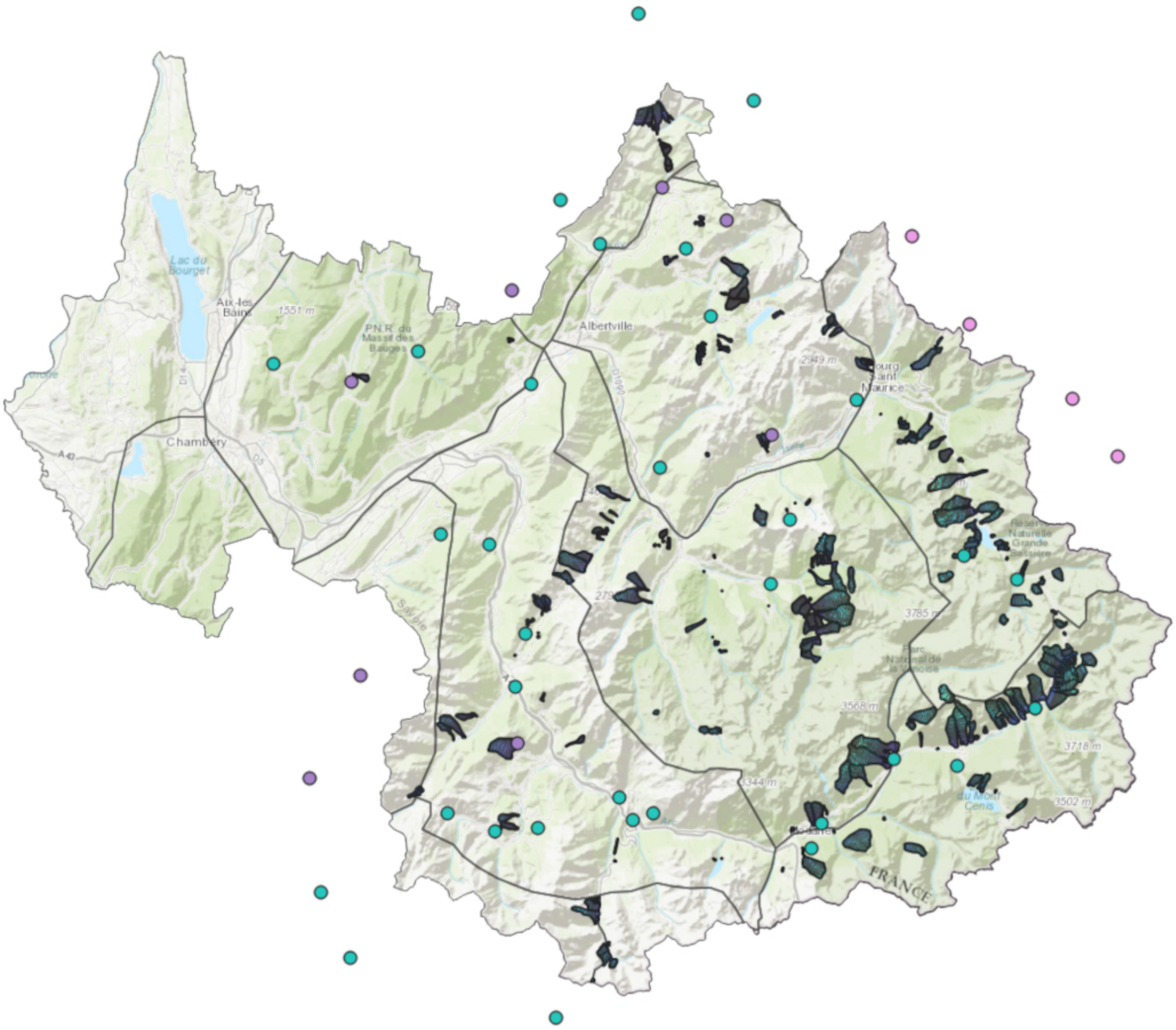

Figure 2: Overview of the 252 monitoring zones, the Alpine massifs, and the weather station network distributed across the Savoie Department (32 Météo-France stations in light blue, 4 stations in Italy from the Centro Funzionale della Valle d'Aosta in pink, and 8 ROMMA stations in purple).

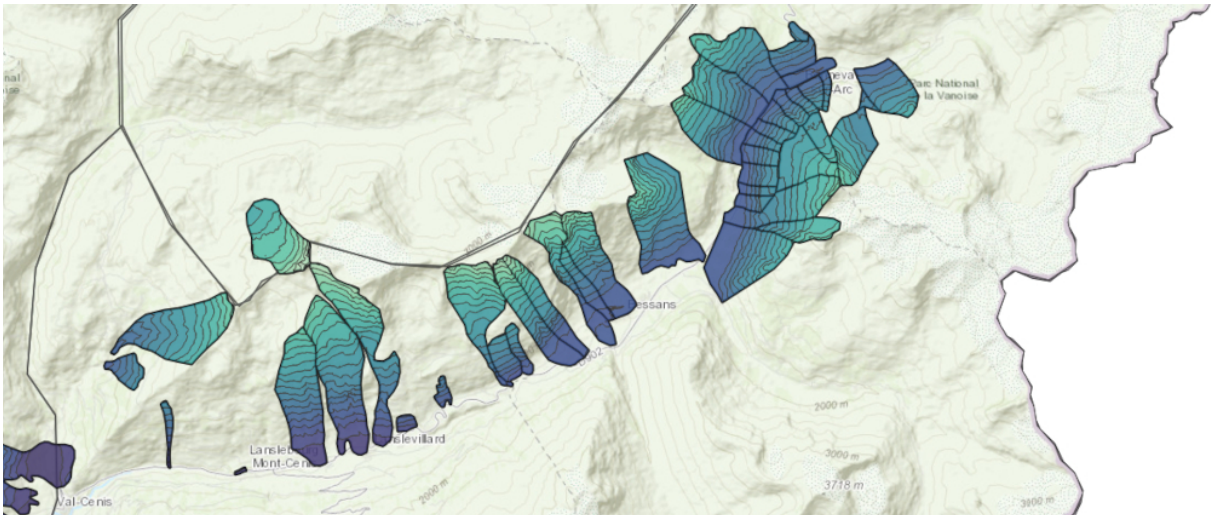

Figure 3: Focus on the zones and sub-zones of the Haute-Maurienne massif, on the eastern side of the Savoie Department. The sub-zones are colored using a blue gradient, with dark blue representing low elevations and light blue representing high elevations.

3.1. Input data

First, our algorithm requires topographic data for each of the 252 zones, whose elevation ranges from 700 to 3700 meters. Each zone is represented by a polygon (see Figure 2) and is then divided into sub-zones (sub-polygons) in 100-meter elevation increments (see Figure 3). Each zone and sub-zone is characterized by its geographic coordinates (latitude and longitude), its average elevation, and the full set of aspects that compose it. Similarly, in order to be able to associate various meteorological data with it, it is necessary to associate it with geographic features — for example, for France, this means the alpine massif and the Department, Savoie in this particular case, although our algorithm remains generic.

Next, our algorithm requires weather data. We combine precipitation data with the rain–snow line to determine the precipitation type (rain or snow). Precipitation data consist of hourly measurements in millimeters, collected from automatic weather stations operated by different providers (Météo-France, ROMMA, and Valle d'Aosta; see Figure 2). The rain–snow lines for the Savoie Department are provided by Météo-France through their daily avalanche reports. Each Alpine massif has its own report, resulting in different rain–snow line time series for each massif. Since the rain–snow line is provided every 6 hours, the hourly precipitation time series are resampled to a 6-hour time step.

Finally, snowpack data come from our database of **ROMANsns** stability tests. Like the monitoring zones, each snow test is characterized by geographical coordinates, elevation, aspect, and, of course, one of the 4 criticality values described above. Snowpack data are considered the reference data for our algorithm: they correspond to geographic points where the criticality of the weak layer is known and from which the extrapolation (similarity) is performed.

3.2. Similarity computation

Similarity is used to quantify the degree of correspondence between two vectors, which represent the feature vectors in our case. Here, similarity is defined as 1 minus the normalized Euclidean distance between the two vectors (see Equation 1), so its values range from 0 (the vectors are far apart and have no similarity) to 1 (the vectors are very close and are highly similar). Similarity is computed between a reference point, corresponding to a stability test, and each monitoring zone.

$$S(p,q) = 1 - \frac{1}{\sqrt{N}} d(p,q) \tag{1}$$

Similarity formula between two vectors p and q, where N is the dimensionality of the vectors and $d(p,q)$ denotes the Euclidean distance between p and q.

To characterize each site and represent it as a vector, we use elevation, aspect, and snow and rain accumulations over different time horizons. Each feature is normalized to a value between 0 and 1 before being used in the similarity computation. The normalization currently used is a simple min–max normalization (see Equation 2).

$$x_{norm} = \frac{x - x_{min}}{x_{max} - x_{min}} \quad (2)$$

Min-max normalization formula of a feature x where x_{min} and x_{max} denote the minimum and maximum allowed values, respectively. Values below x_{min} are clipped to 0, while values above x_{max} are clipped to 1.

3.3. Feature normalization

Elevation

Snowpack stability tests and sub-zones are characterized by their elevation, expressed in meters. For the similarity computation, the relevant parameter is the elevation difference between the reference point (i.e., the stability test) and each sub-zone. Based on discussions with experts regarding how they extrapolate snowpack stability observations, we chose to bound the normalization range to $x_{min} = 0m$ and $x_{max} = 500m$ (see Equation 3). This reflects the assumption that snowpack stability cannot be reliably extrapolated beyond an elevation difference of 500 meters.

Consequently, in the resulting vectors used to compute similarity, the reference point always has a value of 1, while each sub-zone is assigned a value between 0 and 1 depending on its elevation difference from the reference point.

$$Z_{x,norm} = |Z_x - Z_{ref}|/\Delta \quad (3)$$

Normalization formula for the elevation feature, where Z_x and Z_{ref} denote the elevations of the sub-zone and the reference point, respectively, and Δ is the maximum elevation difference x_{max}, with $x_{min} = 0m$.

Aspect

Aspect is represented using discrete values : North = 0°, Northeast = 45°, East = 90°, Southeast = 135°, South = 180°, Southwest = 225°, West = 270°, Northwest = 315°. The reference point is associated with a single aspect value, whereas a sub-zone may encompass a range of aspect values, as its polygonal geometry can span multiple aspects depending on the local topography.

To normalize aspect, the angular difference between the reference point and the sub-zone is first computed, resulting in a value between 0° and 180°. The cosine of this angular difference is then computed (see Equation 4) to obtain the normalized value.

$$\theta_{norm} = \cos(|\theta_x - \theta_{ref}|) \quad (4)$$

Normalization formula for the aspect feature, where θ_x and θ_{ref} denote the aspects of the sub-zone and the reference point, respectively, and θ_{norm} is the normalized value between 0 and 1.

The use of the cosine function, rather than directly normalizing the angular difference between the two aspects, introduces a nonlinear relationship between aspect difference and the normalized value. This ensures that adjacent aspects are assigned more similar values. With this approach, θ_{norm} is always equal to 1 when the sub-zone and reference point have the same aspect, while opposite aspects result in a value of 0.

Snow and rain accumulations

Automatic weather stations measure precipitation, including snow and rain, on an hourly basis at each station location. To estimate precipitation at the reference point and monitoring zone locations, the station measurements are spatially interpolated. The interpolation method used here is barycentric interpolation based on a Delaunay triangulation. Once the precipitation time series have been interpolated, rain and snow time series can then be derived for each reference point and sub-zone using the elevation of the location and the rain–snow line, which is available at 6-hour intervals (see Section 3.1.).

Including hourly time series in the similarity computation would substantially increase the number of dimensions without necessarily improving discrimination. Therefore, cumulative precipitation values are computed over different time horizons to keep the dimensionality under control. To account for the influence of snowfall and rainfall over the short, medium, and long term, the following time horizons are considered: 6 h, 12 h, 18 h, 24 h, 36 h, 48 h, 60 h, and 72 h for the short term; 96 h, 120 h, 144 h, and 168 h for the medium term; and cumulative totals since the beginning of the season for the long term.

Precipitation values over the different time horizons are also normalized using min–max normalization, with a fixed lower bound of 0 and an upper bound derived empirically from historical data rather than from a fixed theoretical maximum. This upper bound is computed as follows. Precipitation time series spanning from October 15 of year $n-1$ to May 15 of year n are collected, covering the entire winter season (November 1 to April 30), with an additional 15-day buffer before and after the season. For each calendar date within the winter period, a fixed 31-day window centered on that date, extending 15 days before and 15 days after, is extracted, regardless of the time horizon considered. Within each window, rolling precipitation sums are computed for each time horizon of interest. Rather than using the overall maximum of the resulting distribution as the normalization bound, which would make the normalization overly sensitive to rare extreme events, the 90^{th} percentile is used instead (see Equation 5). This provides a more robust upper bound that reflects typical high-accumulation conditions while reducing the influence of outliers.

This computation is performed independently for each historical year, yielding one P_{90} value per time horizon and per year. The final threshold used for normalization is then obtained by averaging the P_{90} values across all historical years, separately for each time horizon.

$$X^h_{norm} = X^h / P^h_{90} \quad (5)$$

Normalization formula for the snow and rain accumulations features, where X^h is the accumulations of snow or rain for the time horizon h, P^h_{90} is the corresponding threshold value and X^h_{norm} denotes the resulting normalized accumulation value for the time horizon h.

The full-season horizon is treated as a special case. For each calendar date within the winter period, cumulative precipitation from the beginning of the season up to that date is computed. Because this results in a single cumulative value for each date rather than a distribution of values for a given horizon, a P_{90} value cannot be computed. Instead, the maximum cumulative precipitation reached during the season is used as the upper bound. As for the other time horizons, this value is computed independently for each historical year, and the final threshold is obtained by averaging these annual maxima across all years.

3.4. Final extrapolation

After the normalization process, each location (reference point or sub-zone) can be represented by a 28-dimensional feature vector comprising elevation, aspect, 13 snow accumulation values, and 13 rain accumulation values. The snow and rain accumulation values are each weighted by $\frac{1}{13}$, so that the overall contribution of each accumulation feature is equal to 1, as for elevation and aspect. To account for the potentially complex topography of the sub-zones, the similarity computation (see Section 3.2.) is performed for all possible aspects of each sub-zone.

We ultimately obtain between 1 and 8 similarity values for each sub-zone, depending on the number of aspects represented by its topography. These values are then converted into fuzzy values based on the result of the test at the reference point. They are subsequently incorporated into the final **CRISTAL** computation as input values for the *"Weak layer criticality"* criterion.

4. DISCUSSION & PERSPECTIVES

The **RESIL-AV** project began in September 2025 and will run until September 2028. This paper therefore presents the foundations of an approach that will be progressively refined and expanded over the course of the project.

Starting from the features currently considered, we performed a similarity analysis for each feature individually. This allowed us to better understand the impact of the normalization process and to determine whether one or more features had a disproportionate influence compared with the others. We found that elevation frequently emerged as a dominant feature in the final similarity score. However, part of the elevation effect is already implicitly captured by the precipitation measurements through the rain–snow line.

We hypothesize that incorporating a radiative component into the current set of features could ultimately eliminate the need to explicitly include elevation. Indeed, an irradiance estimate at each point of the DEM could capture the effect of elevation while also accounting for variations in snowpack temperature. Similarly, irradiance could incorporate the effect of aspect, which is currently used as a simplified proxy for irradiance.

As mentioned above, similarity alone cannot determine whether a monitored zone is more or less critical than the test zone. We are therefore investigating the use of displacement vectors alongside the distance measure to account for differences in precipitation and irradiance variations between the two zones being compared. Combining these vectors should allow us to determine the direction of the difference in criticality.

5. CONCLUSION

This paper introduced an operational approach for extrapolating the *"Weak layer criticality"* criterion of the **CRISTAL** decision-support framework across the 252 avalanche release areas monitored by the Savoie Department. By representing stability tests and monitoring sub-zones as normalized feature vectors comprising elevation, aspect, and precipitation accumulations, sparse **ROMANsns** stability test results can be propagated to areas that cannot be directly and continuously monitored, thereby producing a fuzzy criticality value consistent with the **CRISTAL** framework. This "gray-box" approach preserves the level of explainability required for experts to understand and, when necessary, challenge each assessment in the context of winter road safety management.

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