SYSTEMATIC EVALUATION OF THE LOCAL CRITICALITY OF RECENT OVERLOADS AND TEMPERATURE EFFECTS TO MITIGATE AVALANCHE RISK FOR TRAFFIC ROADS

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ABSTRACT: The closing of roads due to snow avalanches is a common issue in mountainous regions during winter. The decision to temporarily restrict traffic access to avalanche-exposed roads often relies on human expertise, fed by a large variety of parameters. The diversity of information nature and sometimes the scarce availability of local data can therefore induce a very complex decision-making process, prone to oversights. Developed and practiced for about two decades, a decision-making support process called **CRISTAL** (ISSW 2023) is now subject to research studies. This approach is based on the criticality of five criteria: topography, current avalanche activity, weak layer properties, recent overloads and temperature effects. It has recently been upgraded to a hierarchical expert system (involving multiple levels of aggregation) based on fuzzy logic, which properly handles the approximate truth coming from scattered field measurements and observations. The system outputs a vigilance mode (*relaxed* / *suspicious* / *alert* / *gamble*) depending on the criticality of the five criteria. So far, the evaluation of each criterion is done manually by the user, who must personally seek information about the current conditions. To make the system more operational in three French alpine departments (Savoie, Isère, Hautes-Alpes), we aim to automatically gather all available information and process them to assess criticalities in real time for specific slopes. We present here a part of the up-to-date expert system that deals with the meteorological data available in the French Alps. This subsystem, part of the first aggregation level, delivers a level of criticality for the criteria of recent overloads and temperature effects (the parts concerning the other criteria will be treated in separate works). First, the subsystem estimates weather-related variables at the slope scale, such as snow surface temperature, thawing, and recent overloads due to fresh snow, wind-blown snow or rain. Once the local variables are assessed, they are each assigned a fuzzy value (e.g. the amount of fresh snow can be *none* / *low* / *moderate* / *high*) and processed through a set of fuzzy rules to deliver a level of criticality (e.g. a leeward slope after a strong wind-transport event raises a high criticality for the recent overload criterion).

KEYWORDS: Avalanches, Traffic roads, Criticality, Expert system, Fuzzy logic.

1. INTRODUCTION

Snow avalanches are a major hazard for transportation infrastructures in mountainous regions. During the winter season, roads located below avalanche paths can be temporarily exposed to danger, typically following intense snowfall or rainfall, or during spring season when warming temperatures can trigger snowpack instabilities. Traffic restriction remains the most flexible mitigation option when structural or active defenses are insufficient. However, unnecessarily long closures can have important economic and social consequences. These restrictions are traditionally decided by local experts, who combine terrain knowledge, real time observations and snowpack monitoring to assess the situation for a given road section. Such expertise is essential because avalanche release results from the interaction of multiple factors and processes acting at different spatial and temporal scales.

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An additional difficulty is the heterogeneity of available information. Some features are measured continuously at automatic weather stations, whereas others are only observed during manual field probing. Moreover, measurements are often unevenly distributed spatially, and similarly, avalanche stability may vary considerably between adjacent slopes with different elevation, aspect and wind exposure. The decision process thus requires both interpretation of heterogeneous observations and extrapolation from measurement locations to the slope of interest.

From the expert perspective, a purely numerical description of each process and feature is therefore not necessarily appropriate for operational decision-making. Instead, the expert will usually reason through a qualitative description of the situation (e.g. *rapid* warming, *a bit of rain*, *very reac-*

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tive weak layer, …) to eventually make a decision.

With this aim, the **CRISTAL** approach (Duclos 2012; Pourraz et al. 2023a), was developed to structure this decision-making process around six observable and concrete criteria: *Slopes steeper than 30°*, *Recent avalanche observed*, *Possible buried weak layer*, *Temperature increase / Snow thawing*, *New overloading* and *Danger level*. The objective of this framework is to systematically estimate a so-called Vigilance Mode (*Relaxed*, *Suspicious*, *Alert* or *Gamble*) at a given location and in real time from the six criteria. This estimation is done by a rule-based system using fuzzy logic. Unlike binary logic (0 or 1), fuzzy logic uses degrees of truth ranging from 0 to 1 to mimic human-like reasoning and decision. The current stage development of **CRISTAL** consists in the aggregation (or combination) of the six criteria to estimate the vigilance mode (Pagnier 2023; Mauris et al. 2025b). The rules that are used to do this aggregation formalize the reasoning of an expert. In the formulation, the use of linguistic values such as *low*, *moderate* or *strong* allows gradual information to be handeled without requiring precise quantitative methods.

So far, the user of the system needs to assess manually each criteria so the system can estimate the vigilance mode. In order to help experts with taking the appropriate decision at the right time, the present work is part of an effort to automate the estimation of five out of the six criteria – the danger level being left out, as it refers to a careful reading of the avalanche danger assessment bulletin produced daily, it is thus not a criterion in itself but rather a mean of partially evaluating the other five criteria. The objective is not to replace the expertise itself, but rather to systematically gather available information, transform it into relevant features and provide a transparent assessment of the criticality of each criterion. The system is being developed for application to avalanche-exposed roads in the French departments of Savoie, Isère and Hautes-Alpes.

This work focuses on the two criteria that are influenced by recent meteorological conditions: *Temperature increase / Snow thawing* and *New overloading*. The temperature criterion accounts for near-surface warming, snow humidification and melting, and the stabilizing effect of melt-freeze crusts. The overloading criterion considers the additional loading brought by fresh snowfall, rain and wind-drifted snow. The other criteria of **CRISTAL** are outside the scope of this paper and will be treated in separate works.

2. METHODS AND DATA

The proposed subsystem follows three successive stages (Fig. 1). First, meteorological and snowpack information is collected from several heterogeneous sources. Second, the measurements are standardized and spatially transposed to the specific slope of interest. Finally, the resulting variables are converted into fuzzy linguistic values and processed using expert rules to produce a criticality level for each criterion.

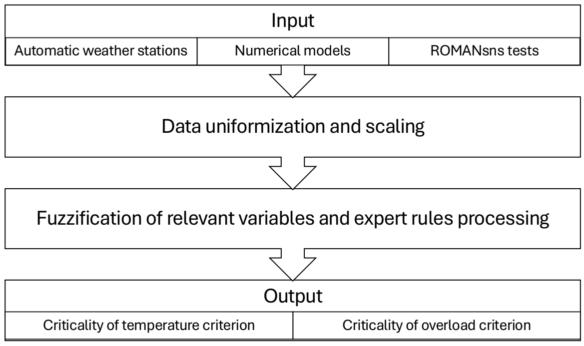

Figure 1: Structure of the system assessing the temperature and overload criteria

Each criterion is broken down into several sub-criteria representing the different processes involved. Each sub-criteria is itself assessed through a specific subsystem (Sections 3 and 4).

2.1. Sources of data

Three main sources of data feed the system, each contributing to the evaluation of an input variable associated with each feature.

Automatic weather stations provide the backbone of the meteorological input thanks to a relatively dense mesh in the monitored area. Two main networks of stations are currently in use: Météo-France stations, and so-called FlowCapt stations owned by the Departments' road administration. Météo-France stations provide a reliable basis for standard variables such as air temperature, wind velocity and precipitations, generally at valley-bottom or mid-elevation sites. FlowCapt stations complement this network at higher elevations, but with a coarser mesh. FlowCapt stations are also equipped with acoustic drift sensors that measure wind blown snow over a 2-meters height. In addition, they have two snow height sensors (Bourgeois et al. 2013) placed at contrasting locations: one on an exposed ridge and one nearby on the leeward side. The differential accumulation measured between these two sensors provides a direct, local proxy for wind transport, which is otherwise difficult to capture from standard stations. All FlowCapts stations also provide measurements of the snow surface temperature (Bourgeois et al. 2026).

Meteorological models are used for variables for which a coarse resolution is sufficient. In the present system, they are mainly used to estimate the cloud cover – a variable required to estimate the radiations driving snow surface temperature – and the freezing level to assess whether the precipitations are rather solid or liquid. In order to get the most reliable data, models with a low temporal resolution and update frequency are prefered. In our case, the model AROME-PI (Auger et al. 2015) is currently used.

ROMANsns stability tests (Duclos et al. 2024; Pourraz et al. 2023b) provide punctual but detailed snowpack information, including full snow profiles and temperature measurements over the whole depth. Currently, at least 4 **ROMANsns** tests are performed per week over the monitored area during winter. While sparser in space and time than the other sources, these observations are used as a solid complementary input when available.

2.2. Data standardization and spatial transposition

Because these sources differ in format, temporal resolution, spatial coverage, and measurement type, a standardization step is required before any variable can be used consistently across the study area. Raw measurements from all sources are converted to common units and time steps and organized into a unified set of variables (temperatures, wind speed/direction, amount and type of precipitation, snow height, snow drift indicator, cloud cover).

Two complementary strategies are then used to transpose station-based or grid-based measurements to the scale of a specific slope, depending on the spatial variability of the variable considered. For variables that vary smoothly over space, such as air temperature, values are spatially interpolated using standard methods accounting for elevation and, where relevant, aspect. Among the tested methods, inverse distance weighting with elevation-correction provided the best compromise between prediction accuracy, computational cost and robustness, and was therefore selected for operational use. For variables with strong local variability driven by terrain exposure – most notably the wind – the closest relevant measurement is instead used directly. It is manually selected according to the exposure similarity between the measurement point and the target slope (e.g., preferentially using a leeward-facing sensor to inform a leeward-facing slope), rather than relying on interpolation, which would smooth out the very contrasts that matter for this criterion. Topographical features (elevation, slope angle, aspect) are therefore used throughout this stage to adjust raw measurements to the local terrain configuration of the targeted slope.

2.3. Fuzzy representation and hierarchical aggregation

The physical variables estimated during the preceding stages are represented using linguistic categories rather than being directly converted into a single deterministic threshold. Each category is defined by a membership function over the numerical range of the variable. For example, the amount of snow fallen during a snowfall event is described as *Low*, *Medium* or *High* (Fig. 2), depending on the precipitation height of the event. The boundaries between these categories are not necessarily abrupt: a given value can simultaneously have a partial membership in two adjacent categories (e.g. in Fig. 2, a value of 38 mm gives a criticality of 0.2 *Medium* and 0.8 *High* for this parameter). This allows the transition between different levels of criticality to be gradual rather than determined by a single threshold.

The fuzzy system then combines these variables (Figs 3, 4) using rules formulated from expert knowledge. This is particularly suitable for avalanche decision support because many relationships are qualitative rather than governed by deterministic thresholds. Each parameter is assigned its own criticality level. They are then aggregated to assess the criticality of the sub-criteria, which are in turn aggregated into the final criteria, also using expert rules. Finally, these criteria form part of the higher-level **CRISTAL** aggregation, leading to a vigilance mode (Pourraz et al. 2023a; Mauris et al. 2025b).

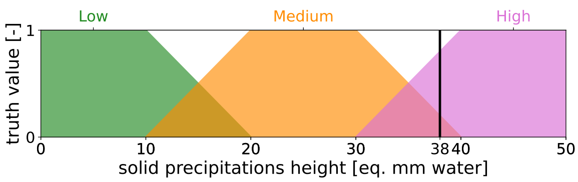

Figure 2: Example of a parameter fuzzification. A value of 38 mm for the *Solid precipitations height* gives a truth value of 0.2 *Medium* and 0.8 *High*.

The advantage of this architecture is that every output can be traced back to physical variables and explicit rules. The system can consequently provide not only a criticality level but also an explanation of which meteorological conditions led to that assessment (Mauris et al. 2025a).

3. CRITICALITY ASSESSMENT OF THE TEMPERATURE CRITERION

The criterion *Temperature increase / Snow thawing* is estimated through a fuzzy system (Fig. 3) structured around three independent sub-criteria: *Temperature increase*, *Humidification and melting* and *Stability from melt-freeze crust*. Each of these sub-criteria captures a different mechanism through which temperature influences snowpack stability.

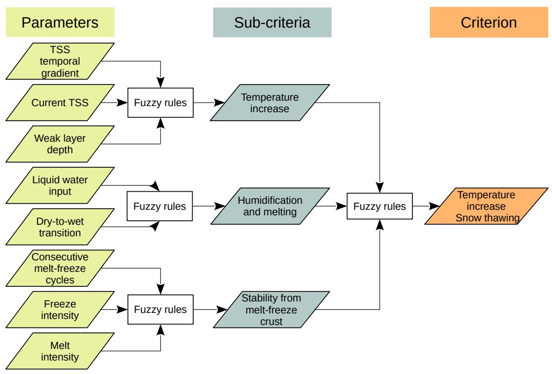

Figure 3: Subsystem assessing the criticality of the temperature criterion

3.1. *Increase of snow surface temperature*

The rapidity of the temperature increase of the snowpack surface is a factor promoting instability according to many experts (Landrø et al. 2020; Reuter and Schweizer 2012). The most admitted explanation is that the elastic modulus – or stiffness – of a snow slab decreases with an increasing temperature, especially from -5°C (Schweizer and Camponovo 2002). Therefore, an increase in the snow surface temperature promotes the deformation of the superficial snow – about the top 30 cm (Exner and Jamieson 2008) – promoting strain rates, energy release rates and therefore instability (Schweizer and Jamieson 2010).

We consider here three parameters: the snow surface temperature (TSS) temporal gradient, the current TSS and the depth of the weak layer.

The temporal gradient is evaluated over a short time window, currently defined as six hours. A rapid increase is assigned a higher fuzzy value, whereas a stable or decreasing temperature is assigned a low or null value. A threshold of approximately +2°C/h is considered as an initial reference for a significant rapid warming signal, consistent with existing expert-oriented approaches (Harvey et al. 2023; Schweizer et al. 2003; Schweizer and Jamieson 2010). The current TSS modulates this effect: a rapid increase reaching temperatures close to or above -5°C is considered more critical than the same increase while the snow remains very cold. Finally, the depth of the weak layer provides a measure of whether the warming is likely to affect the potentially reactive part of the snowpack. A shallow weak layer is therefore associated with a greater potential effect than a deep weak layer.

This formulation deliberately avoids interpreting a rapid surface-temperature increase as intrinsically dangerous. Its criticality depends simultaneously on the absolute temperature and on the depth of the potentially affected weak layer.

3.2. *Humidification and melting*

An important amount of liquid water in the snow cover, coming either from melting or rain, is a well known driver of instability. Above a certain content threshold, liquid water favors the rounding of ice grains, rapidly degrading the mechanical strength of the affected layer (Mitterer et al. 2011; Techel et al. 2011). Here, two parameters are considered: the liquid water input and the thermal state of the snowpack relative to its first significant dry-to-wet transition. The second parameter distinguishes three states: (i) the snowpack is dry and has not previously undergone a significant wetting event, (ii) the snowpack is currently undergoing its first significant dry-to-wet transition, (iii) a significant transition has already occurred.

The distinction between ongoing and past wetting is important because the first transition to wet conditions can be associated with a rapid decrease of the snow strength and more instabilities (Lipkowitz et al. 2023; Techel et al. 2011).

The fuzzy rules assign a strong criticality when either liquid water input is high or a first dry-to-wet transition is ongoing. A smaller liquid-water input in an otherwise dry snowpack gives a medium criticality, while other combinations are considered safe.

Rain is included here only with respect to its contribution to liquid-water input. Its additional mass loading is treated independently in the overload criterion (Section 4).

3.3. Stability from melt-freeze crust

Melt-freeze cycles form a surface crust, typically during the spring season, which provides strength to the snowpack and therefore provides more stability. This sub-criterion therefore estimates the development of a melt-freeze crust from three parameters: the number of consecutive melt-freeze cycles, the melt intensity and the freeze intensity.

A cycle is detected from the snow surface temperature as a period during which TSS exceeds 0°C followed by a period below 0°C. Several consecutive cycles are interpreted as evidence for progressive crust development. However, the number of cycles alone is not sufficient: a small number of intense melt-freeze cycles may produce a substantial crust, whereas cycles with a high melt intensity and a low freeze intensity may have a limited effect.

The rules produce three stabilizing levels. A large number of cycles produces the stronger stabilizing contribution. A smaller number of cycles can also produce a strong stabilizing contribution when both melting and freezing are sufficiently intense. Less intense cycles produce a weaker stabilizing effect.

3.4. Assessment of the temperature criterion

The three sub-criteria do not have equivalent roles in the expert assessment. The relative importance of *Temperature increase*, *Humidification and melting* and *Stability from melt-freeze crust* is therefore explicitly encoded through a set of expert rules (Table 1). In particular, humidification and melting are considered more destabilizing than surface warming alone, while the development of a melt-freeze crust provides a stabilizing effect. The rules combine the criticality levels of the three sub-criteria to produce the final criticality of the temperature criterion. A strong humidification/melting signal combined with no stabilizing crust leads to a *Critical* assessment, whereas a strong warming signal alone generally leads to an *Of Concern* assessment. Conversely, a strong stabilizing contribution from a melt-freeze crust can counterbalance moderate signals of instabilities. The complete set of input combinations and resulting criticality levels is given in Table 1.

4. CRITICALITY ASSESSMENT OF THE OVERLOADING CRITERION

This criterion aims to quantify the mass input onto the snowpack, increasing the stress applied on potentially weak layers, and thus favoring the release of slabs. The criticality is also assessed here through a fuzzy system fed by meteorological data. The *New overloading* criterion is broken down into three independent sub-criteria: *Snow overloads*, *Rain overloads*, and *Wind-drifted snow overloads*. Measurements of precipitations, snow heights, wind and snow transport are used. The system detects and analyses events occurring during the previous ten days. Each snowfall, rainfall and wind-transport event is evaluated independently.

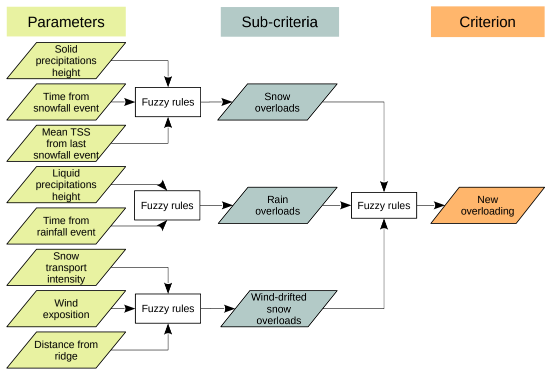

Figure 4: Subsystem assessing the criticality of the overloadings criterion

4.1. Snow overloads

This sub-criterion estimates the criticality of the loading brought by recent snowfalls. It is assessed from the following parameters: precipitation height of recent snow, time since the end of the event and mean TSS since the event. Fresh snow height is estimated from precipitation measurements, elevation and freezing-level information. If the wind during the precipitation event was not significant to induce snow transport, measurements of snow height can also be used. The criticality increases with fresh-snow height and decreases with time elapsed since the end of the precipitation event. This accounts qualitatively for the progressive settling and bonding of new snow onto the old snow cover. The mean snow temperature is used to adjust the time needed for the fresh snow to settle and stabilize. Indeed, warmer temperatures are considered to encourage stability during and after a snowfall event.

4.2. Rain overloads

Similarly, rain events contribute to the additional mass brought on the snowpack. Here, only two parameters are considered: the amount of liquid precipitations and the time since the rain event. We consider that rainfall events are mostly critical

Table 1: Expert rules assessing the criticality of the temperature and overload criteria from the criticality of their correponding sub-criteria. Each sub-criteria can take a *Low*, *Medium* or *Strong* value, while the criteria are assigned a *Safe*, *Of concern* or *Critical* value.

Sub-criteria			**Criterion**
Temperature increase	*Humidification and melting*	*Stability from melt-freeze crust*	*Temperature increase Snow thawing*
Any	Strong	Null	Critical
Any	Strong	Medium	Of concern
Any	Medium	Null	Of concern
Strong	Null or Medium	Null or Medium	Of concern
Medium	Null or Medium	Null	Of concern
	Other combinations		Safe
Snow overloads	*Rain overloads*	*Wind-drifted snow overload*	*New overloading*
Strong	Any	Any	Critical
Any	Strong	Any	Critical
Any	Any	Strong	Critical
Medium	Medium	Low	Critical
Medium	Low	Medium	Critical
Low	Medium	Medium	Critical
Medium	Medium	Medium	Critical
Medium	Low	Low	Of concern
Low	Medium	Low	Of concern
Low	Low	Medium	Of concern
	Other combinations		Safe

while the event is ongoing. Therefore, a few hours after the end of the event, the system outputs a null criticality. During the event, the output criticality increases with the intensity of the precipitations.

4.3. Wind-drifted snow overloads

To estimate the highly complex process of snow redistribution by wind, we consider three parameters: the intensity of the snow transport, the wind exposition of the slope and the proximity of the slope with a ridge. Two approaches are used to assess the intensity of the snow transport, depending on the availability of FlowCapt measurements. When a representative FlowCapt is available, this parameter is directly estimated from the measured wind transport. When no FlowCapt is available, a dedicated subsystem estimates wind transport from snow erodibility, wind velocity and previous transport events. In that case, a crusted or wet snow surface is assumed to produce little or no transport. For dry snow, we consider that transport can start at approximately 15–20 km/h for light snow and 20–25 km/h for heavier, more cohesive snow. Previous transport events are also considered, since exposed areas may progressively lose their transportable snow. Additionally, we consider that at very high wind velocities (>80–100 km/h), the transported snow may disappear in the atmosphere, bringing the wind-transport variable to a low value.

Another dedicated subsystem assesses wind exposure by processing the angle between the direction of the prevailing wind and the orientation of the slope. Accumulation is expected preferentially on the leeward side, particularly if the slope is located near a ridge. For winds crossing the slope, significant accumulation may instead occur in thalwegs and local terrain depressions. Outside these relatively simple configurations, the location of deposition becomes more uncertain. The highest criticality is assigned to this sub-criteria when significant transport is detected (or estimated) and directed towards a leeward slope close to a ridge.

4.4. Assessment of the overloading criterion

The three sub-criteria are combined through a set of expert-defined rules (Table 1), reflecting the relative contribution of snow, rain and wind-drifted snow to the overall overload. A *Strong* criticality in any one of the three sub-criteria is sufficient to produce a *Critical* assessment of the *New overloadings* criterion. Combinations of two *Medium* sub-criteria also lead to a *Critical* assessment, accounting for the cumulative effect of different loading mechanisms. A single *Medium* sub-criterion results in an *Of Concern* value, while all other combinations are considered *Safe*. These rules therefore explicitly formalize the expert reasoning that a recent overload can become critical either because of one particularly significant loading event or through the combination of several moderate events.

5. DISCUSSION

The main challenge of the proposed approach lies in combining heterogeneous sources of information and extrapolating them to the scale of an individual avalanche slope. Most variables cannot be directly combined without a substantial standardization step. This effort is nevertheless necessary, as the more relevant information available, the more constrained and potentially accurate the local estimation becomes. The objective is therefore not to identify a single ideal data source, but to keep the system flexible in order to combine complementary observations while accounting for their respective limitations. The system must also remain sufficiently flexible to accommodate different types of observations and to be transferable to other regions. The current implementation mainly relies on automatic weather stations, FlowCapt measurements and **ROMANsns** tests, as these are the main data available in our area of study. But the architecture does not need to be restricted to these sources. Depending on the region, additional information could include ski-patrol reports, independent field measurements, observations from forest services or road operators, or other local monitoring systems. Such adaptability is particularly important for operational applications, where data availability can vary considerably from one area to another. As part of the French–Italian **RESIL-AV** project, the system developed under the constraints of French data is currently being extended to accommodate the specific characteristics of Italian data.

Another challenge lies in the fact that some of the estimated variables are associated with a significant uncertainty. Wind-drifted snow is a particularly challenging example because transport and deposition are strongly controlled by local terrain and snow-surface conditions. A measurement at one location cannot always be reliably extrapolated to another slope, even over a short distance. In such situations, numerical simulations of wind flow and snow transport could eventually complement the empirical approach and provide a better representation of spatial variability. Similarly, the extrapolation of snow surface temperature could benefit from physically based simulations using the surface energy balance, particularly when direct snow surface temperature measurements are unavailable. Such approaches could improve the spatial consistency of the estimated variables, although their additional complexity and computational cost must be considered for operational use. **ROMANsns** stability tests are therefore particularly valuable within the system. Although they are sparse compared with meteorological measurements, they provide information that cannot be obtained from weather data alone, including snowpack structure, weak-layer characteristics and temperature profiles. Their integration helps constrain variables such as snow surface erodibility, dry-to-wet transition of the snowpack or the depth of the weak layer.

Finally, modeling the system as a set of fuzzy systems and subsystems is well suited to this application because the available information rarely justifies highly precise numerical predictions. Its main advantage is not numerical accuracy but interpretability and explainability. Linguistic variables and explicit rules allow the system to express how different observations contribute to a criticality level, while naturally accommodating uncertain or approximate inputs. The resulting assessment should therefore not be considered a replacement for expert judgment. Rather, it provides a consistent synthesis of the available information, supporting experts in identifying potentially critical situations while reducing the risk of overlooking relevant signals. In this sense, the fuzzy system constitutes a practical tool for assisting expert decision-making and triggering alerts, especially when some of its input variables remain uncertain.

6. CONCLUSION

This work presents a fuzzy expert system designed to automatically assess the criticality of the temperature and overload criteria within the **CRISTAL** decision-support framework. The approach combines heterogeneous meteorological and snowpack observations, spatially interpolates them at the scale of individual slopes, and transforms them into interpretable linguistic variables that are subsequently aggregated through expert rules. The two criteria account for several complementary processes. Temperature effects considers near-surface warming, snowpack humidification and melting, and the stabilizing effect of melt-freeze crusts. The overload criterion considers loading from fresh snowfall, rainfall and wind-drifted snow.

The hierarchical structure allows these different processes to be assessed independently while retaining their interactions at the criterion level. A key strength of the approach is its ability to combine information of different types and levels of uncertainty while maintaining an interpretable reasoning process. The system intends to produce a consistent and transparent assessment of the criticality of current conditions. This makes it a solid tool to assist local experts in their judgment. Particular attention is required for variables such as wind-drifted snow and snow surface temperature, for which numerical modeling could provide useful additional information where observations are sparse. Ultimately, the two subsystems presented here constitute one step towards the broader automation of **CRISTAL**. Their integration with the remaining criteria should provide experts with a systematic synthesis of the available information and, consequently, a more robust and timely support for traffic restriction decisions on avalanche-exposed roads.

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