A NEW OPERATIONAL APPROACH FOR THE DAILY ASSESSMENT OF POTENTIAL AVALANCHE DANGER

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ABSTRACT: Over the past 20 years, the need to identify the spatial distribution of avalanche-prone areas, crucial for evaluating the avalanche risk, has led to the development of several automatic algorithms to detect Potential Avalanche Release Areas (PRAs) and assess terrain predispositions to avalanche release. These algorithms, combined with avalanche dynamic simulations, are widely employed for producing hazard indication maps in mountainous regions. These approaches are rarely used for supporting avalanche forecasting and operational risk mitigation, although the hazard spatial distribution remains a fundamental parameter in assessing avalanche danger. Generally, the generated susceptibility maps are mainly based on terrain characteristics, including predefined snow scenarios. Therefore, they are not suitable for effective operational danger or avalanche risk assessment. In this study, we propose an automated method for identifying slab avalanche release areas, also taking into account the time-specific stability conditions of the local snow cover. This approach was used to calculate the daily potential slab avalanche activity during the winter season 2023-2024 for the Livigno municipality, in the Central Italian Alps. At first, a fuzzy logic approach is used to evaluate the morphological susceptibility of terrain to avalanche release. Then, the current spatialized snowpack stability condition, derived from the SNOWPACK model simulations, is integrated into the results. In particular, stability indices related to the different Typical Avalanche Problems were selected and integrated, always with a fuzzy logic approach, in the previously calculated avalanche release susceptibility of the terrain. Finally, avalanche release areas are used as input for dynamic avalanche simulations. The proposed approach addresses all factors influencing avalanche danger. For each Typical Avalanche Problem, information related to snowpack stability, frequency distribution and expected avalanche size are calculated and showed to the avalanche forecasters. Preliminary results show the potential of the proposed approach to support avalanche forecasters in both avalanche danger prediction and risk assessment. Although further refinements are still needed, this method represents a significant step towards the creation of a more operational tool capable of providing daily assessments of potential avalanche activity, improving its integration into the avalanche forecasting process.

KEYWORDS: PRA, avalanche hazard mapping, avalanche forecasting, Snowpack stability.

1 INTRODUCTION

Avalanche forecasting is a complex procedure aimed at predicting and communicating daily avalanche hazards to the public for a given region (Schweizer and Föhn, 1996). This activity, fundamental in every area of the world where avalanche hazards pose a risk, has traditionally been conducted primarily by avalanche experts through in situ observations. The European Avalanche Warning Service (EAWS) has defined the avalanche danger level (AD) as the most relevant information provided by avalanche bulletins (Standards - Information Pyramid). To define the AD, the EAWS has defined three fundamental parameters to be evaluated (i.e., EAWS matrix parameters), which can be used as input to a look-up table intended to ensure consistency among avalanche forecasters (Standards - EAWS Matrix). The three parameters, further categorized in classes, are: the snow instability (i.e. snowpack predisposition to avalanche release), the frequency (i.e. percentages of points for each stability class relative to all points in avalanche terrain) and the avalanche size (i.e. destructive potential of an avalanche). The AD assessment is performed for each avalanche situation known as Typical Avalanche Problems (TAPs) (Avalanche problems). With respect to snow instability, over the last two decades the development of snowpack evolution models, such as SNOWPACK (Bartelt and Lehning, 2002; Lehning et al., 2002a, b), has allowed avalanche forecasters to integrate classical field observations with automatically simulated information (Monti et al., 2016). At this purposes, various physical stability indices simulating different avalanche-related typical situations have been developed (Viallon-Galinier et al., 2022). On the other hand, avalanche size and frequency parameters are still primarily estimated based on observations and experience, making the forecasting activity still subjective. A possibility to overcome this challenge could derive from integrating avalanche hazard modeling techniques in the forecasting procedure. These tech-

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niques, widely used in territorial planning or engineering purposes, involve the combined use of potential Avalanche Release Area (PRA) models and avalanche dynamic simulations. Terrain factors, indeed, play a fundamental role in avalanche formation, and since the last century, experts have produced hazard zoning maps using the available topographic cartography. Since the early 2000s, many studies on avalanche-terrain interaction have been carried out in a GIS environment (Maggioni and Gruber, 2003a) and subsequently approaches for the automatic detection of PRAs have been developed (Bühler et al., 2018b). These algorithms allow the spatial modelling of avalanche danger in GIS environments, relying mainly on morphological factors, sometimes even including simple external meteorological parameters to model a specific snow and weather scenario (Ghinoi and Chung, 2005). The interest in the physical characteristics of avalanche flow and runout distances, led to the development of various avalanche flow dynamic models such as AvaFrame - The open avalanche framework (Tonnel et al., 2023). Anyway, these models are mainly tuned to simulate large sized avalanches. These simulations require as input a release area, the release depth and a digital elevation model (DEM). Buhler (2018a) proposed an automatic approach to automatically create hazard indication maps for large areas. To date, the limited operational use of these models for risk assessment for avalanche hazard prediction is attributable to the limitations in describing frequent hazard scenarios and the difficulty in integrating current snow conditions. The aim of this study is to develop a geospatial algorithm for avalanche hazard modelling that is able to consider the current snowpack characteristics while taking into account the factors that lead to slab avalanche release (McClung and Schaerer, 2006). The goal is to develop a tool capable of supporting avalanche forecasting activities and operational risk management. The results were then compared to field observation and to avalanche forecasts (i.e. avalanche danger and TAPs) during the 2023-2024 winter season. This study is focusing just on slab avalanches (dry and wet) but not on loose and Gliding snow avalanches.

2 DATA

The study area corresponds to the Livigno municipality (Italy), a village situated in the Central Rhaetian alps, with an area of 211km^2 ranging in altitude from 1790 to 3302 m asl. The terrain configuration, combined with local weather and snow patterns, the presence of human settlements directly exposed to avalanches and high tourist activity among winter outdoor enthusiasts, has led to the development of a local avalanche forecasting system (Monti et al., 2014) and makes the area highly significant for snow and avalanche studies.

Over the past decade, a digital database comprising 357 avalanche release areas has been established through in-situ observations. A 5 m resolution DEM (Geoportale Regione Lombardia) and a binary map of forest cover derived in 2023 from Sentinel-2 satellite images are available for the area. An automatic weather station (AWS) located at an altitude of 2633 m above sea level was used to collect snow and weather parameters. These measurements, combined with data from a numerical weather model (NEMS4) are used as input for the SNOWPACK model. The simulations are constantly validated during the winter season with field observations (i.e., snowpack stratigraphy and stability tests). In this study we focused only on the Alpine elevation range (between 2200-2300 m and 3400 m a.s.l.).

3 METHODS

The approach developed in this study is capable of automatically identifying the PRA and corresponding avalanche flows characteristics at a daily base. The inputs are geospatial variables (DEM and binary forest cover map) that are fixed over time, and time-dependent snow and meteorological variables (snow stability indexes, snowpack structure information, new snow amount and wind snow transport). The latter are derived from SNOWPACK simulations.

3.1 PRA definition

The methodology was initially inspired by Veitinger's work (Veitinger et al., 2016), which proposed a PRA detection algorithm using a fuzzy logic approach that incorporates snow height (HS), here extracted daily by the AWS measurements, to smooth the DEM. The fuzzy logic approach is widely used for geospatial susceptibility modelling of several hydrogeological processes (Gohil et al., 2024). This method enables assigning a degree of membership to a given variable for a specific class (e.g., the PRA class) rather than a binary determination of belonging or not belonging to the class (Zadeh, 1965). In our case, bell-shaped membership functions μ(x) were developed, to relate each of the variables of interest to the propensity for avalanche release (i.e., to the PRA class). As for Veitinger (2016), given a variable *x*, functions are defined by:

$$\mu(x) = 1/(1 + (\frac{x-c}{a})\text{^}2b \qquad (1)$$

The calibration of the shape parameters *a*, *b*, and *c* for each *μ(x)* was based on experience in avalanche forecasting, previous studies on the terrain and snowpack properties susceptibility to slab avalanche release, and statistical analysis of the release area calibration dataset (Figure 1). Once all variables of interest were converted into fuzzy logic (i.e., raster data containing the membership value to the PRA class), they were differently combined using the "fuzzy-AND" operator proposed by Werners (1988) and employed in the work of Veitinger (2016). This results in various PRA scenarios representative of the TAPs related to slab avalanches, here named $\mu_{tot}(x)$. A purely morphologically-based scenario, referred to as the neutral scenario, is then added to the set. Since the SNOWPACK model simulates the snow cover at the four main exposures (North, East, South, and West), to integrate snow and weather variables with DEM-based ones, the former were spatialized using an Inverse Distance Weighting based on terrain aspect. Different SNOWPACK variables were selected for deriving information regarding a specific TAP scenario. In this work the New Snow, Wind Slab, Persistent Weak Layers and Wet Snow TAPs were considered.

For each generated TAP scenario, a proxy variable for EAWS instability is calculated as the average value of each $\mu_{tot}(x)$ raster, reflecting the time-specific snowpack stability. The EAWS frequency variable, instead, can be seen as the number of dangerous pixels relative to all pixels within the area susceptible to avalanche release.

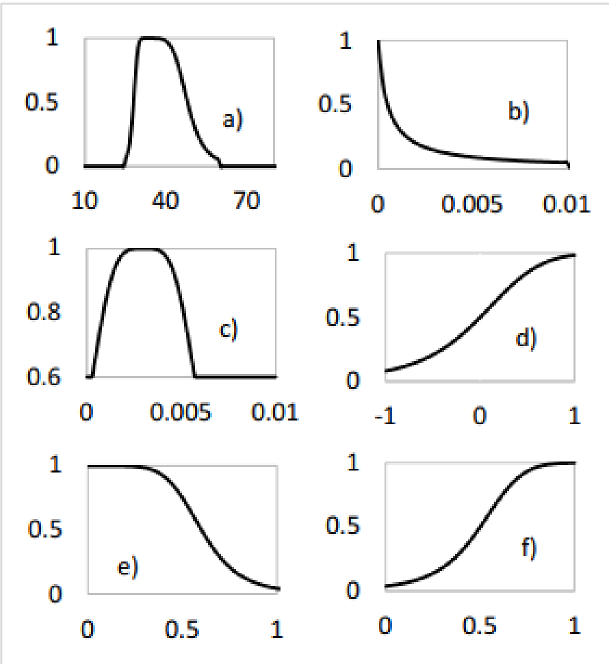

Figure 1: Membership functions for: a) slope, b) ruggedness, c) profile curvature, d) windshelter, e) $RTA\_SK_{38}^{ccl}$, f) LWCi.

3.2 Neutral and New Snow (NS) scenario

The neutral scenario describes the general terrain susceptibility to slab avalanches across the region, given a certain snow height (HS). This DEM-based scenario was created by aggregating slope, terrain ruggedness (as computed by Veitinger), and profile curvature (Vontobel et al., 2013). The influence of these morphological variables on slab avalanche release has been widely explored in previous studies (Maggioni and Gruber, 2003b). This scenario represents all points within the area of interest that are prone to avalanche release and is also intended for further elaboration, such as the production of susceptibility maps, and hazard zonation. For the latter, a representative HS value can be set a priori. This scenario was also used to describe the NS TAP by setting an appropriate release depth in the avalanche dynamic simulations stage.

3.3 Persistent Weak Layer (PWL) scenario

The PWL scenario was developed by combining the spatialized $RTA\_SK_{38}^{ccl}$ stability index with the variables of the NS. This index compares the length of the fracture produced by a skier with the weak layer critical crack length, implicitly considering the movement of the skiers himself through his line load. A publication on this index will follow soon. The relative μ(x) was calibrated by comparing the index to the PWL avalanche activity of the calibration dataset. The presence of the scenario is discriminated by the presence of a PWL within the snowpack.

3.4 Wet Snow (WeS) scenario

The WeS scenario was calculated by incorporating information mainly derived by the Liquid Water Content Index – LWCi (Mitterer et al., 2013) with the variable of the NS. This index, extracted daily from SNOWPACK simulations, is defined as the average liquid water content of the entire snowpack, normalized by the threshold value marking the transition from the pendular to the funicular regime. The specific $\mu(x)$ was calibrated based on the results of Mitterer (2016). The presence of this scenario is discriminated by evaluating the following conditions: i) the snow cover has a LWCi > 0.3 and a snow layer becomes wet for the first time of the season; ii) the snow cover has a LWCi > 1 but it is not isotherm; iii) the snow cover has a LWCi > 1 and is isotherm. After 5 consecutive days with isothermal conditions, the instability is then considered to be removed (empirical evidence).

3.5 Wind slab (WS) scenario

The WS scenario was developed by incorporating the morphological Windshelter parameter into the NS (Plattner et al., 2004). The corresponding μ(x) is the same as proposed in Veitinger's study. To account for wind slab formation, the presence of the scenario is discriminated using a threshold on the mean Wind Transport Index (Lehning and Fierz, 2008) over the two days before and one day after the day of interest. To account the newly formed wind slabs bond with the underlying snow within a few days of formation, depending on air temperature and old snow surface properties (Mariani et al., 2023), the Windshelter μ(x) was multiplied by a dissipation variable, which decreases as a function of time if no new wind transport episodes are simulated. The dissipation variable is defined with the following bell-shaped membership function:

$$Wdis(t) = 1/(\frac{1+t}{50}) \qquad (2)$$

3.6 Avalanche dynamic simulations

To determine the avalanche flow paths and characteristics for each daily set of PRA scenarios, we employed AvaFrame - The open avalanche framework (Tonnel et al., 2023). Different release depths, specifics for each TAP scenario, were extracted from SNOWPACK simulations. These were then spatialized through aspect, as done for the snow and meteorological variables, and trough slope angle according to Burkard (1992). The raster thus obtained was masked to include only areas where *μtot(x)* > 0.7 and subsequently used as input for the avalanche dynamic simulation model. The proposed threshold on the membership value to the class PRA was based on Veitinger's findings and to optimally fit the average dimension of the release areas calibration dataset. The different release depth were selected as follow: for NS scenario, it is the 3-day cumulative new snow depth (HN72), for the PWL scenario, it is the depth of the weak layer identified by the $RTA\_SK_{38}^{ccl}$ stability index, for the WeS scenario, it is the deepest layer meeting the specified conditions for this scenario, and finally, for the WS scenario, it is the depth of the layer identified by the Relative Threshold sum approach (RTA) (Monti and Schweizer, 2013), adjusted in order to consider as potential critical layers the one composed by precipitation and fragmented particles and not the persistent snow grain types.

From the avalanche dynamics simulations, it was possible to calculate the expected potential avalanche size by using the μtot(x) raster combined with the release depth raster as input. The resulting avalanche size is thus already a function of snow instability and frequency and is not an independent variable like the size used in the EAWS matrix: an increase in frequency, stability and release size leads to larger simulated accumulation volumes.

3.7 Validation strategy

The main goal of the performed validation is to understand if the proposed approach can be automatically calculated daily and can produce information related to the real snow cover and stability conditions. Since actual specific stability information are missing and difficult to collect, we used some proxy variables as reference. In particular: i) the observed avalanche release areas were compared to the relative forecasted susceptibility map; ii) the observed avalanches were assigned to a TAP and compared to the most critical TAP forecasted by the proposed approach; iii) the TAP identified within the avalanche bulletin (verified) were compared to the ones forecasted; iv) the AD issued within the avalanche bulletin (verified) was related to the maximum expected avalanche size obtained by the simulations.

The algorithm was operationally executed during the entire 2023-2024 winter season, from December 1st to May 1st. The avalanche release area database was divided into two parts: 65% (232) for algorithm calibration and 35% (127) for validation. The validation part of the dataset corresponds to the avalanches observed during the winter season of 2023-2024. A visual comparison of the outputs on days with observed avalanche activity was performed, focusing on the approach's ability to discriminate the location and probability of avalanche release.

The 75th percentile of the simulated avalanche deposit volumes (S_for) was used to rank the severity of the forecasted scenarios. The resulting forecasted TAPs were compared to the one described within the avalanche bulletins and to the ones assigned to the observed avalanches. The S_for was also used as a proxy variable for the AD.

4 RESULTS AND DISCUSSION

During last winter season the PRA and the relative potential avalanche activity within an area of about 200km^2 was calculated daily with no supervision. The snow cover simulations from the SNOWPACK model were used to calculate four different TAPSs scenarios. The daily calculation time ranged between 20 and 120 minutes depending on the snow cover characteristics (e.g. potential release depths and number of scenarios). This demonstrates the feasibility of using this approach as a tool to support avalanche forecasting operations.

The integration of the time-dependent snow and weather variables with the morphological susceptibility of the terrain results in a different set of PRA raster layers that changes daily, accounting for the evolution of snowpack structure and stability. Within the PRA raster layers each cell represents the probability, ranging from 0 to 1, that a slab avalanche could release according to the specific TAP scenario. In contrast, the characteristics of the corresponding avalanches are visible in raster layers representing flow velocities, thicknesses and pressures. The daily scenarios result in an increased probability and frequency of avalanches along slopes with the predisposing conditions. Given the fixed segmentation threshold on the PRA raster ($\mu_{tot}(x)$ >= 0.7) used for the simulations, this adjusts PRA dimensions, without overcome the morphological constraints, in accordance with practical experience (i.e., sensible increase of the release area size with increasing instability until reaching the morphological constraints of the slope).

4.1 Potential release areas

The probability distribution of the μ_tot(x) obtained by the proposed approach within the observed slab avalanche release areas, reveals insightful characteristics. By using the neutral scenario, which represents the general slab avalanche susceptibility of the area, the 20th percentile is 0.67, indicating that 80% of the observed release areas have a higher probability of avalanche release. Additionally, the 5th percentile is 0.47, and the mean value of the distribution is 0.72, showing the range of probabilities across the study area. These findings highlight the algorithm's effectiveness in identifying areas with increased susceptibility to avalanche release and support the decision to take the $\mu_{tot}(x)$ >= 0.7 as threshold for defining the PRA used for avalanche dynamic simulations.

If considering the specific TAP scenario of the observed avalanche release areas, the release probability is higher than 0.7 for the 74% of the pixels (compared to the 71% when considering the neutral scenario). This can be considered a reasonable result as these areas are already morphologically prone to avalanche release regardless of the snowpack characteristics. (Fig. 2).

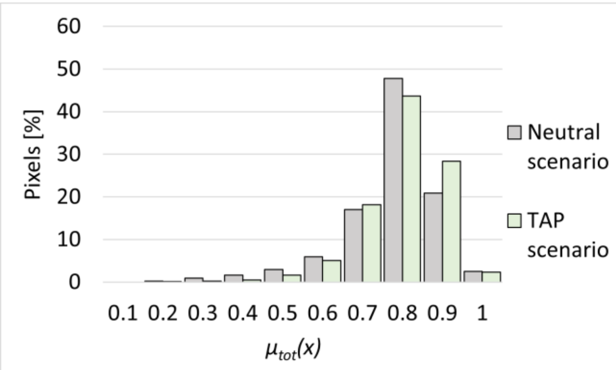

Figure 2: histograms of $\mu_{tot}(x)$ relative to the neutral and the worst daily TAP scenario sampled with observed avalanches.

The simulated EAWS frequency could then be used for a raw evaluation of the specificity of the selected TAP scenario. During the winter season, the mean EAWS frequency proxy of the most critical TAP scenario was 24% with the maximum value of 34% (Figure 3). In other words, even though the percentage of significantly dangerous pixels ($\mu tot(x)$>=0.7) within the observed release areas is similar for both the neutral and the most critical daily TAP scenario, the latter reduces the significantly dangerous area by 70% across the entire study area. This represents a significant improvement in the localization of PRA.

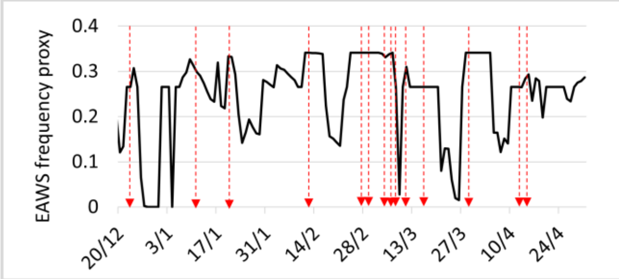

Figure 3: Trend of the EAWS frequency proxy variable during the winter season relative to the most critical TAP scenario. Dashed arrows represent days with observed avalanche activity.

Operationally, the daily TAP scenarios help the avalanche forecasters to visually focus on the avalanche-prone pixels on the specific exposures where avalanches could occur (Figure 4). An in-depth comparison between the observed and simulated avalanche flow dimensions, characteristics, and travel distances was not performed. However, the dimensions of the single simulated avalanches are not always realistic. One possible explanation is that the proposed approach does not consider information on snow drag and snowpack characteristics within the avalanche run-off areas. The friction parameters used for the avalanche dynamics simulations were also kept constant. Furthermore, it is known that models for simulating avalanche dynamics have limitations in reproducing the small sized avalanches.

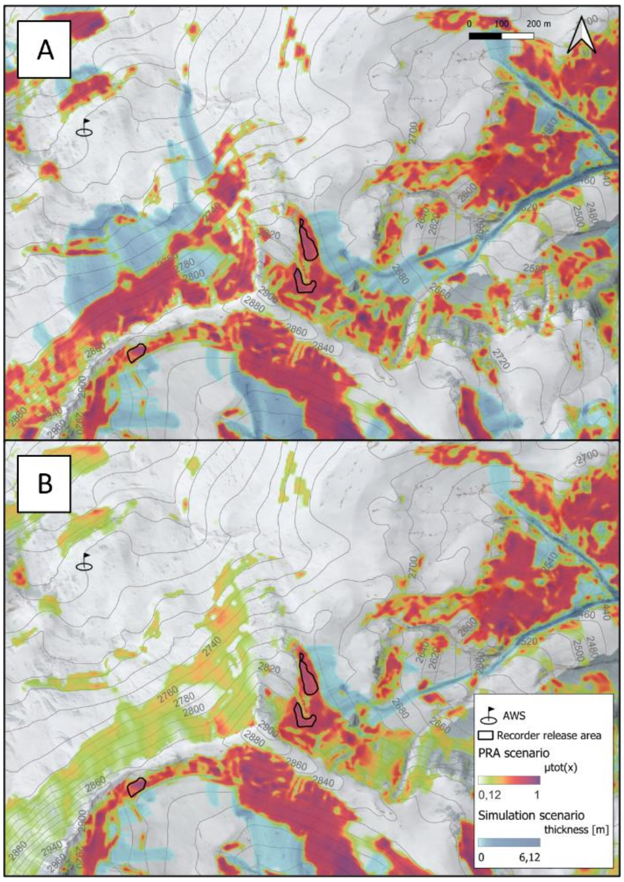

Figure 4: Examples of neutral scenario (A) and Wind Slab scenario (B) forecasted for April 1, 2024, with the daily observed release areas superimposed. A moderate snow drift event due to North-West winds was simulated by SNOWPACK.

4.2 *TAP scenarios*

The proposed approach generates a TAP scenario only if the relative snow cover characteristics allows for it (e.g., if no unstable persistent weak layers are simulated the relative TAP scenario is automatically excluded). During the winter season, 1 to 3 TAPs were calculated every day. Four TAP scenarios were never simultaneously computed, according with field observations and evaluations.

The observed avalanches were manually assigned to the relative TAP. When more TAPs occurred at once and it was not clear the actual problem to be assigned to the avalanche, two TAPs were given (e.g. an unstable and persistent weak layer existing within the snowpack with a new snow overload). They were then compared to the two more critical TAPs forecasted by the proposed approach. In 97% of cases the TAP/TAPs observed and forecasted fully agreed. Nevertheless, in the remaining 3% of cases at least one of the forecasted TAPs matched (Fig. 5).

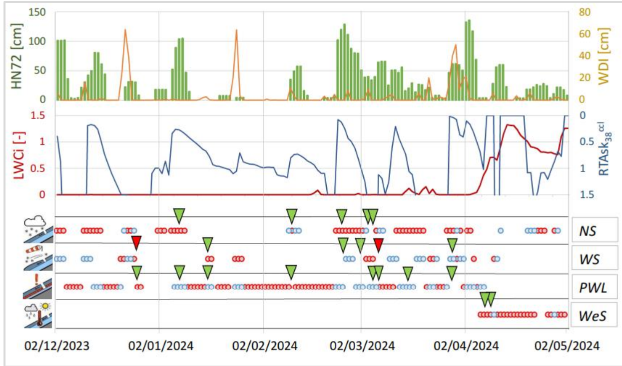

Figure 5: Timeline representing the snow-meteorological parameters used to predict the different TAPs combined with the first (red dots) and second predicted TAP (blue dots). The triangles represent the TAPs to which the observed avalanches were manually referred. One or more avalanches may have been observed on one day. Green triangles indicate full matches between the two TAPs, while red triangles denote days with the matching of only one TAP (no full mismatch was recorded).

The TAPs indicated in the avalanche bulletins by the forecasters during the winter season were then compared to the predicted ones (the two most severe TAPs in function of the S_for). Without considering the danger order of the TAPs, the TAPs calculated with the proposed approach match in the 91% of the days with ones forecasted in the avalanche bulletin. When there was no agreement (9% of cases) it often happened that the bulletin predicted a NS problem while the proposed approach predicted WS or vice versa. The second problem was instead Gliding Snow avalanches which is not calculated by the approach. For the correctly predicted days, in 60% of the cases the order of the TAPs was matching, otherwise it was reversed. This discrepancy could be explained by the fact that the order of TAPs communicated in avalanche bulletins is not only based on their severity, but also on other factors such as communication strategies. (e.g. one avalanche problem is communicated first since it is harder to manage on the terrain by the users). Furthermore, when snowfall occurs, there is no clear rule for deciding between NS TAB and WS TAB, which is a significant problem since when snowfall occurs, it is very often accompanied by strong winds. Again, the preference for one TAB or the other is mainly related to subjective evaluations and communication strategies. Finally, the Livigno avalanche bulletin highlights maximum two TAPs a day, if a third one exists it can be described within the text. Often the decision of which are the TAPs highlighted and the one only mentioned within the text is mainly based on communication strategies (e.g. Avalanche forecasters often chose to report NS or WS TAP as the first problem and Gliding Snow

TAP as the second, while the presence of PWL TAP was only mentioned in the text).

4.3 Avalanche danger level

The S_for, which could be seen as the EAWS matrix proxy parameters for avalanche size, increases exponentially with the AD level (Figure 6). This is consistent with the exponential increase in danger as the AD classes increase (Avalanche danger scale). To be noted, that it is currently not always possible to attribute accumulation volumes to the specific release areas, since these volumes can merge in the deposit zone. More release areas share the same avalanche path more this effect is significant.

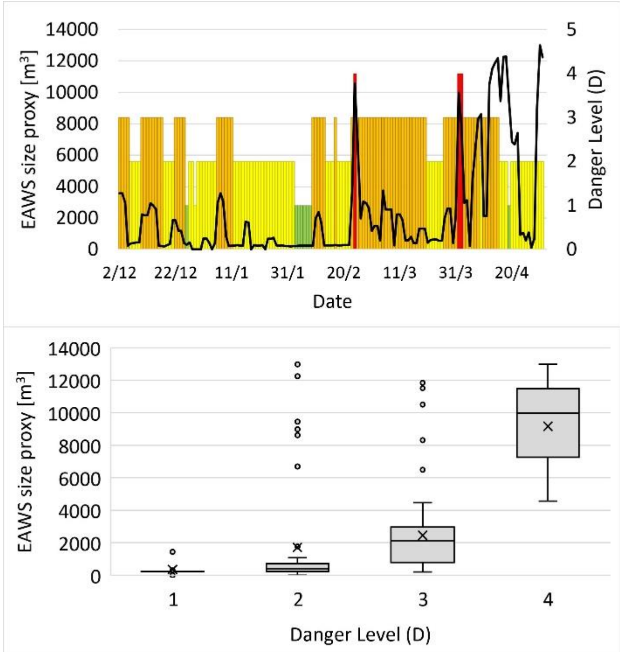

Figure 6: Comparison between the forecasted proxy for the EAWS avalanche size and the AD classes reported in the avalanche bulletin during the 2023-2024 winter season.

This behavior of the S_for in function of the AD supports its selection for ranking the severity of the daily forecasted TAP scenarios. Moreover, this finding supports the possibility of choosing the S_for as an indicator of the overall daily danger of the area for a given TAP scenario. In Figure 6, outliers with significantly high values of S_for, mainly for AD classes 2 and 3, are visible. An in-depth analysis of these cases revealed that all of them occurred at the end of the season (i.e., April), when both the algorithm and the avalanche bulletin agreed on the presence of the WeS TAP. Field observations confirmed a progressive wetting of the snow cover with deeper layers becoming wet for the first time of the season. Thus, the wet snow stability index behaved as expected by forecasting potential wet snow instabilities. This revealed a weakness of the used approach. It is known that wet snow slab avalanches releases primarily when a previous weak layer or capillary barriers is within the snow cover (Baggi and Schweizer, 2009), which is not considered by the applied approach and further studies are needed to properly address this limitation.

5 CONCLUSIONS

In this study, an automated operational approach for identifying slab avalanche release and runout areas, also considering the time-specific stability conditions of the local snow cover, was presented.

During the last winter season, this approach was automatically calculated at a daily base for an area of about 200km^2, showing the potential of having the results available for an operational use. For each day, this results in a series of digital cartographic products describing the potential Typical Avalanche Problems (TAP) to be expected for a certain day. From these outputs several information can be derived, such as the distribution of the area most susceptible to slab avalanches, their frequency over the territory, and indications on their potential size.

By comparing the forecasted potential release areas (PRA) with the observed ones is possible to state the presented approach has the capability of discriminating the areas where an avalanche can occur. By considering the TAP relative to the observed avalanches, the sensitivity increased, accompanied by a notable rise in specificity.

The potential avalanche size (S_for) derived from the simulations (75th percentile of the avalanche deposit volumes of a certain scenario) was used both to select the most severe forecasted TAP and as a proxy variable for the avalanche danger of the area. The most severe forecasted TAP clearly agreed both with the TAP assigned to the observed avalanches and to the ones manually forecasted for the avalanche bulletin of the area. This shows the capability of the proposed approach to correctly identify the sources of instability characterizing a certain day.

The exponential growth of S_for as a function of avalanche danger agrees with the exponential nature of avalanche danger among the different classes and reveals that it could be used as a predictor.

The proposed approach is empirically based and allows the strengths and weaknesses of each component to be assessed. Future developments could improve the snowpack simulations, refine the algorithms to identify potential release areas and optimize the avalanche dynamics simulations by also considering the snowpack characteristics along the path or by adjusting the friction parameters according to different conditions. Finally, to evaluate the applicability and accuracy of this approach, it will be necessary to test it on different climatic and morphological areas. In future this approach could turn in a supporting tool not only for regional but even for site-specific avalanche forecasting.

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