A GIS-BASED METHODOLOGY FOR REAL-TIME PRIORITIZATION OF AVALANCHE CONTROL OPERATIONS IN THE ORDINO ARCALÍS SKI AREA, ANDORRA

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ABSTRACT: Prioritizing avalanche control operations in ski areas requires the integration of terrain susceptibility, snowpack evolution, operational exposure, and expert judgement within a decision framework that is fast enough for real-time use. This study presents a geographic information system (GIS)-based methodology to support prioritization of preventive avalanche-control shots in the Ordino Arcalís ski area, Andorra. The objective is to identify which potential release areas should be treated first according to their relative instability and their capacity to affect ski runs, lifts, buildings, access routes, or other spaces containing exposed people and infrastructure. The workflow integrates four components: avalanche-cadastre and historical information, geomorphological analysis, snow and weather monitoring, and numerical avalanche-dynamics modelling. The spatial database contains 57 potential release areas identified and refined from the avalanche cadastre, topography, photo interpretation, field surveys, and operational knowledge. Recent loading is monitored using automatic snow-weather stations and evaluated over 24, 48, and 72 h windows; this information is complemented by snow profiles, stability tests, and direct observations. An initial threshold of 40 cm of new snow is based on approximately three decades of operational experience by ski-patrol managers, avalanche blasters, and avalanche forecasters at Ordino Arcalís, and is treated as an empirical operational criterion requiring retrospective verification and future recalibration. Current conditions are linked to a library of precomputed RAMMS::AVALANCHE simulations using several release depths and two representative snow configurations to estimate runout and intersections with exposed elements. Final prioritization is based on three binary criteria — recent loading, evidence of instability, and potential consequence — and is always subject to expert validation. The method is intended to improve the efficiency, traceability, and safety of PIDA decisions without replacing the judgement of the avalanche-control manager.

KEYWORDS: avalanche control; GIS; numerical modelling; snowpack stability; decision rules; Ordino Arcalís.

1. INTRODUCTION

Preventive avalanche-risk management in a ski area is a decision problem under severe time constraints. A single control operation may involve numerous potential release areas with different aspects, snow loading, and consequences. The operational question is therefore not only where an avalanche may release, but which areas should be treated first before ski runs, lifts, and access routes are opened, particularly when the number of shots is high and the available PIDA window is limited.

Avalanche formation results from the interaction between terrain, meteorology, and snowpack structure. Snow profiles, stability tests, and field signs provide direct information on current snowpack conditions (Schweizer et al., 2003). In parallel, numerical avalanche-dynamics models can estimate the consequences of an assumed release — runout, flow depth, velocity, or pressure — over three-dimensional terrain (Christen et al., 2010a). The operational value lies in combining these two questions, instability and consequence, within a rapid, transparent, and auditable decision rule.

This study proposes a categorical methodology without numerical weighting, based on three independent criteria: (A) recent snow loading, (B) evidence of instability, and (C) potential impact on exposed elements according to the selected numerical simulation. The method is applied to 57 potential release areas at Ordino Arcalís and uses a library of precomputed simulations to accelerate consultation during operations. This approach is consistent with the use of scenario-based avalanche-dynamics calculations as operational decision support (Stoffel et al., 2018), while final authority remains with the PIDA manager.

2. STUDY AREA AND BACKGROUND

2.1 Snow-climate setting

Ordino Arcalís is located in north-western Andorra in a high-mountain environment with a

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https://doi.org/10.15788/1790099058

marked Atlantic influence. N and NW advections produce a substantial fraction of snowfall events and are frequently associated with strong winds, which can cause redistribution and lee-side loading. The relationship between atmospheric circulation patterns and heavy snowfall in Andorra was described by Esteban et al. (2005); at the Pyrenean scale, García-Sellés et al. (2013) likewise highlighted the importance of combined precipitation-temperature sequences during major avalanche cycles.

Snow-line variability is also important. Cold, dry-snow episodes may alternate rapidly with milder periods or rain reaching high elevations, changing snowpack stability over short time intervals. For this reason, the methodology does not use new snow as a stand-alone indicator, but combines it with direct observations, profiles, stability tests, and evidence of recent avalanche activity (Feich et al., 2012; Stimberis and Rubin, 2011).

2.2 *Avalanche cadastre and historical knowledge*

The Andorran Avalanche Cadastre provides the principal historical cartographic basis. It is an official dataset produced by the Government of Andorra and maintained by the administration responsible for territorial management. The digital cadastre was consolidated through the harmonization and updating of probable avalanche-location maps and is a reference tool for territorial avalanche-risk management (Ferrer and Furdada, 2003). It is not a dynamic model; rather, it delineates known or probable avalanche areas from historical, geomorphological, testimonial, and photo-interpretation evidence.

In this study, cadastre information is combined with topographic analysis, field surveys, and accumulated operational knowledge from the ski area. Historical boundaries are adjusted when terrain morphology or trajectory interpretation suggests a more appropriate release geometry for numerical calculation. The resulting working database includes 57 potential release polygons associated with the initial PIDA shot plan; the inventory remains open and may incorporate additional areas during exceptional events.

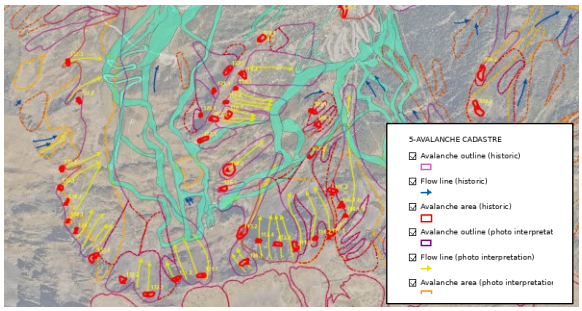


Figure 1: Andorran Avalanche Cadastre at Ordino Arcalís, showing control-shot points and release areas used as the spatial basis of the prioritization system.

3. DATA AND METHODOLOGY

3.1 *Digital elevation model and potential release areas*

The original topographic dataset is a 0.5 × 0.5 m LiDAR digital elevation model. For the simulations, this surface was reinterpolated and smoothed to a 3 × 3 m grid to reduce bare-ground microrelief that may not represent the effective surface beneath a consolidated snow cover and to limit numerical artefacts. The sensitivity of avalanche-model results to digital elevation model quality and resolution is well established (Bühler et al., 2011).

Potential release areas are delineated by combining slope angle, aspect, curvature, elevation, local morphology, avalanche-cadastre information, and expert judgement. Slope classes are used as a geomorphological filter, but not as a stand-alone criterion. They also help differentiate, within the same avalanche path, larger release polygons associated with less frequent, higher-magnitude scenarios and smaller polygons on steeper terrain representative of more frequent, lower-magnitude events (Maggioni and Gruber, 2002; Techel et al., 2020). Both polygon extent and release depth strongly influence simulated results; final release geometries are therefore based on field evidence and the combined interpretation of topography and historical information, consistent with general RAMMS::AVALANCHE guidance (RAMMS AG, 2024).

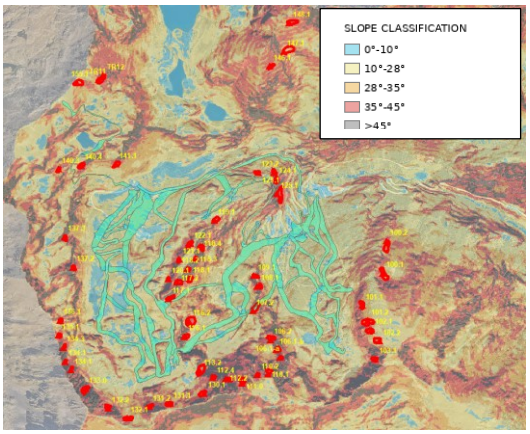


Figure 2: Slope classification used in the geomorphological analysis of potential release areas.

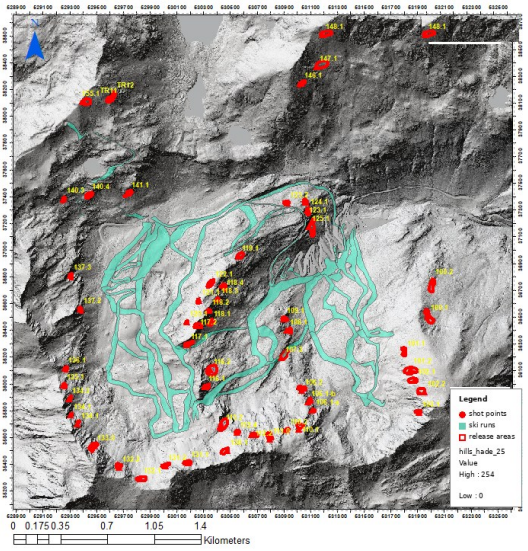


Figure 3: 0.5 × 0.5 m LiDAR digital elevation model with control-shot points, precomputed release areas, and ski-run network.

3.2 Snow monitoring, instability evidence, and activation criterion

During the initial implementation phase, accumulated new snow is monitored mainly using the automatic snow-weather stations available at Ordino Arcalís. The FlowCapt sensor at Fonts d'Arinsal is used as complementary information, particularly to contextualize wind-transport and snow-redistribution episodes. This network provides the operational reference for calculating HN over moving 24, 48, and 72 h windows.

The spatial representativeness of a point measurement is limited in a ski area with substantial differences in elevation, aspect, and wind exposure. A direct recommendation of this study is therefore to progressively expand the automatic sensor network and distribute instruments across representative aspects and elevation bands, prioritizing the most relevant snow-weather variables. The aim is to obtain a more representative estimate of recent loading at release-area scale and reduce dependence on extrapolation between sectors.

Snowpack condition is characterized using stratigraphic profiles, stability tests, and direct observations by avalanche forecasters and operational teams, particularly during and after potentially triggering snow-weather episodes — snowfall, rain-on-snow, wind loading, or rapid warming. Criterion B, 'evidence of instability', is positive when consistent evidence exists from one or more sources: unfavourable stability or propagation-test results, active weak layers, cracking, whumpfs, recent natural activity, reactive wind slabs, or other field signs. The objective is not to reduce snowpack diagnosis to a single test, but to synthesize professional judgement from the full body of evidence.

Criterion A is positive when 40 cm of new snow is reached in any of the 24, 48, or 72 h windows. This value is not presented as a universal physical release threshold; it reflects approximately thirty years of accumulated experience by ski-patrol managers, avalanche blasters, and avalanche forecasters at the ski area, who have found it to be a useful reference for initiating preventive control operations. Here it is formalized as an initial operational threshold. Its validity must be tested through retrospective analysis of previous PIDA operations and prospective validation in future seasons, allowing adjustment by sector, aspect, or avalanche situation where supported by data.

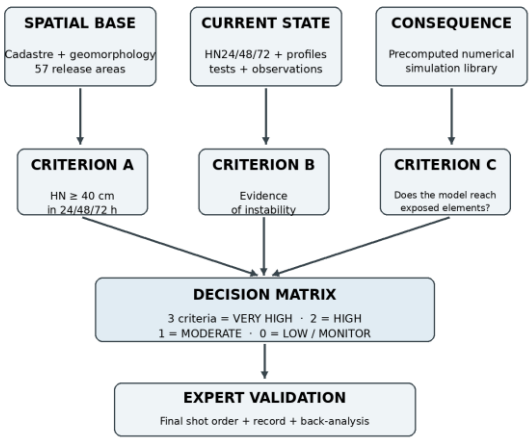


Figure 4: Information flow and architecture of the proposed decision rule. The 40 cm threshold is an empirical operational criterion subject to validation.

The decision matrix is conceptually consistent with the site-specific risk framework proposed by Jaedicke et al. (2023), in which release probability and the probability of an avalanche reaching an exposed element are considered separately. In the present study, this logic is adapted into an

operational prioritization tool based on simple, traceable categorical criteria that can be applied during PIDA operations.

3.3 Library of numerical simulations and physical parameters

Potential consequence is calculated with RAMMS::AVALANCHE, which solves depth-averaged mass and momentum conservation equations and uses a Voellmy-Salm friction formulation (Bartelt et al., 1999; Christen et al., 2010a). For each of the 57 polygons, four release depths measured normal to the terrain — 0.40, 0.60, 0.80, and 1.20 m — are precomputed for two representative snow configurations: a drier, lighter configuration (ρ = 150 kg m^{-3}; N0 = 50 Pa) and a denser configuration (ρ = 350 kg m^{-3}; N0 = 100 Pa). The resulting library contains eight scenarios per release area and 456 initial simulations.

The friction coefficients μ and ξ are assigned using the automatic MuXi procedure implemented in RAMMS::AVALANCHE. The procedure derives spatially variable values from topography — slope, curvature, elevation, and path type — together with global parameters such as volume and return period. The baseline parameterization derives from SLF calibration and the Swiss guidelines embedded in the software; for Ordino Arcalís, consistent criteria are maintained across all scenarios and elevation thresholds are adapted to the Pyrenean setting, avoiding a different manual calibration for every simulation (RAMMS AG, 2024).

Cohesion is introduced through parameter N0, which acts as a yield stress and increases shear resistance; higher values can promote earlier stopping (Bartelt et al., 2015). Density ρ is assumed constant within each simulation. In this formulation, density does not directly modify runout, flow depth, or velocity because it appears in both inertial and resistance terms and cancels from the depth-averaged equations; it does affect derived quantities such as impact pressure. The two configurations should therefore not be interpreted as two kinematically distinct models based solely on density: N0 changes the resisting response, whereas ρ is particularly relevant when quantifying mechanical consequences (RAMMS AG, 2026).

The precomputed scenarios form a consultation library and do not replace a case-specific simulation when an event falls outside the represented domain. Previous modelling and back-analysis of Pyrenean avalanches illustrates the value of using snow parameterizations representative of the regional context and of checking release geometry and physical parameters against observed evidence (Riba et al., 2018).

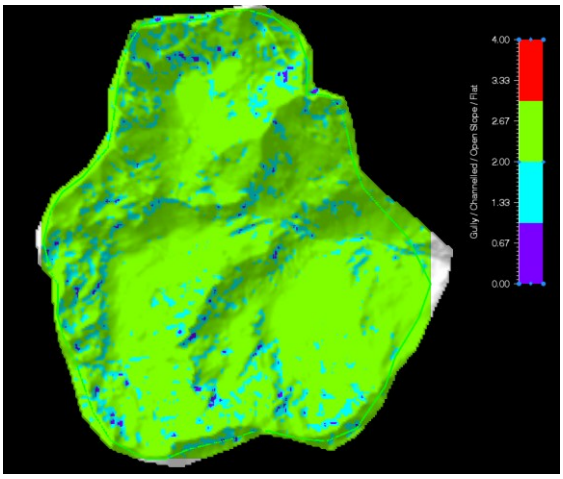


Figure 5: Automatic path-type classification (flat/open slope/channelled/gully) used by the MuXi procedure in RAMMS::AVALANCHE.

Table 1: Structure of the numerical simulation library for each release polygon.

Depth	Dry/light	Dense	Scen./area
0.40 m	ρ=150 kg m^{-3} N0=50 Pa	ρ=350 kg m^{-3} N0=100 Pa	2
0.60 m	ρ=150 kg m^{-3} N0=50 Pa	ρ=350 kg m^{-3} N0=100 Pa	2
0.80 m	ρ=150 kg m^{-3} N0=50 Pa	ρ=350 kg m^{-3} N0=100 Pa	2
1.20 m	ρ=150 kg m^{-3} N0=50 Pa	ρ=350 kg m^{-3} N0=100 Pa	2

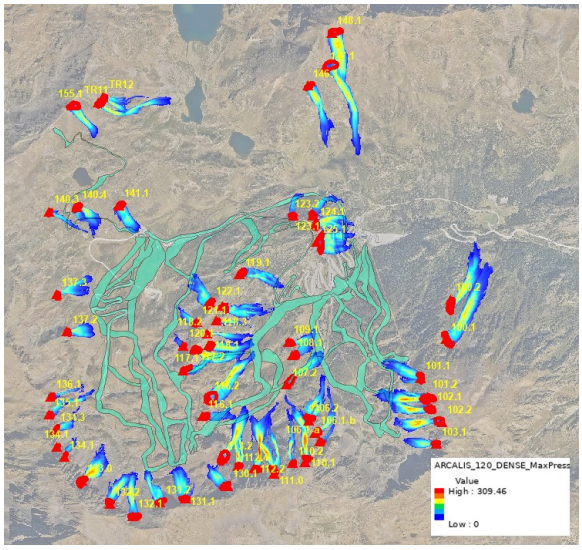


Figure 6: Example of precomputed RAMMS::AVALANCHE results for a 1.20 m release depth, ρ = 350 kg m^{-3}, and N0 = 100 Pa.

3.4 Consequence criterion and GIS integration

Criterion C addresses an operational question: for the selected release area and scenario, does the modelled avalanche extent intersect a ski run, lift, building, access route, facility, or another area

containing exposed people or infrastructure? The answer is obtained by GIS overlay between numerical simulation outputs and operational exposure layers.

This formulation explicitly separates instability forecasting from consequence. The numerical model does not predict when release will occur; it estimates what may happen if a release area mobilizes. Recent loading, profiles, tests, and observations instead describe the current state of the snowpack. Each release area has a unique identifier linking geometry, historical information, snow data, selected scenario, affected exposed elements, priority class, final PIDA-manager decision, and shot result, allowing each decision to be reconstructed retrospectively.

4. DECISION RULE AND OPERATIONAL WORKFLOW

The classification uses three binary criteria and does not apply relative weights. For each release area, the system evaluates: A) whether 40 cm of new snow has been reached in 24, 48, or 72 h; B) whether consistent evidence of instability exists at relevant elevations and aspects; and C) whether the selected numerical simulation reaches an exposed element. Three positive criteria imply very high priority, two high priority, one moderate priority, and none low priority or monitoring status.

Table 2: Complete matrix of the eight decision combinations.

A: snow	B: instability	C: impact	Priority
Yes	Yes	Yes	VERY HIGH
Yes	Yes	No	HIGH
Yes	No	Yes	HIGH
No	Yes	Yes	HIGH
Yes	No	No	MODERATE
No	Yes	No	MODERATE
No	No	Yes	MODERATE
No	No	No	LOW

The high-priority category includes physically different situations. For example, a release area may have significant snowfall and evidence of instability even if the numerical model does not reach an exposed element; conversely, instability evidence and potential consequence may be present with less than 40 cm of new snow, as may occur with a wind slab or a persistent weak layer. This logic prevents the absence of a single indicator from cancelling two independent lines of evidence.

During operations, the 57 release areas are processed through a common sequence: update HN24/48/72, review profiles and field signs, select the corresponding numerical scenario, intersect the result with exposed elements, and assign a priority class. Within the same class, the exact shot order remains an operational decision and may account for accessibility, team safety, dependencies between sectors, and the manager's experience. The avalanche blaster may raise or lower the suggested class when relevant information is not represented by the system; the adjustment should be recorded with a brief justification.

5. VALIDATION AND DISCUSSION

5.1 Retrospective and prospective validation

The methodology should be validated in two stages. First, retrospective analysis of previous PIDA operations should reconstruct, for each treated release area, accumulated new snow, available evidence of instability, the numerical scenario that would have been selected, and the actual shot result. This stage is particularly important for testing the empirical 40 cm threshold and determining whether it should remain global or be adjusted by sector and avalanche situation. Second, prospective validation should compare the proposed priority classes with operational outcomes over future seasons.

The main indicators will be the percentage of positive shots by priority class, the proportion of relevant avalanches anticipated as high or very high priority, agreement between the proposed class and the avalanche blaster's final decision, and the error between simulated and observed runout. Back-analysis of the 11 January 2026 PIDA episode provides an example of the type of comparison that can be incorporated into this validation database by contrasting numerical simulation with the geometry and extent observed in the field.



Figure 7: Avalanche observed during the 11 January 2026 PIDA operation, used as a reference for back-analysis and geometric validation of numerical scenarios.

5.2 Comparison with conventional PIDA workflows

In many Pyrenean PIDA operations, shot order has traditionally been defined through fixed routes or sequential protocols designed primarily to ensure that no control point is omitted and to maintain a safe and efficient progression through the terrain. Historically at Ordino Arcalís, operations generally started in the southern sectors and progressed toward higher terrain following a systematic sequence of control points — often broadly clockwise — with adjustments driven mainly by accessibility and opening priorities. This approach is robust as a checklist, but it does not necessarily establish a prior hierarchy based simultaneously on local snowpack stability, expected avalanche type or magnitude, and consequence for exposed elements.

The proposed methodology adds this analytical layer without replacing either safe route planning or the avalanche blaster's judgement. Relative to site-specific risk frameworks and scenario-based decision support (Stoffel et al., 2018; Jaedicke et al., 2023), the implementation is intentionally simple: three auditable criteria and a precomputed simulation library. To transfer the system to another ski area, a manager requires at minimum a georeferenced inventory of release areas and exposed elements, representative snow-weather and stability observations, a library of propagation scenarios or an equivalent consequence-assessment tool, and a procedure that records the suggested priority, expert overrides, and the final outcome of each control shot.

5.3 Strengths, limitations, and transferability

The principal strength of the system is traceability. A three-criterion matrix makes it immediately clear which evidence drives the priority and avoids the false precision of a weighted index without a sufficient statistical basis. The main limitation is discretization: the release areas, four precomputed release depths, and two physical configurations cannot reproduce the full spatial variability of the snowpack, wind transport, or all possible release geometries. When conditions fall outside the library, a case-specific simulation should be generated or conservative expert judgement applied.

A second limitation is the spatial representativeness of snow and weather data. The observation network should be progressively expanded to cover the main combinations of aspect, elevation, and loading behaviour identified across the avalanche areas. Automatic stations located as representatively as possible are particularly important when snow-weather observations are used to select numerical scenarios and support risk assessment for exposed infrastructure such as ski areas and roads (Glaus et al., 2025).

We also recognize the limitations of RAMMS when reproducing small, short-runout avalanches, for which the acceleration phase and interaction with microtopography can have a proportionally large influence on results (Dreier et al., 2014). This reinforces the need to systematically record and map observed avalanches so that release geometry and numerical parameters can be periodically back-analysed and recalibrated.

Expansion of the observation network, combined with systematic recording of PIDA outcomes, will progressively improve calibration. The overall architecture is transferable to other ski areas, but thresholds, release areas, scenarios, and definitions of exposed elements must be recalibrated locally.

6. CONCLUSIONS

A decision-support system is presented for prioritizing preventive avalanche control at Ordino Arcalís. It integrates a GIS database of release areas, historical and geomorphological information,

monitoring of recent loading and snowpack stability, and precomputed numerical consequence simulations.

The system is consistent with recent site-specific avalanche-risk approaches that explicitly separate release probability from the probability of impact on exposed elements (Jaedicke et al., 2023), and complements the use of scenario-based avalanche-dynamics calculations as operational decision support (Stoffel et al., 2018).

The 40 cm threshold over 24/48/72 h is formalized as an empirical operational criterion derived from approximately three decades of accumulated experience by the ski-area teams. Its inclusion does not make it a universal physical threshold; retrospective analysis of previous PIDA operations and validation over future seasons should determine its sensitivity and any required local adjustments.

The simplicity of the three-criterion rule enables rapid, explainable, and auditable decisions without replacing the judgement of the PIDA manager. Future improvement will depend primarily on denser automatic monitoring across different aspects and elevations, a larger database of validated events, and systematic calibration between numerical simulations and observed avalanches.

ACKNOWLEDGEMENTS

The authors acknowledge the avalanche forecasters, avalanche blasters, ski-patrol managers, and operational teams at Ordino Arcalís, as well as the technical staff who generated and maintained the field, cartographic, and operational information required to develop this methodology.

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