# A METHODOLOGICAL FRAMEWORK TO ASSESS AVALANCHE BULLETIN UNDERSTANDING AND TERRAIN SELECTION: A PROOF OF CONCEPT IN ANDORRA

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ABSTRACT: Understanding how backcountry users interpret and act upon avalanche hazard information and terrain remains a central challenge in avalanche hazard management. This study presents an integrated methodological framework linking avalanche hazard communication, users' hazard perception, and terrain selection under real-world conditions, providing insights into how users combine these sources of information when managing avalanche risk.

The primary objective is to assess whether users' terrain choices are consistent with the spatial distribution of avalanche hazard described in the Avalanche Bulletin, and to what extent terrain selection is used as a risk mitigation strategy. The approach combines structured surveys, drone-based remote sensing, GNNS tracking, geographic information systems (GIS), and statistical analysis to bridge the gap between stated and observed behaviour.

Data collection was conducted in the western Pyrenees (Andorra) and comprised two complementary components. Structured surveys captured user characteristics, avalanche education and experience, use and understanding of the Avalanche Bulletin, information used for itinerary planning, perceived avalanche hazard distribution, and planned route choices. Drone imagery and GNNS tracking were used to characterize observed movement patterns and terrain use under different avalanche danger conditions. These datasets were analyzed in relation to daily Avalanche Bulletin information and Avalanche Terrain Exposure Scale (ATES) classifications.

The complete field dataset enabled the evaluation of relationships between Avalanche Bulletin information, drone-derived observations, and ATES terrain classification, as well as between Avalanche Bulletin information and survey responses. However, fully integrating survey, drone, and Avalanche Bulletin data remains methodologically challenging. Drone observations are subject to temporal uncertainty because operational and weather constraints prevented daily flights. During periods of meteorological stability, observed tracks may therefore represent activity accumulated over several days rather than conditions corresponding exclusively to the flight date.

The results provide a basis for refining the methodology, with future work focusing on improving the temporal alignment between the three data sources and quantifying and reducing uncertainty associated with drone-derived observations. This will support a more robust assessment of the relationships between communicated hazard, perceived risk, and observed decision-making, contributing to human-centred approaches to avalanche safety and improved understanding of how Avalanche Bulletins inform risk management decisions.

KEYWORDS: Avalanche hazard communication; Decision-making; Risk perception; Avalanche safety. Drone, SIG,

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## 1. INTRODUCTION

Avalanche hazard information is intended to support decision-making in avalanche terrain by describing the likelihood and potential size of avalanches and identifying the conditions and terrain in which avalanche problems are expected. However, communication of avalanche hazard does not directly determine user behaviour. Backcountry users must interpret available information, combine it with their own experience and perception of snow and terrain, and translate it into decisions about where, when, and how to travel plus increasing acknowledgment that heuristic-based decision making is a key driver of behaviour in the backcountry tracks/paths followed (Shäfer et al., 2025).

This process may generate gaps between communicated hazard, perceived hazard, planned behaviour, observed behavior and true avalanche danger/hazard exposure (Toft et al. 2024). Users may report that they consider avalanche hazard information when planning an activity, while their actual terrain choices may not necessarily reflect the spatial distribution of the hazard described in the Avalanche Bulletin. Conversely, terrain selection may represent an important risk mitigation strategy, particularly when users adapt their route towards less exposed terrain under high avalanche danger.

Previous approaches to understanding avalanche-related decision-making have often relied on self-reported behaviour or observations of travel behaviour in avalanche terrain, but without taking into account the spatial distribution of avalanche hazard information. Surveys can provide information about users' knowledge, experience, perceptions, and stated decision-making processes (Hallandvik et al., 2017; Landrø et al., 2020), but are subject to the limitations inherent in self-reported data. Observational approaches, including GNSS-based tracking, provide information about actual terrain use and travel behaviour, but generally provide less direct information about the factors and considerations underlying those decisions (Johnson & Hendrikx, 2021).

This has driven a wave of research into behaviour, including studies on decision-making processes, risk-taking behaviour, group dynamics, demographics, used equipment, and terrain use of backcountry skiers using surveys, questionnaires, and interviews (Furman et al., 2010; Happ et al., 2023; Mannberg et al., 2018; Marengo et al., 2017; Silverton et al., 2009; Valle et al., 2022; Zweifel et al., 2006), which are sometimes combined with accident statistics ( Niemann et al., 2022; Pfeifer et al., 2018; Techel et al., 2015; Winkler et al., 2021, 2016).

Recent innovations in crowdsourced data offer complementary approaches. Schäfer et al. (2026) demonstrated that online engagement data can predict daily backcountry skiing activities on a regional scale. While online engagement shows good alignment with GNSS activity on the next day, they found that backcountry skiers' online information seeking is driven by more extreme conditions than those reflected in actual behaviour. Nonetheless, online engagement data provide a cheap and scalable alternative source of revealed preference data, especially compared to privacy-sensitive GNSS data or resource-intensive in-situ counts modelling backcountry skiing base rates. Similarly, Strava Metro data offers an accessible, privacy-respecting proxy for understanding recreation behaviour patterns across multiple regions and seasons, enabling correlation with avalanche forecasts at unprecedented spatial-temporal resolution. Base rates derived from click data and activity platforms could be used to improve the interpretation of avalanche occurrence data, and particularly human-triggered events, in relation to the forecast avalanche danger. To strengthen and extend these findings, future research should involve local experts such as mountain guides to assess whether predicted activity changes under different scenarios align with in-situ experience in avalanche terrain. Additionally, future work could include comparing ground truth data (e.g., Toft et al., 2025) with models to validate and scale predictions to quantify skiing activity in absolute numbers.

As regional analyses are limited to the granularity of warning regions or administrative boundaries, future work could include more detailed terrain information, such as slope, elevation, and overall difficulty of individual tours. This would allow exploration of whether and how skiers adapt route choice to different avalanche and weather conditions. Finally, to more accurately interpret user-generated data, it is important to better understand who contributes to outdoor sport platforms and what motivates them to share information to identify potential biases in the data.

This study develops an integrated field methodology combining structured surveys, Avalanche Bulletin information, GNSS tracking, drone-based remote sensing of ski tracks and avalanche activity and Avalanche Terrain Exposure Scale (ATES) classification. The approach is designed to compare communicated avalanche hazard with both stated and observed terrain selection.

The study objectives are to:

(1) assess how users interpret and report using Avalanche Bulletin information when planning and conducting backcountry activities;

(2) evaluate whether observed terrain selection is consistent with avalanche hazard information communicated in the Avalanche Bulletin;

(3) and assess a methodology for integrating survey-based and spatially observed behavior while accounting for spatial and temporal uncertainty.

## 2. METHODS

### *2.1 Study area*

The proof of concept was conducted within the Parc Natural de la Vall de Sorteny in the central Pyrenees (Andorra), (Figure 1). The study area comprises a mountain hydrographic basin divided into four main sub-valleys: Vall del Forn, Vall de la Cebollera, Vall de Serrera, and Vall de l'Estanyó. Field data were collected between 20 March and 11 April 2026. The area is a popular winter recreation environment outside ski resorts and controlled avalanche terrain. Avalanch exposure is mapped according to ATES 1.0

### *2.2 Survey data*

A structured questionnaire was administered using KoboToolbox and distributed through QR codes at the park entrance, the hut and directly to winter recreationists encountered in the study area.

The questionnaire collected information on participant characteristics, winter backcountry experience, avalanche education, use and understanding of the Avalanche Bulletin, activity planning, terrain selection, and behaviour during the reported activity. Attention was given to variables that could be directly linked to Bulletin information and spatial observations, including perceived avalanche danger, avalanche problems, expected avalanche size, terrain characteristics considered during planning and activity, planned versus conducted routes, and reasons for route modifications.

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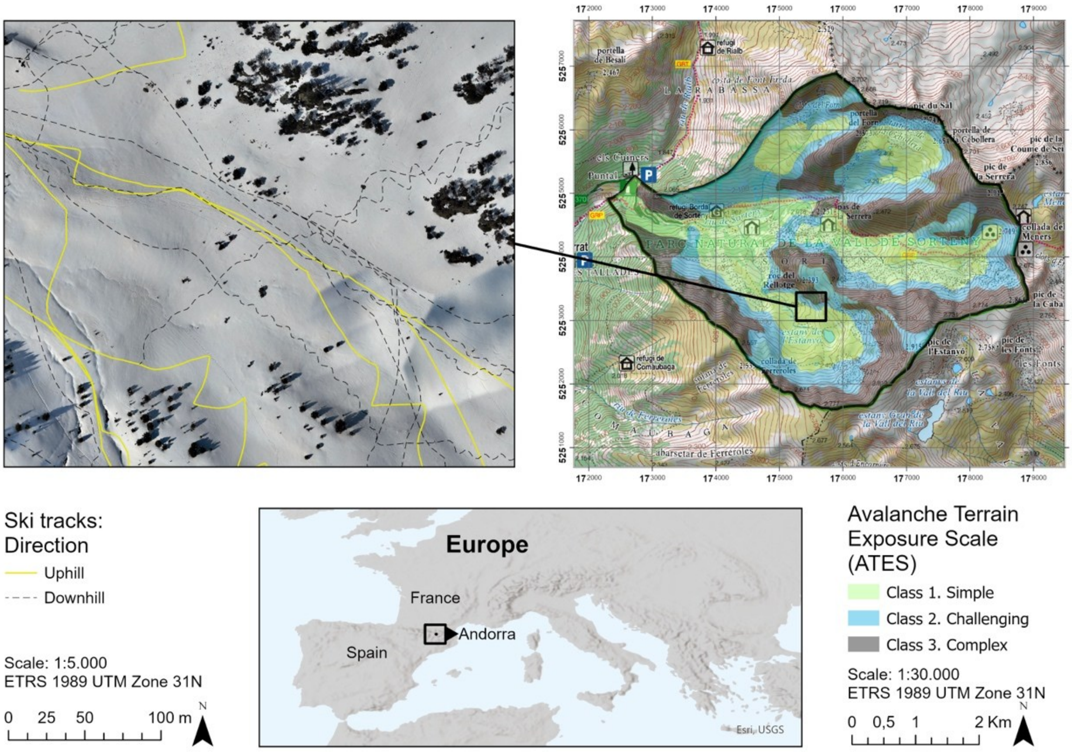


Figure 1. Case study area in the Sorteny Natural park in Andorra with the ATES classification (top-right) and a sample of the tracks gathered by drone imagery (top-left).

### *2.3 Drone and GNSS observations*

Observed terrain use was characterized using drone-based remote sensing and GNSS tracking. Drone observations were acquired using a DJI Matrice 4E between 21 March and 11 April 2026. Eighteen flights were conducted and 16 were further retained after quality control (absence of clouds, good light conditions…) High-resolution aerial photographs collected during the flights were processed to generate orthomosaics with a spatial resolution of 10 cm per pixel. Flights covered the main recreational valleys under a range of different avalanche danger conditions.

GNSS tracks were collected using a Garmin eTrex SE and supplemented by anonymized participant tracks and researcher-recorded routes. A total of 10 GNSS tracks were retained for analysis: one participant-provided track and nine researcher-recorded tracks. GNSS observations were particularly useful in areas where drone acquisition was not feasible (Figure 1).

Both approaches were constrained by weather, personnel availability and safe access to observation locations.

## 3. METHODOLOGICAL FRAMEWORK AND DATA INTEGRATION

The framework integrates four complementary information sources: Avalanche Bulletin information, survey responses, spatial observations from GPS and drones, and ATES terrain classification (Figure 2).

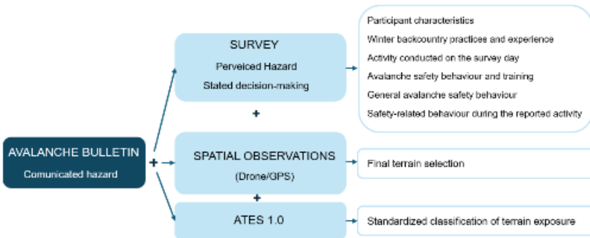


Figure 2. Conceptual framework of the study

The Avalanche Bulletin represents communicated hazard, including danger level, avalanche problem, expected avalanche size and relevant spatial characteristics such as aspect and elevation. The survey captures perceived hazard, planning and stated behaviour. GNSS and drone observations provide an independent representation of observed terrain use, while ATES provides a standardized classification of avalanche terrain exposure.

The datasets are linked primarily through activity date and spatial location. Survey responses refer to a specific activity, while the corresponding Avalanche Bulletin provides the hazard information issued for that date. GNSS tracks can be directly associated with their recording date and compared with both survey responses and Bulletin information. Spatially, observed tracks can be intersected with ATES terrain classes and the spatial characteristics of avalanche problems described in the Bulletin.

A standardized set of Avalanche Bulletin variables was defined to facilitate comparisons across datasets. The initial structure considered danger level, avalanche problem, expected avalanche size, aspect, elevation and spatial distribution. For each bulletin, the primary and, where applicable, secondary avalanche problems were represented.

The same structure was incorporated into the survey, allowing reported understanding of Bulletin information to be compared with the information communicated.

The resulting framework enables three principal comparisons:

1. Avalanche Bulletin ↔ Survey: communicated versus perceived hazard and stated decision-making.
2. Avalanche Bulletin ↔ GPS/drone ↔ ATES: communicated hazard versus observed terrain selection.
3. Avalanche Bulletin ↔ Survey ↔ spatial observations ↔ ATES: integrated comparison of communicated hazard, reported decisions and observed terrain use.

A key methodological limitation is the temporal uncertainty of drone observations. Unlike GPS tracks, which have a known recording date, tracks visible in drone imagery may have been created on previous days. This uncertainty is particularly relevant during periods of stable weather and snow conditions.

## 4. PRELIMINARY RESULTS AND DISCUSSION

### *4.1 Characteristics of the surveyed population*

A total of 57 individuals were approached, of whom 55 (96.5%) completed the questionnaire. The sample comprised 36 men (65.5%), 18 women (32.7%) and one non-binary participant (1.8%). Twenty-nine participants (52.7%) resided in Andorra and 26 (47.3%) in Spain.

Ski touring was the predominant activity, and the sample included a broad range of winter backcountry experience. Most participants reported personal recreational use without a guide (38 participants; 69.1%), although multiple roles could be selected. The three roles most frequently involved in group decision-making accounted for 42 participants (76.4%) of the sample (Figure 3). Most of the surveyed indicated that used avalanche and weather forecast bulletins to plan the activity.

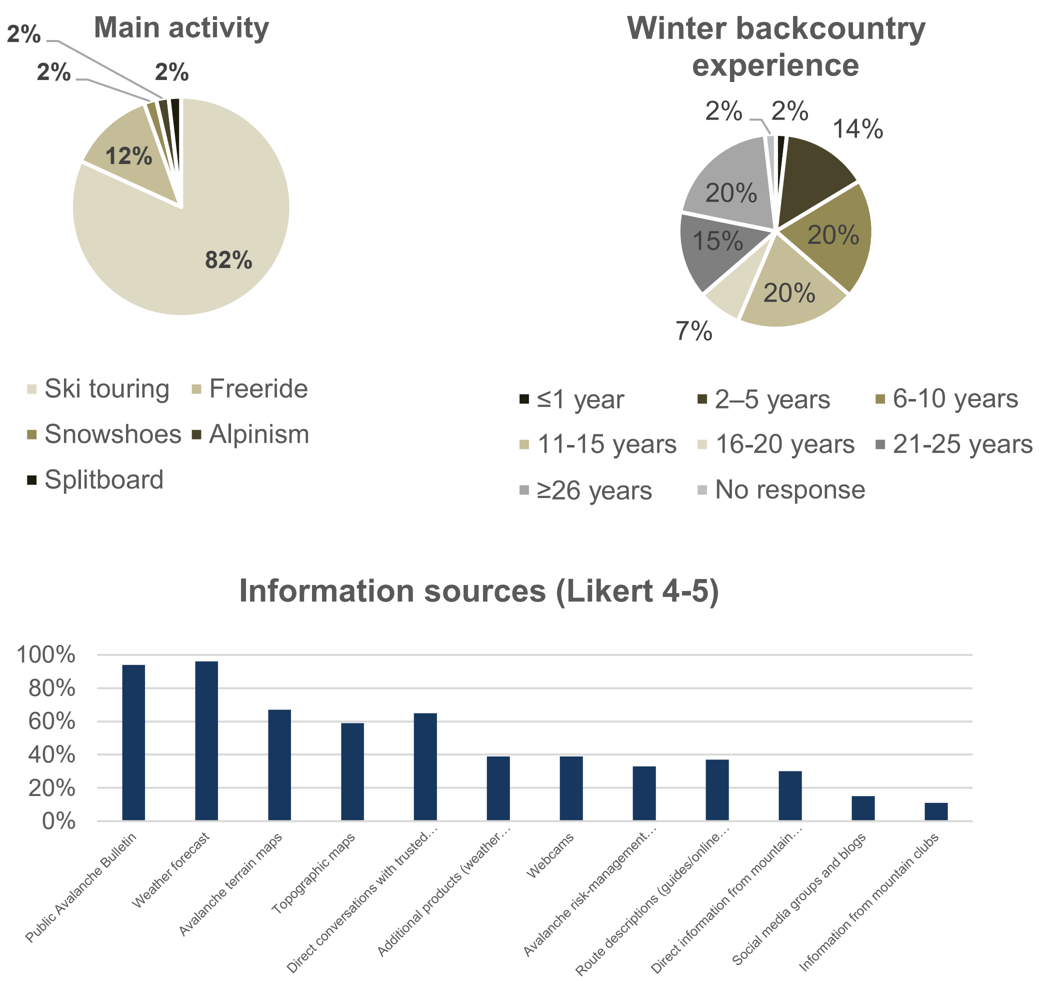


Figure 3. Participants' decision-making role in avalanche risk management (bottom), main activity (top-left) and years of experience (top right) of the surveyed participants.

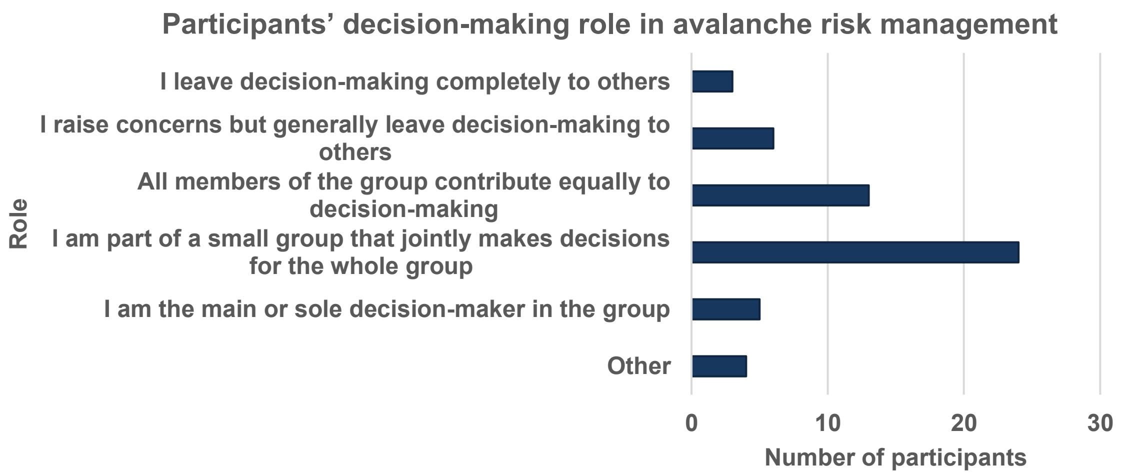


Figure 4. Information sources used to plan the activity in avalanche terrain.

## *4.2 Observed terrain use*

A total of 112 observed tracks were classified according to ATES terrain class, activity and direction of travel. Tracks were distributed across simple (45), challenging (36) and complex terrain (31). Ski touring accounted for most observations (88), followed by snowmobile (19) and snowshoe activity (5).

Terrain use varied according to activity and direction of travel. For ski touring, complex terrain was observed substantially more frequently during descent than ascent, while ascent observations were relatively more concentrated in simpler terrain. Snowshoe observations were restricted to simple and challenging terrain, whereas snowmobile observations occurred across all three ATES classes (Figure 4).

Track counts alone do not represent the amount of terrain travelled. Track length was therefore also calculated by ATES class. Complex terrain contained the longest observed tracks despite having a similar number of tracks to the other classes, indicating that distance travelled provides an additional measure of terrain exposure.

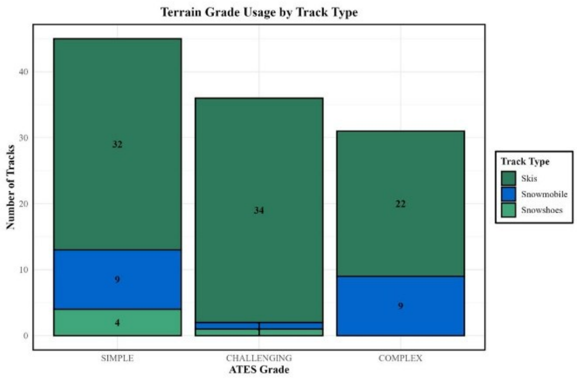


Figure 5. ATES terrain class used by activity type.

Terrain use also varied between observation dates. On 6 April, most observed activity occurred in challenging terrain, whereas on 11 April a larger proportion of observations occurred in complex terrain. These differences provide the basis for comparing terrain selection with the avalanche conditions communicated on each observation date. The percentage of observed terrain use within each ATES class was also calculated for each observation day (Figure 5), providing a standardized measure of daily terrain selection.

### Comparison with survey responses: observed behaviour versus reported behaviour

Participants were asked to classify the avalanche exposure of the terrain they traversed. Of the 55 respondents, 3 (5.5%) classified the terrain as having no exposure, 24 (43.6%) as simple, 22 (40.0%) as challenging, 5 (9.1%) as complex, and 1 (1.8%) as extreme. These responses provide a direct basis for comparing perceived terrain exposure with the ATES classification of the terrain observed through GPS and drone data. Participants also reported differences between ascent and descent routes. Thirty-five participants (63.6%) reported using different routes for ascent and descent, while 20 (36.4%) used the same route. Fifty participants (90.9%) reported using the ascent route to assess snowpack–terrain stability before descending.

A further improvement concerns the linkage between individual survey responses and observed tracks. The initial approach attempted to link each questionnaire to a specific GNSS track using a unique allowing case-level rather than aggregate comparisons code but as most of the users refused to use a GNSS device. However, this approach proved difficult to implement consistently, particularly having mostly drone-derived observations. The questionnaire therefore included a question asking participants to describe the route undertaken, providing an alternative basis for spatial comparison.

## *4.3 Avalanche Bulletin and survey responses*

Participants reported frequent use of the Public Avalanche Bulletin and weather forecasts when assessing avalanche conditions (Figure 3). The danger rating and weather information were the most frequently consulted bulletin components, followed by dangerous locations and avalanche problems.

The comparison between participants' responses and the corresponding Avalanche Bulletin provides a first assessment of bulletin understanding. Across the March and April observations, 55 responses contained valid answers for both the primary avalanche problem and the corresponding danger level. In March, the danger level was correctly identified in 30.4% of cases, compared with 21.7% for the primary avalanche problem. In April, the corresponding proportions were 56.3% and 25.0%, respectively. Thus, in both months, participants were more successful in identifying the overall danger level than the specific avalanche problem reported in the Bulletin. Both elements were correctly identified in 8.7% of March responses and 18.8% of April responses, while neither element was correctly identified in 56.5% and 46.9% of cases, respectively. The proportion of responses in which the danger level was correctly identified but the avalanche problem was not was 21.7% in March and 28.1% in April, compared with 13.0% and 6.3%, respectively, for the opposite pattern. Overall, these results indicate that participants had greater difficulty identifying the specific avalanche problem than the overall danger level, with performance improving from March to April, particularly for danger-level identification.

Observed terrain use varied substantially between observation dates and avalanche conditions (Figure 6). Under danger level 2, terrain use was distributed across the three ATES classes, although the distribution differed between avalanche problems: on 21 March, under a wet-slab

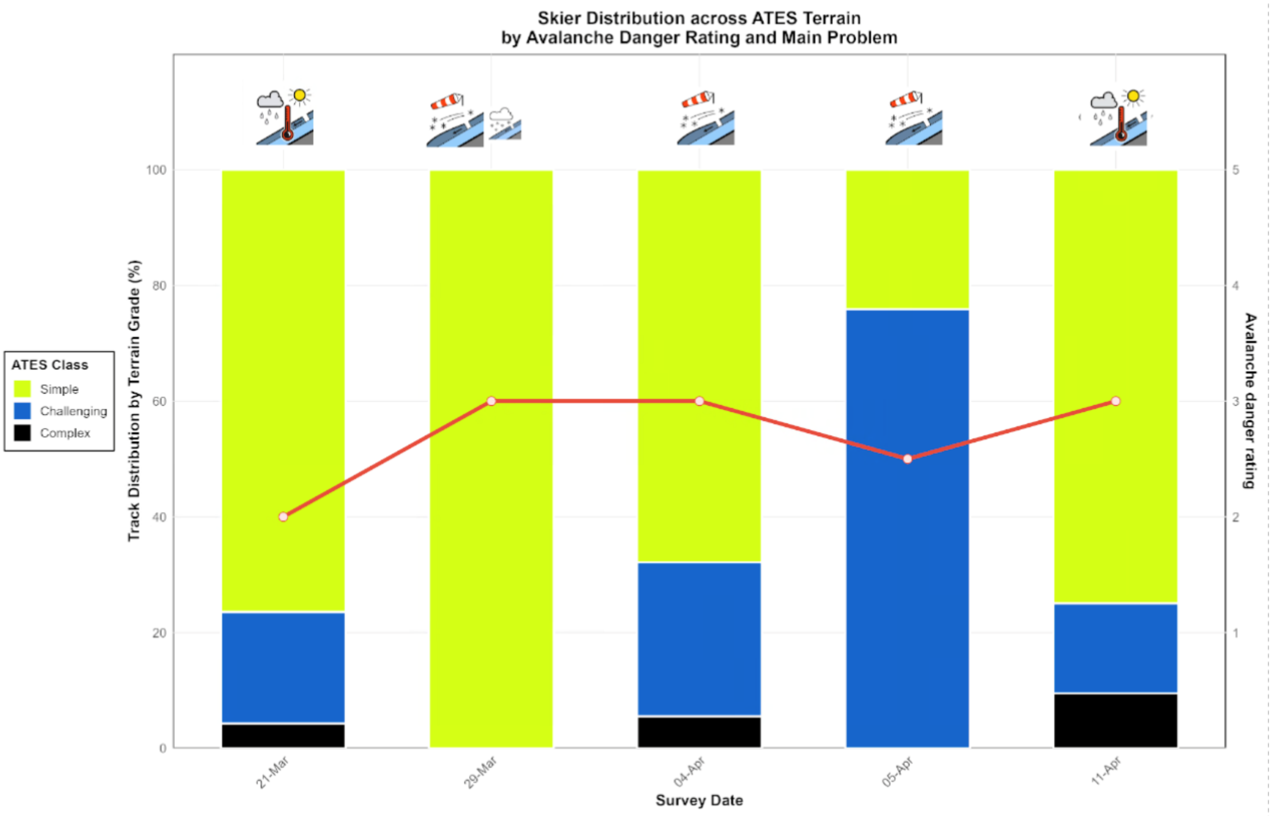


Figure 6. Observed terrain use by ATES class and Avalanche danger rating (red line) and Avalanche problem (icons on top of each day).

problem, approximately 43% of observed tracks were in simple terrain, 36% in challenging terrain and 21% in complex terrain, with similar distribution on 11 April also under wet-avalanche conditions. On 29 March, all the tracks remained in simple terrain, even the main problem was wind-slab, some snow storms introduced loose snow as second problem introducing a higher perception of risk and leading to more conservative use of terrain. On April 4 and 5, under a main wind-slab problem, terrain use was distributed mainly between simple and challenging terrain, with a smaller proportion in complex terrain, while on April 5, with lowering danger level to 2 most of the terrain use was observed in challenging terrain. These observations indicate that the distribution of terrain use varied with both the reported avalanche conditions and the observation date, with the strongest apparent restriction in terrain class occurring on 29 March. However, because the number and spatial coverage of observations differed between dates, these patterns should be interpreted as descriptive evidence of terrain selection under different avalanche conditions rather than as evidence of a direct behavioural response to avalanche danger.

Terrain characteristics were also considered more frequently during the activity than during route planning. Slope and avalanche-path exposure received the highest ratings at both stages, while forest density, terrain traps and avalanche consequences showed the largest increases during the activity. This suggests that terrain characteristics were reassessed in situ and may therefore influence observed terrain selection beyond the initial route plan.

### *4.4 Avalanche Bulletin and observed terrain use*

Observed GNSS and drone derived tracks were spatially linked to the avalanche hazard information reported in the Avalanche Bulletin for the corresponding observation dates. Each observation can therefore be characterized by its ATES terrain class and its relationship with the spatial distribution of the communicated avalanche problem, including relevant elevation and aspect.

## 5. FUTURE WORK AND CONCLUSIONS

The aim of this study was to assess whether avalanche hazard information communicated through the Avalanche Bulletin is correctly understood by backcountry users and whether this understanding is translated into route planning and terrain-selection decisions. The preliminary results show that participants were better able to identify the danger level (56.3%) than the primary avalanche problem (25.0%), suggesting that interpreting the specific nature of the hazard and thus terrain exposure, may be more difficult than recognizing its overall level.

This framework therefore allows assessment of the full process from hazard communication through user understanding to action in the terrain. Observed terrain use varied between avalanche conditions and ATES classes, enabling evaluation of whether users translate avalanche bulletin information into appropriate terrain choices. Drone observations also introduced temporal uncertainty because visible tracks could have been created before the flight and persisted under stable conditions, and users' reluctance to carry GPS trackers complicated the temporal alignment between surveys and actual avalanche terrain use.

Further work is needed to establish a robust link between survey responses and observed tracks while preserving participant anonymity, allowing reported and observed behaviour to be compared at the activity level. This will permit a more robust assessment of whether users understand communicated avalanche hazard and translate this information into appropriate terrain-selection decisions.

This study provides a proof of concept for a framework linking communicated hazard, user understanding, and observed terrain selection, providing a basis for investigating how Avalanche Bulletin information is transformed into decisions in the backcountry activities.

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