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GIS analysis for avalanche susceptibility in the upper sector of Bâlea Valley (Făgăraș Mountains, Romania)

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GIS analysis for avalanche susceptibility in the upper sector of Bâlea Valley (Făgăraș Mountains, Romania)

Denisa-Ionela MUNTEANU

Analiză GIS pentru susceptibilitatea la avalanșe în sectorul superior al Văii Bâlea (Munții Făgăraș, România). Menținerea funcționalității drumurilor montane în sezonul rece reprezintă o provocare majoră în contextul intensificării hazardelor naturale și al creșterii presiunii turistice asupra regiunilor alpine. Sectorul Cabana Bâlea Cascadă – Bâlea Lac (DN7C – Transfăgărășan) este caracterizat printr-o vulnerabilitate ridicată la avalanșe, ceea ce determină închiderea anuală a circulației pentru perioade extinse. Lucrarea are ca obiectiv evaluarea riscului de avalanșă și identificarea unor soluții de amenajare rutieră care să permită extinderea perioadei de acces în condiții de siguranță. Metodologia integrează tehnici GIS și analiză multicriterială, utilizând date open source și modele digitale ale terenului. Au fost analizați principalii factori geomorfologici (panta, orientarea versanților, altitudinea, curbura și utilizarea terenurilor), iar evaluarea riscului a fost realizată diferențiat sezonier, pentru condițiile specifice iernii și primăverii. Rezultatele evidențiază distribuția spațială a zonelor cu susceptibilitate ridicată la avalanșe și rolul determinant al geodeclivității și orientării versanților. Pe baza analizei au fost identificate sectoare critice și formulate propuneri de intervenție, precum galerii de protecție, paravane anti-avalanșă și adaptări locale ale traseului rutier. Studiul demonstrează eficiența utilizării GIS în evaluarea riscurilor naturale și contribuie la fundamentarea unor soluții sustenabile pentru creșterea siguranței și accesibilității infrastructurii montane.

Cuvinte cheie: avalanșă, susceptibilitate, GIS, analiză multicriterială, infrastructură rutieră, Transfăgărășan.

GIS analysis for avalanche susceptibility in the upper sector of Bâlea Valley (Făgăraș Mountains, Romania). Maintaining the functionality of mountain roads during the winter season represents a major challenge in the context of increasing natural hazards and growing tourism pressure in alpine regions. The Bâlea Cascadă – Bâlea Lake sector (DN7C – Transfăgărășan) is highly exposed to avalanche activity, leading to prolonged annual road closures. This study aims to assess avalanche risk and to identify technical solutions for road infrastructure that could extend the accessibility period under safe conditions. The methodology integrates GIS techniques and multicriteria analysis, based on open-source datasets and digital elevation models. Key geomorphological factors (slope, aspect, altitude, curvature, and land use) were analyzed, and risk assessment was performed seasonally, distinguishing between winter and spring avalanche conditions. The results highlight the spatial distribution of high-susceptibility areas and emphasize the influence of slope and aspect on avalanche occurrence. Critical sectors were identified, and mitigation measures such as snow sheds, avalanche barriers, and local route adjustments were proposed. The study demonstrates the effectiveness of GIS-based approaches in natural hazard assessment and supports the development of sustainable strategies for improving safety and accessibility of mountain road infrastructure.

Keywords: avalanche, susceptibility, GIS, multi-criteria analysis, mountainous roads, Transfagarasan.

1. INTRODUCTION

Maintaining the functionality of mountain roads during the winter season represents a major challenge in the context of increasing natural hazards and growing tourism pressure on alpine regions. Snow avalanches constitute one of the primary natural risks affecting mountain road infrastructure, frequently leading to road closures and generating significant economic and social impacts. Alpine roads play a crucial role in ensuring accessibility, supporting tourism, and connecting remote areas, which necessitates the development of effective risk management solutions (O'Gorman, Jones, 2005; Keller, Sherar, 2003).

The Transfăgărășan Road (DN7C), one of the most important mountain roads in Romania, crosses the Făgăraș Mountains and is widely recognized for its touristic and strategic importance. The upper sector of the Bâlea Valley, located between Bâlea Cascadă Chalet and Bâlea Lake, is characterized by a high susceptibility to avalanches, driven by specific geomorphological and climatic conditions, including elevations exceeding 1600 m, steep slopes, and slope orientations that favor snow accumulation and instability. Under these conditions, the road is closed annually for an extended period (October–June), affecting accessibility, economic activities, and tourist flows.

At the international level, avalanche susceptibility analysis has significantly advanced through the use of GIS techniques and multicriteria models that integrate key factors such as slope, aspect, elevation, and land use (Grêt-Regamey, Straub, 2006; Parshad et al., 2017). These approaches enable spatial risk assessment and support the development of effective prevention and protection measures.

In this context, the main objective of this study is to assess avalanche risk in the upper sector of the Bâlea Valley and to identify road engineering solutions aimed at extending the operational period of the road under safe conditions. The analysis is based on the integration of geomorphological factors within a GIS-based multicriteria model, with the purpose of delineating vulnerable areas and supporting decision-making processes related to mountain infrastructure management.

2. METHODOLOGY

2.1. Study area

The analyzed sector is located in the northern part of the Făgăraș Mountains and corresponds to the road segment between Bâlea Cascadă and Bâlea Lake, part of the DN7C-Transfăgărășan highway. The geographical position of the study area is illustrated in Figure 1, which highlights its location within the mountain unit, as well as its relationship with the main landforms and the hydrographic network.

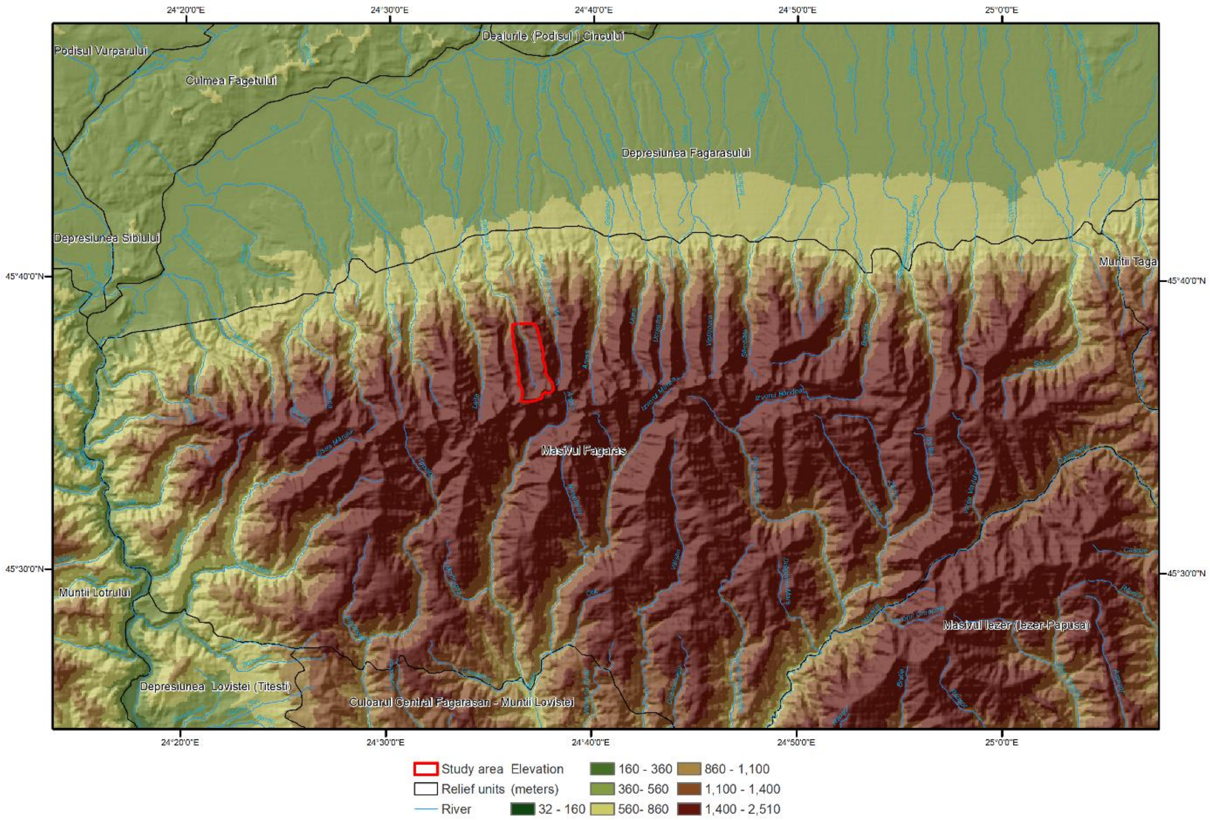

Figure 1. Location of the study area

From a geomorphological perspective, the Bâlea Valley is characterized by highly fragmented apline relief, dominated by glacial landforms such as cirques, U-shaped valleys, steep slopes, and moraines, formed because of Quaternary glacial processes. Elevations range from approximately 1700 m to over 2000 m, while slopes frequently exceed 30–35°, conditions that significantly favor the initiation of snow-related processes.

The climate of the area is alpine, characterized by low mean annual temperatures ranging between −2°C and 2°C, as well as by a prolonged cold season. Snow cover generally persists from November to May, reaching considerable thickness during the winter months. These climatic conditions, together with the influence of dominant winds, lead to uneven snow accumulation and contribute to snowpack instability.

These physical-geographical characteristics result in a high susceptibility to avalanches within the analyzed sector. Documented events, including both historical and recent avalanches, highlight the frequency and intensity of this hazard, as well as its impact on road infrastructure and tourism-related activities.

Currently, the road segment is closed to traffic during the winter season due to avalanche risk and extreme weather conditions. Existing mitigation measures are limited and do not include permanent protective structures, which maintains the high vulnerability of this sector.

Therefore, the geomorphological and climatic particularities of the Bâlea Valley justify the selection of this area as a case study for avalanche susceptibility analysis and for the development of site-specific mitigation measures adapted to local conditions.

2.2. Data and methods

The avalanche susceptibility analysis in the upper sector of the Bâlea Valley was carried out using GIS techniques and a multicriteria approach, based on the integration of geospatial datasets derived from open-source sources and processed in the ArcMap 10.6.1 environment. The methodological framework aimed to identify the key geomorphological factors influencing avalanche occurrence and to evaluate their contribution within a spatial risk model.

In the initial stage, only freely available datasets were used, enabling the physical-geographical characterization of the study area and the implementation of spatial analyses. The database included Digital Elevation Models (DEM), contour lines, hydrographic network data, geomorphological unit boundaries, land use data, and elevation points. These datasets were used to generate thematic raster layers required for morphometric analysis.

The methodological approach integrated several techniques specific to geographical and spatial analysis, including direct observation, cartographic and graphical methods, morphometric and morphological terrain analysis, comparative analysis, and deductive interpretation. These methods enabled the correlation between terrain characteristics and snow-related processes, as well as the assessment of the relationship between natural factors and road infrastructure.

Within the GIS-based analysis, five main factors were considered: slope (geodeclivity), aspect, elevation, plan curvature, and land use. The derivation and processing of these factors were performed using specific GIS tools (Slope, Aspect, Curvature, Reclassify), while a synthesis of the indicators and processing methods is presented in Table 1.

Based on the Digital Elevation Model (DEM) and the thematic datasets, a series of derived maps were generated, representing slope (geodeclivity), aspect, elevation, plan curvature, and land use. These cartographic products provided the foundation for multicriteria analysis.

Data processing involved the reclassification of each factor to standardize values and express their relative influence on avalanche susceptibility. The process was carried out in two stages: an initial reclassification of the original values, followed by the assignment of weighted values according to the relevance of each class.

Table 1. Indicators used and GIS processing methods

Indicator	GIS tool used	Processing method	Analyzed geographical characteristic	Relevance for avalanches
Slope (Gradient)	Spatial Analyst Tools – Surface → Slope	Slope inclination in degrees	Terrain morphology	Areas with steep slopes (>30°) present a higher avalanche triggering risk.
Slope aspect	Spatial Analyst Tools – Surface → Aspect	Cardinal orientation of slopes	Solar exposure / atmospheric circulation	North-facing slopes retain snow longer, while south-facing slopes experience accelerated snowmelt.
Absolute elevation (m)	DEM / Extract by Mask / Zonal Statistics	Terrain elevation above sea level	Terrain elevation above sea level	High-altitude areas retain snow for longer periods and are more prone to avalanches.
Plan curvature	Spatial Analyst Tools – Surface → Curvature	Lateral slope shape (horizontal curvature)	Horizontal landform shape (concave or convex)	Concave areas accumulate more snow, favoring snow deposition.
Land use	Corine Land Cover (2018)	Type of land cover and land use	Vegetation, buildings, pastures, grasslands, etc.	Forested areas retain snow and reduce avalanche risk, while alpine open areas favor snow sliding.

Avalanche susceptibility was assessed by integrating the analyzed factors into an overlay model, based on the combination of reclassified raster layers. The applied relationship is:

$$Ar = G \times A \times Pc \times E \times Le$$

where Ar represents avalanche risk, G – slope (geodeclivity), A – aspect, Pc – plan curvature, E – elevation and Le – land use.

An important aspect of the methodology is the seasonal differentiation of the analysis. Thus, slope aspect was treated distinctly for the winter and spring seasons, to reflect variations in avalanche triggering mechanisms. During winter, the risk is primarily associated with snow accumulation on north-facing slopes, whereas in spring it is driven by accelerated melting processes on south-facing slopes.

The integration of these factors enabled the identification of areas with high avalanche susceptibility and the assessment of the vulnerability of road infrastructure. The results obtained provide the basis for subsequent analysis and for the formulation of road engineering solutions adapted to the geomorphological and climatic conditions of the study area.

3. RESULTS

The multicriteria analysis enabled the identification and spatial delineation of areas with high avalanche susceptibility within the Cabana Bâlea Cascadă – Bâlea Lake sector. The integration of geomorphological and land use factors highlighted a differentiated spatial distribution of risk, as well as significant seasonal variations, confirming the importance of a seasonal approach in the assessment of snow-related hazards.

3.1. Avalanche risk distribution in the winter season

The results obtained for the winter season highlight a concentration of high-susceptibility areas on north-facing and north-west-facing slopes, where shading conditions and low temperatures favor the accumulation and persistence of an unstable snowpack. These areas are characterized by slope angles ranging between 25° and 45°, elevations exceeding 1600 m, and the absence of forest vegetation, factors that act cumulatively to increase avalanche risk (Figure 2). For the avalanche risk in winter, high susceptibility values are concentrated in the upper sectors of the valley and on the steep slopes overlooking the road corridor. Under these conditions, the risk is primarily driven by the rapid accumulation of fresh snow over an unstable layer, a process typical of dry snow avalanches during the winter season.

3.2. Avalanche risk distribution in the spring season

The model developed for the spring season indicates a significant shift in the spatial distribution of avalanche risk, driven by increasing temperatures and intensified solar radiation. As a result, south-facing, south-east-facing, and south-west-facing slopes become the most vulnerable, due to accelerated snowmelt and the loss of snowpack cohesion.

From a morphometric perspective, the highest susceptibility values are associated with slope angles ranging between 25° and 45°, like those identified in the winter season. However, the key difference lies in the change in slope orientation. During the spring season, these slope intervals become critical particularly on sun-exposed slopes, where melting processes are more intense.

Elevation continues to play an important role, with areas located between approximately 1600 m and 2350 m being the most affected (Figure 3), due to the significant snow accumulation during winter and its persistence into the warming period. Under these conditions, the snowpack becomes saturated with water, leading to a substantial decrease in stability.

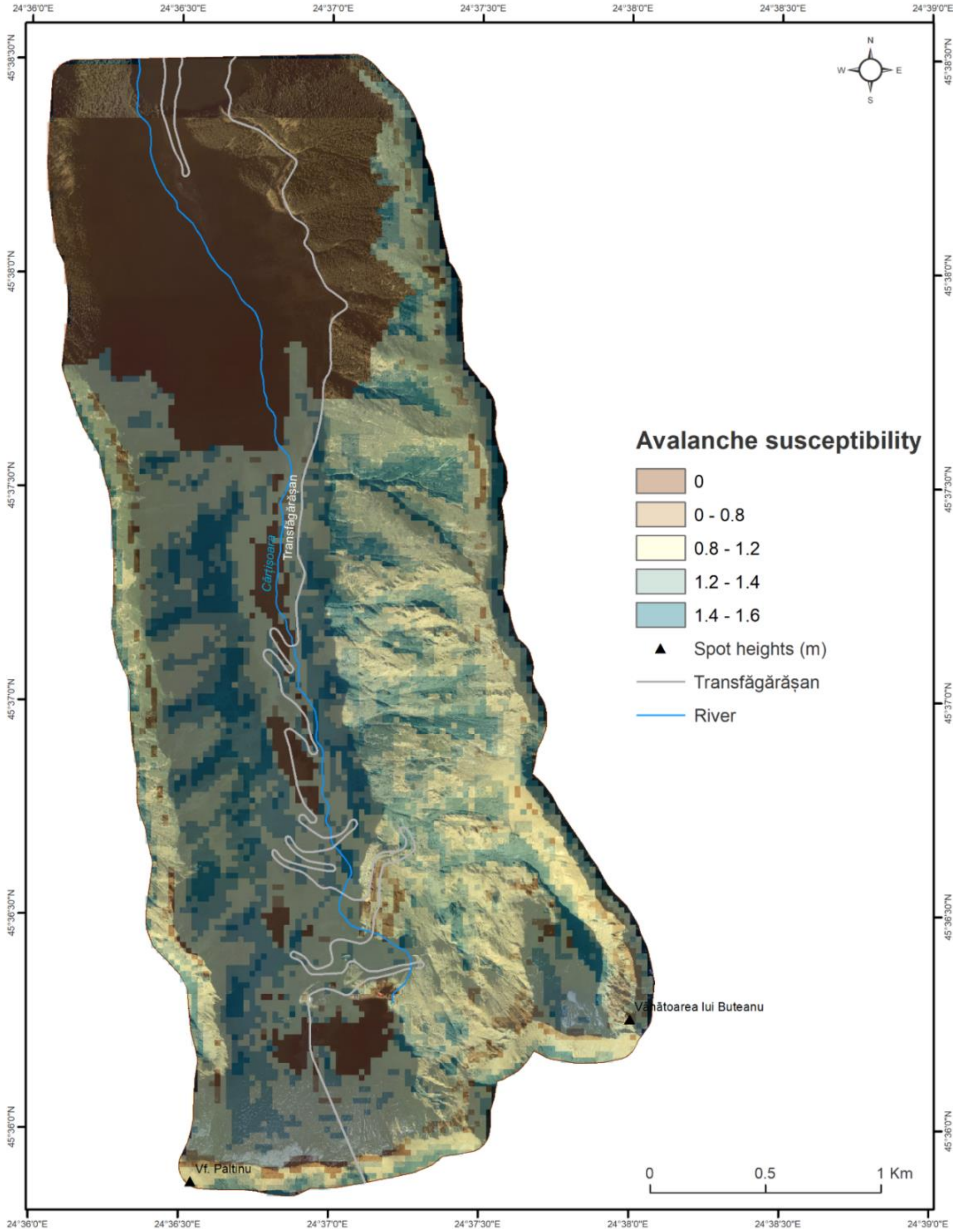

Figure 2. Avalanche risk in winter

Avalanche risk in spring highlights the shift of high-susceptibility zones toward south-facing and south-east-facing slopes. Avalanches characteristic of this season are predominantly wet snow avalanches, generated by water infiltration within the snowpack and the resulting reduction in internal friction.

3.3. Seasonal comparative analysis

The comparison of the two models highlights a clear seasonal dynamic of avalanche risk. While the winter season is characterized by snow accumulation on north-facing and north-west-facing slopes, in spring the risk shifts toward south-facing, south-east-facing, and south-west-facing slopes, where melting processes become dominant (Figure 4).

The overlay of avalanche risk (winter and spring) allows the identification of both seasonally controlled risk areas and zones with persistent susceptibility. Areas where high susceptibility values overlap in both models represent critical sectors, characterized by the convergence of favorable conditions such as steep slopes, high elevations, and the absence of forest vegetation.

The overlay analysis highlights that these sectors are predominantly located in the middle and upper sections of the route, where steep terrain and slope exposure favor both snow accumulation during the winter season and accelerated melting processes in spring.

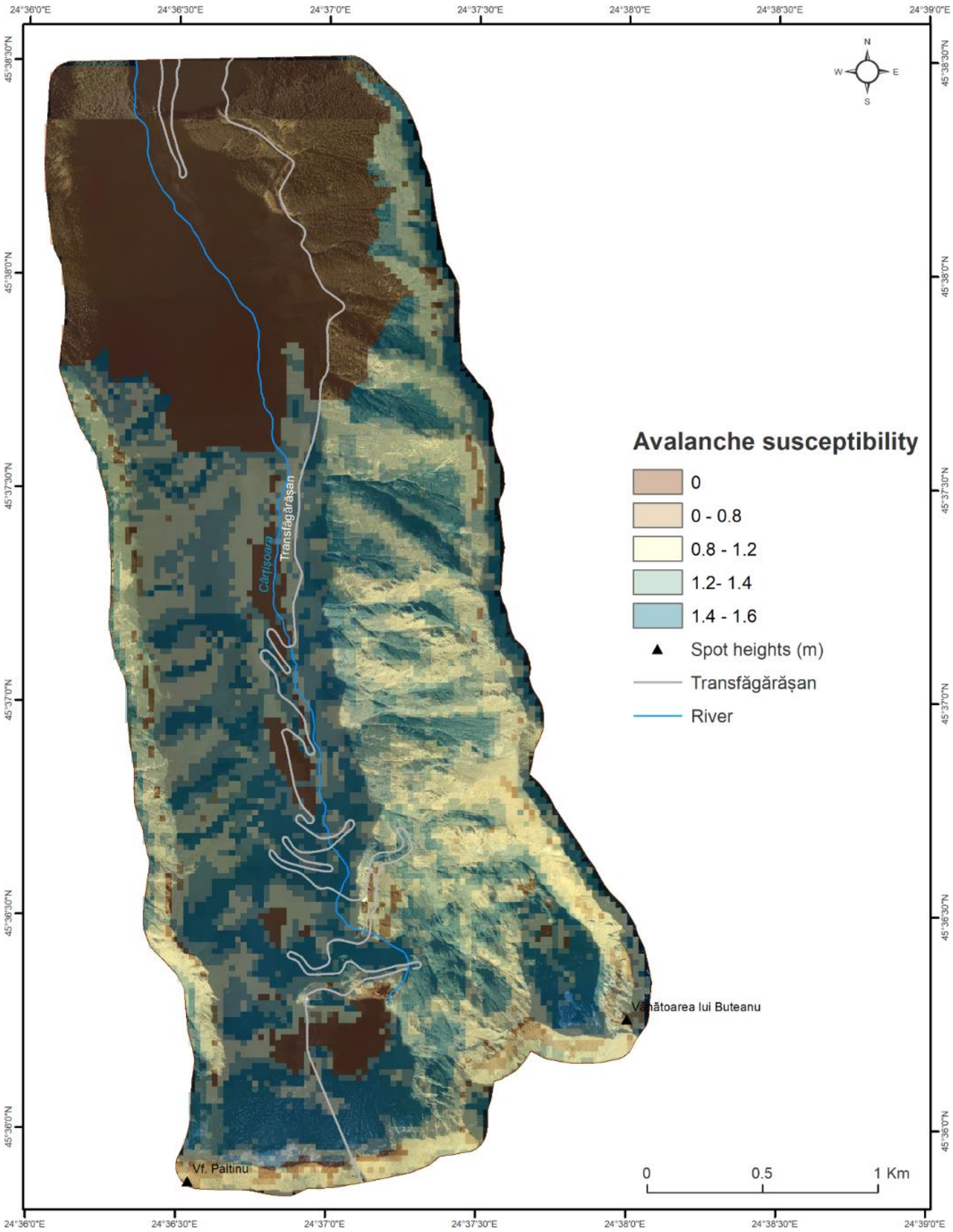

Figure 3. Avalanche risk in spring

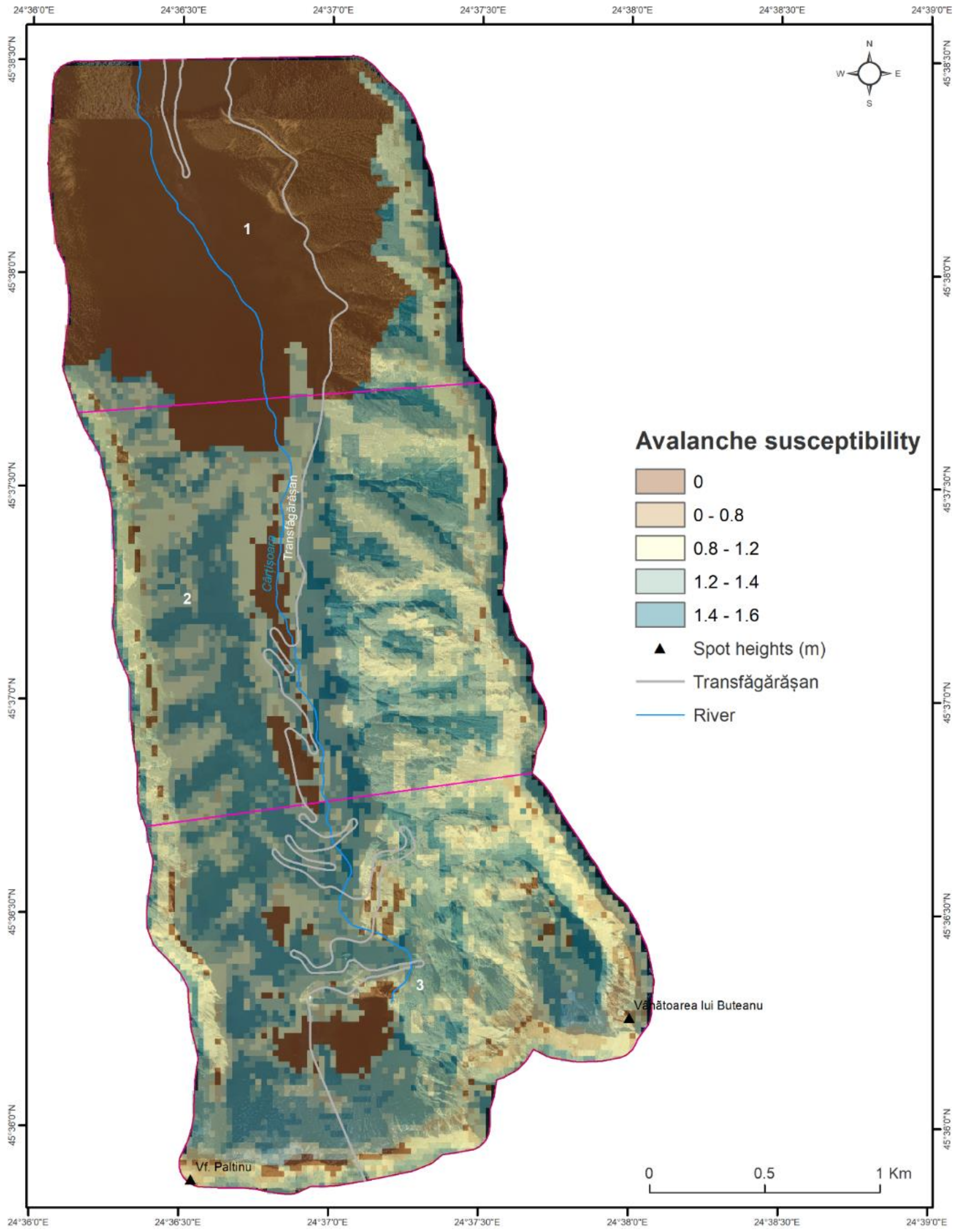

Figure 4. Seasonal evolution of avalanche risk in the upper Bâlea Valley (winter vs. spring)

4. DISCUSSION

4.1. Implications for road accessibility

The results highlight a direct relationship between the spatial distribution of avalanche risk and the vulnerability of the road sector analyzed. Areas with high susceptibility frequently overlap with the Transfăgărășan route or with its adjacent slopes, which explains the frequent blockages and the necessity of road closure during the winter season.

The lower sector, located near Bâlea Cascadă Chalet, presents a lower level of risk due to its lower elevation and the presence of forest vegetation. In contrast, the upper sectors, characterized by steep terrain and direct exposure to snow-related processes, exhibit a high level of risk, particularly in areas where the road intersects potential avalanche paths.

Areas identified as having persistent risk, highlighted through the overlap of the two seasonal models, represent critical points for road infrastructure and require priority interventions. In these sectors, risk is present throughout the entire cold season, being generated by both snow accumulation and snowmelt processes.

Therefore, the GIS-based analysis provides essential support for identifying vulnerable sectors and for substantiating protective measures, contributing to increased traffic safety and to the extension of the road's operational period.

4.2. Road engineering proposals

The results of the multicriteria analysis highlight the presence of sectors with high avalanche susceptibility, both in winter and spring, particularly in areas where steep slopes, high elevations, and the absence of forest vegetation overlap. The areas with persistent risk, identified through the overlap of seasonal models, represent critical sectors for road infrastructure and require priority interventions.

Based on these findings, a set of road engineering solutions has been proposed, tailored to local conditions, with the main objective of reducing risk and extending the operational period of Cabana Bâlea Cascadă – Bâlea Lake road sector.

In sectors with high and persistent risk, particularly where the road is located at the base of steep slopes identified in the GIS analysis, the construction of avalanche protection galleries (snow sheds) is recommended. These structures allow snow masses to pass over the roadway, thereby reducing the direct impact on the infrastructure. Their implementation is especially recommended in the upper sections of the route, where high susceptibility values were identified in both seasonal scenarios.

To reduce snow accumulation in potential release areas, the installation of avalanche control structures such as snow fences is proposed in the upper parts of the slopes. These structures contribute to stabilizing the snowpack and limiting avalanche formation. Their placement should be adapted seasonally, recommended on the north-facing slopes to reduce winter snow accumulation and on south-facing slopes to mitigate wet snow avalanches during spring.

In addition to structural measures, the implementation of non-structural solutions is recommended, including continuous monitoring of snowpack conditions, early warning systems, and controlled avalanche triggering under safe conditions. Furthermore, the establishment of flexible protocols for road closure and reopening, based on seasonal risk levels, can contribute to more efficient infrastructure management.

The implementation of these measures can significantly improve traffic safety and reduce the duration of road closures during the winter season. At the same time, enhanced accessibility may have positive effects on tourism and the local economy. However, all interventions should be carried out in accordance with sustainable development principles, ensuring minimal impact on the mountain environment.

5. CONCLUSIONS

The study conducted on the Cabana Bâlea Cascadă – Bâlea Lake sector highlights the complexity of the factors influencing avalanche occurrence and their impact on mountain road infrastructure. The integration of GIS techniques and multicriteria analysis enabled the identification and delineation of areas with high avalanche susceptibility, as well as the assessment of seasonal variations in risk.

The results indicate that risk distribution is primarily controlled by slope (geodeclivity), aspect, and elevation, factors that operate differently depending on the season. During winter, the most vulnerable areas are located on north-facing and north-west-facing slopes, where snow accumulation is favored by shading conditions. In contrast, during the spring season, the risk shifts toward south-facing, south-east-facing, and south-west-facing slopes, because of accelerated snowmelt processes.

The seasonal comparative analysis highlighted the presence of sectors with persistent risk, where conditions favorable to avalanche release are present throughout the entire cold season. These areas represent critical points for road infrastructure and require priority interventions to reduce vulnerability.

Based on the results obtained, a series of road engineering proposals were formulated, including avalanche protection galleries, snow fences, and risk management measures. Their implementation can contribute to improved traffic safety and to extending the operational period of the Transfăgărășan road within the analyzed sector.

In conclusion, the study demonstrates the effectiveness of GIS-based approaches in natural hazard assessment and emphasizes the importance of an integrated methodology adapted to local conditions and seasonal variability. The results can provide valuable support for decision-making processes related to mountain infrastructure management and the development of sustainable risk mitigation strategies.

6. ACKOWLEDGEMENTS

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