A systematic hazard-profiling framework for mountain pedestrian trails in multifunctional protected landscapes

Marco sistemático para perfilar peligros en senderos peatonales de montaña en paisajes protegidos multifuncionales

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Abstract

Introduction: Hiking is an accessible form of outdoor recreation, but growing trail use increases exposure to environmental and infrastructure hazards in protected landscapes with overlapping recreational and traditional uses.
Objective: This study developed and applied a systematic framework for profiling hazards on mountain pedestrian trails.
Methodology: A systematic observational cross-sectional assessment covered 14 official short-route trails in the Peneda-Gerês region, northern Portugal. Three independent assessors recorded observable hazards, which an independent expert panel reviewed. Hazards were classified and rated for probability and consequence to obtain a semi-quantitative risk value.
Results: Among 160 hazards, material hazards predominated (84.4%), particularly motorized-vehicle conflicts and signage deficiencies. Geomorphological hazards were less frequent (13.8%) but had higher risk values than material hazards (8.59 vs. 3.91; $p < 0.001$). Water-related features accounted for all hazards with catastrophic potential. Accumulated risk increased with trail length, elevation gain, and duration; trail configuration showed no significant differences.
Discussion: The findings revealed frequent modifiable operational hazards alongside less frequent natural hazards with greater potential severity.
Conclusions: The framework supports transferable prioritization of inspection, communication, maintenance, and targeted mitigation in protected mountain landscapes.

Keywords

Hiking safety; mountain trails; outdoor recreation; risk assessment; risk profiling.

Resumen

Introducción: El senderismo es una forma accesible de recreación al aire libre, pero el aumento del uso de senderos incrementa la exposición a peligros ambientales y de infraestructura en paisajes protegidos con usos recreativos y tradicionales superpuestos.
Objetivo: Este estudio desarrolló y aplicó un marco sistemático para perfilar peligros en senderos peatonales de montaña.
Metodología: Se realizó una evaluación observacional transversal de 14 senderos oficiales de pequeña ruta en la región de Peneda-Gerês, norte de Portugal. Tres evaluadores independientes registraron los peligros observables, posteriormente revisados por un panel experto independiente. Los peligros se clasificaron y valoraron según su probabilidad y consecuencia para obtener un valor de riesgo semicuantitativo.
Resultados: Entre 160 peligros, predominaron los materiales (84,4%), especialmente los conflictos con vehículos motorizados y las deficiencias de señalización. Los peligros geomorfológicos fueron menos frecuentes (13,8%), pero presentaron valores de riesgo superiores a los materiales (8,59 frente a 3,91; $p < 0,001$). Los elementos relacionados con el agua concentraron todos los peligros con potencial catastrófico. El riesgo acumulado aumentó con la longitud, el desnivel y la duración; la configuración del sendero no mostró diferencias significativas.
Discusión: Los resultados mostraron peligros operativos frecuentes y modificables junto con peligros naturales menos frecuentes, pero potencialmente más graves.
Conclusiones: El marco permite priorizar inspecciones, comunicación, mantenimiento y mitigación específica en paisajes montañosos protegidos.

Palabras clave

Evaluación de riesgos; perfil de riesgos; recreación al aire libre; seguridad en senderismo; senderos de montaña.

Introduction

Participation in outdoor physical activities in natural environments has expanded substantially in recent decades, driven by growing recognition of their physical, psychological, and social health benefits and increasing appreciation of contact with green and blue spaces as determinants of well-being (Frumkin et al., 2017; Gascon et al., 2015; White et al., 2019). Within this context, hiking on pedestrian trails represents one of the most accessible and widely practiced forms of nature-based recreation, requiring minimal specialized equipment, accommodating diverse age groups and fitness levels, and playing an increasingly prominent role in nature tourism and active leisure strategies that support rural and mountain region development (Eigenschenk et al., 2019; Rantala et al., 2018).

The expansion of trail-based recreation, while beneficial from public health and socio-economic perspectives, inevitably increases exposure to hazards inherent to natural and semi-natural environments (Brandão, Pereira, et al., 2018). Trail-related hazards arise from complex interactions among environmental factors such as geomorphology, weather conditions, and hydrological features; infrastructure-related elements including trail surfaces, gradients, obstacles, and signage; concurrent land uses, particularly shared access with motorized traffic; and human factors encompassing physiological capacity, cognitive and technical skills, equipment choices, and planning decisions (Forrester & Holstege, 2009; Heggie & Amundson, 2009; Salmon et al., 2010). International evidence from protected areas and national parks indicates that incidents and accidents requiring search and rescue interventions are frequent and predominantly associated with hiking activities, underscoring the importance of understanding and managing hazards inherent to pedestrian trail systems (Gstaettner, 2020; Heggie & Heggie, 2009; Ramos Cabal, 2022).

From an etiological perspective, incidents on pedestrian trails rarely result from single isolated factors but instead emerge from multifactorial causal chains in which environmental hazards interact dynamically with human behavior and decision-making (Salmon et al., 2010). Documented accident types include falls and lower-limb injuries on unstable or slippery surfaces, heat-related exhaustion and dehydration on exposed routes, navigational errors linked to inadequate or misleading signage, and high-consequence events at water features such as stream crossings, pools, and hydraulic structures where drowning risk is present (Forrester & Holstege, 2009; McIntosh et al., 2007). Although some of these events may occur infrequently, their potential for severe or fatal outcomes justifies precautionary approaches to hazard identification and risk prioritization (Peden et al., 2016).

Despite the relevance of trail safety for both public health and sustainable nature tourism, the scientific literature remains uneven. Existing research has focused primarily on retrospective analyses of accidents and search and rescue operations in specific locations (Heggie & Heggie, 2009) or on psychological dimensions such as risk perception among recreationists (She et al., 2019). In contrast, prospective, systematic studies that comprehensively characterize hazard profiles across trail networks remain comparatively scarce, particularly those designed as operational protocols that can be applied consistently across trail systems to support comparative assessment and management decision-making. This gap is especially consequential in multifunctional mountain landscapes where pedestrian routes commonly overlap with forestry and agricultural access infrastructure, creating exposure patterns that differ from wilderness-oriented settings. The limitation is therefore not only geographic, but also methodological, given the need for transferable procedures that can move beyond incident-based descriptions toward structured, prospective hazard profiling.

Systematic hazard profiling, defined as the structured identification, classification, and characterization of hazards within a defined system, offers a robust framework for addressing these gaps and supporting evidence-based trail management (Brandão & Soteras, 2025). Such profiling provides quantitative baselines for understanding hazard prevalence, distribution, and severity; enables identification of hazard patterns associated with specific trail characteristics or environmental contexts; supports prioritization of management interventions and allocation of limited resources; and establishes reference points for monitoring temporal changes related to environmental dynamics, infrastructure degradation, or management actions (Leung et al., 2000; Marion & Reid, 2007). In this respect, hazard profiling complements broader approaches used in trail assessment and outdoor recreation safety by translating complex, interacting sources of risk into actionable categories and comparative indicators that can inform maintenance planning, risk communication, and targeted intervention. It also intersects with trail impact and management frameworks by providing systematic, spatially explicit evidence to guide where and how limited resources should be deployed across trail networks (Leung et al., 2000; Marion & Reid, 2007). Understanding how hazard profiles relate to trail characteristics such as typology (linear versus circular routes), technical difficulty, length and duration, and topographic demands, including elevation gain, is particularly relevant for informing trail design, maintenance planning, and user information strategies, including digital route-planning and navigation resources (Hamza Mayora et al., 2025). Likewise, proximity to settlements, agricultural areas, or transport infrastructure may influence the prevalence of specific hazard categories, including motorized vehicle conflicts or livestock encounters, further underscoring the need for context-sensitive assessment (Olive & Marion, 2009; Pickering et al., 2010).

Recent evidence reinforces the need to move from reactive accident descriptions to proactive visitor-risk management in protected and mountain environments. Retrospective analyses show that incidents are concentrated around recurring mechanisms, including trips and falls, disorientation, water-related events, inadequate preparation, and delayed rescue response (Gstaettner, 2020; Sahri et al., 2024; Westman & Björnstig, 2024). In the Peneda-Gerês National Park, occurrence records from 2006 to 2015 identified vulnerabilities associated with mountain activities, including rescue-access asymmetries and longer response times in areas farther from passable roads (Pereira et al., 2020). These findings are consistent with protected-area and active-tourism literature emphasizing shared responsibility, targeted information, infrastructure monitoring, emergency procedures, and site-specific risk communication rather than generalized warnings alone (Gstaettner et al., 2022; Leung et al., 2018; Ramos Cabal, 2022). Prospective hazard profiling can therefore complement accident records by identifying latent risk conditions before they materialize into incidents.

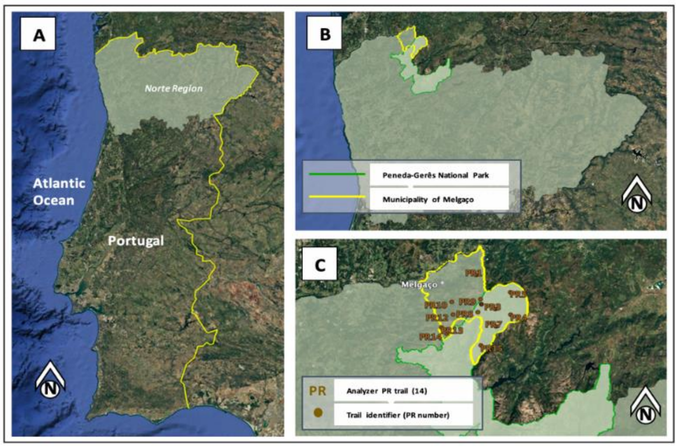
The present study develops and applies a systematic hazard-profiling framework for multifunctional mountain pedestrian trail systems, using Peneda-Gerês as an exemplar case. The objectives were to systematically identify and classify hazards across a diverse sample of short-route pedestrian trails, characterize hazard distribution by category, type, and associated risk levels, examine hazard density and risk patterns in relation to trail characteristics including typology, length, technical difficulty, and topographic demands, compare hazard profiles between linear and circular trail configurations, and identify high-priority hazards for management intervention based on potential consequence severity. By foregrounding a structured, transferable protocol rather than a purely site-specific inventory, this study aims to advance methodological conversations in outdoor recreation safety and trail management while providing a practical evidence base for risk prioritization and targeted mitigation in protected mountain landscapes.

Method

Study design, territorial setting, and management context

A systematic observational cross-sectional study was conducted to identify and characterize hazards on mountain pedestrian trails. The study focused on officially designated short-route pedestrian trails located within and immediately adjacent to the Peneda-Gerês National Park, northern Portugal (Figure 1).

Figure 1. Location of the Peneda-Gerês National Park, municipality of Melgaço and analyzed pedestrian trails. A: North region of Portugal; B: Peneda-Gerês National Park and municipality of Melgaço geographic location; C: All Pedestrian Routes assessed.



The Peneda-Gerês National Park is located in the north of Portugal, along the transition between Minho and Trás-os-Montes, and extends across the municipalities of Melgaço, Arcos de Valdevez, Ponte da Barca, Terras de Bouro, and Montalegre. It is Portugal's only national park and is characterized by a multifunctional mountain landscape where protected natural values coexist with villages, pastoral and agricultural activities, forest tracks, local roads, tourism infrastructure, and recreational use. This territorial configuration is relevant for trail safety because pedestrian routes often overlap with traditional access routes and areas of mixed use, increasing exposure to hazards related to motorized traffic, signage, terrain, water features, and livestock.

To strengthen the territorial and management framing of the study, the following strategic and regulatory documents were consulted: the Management Plan of the Peneda-Gerês National Park approved by Resolution of the Council of Ministers No. 11-A/2011; the Peneda-Gerês National Park Co-management Plan 2022–2027; and the complementary documents associated with the Co-management Plan, particularly the characterization of the protected area, prospective diagnosis, key stakeholders, programme of measures, and communication/sensitization plan. These documents were not used to assign risk scores to individual hazards. Instead, they were used to contextualize the study area, interpret the management relevance of the findings, and align the discussion with existing territorial planning and visitor-safety priorities.

Assessors and expert validation panel

Field data collection was conducted by three independent assessors. Two assessors held a master's degree in nature sports with specialized training in risk management, and one assessor held a PhD in the same field, with a specific focus on safety in mountain activities. The assessors walked each hiking trail in its entirety and independently applied a structured recording form designed to identify, categorize, and rate hazards by kilometer segment. Following field data collection, the database was validated by an independent expert panel composed of three members: (i) a PhD-level researcher in nature sports with expertise in risk and safety; (ii) an operational member of the mountain rescue team working in the intervention area, with academic training in sport and risk management; and (iii) a specialist in risk management in mountain-based activities. The validation process assessed the clarity and completeness of hazard identification, the internal coherence of probability and consequence ratings, and the adequacy of the proposed mitigation measures. Disagreements or ambiguous cases were reviewed until consensus was reached. No direct institutional interviews with the Peneda-Gerês National Park management authority were conducted for the purpose of assigning hazard scores. This decision was taken to preserve the independence of the field-based assessment. Nevertheless, official management and planning documents from the protected area were consulted to frame the territorial context and interpret the practical relevance of the results.

Trail Selection

Trails were selected using purposive sampling to ensure variability in characteristics relevant to hazard exposure while maintaining the feasibility of comprehensive field assessment. Inclusion criteria were official PR (Pequena Rota - Short route) designation by the Portuguese Federation of Camping and Mountaineering, trail length between 4 and 30 km, technical difficulty levels II to V, presence of official signage, and accessibility during the study period (May–September 2024). Trails closed for safety or conservation reasons, or requiring technical mountaineering equipment, were excluded. Fourteen trails were selected to represent heterogeneity in typology (linear vs. circular), length, technical difficulty, and topographic demands.

Hazard identification and classification

Hazard identification was guided by established risk frameworks in outdoor recreation and nature sports (Ayora, 2012; Salmon et al., 2010). Field assessment focused on trail-inherent, directly observable environmental hazards. Identified hazards were classified into three primary categories: material hazards related to infrastructure, signage, maintenance, and shared land use; geomorphological hazards related to terrain and natural features; and fauna-associated hazards involving wild or domestic animals. Specific hazard types within each category were defined based on existing literature and pilot testing (Ayora, 2012).

Risk Rating

Each hazard was assigned a probability rating and a consequence rating on five-point ordinal scales. Probability reflected the likelihood of hazard exposure resulting in an accident, while consequence reflected the potential severity of outcomes. A risk value (R) was calculated as the product of probability and consequence scores ($R = P \times C$), yielding values from 1 to 25. Risk values were categorized into acceptability zones as acceptable ($R \leq 5$), intermediate ($6 \leq R \leq 12$), and unacceptable ($R > 12$) (Ayora, 2012).

Data collection protocol and seasonal scope

Data collection followed a standardized field protocol developed to ensure consistency across trails. First, assessors reviewed the official trail information, including trail code, typology, distance, estimated duration, difficulty level, and elevation gain. Second, each trail was walked in its entirety in the official direction of use whenever such direction was indicated. Third, hazards were recorded continuously and organized by kilometer segment. Fourth, each hazard was classified according to category and specific type, georeferenced whenever possible, and documented through field notes and photographs. Fifth, probability and consequence scores were assigned using five-point ordinal scales. Sixth, the risk value was calculated as the product of probability and consequence scores. Finally, the database was checked for completeness and submitted to expert-panel validation. The field recording grid included the trail code, trail typology, kilometer segment, GPS point or approximate location, photograph code, hazard category, specific hazard type, description of the hazard, environmental or infrastructure conditions, probability score, consequence score, calculated risk value, risk acceptability zone, proposed mitigation measure, and assessor comments. The same grid was used for all trails. All field assessments were conducted between May and September 2024, corresponding predominantly to snow-free and peak-use conditions. Therefore, the present study characterizes a warm-season hazard profile and does not allow direct inference about winter risk. Winter conditions may alter the probability and consequence of several hazards, particularly slippery terrain, stream crossings, reduced visibility, exposure to cold, snow or ice, and delayed rescue access. For this reason, winter-specific profiling should be considered a priority for future longitudinal monitoring. Table 1 presents the field data collection grid.

Table 1. Field data collection grid used during hazard assessment.

Variable	Description
Trail code	Official PR trail identification
Trail typology	Linear or circular route
Kilometer segment	Kilometer or segment in which the hazard was recorded
Location	GPS coordinate or approximate location
Photograph code	Identification code of the georeferenced photograph
Hazard category	Material, geomorphological, or fauna-associated
Specific hazard type	Example: vehicle traffic, signage lacking, water point, slippery area
Hazard description	Short description of the observed condition
Contextual conditions	Surface condition, visibility, exposure, water flow, or nearby land use

Probability score	Five-point ordinal probability rating
Consequence score	Five-point ordinal consequence rating
Risk value	Probability × consequence
Risk zone	Acceptable, intermediate, or high/unacceptable
Proposed mitigation	Suggested management or communication measure
Assessor notes	Free-text observations
Validation status	Confirmed, revised, or excluded after expert validation

Statistical analysis

Descriptive statistics summarized hazard frequency, density, and risk distributions. Normality was assessed using the Shapiro–Wilk test. Since most distributions significantly deviated from normality ($p < .05$), non-parametric tests were used in subsequent analyses. Differences in risk values between hazard categories were examined using Kruskal-Wallis tests with post hoc comparisons when appropriate. Differences between linear and circular trails were assessed using independent samples t-tests or non-parametric equivalents. Associations between trail characteristics and hazard metrics were explored using Spearman's rank correlations. Hazard density was calculated as hazards per kilometer, and accumulated risk as the sum of risk values per trail. Statistical significance was set at $\alpha = 0.05$. All statistical analyses were conducted using JASP (version 0.17).

Results

Fourteen short-route pedestrian trails were analyzed, representing diverse configurations and demands (Table 2). The sample included 5 linear routes (35.7%) and 9 circular routes (64.3%). Trail length ranged from 4.3 to 25.7 km (M = 10.1 km, SD = 6.4 km), with estimated durations from 1h45 to 7h30 (M = 4h12, SD = 1h51). Technical difficulty distribution was (i) level II (easy, n=4, 28.6%), level III (somewhat easy, n=3, 21.4%), level IV (difficult, n=6, 42.9%), and level V (very difficult, n=1, 7.1%). Accumulated positive elevation gain ranged from 135 to 1122 m (M = 485 m, SD = 302 m).

Table 2. Characteristics of analyzed pedestrian trails (n = 14).

Trail	Type	Length (km)	Duration	Difficulty	Elevation Gain (m)
PR1	Linear	15.8	5h30	IV (difficult)	1122
PR2	Linear	6.5	2h45	III (somewhat easy)	322
PR3	Circular	16.7	6h00	IV (difficult)	839
PR4	Circular	5.2	2h00	II (easy)	223
PR5	Circular	25.7	7h30	IV (difficult)	682
PR7	Circular	6.0	2h30	II (easy)	296
PR8	Linear	11.9	6h00	IV (difficult)	607
PR9	Circular	4.4	2h00	II (easy)	135
PR10	Linear	9.3	4h00	III (somewhat easy)	249
PR12	Circular	16.2	6h00	IV (difficult)	740
PR13	Circular	4.3	1h45	III (somewhat easy)	202
PR14	Circular	6.1	2h45	II (easy)	215
PR15	Circular	7.3	4h30	V (very difficult)	522
PR16	Linear	4.3	3h30	IV (difficult)	635

Note. PR = pedestrian route.

Systematic field assessment identified 160 discrete hazards across the 14 trails. Hazard frequency per trail ranged from 5 to 23 (M = 11.4, SD = 5.8). Hazards were distributed across three primary categories (Table 3). Material hazards predominated with 135 occurrences (84.4%), followed by geomorphological hazards with 22 occurrences (13.8%), and fauna-associated hazards with 3 occurrences (1.9%).

Table 3. Distribution of identified hazards by category and specific type (n = 160).

Hazard Category	Specific Hazard Type	n	% of Total	% of Category
Material		135	84.4%	
	Possible off-road vehicle traffic	44	27.5%	32.6%
	Possible common vehicle traffic	47	29.4%	34.8%
	Signage lacking	36	22.5%	26.7%

	Incorrect/swapped signage	3	1.9%	2.2%
	Missing trail marker post	2	1.3%	1.5%
	Missing manhole cover	2	1.3%	1.5%
	Barbed wire	1	0.6%	0.7%
Geomorphological		22	13.8%	
	Water point (stream, pool, reservoir)	12	7.5%	54.5%
	Slippery area	4	2.5%	18.2%
	Dam/weir structure	3	1.9%	13.6%
	Fall risk / bridge crossing	2	1.3%	9.1%
	Steep area with loose rocks	1	0.6%	4.5%
Fauna-associated		3	1.9%	
	Beehives	2	1.3%	66.7%
	Cattle/domestic animals	1	0.6%	33.3%
TOTAL		160	100.0%	

Geomorphological hazards exhibited markedly higher mean risk (M = 8.59, SD = 2.86) compared to material hazards (M = 3.91, SD = 1.75), driven primarily by higher consequence ratings (C: 3.95 vs 2.56) despite only moderately elevated probability ratings (P: 2.18 vs 1.53) (Table 4).

Table 4. Distribution of hazards across risk-acceptability zones by category.

Category	$R \leq 5$ (Acceptable)	$6 \leq R \leq 12$ (Intermediate)	$R > 12$ (High)	Total
Material	85 (63.0%)	50 (37.0%)	0 (0%)	135
Geomorphological	5 (22.7%)	16 (72.7%)	1 (4.5%)	22
Fauna	1 (33.3%)	2 (66.7%)	0 (0%)	3
Total	91 (56.9%)	68 (42.5%)	1 (0.6%)	160

Inferential comparisons of initial risk values between hazard categories are presented in Table 5.

Table 5. Comparisons of risk values among hazard categories.

Hazard Category	Mean ± SD	Kruskal-Wallis H (df)	p-value	ε^2	Material vs Geomorph.	Material vs Fauna	Geomorph. vs Fauna
Material	3.91 ± 1.75	38.79 (2)	< 0.001	0.234	< 0.001	0.395	0.395
Geomorphological	8.59 ± 2.86	38.79 (2)	< 0.001	0.234	< 0.001	0.395	0.395
Fauna	6.00 ± 3.00	38.79 (2)	< 0.001	0.234	< 0.001	0.395	0.395

Note. Kruskal-Wallis tests revealed significant differences among hazard categories. Pairwise comparisons used Dunn's test with Holm correction. The last three columns contain adjusted p values.

Welch independent-samples t tests compared linear and circular trails for total hazards, hazard density, mean risk, and accumulated risk. No statistically significant differences were observed between trail typologies for any outcome (all $p > 0.05$; Table 6).

Table 6. Comparisons between linear and circular trails.

Outcome	Linear (Mean ± SD)	Circular (Mean ± SD)	Test	t (df)	p-value	Effect size (Hedges g)
Total hazards per trail	12.20 ± 6.22	11.00 ± 6.00	Welch t	-0.35 (8.12)	0.735	-0.18
Hazard density (hazards/km)	1.64 ± 1.48	1.21 ± 0.27	Welch t	-0.64 (4.15)	0.554	-0.38
Mean risk per trail	4.49 ± 1.15	4.98 ± 1.22	Welch t	0.75 (8.84)	0.473	0.39
Accumulated risk per trail	49.80 ± 19.75	54.00 ± 28.69	Welch t	0.32 (11.19)	0.753	0.16

Note. Welch's t test was used for all comparisons. Effect sizes are reported as Hedges' g. No comparison reached statistical significance.

Spearman's rank correlations (Table 7) indicated that technical difficulty was positively associated with trail elevation gain, duration, and length. Trail length showed a very strong positive association with duration and a strong association with elevation gain, while elevation gain was also strongly associated with duration. Accumulated risk increased with trail length, elevation gain, and duration, showing positive associations between accumulated risk and trail length, elevation gain, and duration.

Table 7. Spearman correlations among trail characteristics and risk metrics.

Correlation block	Pairwise association	ρ	p
Technical difficulty associations	Technical difficulty × Elevation gain (m)	0.782	0.001
Technical difficulty associations	Technical difficulty × Duration (h)	0.774	0.001
Technical difficulty associations	Technical difficulty × Length (km)	0.560	0.037
Trail morphology associations	Length (km) × Duration (h)	0.901	< 0.001
Trail morphology associations	Length (km) × Elevation gain (m)	0.733	0.003
Trail morphology associations	Elevation gain (m) × Duration (h)	0.841	< 0.001
Accumulated risk associations	Accumulated risk × Elevation gain (m)	0.614	0.020
Accumulated risk associations	Accumulated risk × Duration (h)	0.615	0.019
Accumulated risk associations	Accumulated risk × Length (km)	0.548	0.042
Total-hazard associations	Total hazards × Accumulated risk	0.855	< 0.001
Total-hazard associations	Total hazards × Elevation gain (m)	0.720	0.004
Total-hazard associations	Total hazards × Duration (h)	0.564	0.035

No seasonal comparisons were performed because all assessments were conducted between May and September 2024. Accordingly, the risk values reported in this study should be interpreted as reflecting snow-free, warm-season, and peak-use conditions. Winter-specific hazards, including ice, snow, reduced visibility, colder temperatures, and altered hydrological conditions, were outside the empirical scope of the present study.

Discussion

The present study aimed to develop and apply a systematic hazard-profiling framework for mountain pedestrian trails and to examine how hazard patterns emerge within multifunctional protected landscapes. The hazard profile was dominated by material hazards, particularly shared-use exposure with motorized vehicles and signage deficiencies. The geomorphological hazards were less frequent but presented higher risk values, mainly because of greater potential consequence severity, especially where water-related features were present. The accumulated risk increased with trail length, elevation gain, and duration, whereas trail configuration alone, expressed as linear versus circular typology, did not differentiate hazard exposure. Together, these findings show that the risk landscape of trails embedded in long-managed mountain territories does not fully align with assumptions derived from more wilderness-oriented outdoor recreation contexts (Heggie & Amundson, 2009; Heggie & Heggie, 2009).

The predominance of material hazards is especially relevant in the context of the Peneda-Gerês National Park. A substantial share of prior trail-safety knowledge has been derived from North American national parks and other settings where trails are often conceptualized as relatively segregated recreational corridors. In those contexts, incident-based accounts commonly emphasize wildlife encounters, weather exposure, navigational errors, and search-and-rescue events as prominent drivers of serious outcomes (Heggie & Amundson, 2009; Heggie & Heggie, 2009). The pattern observed in the Peneda-Gerês region differs in a way that appears structural rather than incidental. Many pedestrian routes operate within humanized mountain landscapes shaped by villages, agricultural activity, pastoral use, forestry access, local roads, and tourism infrastructure. This territorial configuration helps explain why shared access with conventional motor vehicles and off-road vehicles accounted for a substantial proportion of identified hazards. In such systems, hazards linked to shared access and to operational characteristics such as signage quality are not peripheral but intrinsic to the trail system itself (Mata et al., 2023). Evidence from adventure tourism and European multi-use outdoor contexts also suggests that infrastructure, overlapping uses, and operational management conditions can be central determinants of safety outcomes (Bentley et al., 2004). Therefore, multifunctionality should be treated as a core explanatory condition of trail risk rather than as a contextual determinant.

The findings also help position the present framework in relation to dominant approaches in the literature. Retrospective analyses of incidents and search-and-rescue records offer valuable information about accident outcomes and their proximal triggers, but they are often constrained by reporting bias, incomplete documentation, and the low base rate of severe events for many hazard types (Heggie & Heggie, 2009). Research focused on risk perception provides a complementary understanding of how recreationists interpret hazards and make decisions in situ, although perceived risk does not always correspond to structurally embedded hazards that remain relatively stable across users (She et al., 2019). Prospective hazard profiling complements these approaches by identifying latent hazards independently of whether an accident has already occurred and by translating observed trail conditions into a structured evidence base for prioritization, monitoring, and management action (Ayora, 2012; Brandão, Marques, et al., 2018). In this sense, the present study proposed a methodological approach that is particularly useful in protected areas where accident databases are limited, fragmented, or not georeferenced at trail level.

A central contribution of the present study is the identification of a two-tier risk structure across the analyzed trail network. On the one hand, the trail system was characterized by frequent, generally manageable material hazards, especially shared access with motorized vehicles and deficiencies in signage. These hazards tended to produce low to moderate risk values because they combined relatively moderate exposure likelihood with consequences that, although potentially serious, were typically less catastrophic than those associated with specific natural features (Ayora, 2011). On the other hand, a smaller set of geomorphological hazards concentrated higher risk values, driven primarily by elevated consequence ratings rather than markedly higher probability. Water-related features, including streams, pools, reservoirs, and dam or weir structures, were particularly salient within this second tier. Even when such hazards are not the most frequent, their potential for severe or fatal outcomes warrants prioritization, and this is consistent with evidence identifying natural water bodies and associated structures as important contributors to fatal outdoor recreation events (Peden et al., 2016; Westman & Björnstig, 2024). Therefore, risk management should not be guided by frequency alone, because low-frequency hazards may dominate severity profiles and drive the most consequential safety outcomes.

A comparison with available accident and rescue evidence from the study area provides additional contextual support for these findings. Previous research in the Peneda-Gerês National Park, based on occurrence records from 2006 to 2015, identified vulnerabilities related to mountain activities, rescue accessibility, and response times in areas farther from passable roads (Pereira et al., 2020). More recent publicly reported data from the Guarda Nacional Republicana (GNR), a law enforcement service, specifically from its Emergency Protection and Relief Unit, indicate 237 search-and-rescue interventions in the Peneda-Gerês National Park between 2020 and 2024, with 2023 showing the highest number of occurrences. In 2024, reported interventions included 19 rescues due to falls, 19 searches for missing or disoriented visitors, 15 first-aid interventions, one climber rescue, and three support actions for motorists with circulation problems in mountain areas (Jornal de Notícias, 2025; O Minho, 2025). These recent data are consistent with previous research in the Peneda-Gerês National Park, which identified vulnerabilities related to mountain-activity incidents, user-flow organization, occurrence registration, and rescue response (Pereira et al., 2020). However, because the publicly available GNR data are reported in aggregate form and are not georeferenced by trail segment, they cannot be directly matched with the hazards recorded in the present study. Therefore, the comparison should be interpreted as contextual alignment rather than causal validation. In this sense, the reported searches for missing or disoriented visitors make the present findings on signage and wayfinding hazards operationally relevant, while the reported rescues due to falls are compatible with the higher risk values observed for geomorphological hazards.

The distinction between material and geomorphological hazards also clarifies why management strategies should be differentiated by hazard class. Material hazards are often amenable to probability reduction through improvements in infrastructure, signage, wayfinding reliability, shared-access communication, and visitor information. In contrast, geomorphological hazards frequently carry consequence severity that is largely inherent to the setting, meaning that risk reduction must focus on exposure, warning, decision-making, and behavior pathways rather than on eliminating the hazard itself (Ayora, 2011, 2012; Brandão, Marques, et al., 2018). This is especially relevant in protected areas, where extensive modification of natural features may be incompatible with conservation mandates and visitor-experience objectives (Leung et al., 2018). The profile observed here therefore supports a pragmatic management balance: network-wide interventions should address the most prevalent and modifiable hazards, while targeted measures should focus on specific high-consequence locations where severity and exposure likelihood intersect.

Furthermore, trail configuration, in the form of linear versus circular design, did not differentiate hazard exposure in this dataset, suggesting that route geometry alone is not a reliable proxy for safety prioritization. Instead, accumulated risk increased with trail length, elevation gain, and duration. This finding aligns with exposure-based perspectives in outdoor recreation safety, which emphasize cumulative interaction with environmental, infrastructural, and operational hazards over time (Ayora, 2012; Heggie & Heggie, 2009). From a management standpoint, these associations can be translated into practical decision heuristics: longer routes, routes with greater elevation gain, and routes requiring more time on trail should be treated as higher monitoring priorities, not necessarily because each individual segment is more hazardous, but because the cumulative number of hazard encounters and opportunities for compounding effects is greater. This is particularly relevant in protected areas with limited human and financial resources, where inspection frequency, maintenance scheduling, signage audits, and hazard-specific warnings must be prioritized strategically (Leung et al., 2018; Mata et al., 2023).

The predominance of motorized vehicle-related hazards and signage deficiencies also has direct practical implications for trail management. At the network level, systematic signage audits, replacement of missing or deteriorated markers, warnings about shared vehicle access, and clearer pre-trail information could reduce exposure to the most frequent material hazards. Mobile applications may complement these measures by supporting route planning, navigation, and visitor-flow management, although they should not replace reliable on-site signage (Hamza Mayora et al., 2025). In multifunctional landscapes where traditional land uses must be respected, the objective should not necessarily be the categorical exclusion of motorized or agricultural access, but rather conflict reduction through clear communication, visibility enhancement, consistent warning systems, and user education (Bentley et al., 2004; Gstaettner et al., 2022). At the site-specific level, water-related features, bridge crossings, steep loose terrain, and slippery areas require targeted attention because they may generate severe outcomes even when they occur less frequently (Peden et al., 2016; Westman & Björnstig, 2024). This approach is consistent with protected-area management principles that seek to reduce preventable harm while maintaining ecological integrity, cultural landscape values, and the experiential qualities of outdoor recreation settings (Gstaettner et al., 2022).

Several limitations should be acknowledged. First, risk ratings were based on structured expert judgment rather than direct accident probabilities derived from trail-specific incident databases. This introduces subjectivity, particularly in probability scoring, although expert-informed assessment is widely used when direct observation, contextual knowledge, and professional judgment are needed in complex outdoor environments (Ayora, 2012; Brandão, Pereira, et al., 2018). Second, available accident and rescue data for the Peneda-Gerês National Park are aggregated and do not allow direct georeferenced comparison with each hazard recorded in the present study. Therefore, the relationship between hazard profile and accident occurrence should be interpreted as contextual alignment rather than causal confirmation. Third, data were collected between May and September 2024, meaning that winter-specific risk profiles were not assessed. Snow, ice, fog, heavy rain, altered stream flow, colder temperatures, and delayed rescue access may substantially modify both probability and consequence ratings. Fourth, although official management documents were consulted to frame the study area, direct interviews with National Park managers were not included. Future research should integrate repeated seasonal assessments, georeferenced incident and rescue databases, visitor-flow data, and direct collaboration with protected-area managers, rescue authorities, and local stakeholders.

Despite such limitations, the present study demonstrates that systematic hazard profiling can provide a practical bridge between field observation, risk prioritization, and protected-area management. By identifying both frequent modifiable hazards and less frequent high-consequence hazards, the proposed framework supports more transparent decisions about where to allocate limited inspection, maintenance, communication, and mitigation resources. Future research should extend this approach across multiple regions to distinguish context-specific features from broader Southern European patterns, incorporate longitudinal monitoring to capture seasonal and infrastructural change, and examine how user risk perception interacts with signage, warnings, and decision-making at high-consequence locations.

Conclusions

This study provides a systematic hazard profile of officially designated mountain pedestrian trails in the Peneda-Gerês National Park region. The findings show that most identified hazards were material in nature, especially shared access with motorized vehicles and signage deficiencies. However, geomorphological hazards presented higher risk values, mainly because of their greater potential severity, with water-related features representing the most critical high-consequence locations. Accumulated risk increased with trail length, elevation gain, and duration, whereas linear or circular trail configuration did not meaningfully differentiate risk exposure. These results suggest that trail-management priorities should combine network-wide actions, such as signage improvement and shared-access communication, with targeted mitigation at high-consequence sites, especially water features, bridge crossings, slippery areas, and steep unstable terrain. The proposed framework offers a transferable and operational method for proactive trail-risk assessment in multifunctional protected landscapes. Nevertheless, the results should be interpreted as reflecting snow-free, warm-season conditions. Future research should include winter-specific assessments, repeated monitoring across seasons, georeferenced accident and rescue data, visitor-flow indicators, and closer integration with protected-area management authorities. Such developments would allow hazard profiling to evolve from a cross-sectional assessment into a continuous decision-support tool for safer and more sustainable mountain trail management.

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