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ASSESSMENT OF CONSERVATION STATUS OF VULNERABLE ZONES PRONE TO LANDSLIDES IN THE MUSCEL STREAM HYDROGRAPHIC BASIN

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Abstract

Identifying high-risk areas prone to landslides and predicting their triggering moments represents a highly relevant research topic in terms of environmental conservation. Research studies were conducted between 2018 and 2023 in the Muscel stream hydrographic basin, a tributary of the Dambovita River, where 31 landslides were identified in different stages of evolution, including an extreme event in 2018. To analyse the state of the investigated area and establish vulnerable landslide zones, the Shannon entropy model was used by overlapping thematic maps. A total of 15 factors influencing landslides were analyzed, the most significant being terrain slope (106.22%), regional geology (42.7%), and slope aspect (28.92%). Of the total studied land surface, 16.04% has a low probability of landslides, associated with moderate conditions and low precipitation levels. The medium probability category, representing 56.95%, affects the largest part of the study area, mainly due to climatic and geological instabilities. The high-probability zones, covering 27.01%, are the most hazardous, being associated with extreme factors, such as heavy rainfall or earthquakes. The obtained results indicate that most of the land is exposed to moderate risks. However, high-probability zones require priority preservation measures, as they significantly impact local communities, particularly on agricultural lands.

***Keywords**: Shannon entropy; preservation masures; landslide; mapping; GIS*

Introduction

Landslides, defined as natural displacement and movement of a rock mass on an inclined surface, have become increasingly common worldwide and are influenced by various natural or anthropogenic factors. In Romania, these events may even result in loss of human lives, especially in densely populated areas [1].

Landslide susceptibility mapping (LSM) represents a key technique for understanding and anticipating future hazards, as well as for establishing the most effective mitigation strategies to reduce their consequences [2, 3]. The LSM process relies on statistical or deterministic methods

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that can serve as a foundation for decision-making regarding assistance for residents in vulnerable areas, and for design and construction, being used by specialists to reduce the ecological risks [4, 5].

The generated vulnerability maps provide critical information for predicting landslide hazards and estimating the timeframes for occurring land displacement [6]. When developing a landslide vulnerability map, the direct mapping method involves identifying areas susceptible to slope failure by comparing geological and geomorphological properties with those of typical landslide-prone sites [4, 7, 8]. Landslides are frequently encountered in Romania, particularly affecting the Subcarpathian hills due to geomorphological and climatic conditions, as well as human interventions such as deforestation and agricultural expansion on sloped terrains [9]. To effectively manage ecological risks, it is essential to map landslide susceptibility, which can be developed by using the Shannon entropy method, which provides a detailed GIS-integrated approach [10].

The study was conducted in the Muscel stream hydrographic basin, located northwest of Dambovita County, and examined topographic, geological, hydrological, and anthropogenic factors influencing landslides. The studied area includes villages and agricultural lands, where orchard cultivation is predominant, and presents increasing soil erosion and landslides. The slopes, ranging between 20% and 35%, exhibit complex formations with landslide-deposited layers. Annual precipitation averages of 737.5mm, with maximum levels occurring in summer, and with dominant winds from the north (20.8%) and northeast (13.5%), contribute differently to erosion and soil displacement. Additionally, anthropogenic activities such as deforestation and overgrazing have accelerated soil degradation, reducing fertility and increasing erosion risk. For example, in hilly areas, cutting down forests for household needs has compromised the terrain stability, eliminating a natural barrier against landslides [11, 12]. The land distribution in the Muscel watershed is increasingly affected by textural degradation, gleying, and stagnogleying, thus reducing agricultural productivity.

Landslides in the Muscel stream hydrographic basin have been documented since 1979 when a major landslide blocked the Dambovita River and impacted National Road 72A. In 2018, a significant landslide in Valeni-Dambovita destroyed the local infrastructure and led to the evacuation of 10 households, highlighting the region's heightened vulnerability to such natural hazards. Therefore, this study provides possible solutions for reducing landslide risks and improving sustainable land management in the Muscel area.

Experimental

Materials

The research was conducted in the northwest of Dambovita County, in the Muscel stream hydrographic basin, and includes Valeni-Dambovita and Mesteacan villages (Figure 1).

To overlay maps, the statistical entropy model developed by Claude Shannon was used. A database that contains information regarding the landslides was developed in terms of landmarks migration over 12 seasonal cycles (spring-winter of 2018-2023). These data were digitized and integrated into ArcMap to generate predictive maps that highlight vulnerable zones prone to landslides.

The studied period was 2018-2023 to evaluate different stages of landslide evolution. Two landslides were instrumented with monitoring benchmarks [13], allowing for precise measurement of soil displacement. A vulnerability map was generated by overlaying multiple thematic maps, helping to identify high-risk areas for future landslides.

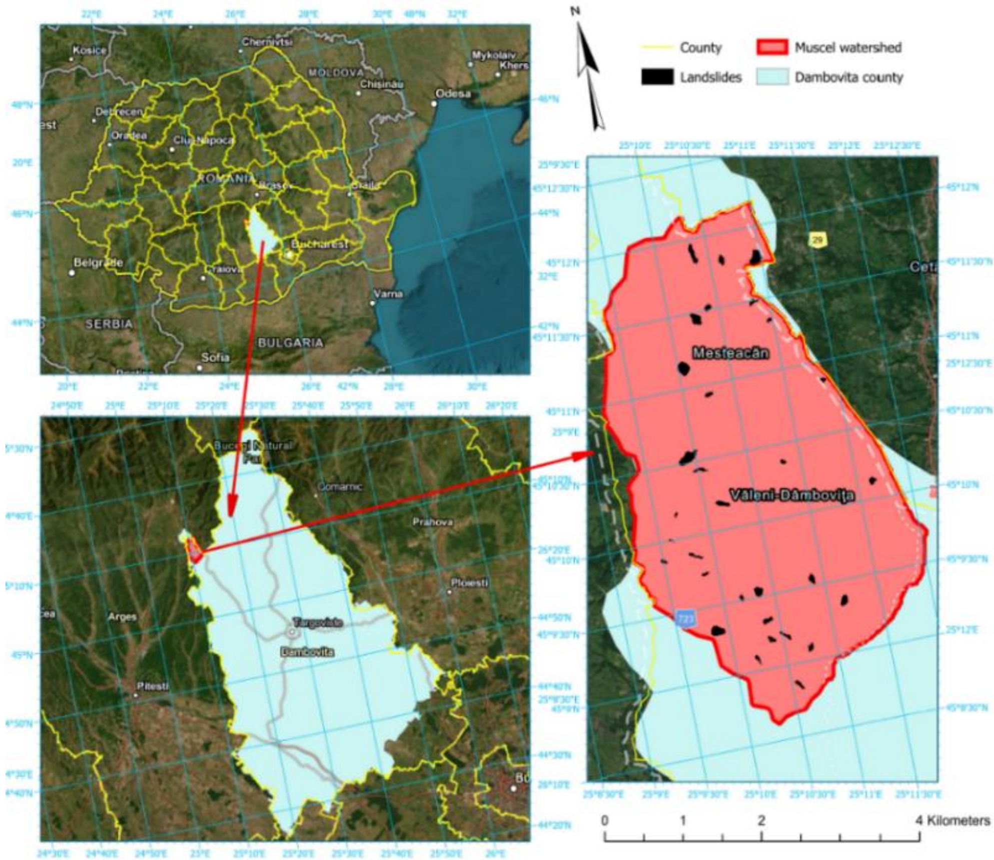


Fig. 1. Location of the study area

The data required for this study were obtained from local institutions, including topographic, hydrological, and climatic maps. Supplementary data were extracted from online sources, namely from the United States Geological Survey (USGS) portal, contributing to the consolidation of this analysis.

Methods

To develop the frequency ratio model (FR), a series of influencing factors were considered, and multiple data sets were used. The mathematical representation of this model is given by the following equation [14, 15]:

$$FR = \frac{N_I^P/N}{N_i^{Ip}/N^I}, \quad (1)$$

where:

N_i^p - represents the number of pixels in the graphic representation of each factor, while N is the total number of pixels in the studied area. N_i^{Ip} - represents the number of pixels corresponding to landslide occurrences for each included factor class. N^I - represents the total number of pixels corresponding to landslides in the studied area.

These calculations allow for the determination of the Landslide Susceptibility Index (LSI), an essential tool for assessing terrain vulnerability to landslides.

The data obtained from the calculation were further used in the Shannon Entropy (SE) model, which measures the influence of causal factors in landslide occurrences, following the formula:

$$\text{Pij} = \frac{FR}{\sum_{j=1}^{M_j} \text{FR}}, \quad (2)$$

where Pij represents the probability density for each class.

The probability density for each class (Pij) was used to determine the entropy values (Eij and Hij) and the weights of the causal factors (Wij) [16].

$$\text{Eij} = -\sum_{i=1}^{Mj} P_{ij} log_2 P_{ij} \quad (3)$$

$$\text{H}_{ij} = 1 + \sum_{i=1}^{Mj} E_{ij} \quad (4)$$

$$\text{Wij} = \text{H}_{ij} \,/\, \sum_{j=1}^{M_j} \text{H}_{ij} \quad (5)$$

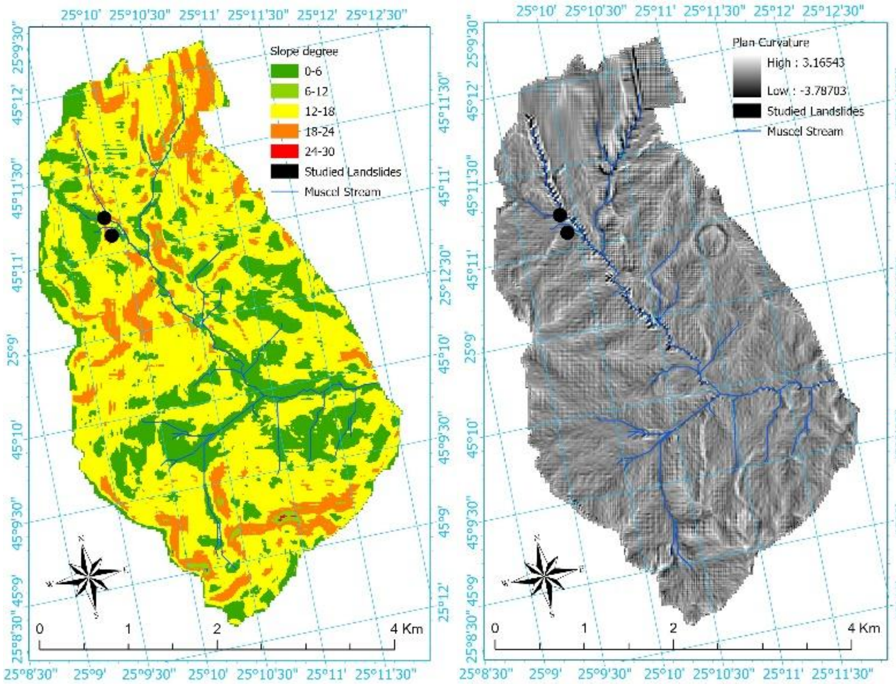
The Digital Terrain Model (DTM) for Romania was downloaded from the USGS portal, from which the DTM of the Muscel hydrographic basin was extracted. The DTM of the Muscel hydrographic basin was then converted to a resolution of approximately 10×10 m, ensuring that each pixel covers an area of 100 square meters. By processing the DTM using ArcMap, several thematic maps were generated, including Slope map, Curvature map, Slope aspect (orientation) map, Elevation model, Terrain fragmentation, Normalized Difference Water Index (NDWI), Water flow direction, Surface water accumulation zones.

Results and discussion

Among conditional factors for landslide triggering, slope inclination and terrain curvature (the horizontal shape of the land indicating concave or convex areas) play a crucial role in assessing the slope stability and implementing preservation measures, based on which soil mass behavior under the action of gravity and external factors can be determined. Thus, Figure 2 presents both the slope degree and plan curvature of the studied area.

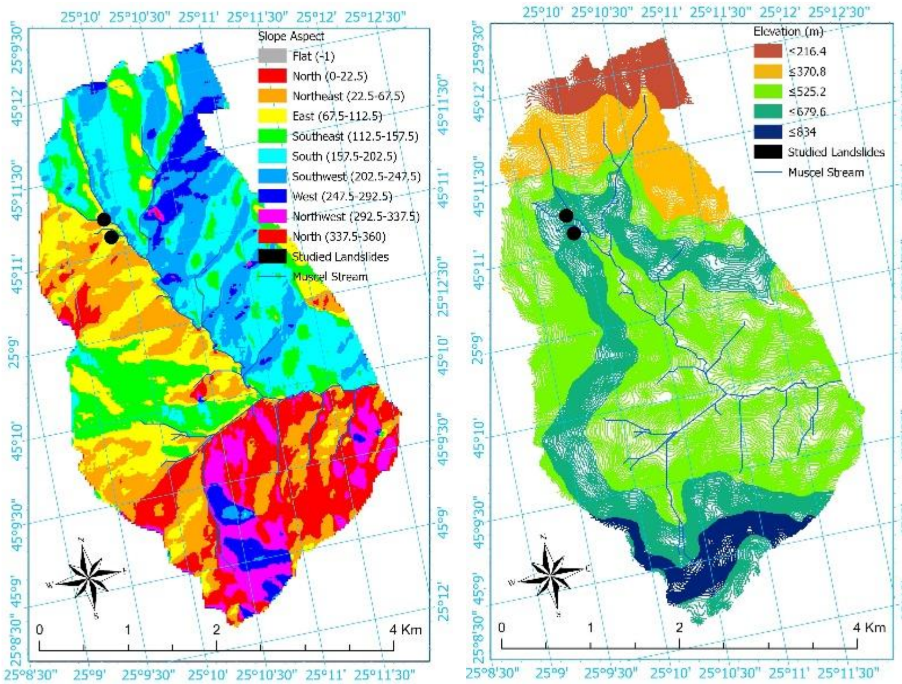
Within the Muscel hydrographic basin, the slopes are moderate, ranging between 0° and 30°. Most of the slope values are between 12° – 18°, making the area less susceptible to landslides. Particularly, there are some small areas with slope values between 24° – 30°, corresponding to those in which the monitoring benchmarks were installed, highlighting their highly sensitive character and liability to landslide.

The values of the plan curvature range between -3.8 and 3.16, which defines the terrain as being slightly curved. A value higher than 3 represents a concave area, where, if water accumulation exists, the risk of landslides is increased. As it can be seen in Fig. 2b, one of these areas corresponds with the landmark points, validating the model.



a) **b)**

Fig. 2 Slope degree a) and plan curvature of the studied area b) along with the main monitored landmark points.



a) b)

Fig. 3 The slope aspect (a) and terrain elevation (b)

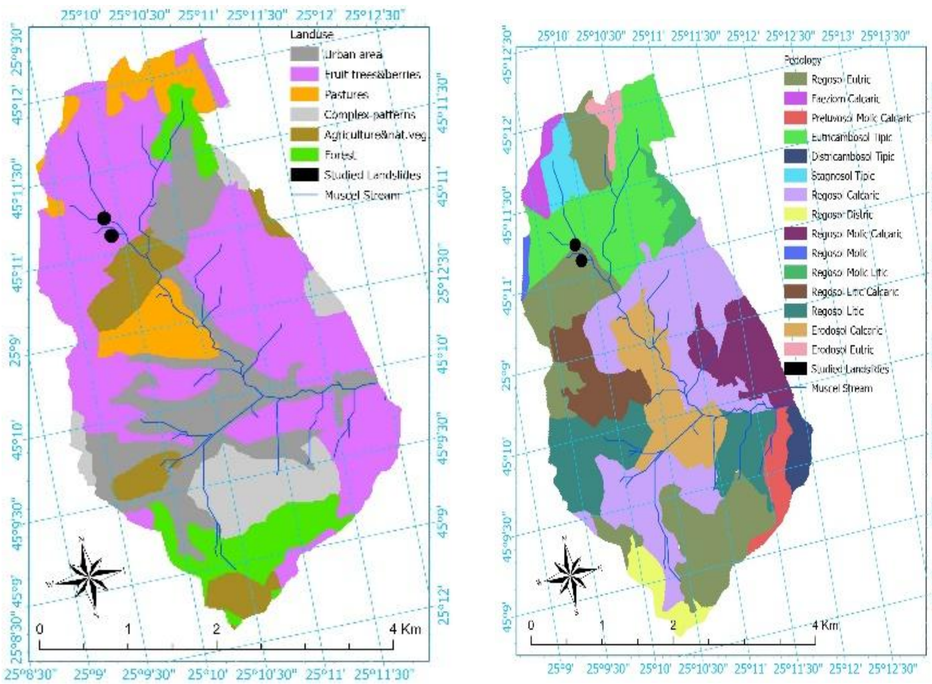
The slope orientation significantly impacts microclimate, slope stability, vegetation, as well as the distribution of water, snow retention, and landslide risk. In this context, Figure 3 presents the slope aspect of the Muscel hydrographic basin along with its terrain elevation.

Although south-facing slopes are generally warmer and drier, favoring drought-resistant crops, they are also more exposed to erosion. Conversely, north-facing slopes tend to be cooler and more humid, featuring more stable soils and denser vegetation. In tight relation with slope orientation is the terrain elevation, which plays a critical role in landslide susceptibility. The monitored landmarks are situated in areas with high altitudes (577 – 662 m), being more exposed to intense erosion due to precipitation and groundwater accumulation, which can destabilize slopes.

The land use depends on terrain elevation, therefore, the higher altitudes in the studied areas (around 700 m) diminish the possibilities of land use with strong and fibrous root vegetation (Figure 4a). As emphasized in the landmark study area, the predominant vegetation is determined by crops with weak and fibrous roots, less than 1 mm in diameter, and natural vegetation, often grass roots with low density, which favors the increase of landslide risk.

The geological structure of the studied terrain is essential for assessing landslide susceptibility, as soil properties regarding water infiltration directly influence stability. Thus, in Figure 4b is presented the pedology of the Muscel hydrographic basin.

An overview of the studied area highlights that the zone pedology is generally characterized by the presence of regosols, which are very weakly developed mineral soils [17]. Particularly, in the landmark areas, predominant soils are regosols (poorly consolidated soils that appeared on the surface because of geological erosion processes) and erodosols (strongly eroded or uncovered soils caused by human action), both types of soils being vulnerable to landslides.



a) b)

Fig. 4 Land use (a) and pedology (b) of the studied area

The modeling results are presented in Table 1 and highlight the current state of the monitored area, especially in the landslide zones. Each landslide causative factor potentially influences the occurrences of landslides in the Muscel stream hydrographic basin. However, from the total modeled parameters, Table 1 presents the most relevant ones with an important impact on the model.

Table 1. Landslide conditioning factors

Layers	Class	Class pixels	Landslide pixels	FR	SE			
					Pij	Eij	Hij	Wij (%)
Slope degree	0-6	42523	194	0.005	0.009	-0.019	0.412	0.124
	6-18	116997	4688	0.128	0.264	-0.213		
	18-30	1066	44	0.352	0.726	-0.179		
Land use	Urbanization	32102	88	0.003	0.010	-0.021	0.173	0.052
	Fruit trees and berries	75843	1532	0.020	0.076	-0.085		
	Pastures	13149	1290	0.098	0.370	-0.160		
	Complex patterns	14563	956	0.066	0.248	-0.150		
	Agriculture and nat. veg.	12375	236	0.019	0.072	-0.082		
	Forest	13849	822	0.059	0.224	-0.146		
Pedology	Regosol	61553	1730	0.028	0.039	-0.055	0.435	0.131
	Faeziom calcaric	5029	1000	0.199	0.278	-0.155		
	Preluvosol molic calcaric	7987	1148	0.144	0.201	-0.140		
	Eutricambosol Tipic	45364	17	0.000	0.001	-0.002		
	Districambosol Tipic	5593	135	0.024	0.034	-0.050		
	Stagnosol Tipic	7764	30	0.004	0.005	-0.012		
	Erodosol	31616	40	0.004	0.006	-0.0013		

The Landslide Susceptibility Index (LSI) is calculated based on a weighted combination of key factors, such as slope, land use, geology, and precipitation, with weights ranging between 0.005 and 0.238.

Landslide Susceptibility Index (LSI) =
="Slope"*0.124 + "Plan Curvature " *0.007 + "Slope Aspect" *0.020 + "Elevation" *0.029 + "Land use" *0.052 + "Pedology" *0.131 + "Geology" *0.005 + "Distance from Roads" *0.017 + "Distance from Rivers" *0.144 + "Fragmentation" *0.040 + "NDWI" *0.014 + "Rainfall" *0.238 + "Flow Direction " *0.015 + "Flow Accumulation" *0.082+ "Buildings" *0.088

For example, the monitored area is characterized by inclined slopes (class 6-18) because this class contains the highest number of pixels (116997). Among them, most of the pixels (≈ 4%) are concentrated in landslide areas, at the landmark points. In terms of land use, it can be noticed that the higher concentration of pixels from the landslide zones is assigned to the pastures and berries, weak vegetation with low density, in good correlation with the thematic maps results presented above.

Starting from the frequency rate values, the prediction rate (PR) weights of each studied factor, which determine the landslide susceptibility, were determined, and the results are presented in Figure 5.

Factors such as pedology (0.10%), precipitation (0.30%), and distance to rivers (0.60%) have a very low impact. The critical factors are related to topography, with terrain curvature

(26.30%), slope aspect (28.93%), geology (42.70%), and especially slope angle (106.22%) dominating the susceptibility analysis. The general trend indicates an exponential increase in the weight of factors related to slope and terrain structure, as these have the greatest influence on landslide risk. The graphical representation highlights that slope steepness is the most critical factor, determining terrain instability through gravitational effects.

The implementation of Shannon entropy weighting in the causal factor analysis produced similar results to the FR model, while providing a simplified equation for landslide susceptibility.

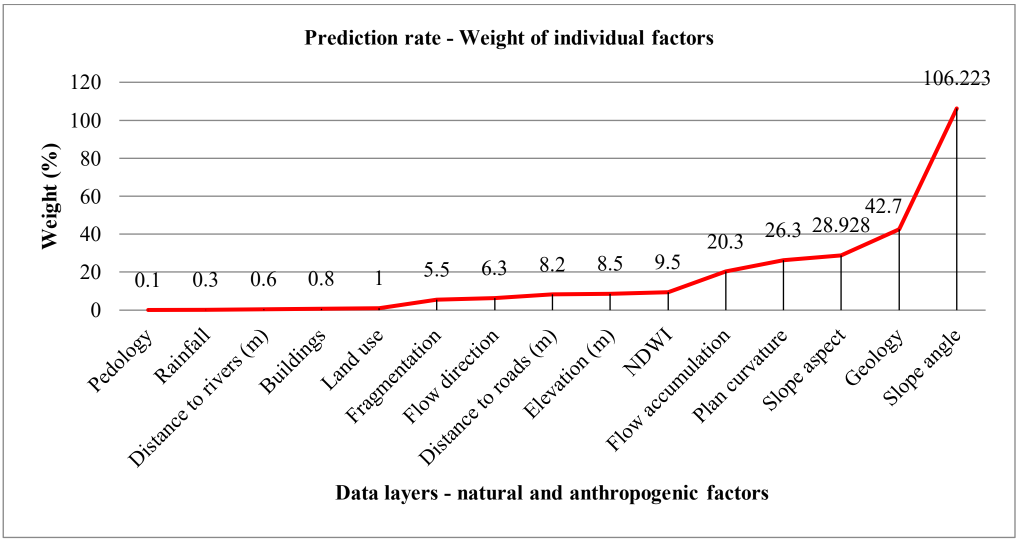


Fig. 5 Weight of individual factors

The landslide susceptibility map (Figure 6) is a valuable tool for providing information in terms of potential landslide locations in the Muscel stream hydrographic basin.

The map depicts the probability and the distribution of landslide occurrences in the area based on links between existing landslides, environmental conditions, and contributing factors. However, the map cannot predict the exact time or the volume of material displacement, or the aerial distribution of landslides. Despite some limitations of the map, the predictive models provide valuable insights for effective land-use planning within the Muscel stream hydrographic basin and are useful for local and regional authorities to reduce landslide risks and increase hazard mitigation and disaster responses. The final map categorized the landslide-prone area into three probability levels: low (16.04%) corresponding to a surface of 516.63 ha; medium (56.95%) corresponding to a surface equivalent of 1833.66 ha; and high (27.01%) representing a surface of 869.70 ha.

The Frequency Ratio Model (FRM) calculates risk based on condition frequency, providing a simple, data-driven hazard map (Figure 7). The Shannon Entropy model, rooted in information theory, measures uncertainty in hazard distribution, offering insights into randomness and predictability of hazard patterns. FRM is simpler and focuses on direct frequency relationships, whereas Shannon Entropy provides a more complex analysis of hazard distribution and variability. FRM is easier to interpret, while Shannon Entropy (SE) allows for a deeper and more flexible analysis.

Compared to the Frequency Ratio Model (87.14%), the AUC (Area Under the Curve) graph evaluates sensitivity compared to specificity. This indicates that the Shannon Entropy model has a lower accuracy rate (76.18%) due to its higher complexity and more factors considered.

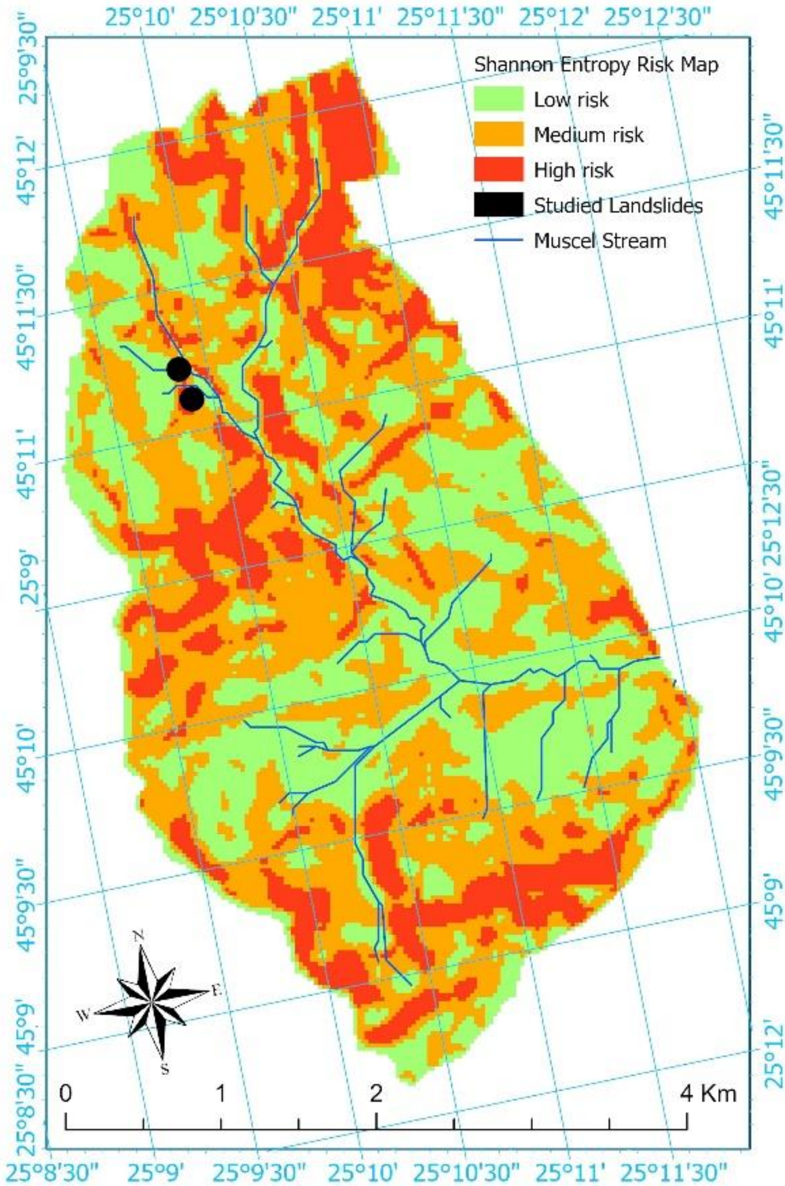


Fig. 6. Landslide susceptibility map

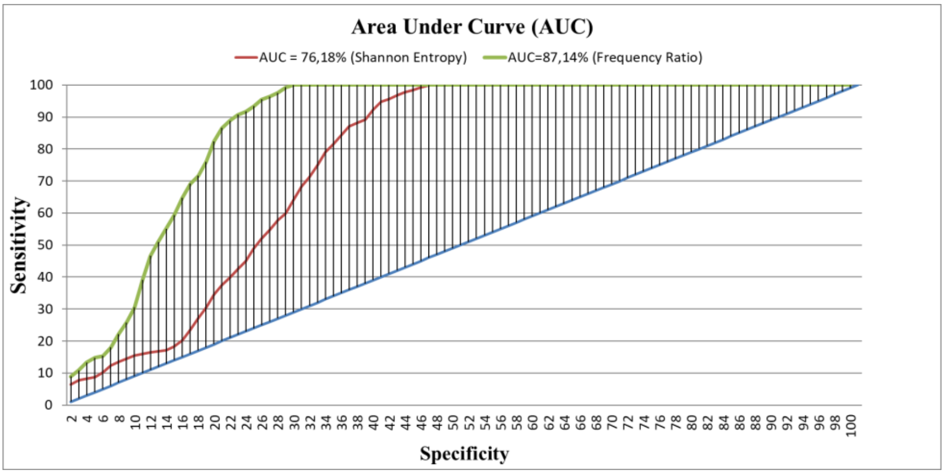


Fig. 7 Area under the curve. Comparison between the Frequency ratio model and the Shannon entropy model

The FRM method and SE are used to quantify the contribution of each factor. These calculations allow for the determination of the Landslide Susceptibility Index (LSI), an essential tool for assessing terrain vulnerability to landslides.

Conclusions

Following the landslide susceptibility analysis in the Muscel stream hydrographic basin, conducted through the integration of topographic, geological, hydrological, and anthropogenic data, significant results were obtained, emphasizing the importance of integrated risk management. Factors such as terrain slope, geology, curvature, and slope aspect were found to have a major impact on slope stability, and statistical analysis highlighted the higher landslide risk on steep slopes.

The use of GIS techniques for generating risk maps is essential in identifying vulnerable areas. Precipitation and soil water accumulation were identified as key determinants, and anthropogenic activities, such as deforestation and unsustainable construction, have contributed to increased vulnerability in the region.

The Shannon entropy model provided an accurate risk assessment, highlighting the urgent need for interventions to protect slopes and, consequently, to safeguard infrastructure and residential areas. The resulting maps, which indicate the landslide probability of the studied area (low – 16.04%, medium – 56.95%, high – 27.01%), can guide local authorities in implementing preventive and mitigation measures, thereby reducing the impact of landslides.

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