Landslide25_19

Spatial Analysis of Landslide Hazard Based on Satellite-Derived Slope Gradient and Soil Moisture: The Zagora Province, Morocco

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SUMMARY

The study aims to identify areas of the Zagora province, Morocco, that are prone to landslide hazards by analyzing slope steepnesses of the territory and the Normalized Difference Moisture Index. The Google Earth Engine software was used to analyze spatial patterns between terrain morphology and surface moisture. In this work, we propose assessing the synergistic effect of a combination of hazardous exogenous geological processes, water supply, and anthropogenic factors using satellite data from Sentinel-1 and Sentinel-2, along with SRTM-based elevation models. As a result, the risk matrix was created, and five slope and NDMI classes were defined. The results show that more than 84% of the territory lies in very low to low landslide risk zones (slope <15°), while high and very high-risk zones (slope >25°) comprise less than 5%. Most of the province remains semi-arid, with NDMI values indicating low moisture levels. However, localized areas along the Draa floodplain, their tributaries and oases show higher NDMI values. The study highlights the need for early warning systems and targeted monitoring during seasonal rainfall or seismic activity, contributing to sustainable land management and disaster prevention strategies.

Introduction

Early warning systems for land degradation and landslide hazards are crucial for implementing prevention strategies and reducing the risk to infrastructure, agriculture, and human safety *(Abdelmonaim et al., 2024; Popov et al., 2023)*. Understanding the engineering and geological properties of source rocks, as well as regional and local engineering and geological conditions, is a crucial prerequisite for addressing the issue of land vulnerability to land degradation and the activation of landslide hazard processes.

One of the geomorphological parameters relevant to a landslide susceptibility study is the slope gradient, as it plays a vital role in gravitational movements. The slope gradient represents elevation points that are greatly affected by the resolution of the DEM and SRTM *(Stankevich et al., 2020)*. The slope angle is typically considered one of the most influential factors in landslide modelling, as it controls the shear forces acting on hill slopes. There are different classifications and gradations of slopes, depending on the geological conditions and the type and properties of the rocks that form the slope, as well as various types of anthropogenic loading or development. Landslides on river slopes can occur due to the interaction of several conditions *(Kril & Orlenko, 2022)*, including morphological conditions, geological structure, hydrology, and land use. Slopes will be vulnerable to trigger factors such as intense rainfall events, seismic activity, or human actions (excavation, loading, and others). Therefore, the primary goal is to have an inventory of historical data on landslide events to identify areas that will be affected by future landslides, caused by both natural and artificial factors.

The research aims to assess landslide hazard risks by analyzing meteorological and geomorphological factors, specifically slope instability related to the moisture content in upper soil layers and slope steepness, as well as seismic activity in the territory. Research task is to analyze of geomorphological conditions; collection and processing of anomalous synoptic situations for the period 2015-2025, creation of a database of multispectral images of the Sentinel-2 satellite to determine the moisture capacity of the territory (NDMI - index), and radar images processing to determine the vertical displacements of the Sentinel-1 territory, SRTM processing of correlations between the slope angle and the NDMI level, construction of a risk matrix. The study area is located in the Zagora province of Morocco, specifically in the Draa River valley, a research site within the framework of the EWALD project *(https://cordis.europa.eu/project/id/101086250)*.

Materials and Methods

The study used the Google Earth Engine cloud processing service to process geospatial data from remote sensing. In this study, we utilize Sentinel-2 multispectral satellite images to calculate a combined mosaic NDMI index and SRTM data to determine the risk level of hazardous landslides in the Zagora province *(Bouazzaoui et al., 2016)*, Morocco. A 30 m resolution digital elevation model and SRTM were used to calculate the slope steepness. To assess the relationship between physical and geographical characteristics and land cover degradation levels in the Zagora province (Morocco), a multi-stage spatial analysis was conducted. Surface steepness was estimated using the GEE "Slope". For each cell of the digital relief model, the "Slope" tool calculates the maximum degree of change in the value of height z between the cell and its neighbours. The "Slope" determines the degree of surface change in the horizontal and vertical directions relative to the central cell *(Babichev et al., 2021)*. The slope gradient was divided into five classes (*Table 1*) based on the slope classification. The NDMI is a normalized difference moisture index that uses NIR and SWIR bands to display moisture. The degree of moisture is determined using the normalized difference moisture index (NDMI), which uses NIR and SWIR1 bands to display it according to previous research *(Dapke et al., 2025; Babichev et al., 2021).*

The images of the Copernicus Sentinel-2 satellite mission were used to determine the values of the NDMI index *(Karmaoui et al., 2022)*. The satellite is equipped with an optical-electronic multispectral sensor that allows for observation with a resolution of 10 to 60 m in the visible, near-infrared (VNIR), and short-wave infrared (SWIR) spectral zones, featuring 13 spectral channels *(Chrysafi et al., 2025)*. The NDMI values from -1 to 1 were divided into five classes *(Kruglyk, 2025)*. The risk of landslide hazard depends on the combination of probability (determined by slope angle and moisture according to NDMI) and potential consequences. A qualitative risk assessment *(Table 1)* was performed at five levels: very low (1), low (2), medium (3), high (4), and very high (5).

Table 1. *Combine the data with the corresponding gradation of factors*

		Normalized Difference Moisture Index				
		≤-0.1	-0.1-0.1	0.1-0.15	0.15-0.3	>0.3
Slope Steepness	≤2°40'	1	1	1	2	2
	2°40'-5°40'	1	2	2	3	3
	5°40'-11°20'	2	2	3	4	4
	11°20'-24°	3	3	4	4	5
	>24°	4	4	5	5	5

Result

The Zagora provinces are part of the Anti-Atlas Mountains and their sub-Saharan regions, characterized by an arid climate, with no major industries and a fairly developed level of agriculture, including the cultivation of date palm forests *(Sadiq et al., 2024)*. The development of a dangerous mass movement process characterizes the region located in the Anti-Atlas domain, which is characterized by sedimentary deposits, including conglomerates and sandstones, as well as volcanism *(Nouayti et al., 2024)*. The study area covers 23000 square kilometres and has a hot desert climate. Based on the digital elevation model (SRTM), a morphometric analysis of the relief features was conducted for the Zagora province. The area was categorized into five classes of potential hazards based on the surface slope calculation, which corresponded to varying levels of landslide risk (Fig. 1A).

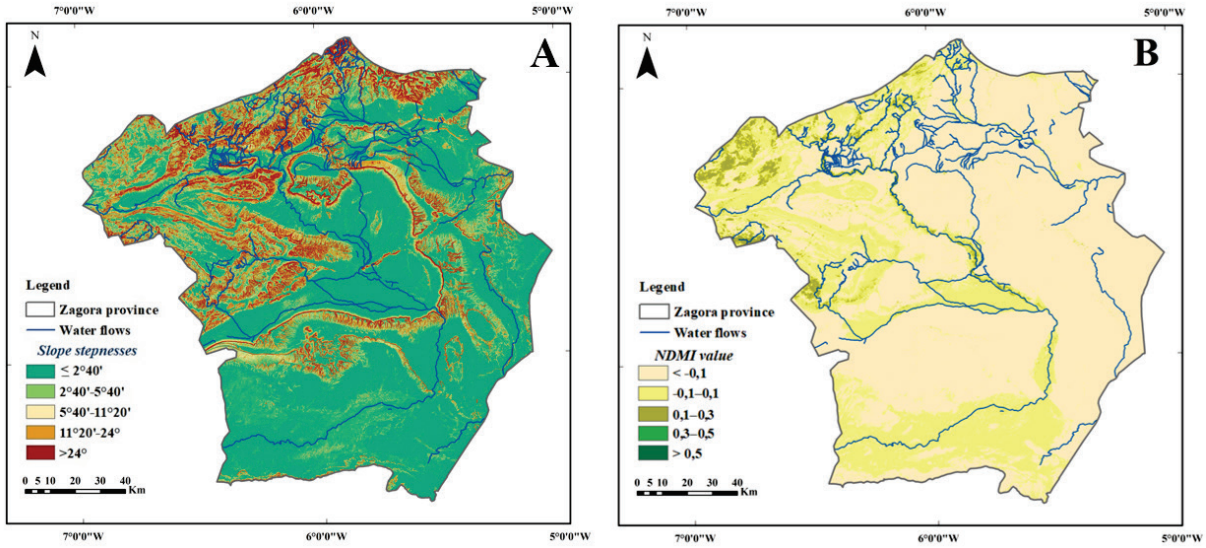

Figure 1. *Distribution of factors in the study area: A – Slope steepness map, B – NDMI index of the study region, Zagora province, Morocco.*

Over 84% of the land has a slope of up to 15°, indicating that flat and gently undulating landforms predominate and that there is little risk of landslide processes or erosion-related degradation. Roughly 11% of the area is classified as moderately risky (15–25°), meaning it may be vulnerable to surface washout processes and the early stages of slope erosion. Areas with a slope of more than 25°, which are already categorized as high- and very high-risk, account for only 4.87% of the land. These are the areas that require close observation and monitoring, particularly when both natural and artificial factors contribute to degradation. Analysis of statistical data on the average monthly rainfall showed that the most significant values occur in the spring period, specifically in May; therefore, the period of May 2024 was chosen for the study, taking into account the flood regime of the Draa River (R. Bouazzaoui, 2016). According to the findings of the NDMI analysis (Fig. 1B), the majority of Zagora province is covered by arid conditions. Low NDMI values, indicating dry surface conditions, are present in the majority of the territory (more than

68%). This reflects the region's arid or semi-arid climate, characterized by limited soil and vegetation moisture availability. Moderate NDMI values, indicating low to medium moisture levels, are found in approximately 20% of the territory. Seasonal vegetation zones or regions with higher soil moisture following the rainy season may be examples of such areas. Less than 2 % of the region has high NDMI values, which could be indicative of local oases, humid valleys, or sparsely vegetated areas. They are confined to the bed of the Draa River and individual oases that are artificially moistened. NDMI reveals a spatial gradient of moisture, clearly correlated with morphometric parameters. Areas with gentle relief are key zones for moisture accumulation, while steeper slopes remain predominantly dry. This suggests a potential vulnerability to slope erosion and highlights the importance of considering morphometry when evaluating degradation processes.

Figure 2 illustrates that the large study area is humidified at NDMI ≤ 0.3 and has a slope of up to 5°40′, which is typical for lowland and plain areas with mainly moderate or low humidity.

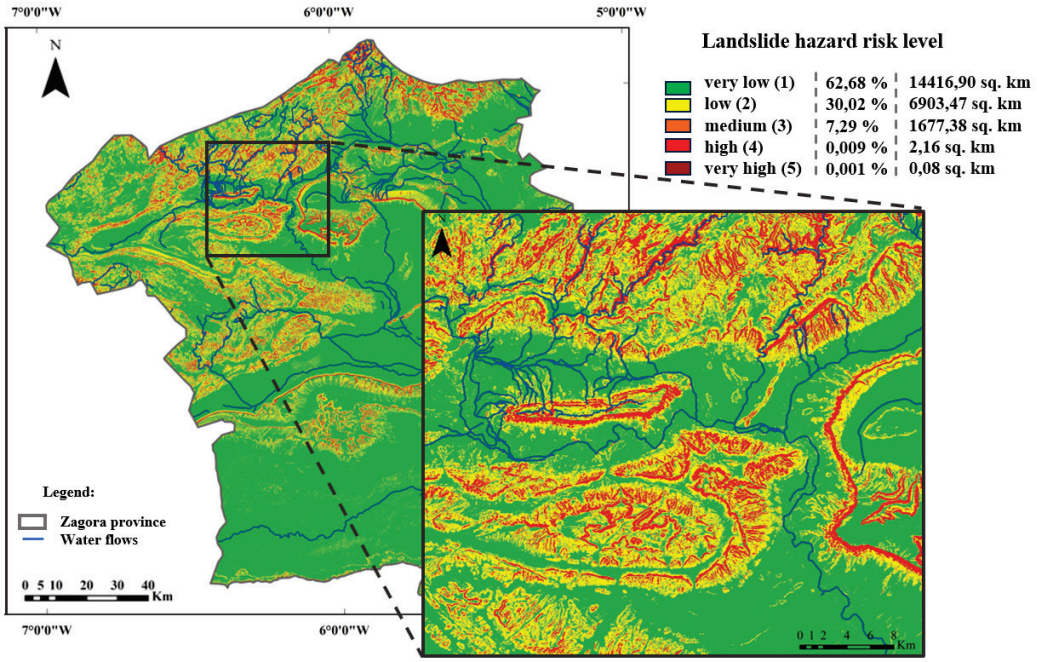

Figure 2. *Distribution of the landslide hazard assessment risk*

The 14,416.90 square kilometres of the Zagora Province, or 62.68%, is classified as a very low risk for landslides, according to the map. Just 7.29% (1,677.38 sq. km) have a medium risk, where 30.02% (6,903.47 sq. km) is in the low-risk zone. Steep slopes are mostly dry, according to an analysis of slope and NDMI values, which specifies when the NDMI is greater than 0.15. Low-mountain or flat terrain tends to retain more moisture. There are very few high and very high-risk areas, 0.009% (2.16 sq. km) and 0.001% (0.08 sq. km), respectively. This implies that only a few areas in the region are seriously at risk of landslides, indicating that the region is generally geologically stable.

Conclusions

As a result, the level of landslide hazard in the Zagora region of Morocco, specifically in the Draa River valley, is low due to geological conditions and consistently low ground moisture levels throughout the year. During a rainy spring period, when the Draa River is in full flow, seismic activity triggers dangerous exogenous processes, and the number of landslide processes increases rapidly. Landslides are uncertain and instant events, causing damage to life and property. Therefore, it is not possible to develop a model of uncertainty with 100% accuracy. However, landslides can be systematically managed even though comprehensive prevention is impossible.

Acknowledgements
This research is funded by the European Union's Framework Programme for Research and Innovation Horizon Europe – the Framework Programme for Research and Innovation (2021-2027), Grant Agreement No. – ID 101086250.

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