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EVALUATING LANDSLIDE HAZARD IN THE BOUDINAR BASIN (MOROCCO) THROUGH SOIL PROPERTIES

SUMMARY

This research assesses landslide hazards in the Boudinar Basin (Morocco) through an evaluation of the area's soil properties and their interaction with the landslide processes. From exhaustive soil sampling and analysis, three distinct zones of landslide susceptibility were established: northern, central, and southern areas. The northern area, which is relatively flat, has a low carbonate content and a very high organic matter, contributing to low landslide risk. In contrast, the central area has a relatively moderate landslide risk due to the great number of samples with moderate organic matter and high carbonate that increases landslide hazards. Southern areas which have steep slopes are very prone to landslides as a result of great mass movement. These results show the predominant role of the topographic factor and the nature of soils in the landslide risks assessment and underline the need for advanced soil conservation and risk management measures in the Boudinar Basin.

Keywords: carbonate, organic matter, slope, soil

INTRODUCTION

The mountainous regions of northern Morocco are prone to significant landslide risks. This susceptibility is heightened by both geological factors, such as tectonic activity in the eastern areas like Al-Hoceima and Driouch (Taher and Mourabit, 2022; Taher *et al*., 2024), as well as climatic conditions, particularly notable precipitation levels in the western regions including Tanger, Tetouan, and Chefchaouen. These factors, combined with fragile lithology like shale, contribute to the prevalence of landslides in the Rif region. Data from field surveys conducted by the Moroccan Provincial Directorate of Practical Work reveal a history of landslides in the region. For instance, up until 1992, Chefchaouen province experienced 47 landslides, Tanger 17, Tetouan 19, and Al-Hoceima one. Recent data, such as that from 2004 to 2016, indicates a significant

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increase in landslide occurrences. For example, Al-Hoceima saw 151 landslides during this period (Byou, 2021). As a result, infrastructure such as roads (fig. 1), bridges, and communities are increasingly vulnerable to landslide hazards.

In recent years, progress in remote sensing and geographic information system (GIS) technologies has significantly enhanced the classification of various factors that trigger landslides, facilitating the creation of detailed landslide inventory maps (Gupta, Pal and Das, 2022; Ait Omar *et al.*, 2024). The utilization of GIS tools for generating, managing, and analyzing geographic data has become pervasive, particularly in forecasting potential landslide hazards (KC, Dangi and Hu, 2022). A range of GIS-based methodologies has been employed for landslide susceptibility mapping, including the Analytical Hierarchy Processes (AHP) (Afzal et al., 2022; Taher et al., 2025), the Frequency Ratio model (FR) (Sheng *et al*., 2022), and machine learning (ML) techniques (Trinh *et al*., 2022).

Figure 1 : The photos depict landslides threatening roads in the Boudinar basin

Many studies have demonstrated the influence of soil properties on landslide processes. For example, Louino et al. (2022) found in Lombardy, Italy, that coarse-textured soils are more prone to landslides compared to fine-textured soils. Similar results were reported by Cerri et al. (2020) in the Serra do Mar Mountain range in Brazil. The increased pore pressure due to water saturation also raises the risk of landslides, highlighting the importance of understanding the dynamic interaction between soil hydrology and landslide processes (Sidle et al. 2016; Bogaard et al. 2016). From these previous studies, we conclude that soil properties play a critical role in landslide dynamics.

In this context, the main objective of this study is to evaluate the impact of various soil properties on landslide processes. Specifically, we focus on key factors such as organic matter content, and carbonate levels. Understanding the role of these properties is essential for identifying areas prone to landslides and improving risk assessment and mitigation strategies. Through this study, we aim to provide valuable insights into the dynamic interactions between soil characteristics and landslide susceptibility, contributing to a more comprehensive understanding of the underlying mechanisms driving these natural hazards

MATERIALS AND METHODS

Study area

The Boudinar Basin, located in the northeastern region of Morocco (Fig. 2), is situated within the administrative boundaries of the Driouch province and encompasses several municipalities, including Trougout, Boudinar etc.

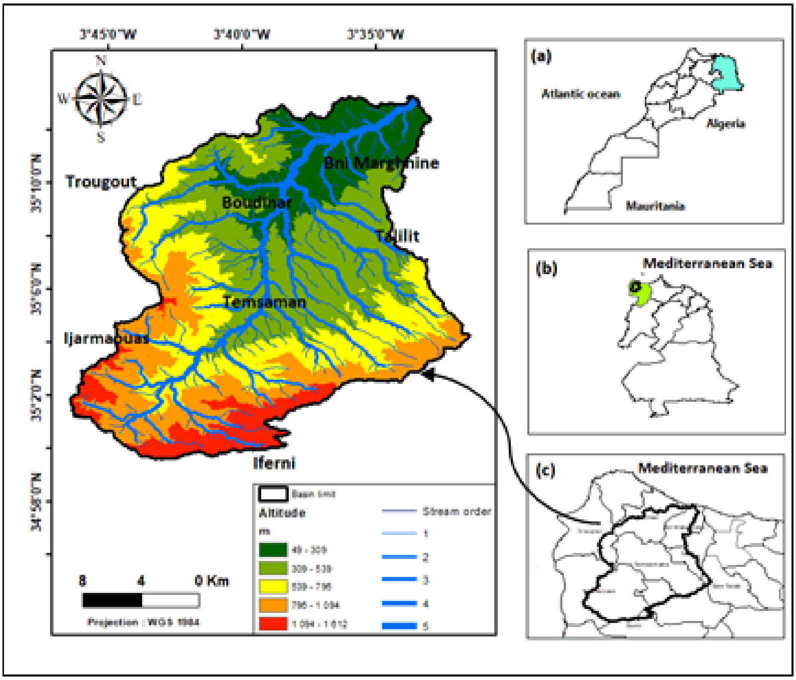

Figure 2 : The Geographical and administrative location of the Boudinar Basin (Taher et al., 2023)

Through the application of Geographic Information System (GIS) techniques, the basin has been precisely delineated, covering an expansive area of 350 square kilometers. Extending from latitude 35.22 to 34.99 north and longitude 3.52 to 3.77 west, its geographical expanse is substantial (Taher et al., 2023). The primary watercourse within the basin is the Oued Amakran, which traverses approximately 40 kilometers before reaching its terminus at the Mediterranean Sea. The altitude profile within the study area presents a diverse topography, with elevations ranging from 49 to 1612 meters above sea level. This variation in altitude contributes to the dynamic landscape of the Boudinar Basin, shaping its ecological and geological features. Additionally, the slopes within the basin exhibit a wide spectrum, ranging from gentle inclines of 0 degrees to steep gradients of up to 63 degrees.

This variability in slope inclination further adds to the complexity of the basin's terrain, influencing factors such as soil erosion, land use suitability, and hydrological processes (Taher et al., 2023).

Soil sampling

Ten soil samples were collected from the Boudinar basin during field mission, with their coordinates noted using GPS (fig. 3). In the geology laboratory at the Faculty of Science and Technology in Al Hoceima, five soil properties of Boudinar basin soil were determined, soil pH was assessed using a palliasse pH meter in a soil-water suspension (fig. 4D). Additionally, bound water, organic matter, and carbonate contents were determined through loss on ignition using high accuracy balance and drying furnaces (fig. 4A&C). Magnetic susceptibility was measured directly using a portable SM30 susceptibility meter with a sensitivity of 10-3 SI and an operating frequency of 8 kHz (fig. 4B) (Dakiri et al., 2021; Tawfik et al., 2024).

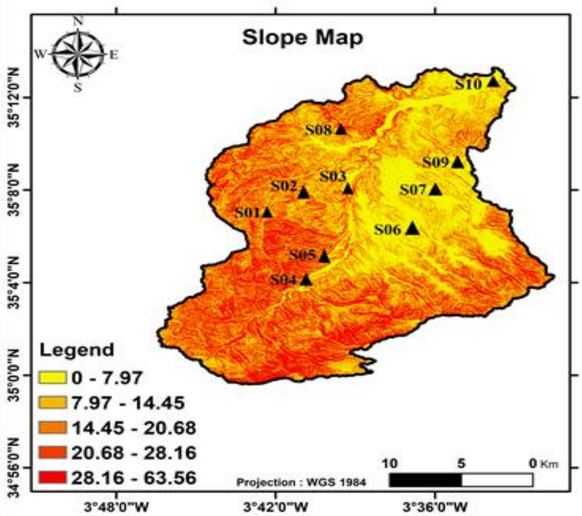

Figure 3: Soil sampling locations in the Boudinar basin

Figure 4: Laboratory equipment employed for the examination of the soil properties attributes of Boudinar soil samples includes: A: analytical balance B: susceptibility meter, C: drying furnaces, D: pH meter

Multi-Criteria Decision Analysis (MCDA)

A comprehensive landslides susceptibility map was developed by integrating nine key parameters. These parameters underwent classification through a weighted overlay analysis and MCDA technique. The rainfall distribution map was meticulously crafted using the inverse distance weighted (IDW) method, drawing upon data from the Power Larc Project, supported by NASA, spanning the years 2010 to 2021. Faults and lithology were mapped digitally, referencing the Boudinar geological map at a scale of 1/50000, sourced from the geological survey of Morocco. Road networks were digitally mapped using data from Google Earth. Furthermore, a digital elevation model (DEM) sourced from the Earth Data (NASA) website was utilized to generate topographic layers such as aspect, slope, and elevation. Finally, NDVI maps were produced using Landsat 9 OLI data acquired from the United States Geological Survey (USGS).

RESULTS AND DISCUSSION

Results

Soil properties of the Boudinar basin

Table 1 offers information on many soil properties, including pH, Bound Water (BW%), Organic Matter (OM%), Carbonate ($CaCO_3$%), and Magnetic Susceptibility (X), therefore illuminating the features and behaviour of the soil.. The pH values range from 8.014 to 8.572, indicating consistently alkaline conditions across all samples. Bound Water (BW%) varies between 1.10% and 4.38%, reflecting the amount of water tightly bound to soil particles, with higher values suggesting greater water retention capacity.

Table 1 : The pedological characteristics of soil samples

Soil sample N°	Longitude	Latitude	pH	BW%	OM%	$CaCO_3$	X(10^{-6}SI)
S01	3.71301	35.12664	8.014	1.85	1.56	0.16	4000
S02	3.68038	35.13802	8.513	1.57	1.88	2.90	92
S03	3.63966	35.10393	8.330	3.67	2.91	3.14	2625
S04	3.68120	35.06073	8.389	2.88	1.94	0.97	1670
S05	3.66928	35.07542	8.572	1.77	1.29	1.41	1235
S06	3.61061	35.11447	8.528	1.86	1.99	2.49	2490
S07	3.60037	35.13375	8.527	2.03	1.84	3.78	782
S08	3.65865	35.18137	8.542	1.10	1.25	1.63	509
S09	3.58561	35.15503	8.350	2.37	2.09	5.68	2460
S10	3.56610	35.21595	8.324	4.38	2.69	1.99	42

BW: Bound Water; OM: Organic matter; $CaCO_3$: Carbonate; X: magnetic susceptibility

Organic Matter (OM%) ranges from 1.29% to 2.91%, which is vital for soil fertility and nutrient retention. Carbonate content ($CaCO_3$%) fluctuates from 0.16% to 5.68%, influencing soil structure and pH levels. Lastly, Magnetic Susceptibility (X) spans from 42 to 4000, with higher values potentially indicating the presence of magnetic minerals such as magnetite or iron oxides, which can affect both soil properties and fertility.

Landslide Susceptibility Map

The Landslide Susceptibility Map of the Boudinar basin has been categorized into three classes: low, moderate, and high, as depicted in Figure 5. The high susceptibility category, encompassing 88 km2 of the study area, is predominantly concentrated in the southern and southeastern regions. The analysis suggests that slope, lithology, altitude, and NDVI are the most influential factors contributing to landslide susceptibility. In contrast, the moderate susceptibility category, covering 242 km2 of the total area, is predominantly situated in the central part of the Boudinar basin. The low susceptibility class, accounting for 18 km2, is primarily located in the northern region.

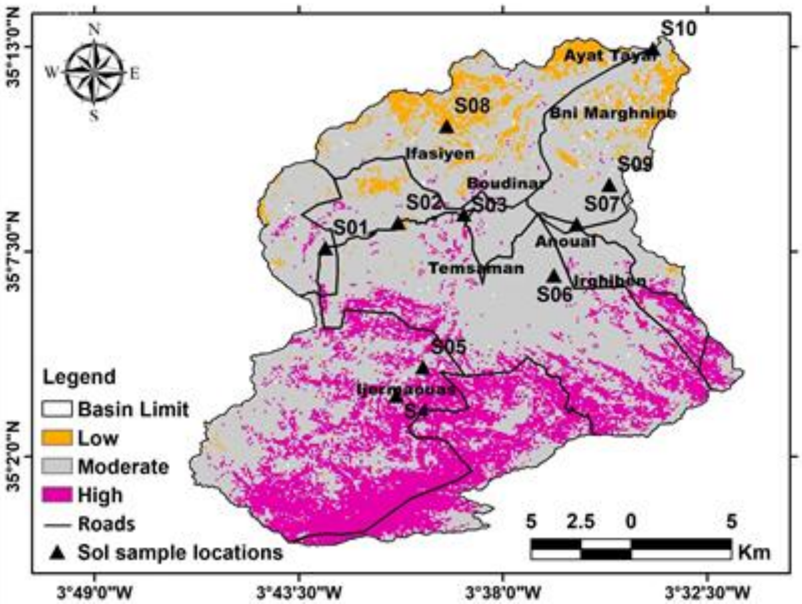

Figure 5: Landslide susceptibility map of the Boudinar basin

Discussion

The map (figure 5) shows distinct landslide susceptibility classes (low, moderate, and high) across the Boudinar basin. These classes correlate with the spatial distribution of soil properties, and slope map (figure 3):

The northern part of the basin is predominantly categorized as having low landslide susceptibility. The soil properties of this area are characterized by low carbonate content, with sample S10 showing 1.99% and sample S08 at 1.63%. This low carbonate content could lead to reduced soil cohesion when saturated (Kemper, Rosenau, and Dexter, 1987). Additionally, sample S10 exhibits high organic matter at 2.69%, which helps stabilize soils by enhancing root binding and reducing erosion (Tisdall and Oades, 1982). However, the flat terrain and stable geological conditions further minimize landslide risk (figure3).

The central region is predominantly characterized by moderate landslide susceptibility. Soil properties in this area show that most samples contain moderate organic matter and high carbonate levels, both of which contribute to an increased landslide risk. Eskene's study highlights that variations in near-surface soil carbonate profiles are closely linked to soil erosion and deposition, with its concentrations typically rising in erosional zones. This suggests that high carbonate content is associated with soil displacement and surface instability, factors that exacerbate erosion and landslide risks (Erskine *et al*., 2017). For instance, at site S03, high bound water content (3.67%) increases pore-water pressure, which can destabilize slopes during heavy rainfall. The combination of moderate slopes, moderate organic matter, high carbonate levels, and moisture-retaining soils in this region contributes to its moderate susceptibility to landslides.

The southern part of the basin is predominantly characterized by high landslide susceptibility. The soil characteristics in this section of the study area do not exhibit specific patterns in carbonate content or organic matter. The primary factor contributing to landslide risk here is topography, as depicted in Figure 3, where the area is defined by very steep slopes. Vanacker *et al*. (2019) emphasize that topography plays a crucial role in controlling soil movement and the redistribution of pedogenic material, with steep slopes showing clear spatial differences in weathering and increased material fluxes.

In light of these results, organic matter plays a critical role in the initial stages of soil formation on landslides, positively affecting microbial biomass and enzyme activities essential for soil recovery and stability (E. Błońska *et al*., 2018). Moreover, its addition to soil can significantly reduce the duration and volume of landslides, even under varying rainfall intensities, suggesting that organic matter enhances soil cohesion and stability, thereby mitigating landslide impacts (Rofiq et al., 2022). On the other hand, carbonate content in soil plays a significant role in landslide dynamics by affecting soil stability and chemical properties. The dissolution of carbonates can weaken soil structure, making it more susceptible to landslides, especially in areas with steep slopes and heavy rainfall (Ying *et al*., 2020; Forte *et al*., 2019; Cheng *et al*., 2016).

CONCLUSION

The study of the spatial distribution of soil properties across the Boudinar Basin has shown a moderate correlation with landslide susceptibility. However, other factors also contribute to landslides. Therefore, it is essential to correlate these findings with additional factors, such as geological and anthropogenic influences.

In conclusion, the landslide susceptibility in the Boudinar Basin varies across its regions due to differences in soil properties and topography. The northern region, with its low carbonate content, high organic matter, and flat terrain, has a low susceptibility to landslides. In contrast, the central region, characterized by moderate slopes, moderate organic matter, high carbonate levels, and moisture-retaining soils, exhibits a moderate landslide risk. The southern region, marked by very steep slopes, experiences the highest landslide susceptibility, with topography being the dominant factor influencing landslide risk. Overall, the study highlights the significant role of both soil properties and topography in determining landslide susceptibility in the basin.

As a perspective, we recommend that future research investigate soil properties using multiple deep soil samples across the study area to better evaluate landslide risks. Understanding these relationships can aid in effective land management and mitigation strategies to reduce landslide risk in vulnerable areas.

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