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Research Article

Mapping of Landslide Risk Zones Using the Analytic Hierarchy Process (AHP) in the Vicinity of National Road RN16 between Bouchegouf and Souk-Ahras (Algeria)

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Abstract:

Landslides are among the most damaging natural hazards in northeastern Algeria, particularly along transport corridors traversing complex terrain. This study focuses on mapping the landslide susceptibility zones along the RN16 road section connecting Bouchegouf and Souk-Ahras using a multi-criteria decision-making approach based on the Analytic Hierarchy Process (AHP) integrated with Geographic Information Systems (GIS). Fourteen conditioning factors were selected, including topographic, hydrological, geological, and anthropogenic parameters. Thematic maps were generated for each factor, including a Digital Terrain Model (DTM), slope, aspect, elevation, plan curvature, profile curvature, Topographic Wetness Index (TWI), hydrographic network, distance to rivers, land use, land cover, road network, precipitation, lithology, and geology. The AHP was applied to compute the relative weights of these factors. The final susceptibility map was classified into five zones: very low, low, moderate, high, and very high susceptibility. Validation using known landslide occurrences demonstrated that all of the inventoried landslides fall within high and very high susceptibility classes. The results highlight the dominant influence of slope, lithology, precipitation, and land use in slope instability. The resulting map serves as a valuable tool for land-use planning, infrastructure protection, and disaster risk reduction along the RN16 corridor.

1. Introduction

Landslides represent a major natural hazard in northeastern Algeria, particularly threatening critical infrastructure such as road networks traversing complex terrain. The region's steep topography, diverse lithology, and variable precipitation patterns contribute to frequent slope instability, posing significant risks to transportation corridors and local communities [1-3]. Accurate mapping of landslide-prone zones is therefore essential for effective land-use planning, infrastructure protection, and disaster risk reduction.Recent advances in landslide susceptibility assessment have emphasized the integration of multi-criteria decision-making methods, notably the Analytic Hierarchy Process (AHP), with Geographic Information Systems (GIS). The AHP enables systematic weighting of diverse conditioning factors—such as slope, lithology, precipitation, land use, and proximity to roads or rivers—based on their relative influence on landslide occurrence [1-4]. This approach allows for the synthesis of complex spatial data into susceptibility maps that classify areas into risk zones, supporting targeted mitigation strategies.In Algeria, several studies have demonstrated the effectiveness of AHP-based GIS models for landslide susceptibility mapping. For example, in the Tellian Atlas and Constantine regions, AHP frameworks incorporating topographic, geological, hydrological, and anthropogenic parameters have produced susceptibility maps validated by landslide inventories and receiver operating characteristic (ROC) analyses, with area under the curve (AUC) values indicating good predictive performance [1-3,5]. These studies consistently highlight the dominant roles of slope, lithology, and precipitation in determining landslide risk, and underscore the value of such models for spatial planning and hazard mitigation.

Different works on landslide susceptibility in Algeria (until 2025)

In Algeria, research on landslide susceptibility is relatively recent. Several studies have applied heuristic and statistical approaches to determine areas that are potentially exposed to landslide hazards (Table 1). Most of these investigations have been conducted in the eastern part of the country [6,7].Applying the Analytic Hierarchy Process (AHP) methode integrated with Geographic Information Systems (GIS)se to the RN16 corridor between Bouchegouf and Souk-Ahras (East of Algeria) is particularly relevant, given the area's exposure to landslide hazards and the strategic importance of the roadway. AHP method was selected because it is still useful, especially for large-scale assessments or for areas with no available landslide inventory.The objectives of this study are threefold:

- To identify and analyze the main factors influencing landslide occurrence along the RN16 corridor;
- To apply the AHP method to compute the relative significance of these factors; and
- To produce a detailed susceptibility map that can assist decision-makers in developing preventive and mitigation strategies.The integration of AHP and GIS provides a robust framework for identifying high-risk zones, informing infrastructure management, and enhancing regional resilience to natural disasters[1-3,5].This research contributes to the regional understanding of slope hazards and provides a scientific basis for sustainable road management and risk-reduction planning in northeastern Algeria.

Table 1: *Different research works on landslide susceptibility in Algeria (until 2025)*

Authors	Study Area	Parameters	Techniques / Methods
Bourenane et al., 2014 [6]	City of Constantine (East of Algeria)	Slope gradient, slope aspect, lithology, precipitation, distance to streams, land use, distance to roads, distance to faults	Geomorphological analysis & SI
Achour et al., 2017 [8]	Highway section / Constantine Province	Lithology, distance to faults, slope gradient, slope aspect, distance to streams, land use, cohesion, internal friction	AHP & IV
Manchar et al., 2018 [7]	Constantine City	Lithology, slope gradient, slope aspect, elevation, distance to lineaments, distance to streams, rainfall, NDVI	IV, WoE & FR
Hadji et al., 2018 [9]	Oued Mellah Basin	Lithology, faults, slope, elevation, aspect, streams, roads, precipitation	AHP, LI & LR
Mahadadi & Boumezbeur (2020).[10]	Souk Ahras region (NE Algeria).	Slope, lithology, aspect, elevation, distance to streams, land use, rainfall.	Logistic Regression (LR) & Frequency Ratio (FR).
Senouci et al. (2021).[11]	Mostaganem coastal district (W Algeria).	Slope, lithology, aspect, land use, distance to roads, distance to streams, faults, precipitation.	Knowledge-driven expert scoring + AHP in GIS; LSM produced and validated.
Benbouras et al. (2022). [12]	Comparative / methodological study (Algerian datasets).	Multiple geomorphological and hydrological conditioning factors.	Hybrid meta-heuristic + ANN (PSOGSA-ANN) and comparative ML models — showed hybrid ML outperforms simpler models.
Seddiki et al. (2022).[13]	the Mila area (East Algeria).	Slope, lithology, land use, faults, streams, road proximity.	AHP integrated with GIS for regional susceptibility mapping.

Benzenine et al. (2023). [14]	Bensekrane area (NW Algeria).	Slope, lithology, rainfall, land cover, distance to streams/roads, NDVI.	FR, IV, and comparative mapping (GIS) — applied local validation with inventory.
Chaabane et al. (2024). [15]	Mila region (NE Algeria) — earthquake-triggered landslides (Aug 2020).	Seismotectonic context, lithology, slope, distance to faults/lineaments, rainfall.	Inventory of ~270 events; susceptibility mapping and spatial analysis of earthquake-triggered landslides. (Springer / Landslides).
Z. Roukh (2023).[16]	Echorfa region (NW Algeria / Arzew sector).	Slope, aspect, lithology, distance to faults/lineaments, precipitation, land use, altitude.	AHP, Weight of Evidence (WoE), Logistic Regression (LR) combined in GIS.
Mersni et al. (2025).[17]	(Recent Algerian case studies reported in 2025).	Rainfall, slope, aspect, TRI, lithology, land use.	ANN + AHP hybrid for factor weighting and susceptibility classification (MDPI Geosciences / 2025).
Regional PhD / thesis work (2020–2024)[18]	Mila, Constantine, Jijel and Kabylie basins.	Similar sets: slope, lithology, aspect, elevation, faults, roads, rainfall, NDVI.	Multiple: FR, IV, LR, AHP, WoE, ML hybrids and InSAR time-series (growing use).

General Characteristics of the study area

The study area encompasses the section of National Road RN16 that connects Bouchegouf and Souk-Ahras in northeastern Algeria (Figure 1). This corridor lies within the Tellian Atlas domain. The geomorphological and structural complexity of the Tellian Atlas domain, including steep topography and fractured geological formations, has been highlighted in studies investigating slope movements and landslide susceptibility in the region[19, 20]. It is a morphologically complex region characterized by rugged topography, steep slopes, and highly fractured geological formations. Elevations across the study area range from approximately 270 to over 950 m above sea level, creating strong vertical gradients that contribute significantly to slope instability issues by increasing gravitational forces and aiding erosion. Similar observations have been documented in slope instability assessments along infrastructure corridors in northeastern Algeria, with specific attention to how geological and topographic factors interact [21-23]

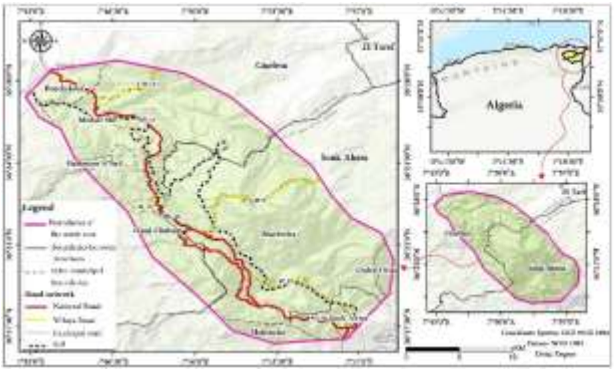

***Figure 1**: Location map of the study area.*

The geological setting is dominated by sedimentary and metamorphic formations such as marls, claystones, limestones, and sandstones (Figure 2). These lithological units demonstrate variable mechanical behaviors and differential weathering rates, contributing to spatial variability in landslide susceptibility. Additionally, the region is traversed by structural lineaments and fault systems associated with active compressive tectonics. These combined geological and structural factors significantly influence slope stability. For example, research addressing slope instability caused by weathering processes and structural discontinuities corroborates the impact of lithological variability on slope behavior in similar regions [24,25].

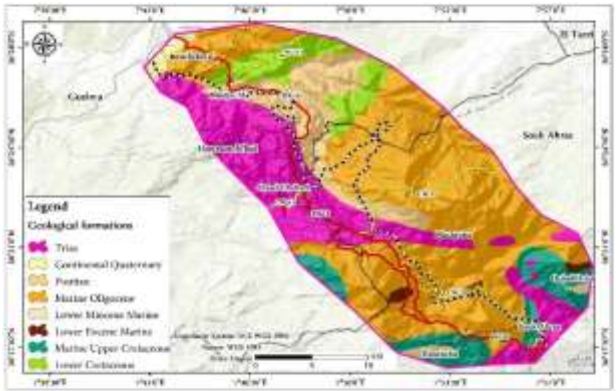

***Figure 2:** Geological map of the study area.*

Heavy seasonal rainfall and extreme storm events worsen slope instability by accelerating erosion processes, raising pore-water pressures, and saturating surface materials—conditions that are often responsible for landslide initiation. These rainfall-induced mechanisms are consistent with findings reported for northeastern Algeria, where precipitation has been identified as a major trigger of shallow landslides and a factor that increases instability in already sensitive areas.[26]The RN16 corridor is one of the main road links between the coastal zone of Annaba and the uplands of Souk-Ahras, and it is regularly affected by slope failures such as landslides, rockfalls and debris flows. Recent investigations emphasize that this area represents a complex interaction between steep relief, fractured rock formations, and repeated slope instabilities along major transportation routes in comparable geomorphological settings [27,28].In addition, several human-induced actions including urban development, land clearing, excavation of slopes, and roadway construction, contribute to further reducing slope stability and intensifying the occurrence of mass movements. Such anthropogenic influences have been broadly reported along key infrastructure corridors in Algeria, where terrain modification and the loss of vegetation heighten erosion processes and accelerate slope deterioration [26,29]The combination of geological, geomorphological, and anthropogenic elements makes the Bouchegouf–Souk-Ahras section a prime case study for understanding landslide susceptibility. Detailed geological mapping (as mentioned in studies focused on structural styles and sedimentary stratigraphy) and comprehensive susceptibility models based on advanced GIS and multi-criteria analysis validate the strategic importance of this region for risk-based spatial planning [20,25].

Landslides in the Study Area

Based on our repeated field surveys conducted over the past several years, we were able to inventory numerous landslide points along the investigated corridor. These can be summarized at the following chainage locations:

- Mechroha: PK77+700, PK79+800, PK80+500
- Aïn Seynour: PK81+400, PK85+000
- Bouchegouf (Guelma Province) – Aïn Tehmamine: PK65+800, PK67+600.

In reality, at each of these chainage locations, not only a single landslide point is observed, but rather a series of retrogressive landslides (figure 3) that continue to evolve from one year to the next.

Figure 3: *Location of the different zones (I to IV bis) of landslides recorded on the RN 16 (Google Earth photo) between pk 65+400 and pk 68+800*

2. Material and Methods

2.1. Dataset and Data Sources

This study integrates multiple spatial datasets to generate the landslide susceptibility map of the RN16 corridor, between the wilaya of GUELMA and wilaya of SOUK-AHRAS, exactly between BOUCHEGOUF city and SOUK-AHRAS city. The Digital Terrain Model (DTM) with a spatial resolution of 30 m was obtained from the ASTER GDEM. Geological and lithological data were extracted from the Algerian Geological Survey maps, while precipitation and hydrological data were collected from national hydrometeorological records. Land use and land cover layers were derived from Sentinel-2 imagery. Road networks and urban boundaries were extracted from national infrastructure databases.All datasets were projected to the same coordinate system and converted into raster format. Standard GIS preprocessing techniques were applied, including clipping, resampling, rasterization, and spatial adjustment.

2.2. Selection of Conditioning Factors

Fourteen terrain, geological, hydrological, and anthropogenic parameters were used to model landslide susceptibility along the RN16 corridor. The choice of parameters was based on earlier studies in Algeria where topographic and geological criteria were shown to be dominant factors influencing slope instability [2,6,10,13]. Similar factor selection approaches have also been widely adopted in landslide studies in the Tellian Atlas and Constantine regions [1,14].Each factor was classified into suitable categories according to its influence on slope instability.

2.3. GIS-based Thematic Mapping

The thematic layers were generated in ArcGIS 10.4. Terrain derivatives such as slope, aspect, and curvature were derived from the DTM. Hydrological indices, drainage networks and distance maps were produced using the spatial analyst tools. The remaining maps were digitized, reclassified and converted into a consistent raster format with the same pixel size.

2.4. Analytical Hierarchy Process (AHP) and selection of parameters

The AHP technique was applied to quantify the contribution of each factor. Table 2 presents the pairwise comparison matrix, the normalized weights and the Consistency Ratio (CR) of the comparison. The CR value of 0.09 confirms the coherence and consistency of the expert comparisons, as values lower than 0.10 are considered acceptable according to Saaty's criterion [19].

2.5. Calculation of the weighting coefficients

Table 2 shows the results of the pairwise comparison and the final AHP weights assigned to each factor. The parameters that were assigned the highest weights are:
Slope (0.19)
Land use (0.18)
Distance to rivers (0.17)
Lithology (0.15)
These results are in line with previous research conducted in northeastern Algeria, where slope geometry and lithology have repeatedly been proven to be the major triggers of landslides along roadway corridors [6,10,28].Factors with moderate influence include precipitation (0.08), aspect (0.08), profile curvature (0.07), elevation (0.07), and plan curvature (0.06). The Topographic Wetness Index (TWI) recorded the lowest weight (0.05), although hydrological conditions are still considered relevant in increasing pore water pressure and inducing slope failure [25,26].

Table 2. *The main parameters and the calculation of their weighting coefficients for the AHP method*

	slope	elevation	curvature	lithology	precipitation	land use	TWI	Aspect	plan curvature	distance to rivers	poids
slope	1	3	3	1	2	1	5	2	6	3	0,19
elevation	0,33	1	2	0,36	2	0,2	3	0,5	0,5	0,5	0,07
curvature	0,35	0,5	1	0,5	1	0,32	1	2	2	0,33	0,07
lithology	1	4	2	1	2	1	3	1	3	2	0,15
precipitation	0,5	0,5	1	0,6	1	0,5	2	2	2	0,4	0,08
land use	1	5	3	1	2	1	4	3	3	1	0,18
TWI	0,2	0,35	1	0,32	0,5	0,35	1	0	0,54	0,25	0,05
Aspect	0,6	2	0,54	1	0,5	0,36	2	1	1	0,35	0,08
plan curvature	0,3	2	0,5	0,36	0,5	0,5	2	1	1	0,55	0,06
distance to river	0,35	2	3	0,6	2	1	5	3	2	2	0,17
CR=0,09											

2.3. Weighted overlay analysis

Each conditioning parameter was converted into a raster layer and reclassified according to its susceptibility level. Using the AHP weights Wi from Table 2, the Landslide Susceptibility Index (LSI) was computed as:

$$Wi = \sum_{i=1}^{n} Wi \times Ri$$

Where *Ri* is the rating classes for each layer and *Wi* is the weights for the each of the landslide conditioning factors.
The generated susceptibility map was classified into five zonation classes: very low, low, moderate, high, and very high risk. Similar classification has been used in studies conducted in Constantine, Souk-Ahras and Mila regions [2,7,13].

3. Results and Discussions

3.1. Interpretation of parameter weights

As shown in Table 2, slope received the highest weight (0.19). This is consistent with regional studies demonstrating the dominant role of slope angle in controlling mass movements in Algeria [6,7,10]. Land use (0.18) and distance to rivers (0.17) also significantly influence susceptibility, highlighting the effect of anthropogenic activity and fluvial erosion on slope failure [12,13].
Lithology (0.15) is another parameter strongly correlated with landslide occurrence. Weak sedimentary formations such as marls and claystones are highly susceptible to mechanical weathering, a

result also reported in Boumezbeur et al. (2020)[10,27] and Benzenine et al. (2023)[14].

3.2. Spatial distribution of susceptibility

The final susceptibility map indicates that the central and northeastern segments of the RN16 corridor are most exposed to landslides. These zones are characterized by steep terrain, high precipitation, fragile lithology, and proximity to drainage paths. Similar spatial patterns have been identified in other Algerian case studies, particularly in Mostaganem and Constantine [3,14].
Conversely, low-risk zones correspond to flat areas or stable geological units with limited hydrological influence.

3.3. Comparison with previous studies

The ranking of factors in Table 2 confirms previously published conclusions stating that slope and lithology are the most influential parameters for landslide susceptibility in northeastern Algeria [2][7][10]. The AHP weighting distribution also corresponds well with recent machine-learning based models in the region, which found precipitation, land use, and drainage proximity as secondary, yet still relevant contributors [12][14].

3.4. Validation of the model

Overlaying the landslide inventory with the susceptibility classes showed that all of the recorded events fall within the high and very-high categories. This performance is comparable to other AHP-based or hybrid approaches applied in Algeria and the Mediterranean [3,11,15].

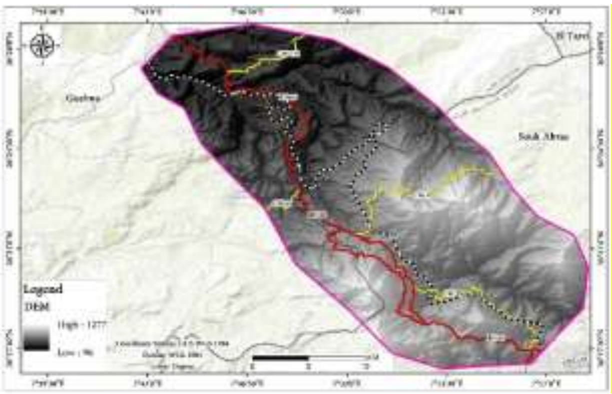

Figure 4: *Digital Terrain Model (DTM).*

The DTM shows the elevation variation across the study area. Higher altitudes dominate the central and northern sectors, forming steep slopes that contribute to elevated landslide susceptibility. Lower, flatter terrain is mainly concentrated toward the periphery, where instability potential is reduced.

Road Network Map (Figure 5)

Figure 5: *Road network map*

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This map outlines the RN16 road and secondary tracks. Sections of the RN16 that traverse steep slopes appear more vulnerable to slope failures. Proximity to roads is a critical factor because cut-slopes and human alterations often destabilize natural terrains.

Hydrographic Network (Figure 6)

The hydrographic network reveals the drainage pattern controlling surface water flow. Areas near dense stream networks exhibit higher erosion and infiltration, increasing the likelihood of slope instability, particularly during intense rainfall events.

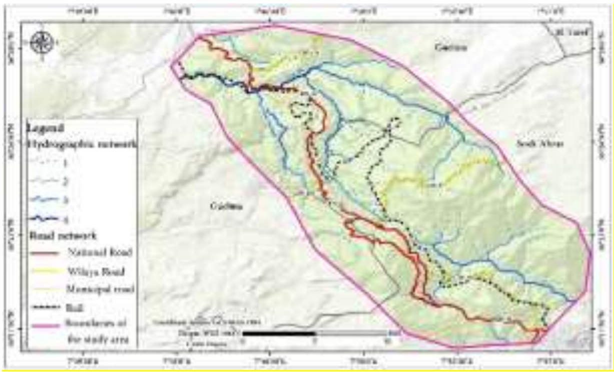

Figure *6: Hydrographic network map.*

Distance to Rivers (Figure 7)

This map classifies terrain according to proximity to rivers. High-risk zones occur near rivers and tributaries due to erosion, toe-undermining, and increased pore-water pressure. Susceptibility decreases as distance from drainage pathways increases.

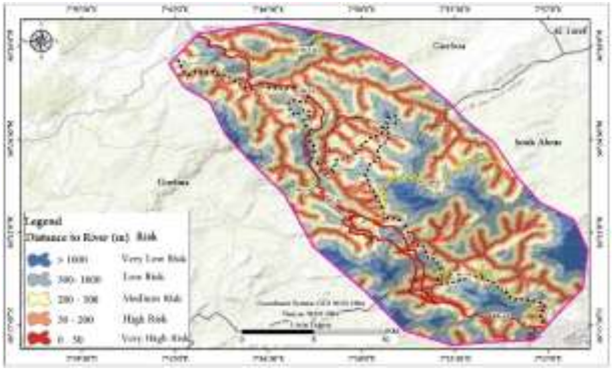

Figure 7: *Distance from rivers map.*

Topographic Wetness Index (TWI) (figure8)

High TWI values indicate zones where water tends to accumulate. These saturated areas are more prone to shallow landslides and soil weakening. Low TWI zones represent well-drained terrain with lower susceptibility.

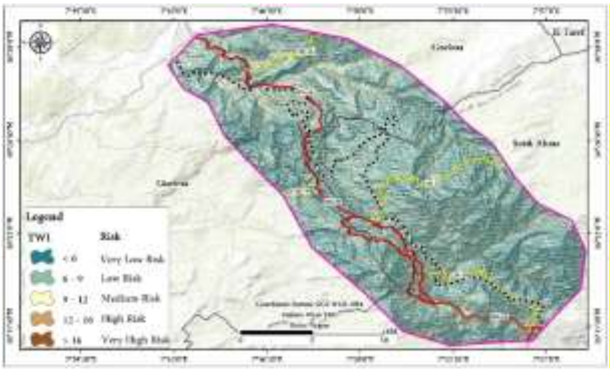

Figure 8: *Topographic Wetness Index (TWI) map.*

Aspect Map (figure9)

Aspect identifies slope orientation. South- and southwest-facing slopes tend to be drier, while north-facing slopes retain more moisture. Moisture-rich orientations are more exposed to weathering and instability.

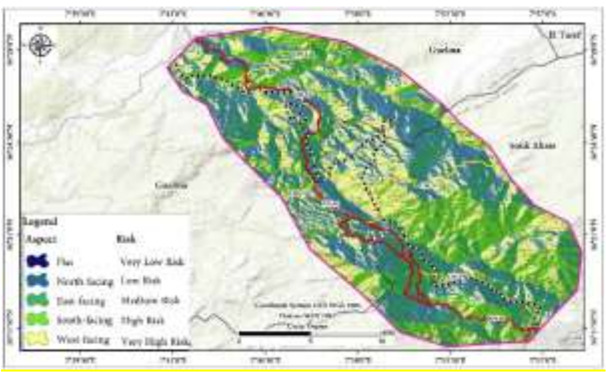

Figure 9: *Aspect map.*

Slope Map (figure 10)

Steep slope zones dominate the central corridor and coincide with most landslide occurrences. High slope angles significantly increase gravitational forces, explaining the strong weighting of the slope factor in the AHP model.

Figure 10: *Slope map.*

Elevation Map (figure11)

Elevation varies markedly across the area, reflecting rugged topography. Higher terrain correlates with steep, erosion-prone slopes, whereas lower zones exhibit more stable profiles.

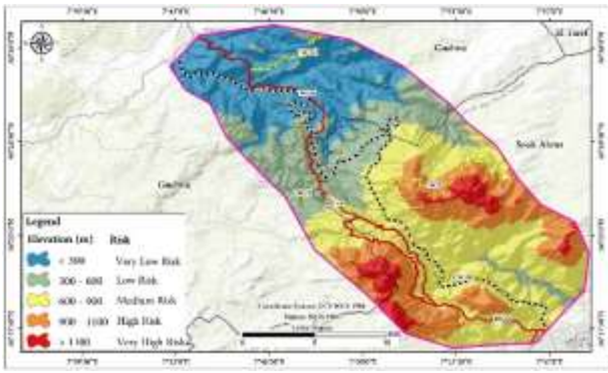

Figure 11: *Elevation map.*

Precipitation Map (figure12)

Rainfall intensity is higher in the central and eastern parts of the study area. These areas are more susceptible to rainfall-triggered landslides due to the increased likelihood of soil saturation and runoff concentration.

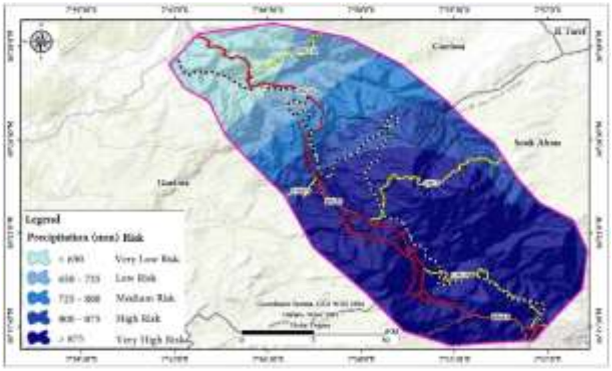

Figure 12: *Precipitation map.*

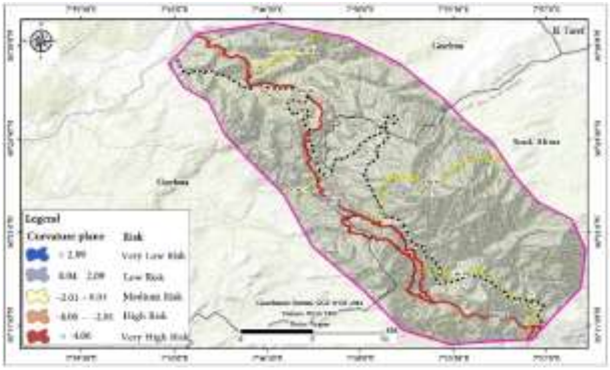

Figure 13: *Plan curvature map.*

Plan Curvature Map (figure13)

Concave plan curvature zones enhance runoff convergence, increasing erosion and instability, while convex zones disperse water and typically remain more stable.

Profile Curvature Map (figure14)

This map shows how slopes accelerate or decelerate water flow. Concave profiles slow down water, promoting infiltration and instability; convex profiles speed flow, reducing infiltration and enhancing stability.

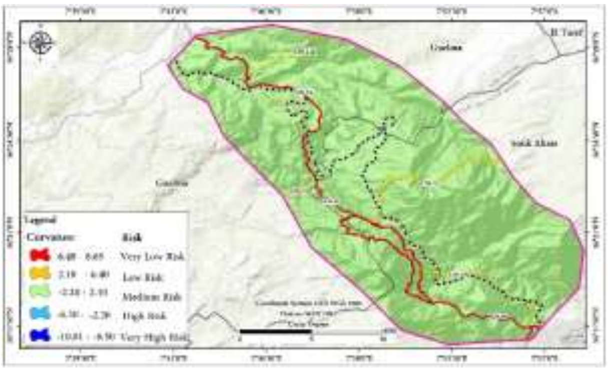

Figure 14: *Profile curvature map*

Land Cover Map (figure15)

Vegetated areas generally exhibit greater stability, while bare or sparsely vegetated areas show higher susceptibility to erosion and shallow landslides. Human-modified surfaces such as agriculture and settlements also show increased risk.

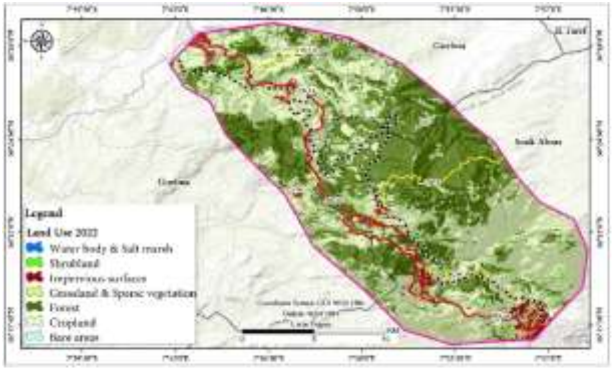

Figure 15: *Land cover map.*

Land Use Map (figure 16)

Land use categories highlight anthropogenic pressure. Agricultural zones, urban expansion, and road cuts increase exposure to slope failures due to surface disturbance and vegetation loss.

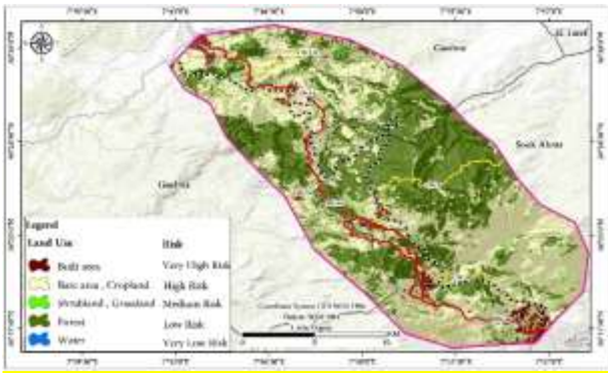

Figure 16: *Land use map.*

Lithological Formations Map (figure 17)

Weak formations such as marls, claystones, and weathered sedimentary rocks dominate many unstable zones. More competent units, such as limestones and sandstones, are located mostly in stable areas. Lithology shows strong spatial correlation with mapped susceptibility classes.

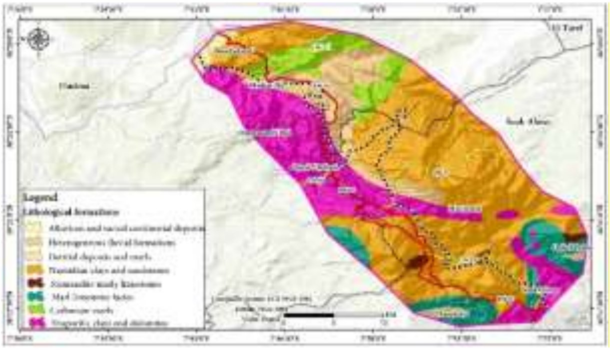

Figure 17: *Lithological formations map of the study area.*

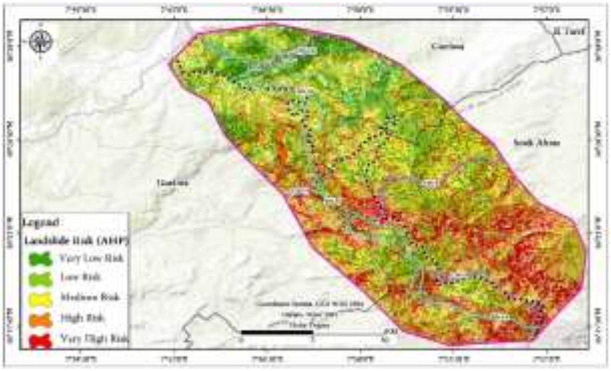

Figure 18: *Final Landslide Susceptibility Map (AHP).*

Final Landslide Susceptibility Map (AHP)

The integrated map (figure 18) delineates five susceptibility classes. High and very-high risk zones align with steep slopes, weak lithological units, and areas close to rivers. The RN16 road crosses several high-risk sectors, particularly within the central and northeastern parts of the study area confirming the need for continuous monitoring and slope stabilization.

4. Conclusions

This study produces a landslide susceptibility map for the RN16 corridor between Bouchegouf and Souk-Ahras using an AHP-GIS approach. The analysis incorporated fourteen conditioning factors, and the pairwise comparison matrix (Table 2) provided reliable weights, with a CR of 0.09.
The results demonstrate that slope, land use, distance to rivers, and lithology are the most influential factors controlling landslide susceptibility, followed by precipitation and elevation. The spatial patterns of susceptibility are consistent with documented field observations and previous regional studies.
The final susceptibility map successfully identifies high-risk areas and confirms that most inventoried landslides occur in the high and very-high classes. This confirms the strong predictive capability of the AHP model.
The outcomes of this study provide a scientific basis for infrastructure protection and planning along RN16. The methodology is transferable to similar geomorphological environments in Algeria and may be improved in future studies through the integration of real-time monitoring, rainfall thresholds, or machine learning.

Author Statements:

- **Ethical approval:** The conducted research is not related to either human or animal use.
- **Conflict of interest:** The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper
- **Acknowledgement:** The authors declare that they have nobody or no-company to acknowledge.
- **Author contributions:** The authors declare that they have equal right on this paper.
- **Funding information:** The authors declare that there is no funding to be acknowledged.
- **Data availability statement:** The data that support the findings of this study are available on request from the corresponding author. The data are not publicly available due to privacy or ethical restrictions.

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