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SPATIAL ASSESSMENT OF VULNERABILITY TO WATER EROSION IN THE OUED HONAINE WATERSHED (NORTHWEST ALGERIA) THROUGH MAPPING OF SENSITIVE AREAS

MERIOUA S.M.[1], MEGHRAOUI M.[2*], HABI M.[3], SELADJI A.[2], BRIGHT D.[4]

[1] Associate Professor, SalhiAhmed University Center Naâma, Algeria
[2] Researchers, National Institute of Forestry Research, Tlemcen, Algeria
[3] Professor, Department of hydraulic, University of Tlemcen, Algeria
[4] Associate Researcher, Department of Forest Resources, University of Tlemcen, Algeria

(*) meghraoui_forestier@yahoo.fr

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ABSTRACT

Water erosion in soils is a major problem caused by agricultural intensification, land degradation, and extreme climate variations. The objective of this study is to develop a method based on the integration of satellite imagery and cartographic data into a geographic information system for the identification and mapping of areas sensitive to water erosion in the soils of the Honaine micro-watershed in the Honaine region (Northwest Algeria). Three factors—slope, material friability, and land use appear to control erosion. To achieve this, the study used GIS. The resulting erosion sensitivity map shows four zones vulnerable to water erosion: low sensitivity, moderate sensitivity, high sensitivity, and very high sensitivity. The moderately sensitive zone covers 80% in total and corresponds well with field observations.

Keywords: Water erosion, Remote sensing, Geographic Information System (GIS), Mapping, Oued Honaine Watershed, Northwest Algeria.

INTRODUCTION

The development of mountain regions represents a major strategic challenge for Algeria (Zerkaoui et al., 2016). These territories, with their vast expanse and rich in natural resources such as wtater resources (Benslimane et al., 2015), forests and biodiversity, mineral resources, agricultural land, and renewable energy potential, hold significant potential for sustainable development (Djabri et al., 2015; Aroua, 2022). Sustainable development affects various sectors, highlighting practices that meet current needs without compromising the ability of future generations. The vital sectors concerned are multiple such as: Renewable Energy Initiatives (Boubou- Bouziani, 2015; Birbal and Azamathulla, 2024), Sustainable Agriculture, Sustainable Hydraulic Engineering and practices (Hountondji et al., 2019; Benslimane et al., 2020; Remini and Amitouche, 2023; Baudhanwala et al., 2023), Water Resource Management (Paulo Monteiro and Costa Manuel, 2004; Khemmoudj et al., 2016; Pandey et al., 2022; Aroua, 2023; Qureshi et al., 2024), Eco-Friendly Urban Planning (Ouattara et al., 2022; Long et al., 2023), Circular Economy Practices (Benslimane et al., 2011; Boutebba et al., 2014; Faye, 2016; Goran and Jelisavka, 2016; Jayasena et al., 2021; Kouloughli and Telli, 2023; Berrezel et al., 2023; Kezzar and Souar, 2024), Conservation and Reforestation (Boulghobra, 2013).

Furthermore; in the context of sustainable development and Eco-Friendly Practices, many studies explored traditional irrigation systems and water harvesting methods in semi-arid regions, emphasizing their role in ensuring water availability for agricultural activities, which is crucial for developing effective strategies in mountainous and water-scarce areas (Rezzoug et al., 2016; Jelisavka and Goran, 2018; Remini, 2019; Derdour et al., 2022).

However, mountain regions, especially their water resources, are now severely threatened by a growing ecological imbalance resulting from both anthropogenic pressures and climate change, which requires advanced development models (Haouchine et al., 2015; Laghzal et al., 2019; Pang and Tan, 2023). This situation compromises their environmental stability and risks hindering their socio-economic progress in the long term (Choukrani et al., 2018).

In the context of climate change and water scarcity, studies discussed the strategic importance of surface, dam, and groundwater resources in Algeria, underscoring the need for sustainable management practices (Remini, 2024; Remini, 2025). However, this state of affairs does not only concern Algeria, but many regions across the world (Kouassi et al., 2013; Ouhamdouch et al., 2016; Assemian et al., 2021; Chadee et al., 2023).

According to many studies such as those of Beatriz et al. (2002), Remini (2017), and Chabokpour and Azamathulla (2025), water erosion results from the interaction of various natural factors and is frequently exacerbated by inappropriate human practices. It is one of the leading causes of land and river banks degradation on a global scale (Mfoutou and Diabangouaya, 2019). Water erosion is one of the most concerning phenomena affecting the Honaine region. This natural process, although essential in shaping landscapes, is significantly intensified by human activities. Deforestation, intensive agricultural practices, and unplanned urbanization accelerate soil erosion, thereby threatening land fertility, water resource availability, and local biodiversity.

This process occurs in three distinct phases: the detachment of soil particles (Ansari et al., 2024), which requires significant energy; the transport of sediments (Meguenni and Remini, 2008; Meddi, 2015; Bougamouza et al., 2020), which depends on runoff volume, and finally, sedimentation (Remini and Remini, 2003), influenced by the water’s transport capacity and the granulometry of the sediments (Roose et al., 2010). Runoff, the primary driver of water erosion which must be perfectly estimated and mastered by powerful models (Faregh and Benkhaled, 2016; Riahi et al., 2020; Mehta and Yadav, 2024), mainly occurs during intense rainfall events when water can no longer infiltrate the soil (Mah et al., 2023). Two types of runoffs are distinguished: Horton overland flow, which occurs when rainfall exceeds the soil's infiltration capacity, and saturation overland flow, which occurs on saturated surfaces (Choley, 2022).

Mediterranean regions are particularly vulnerable to this phenomenon, especially due to increasing aridity linked to climate change (De Ploey et al., 1991; Chibane and Ali-Rahmani, 2015; Boubakeur, 2018). Soil erosion represents a major environmental challenge in these areas, impacting land fertility and water resource quality (Bou Kheir et al., 2001). This phenomenon is influenced by various factors, including topography, soil properties, lithology, and land use dynamics. Soil erosion caused by rainfall and runoff is widespread across Mediterranean countries and continues to grow significantly, particularly on slopes due to the torrential nature of rainfall, the high vulnerability of terrains (soft rocks, fragile soils, steep slopes, and often degraded vegetation), overgrazing, and the adverse impact of human activities such as deforestation, fires, poor agricultural practices, chaotic urbanization, and quarrying (Benabadji and Ouadah, 2020).

In this context, spatial observation serves as a critical tool for diagnosing and managing vulnerable environments. The integration of remote sensing technologies and Geographic Information Systems (GIS) enables a comprehensive approach to addressing ecological challenges, such as climate change, pollution, water scarcity, urbanization, and even more (El Hmaidi et al., 2015; Kerboub et al., 2016; Saidi et al., 2016; Hamimed et al., 2017; Jaiswal et al., 2023; Deb, 2024). This approach is essential to establish a precise diagnosis of ecological conditions and ongoing degradation processes, allowing for a clear understanding of the factors driving environmental change. By developing erosion hazard and soil sensitivity maps, it becomes possible to identify the most vulnerable areas, providing a foundation for targeted interventions. Furthermore, these tools guide land management and conservation strategies, ensuring the preservation of these spaces while promoting balanced and sustainable development that aligns with both ecological and socio-economic goals.

Several authors have highlighted the effectiveness of GIS and remote sensing for mapping areas vulnerable to erosion and developing predictive models (Wachal and Hudak, 2000; Shrimalil et al., 2001; Lee, 2004; Bou Kheir et al., 2006). Integrating these technologies into soil conservation and erosion control strategies is crucial to mitigating the impacts of water erosion and ensuring the sustainable management of vulnerable territories.

In this framework, the development of erosion susceptibility maps for the Honaine region is based on the overlay of several environmental parameters, including slope and lithology. The method used is the pairwise comparison approach developed by Saaty (1977) within the decision-making process known as the Analytical Hierarchy Process (AHP). In this technique, the effect of two factors is evaluated using a square matrix of pairwise comparisons between different criteria, known as a decision matrix. This approach allows for weighting the relative importance of criteria based on their influence on the phenomenon under study.

This study aims to analyze water erosion dynamics by leveraging geomatics tools to develop tailored approaches for the preservation of natural resources. The first part of this article will present the methodology adopted for the acquisition and processing of spatial data. Next, we will discuss the results obtained through erosion susceptibility maps and predictive models. Finally, we will propose recommendations for the sustainable management of mountain regions in the face of erosion risks.

STUDY AREA

The watershed known as "Oued Honaine" is situated in the Honaine region (Fig. 1), northeast of the Trara Mountains (Tlemcen province). It covers an area of 2769 hectares. The terrain is rugged and mountainous, marked by torrential morphology. This is the origin of significant elevation differences and steep slopes of up to 25%. The topographic nature of the terrain influences surface features, making the study area endowed with a dense hydrographic network rich in wadis. Land use appears to be dominated by extensive forest formations, covering 95% of the watershed, characterized by a wide diversity of flora, including various vegetation layers. This landscape can somewhat reflect certain environmental characteristics, such as climate, geomorphological patterns, and geology. According to Seladji (2006), three main botanical layers can be observed, including the arboreal, shrubby, and herbaceous layers. The arboreal formation includes species such as *Tetraclinis articulata, Pinus halepensis, Quercus coccifera, Olea europea, and Pistacia lentiscus*. However, the shrubby layer comprises of species such as *Daphne gnidium*, *Lavandula multifida*, *Chamaerops humilis subsp. argentea, Erica multiflora, Rhamnus lycioides, Cistus ladaniferus, Calycotome villosa, Ampelodesma mauritanicum, Lavandula dentata*, etc. The herbaceous layer is composed of species like *Asteriscus maritimus, Pallenis spinosa, Arisarum vulgare, Papaver rhoeas, Convolvulus althaeoïdes, Echium vulgare, Oxalis corniculata, Teucrium pollium, Centaurea pullata, Anagallis arvensis, Plantago lagopus, Urginea maritima*, etc.

The climate is Mediterranean type characterized by a wet period lasting approximately five months (November to March) and a longer dry period spanning seven months (April to October), with an average annual rainfall of about 439.16 mm covering the period from 1985 to 2020 (ONM, 2020). In 1978, Djebaili identified rainfall as an essential factor in determining climate type. Indeed, it influences both the maintenance and distribution of vegetation cover as well as natural habitat degradation due to erosion. The average minimum annual temperature in January is 8.69 °C, while the average maximum annual temperature in August is 29.45°C (ONM, 2020). These two average temperatures define the climate type of the study area, which is indeed of the coastal type M-m = 20.76 °C (Debrach, 1953). Regarding vegetation zones, it is defined as thermo-Mediterranean and belongs to the subhumid bioclimatic zone, with warm winters.

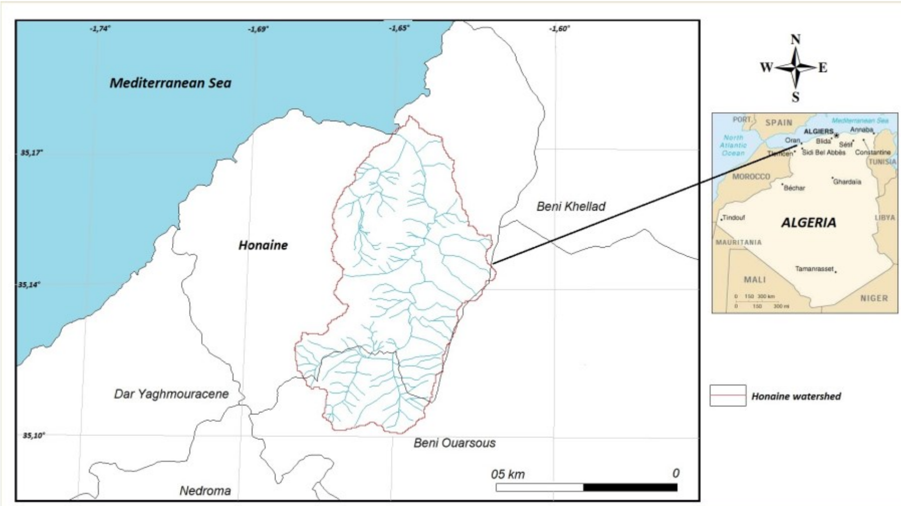

Figure 1: Map of the study area

MATERIAL AND METHODS

The present study used an approach which integrates and analyzes the information layers produced by the Geographic Information System (GIS) using a multicriteria evaluation method. This involves the simultaneous consideration of several relevant criteria for the studied issue. For instance, the study incorporates criteria like terrain slope, soil type (lithology), land use, hydrology, vegetation, and others, with fieldwork observations verifying these data. By intersecting these different information layers, a comprehensive and in-depth understanding of the studied situation is obtained, aiding in better understanding the interactions between various environmental factors and making more informed decisions regarding natural resource management and spatial planning (Adja et al., 2021). This approach provides a strengthened methodology for evaluating and mapping areas susceptible to water erosion. Could this approach serve as a valuable tool for decision-making in the fields of land management and natural risk management?

The integrated GIS and multicriteria evaluation approach provides a valuable framework for assessing and mapping areas susceptible to water erosion, combining multiple data layers and field observations for informed decision-making. This methodology builds on foundational work by Saaty (1977), who developed the Analytic Hierarchy Process (AHP) for structuring complex decisions, and has been further refined by Malczewski (1999) in the context of spatial decision support systems. Tools like those introduced by Eastman (2003) have also advanced the integration of GIS and multicriteria analysis, making it accessible for practical applications. However, acknowledging its limitations (data quality, dynamic modeling, stakeholder engagement) and addressing them will enhance its scientific rigor. With continuous refinement, this method can become a vital tool for decision-makers in land and natural risk management.

Geospatial data

The creation of the soil sensitivity to erosion map relied on the integration of several key spatial datasets. These included a lithological map, which provides information on rock types and composition, as well as a slope map, essential for assessing the influence of terrain on erosion. A land use map was also utilized to analyze the impact of human activities and vegetation cover. Combined with other relevant data, these resources enabled the development of a precise and detailed map highlighting areas at risk of erosion.

Lithological map

As lithological data were unavailable for our study area, the study relied on information regarding the geology of superficial formations. Fig. 2 illustrates the different lithological classes of the study area, based on the geological map of Northwestern Orania (Guardia, 1975), at a scale of 1/100,000, to provide insights into their distribution. The study analyzed each geological formation in terms of cohesion, hydrogeological properties, grain size, and heterogeneity. The combination of these parameters determines the erodibility classes. The geology of superficial formations provides information on surface alteration products derived from the bedrock, where they exist (Dumas, 2010). The lithological map enabled the identification of the main units. Consequently, five classes of material variability were distinguished in Table 1, ranging from very resistant to very vulnerable. Each class was assigned an index ranging from 1 to 5, with 1 corresponding to materials least exposed to erosion and 5 to materials most exposed to erosion.

Table 1: Material friability class and assigned indices

Facies	Material Friability	Assigned index
Volcanosedimentary Formation	Very resistant materials	1
Hard Limestone Formation	Resistant materials	2
Non-Carbonate Formation	Moderately resistant materials	3
Soft Limestone Formation	Vulnerable materials	4
Aeolian Formations	Very vulnerable materials	5

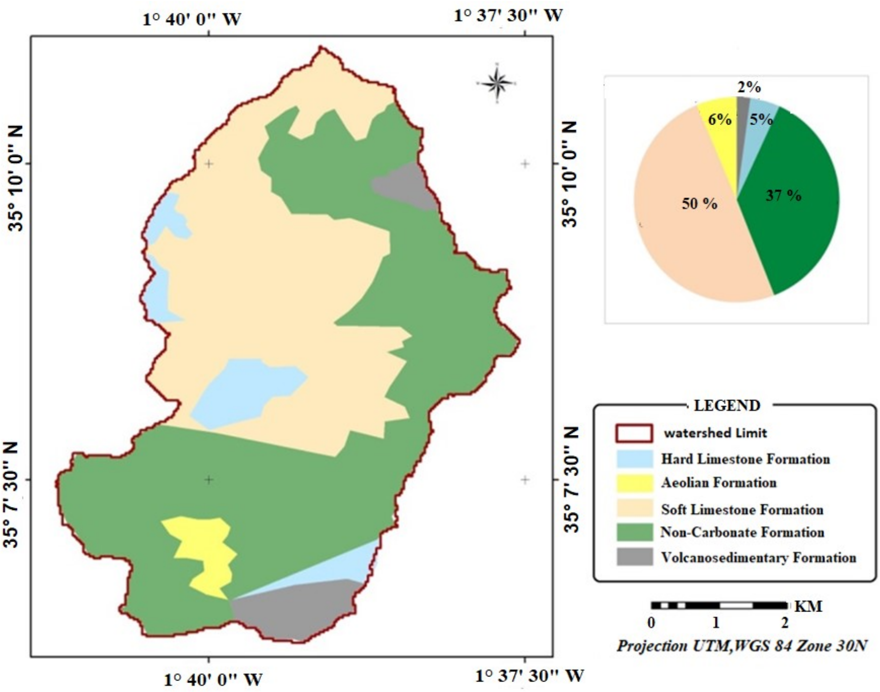

Figure 2: Lithological map of the study area

Slope Map

In the context of the Slope Map, the indices physically represent the sensitivity of the terrain to erosion based on the steepness of the slope. The primary factor influencing soil sensitivity to erosion is slope (Dumas, 2010). The Slope Map was generated using MapInfo 8 software, with data digitized from topographic maps at a scale of 1:50,000. This process enabled the creation of a Digital Elevation Model (DEM), from which the slope variable was calculated. At each point on the map, there are corresponding slope values for the terrain as shown in Fig. 3. These slope values were subdivided into five slope classes: 0 to 3%, 3 to 6%, 6 to 12.5%, 12.5 to 25%, and greater than 25%.

Each slope class is assigned an index ranging from 1 to 5 mentioned in Table 2, as follows:

- Index 1 (0-3% slope): Represents nearly flat or gently sloping terrain. These areas are least sensitive to erosion because the low gradient minimizes the potential for water runoff and soil displacement.

- Index 2 (3-6% slope): Represents mildly sloping terrain. These areas have a slightly higher risk of erosion compared to flat areas, as the gradient allows for moderate water flow, which can begin to displace soil particles.

- Index 3 (6-12.5% slope): Represents moderately sloping terrain. These areas are more sensitive to erosion due to increased water runoff velocity, which can lead to more significant soil displacement and sediment transport.

- Index 4 (12.5-25% slope): Represents steeply sloping terrain. These areas are highly sensitive to erosion, as the steep gradient accelerates water runoff, increasing the likelihood of soil loss and gully formation.

- Index 5 (>25% slope): Represents very steep or extremely steep terrain. These areas are the most sensitive to erosion, as the high gradient results in rapid water runoff, leading to severe soil erosion, landslides, and other forms of mass wasting.

Table 2: Slope classes and assigned indices

Slope Degree (%)	Assigned Index
0-3	1
3-6	2
6-12.5	3
12.5-25	4
> 25	5

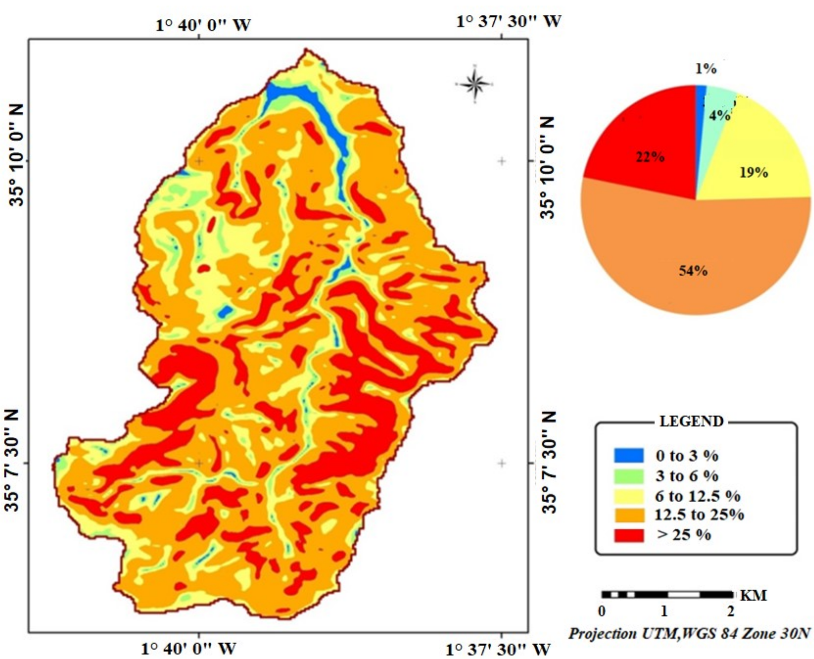

Figure 3: Slope map of the study area

Land use map

The land use mapping is supported by the analysis of a satellite image dated September 23, 2022 (provided by the ETM+ Landsat 8 T1 sensor, path/row 198/035).

We used supervised classification in the ENVI 5.1 software, relying on the Maximum Likelihood algorithm. This method, widely recognized for its robustness, allows for the classification of pixels in a satellite image into different thematic categories (such as forest, water, bare soil, etc.) based on reference samples (ROI - Regions of Interest).

In our study, the results show an overall accuracy ranging between 85% and 95%, indicating high-quality classification. Additionally, a Kappa coefficient of 0.9 confirms the high reliability of our classification, demonstrating an almost perfect agreement between the classification results and the reference data. These performances demonstrate that our approach is well-suited for the analysis of the studied landscapes and that the methods used are robust.

Supervised classification methods, combined with spatial segmentation based on the division of large morphological landscape units, were used to characterize five land use themes. This classification, which is highly accurate, is supported by field observations, as shown in Fig. 4. Five classes were identified: urban areas, forests, pre-forest formations (dense shrubland, sparse shrubland), and agricultural land. Based on their relative effectiveness in soil erosion protection (Roose, 1977), each class was assigned a value ranging from 1 to 5, as presented in Table 3.

Table 3: Land use and assigned indices

Land use	Assigned index
Urban	1
Forest	2
Dense Matorral	3
Sparse Matorral	4
Agriculture	5

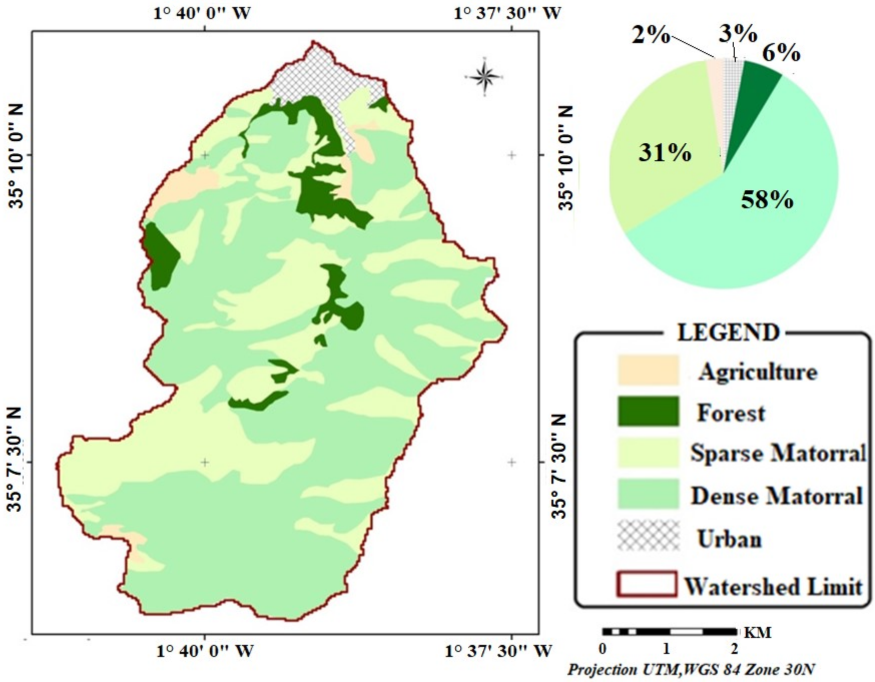

Figure 4: Land use map of the study area

RESULTS

The methodology developed in this study employs qualitative rules to evaluate and rank the key parameters influencing water erosion: material friability, slope degree, and land use. These parameters were carefully assessed to determine their relative contributions to erosion susceptibility. All the collected data was systematically integrated into a Geographic Information System (GIS), specifically using MapInfo 8 software, to facilitate efficient data management, analysis, and visualization.

To evaluate the interaction and relative importance of these factors, a pairwise comparison matrix (also referred to as a decision matrix) was constructed. This matrix, based on the principles of the Analytic Hierarchy Process (AHP) (Saaty, 1977), compares the criteria in pairs to reflect their relative significance in relation to the study's objective—assessing erosion risk. The combinations within the matrix highlight the weighted influence of each parameter on the overall erosion hazard.

Using the decision matrix presented in Table 4, the individual parameter maps (material friability, slope degree, and land use) were combined to produce a comprehensive thematic map known as the erosion hazard map (shown in Fig. 5). This map categorizes the study area into three distinct classes of erosion risk, as outlined in Table 4, providing a clear visual representation of areas with low, moderate, and high susceptibility to water erosion.

Table 4: Decision matrix for erosion hazard evaluation

Slope index / Lithology index	1 (0-3) %	2 (3-6) %	3 (6-12.5) %	4 (12.5-25) %	5 (> 25) %
1-Volcanosedimentary Formation	1	1	2	2	3
2-Hard Limestone Formation	1	2	2	2	3
3-Non-Carbonate Formation	2	2	2	3	3
4-Soft Limestone Formation	2	2	3	3	3
5-Aeolian Formations	2	3	3	3	3

The erosion hazard decision matrix (Table 4) provides a systematic evaluation of erosion risk by cross-referencing lithological characteristics with slope gradients. The horizontal axis demonstrates how erosion susceptibility escalates with increasing slope angles - for instance, volcanosedimentary formations progress from low risk (level 1) on flat terrain (0-3%) to moderate risk (level 3) on steep slopes (>25%). The vertical comparison reveals significant variations in geological resistance, with hard limestone formations showing the greatest stability while aeolian deposits emerge as most vulnerable.

Key patterns emerge from this analysis: slopes exceeding 25% consistently generate substantial erosion risk (level 3) regardless of lithology, highlighting slope gradient as a primary risk factor. However, the matrix also shows how geological properties modify this relationship - hard limestone maintains relatively low risk across most slopes, whereas softer formations like aeolian deposits show heightened sensitivity even on moderate slopes. This dual-factor assessment enables precise identification of critical slope-lithology combinations that demand prioritized conservation measures, providing land managers with a science-based tool for targeted erosion prevention strategies. The clear gradation of risk levels (1-3) facilitates differentiated landscape management based on actual vulnerability rather than generalized assumptions.

The erosion sensitivity map in Fig. 6 is a visual tool that identifies areas where erosion is most likely to occur, based on natural risks and land use. To conduct this analysis, we used a decision matrix presented in Table 5. This matrix allows for the cross-referencing of erosion hazard data with land use types to assess their combined vulnerability to erosion. It served as a method to integrate these two factors. The results are classified into four sensitivity levels, providing a clear understanding of at-risk areas and thus facilitating decision-making for erosion management and prevention.

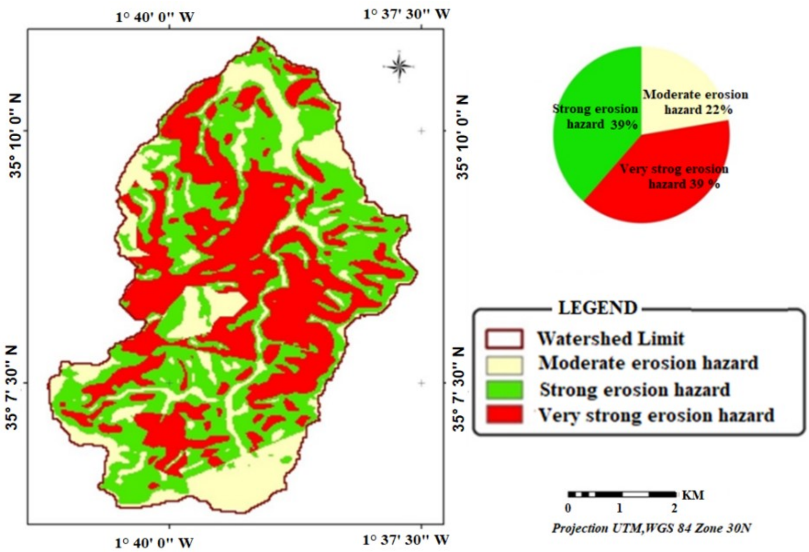

Figure 5: Erosion hazard map: Lithology and slope-based risk assessment

Table 5: Erosion sensitivity decision matrix

Erosion hazard index / Land use index	Moderate	Strong erosion		Very strong	
	1	**2**	**3**	**4**	**5**
1- Urban	1	1	2	3	4
2- Forest	1	2	3	4	4
3- Dense Matorral	2	3	3	4	4
4- Sparse Matorral	2	3	4	4	4
5 -Agriculture	2	4	4	4	4

The erosion sensitivity matrix serves as a critical tool for assessing soil erosion risk by analyzing the interaction between two key parameters: land use type and erosion hazard intensity. The results, ranked on a scale from 1 (negligible risk) to 4 (very high risk), reveal clear patterns. Urban areas (index 1) demonstrate notable resistance, reaching a maximum risk level of 3 even under severe erosion conditions. Forested lands (index 2) provide substantial protection but escalate to risk level 4 when facing intense erosion hazards. Dense shrublands (index 3) offer intermediate protection, while sparse shrublands (index 4) and particularly agricultural lands (index 5) prove highly vulnerable, consistently reaching the maximum risk level 4 when exposed to moderate to severe erosion hazards.

This risk gradation highlights the need for tailored protective measures according to each land use type, with special attention required for agricultural areas and sparsely vegetated zones where soil conservation challenges are most acute. The matrix enables clear prioritization of intervention areas, facilitating targeted and effective erosion risk management strategies. The tool's systematic approach helps optimize resource allocation by focusing conservation efforts where they are most urgently needed, while preventing unnecessary expenditure on low-risk zones. By providing this nuanced understanding of erosion vulnerability across different landscapes, the matrix supports evidence-based decision-making for sustainable land management and erosion prevention.

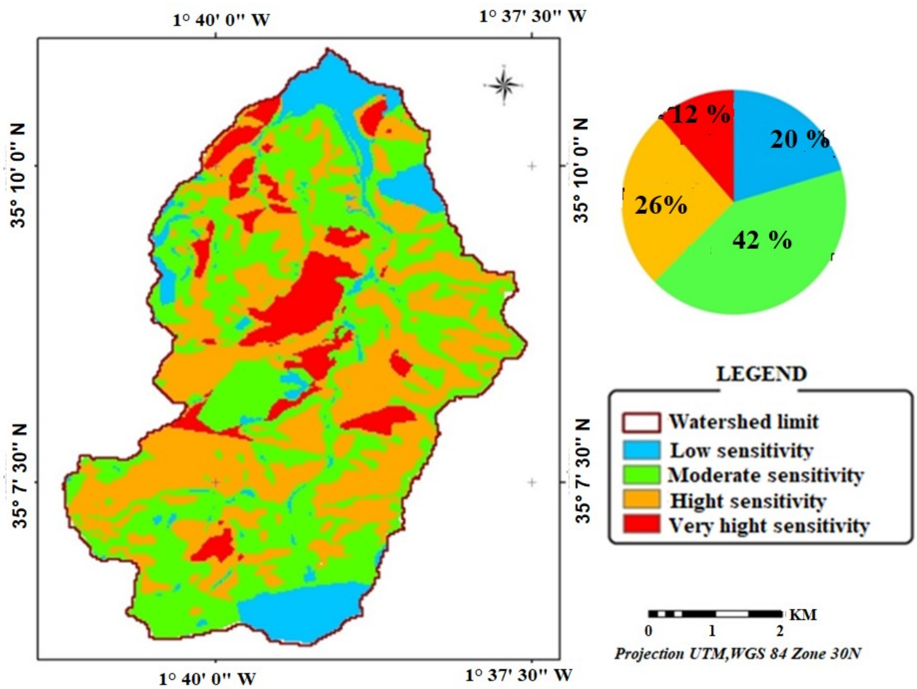

Figure 6: Land sensitivity to water erosion: Results from decision matrix analysis

The map of erosion-sensitive areas constitutes an illuminating synthesis, highlighting the vulnerability of the study area to this phenomenon, with an alarming rate reaching 88%. Among these figures, 26% correspond to areas extremely sensitive to erosion, mainly due to the predominance of highly vulnerable lithological formations, which exceed the critical threshold of 50%. These formations are often located on steep slopes (over 12.5%), thus representing a significant area of 75%.

DISCUSSION

About 75% area of the watershed has slopes exceeding 12.5%. The effect of slope on erosion is a crucial aspect to consider in studying erosive processes. The steeper the slope, the greater the water force, resulting in a higher capacity to transport soil particles. The steeper the slope, the greater the force of water, leading to a higher capacity to transport soil particles. Moreover, on steep slopes, the soil is often less stable, facilitating its detachment and transport by runoff water. According to Dumas (2010), slope contributes to erosion phenomena due to its shape, steepness, and length.

Additionally, the study area is characterized by soft limestone and non-carbonate formations, covering 87% of the area. In our opinion, these highly friable and vulnerable rocks to water erosion led to a significant erosion hazard presented in Table 6 that can only be reduced by maintaining and expanding existing vegetation cover.

Table 6: Areas of erosion hazard risk

Class designations	Area (ha)	(%)
Moderate erosion hazard	618.31	22
Strong erosion hazard	1083.04	39
Very strong erosion hazard	1067.65	39
Total	2769.00	100

The study created a second map by combining the map of actual land use with that of erosion risk. Watershed-scale studies have highlighted that erosion generally decreases with increasing vegetation cover (Goff et al., 1993; Snelder and Bryan, 1995; Morgan et al., 1997; Roose et al., 1998; Cerda, 1998,1999; Reid et al., 1999; Battany and Grismer, 2000; Rey, 2002).

It is evident that the presence of adequate vegetation cover is essential for mitigating erosion and maintaining soil stability. This vegetation cover protects against raindrop impact, thereby extending soil permeability and reducing runoff (Dumas, 2010). Moreover, vegetation reduces the kinetic energy of raindrops, decreasing the splash effect (Bonnet, 1983).

According to some experimental observations, forests are considered to offer the best protection against erosion in mountainous areas. However, other studies have shown that shrub cover (Francis and Thornes, 1990) or low vegetation (Roose et al., 1998) can also provide similar erosion protection. Nevertheless, under torrential flow conditions, herbaceous cover may sometimes be insufficient to combat concentrated erosion, underscoring that grass is not always the best solution for preventing bank erosion (Harmel et al., 1999).

In the field, we observed that areas covered by vegetation are better protected against soil degradation. This synthesis of cartographic data has thus allowed the delineation of areas according to their degree of erosion sensitivity as shown in Table 7.

Table 7: Areas of erosion sensitivity risk

Class designations	Area (ha)	(%)
Low sensitivity zone	563.60	20
Moderately sensitive zone	1166.92	42
Highly sensitive zone	723.37	12
Very highly sensitive zone	315.11	26
Total	2769.00	100

Tables 6 and 7 expose the area in question to a high risk of erosion, reaching up to 80%. However, a high rate of vegetation cover can mask this erosive phenomenon. Therefore, the sustainable preservation of these soils requires measures to protect against fires, excessive logging, and unregulated human activities.

The effects of erosion are even more severe when humans settle in unstable areas. This can lead to gullying phenomena that carry away up to 300 tons of soil per hectare per day, as well as the risks of flooding and landslides endangering infrastructure and human lives (Veyret and Pech, 1993).

Recent studies on vulnerability to climate change in the Mediterranean region reveal a trend towards increased aridity, which accelerates the process of water erosion (De Ploey et al., 1991; Shaban and Khawlie, 1998). To prevent these risks and ensure soil sustainability, it is imperative to implement appropriate management measures, including vegetation protection and regulation of human activities in these sensitive areas.

CONCLUSION

This methodological study has resulted in the creation of an erosion sensitivity map, validated in the field with an accuracy rate of approximately 90%. In the Honaine region, soil erosion poses a major challenge, largely attributable to steep slopes, soil fragility, overgrazing, and harmful human activities. Recent fires have exacerbated this problem by altering soil structure and promoting erosion. Thus, remote sensing technology and GIS are of crucial importance for assessing erosion vulnerability in mountainous environments.

Moreover, although vegetation cover is significant in the region, it does not guarantee complete protection against erosion. However, it is undeniable that the presence of adequate vegetation plays a crucial role in soil preservation. The map of erosion-sensitive areas could thus serve as a basis for any development proposals aimed at reducing this phenomenon.

The analysis of the results has identified erosion-sensitive areas in the Honaine watershed, highlighting the correlation between land sensitivity to erosion and various parameters such as land use, topographic characteristics, and the lithology of the study area. This relationship is supported by previous research demonstrating the impact of water erosion on agricultural land and the need to adopt soil conservation practices to mitigate this problem. Human influence on erosion is mainly indirect, primarily by accelerating soil erosion and increasing the devastation that ensues. Indirect human action mainly involves the destruction of natural vegetation, the cultivation of crops with low soil protective effects, the exposure of bare soil, and the increase and concentration of surface runoff. Additionally, the grazing of domestic animals is another way in which humans indirectly influence erosion.

Therefore, land restoration actions are recommended to address the challenges posed by erosion, including overgrazing, fires, and abusive land use. It is recommended that forestry services take the initiative to implement terracing systems or wooded benches (Morgan, 2005), adapted to local topography, with the aim of restoring vegetation cover and regulating torrential flow to limit flash floods in the region. These measures would not only help reduce erosion but also restore the ecological balance of the Honaine region.

To address the challenges of erosion in the Honaine region, several concrete actions can be considered. First, it would be relevant to conduct pilot reforestation projects in areas identified as most vulnerable to erosion. These projects could include the introduction of local plant species that are resilient and adapted to the region's climatic and soil conditions. The effectiveness of these plantings would be assessed through regular monitoring of soil stability and erosion rate reduction. Raising awareness and training local communities are also essential. Programs could be implemented to involve populations in soil conservation efforts. These initiatives would include workshops on sustainable agricultural practices, pasture management, and fire prevention, to strengthen their commitment to land preservation.

Declaration of competing 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.

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