Assessing Water Erosion Vulnerability in the Lower Ziz Watershed: Integrating PAP/RAC methodology with Remote Sensing and GIS

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Abstract. Degradation presents a significant challenge, particularly exacerbated by current climate change. Our study focuses on the Lower Ziz watershed, located in southeastern Morocco, which is characterized by a semi-desert climate and is at high risk of land degradation due to water and wind erosion. Natural factors such as precipitation intensity and frequency, slope inclinations, low vegetation cover density, and soil characteristics, combined with anthropogenic activities, contribute to increasing the erosion risk within this watershed. The use of unsustainable agricultural practices has also contributed to this growing vulnerability. To investigate this phenomenon, we adopted the PAP/CAR method, a qualitative approach for mapping and assessing vulnerability to water erosion in the watershed. This method integrates essential physical data such as topography, lithology, soil types, and vegetation cover, facilitating a comprehensive analysis of erosion risk. Through the use of remote sensing tools and geographic information systems (GIS), we have generated detailed thematic maps, streamlined the mapping process, and improved data management. The findings of this research provide valuable insights for sustainable land and natural resource management in the Lower Ziz watershed and can aid in the formulation of prevention and mitigation strategies for water erosion in similar contexts globally. Our predictive mapping approach indicates that 37.34% of the watershed exhibits low to very low susceptibility to water erosion, while 55.96% experiences moderate erosion, with the remaining 6.7% being highly erodible. Additionally, our descriptive analysis highlights the prevalence of gully and surface gullying erosion, encompassing 49.32% of the area, as well as deep gully erosion, affecting 41.89%."

1. Introduction

Soil erosion is a major environmental issue affecting Mediterranean regions with sub-desertic climates, including Morocco [1,2]. This phenomenon has serious consequences on natural resources, agriculture, and local communities, with significant socio-economic and environmental repercussions. In arid and semi-arid regions such as the Lower Ziz watershed (southeastern Morocco), soil degradation is exacerbated by factors such as climatic aridity, soil poverty, and unsustainable agricultural practices.

The consequences of water erosion are not limited to Morocco, but also affect numerous other countries worldwide, including those in Latin America and Central America, Europe, and North Africa. In Latin America and Central America, respectively 14.3% and 26% of lands have been affected [3]. In Europe, over 17% of lands are also affected by this phenomenon [4]. Water erosion is also widespread in North Africa, with specific degradations exceeding 2000 tonnes/km²/year in the majority of watersheds [5]. In Morocco, similar to other North African countries, water erosion annually results in soil losses ranging from 500 tonnes/km² to over 5000 tonnes/km² depending on the region. Additionally, it leads to sedimentation in dam reservoirs, reaching approximately 75 million cubic meters annually, representing a reduction of 0.5% in their storage capacity. These phenomena cause significant water losses, affecting irrigation of over 10,000 hectares per year and deteriorating the quality of potable water resources [6]. Hence, this issue is of global importance

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and requires particular attention for its understanding and management.

To evaluate and understand this phenomenon, various approaches and techniques are utilized, ranging from field methods to modeling approaches. The utilization of remote sensing and geographic information systems (GIS) has significantly enhanced our ability to map and model water erosion, thereby enabling more informed decision-making regarding land and water resource management.

In Morocco, several researchers have applied this approach to model the risk of water erosion in the Rif mountain [7 - 9], in the Middle Atlas [10], the central plateau [11], the High Atlas [12], and in regions with similar arid or desert climates in Algeria [13] and Tunisia [14].

In this study, we specifically focus on the Lower Ziz watershed, a region characterized by its semi-desert climate and susceptibility to water erosion. We propose an integrated approach based on the PAP/RAC potential erosion model to assess erosion risk in this area. This approach combines field data with modeling techniques to provide an accurate evaluation of erosion risk and recommendations for sustainable land management.

2. Materials and Methodology

2.1. Area of Study

The Lower Ziz watershed is situated in the southeastern region of the country, bordered by the Algerian frontier to the east and south, while the High Atlas Mountains lie to the north and the Anti-Atlas Mountains to the southwest. Encompassing an area of 2210 km², this basin forms part of the extensive Ziz watershed, positioned to the south of the latter and representing a key tributary of the Oued Ziz, which has sculpted the landscape from the heights of the eastern High Atlas to the southern reaches and the Sahara (Fig. 1). Characterized by an arid climate with pronounced continental influences, the Lower Ziz watershed is shielded from moist oceanic influences by the mountainous reliefs of the High and Anti-Atlas to the north and west, while its southern exposure intensifies Saharan influences, notably through the drying "Chergui" winds prevailing from the northeast in summer and the "Sahel" winds from the southwest in winter. Annual precipitation is scant, averaging 95 mm in the city of Erfoud and 75 mm in Rissani. Mean annual temperatures are notably high, hovering around 20°C, with considerable annual and diurnal temperature fluctuations (50°C and 20°C respectively). In 2006, the region experienced a sudden, out-of-season return of rainfall, coupled with a marked temperature increase, leading to heightened drought frequency, severity, and spatial extent. This drought trend is exacerbated by global climate change, posing challenges to various socio-economic sectors. The water resources of the Ziz, along with its recent and ongoing sedimentary deposits, have facilitated the development of two of North Africa's largest oases: the Ziz Valley and the Tafilalet Plain. The hydrological network within this watershed is endorheic, allowing for the retention of water within the region itself, with downstream losses occurring within the desert.

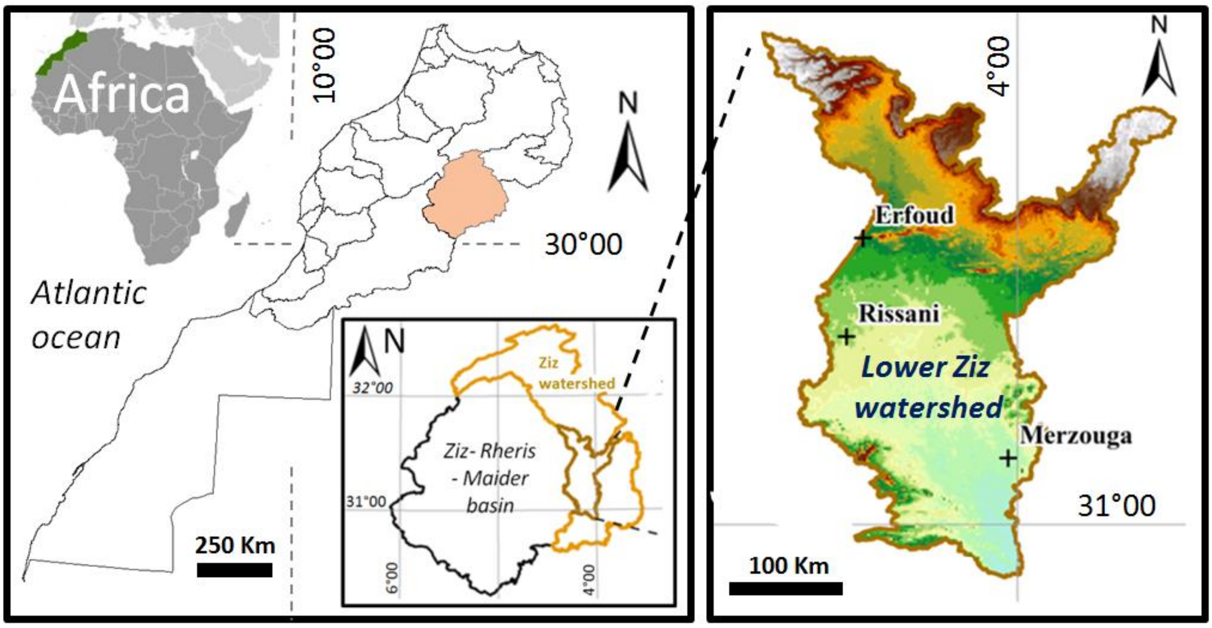

Fig. 1. Location of the Lower Ziz watershed in Ziz-Rheris-Maider basin, in hydrological basins in Morocco

2.2. Materials

To assess soil sensitivity to water erosion in the Lower Ziz watershed, we employed a qualitative model that incorporates data on topography, geology, vegetation cover, and field observations. Our methodology involved combining satellite images from Landsat 8 (OLI) with aerial photographs, ground observations, and a digital elevation model (DEM) to create a detailed map of the study area. Additionally, we consulted the 1/100,000 geological map of Morocco to gather precise information on the geological features of the region.

2.3. Methodology

The PAP/RAC method, a tool developed by the UNEP Mediterranean Action Plan [15], is used to identify, describe, and measure dynamic processes, including extreme situations such as irreversible degradation and stable unaffected areas. One key indicator of the sustainability of a development plan is the degree of erosion, which is mapped to understand the distribution and geographical extent of the phenomenon. This characterization includes both qualitative and quantitative aspects.

To create an erosion resistance map, we utilized the lithofacies map and applied the PAP/RAC method, which assigns a code to each class based on its relative degree of cohesion and erosion resistance. The codes range from (a) for highly compact and resistant rocks to (e) for less compact and resistant rocks (Table 1). The susceptibility map to water erosion was developed using the PAP/RAC method [3], which consists of three approaches (Fig.2) [16].

Table 1. Classification of the parameters of the predictive approach according to Griesbach et al. [16].

Slope			Lithofacies		
Classes	Inclination	Degree	Classes	Resistance	Type of material
1	None to low	(0%-3%)	(a)	Very strong	Unweathered compact rocks, strongly cemented conglomerates, etc.
2	Moderate	(3%-12%)	(b)	Strong	Fractured or moderately weathered cohesive rocks or soils
3	Abrupt	(12%-20%)	(c)	Medium	Sedimentary rocks or soils weakly or moderately compacted (slate, shale, marl, etc.)
4	Very abrupt	(20%-35%)	(d)	Low	Rocks and/or soils with little resistance or strongly/ deeply altered (marl, gypsum, clay slate, etc.)
5	Extreme	(>35%)	(e)	Very low	Soft, non-cohesive sediments or soils Cohesive and detrital materials.

Land use			Degree of vegetation cover		
Classes	Protection	Type of cover	Classes	Protection	Degree of vegetation cover
1	Very low	Dry crop (herbaceous)	1	Low	<25%
2	Low	Arboriculture, row crop and reforestation	2	Medium	25%-50%
3	Medium	Intensive cultivation in the proximity of the habitat	3	High	50%-75%
4	Strong	Forests	4	Extreme	>75%
5	Very high	Dense shrubs			
6	Extreme	Sparse shrubs, Pasture			

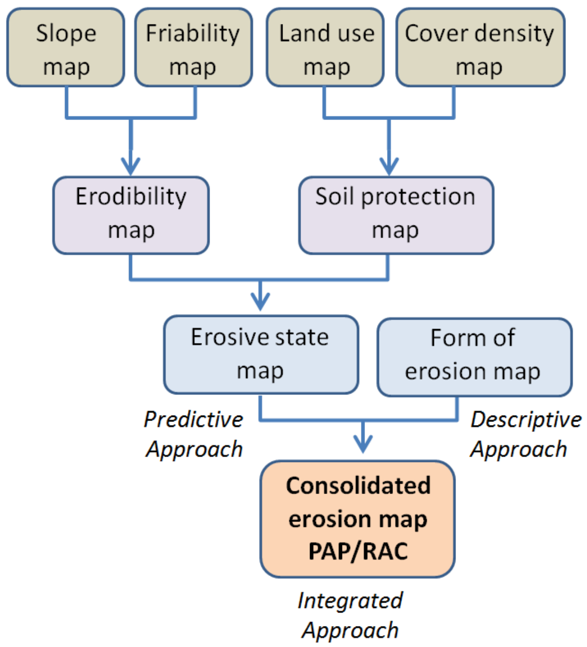

Fig. 2. Diagram of the adopted Methodology [3].

2.3.1. Predictive approach

This study employs a comprehensive approach to assess erosion risk in the Lower Ziz basin. By integrating spatial data on slope, geological composition, land use, and vegetation cover, we develop a preliminary framework for understanding erosion risk. The resulting map is a composite of two key components: the erosion susceptibility map and the soil conservation map (Figure 2). The erosion susceptibility map is generated by combining topographic and geological factors (Table 1). The slope map is derived from a digital terrain model, while the lithological map is based on geological data at a scale of 1/100,000. The substrates are classified into 5 categories to produce a map of erodibility. The soil conservation map, on the other hand, is created by integrating information on land use and vegetation cover (Table 3). High-resolution satellite imagery (30 m) was used to classify land cover and estimate vegetation density. The Normalized Difference Vegetation Index (NDVI) was calculated using a mathematical formula to estimate vegetation density (Equation 1). The soil conservation map is then generated by overlaying the land cover map and the vegetation cover density map (Table 3).

$$NDVI = \frac{(\mathbf{NIR-R})}{(\mathbf{NIR+R})} \qquad (1)$$

Where R and NIR represent spectral reflectance measurements acquired in the visible red (R) and near-infrared (NIR) bands respectively.

Table 2. Matrix between slope and friability classes.

Slope Classes	Class of lithofacies				
	1(a)	2(b)	3(c)	4(d)	5(e)
1	1(EN)	1(EN)	1(EN)	1(EN)	2(EB)
2	1(EN)	1(EN)	2(EB)	3(EM)	3(EM)
3	2(EB)	2(EB)	3(EM	4(EA)	4(EA)
4	3(EM)	3(EM)	4(EA)	5(EX)	5(EX)
5	4(EA)	4(EA)	5(EX)	5(EX)	5(EX)

Table 3. Matrix between land cover and vegetation cover classes (VH: Very high, H: High, M: Medium, L: Low, and VL: Very Low).

Land use	Degree of vegetation cover			
	1	2	3	4
1	5(MB)	5(MB)	4(B)	4(B)
2	5(MB)	5(MB)	4(B)	3(M)
3	3(M)	2(A)	1(MA)	1(MA)
4	4(B)	3(M)	2(A)	1(MA)
5	5(MB)	4(B)	3(M)	2(A)
6	5(MB)	4(B)	3(M)	2(A)

Table 4. Matrix between soil protection degree and erodibility classes.

Degree of soil protection	Degree of erodibility				
	1(EN)	2(EB)	3(EM)	4(EA)	5(EX)
1(MA)	1	1	1	2	2
2(A)	1	1	2	3	4
3(M)	1	2	3	4	4
4(B)	2	3	3	5	5
5(MB)	2	3	4	5	5

2.3.2. Descriptive Method

This approach provides a realistic image of the various forms of erosion present in the study area and their degrees of exposure to degradation. It is conducted using aerial photos, and rectified by ground observations.

2.3.3. Integration approach

The integration method involves combining the erosive condition map, created through thematic mapping, with the erosion forms map, established through direct descriptive mapping of erosion features in the field and from aerial photographs (Fig. 2).

3. Results

3.1. Predictive Method

3.1.1. Slope map

The slope map database was analyzed to calculate the relative areas of each segment. As shown in Figure 3(A), the results indicate that 87.91% (1941 km²) and 11.87% (262 km²) of the area fall within classes 2 and 3, representing moderate and steep slopes, respectively. Areas with zero to low slopes account for only 0.23% (5 km²) of the total area. This suggests that our watershed exhibits relatively even terrain, which may make it less susceptible to erosion from precipitation and the increased activity of flowing water.

3.1.2. Friability map

Based on substrate vulnerability to erosion, materials delineated on the lithofacies map were categorized into five friability classes, representing their resistance to erosion (Table 1). Fig. 3(B) indicates that the majority of the basin comprises sediments, loose non-cohesive soil, and detrital material (class e), along with rocks and soils exhibiting little resistance or significant alteration (class d), accounting for over 63% and 10.94% respectively. These are primarily situated in the central and downstream regions of the watershed, characterized by reduced altitude and low to very low slopes. Thus, this distribution informs us about the fate of these substrates; lower slopes correspond to lower flow velocity. The low slope in the central and downstream areas likely originates this low resistance soil. Conversely, the steeper slopes in the upstream portion give rise to compact, unweathered rocks, strongly cemented conglomerates, crusts, and outcrops of ferruginous sandstone (class a); cohesive fractured or moderately altered rocks and soils (class b); and weakly to moderately compacted sedimentary rocks and soils (slate, shale, marl) (class c), prevalent in areas with higher altitudes and moderately steep slopes. The prevalence of alternating marl and limestone formations, classified as loose formations, on slopes enhances the erosive potential of the watershed.

3.1.3. Erodibility map

The erodibility map results from overlaying the slope map and the lithofacies map (Fig. 3C). The polygons generated by this overlay are categorized according to the matrix depicted in Table 2, which aims to prioritize terrain based on erodibility levels (Table 1). Spatially, the distribution of erodibility classes reveals that the most significant areas belong to classes 1 and 2, representing low and moderate erodibility respectively, covering areas exceeding 2000 km². Conversely, areas classified as highly and extremely erodible do not exceed 172 km². This could have severe long-term consequences if protection quality remains low.

The distribution of erodibility classes, as illustrated in Fig. 3(C), indicates that in regions where slopes are steep and/or terrain strength is low, erodibility tends to be extreme. This trend is evident in the upstream section of the watershed, where despite varying lithofacies resistance, the presence of medium to steep slopes exacerbates erodibility. Conversely, in the central and downstream regions of the watershed, the situation is less alarming due to the prevalence of weak to moderate erodibility classes. Here, the lithofacies exhibit low resistance but are accompanied by moderate slopes, placing this area in the moderate to medium erodibility classes. This distribution can be attributed to the mitigating effect of moderate slopes on erodibility levels.

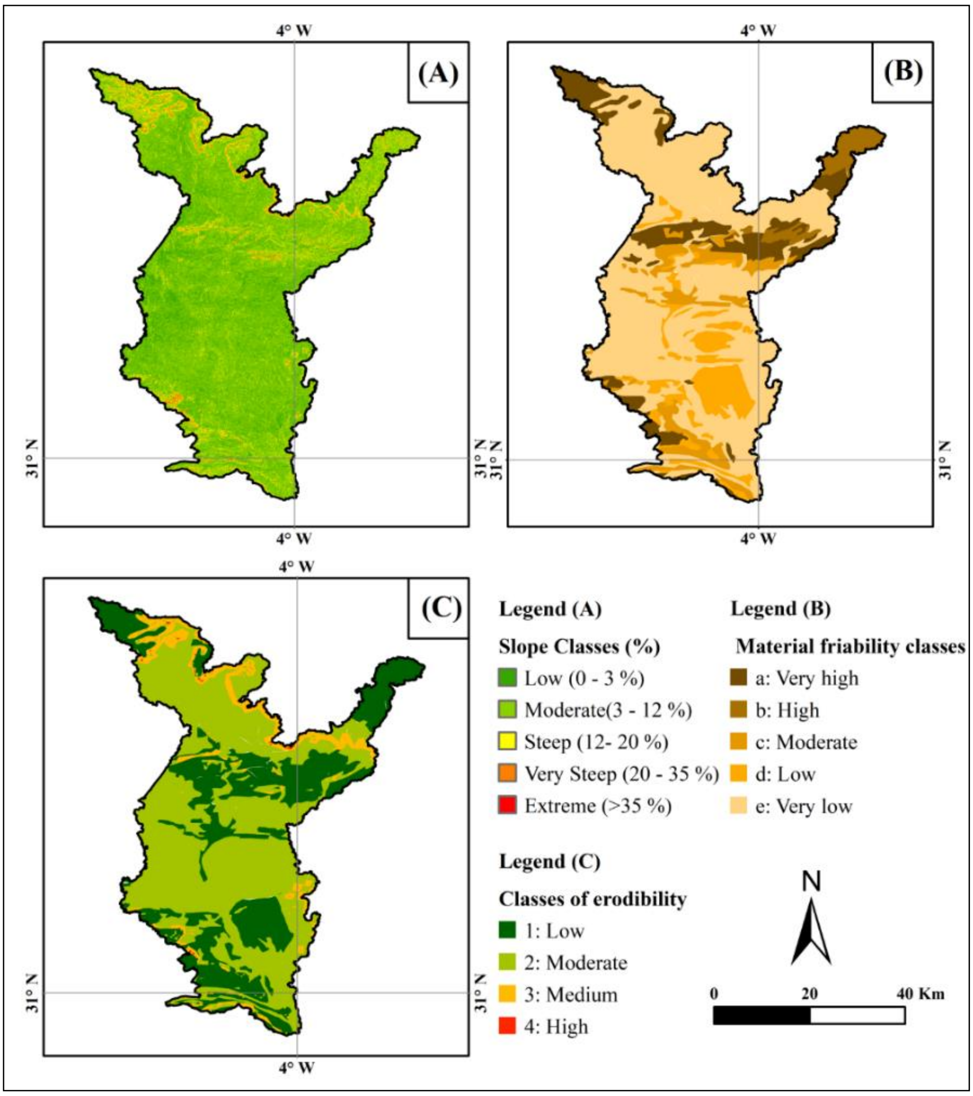

Fig. 3. (A) Slope map; (B) Friability map; (C) Erodibility map.

3.1.4. Map depicting Land Use

The land use map provides insights into land area percentages (Fig. 4A). Predominantly, dry or bare land covers 2010 km², representing 91.28% of the total area. Intensive cultivation near residential areas and open shrublands are moderately represented, covering areas of 65 km² and 127 km² respectively. Each of these surface types accounts for less than 9% of the total area. Arboriculture and reforestation occupy almost no surface area. The distribution of different land use types reveals that the upstream section encompasses a variety of land use types, with dry crops or bare land being the most prevalent. This indicates that the soils in this region remain susceptible to erosion. This pattern is influenced by the spatial distribution of water quantities in the basin. Additionally, there is evidence of intensive cultivation near residential areas and sparse shrublands, albeit weakly represented, indicating the replacement of natural vegetation with cultivated land. This distribution suggests that the upstream and central portions of the watershed are better protected due to the presence of sparse shrublands and intensive cultivation compared to the downstream area, which is predominantly bare ground. Further verification is required upon overlaying with the vegetation cover density map (Fig. 4A).

3.1.5. Vegetation cover map

This map serves two primary purposes: firstly, to refine the land use map, and secondly, to incorporate a critical factor influencing soil resilience. Dense vegetation cover enhances soil protection and mitigates the erosive effects of rainfall. As depicted in Figure 4(B), the most prevalent area is class 1 (< 25%), characterized by sparse vegetation, covering an area of 2011 km², rendering the soil more susceptible to water erosion. Classes 2 (25% - 50%) and 3 (50% - 75%) encompass areas of 127 km² and 65 km² respectively, with class 4 (> 75%) absent. Across the Lower Ziz watershed, low vegetation densities are widespread, with only small pockets of high density observed in the upstream and middle sections. These areas of high density, as indicated by the land use map (Fig. 4A), are primarily attributed to land clearing, wildfires, and overgrazing.

3.1.6. Soil protection map

The map illustrating soil protection was constructed by overlapping the land use map and map illustrating the density of ground cover (Fig. 4C). This map aims to prioritize the Lower Ziz Basin into polygons according to their protection level. This step is essential as it enables the identification of areas with varying degrees of protection, highlighting those at risk requiring urgent intervention, such as reforestation, to stabilize the soil. The resulting polygons from overlaying the two reference maps (Fig. 4A and 4B) are categorized according to the matrix presented in Table 4, facilitating the determination of the required protection level based on land use classes and cover percentage. The resulting map reveals a significant lack of protection in the Lower Ziz watershed, with class 5 being the most prevalent, covering an area of 2011 km², representing 91.28% of the total basin area. Across other classes, surface area values decrease from weakest to strongest degree of protection, indicating that larger areas correspond to weaker protection levels.

Furthermore, the distribution of soil protection classes demonstrates that areas with very low protection are widespread throughout the basin, particularly in the southern region. Conversely, areas with high protection are scarce, primarily located in the northern and central regions. This suggests that the matrix is adaptable to changes and degradation in vegetation cover over time and space.

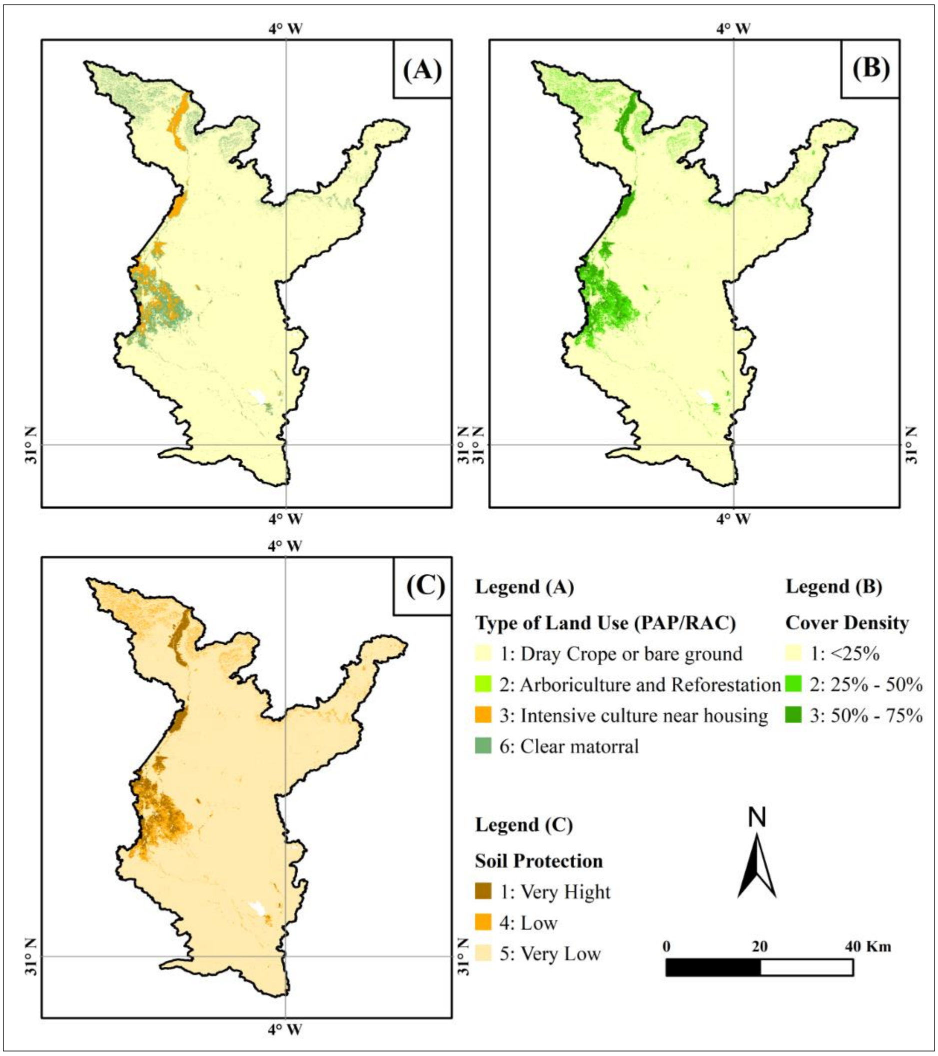

Fig. 4. (A) Land use map; (B) Land cover density map; (C) Land protection map.

3.1.7. Erosion Condition Map

The culmination of the predictive approach is depicted in Figure 5(A), which overlays previous map outputs (Figures 3C and 4C). The results show that the most prevalent erosion class is average erosion, covering 1263.57 km² or 55.96% in total watershed area. High and very high erosion classes represent 2.49 km² and 148.90 km², respectively, making up 6.7% in total area. In contrast, low and very low erosion classes cover 778.89 km² and 64.08 km², respectively, accounting for 37.34% of the watershed's total surface. These findings indicate a significant degree of erosion within the Lower Ziz watershed, which has implications for soil productivity and ultimately, the quality of life for the local population.

An analysis of erosive condition areas on the map reveals that the most eroded regions are located in the northern basin compared to the southern region. Additionally, high erosion patterns align with the hydrographic network. In the central and southern areas of the basin, erosion is currently notable. However, considering the human factor, populated areas coincide with zones of high erosion, with small settlements developing in areas where soil composition is suitable. Areas with low erosion are limited, particularly in the north where vegetation cover is dense, and in the central and southern regions where slopes are gentle.

3.2. Descriptive approach

Erosion Forms Map (Fig. 5B) is derived from aerial photographs rectified through field surveys. Analysis of this map indicates that erosion forms have expanded and multiplied, with old forms generally increasing in size. Within the Lower Ziz watershed, gullies and surface gullying are the most prominent forms, covering an area of 432 km², followed by deep gullies, encompassing nearly 367 km². Landslides and solifluction constitute 65 km² (7.42% of the total watershed area), while diffuse runoff or sheet erosion is minimal, not exceeding 12 km². Similar erosion forms and their causes have been identified in the Oued Aoudour watershed in the central Rif [18]. The prevalence of gullies and surface gullying in the watershed can be attributed to the soil's friability in this region and the presence of watercourses, which exacerbate land vulnerability to water and anthropogenic influences.

3.3. Integration Method: Development of the Comprehensive PAP/RAC Erosion Map

The integrated PAP/RAC erosion map combines qualitative data from two previous stages (Fig. 5A and 5B) to provide a comprehensive understanding of soil deterioration and projected erosion trends. The map is created by merging the results of predictive modeling with descriptive information about erosion phenomena from the second phase. By overlaying the map indicating erosive conditions and the map detailing erosion forms, a precise cartographic representation is generated, revealing the different forms, intensities, and evolutionary trajectories of erosion (Fig. 5C). The risk of erosion varies across different areas. Low to moderate risk areas are characterized by gully and surface gullying erosion, while high and very high risk areas are associated with medium-deep gullies. The presence of deep gullies is linked to steep slopes and intense rainfall. In areas with dense vegetation cover, visible erosion is less likely to occur due to the protective effect of the vegetation. The central region of the study area exhibits a diverse range of erosion types, including gullies, deep gullies, and diffuse runoff, which are primarily influenced by human activities and climate factors acting on weak substrates. The southern region is characterized by landslides occurring on moderate slopes, while badlands are typically found on steep slopes with sparse cover, primarily in the northern part of the basin. Overall, the northern part of the watershed is most vulnerable to erosion due to the combination of predictive and descriptive data, highlighting the need for targeted conservation efforts to mitigate this risk.

4. Discussions

Desertification, exacerbated by extreme climatic conditions, significantly impacts extensive areas within the Lower Ziz watershed. Successive droughts have severely diminished environmental productivity and heightened fragility, thereby promoting soil water erosion [19, 20]. The PAP/RAC method, utilized in various studies, effectively assesses watershed erosive status by integrating natural factors such as erodibility, slope, soil type, and lithology. Noteworthy research [13, 14, 17, 18, 21-23] demonstrates the method's efficacy in estimating water erosion.

Results from this study reveal water erosion dominance in three forms: gullies and surface gullying, covering 49.32% of the total area, primarily in the northern part of the basin (High Atlas), where abundant rainfall induces significant storms [24]. Deep gullying affects 41.89% of the total watershed, with a major portion located in the North Central zone, where significant tributaries converge, sometimes carrying substantial loads from seasonal floods. This situation can compromise water quality and reservoir management, exemplified by the Hassan Dakhil dam, projected to cease full irrigation functionality by 2050 [25]. Additionally, limited vegetation cover and absence of forestation exacerbate erosion, as the protective root systems and canopy are absent.

Sheet erosion prevalence in the Lower Ziz watershed, located in southeastern Morocco, is minimal, representing 1.37% of the total area. In contrast, the watershed of the Allal El Fassi Dam in the Middle Atlas (Northern Morocco) and Asfalou Dam in Northern Morocco (Rif) exhibit sheet erosion dominance, attributed to steep relief slopes and abundant precipitation, favoring vegetative cover development.

In conclusion, climatic severity, soil fragility, and lack of vegetation cover are primary factors driving water erosion in the Lower Ziz watershed. Although anti-erosion interventions mitigate erosion in certain areas, overall erosion rates remain high throughout much of the watershed.

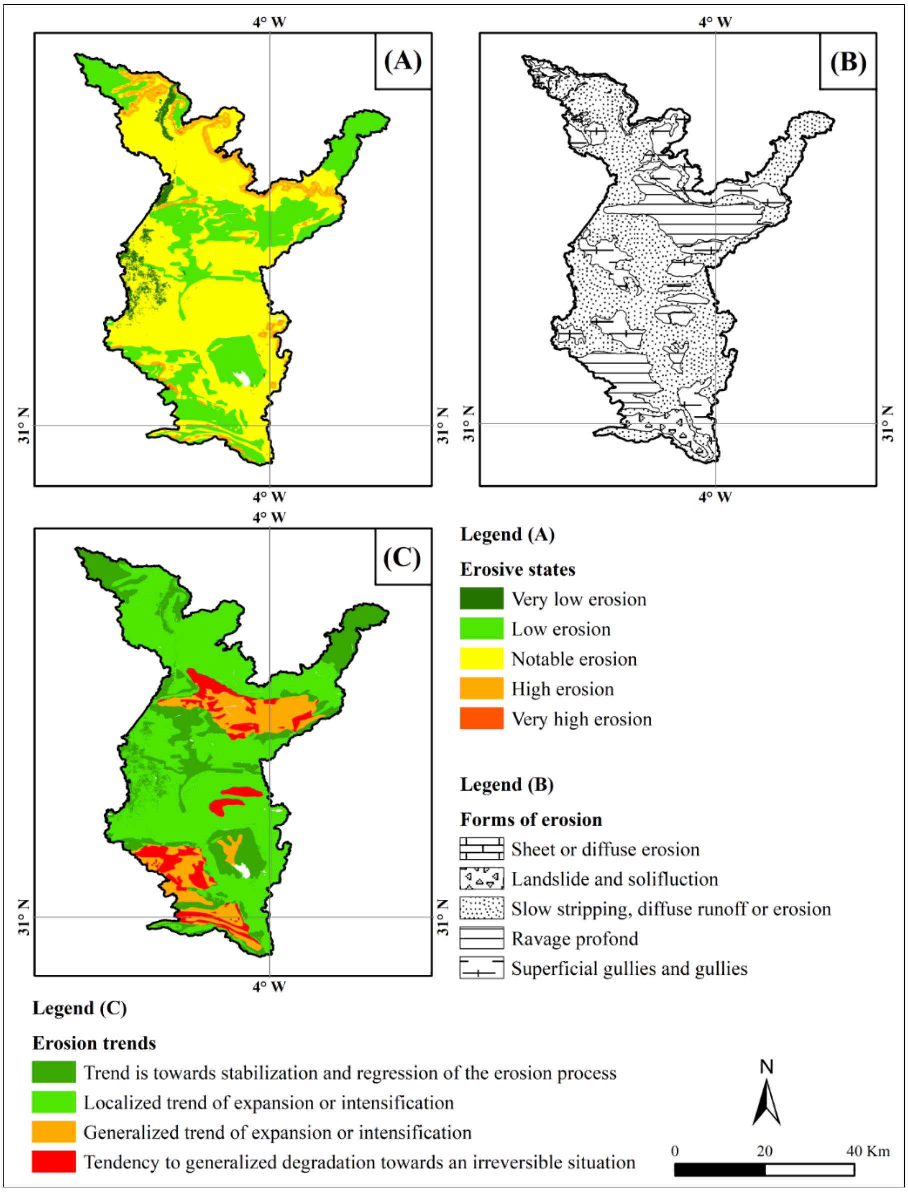

Fig.5. (A) Map of erosive conditions; (B) Map of erosive forms; (C) Consolidated PAP/RAC erosion map of the Lower Ziz watershed.

5. Conclusion

The Lower Ziz watershed experiences a semi-desert climate, heavily influenced by Saharan conditions and continental factors, characterized by high temperatures and sporadic, intense rainfall events that exacerbate water erosion. This study utilized the consolidated PAP/RAC method, primarily focusing on natural factors such as slope, vegetation cover, and lithology, to map water erosion and identify causal trends.

The predictive approach mapping reveals that 37.34% of the watershed has low to very low susceptibility to water erosion, while 55.96% experiences average erosion, and the remaining 6.7% is highly erodible. Meanwhile, the descriptive approach highlights gully and surface gullying erosion, covering 49.32% of the area, and deep gully erosion, affecting 41.89%.

Combining these approaches indicates that combined gully and surface gullying erosion are most prevalent, correlating with areas exhibiting notable to high erosion degrees, whereas deep gully erosion occurs in regions with lower erosion susceptibility.

In summary, this study underscores the critical yet not irreversible state of the basin. Climate change, particularly in our region, intensifies rainfall variability, amplifying soil erosion phenomena, which adversely affect infrastructure and agricultural lands, thereby diminishing the quality of life for the populace. Addressing this issue necessitates a collective and individual commitment to implement effective solutions. Future strategies must be developed within the context of climate change to reverse erosion trends and safeguard against its impacts.

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