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Qualitative Evaluation and Mapping of Water Erosion Risks in the Central Pre-Rif (Northern Morocco) – The Case of the Oued Lebene Watershed

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ABSTRACT

The Oued Lebene watershed is a sub-basin of the Sebou River located in the central part of the Rif region. The objective of this study is the modeling and mapping of areas sensitive to water erosion, using the guidelines of the classical PAP/CAR methodology in comparison with a modified approach based on the introduction of the slope length factor instead of slope, and soil type instead of lithology. This is combined with Geographic Information Systems (GIS) and validation through field observations.The predictive phase, illustrated by the thematic map of erosive states using the classical modeling approach, shows that the average to high erosion degree covers 71.57% of the study area. Modeling with the introduction of the LS factor and soil type highlights a sensitivity to erosion ranging from moderate to high, at an order of 45.26%. Mapping current erosion as a descriptive approach, based on the processing of current satellite images from Google Earth and field observations, allows for the spatialization of different types of water erosion and the creation of a real map of the distribution of erosion forms. Analysis of the latter reveals that linear erosion and surface gullies cover 88.42% of the total basin area. The consolidated PAP/CAR map resulting from the overlay of the previous maps reveals that the localized trend of expansion or intensification is represented by 66.15% in the classical version, decreasing to 33.58% after the modification of input parameters. The approach used has revealed that slope length and soil type significantly influence the spatial distribution of various forms of erosion. This study also highlights the importance of incorporating other factors affecting the erosion process and identifies high-risk areas that require prompt and sustainable intervention in the Oued Leben watershed.

Keywords: PAP/CAR; water erosion; PAP/CAR modified; GIS; modeling/mapping; Oued Lebene watershed; Rif Region Morocco.

INTRODUCTION

The degradation of soils is intensifying globally, affecting 30% of lands designated as forests, over 20% of agricultural lands, and 10% of meadows (Bai et al., 2008). These soils are frequently exposed to the increasing threat of water erosion, a phenomenon persisting in many regions worldwide. This continually evolving threat is perceived as the primary form of land degradation, leading to severe socio-economic and environmental consequences (Nanna 1996; Pimentel et al., 1995; Flanagan et al., 2002; FAO 2015). In Mediterranean regions, substrates are vulnerable to erosion due to intense precipitation that causes significant runoff. This phenomenon is accentuated by the nature of the terrain, topography, and low vegetation cover density (Albergel et al., 2011). Ecologically, economically, and environmentally, Morocco is not immune to erosion phenomena that have intensified over the years, especially in the mountains and hills of the Rif and pre-Rif regions

(Tahiri 2014; Laouina et al., 1998; Moufaddal 2002; Sadiki et al., 2009; Tahouri, et al., 2019). In this context, numerous studies have been dedicated to examining erosion processes in the Moroccan mountains, and several tools and methods have been developed for estimating water erosion (RUSLE, USLE, PAP/CAR, etc.).

The methods and predictive models developed for estimating water erosion are generally grouped into three categories: empirical models, physical models, and conceptual models. The choice of the model to use typically depends on data availability. Many researchers have employed the PAP/CAR approach to map and model water erosion, demonstrating its utility (Tahouri, et al., 2019; Bachaoui et al., 2007; Elbouqdaoui, et al., 2006; Lahlaoi et al., 2015; Iaaich et al., 2016; Aroussi, et al., 2013; Akalai et al. 2014; Mesrar et al., 2015). In Morocco, this research has been conducted using GIS tools and the guidelines of the PAP/CAR method for assessing watershed sensitivity to erosion risks. In this context, Mesrar et al. (2015) conducted a study in the Sahla watershed to model water erosion and its causal factors, applying the guidelines of the aforementioned method. Boukrim et al. (2016) also utilized this method for qualitative erosion mapping in the Aoudour watershed (Rif, Morocco). The current study on water erosion modeling in the Oued Lebene watershed, using remote sensing tools and geographic information systems, aims to highlight the severity and progression of water erosion through the classical PAP/CAR model approach. Additionally, it demonstrates the significant utility of the modified approach in understanding the trends of water erosion. This modified approach incorporates the geometric factor of slope length instead of slope, and replaces lithology with the soil type factor, offering a more insightful analysis of this hazard.

The rest of the manuscript is structured as follows: Section 2 is devoted to describing the study area and the dataset used. We also provide a detailed explanation of the methodology applied, along with the two parameters (slope length and soil type) that were incorporated to modify the classical approach. Finally, the results of the experimental study are presented and discussed in Section 3, followed by a conclusion that highlights the significance of this work.

MATERIELS AND METHODES

Study area

The Oued Leben watershed covers a total area of 1386 km² and is located on the southern slope of the Rif, as shown in Figure 1. It stretches over several

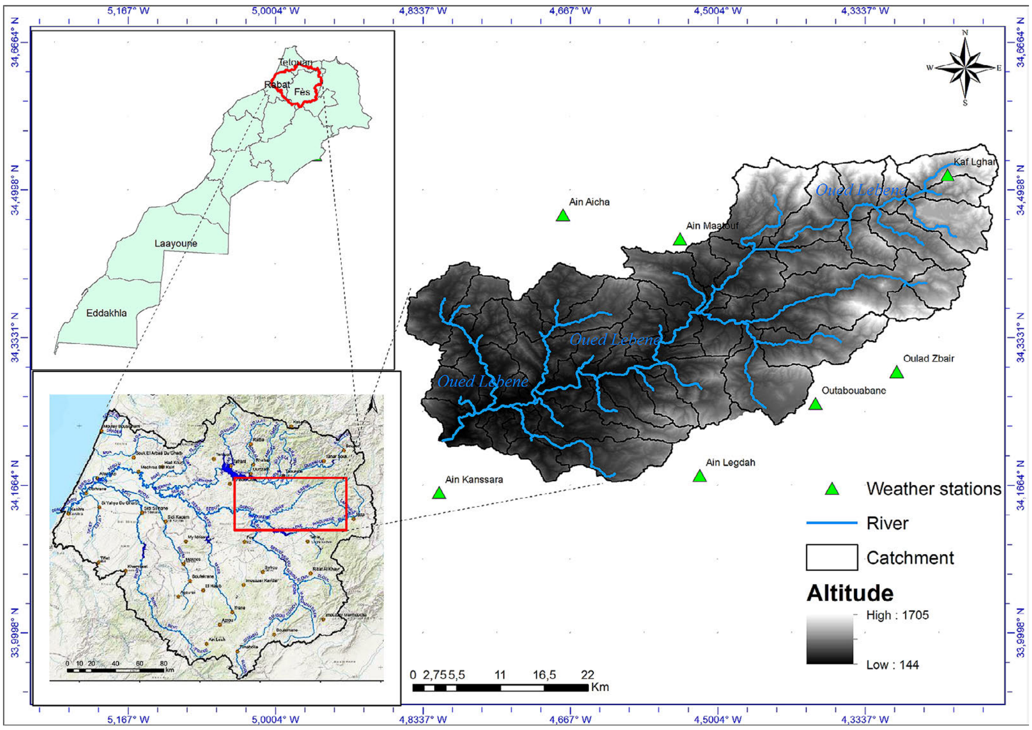

Figure 1. Location map of the Oued Lebene watershed

tens of kilometers in an elongated direction, oriented from NNE to SSW, and exhibits altitude variations over short distances (Gartet et Gartet 2005). This basin is drained by the rivers Oued Lebene, with a total length of 67.39 km. It lies in the geological transition zone between the high mountains of the southern Rif, reaching a maximum altitude of 1700 m, and the low-altitude hills, approximately 300 m, of the eastern and central pre-Rif.

The lithology of the upstream part of the watershed is mainly composed of black shales, with some sandstone beds and intercalations of clayey limestone dating from the Cretaceous. In contrast, in the downstream part of the study area, there are formations of marls, marl-limestones, intraformational conglomerates, and siliceous oolitic limestones dating from the Upper Jurassic, as well as conglomerates and detrital limestones from the Middle Miocene.

The climate of the study area is of a subhumid Mediterranean type, characterized by cold winters and a dry season in summer. The wet period extends from November to May. Annual precipitation ranges from 600 to 1013 mm per year depending on the regions, with significant variability.

Methodologies and data sets

The qualitative assessment of water erosion according to the PAP/CAR model is based on interconnections of causal risk parameters. The intersection of all these factors requires a cartographic approach and data processing and analysis operations. The fundamental method comprises three consecutive approaches (PAP/CAR 1998; PAM/PNUE 1998; 2001), namely:

1. Predictive: It utilizes thematic mapping of factors influencing erosion (lithology, slope, land use, and degree of vegetation cover) to deduce homogeneous units of erosive states, providing a mapping model of erosion states. The following operations are analogously performed:
- Generation of slope and lithology maps.
- Creation of friability and erodibility map by overlaying slope and lithofacies maps.
- Production of vegetation cover and land use map, based on the processing of Landsat-8 satellite imagery with a 30 m resolution dated 03/05/2023.
- Development of soil protection map by overlaying land use and vegetation cover density map.
- Creation of a thematic map of erosive states by overlaying erodibility map and soil protection map.
2. Descriptive: This involves mapping the current erosion, aiming to identify, describe, and evaluate the ongoing water erosion process on the site, as well as the degree of exposure to degradation.
3. Integration: This involves creating the final synthetic map of water erosion trends, resulting from the overlay and integration of qualitative information from the predictive and descriptive phases. It provides erosion trends by integrating the degree of erosive state and the intensity of the erosion form (Fig. 2).

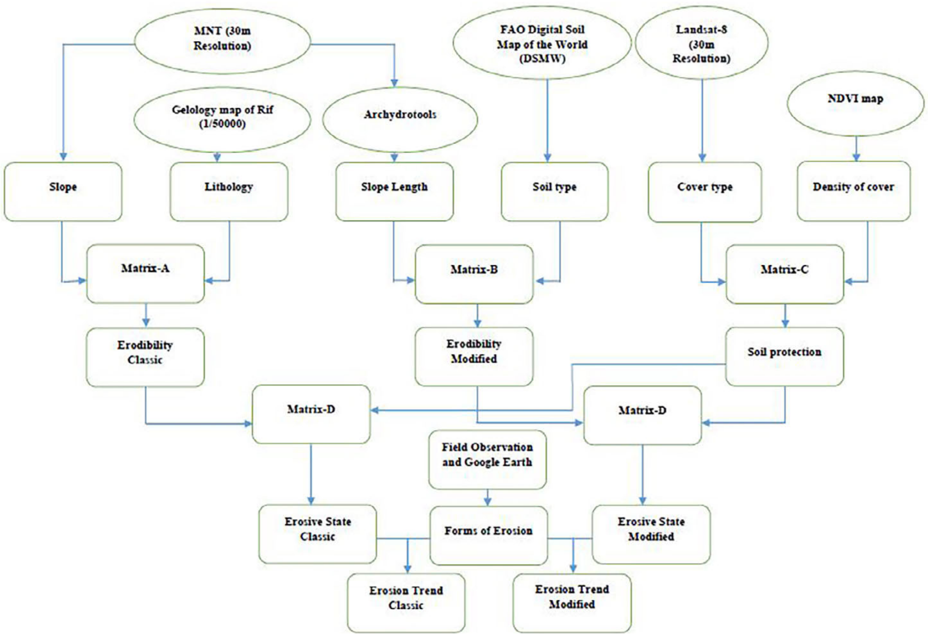

Figure 2. Schematic representation of methods

The correlation of input parameters is achieved by overlaying them, following the matrices defined by the PAP/CAR guidelines (Table 1). These matrices are the outcome of studies conducted in several Mediterranean countries. The aim of these studies was to identify various correlations between the relevant parameters (PAP/CAR 1998; PAM/PNUE 1998; 2001).

The causal factors of water erosion are organized based on their risk levels. This includes slope, classified into 5 classes ranging from very low (0–3%) to extreme (over 35%) (Table 3). This classification is based on the degree of slope inclination and its relationship with runoff. The behavior of lithofacies in response to mechanical resistance to weathering is also considered (Table 4). The degree of soil protection (Table 7) depends on both the type of land use (cultivation, reforestation, forest) and the density of vegetation cover (Table 5), which is divided into four classes ranging from less dense (less than 25%) to more dense (over 75%). Thus, output parameters, including erodibility (Table 6), soil protection, and erosive states (Table 8), are classified into 5 categories. These categories range from a low state, indicating minimal sensitivity, to an extreme risk state, denoting high sensitivity.

The qualitative approach used to map soil vulnerability to water erosion in the Oued Lebene watershed relies on the analysis of topographic, geological, vegetation cover data, and field observations. The digital terrain model (DTM) with a resolution of 30m from SRTM images, Landsat-8 images with a 30m resolution, Google Earth, field observations, and the 1/500,000 geological map of the Rif chain were used for delineating the study area and creating various thematic maps. Using remote sensing and GIS software, these data were georeferenced according to the North Morocco coordinate system (Table 2).

The qualitative assessment of water erosion using the classical modeling approach of the PAP/CAR is widely employed in the Rif region and the Middle Atlas, particularly in the Amzaz

Table 1. PAP/CAR matrix

Slope class	Slope type (%)	Slope type	Area in km²	Area in %
1	0-3	Low	237.28	17.10
2	3-12	Moderate	959.37	69.15
3	12-20	Steep	175.41	12.64
4	20-35	Strong	14.88	1.07
5	>35	Extreme	0.43	0.03
LS class	Ls type (m²)	LS state	Area in km²	Area in %
1	0-12	Very weak	443.81	31.98
2	12-30	Low	223.65	16.12
3	30-50	Average	338.64	24.40
4	50-70	Strong	138.07	9.95
5	70-86	Extreme	243.48	17.55

Table 2. Study data and data sources

Friability class	Friability type	Friability state	Area in km²	Area in %
1	Moderately altered rock	Low	220.93	16.29
2	Compact rock/Crude minrals	Very weak	27.74	2.05
3	Detrital materials/Non cohisiverocks	Very strong	147.31	10.86
4	Slightly resistant rocks	Strong	450.70	33.24
5	Weakly/Moderately compacted rocks	Average	509.15	37.55
Soil type class	Soil type name	Area	Area in km²	Area in %
1	Calcic Combisols	53593,5	535.94	38.62
2	Calcic Vertisole	48,96	0.49	0.04
3	Calcic Kastamozens	85123,2	851.23	61.34

watershed (Mesrar et al., 2013), Oued Zgane (Ousmana et al., 2017), Sahla (Mesrar et al., 2015), Kharouba (Dallahi et al., 2021), Oued Beht (Ait Yacine et al., 2019), Oued Larbaa (Sadiki et al., 2009), and the Assfalou watershed (Tahouri et al., 2019), (Tahouri et al., 2016). The evaluation of the results of these studies has revealed certain shortcomings, manifested by an overestimation in the spatial distribution of erosion risk classes.

In this perspective, and to enhance the effectiveness of these results, input parameters for the development of the erodibility map were modified by incorporating more precise factors, replacing lithology with soil type derived from the world soil map (Table 3) (Mesrar et al., 2013). Soils were classified based on their resistance using the *k* factor (erodibility) from the universal soil loss equation (Smith, 1978). This factor is determined from soil structure and organic matter according to Equation (1) (Williams et al., 1996).

$$KRUSLE = FCsand \times Fcl_{si} \times FOrgc \times Fhisand \quad (1)$$

where: $KRUSLE$ is the erodibility factor, $Orgc$ is the percentage of organic carbon, $Csand$ is the percentage of coarse sand, cl_{si} is the percentage of clay and silt, $hisand$ is the percentage of sand.

Thus, the slope in the classical PAP/CAR approach was subsequently replaced by the LS factor (slope length) of the Universal Soil Loss Equation calculated according to Equation 2 (Mesrar et al., 2013; Williams et al., 1996).

$$LS = (Flow\ Accumulation \times Cell\ size/22.13)0.4 \times \times (Sin\ slope/0.0896)1.3 \quad (2)$$

RESULTS AND DISCUSSION

Predictive approach

The causal factors of water erosion

The initiation of erosion processes strongly depends on the slope. The steeper the slope, the faster the runoff accelerates, and the soil becomes more vulnerable. The analysis of the slope map (Table 3 and Fig. 3a) reveals that in the middle part of the Oued Lebene watershed, the slope degree is low to moderate and gradually increases towards the northeast and upstream of the study area. Slope classes ranging from low to moderate, not exceeding 12%, cover 86.25% of the overall study area (1196.65 km²). The steep slope class (12–20%) represents 12.64% of the total area of the watershed, covering 175.15 km². High and very high slope classes, with an interval between 20% to 35% and more than 35%, occupy 1.07% and 0.03% of the territory, equivalent to 14.88 km² and 0.43 km², respectively. Indeed, the steep inclination presented by these last two classes, which account for 15.31 km² of land with slopes exceeding 20%, makes the watershed susceptible to erosion caused by intense rainfall and the action of runoff, leading to significant gullies and ravine formation.

The Oued Lebene watershed, due to its geographical location between the low altitudes of the central and eastern Rif and the high mountains of the southern Rif, exhibits a complex geological structure. Examination of the lithological map (Fig. 3c) reveals that the study area is characterized upstream by a lithological formation dominated by rocks of varying mechanical resistance to weathering, illustrated by limestones, dolomites,

Table 3. Slope and LS proprietes of Oued Lebene watershed

Land use class	Land use type	Area in km²	Area in %
1	Arboriculture & reforestation	37.89	2.73
2	Mattoral with dense cover	21.47	1.55
3	Forest	77.19	5.56
4	Mattoral with clear cover	936.27	67.47
5	Bare ground / cultivation in dry	208.17	15.00
6	Intensive irrigated cultivation	106.67	7.69
Cover density class	Type and state	Area in km²	Area in %
1	Low <25%	1098.03	79.14
2	Average 25–50%	243.05	17.52
3	Strong 50–75%	45.08	3.25
4	Extreme >75%	1.24	0.09

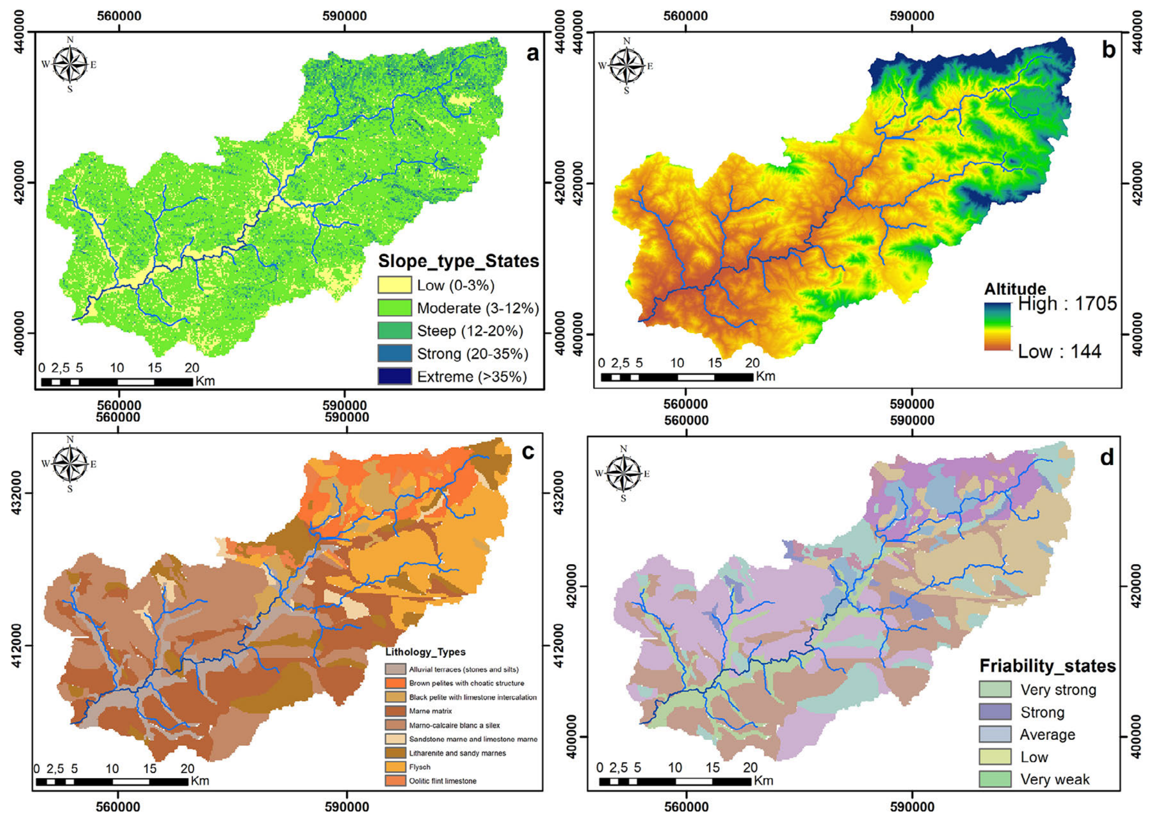

Figure 3. Slope class (a) altitude (b) lithology map (c) and friability map (d)

sandstones, and flysch. The lithology changes from NNE-SSW to less resistant formations, including marls, marly limestones, flint marls, marls with intercalated sandstone beds, and soft marls of the Triassic complex, extending to the point where Oued Lebene meets Oued Inaouène.

The analysis of the geological map processing results reveals that the friability of the rocks exposed on the lithofacies map has allowed the distinction of five categories classified based on the vulnerability of substrates to erodibility (Fig. 3d). Thus, oolitic limestone with flint and intraformational conglomerates of the Lias cover 2.05% of the total area (27.74 km²) and correspond to the category of low sensitivity to erosion.

Categories 3 and 4, consisting of poorly resistant or highly weathered sedimentary rocks or soils (marly matrix, white flinty marly limestone, sandy marls, and chaotic structure black pelite), represent the majority of the watershed territory at 70.79%, covering an area of 959.85 km². Category (5), with very high sensitivity to erosion, encompassing litharenite and sandy marls from the Middle Miocene, occupies 147.31 km², accounting for 10.86% of the total watershed area (Table 4).

The LS factor illustrates the influence of topography on soil erosion. It is determined by the combination of slope length (L) and slope steepness (S) relative to a unit cell (grid). Slope length (L) is defined as the distance from the runoff source to the point where deposition begins or where runoff enters a well-defined channel that is part of the drainage network (Mesrar et al., 2013; Williams et al. 1996). The analysis of the synthetic map indicates that the LS value ranges from 0 to 86 (Fig. 4a). However, the class of very low slope length is the highest at 31.98%, followed by the moderate and extreme classes covering 24.40% and 17.55%, respectively (Table 3). The high class is the least widespread at 9.95%, mainly found along watercourses and their surroundings.

Soils are classified based on their resistance level; the classification shows that the two soil type classes, Calcic Kastamozens and Calcic Combisols according to the FAO classification, are the most dominant in the watersheds, accounting for 61.34% and 38.62%, respectively (Fig. 4b).

The class of bare soil and dry crops dominates land use and covers almost the entire studied watershed (Fig. 5a). It represents approximately 67.47% of the overall study area, totaling 936.27 km². This class is generally found upstream, downstream, on the periphery,

Table 4. Friability and soil type proprieties of Oued Lebene watershed

Erodibility class (classic modelling)	Erodibility state	Area in km²	Area in %
1	Low	330.80	23.85
2	Moderate	237.08	17.10
3	Average	697.86	50.32
4	Strong	104.67	7.55
5	Extreme	16.35	1.18
Erodibilit class (introduction of Lsand soil type)	Erodibilit state	Area in km²	Area in %
1	Low	568.20	40.97
2	Moderate	290.45	20.94
3	Average	267.30	19.27
4	Strong	171.49	12.37
5	Extreme	89.33	6.44

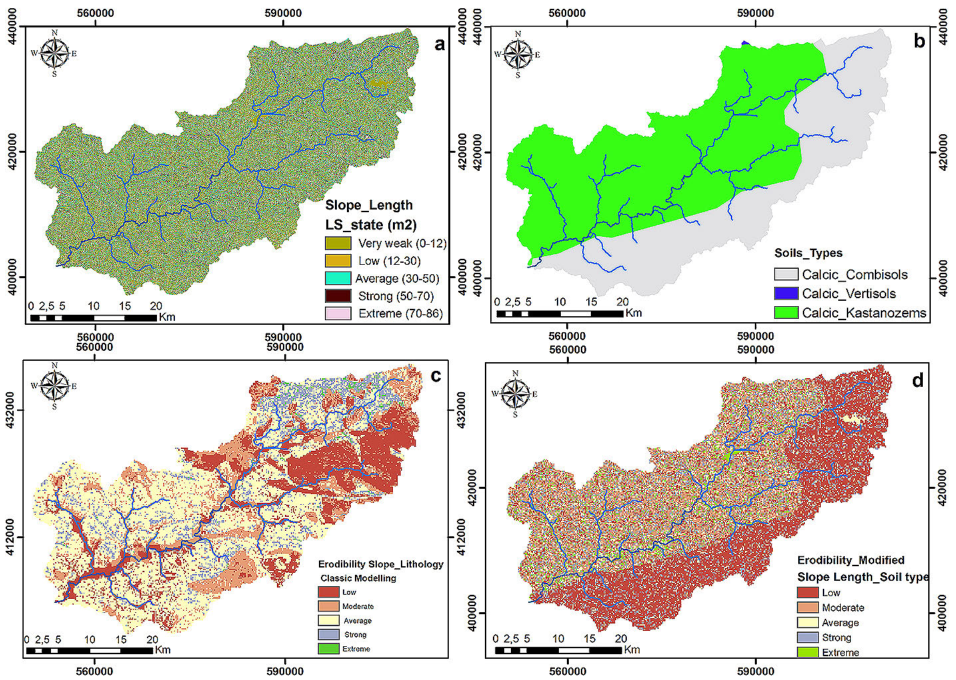

Figure 4. LS state (a) soil type (b) erodibility classic modelling (c) and erodibility modified modelling (d)

and at the center of the watershed. The class of sparse shrubland and grazing land extends over 208.17 km², accounting for 15%, and is located in the middle part of the study area. The classes of intensive irrigated crops, forests, and the class of reforestation, orchards, and row crops (olive and fruit trees) cover areas of 106.67 km², 77.19 km², and 37.89 km², respectively, representing 7.69%, 5.56%, and 2.73% of the total area (Table 5). Forests are mainly located upstream in the watershed and remain preserved in their initial state, while intensive crops are found along the main hydrographic network of Oued Lebene and on the edges of secondary wadis (Oued Lahmar). In contrast, the class of orchards and row crops, mainly formed by reforestation of olive trees planted under the D.E.R.R.O (Economic and Rural Development of Western Rif) project for land conservation and restoration against water erosion, is situated halfway up the hills from Tissa in the south to Ain Aicha in the northwest. Thus, the dominance of pasturelands with herbaceous vegetation cover across the entire study area makes the soils increasingly vulnerable to erosion (Fig. 5a).

Vegetative cover is a crucial factor in protecting the soil against the scourge of water erosion. However, dense vegetation cover promotes

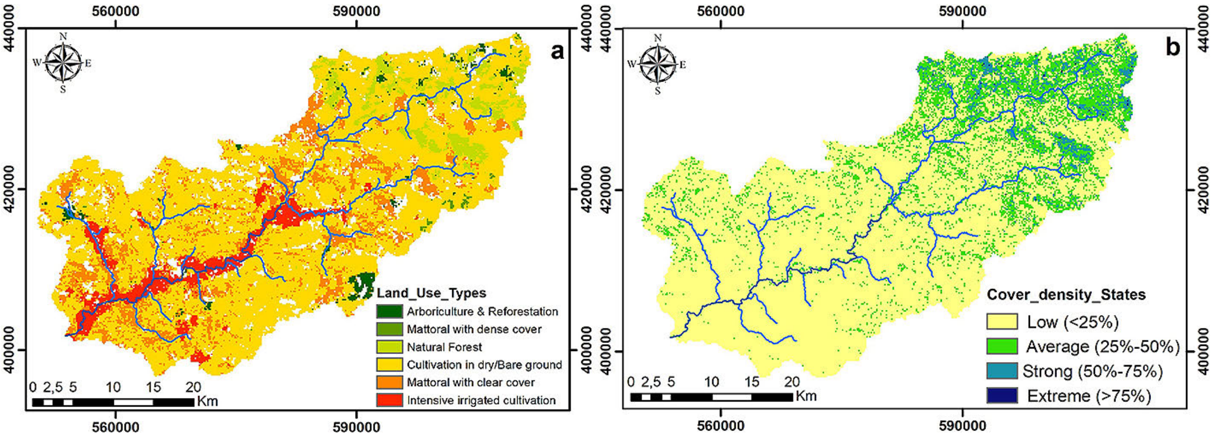

Figure 5. Land use map and cover density map of Oued Lebene watershed

Table 5. Land use and cover density of Oued Lebene watershed

Soil protection class	Soil protection state	Area in km²	Area in %
1	Very high	33.93	2.45
2	High	64.42	4.65
3	Average	161.84	11.67
4	Weak	171.06	12.34
5	Very weak	955.41	68.90

water infiltration into the deeper horizons of the soil, reducing the erosive energy of surface water by intercepting raindrops. This is closely tied to the degree of density of the vegetation cover. The calculation of the normalized difference vegetation index (NDVI) allowed the establishment of a map indicating the density degree of the vegetation cover in the Oued Lebene watershed, based on a Landsat-8 satellite image taken on 19/03/2023. The classification is represented by four categories of cover density: bare soil or denuded low (<25%), medium (25–50%), high (50–75%), and very high (>75%).

Thus, maximum NDVI values close to 1 (0.517–0.690) characterize natural forested areas untouched by anthropogenic activities, where the vegetation cover is very dense. Values ranging from 0.345 to 0.517 correspond to dense shrublands and reforestation (artificial forests and olive tree plantations), while the medium-density vegetation characterized by sparse shrublands and intensive crops falls within the range of values between 0.173 and 0.345. Cultivated areas, pasturelands, and sparse vegetation zones correspond to low values (-0.276–0.173).

The analysis of the thematic map (Fig. 5b) indicates that the Oued Lebene watershed has less abundant vegetation in the (50%–75%) and >75% density classes, covering respective areas of 45.08 km² and 1.24 km². These high-density classes are primarily located in the northern and northeastern parts and are absent in the middle and downstream areas. The (25%–50%) density class covers 17.52% of the study area with an area of approximately 243.05 km². Thus, the vegetation class below 25% is the most representative, covering 79.14% and extending across the entire watershed (Table 5).

Erodibility

The thematic map of erodibility (Fig. 4c), established using the classical PAP/CAR modeling, is the result of overlaying maps of slopes and material resistance to erosion. The polygons resulting from the intersection of the two tables are stratified and classified according to a matrix (Table 1a) to determine the degree of erodibility. This factor is extreme when the terrain has low resistance and/or the slope is steep. The spatial distribution of low erodibility (EN) and moderate erodibility (EB) classes covers 40.95% of the total watershed area. The moderate erodibility class (EM) covers 50.32%, totaling an area of 697.86 km². However, only 8.73% of the land exhibits strong (EA) and extreme

Table 6. Erodibility classic and erodibilty modified of Oued Lebene watershed

Erosion state (classic modelling)	Erosion state (classic modelling)	Area in km²	Area in %
1	Very low	95.99	6.92
2	Low	298.57	21.52
3	Notable	314.39	22.66
4	Hight	562.72	40.55
5	Very hight	116.01	8.36
Erosion class (modified modelling)	Erosion state (modified modelling)	Area in km²	Area in %
1	Very low	90.49	6.52
2	Low	669.09	48.22
3	Notable	204.29	14.72
4	High	175.94	12.68
5	Very high	247.85	17.86

(EX) erodibility (Table 6). The predominance of low to moderate erodibility lands, spanning 91.27%, is explained by the presence of moderately weathered sedimentary substrates, moderately resistant soils, and irregular terrains characterized by the widespread moderate slope class covering 69.15% of the entire territory.

The slope of the terrain, expressed by the slope factor, plays a crucial role in the runoff process, directly influencing the phenomenon of water erosion (Chaplot et Le Bissonnais, 2000; Bryan et Poesen 1989; Fox, Bryan, et Price 1997; Fox et Bryan, 1999). The increase in runoff is strongly linked to the length and steepness of the slope, directly influencing the production and intensification of sediment load resulting from water erosion (Chaplot et Le Bissonnais, 2000; Duffa, et Danic, 2006; Kieffer et Bois, 2001; Duchemin et al. 2005; Loulergue 2007). The introduction of the LS factor instead of slope and soil type instead of lithology (Fig. 4d) according to the matrix (Table 1b) shows that the degree of erodibility has undergone significant regressive changes, expressed by a decrease of 31.05% in the moderate erodibility class in favor of the low and moderate classes. In contrast, the strong and extreme erodibility classes increased from 7.55% to 12.37% and from 1.18% to 6.44%, respectively.

The modeling of erodibility using topographic factors and soil type revealed that the classical modeling overestimates the degree of erodibility for the moderate class (EM). However, the Oued Lebene watershed exhibits low erodibility over 61.91% of the total area, compared to a proportion of 40.95% according to the classical PAP/CAR approach.

Soil protection map

The aerial part of plants plays a very important role in soil protection against water erosion by intercepting raindrops, reducing erosive force through the prevention of soil detachment, and diminishing the energy of rainfall erosion (Rey et al., 2004; Battany, et Grismer, 2000; IONESCO, 1964; Hill, et Mervyn, 1999). Vegetative cover effectively contributes to controlling runoff while promoting the infiltration of rainwater into the deeper soil horizons (Thomas, Weihua, et Brian, 1991; Derouiche, 1995; Cerdà, 1998; Carroll, Merton, et Burger, 2000; Brown, 1990). However, the effect of this vegetative cover can vary depending on land use and the nature of plant formations (mixed deciduous and coniferous forests, reforestation, orchards, etc.). The soil protection map was developed by overlaying the land use map and vegetation cover density. The matrix used for this overlay is specific to Mediterranean bioclimatic conditions and therefore cannot be used in other contexts (Mesrar et al., 2015). This soil protection map provides information on the nature and distribution of vegetation (Tahouri, H et al., 2022). In this light, the soil protection map is essential for locating areas with high or low degrees of protection and thus identifying polygons most affected by the erosion phenomenon. These areas will be classified as a top priority during the implementation of anti-erosion development plans for soil fixation and stabilization.

The analysis of the thematic soil protection map has allowed the distinction of different zones into five classes: very high (MA), high (A), medium (M), low (B), and very low (MB) (Fig. 6). The class of very low protection (MB) is located over

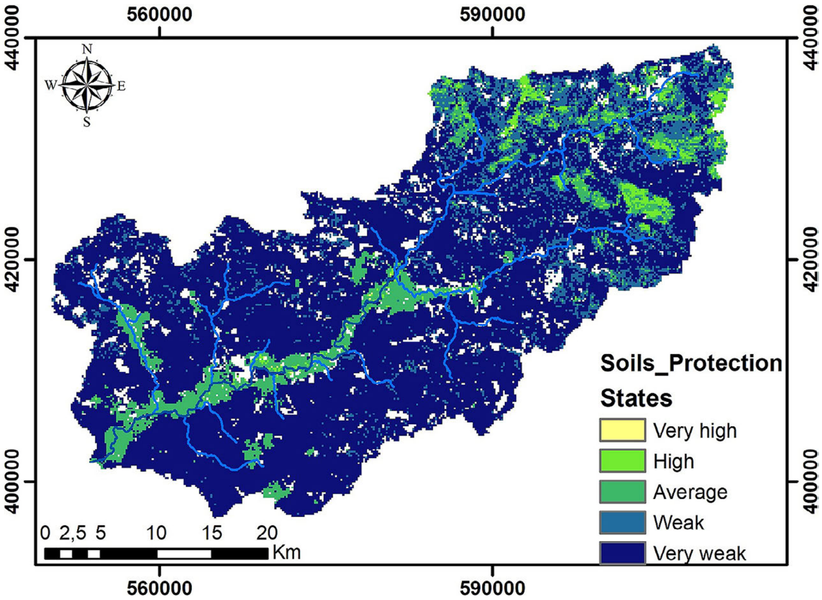

Figure 6. Soil protection map of Oued Lebene watershed

almost the entire watershed, especially in areas with lithological formations based on marly matrices and sandy marls and with a low slope (<12%). It covers an area of approximately 955.41 km², accounting for 68.90% of the total surface. This can be explained by the prevalence of highly degraded vegetative cover combined with anthropogenic activities (cultivation, overgrazing, and deforestation). The low protection (B) and medium protection (M) classes cover areas of 171.06 km² (12.34%) and 161.84 km² (11.67%), respectively, situated in the southwest, northeast, and downstream parts of the watershed up to the outlet. The high and very high protection classes are distributed over 98.35 km², representing 7.1% of the total area and are located upstream and on slopes occupied by forest formations (Table 7).

Maps of erosive states

The thematic map of erosive states (Fig. 7a, 7b) is the result of cartographic synthesis, overlaying the soil protection and erodibility cartographic products. The objective of modeling erosive states is to illustrate the various combinations of factors influencing water erosion and to classify the watershed area into homogeneous units based on the level of erosion risk.

The results of the classical modeling (Fig. 7a and Table 8) show that 48.91% of the watershed is subject to high erosion, marked by two classes with a risk of high to very high erosion, occupying 562.72 km² and 116.01 km², respectively. Indeed, these areas experiencing pronounced erosion are dominated by steep terrains with highly degraded or absent vegetative cover (bare soil/bad lands). The classes with low and very low erosion risk cover 28.44% of the watershed, totaling an area of 394.56 km² mainly located in the upstream and middle parts. This can be explained by the presence of vegetative formations consisting of forests and dense shrublands, coinciding with areas of low erodibility where the lithology is marked by the presence of cohesive and resistant rocks. The notable erosion class is dispersed throughout the watershed where the slope is considerable

Table 7. Soil protection class, state an area of Oued Lebene watershed

Forme of erosion class	Forme of erosion state	Area in km²	Area in %
1	L1, Sheet erosion	663.19	47.79
2	D2, Surface rills and gullies	563.78	40.63
3	C1, Surface ravines	24.73	1.78
4	C2, Moderately depp ravines	113.38	8.17
5	C3, Deep ravines	22.59	1.63

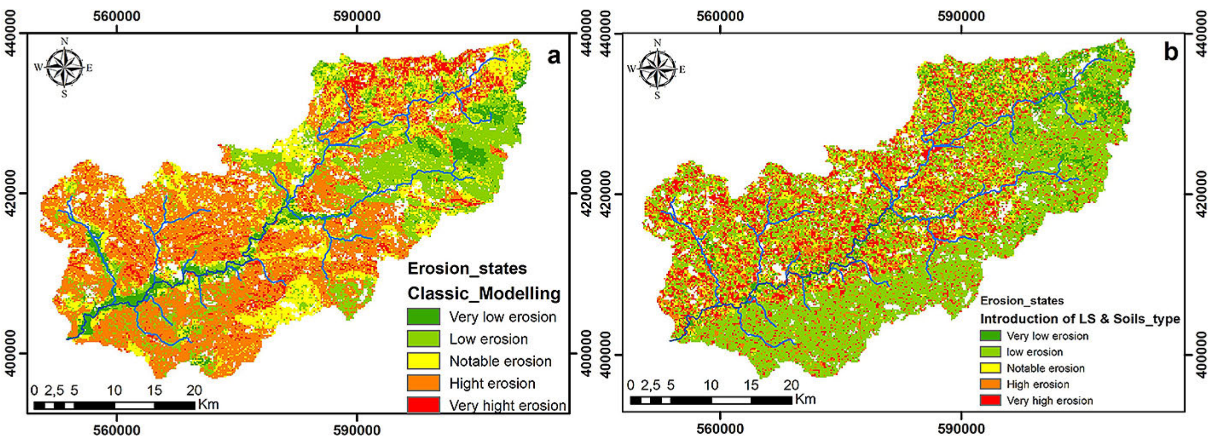

Figure 7. Erosion state map (classic and modified modeling) of Oued Lebene watershed

Table 8. Erosion class, state an area (classic and modified modelling) of Oued Lebene watershed

Erosion trend class (classic modelling)	Erosion trend state (classic modelling)	Area in km²	Area in %
1	Tendency to stabilize, regress or limit the spatial expansion of the erosion process	308.37	22.22
2	Localized tendency to expand or intensify	917.96	66.15
3	Generalized tendency to expand or intensify	44.37	3.20
4	Trend of general deterioration towards an irreversible situation	116.96	8.43
Erosion trend class (modified modelling)	Erosion trend state (modified modelling)	Area in km²	Area in %
1	Tendency to stabilize, regress or limit the spatial expansion of the erosion process	752.25	54.21
2	Localized tendency to expand or intensify	466.00	33.58
3	Generalized tendency to expand or intensify	75.24	5.42
4	Trend of general deterioration towards an irreversible situation	94.17	6.79

(<35%), with lithology characterized by moderately weathered and less cohesive soils, and vegetation cover mainly represented by olive plantations along contour lines and permanent crops at the edges of watercourses.

The analysis of the results from the erosion state modeling by introducing the slope length (LS) factor and soil type (Fig. 7b) shows that the classes of low and very low erosion risk are the most representative, covering 54.74% of the watershed, equivalent to an area of 759.58 km². The notable erosive state represents 14.72%, while the high and very high erosion classes occupy 30.54%.

In light of these results, it is evident that the Oued Lebene watershed is exposed to a significant risk of erosion. The introduction of the LS and soil type factors into the modeling has reduced the high and very high erosive state by 18.37%, decreasing from 48.91% to 30.54%. However, the low and very low erosion classes have increased from 28.44% to 54.74%, representing a rise of 26.30%.

Descriptive approach

Map of erosion forms

The Oued Lebene watershed is characterized by diversified erosion processes highly correlated with the topography, lithology, and vegetation cover density. The comprehensive map of erosion forms (Fig. 8) is the result of satellite image mapping using Google Earth, combined with on-site observations.

The analysis of the sectoral distribution of erosion forms in the watershed reveals the dominance of L1-type erosion (linear erosion) and D2-type erosion (surface gullies and channels), covering 47.79% and 40.63%, respectively. These two forms of erosion are present along the edges of rivers and watercourses due to the vulnerability of the terrain, primarily composed of marly matrices and sandy marls, as well as the impact of runoff and human activity. The prevalence of these two erosion processes and their causal factors has

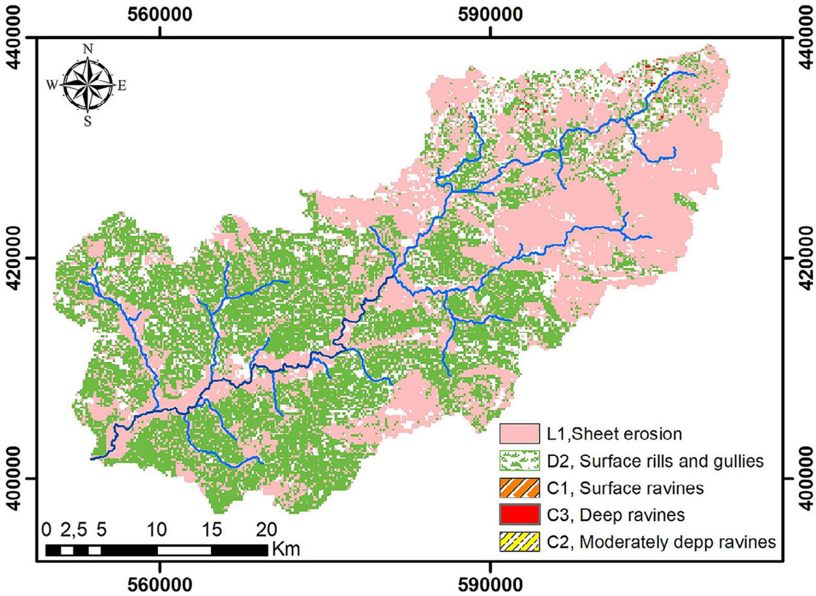

Figure 8. Formes of erosion map of Oued Lebene watershed

been identified in the Central Rif in the watershed of Oued Aoudour (Tahouri, et al., 2019; Mesrar et al., 2015; Tahouri, H et al., 2022; Boukrim et al., 2016) and in the Middle Atlas Tabular in the watershed of Oued Zgane (Ousmana et al., 2017). On the other hand, deep, moderately deep, and superficial ravines (C1, C2, and C3) are less abundant, affecting only 13.97% of the watershed area and located in the southeast and slightly upstream of the studied sector (Fig. 8 and Table 9).

Integration approach

Consolidated erosion map PAP/CAR

The consolidated PAP/CAR erosion map is a qualitative representation obtained by combining the results of predictive and descriptive phases. It includes comprehensive data and information about various erosion forms and processes. The consolidated PAP/CAR erosion map (Fig. 9a and 9b) allows for the identification and evaluation of the intensity and evolution of potential water erosion in its various forms at the current state. It results from overlaying the map of erosion forms (actual mapping) and the map of erosive states (thematic mapping).

Based on the guidelines of the PAP/CAR model, erosion trends are expressed by an index ranging from 1 to 4, namely:

1. Trend toward stabilization, regression, or limitation of the spatial expansion of the erosion process;
2. Localized trend toward expansion or intensification;
3. Generalized trend toward expansion or intensification;
4. Trend toward overall deterioration towards an irreversible situation.

The analysis of the results from the classic PAP/CAR modeling approach (Fig. 9a) reveals that areas with a very high and high degree of erosion are characterized by the presence of various erosion forms, mainly deep and moderately deep gullies. Sheet erosion occurs in areas where the slope is moderate and does not exceed 12%. The average degree of erosion coincides with erosion

Table 9. Classes, states and area of erosion forme of Oued Lebene watershed

Forme of erosion class	Forme of erosion state	Area in km²	Area in %
1	L1, Sheet erosion	663.19	47.79
2	D2, Surface rills and gullies	563.78	40.63
3	C1, Surface ravines	24.73	1.78
4	C2, Moderately depp ravines	113.38	8.17
5	C3, Deep ravines	22.59	1.63

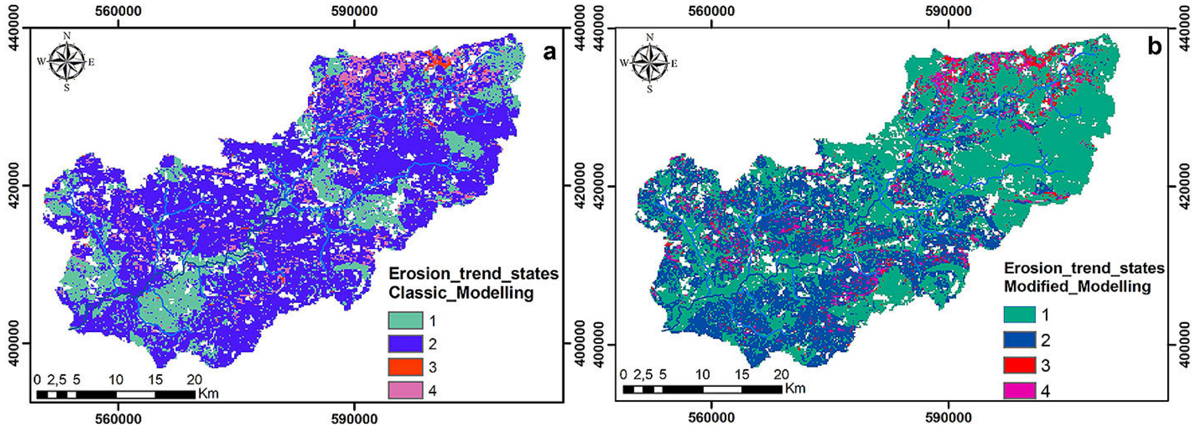

Figure 9. Erosion trend map (classic and modiefied modelling) of Oued Lebene watershed

forms of type C1 (surface gullies), D2 (surface gullies and channels) on scattered surfaces, and the concentration of sheet erosion in the southeast where the lithology is mainly composed of oolithic limestones and Upper Jurassic flysch. Sheet erosion forms are widespread over almost all areas with a low to very low erosion risk, with scattered surface gullies on slopes marked by low-density vegetation and dry farming lands (monoculture and inadequate agricultural practices).

The Oued Lebene watershed is exposed to a trend of erosion marked by the dominance of a localized trend toward expansion or intensification, covering almost the entire study area with 66.15%. The trend toward stabilization, regression, or limitation of the spatial expansion of the erosion process covers an area of 308.37 km², equivalent to 22.22%. The types of trends generalized to expansion or intensification and a trend toward overall deterioration towards an irreversible situation are represented respectively by 3.20% and 8.43% (Fig. 9a and Table 10)

The introduction of the topographical factor expressed by the slope length and soil type (Fig. 9b and Table 10) has caused a remarkable decrease in the trend of localized erosion expansion or intensification, evaluated at 33.58%, and a significant increase in the trend toward stabilization, regression, or limitation of the spatial expansion of the erosion process with a value of 54.21%, representing an increase of 32%. The class of trend toward overall deterioration towards an irreversible situation has also decreased by a minimal value in favor of the class of trend toward generalized expansion or intensification.

The results obtained in this qualitative study on water erosion using the guidelines of the PAP/CAR method show that the Oued Lebene watershed generally exhibits a high risk of erosion. This is due to the influence of several biophysical factors complementing each other in this process. It is explained by the presence of friable substrates covering 70% of the total area of the study area, whose resistance to erosion is very low. Thus,

Table 10. Classes, states and area of erosion trend (classic and modified modelling)

Erosion trend class (classic modelling)	Erosion trend state (classic modelling)	Area in km²	Area in %
1	Tendency to stabilize, regress or limit the spatial expansion of the erosion process	308.37	22.22
2	Localized tendency to expand or intensify	917.96	66.15
3	Generalized tendency to expand or intensify	44.37	3.20
4	Trend of general deterioration towards an irreversible situation	116.96	8.43
Erosion trend class (modified modelling)	**Erosion trend state (modified modelling)**	**Area in km²**	**Area in %**
1	Tendency to stabilize, regress or limit the spatial expansion of the erosion process	752.25	54.21
2	Localized tendency to expand or intensify	466.00	33.58
3	Generalized tendency to expand or intensify	75.24	5.42
4	Trend of general deterioration towards an irreversible situation	94.17	6.79

vegetation cover less than 25%, according to the NDVI index, occupies 79.14% of the territory marked by formations based on light shrubs that promote runoff and further worsen the stability of the lithologically friable soil.

The results of the water erosion modeling using the classical PAP/CAR approach in Oued Lebene are in perfect agreement with research studies conducted in the central Rif in the Sahla, Oued l'Aoudour, Asfalou watershed (Mesrar et al., 2013; Tahouri, et al, 2016; Boukrim et al., 2016). Other studies have also been conducted following the PAP/CAR guidelines, demonstrating the effectiveness of this methodology in estimating the degree of water erosion (Sadiki et al., 2009; Ouallali et al., 2016; Lakhili et al., 2017) [11]. However, the improvement of this approach by introducing new factors such as slope length and soil type has provided satisfactory results in terms of the spatial distribution of erosive states, more or less in line with the reality found on the ground. The results obtained by this modification are compatible with those found by Mesrar et al., 2015 and Tahouri et al., 2022.

CONCLUSIONS

The qualitative assessment of water erosion using the PAP/CAR model guidelines, which takes into account causal factors such as topography (slope), lithological formations (lithofacies), land use and land cover, vegetation density, and actual mapping, allowed for a diagnosis and analysis of the erosion issue in the Oued Lebene watershed.

The approach followed yielded significant results regarding causal factors, indicating that the Oued Lebene watershed is highly exposed to high to very high erosion, covering over 48% of its total area. Low and very low erosion risk covers 28.44% of the watershed. The watershed exhibits a vulnerability of the natural space marked by various forms of erosion and extensive areas of uncultivated land lacking fertile substrates and affected by widespread sheet erosion. The erosive state resulting from the modified modeling by introducing LS and soil type factors reduced the high and very high erosive state by 18.37%, decreasing from 48.91% to 30.54%. However, the low and very low erosion classes increased from 28.44% to 54.74%, a rise of 26.30%.

The descriptive approach describing erosion forms highlights the dominance of sheet erosion covering 47.79% scattered throughout the entire watershed, along with small superficial ravines covering 40.63% of the total area, located on dry and intensive cultivation lands marked by inadequate agricultural practices (monoculture, slope cultivation, and absence of support practices). Consolidation maps from the integration phase showed that the modified modeling reduced the overestimation produced by the classical PAP/CAR modeling.

Given the reported results and the escalating threats of degradation to the sustainability of natural resources (biodiversity, soils, water, etc.) and to infrastructure and settlements in the study area, and consequently the quality of life of the population affected by this scourge, it is essential to implement urgent interventions through corrective anti-erosion measures using a comprehensive, integrated, and innovative co-management approach. This will enable reconciling the limited potential of natural resources, which are depleting due to overexploitation, with the impact of global changes and the growing needs of a constantly increasing population in the future.

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