

## Estimating Soil Erosion and Sediment Yield Using GIS in the Central Pre-Rif (Northern Morocco) – The Case of the Oued Lebene Watershed

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### ABSTRACT

The alarming degradation of soils, particularly in the Moroccan Rif region, is the result of various forms of water erosion processes, leading to significant environmental and economic damage in the area. The Oued Lebene watershed is a sub-basin of the Sebou River, located in the central part of the Pre-Rif. Using GIS, remote sensing, and the universal soil loss Equation modified for North African conditions and validated by field observations, this study aimed to measure soil losses, sediment delivery capacity, and sediment yield rates. The estimation of soil loss reveals that the watershed is exposed to a high degree of erosion, reflected by an estimated total annual loss of 6 379 314 t/yr, with an average annual rate of 46.17 t/ha/yr. The severe erosion class covers 52.25% of the study area, contributing to 90.67% of sediment production with an average of 80.11 t/ha/yr<sup>1</sup>. The erosion class below the tolerance threshold according to Wischmeier represents 48 108 hectares, or 34.82% of the total watershed area. Analysis of the synthetic sediment delivery ratio (SDR) map shows that the sediment delivery capacity is approximately 0.17, and the sediment yield (SY) in the Oued Lebene watershed is estimated at 770 440.32 t/yr. This is the outcome of the interaction between multiple causative factors, including steep slopes, friable substrates, severely degraded vegetation cover, etc., which increasingly accelerate the degradation of water resources in the downstream Oued Sebou, a source of irrigation for agricultural lands.

**Keywords:** erosion, sediment yield, sediment delivery ratio, universal soil loss equation modified, Oued Lebene watershed, Moroccan Rif region.

### INTRODUCTION

The water erosion process encompasses the weathering and transport of disintegrated particles, as well as their deposition and accumulation (Lahlaoui et al., 2015). During the arid and dry seasons, vegetation density decreases, making the surface more vulnerable to splash effects during the wet season (Shikangalah et al., 2017; Chalise et al., 2019). This leads to notable soil erosion, resulting in the ongoing breakdown of soil aggregates and topsoil depletion, ultimately disrupting agricultural production systems (Chalise et al.,

2019; Chalise et al., 2020). On a global scale, land degradation continues to worsen and poses a concerning magnitude on over 30% of forests, 20% of cultivated lands, and 10% of areas covered by secondary species (Bai et al., 2008). The primary form of this degradation is marked by water erosion, which leads to severe socio-economic and environmental consequences (Suryana, 1997; Pimentel et al., 1995; Duiker et al., 2001). In Mediterranean regions, substrates are vulnerable to erosion due to heavy, intense precipitation that causes significant runoff. This phenomenon is exacerbated by the nature of the terrain, topography,

and a low density of vegetative cover (Albergel et al., 2011). It is believed that the mean annual soil erosion globally ranges from 12 to 15 tons per hectare (Ashiagbor et al., 2013). Morocco suffers from the impact of erosion, experiencing its deleterious effects on its environment and economy. Agricultural services have conducted the initial studies on this hazard since the 1960s (Heusch et al., 1970). These efforts were undertaken to gain insight into the rate of degradation of soil and water resources and in terms of the annual loss of storage capacity in dams, estimated at  $7 \times 10^8$  m<sup>3</sup> of sediment accumulating in dam reservoirs (Moukhchane, 2002). In Morocco, soil erosion impacts nearly every watershed, with soil loss rates ranging from 15 to 50 tons per hectare per year (FAO, 2015).

Methods and predictive models have been developed worldwide for estimating water erosion. Typically, these models fall into three main categories: conceptual, physical, and empirical. The selection of the model to utilize usually relies on the availability of data. Several researchers have employed the revised universal soil loss equation (RUSLE) methodology for mapping and modeling water erosion, demonstrating its utility (Tahiri et al., 2016; Issa et al., 2014; Lahlaoui et al., 2015; Sadiki et al., 2004; 2009). In Morocco, these research efforts have been carried out using GIS tools. In this context, modeling work on water erosion and its causal factors (Moukhchane 2002; FAO 2015; Issa et al., 2014) has been conducted in the watersheds of Oued Haricha, Oued Lkhmiss, and Oued Boussouab, with soil loss estimated at 62.72, 36, and 55.35 tons per hectare per year, respectively.

Government bodies have initiated further initiatives covering the majority of the nation's main watersheds, utilizing remote sensing and GIS. As part of the recent restructuring of the department, the National Agency for Water and Forests has launched a countrywide initiative to assess soil erosion in the 14 watersheds spanning the entire national territory. In the Sebou watershed, the outcomes of this initiative have revealed a specific degradation ranging from 1000 to 2000 tons per square kilometer (HCEFLCD, 2014).

The preservation of water quality in rivers and dams, as well as soil sustainability, is directly affected by the sediments resulting from watershed erosion (Tahiri et al., 2016; Kanito et al., 2023; Tsegaye and Bharti, 2021). The research on sediment rates for Moroccan watersheds is rarely undertaken. Several approaches are recognized

as highly useful, such as the SDR, the sediment distributed delivery (SEDD), the soil and water assessment tool (SWAT), and others. These sediment yield and delivery prediction approaches are influenced by factors characterizing the studied watersheds, including topography, land use, soil physical parameters, and sediment source areas (Syvitski and Milliman, 2007; Pelletier 2012; de Vente and Poesen, 2005; Vanmaercke et al., 2014). SDR enables to evaluate the volume of sediments expected to be conveyed to watercourses from the upstream drainage area (Renard et al., 1991). A prediction based on the SDR approach is a significant and effective method for estimating sediment yield (Kanito et al., 2023; Ferro and Minacapilli, 1995; Ahmad et al., 2022).

The modeling of water erosion and the estimation of sediment load through the integration of the SDR approach with the RUSLE model are rarely used for Moroccan watersheds, which are typically affected by intense soil water erosion and severe sediment transport. In this perspective, and for effective governance of water and soil resources, quantifying the sedimentation rate is crucial. The present investigation into water erosion modeling within the Oued Lebene watershed utilizes remote sensing, geographic information systems, and the SDR approach in conjunction with the RUSLE model. Its primary objective is to quantify sediment yield rates (SY) and soil loss. The findings of this study will empower decision-makers and relevant institutional authorities to devise an efficient action strategy for mitigating the repercussions of erosion on downstream irrigated lands.

## **METHODS AND MATERIALS**

### **The area study**

The Oued Lebene watershed, covering a total area of 1386 km<sup>2</sup>, is located on the southern slope of the Pre-Rif (Figure 1). It has an elongated shape-oriented NNE-SSW, stretching over several tens of kilometers, with variations in the bottom elevation over short distances (Gartet and Gartet, 2005). Oued Lebene primarily drains the watershed with a length of 67.39 km, situated in the transitional Rif's geological zone between the high mountains of the southern Rif, reaching a maximum altitude of 1700 m, and the low hills of the eastern and

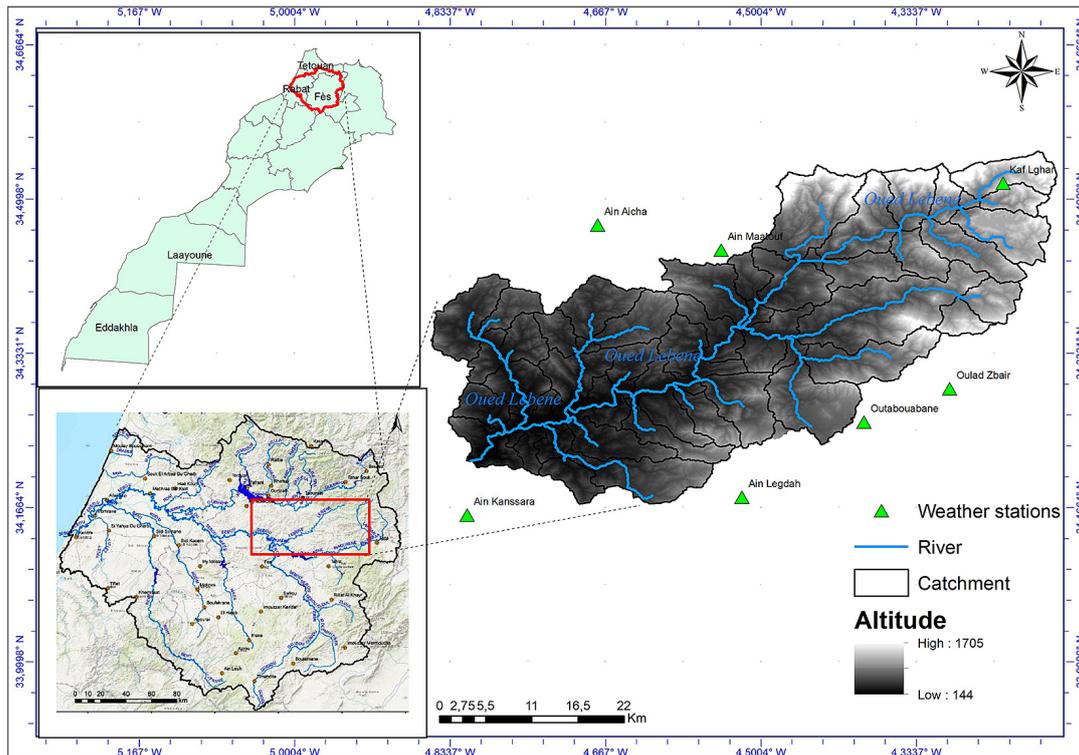


Figure 1. Oued Lebene watershed

central Pre-Rif, with a minimum altitude of 300 m. Upstream in the watershed, the lithology is primarily composed of black shales with occasional small sandstone layers and intercalations of clayey limestone from the Cretaceous period. Downstream, the study area is dominated by formations consisting of marls, marl-limestone, intraformational conglomerates, oolitic limestone with flint from the Lias period, as well as detrital conglomerates and limestone from the Middle Miocene. The research region is characterized by a semi-humid Mediterranean climate, marked by chilly winters and arid summers. Precipitation occurs predominantly from November to May, with yearly rainfall

varying from 600 to 1013 mm, displaying notable diversity among various locales.

### Methodologies and data sets

In the context of this study, the RUSLE parameters were established using the data generated from various sources. Field observations, the FAO soil database, meteorological data, a Landsat-8 image dated 03/05/2023, and an ASTER-type digital elevation model were used for this purpose (Table 1). The regional agricultural department and the water and forestry services of the Fes-Meknes region provided climate data, covering 30 years (1992–2022). Additionally, an image of Landsat-8 with a thirty-meter-resolution

Table 1. Study data and data sources

Data	Description	Resolution	Source
Rainfall	Weather stations (30 years of annual rainfall)	Interpolation with 30 m resolution	The regional agriculture department (DRA) and the water and forestry services (ANEF) of the Fes-Meknes region
Soil	Chemical and physical (% sand, % silt, % clay, bulk density) properties of the subsoil and topsoil	30 m	FAO digital soil map of the world (DSMW)
Topography	DEM ASTER	30 m	USGS database
	Landsat-8		NASAn earth explorer

was sourced from the website of (USGS), and a 30-meter-resolution ASTER-type DEM was obtained from the NASA Earth Explorer website.

The revised universal soil loss equation developed by Renard et al. (1991) represents a revision of the USLE model initially proposed by Wischmeier & Smith. The methodology involves analyzing and evaluating the key factors in Equation 1 that play a role in erosion processes to quantify and establish a spatial distribution map of the risk of this phenomenon.

$$A = R \times K \times LS \times C \times P \quad (1)$$

where:  $A$  – the average annual soil loss ( $t \cdot ha^{-1} \cdot yr^{-1}$ );  $R$  – represents the rainfall erosivity factor ( $MJ \cdot mm \cdot ha^{-1} \cdot h^{-1} \cdot yr^{-1}$ ),  $K$  – indicates the soil erodibility factor ( $t \cdot ha \cdot h \cdot ha^{-1} \cdot MJ^{-1} \cdot mm^{-1}$ ),  $LS$  – represents the slope length and

steepness factor,  $C$  – the land cover management factor and  $P$  refers to the conservation practice factor.

Soil loss estimation was determined by multiplying the individual parameter values following the flowchart depicted in the RUSLE model, as illustrated in Figure 2.

### Rainfall erosivity factor

Rainfall erosivity factor ( $R$ ), defined as the product of the total kinetic energy of rainfall ( $E$ ) and the maximum 30-minute intensity ( $I_{30}$ ) as per Renard et al. (1991), presents calculation challenges in the considered study area due to the lack of data on kinetic energy and precipitation intensity. To overcome this constraint, the precipitation

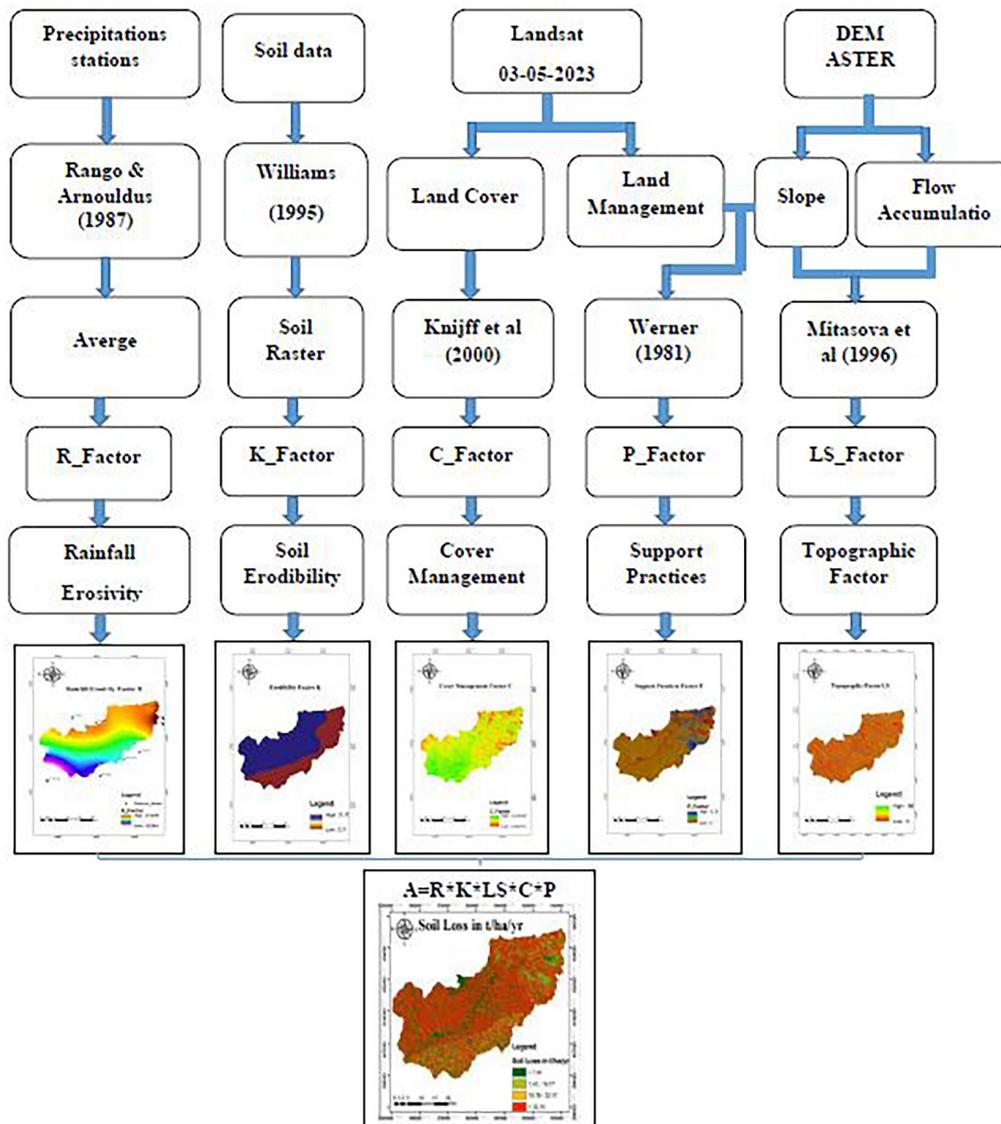


Figure 2. Schematic illustration of methods

data over 30 years (1992–2022) were collected from ten weather stations. The data gaps in rainfall for all stations were addressed by employing the nearest-neighbor interpolation method.

The rainfall erosivity variable (Figure 3b) was calculated for each station based on monthly and annual precipitation data, following Equation 2 developed by Rango and Arnoldus (1980), and the outcomes were determined by applying the inverse distance weighting (IDW) method for interpolation.

$$\text{Log } R = 1.74 \times \text{Log} \sum \left( \frac{P_i^2}{P} \right) + 1.29 \quad (2)$$

where:  $P$  – represents annual precipitation and  $P_i$  represents monthly precipitation in mm.

The values of this factor within the Oued Leben watershed vary from 31.19 to 49.85  $\text{MJ} \cdot \text{mm} \cdot \text{ha}^{-1} \cdot \text{h}^{-1} \cdot \text{yr}^{-1}$ . The minimum values are observed in the southwest region downstream of the watershed, while the maximum values are found upstream, towards the east and northwest. This variation is explained by the higher precipitation to the north, decreasing relatively as one moves south and southwest.

According to Figure 3b, the range of variation for the erosivity factor is relatively low compared to the results reported by Khali Issa et al. (Issa et al., 2014) for the Oued Lkhmis watershed in the

Western Rif, which recorded a minimum value of 87 and a maximum of 113. In contrast, the factor  $R$  varies from 162 to 192 and from 215 to 228, respectively, for Oued Sahla (Central Rif) and the Telata watershed (Sadiki et al., 2009). However, the values found in the present study align with the results obtained by Sadiki et al. (2004) in the Eastern Rif within the Oued Boussouab watershed, where values range from 31.2 to 60  $\text{MJ} \cdot \text{mm} \cdot \text{ha}^{-1} \cdot \text{h}^{-1} \cdot \text{yr}^{-1}$ . Additionally, an average of 50.75  $\text{MJ} \cdot \text{mm} \cdot \text{ha}^{-1} \cdot \text{h}^{-1} \cdot \text{yr}^{-1}$  for Oued Sania (Tahiri, 2014), and 37.89  $\text{MJ} \cdot \text{mm} \cdot \text{ha}^{-1} \cdot \text{h}^{-1} \cdot \text{yr}^{-1}$  for Oued Haricha (Tahiri et al., 2016).

### Soil erodability factor

Erodibility refers to the soil’s susceptibility to erosion and is determined by its composition as well as structure. While texture primarily dictates erodibility ( $K$ ), other factors such as organic matter content, permeability, and soil structure also contribute significantly (Stone and Hilbron, 2000). Williams (1996) proposed Equation 3 to calculate the  $K$  factor.

$$K_{RUSLE} = F C_{sand} \times F c l_{si} \times F O_{rgc} \times F h_{isand} \quad (3)$$

where:  $K_{RUSLE}$  – represents the erodibility factor;  $O_{rgc}$  – the percentage of organic carbon;  $C_{sand}$  – percentage of coarse sand;  $Cl_{si}$

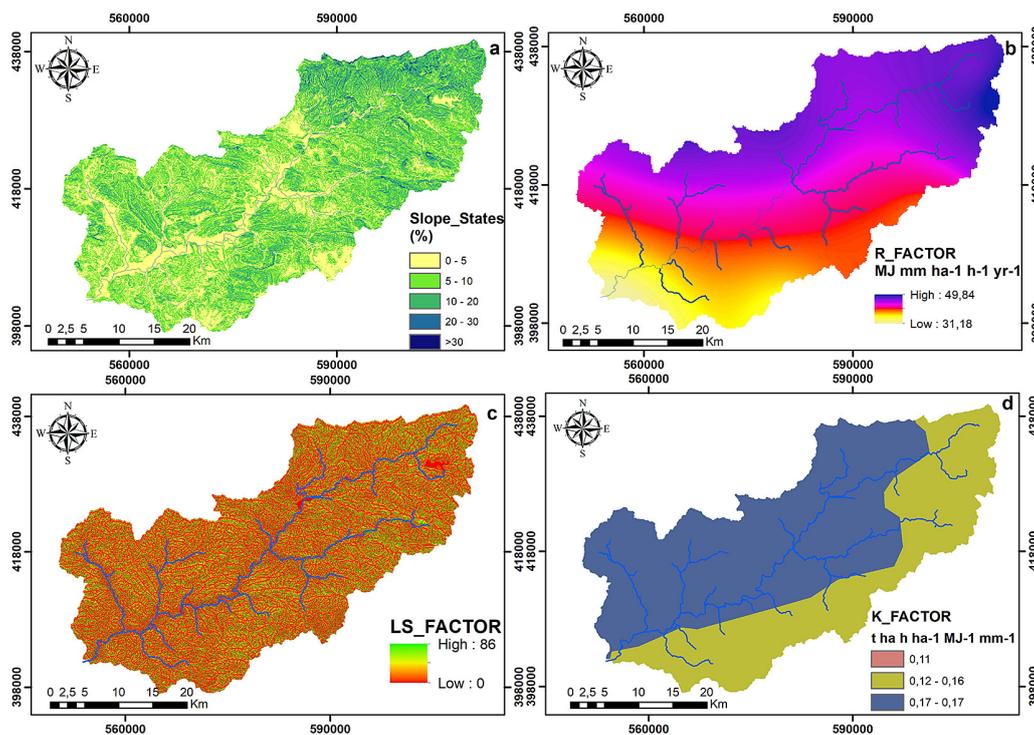


Figure 3. Slope class (a), R factor (b), LS factor (c), and K factor (d) of the Oued Lebene watershed

–percentage of clay and silt; *hisand* – percentage of sand.

The computation of the parameters in Equation 3 relies on the proportions of sand, clay, and carbon present in the soil layer. This analysis indicated that the K factor ranges from 0.11 to 0.17 t·ha·h·ha<sup>-1</sup>·MJ<sup>-1</sup>·mm<sup>-1</sup>. The distribution map shows that the study area exhibits moderate vulnerability to erosion, with 3.5% of the area having low erodibility (Table 2) and (Figure 3d).

### Topographic factor

The topographic factor (LS factor) depicts how the landscape affects soil erosion, calculated by considering both slope length (L) and slope steepness (S) within a given grid cell. Slope length (L) represents the distance from where runoff originates to where sediment deposition initiates or where runoff enters a defined channel within the drainage network. Several Equations are available to determine this factor using the digital terrain model (with a 30 m resolution), including the formulations proposed by Wischmeier and Smith. The majority of current research on water erosion using the RUSLE model commonly employs the formula established by Mitasova et al. (1996). This Equation 4 relies on parameters such as slope gradient, flow direction, and flow accumulation. It is mathematically represented as follows:

$$LS = (Flow\ accumulation \times Cell\ size / 22.13)^{0.4} \times (Sin\ slope / 0.0896)^{1.3} \quad (4)$$

The integrated map indicates that the LS values vary between 0 and 86 (Figure 3c). These values align perfectly with those recorded in the Oued Sahla watershed, which range from 0.48 to 87.9 (Sadiki et al., 2004) However, they are relatively high compared to the results found by Khali Issa et al. (2014) in the western Rif region, in the Oued Lkhmiss watershed, where the values range from 5 to 55.

### Cover factor

Cover factor (C) delineates the soil loss rate under defined conditions in contrast to the rates observed for continuous fallow and plowed lands (Wischmeier and Smith 1978). Factor C portrays the influence of agricultural practices on erosion. It signifies the extent of soil exposure to rainfall. Elevated C values signify sparse vegetative cover, contributing to increased erosion rates during rainfall, whereas low C values indicate substantial vegetative cover, which reduces erosion rates.

In this study, the vegetation cover intensity factor map was developed from a Landsat-8 image taken on 03/05/2023 using a GIS environment, followed by meticulous ground verification. The Landsat-8 image was subjected to NDVI index calculation to estimate the C factor values. Furthermore, the C factor value is computed for the current study according to De Jong’s Equation 5 (De Jong, 1994).

$$C = 0.431 - 0.805 \times NDVI \quad (5)$$

The map obtained according to Equation 5 (Figure 4b) shows that the southeastern part, representing the downstream of the studied watershed, records the highest values, indicating alarming susceptibility to erosion. This is explained by the continuous agricultural land and intensive human activities in this area. The combination of altitude, precipitation, and the presence of forested areas has contributed to the protection of the upstream part, the eastern and northern slopes, with values recorded below 0.2.

### Conservation practice factor

The support practice factor indicates the proportion of soil erosion observed with a particular support method relative to the erosion occurring with uphill and downhill slope cultivation (Wischmeier and Smith, 1978). This factor takes into account the erosion control methods used at the study site, which mitigate the erosive effects of precipitation and runoff by altering drainage networks (Kim, 2006). Due to

**Table 2.** Soil type (FAO classification) and K\_ Value of the Oued Lebene watershed

FAO soil code	Soil type	Area (ha)	K value
Kk11-3b	Calcic_Kastamozens	85123.17	0.17
Kk13-3b	Calcic_Vertisols	48.96	0.16
Bk16-2b	Calcic_Combisols	53593.47	0.11

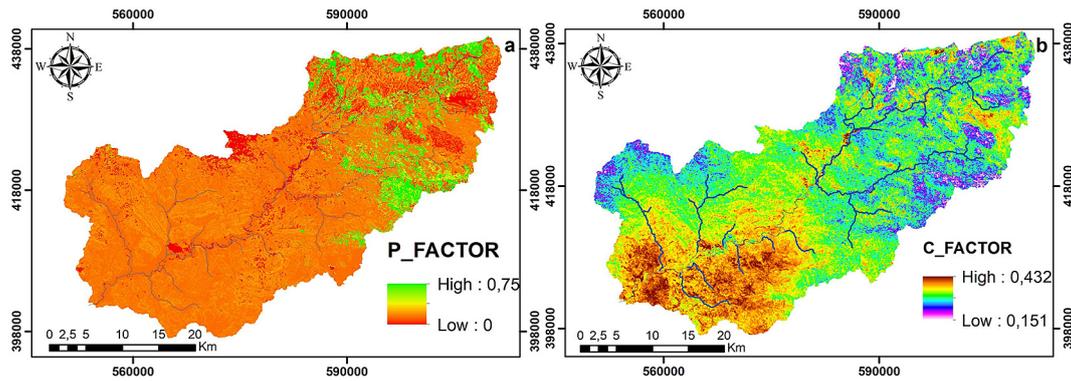


Figure 4. P factor (a) and C factor (b) of the Oued Lebene watershed

Table 3. Slope class (FAO classification) of the Oued Lebene watershed

Slope class %		Designation	Area (ha)	Area (%)
0–5		Flat	48634.85	35.23
5–10		Gently sloping	48750.17	35.31
10–20		Sloping	38154.64	27.64
20–30		Strongly sloping	2380.41	1.72
>30	30–50	Steep	142.00	0.10
	50–100			

limited information on management practices, the conservation practice factor (P) was established through combinations of data related to land use and slope, a commonly employed method applicable to terrains with diverse slope conditions (Bewket and Teferi, 2009).

To determine the value, the watershed was divided into five land use categories: agriculture, forests, bare land, grazing lands, and water bodies. Moreover, each land use category was subdivided based on slope classifications (refer to Table 3, Figure 3a), considering the connection between management practices and slope. Layers of land use and watershed slope were superimposed in ArcGIS to generate a layer for each land use category with distinct slope classifications, and the P factor was allocated to each corresponding slope classification (Bewket and Teferi 2009) using Werner’s Equation 6 (Werner, 1981).

$$P = 0.2 + 0.03 \times S \quad (6)$$

The analysis of Table 4 and Figure 4a reveals that the P value varies from 0 to 0.75. Indeed, 62.09% of the watershed area is occupied by croplands with slopes less than 10%, which explains the dominance of the P class below 0.14. The highest values are found in the areas with badlands combined with short and steep slopes.

A value of 0 is assigned to water bodies and buildings where erosion is absent.

#### Sediment delivery ration

Various techniques to calculate soil erosion exist, such as sediment deposition assessments, sediment rating curves, and empirical approaches. Not all eroded soil during rainfall is carried to the watershed channels and outlets. Sediment delivery ration (SDR) represents the proportion of sediment transported to the watershed outlet compared to the total soil erosion within the watershed (Maidment, 1993). Sediment production models are frequently developed using empirical methods, with SDR being a common concept employed in such models (Verstraeten and Poesen, 2002). It evaluates the efficiency of sediment transfer, taking into account the volume of sediment transported from erosion sites to drainage channels and the outlet, relative to the total soil detached and eroded above the channels or outlet.

Topographic features play a role in the SDR of watersheds, where regions with short and steep slopes tend to produce more sediment than those with longer and gentler slopes. In this study, SDR was calculated based on the slopes of the

**Table 4.** Land use, slope, and p value of the Oued Lebene watershed

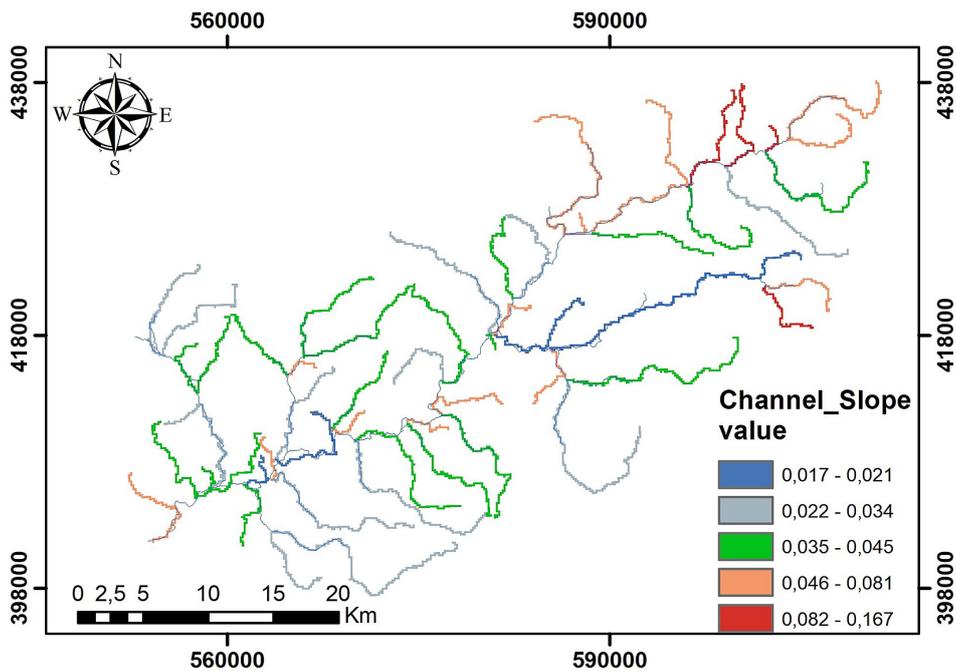
Land use class	Slope (%)	P factor	Area (ha)	Area (%)
Agricultural land	0–5	0.10	40399.40	29.09
Agricultural land	5–10	0.12	45828.65	33.00
Agricultural land	10–20	0.14	20218.73	14.56
Agricultural land	20–30	0.17	828.51	0.60
Agricultural land	30–50	0.25	28.47	0.02
Agricultural land	50–100	0.70	0.10	0.00
Forest	0–5	0.03	2254.41	1.62
Forest	5–10	0.05	2898.10	2.09
Forest	10–20	0.10	7887.55	5.68
Forest	20–30	0.20	1271.66	0.92
Forest	30–50	0.00	100.36	0.07
Forest	50–100	0.60	1.44	0.00
Bad land	0–5	0.25	2177.91	1.57
Bad land	5–10	0.35	4814.60	3.47
Bad land	10–20	0.45	4845.76	3.49
Bad land	20–30	0.55	594.90	0.43
Bad land	30–50	0.75	41.22	0.03
Urban land	0–100	0.00	2350.07	1.69
Water	0–100	0.00	2324.96	1.67

watershed channels using a specific Equation (Gebrehiwot et al., 2014).

$$SDR = 0.627 \times SLP^{0.403} \quad (7)$$

where: *SLP* – represents the slope of the drainage channels in percentage.

Evaluating SDR based on the slopes of drainage channels yields the results that closely approximate reality in watersheds where sediment data are insufficient. The gradient of the drainage network channels was derived from the digital elevation model through the



**Figure 5.** Channel slope map of the Oued Lebene watershed

utilization of the Arc Hydro tool (Figure 5). After analyzing the terrain and watershed using DEM, the average gradient of each cell along the stream paths was calculated. When computing SDR, each cell along the flow path is considered the outlet of its respective upstream watershed. The slope values within the watershed channels range from 0.017 to 0.167.

*Sediment yield*

Sediment yield, labeled as sediment yield (SY), indicates the amount of sediment carried to the watershed outlet, whether through channels or sediment basins. It represents the sediment load adjusted for the drainage area and indicates the balance between erosion and deposition processes within the watershed. In watersheds without well-documented sediment data, sediment yield is typically challenging to directly measure. Precisely assessing the relationship between SDR and soil loss within the ArcGIS framework is a crucial and effective method for predicting sediment yield (Mutua and Klik, 2006). In this study, sediment yield is determined by overlaying layers of soil loss and SDR within the watershed using a specific formula Equation 8 as depicted in Figure 6.

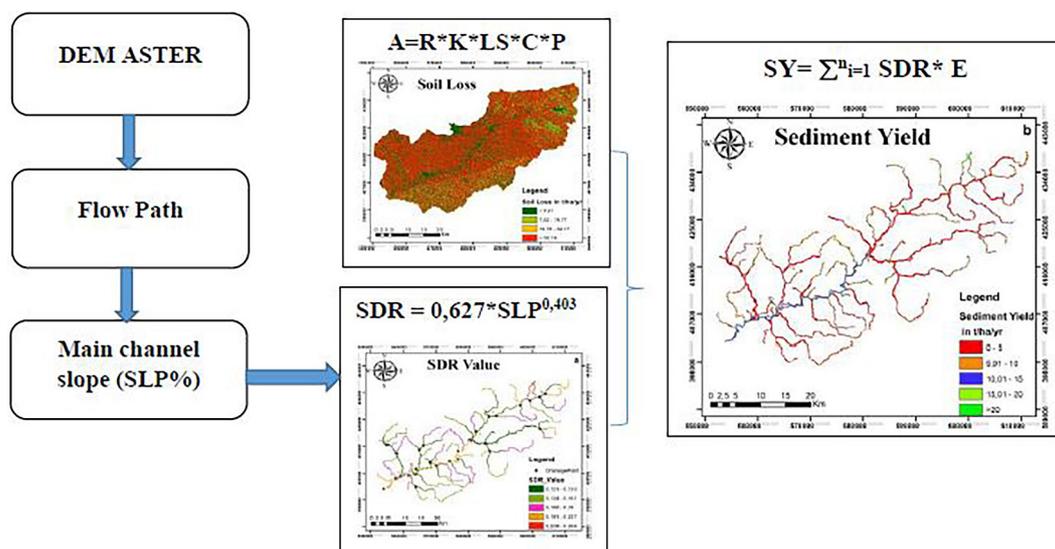
$$SY = \sum_{I=1}^n SDR \times E \quad (8)$$

where: *SDR* – represents the sediment delivery ratio, *SY*– the sediment yield, *E*– the soil loss.

**RESULTS**

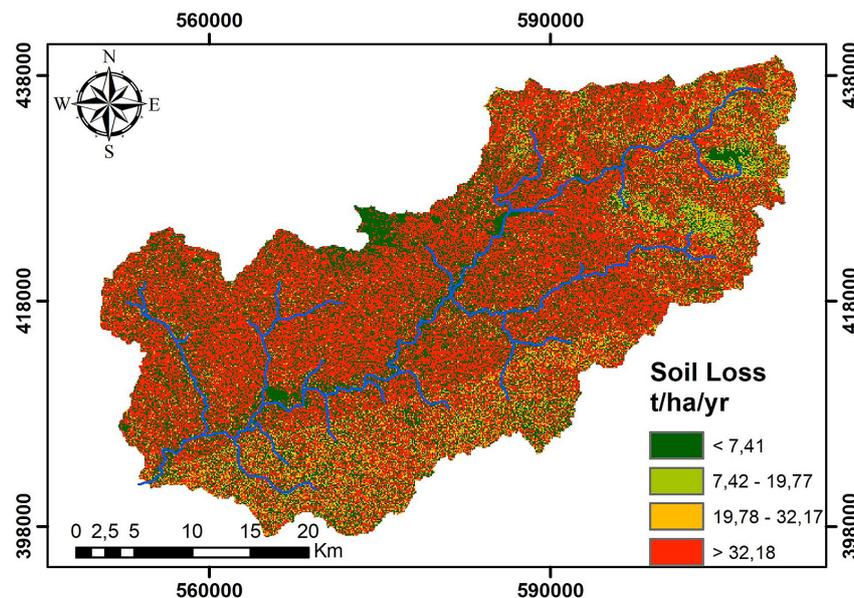
**Soil loss**

To map and quantify water erosion in the Oued Leben watershed, the key factors influencing this process were intersected and multiplied within the ArcGIS 10.3.1 environment, and the soil loss rate was computed using Equation 1. Annual soil loss varies from 0 to 752 t·ha<sup>-1</sup>·yr<sup>-1</sup>, with an average annual soil loss rate of approximately 46.17 t·ha<sup>-1</sup>·yr<sup>-1</sup>. However, according to the Wischmeier classification, the watershed was divided into four erosion risk classes: slight (<7.41), moderate (7.41–19.77), very high (19.77–32.17), and extremely severe (>32.17) t·ha<sup>-1</sup>·yr<sup>-1</sup> (Table 5 and Figure 7). The class of extreme severity encompasses 52.25% of the entire watershed area, accounting for 90.67% of sediment production with an average of 80.11 t/ha/yr, indicating a high degree of erosion exceeding Wischmeier’s tolerance threshold. In contrast, 34.82% represents 48 108 hectares of the study area below the tolerance threshold (<7.41 t·ha<sup>-1</sup>·yr<sup>-1</sup>). The other erosion risk classes of moderate and very high account for 2.73% and 10.19% of the total watershed area, producing 0.80% and 5.73% of the sediments, respectively. The annual soil loss totaled 6,379,314 tons per year. The results indicate that the highest values come from the areas characterized by the presence of bare land combined with very steep and short slopes, primarily located in the upstream part and at the first water collection point, which is the source of



**Table 5.** Erosion risk class and soil loss of the Oued Lebene watershed

Soil loss (t·ha <sup>-1</sup> ·yr <sup>-1</sup> )	Erosion risk class	Area (ha)	Area (%)	Soil loss (t·yr <sup>-1</sup> )	Soil loss (%)
<7.41	Slight erosion	48108.00	34.82	178240	2.79
7.41–19.77	Moderate erosion	3776.00	2.73	51316	0.80
19.77–32.17	Severe erosion	14084.00	10.19	365761	5.73
>32.17	Very severe erosion	72199.00	52.25	5783997	90.67
		138167.00	100.00	6379314	100.00



**Figure 7.** Soil loss of the Oued Leben watershed (Wischmeier classification)

the main river. These conditions are also found in the middle part of the west-facing watershed, where anthropogenic activity is intense, primarily due to intensive farming practices combined with poor land management (Figure 7). Classifying erosion risk according to the Wischmeier tolerance threshold will help prioritize areas for conservation and rehabilitation measures.

### Sediment delivery ratio

The calculated SDR value according to Equation 7 implies the ability of sediments to be delivered to a deposition location or outlet. The results obtained have shown that the SDR value in the Oued Leben watershed varies within a range of 0.121 to 0.306 with an average of 0.17. These results indicate that 17% of particles and soil materials originating from upstream erosion will pass through the drainage networks.

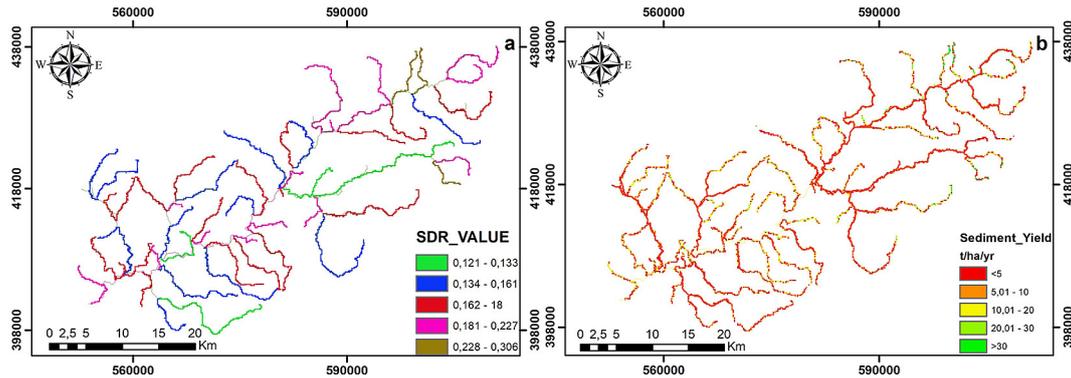
Analysis of Figure 8a reveals that this value is positively correlated with the slope of the

watercourses. The SDR class (0.228–0.306), representing only 21.75% of the drainage channel surface, is found in the areas where the watercourse slope is very steep, with a significant sediment delivery capacity. The SDR classes (0.134–0.161), (0.162–0.18), and (0.181–0.227) cover over 43% of the sediment transport surface, accounting for 21.80%, 13.12%, and 8.46%, respectively. The lowest SDR values cover 34.87% of the total area, with a sediment transfer capacity below 13.3% (Table 6).

The SDR approach indicates that, on average, 17% of eroded soil particles can be transported through the drainage channels, and exported downstream at the outlet of the Oued Leben watershed. A significant amount of sediment, approximately 83%, remains trapped and will be deposited outside the drainage channels. In light of these figures, this issue, resulting in significant nutrient and soil loss, will affect agricultural lands covering more than 70% of the total watershed area.

**Table 6.** Channel SDR value of the Oued Lebene watershed

SDR value	Average	Area (ha)	Area (%)
0.121–0.133	0.127	15835.2	34.87
0.134–0.161	0.148	9902.08	21.80
0.162–0.18	0.171	5959.68	13.12
0.181–0.227	0.204	3840	8.46
0.228–0.306	0.267	9877.44	21.75
		45414.4	100.00



**Figure 8.** SDR value (a) and sediment yield (b) of the Oued Lebene watershed

**Sediment yield**

The sediment yield results from the intersection of the raster layer of soil loss and SDR according to Equation 8. This factor ranges from 0 to 163 t·ha<sup>-1</sup>·yr<sup>-1</sup> in the Oued Leben watershed, with an average value of 7.71 t·ha<sup>-1</sup>·yr<sup>-1</sup>. This contributes to a total quantification of 1 083 589.92 t·yr<sup>-1</sup> as the overall sediment yield at the watershed scale.

The spatial distribution of these results (Figure 8b) shows that the sediment yield distribution pattern is similar to that of SDR. The severe sediment yield class represents 21.75% of the drainage surface, contributing to 770,440.32 t·yr<sup>-1</sup> with an average of 78 t·ha<sup>-1</sup>·yr<sup>-1</sup>, considered very high, and leading to

alarming degradation of water and soil resources. The severe, high, and moderate sediment classes cover 8.46%, 13.12%, and 21.80%, and their sediment yields are approximately 124 800, 74 496, and 74 265.6 t·yr<sup>-1</sup>, respectively. The lowest sediment yield rate is associated with the low class, which represents the largest drainage area, over 34% (Table 7).

In this context, considering the total estimated soil loss of 6,379,315 t·yr<sup>-1</sup> across the entire Oued Leben watershed, with a total area of 138 621.32 hectares, the transport of sediment load through drainage networks and their deposition along these channels and at the watershed outlet affects only 1 083 589.92 t·yr<sup>-1</sup>. However, this quantity of sediment will not entirely make its way out of the watershed area, and a significant amount remains

**Table 7.** Channel sediment delivered (class and area) of the Oued Lebene watershed

SY (t·ha <sup>-1</sup> ·yr <sup>-1</sup> )	SY class	Area (ha)	Area (%)	SY (t·yr <sup>-1</sup> )
0–5	Low	15835.2	34.87	39588
5–10	Moderate	9902.08	21.80	74265.6
10–15	High	5959.68	13.12	74496
15–20	Very high	3840	8.46	124800
>20	Severe	9877.44	21.75	770440.32
		45414.4	100	1083589.92

trapped in the drainage channels and their surroundings. This is explained by the length of the main watercourse, which is estimated to be 67.39 km. The sediment yield at the Oued Leben outlet, as defined in Equation 8, is the result of multiplying the total soil loss value and the SDR value at its location, resulting in  $765\,517.8\text{ t}\cdot\text{yr}^{-1}$  of sediment that will be delivered to the exit point.

## DISCUSSION

Predicting the hazard of water erosion is a fundamental issue for the development of effective preventive action plans. Water erosion risk is strongly linked to both natural and anthropogenic factors. Several methods and approaches have been developed to estimate the danger of water erosion and its causal factors. The revised universal soil loss equation is the most widely used model worldwide, demonstrating its effectiveness and reliability in soil loss estimation (Swarnkar et al., 2018; Maqsoom et al., 2020; Ullah et al., 2018). Estimating soil erosion by this model depends on the availability of data, which is a barrier for African countries (Fenta et al., 2020; Farhan and Nawaiseh, 2015; Swarnkar et al., 2018; Asmamaw and Yosef, 2015). Morocco, like the Mediterranean region, is exposed to torrential rainfall (Saidi et al., 2010; Clément, 2002; Rifai, Khattabi, and Rhazi, 2014; Hssaine, 2014; El Haj, et al., 2023), combined with a topography characterized by steep slopes, improper land practices, and degrading vegetation cover, increasing the region's vulnerability to soil erosion hazards (Kusi et al., 2023; 2021; Chebli et al., 2018; Maanan et al., 2019). Using RUSLE requires data availability in terms of precipitation, soil type, topography, vegetation cover, and land management practices according to Equation 1 (Sadiki et al., 2004; 2009; HCEFLCD 2014; Kanito et al., 2023; Tsegaye and Bharti 2021; Vanmaercke et al., 2014).

The Oued Leben watershed, located between the Prerif hills and the high Rif mountains (Gartet and Gartet, 2005), with an average elevation of 924 m, receives an average precipitation of 524.72 mm, providing an erosive factor ranging from 31.18 to 49.84 MJ mm ha<sup>-1</sup> h<sup>-1</sup> yr<sup>-1</sup>. The undulating topography, with slopes ranging from 0 to 71.11%, generates a range of LS values from 0 to 86. The Oued Leben watershed is predominantly occupied by croplands (Table 4), with some enclaves of natural forests and reforestation with

Aleppo pine as well as carob trees. This results in average factor C values ranging from 0.151 to 0.432 and a factor P related to land management practices ranging from 0 to 0.75. According to Figure 3b, the rainfall erosivity factor varies from 31.18 to 49.84 MJ·mm·ha<sup>-1</sup>·h<sup>-1</sup>·yr<sup>-1</sup>, with the highest values recorded in the upper upstream part of the watershed and the northwest part. These values gradually decrease downstream and from west to east. The lowest values are located downstream and in the southern part. These results fall within the range of variation found by Sadiki et al. (2004), and Tahiri et al. (2014). These values are lower than those found by Lahlaoui et al. (2015), Sadiki et al. (2009), and Khali Issa et al. (2014). The soil erodibility factor is obtained from the processing of the soil map (FAO Digital Soil Map of the World, DSMW). The values of factor K range from 0.11 to 0.17 t·h·ha·ha<sup>-1</sup>·MJ<sup>-1</sup>·mm<sup>-1</sup> (Figure 3d), indicating low to moderate fragility compared to other watersheds. Indeed, according to (Sadiki et al., 2004; Zouagui et al., 2018; Yjjou et al., 2014; Ouallali et al., 2016), the values of this factor range from 0 to 0.5, 0.15 to 0.35, 0.1 to 0.44, and 0.23 to 0.34 t·h·ha·ha<sup>-1</sup>·MJ<sup>-1</sup>·mm<sup>-1</sup>, respectively, for the Oum Errabia, Oued Boussaouab, Moulay Bouchta, and Oued Arbaa Ayacha watersheds. The topographic variation in the study area, reflected by the variation in slope and slope length, produces LS values ranging from 0 to 86 (Figure 3c). The high LS values correspond to the steepest slopes located upstream, in the southeast, and in the eastern part of the watershed. Lower values are recorded along the watercourse, which coincides with the slope class of less than 5%.

Factor C varies from 0.151 to 0.432, with the highest value found in cropland areas and the lowest values in natural forests. As for the land management practices factor, the highest value is observed in badlands, while a value of 0 is assigned to water bodies.

The average soil losses in the Oued Leben watershed range from 0 in flat slope areas (approximately 47 915 ha) to 752 t·ha·yr in steep slope areas. The average annual soil loss rate is approximately 46.17 t·ha·yr. The total soil losses caused by water erosion across the entire watershed amount to 6 379 314 t·ha·yr. This figure is governed by the interaction of various factors involved in the erosion process. Indeed, the extremely severe erosion class covers 52% of the watershed's area and is responsible for over 90% of sediment production, primarily related to the slope length factor. Soil

**Table 8.** Soil loss estimation of different watersheds in Morocco

Study area	R	K	LS	P	C	A
Oued el Mellah	62.59–104.63	0.07–0.39	1.5–4.5	0.5–1	0.05–1	8.21
Oued Sahla	153–185	0.38–0.60	0.48–87.9	1	0.1–1	22.01
Oued Boussouab	31.2–60	0.021–0.6	0.48–87.9	1	0.058–1	55.35
Tahhadart	39.21	0.22–0.31	0.5–55	1	0.22–0.33	202.34
Oued Haricha	37.89	0.12–0.40	0–40	1	0–0.70	62.72
Moulay Bouchta	63–76	0.23–0.34	0–116	0.4–1	0.39	39.5
Oum Er–Rabia	90–119	0.01–0.54	0–216	1	0–1	224

loss follows a spatial distribution consistent with that of the LS factor, except for irregularities in the southeastern and central parts of the watershed. It can be concluded that this factor plays a decisive role in erosion control.

Soil losses are influenced by the rainfall erosivity factor, which increases linearly upstream and shows remarkable irregularities in the rest of the watershed. This suggests that it is a determining factor in the erosion process, albeit to a somewhat lesser degree than LS. On the other hand, vegetation cover and land management practices have a less significant linear influence on soil losses. This is explained by changes in land use driven by human activities, leading to deforestation and alarming degradation of natural resources. These results are compared with studies conducted in northern Morocco in the Rif region, where precipitation, lithological conditions, topography, and land use are similar to that in the considered study area. The resulting model estimate falls within the range of study results shown in Table 8.

The sediment delivery capacity in the Oued Leben watershed is approximately 17%, which is lower than in many previous studies. For example, El Garouani et al. (2008) employed a sedimentation model utilizing the Revised Universal Soil Loss Equation and the spatial variability of the terrain to ascertain the soil transportation to the outlet of the Telata watershed, yielding an estimated value of 50%. El Gaatib and Erraji (2014) investigated the Oued and Beht watershed using the USLE model, combining precipitation and flow data. They estimated that 65% of the sediment load was transported to the Kansara dam (Sabri et al. 2016). Additionally, in the Adour, Sebou, and Souss watersheds, the SDR values are 20.93%, 46.45%, and 77.05%, respectively (Snoussi, Jouanneau, et Latouche 1990). The sediment delivery capacity in the Oued Leben watershed remains low in comparison to the mentioned

studies, even though the topographic conditions are more or less similar in terms of slope gradient.

## CONCLUSIONS

The watershed of Oued Leben, located on the southern slope of the pre-Rif region, is predominantly agricultural, covering over 70% of the total area. Climatic, topographic, satellite imagery, and 30 m resolution DEM data were organized and analyzed using ArcGIS 10.3.2 to estimate soil losses, sediment delivery capacity, and sediment yield within the study area. The RUSLE model estimated a soil loss rate of  $46.17 \text{ t}\cdot\text{ha}\cdot\text{yr}^{-1}$  with an annual loss of  $6\,379\,314 \text{ t}\cdot\text{yr}$ . Sediment yield for the study sector is calculated by multiplying the annual soil loss by the sediment delivery ratio, which is determined based on the average slope of the drainage channels.

The results reveal that 52.25% of the total area of the Oued Leben watershed is susceptible to very severe erosion, contributing to 90.67% of sediment production with an average of  $80.11 \text{ t/ha/yr}$ . This is due to a combination of factors affecting the process of water erosion, such as the steep and short slopes in the upstream area, low vegetation cover density, inappropriate farming practices, and overgrazing. Furthermore, the sediment delivery ratio for the entire watershed is 0.17, indicating that 17% of the eroded materials are transported by the drainage channels to the outlet.

In light of these results, out of the  $6\,379\,314 \text{ t}\cdot\text{yr}$  of eroded materials, only  $770\,440.32 \text{ t}\cdot\text{yr}$  reach the watershed's outlet in terms of sediment yield. In general, the RUSLE and SDR models in a GIS environment are effective methods for mapping, assessing, and predicting soil losses, sediment delivery capacity, and sediment yield to identify erosion-sensitive areas and

design conservation measures that take into account the sustainability of soil and water resources.

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