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ASSESSING SOIL EROSION AND RUNOFF DYNAMICS IN THE EL-MAKHAZINE WATERSHED: A COMPREHENSIVE ANALYSIS WITH THE IntErO ALGORITHM

SUMMARY

In recent years, Morocco has been identified as one of the most sensitive areas to the negative consequences of climate change. Extended droughts, interspersed by significant rainfall events, result in extreme phenomena such as floods and intense rainfall. This is particularly evident in northern Morocco's Rif region, known for its high susceptibility to surface runoff and soil erosion. Watershed management has emerged as one of the most successful techniques for reducing erosion and conserving water and soil resources. The current work aims to demonstrate the efficacy of hydrological modeling of watersheds as a necessary step before implementing any anti-erosion interventions. The integrated potential erosion method (EPM) within the IntErO (Intensity of Erosion and Outflow) algorithm is one of the most effective approaches. Still, it has been underutilized in Morocco for modelling the impact of surface runoff and calculating erosion rates and sediment yield on hydraulic infrastructures. The algorithm was tested in the El Makhazine watershed, which includes one of Morocco's largest dams that provides over 300 million cubic meters of potable water and irrigates more than 34,000 hectares of agricultural land. The watershed is highly sensitive to erosion due to its geological formations, soil types, slopes, and land use, resulting in an average loss of 1870.06 $m^3/km^2/year$ (equivalent to 29.4 t ha^{-1} $year^{-1}$). IntErO assigns the studied area to category III in terms of destruction and deterioration, with a Z coefficient of 0.631. Surface erosion is the most common type of erosion in the watershed, ranging into category II according to Gavrilovic's classification and

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mobilizing large volumes of sediment toward the downstream dam. This study highlights the effectiveness of IntErO, based on the EPM model, for rapidly and efficiently mapping and quantifying water erosion. It can be utilized by decision-makers and land planners for effective management interventions related to water and soil resources in the El Makhazine watershed.

Keywords: Runoff dynamics, hydrological modelling, Soil erosion, IntErO Algorithm, North Morocco.

INTRODUCTION

The erosion phenomenon is a significant issue in environmental policies and has become a major natural hazard due to its direct and indirect effects, both on-site and off-site (Ilyas *et al*. 2023; Bammou *et al.* 2024). The physical degradation of soils has numerous consequences, comparable in significance to the phenomenon itself (Molnárová *et al.* 2023; Wang *et al*. 2023). Other issues associated with this include immediate impacts such as mudslides and long-term problems such as reservoir siltation and the transfer of sediments into rivers/coastal areas over time, as well as loss of fertile land and subsequent effects on agriculture (Xue *et al*. 2022; Bakshi *et al.* 2023; Ouallali *et al*. 2024). Consequently, priority intervention should focus on high-erosion areas if erosion rates are expected to decrease using new methods. To this end, mapping soil vulnerability at a regional scale and predicting erosion is essential for designing appropriate conservation strategies.

GIS and remote sensing technologies have been utilized more and more in the past few decades to research surface phenomena such as erosion (Senanayake *et al.* 2020; Meliho *et al.* 2020). These technologies are combined with physical and empirical soil loss models to create a spatial representation of the phenomenon over enormous areas. Like other Mediterranean countries, Morocco's soils have experienced decades of permanent loss and degradation (Benmansour *et al*. 2013; El Jazouli *et al.* 2016) as a result of rising demands from human activities, mainly agriculture, with erosion rates surpassing limits and the soil's potential for pedogenesis being reduced (Raissouni *et al.* 2016; Ouallali *et al*. 2023). According to FAO research from 1990, 40% of Moroccan fields have been affected by erosion, with the Rif region incurring the most, sometimes at rates surpassing 60 t/ha/year (Swearingen & Benche, 2019; Bouayad *et al.* 2023). Therefore, runoff and soil erosion are natural occurrences that have significant impacts on ecosystem sustainability, soil productivity, and landscape dynamics. Extreme weather and intensive farming methods aggravate these processes in mountainous areas such as the Moroccan Rif (Chaachouay & Zidane2024; El Amarty *et al*. 2024), resulting in the loss of arable soils and sedimentation in rivers and reservoirs.

Numerous studies have been conducted using various tools and hydrological models to assess runoff and erosion in different watersheds worldwide. The Erosion Potential Method (EPM), developed by Gavrilović, has shown to be especially successful among these models (Spalevic *et al.* 2021; Dragičević *et al.* 2018). The EPM is an empirical method for estimating soil loss and sediment production that incorporates variables such as geology, soil type, slope, vegetation cover, and precipitation (Ebadati *et al.* 2022; Bezak *et al.* 2024). This technique has been effectively used to assess erosion and forecast the effects of soil management techniques in various geographic and climatic scenarios.

However, within the context of Moroccan watersheds, the particular application of the IntErO model (Intensity of Erosion and Outflow, https://www.geasci.org/IntErO), which integrates the EPM method to assist its implementation, remains little applicable (Sabri *et al*. 2022; Ouallali *et al.* 2024). When evaluating erosion and runoff intensity, the IntErO model provides an adaptable and integrated method that considers regional characteristics including environment, vegetation cover, and land use practices (Kumar *et al*. 2022; Sestras *et al*. 2023).

To enhance natural resource management in this vulnerable area, a thorough understanding of how this model can be modified and implemented in the specific Moroccan Rif conditions is necessary. This study aims to gain a deeper understanding of the erosion phenomenon in the Rif region, specifically in the Makhazine basin, at the watershed scale from an integrated risk and watershed management perspective. This watershed's geomorphological characteristics and the amount of precipitation in the area make it especially susceptible to these events. By incorporating the IntErO algorithm into a GIS platform, the goal is to map water erosion using a multi-criteria analysis, evaluating the area's susceptibility to erosion and calculating annual losses per unit area. This approach will provide essential data for informed risk management and decision-making regarding the preservation of natural resources.

The primary goals of this research are to identify how the IntErO model can effectively estimate soil erosion and runoff in the Makhazine watershed; afterwards, to adapt the IntErO model to the local conditions in the Makhazine basin; but also, to use the IntErO model to estimate erosion and runoff rates and finally to validate the predictions by comparing the results to field observations and other existing models.

The use of IntErO as a methodological model over alternative erosion assessment models is justified for various reasons. First, IntErO incorporates the EPM approach, which is recognized for its simplicity and efficiency in different geographic contexts. This integration enables quick and relatively accurate prediction of erosion rates, even in areas with insufficient data. Second, the IntErO model is adaptable to specific local conditions, which are crucial for accurate assessment in areas such as the Moroccan Rif, which has substantial geographical and climatic differences (Ouallali *et al.* 2016; El Brahimi *et al.* 2024). Finally, IntErO has an easy-to-use interface and moderate data needs, making it suitable for watershed managers and researchers. This research has implications for protecting water and soil resources in the context of climate change.

Climate change accelerates erosion and runoff, increasing the likelihood of soil degradation and land fertility loss. Reservoir sedimentation limits storage capacity, affecting the durability of dams, which play a crucial role in water resource management. A reliable assessment of erosion and runoff in the Makhazine watershed will enable the development of management solutions that reduce these consequences while preserving major hydraulic infrastructure.

MATERIAL AND METHODS

Description of study area. This study focused on the Oued El Makhazine watershed in Morocco's Rif region. This watershed was chosen for its high sensitivity to erosion, data availability, and ecological importance. The landscape in this watershed is characterized by steep slopes, fragile lithologies mainly formed of marl and clay, and a deteriorating vegetation cover. The watershed features a downstream dam that supplies 800 million cubic meters of water to nearby cities, as well as 20 million cubic meters of potable and industrial water, and irrigation for 340 km² of agricultural land in the Loukkos region. The watershed was delineated using topographic data from topographic maps, digital elevation models (DEM), and Geographic Information Systems (GIS). This method enabled the estimation of major geomorphological characteristics, including area (A), length of the main watercourse (O), and average watershed slope (Isr) (Figure 1).

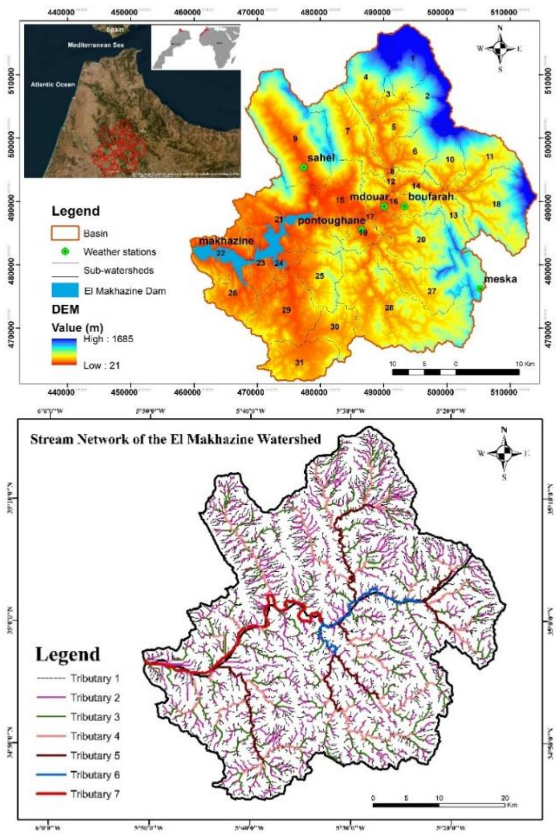

Figure 1. Location of the Watershed, Digital Terrain Model, and Stream Network

Implementation of the IntErO model. The IntErO model, designed to quantify erosion and runoff intensity, largely depends on Gavrilović's Erosion Potential Method (EPM). The EPM, first presented in 1972, is an empirical approach for estimating soil loss caused by erosion and sediment generation, considering geology, soil, slope, vegetation cover, and precipitation. Gavrilović (1988) found that this approach is advantageous in unstudied regions or torrential rivers where accurate data is limited. Integrating EPM into the IntErO model simplified its application while also enhancing the precision of predictions. The IntErO model utilizes EPM concepts to calculate erosion and runoff intensity, taking into account the unique characteristics of specific watersheds. This combination offers a robust and adaptable approach that can respond to local variations in environmental and human factors.

Compared to other models such as the Universal Soil Loss Equation (USLE), Revised Universal Soil Loss Equation (RUSLE), Soil and Water Assessment Tool (SWAT), and Water Erosion Prediction Project (WEPP), the IntErO model provides several significant advantages. While USLE and RUSLE are easy to use and commonly employed, they are largely empirical, focusing on sheet erosion rather than temporal changes. SWAT and WEPP models, on the other hand, provide process-based modeling with high accuracy but are frequently complex and require comprehensive data that is difficult to collect. The IntErO model, which incorporates the EPM approach, provides an intermediate solution that combines simplicity with the capacity to adapt to specific local conditions. This property makes it suitable for studies in areas with limited data, such as the Makhazine watershed, while still allowing for reliable and useful projections for sustainable natural resource management.

Data preparation. The geomorphological data has been obtained using a Digital Elevation Model (DEM) with a 12-meter resolution. The main parameters calculated are Watershed Area (A), measured in km², the length of the main watercourse (O) in km, and the average watershed slope (Isr). The average annual precipitation (P) and rainfall intensity data were collected from local meteorological stations over 41 years. This climatic data was used to determine the erosive intensity of rainfall. The soil types observed in the watershed were identified using Belasri et al. (2017) soil map of the El Makhazine watershed, which was produced as part of soil characterization research in the area. Soil erosion susceptibility was estimated using the sediment production factor (Y), which was computed using the Erosion Potential Method (EPM).

The lithological data for the basin were obtained from a 1:50,000 scale geological map (Kornprobst and Durand-Delga, 1985), as presented in Figure 2. The basin covers a wide range of lithologic formations. These data were then reclassified into three categories based on permeability: The river basin's very permeable rock formations (fp), including limestones, sand, and gravel, were estimated to cover 17% of the basin area. Medium-permeable rocks (fpp) made up about 47% of the basin's area. 36% of the basin area was made up of rocks with low water permeability (fo), presented in Table 1.

Table 1. Lithological classes and permeability levels of the formations in the El Makhazine watershed

Lithology	Symbol	Permeability
Marl with limestone microbereccia	Lower Cretaceous	Medium permeability
Marl	Upper- middle Cretaceous	Impermeable
Marl with limestone interbeds	lower Eocene	Medium permeability
Limestone (marl with sandstone beds)	Eocene and Oligocene	Medium permeability
Sandy limestone	Oligo–Miocene	Medium permeability
Shale and sandstone series	Middle Jurassic	Practically impermeable
Blue marls and sands	Middle Miocene	Medium permeability
Blue marls	Upper Miocene	Impermeable
Quaternary formations	Quaternary	Permeable
Red argillaceous conglomerate formations	Villafranchian Quaternary	Medium permeability
Gypsum formations	Trias	Medium permeability

Regarding the preparation of land-use and land-cover data (LULC), this study used data from a recent high-resolution Sentinel-2 satellite image (https://scihub.copernicus.eu/), which allowed for the classification of different LULC types. The assessment of cloud cover above the Oued El Makhazine basin influenced the choice of a suitable satellite image. Based on this criterion, the ideal date for classifying land use is May 16, 2022. An interactive supervised classification approach was employed to create the land cover map for the study area, with zones of interest selected to enhance the accuracy of the results. Figure 2 summarizes the distribution of the various LULCs in the basin.

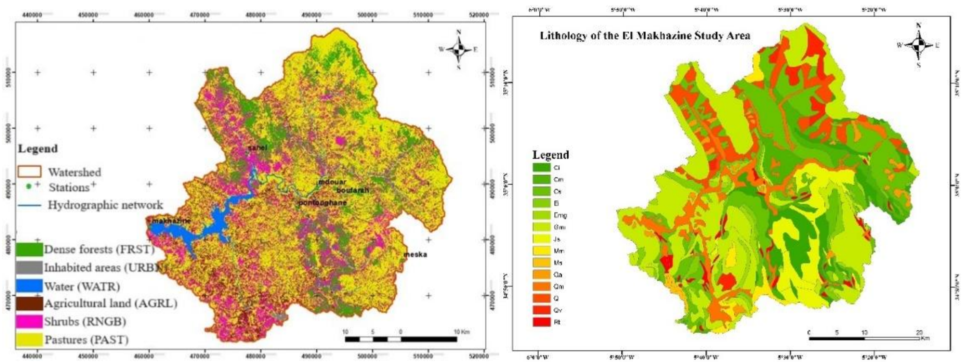

Figure 2. Land use map and lithological map of the study area

According to the land use map of the El Makhazine watershed, the basin is divided into three categories based on the type of land cover. The river basin was classified into three sections: the portion of the river basin under forests (fš), the portion under grass, meadows, pastures, and orchards (ft), and the portion consisting of bare land, plough-land, and ground without grass vegetation (fg), Figure 3.

Figure 3. Examples of land use types (cropland, pasture, reforestation, and forests) in the watershed

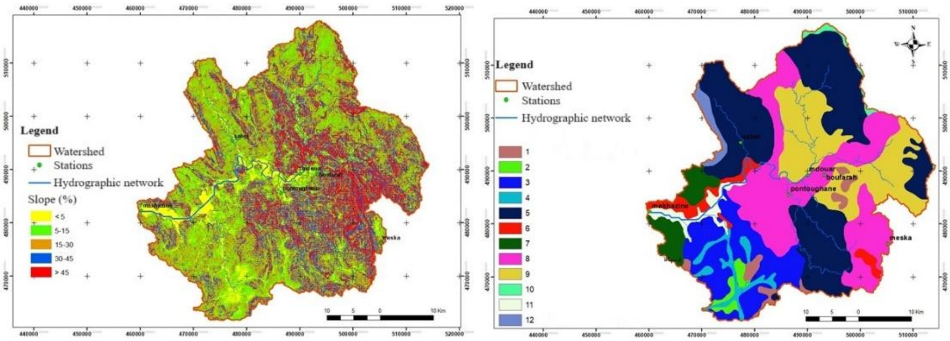

Figure 4. Map of slopes and soil types in the study area (Belasri *et al*. 2017): 1: Ferralitic soils, 2: Vertisols, 3: Calcimagnesic soils, 4: Undeveloped soils, 5: Poorly developed brown soils, 6: Soils with raw minerals, 7: Vertisols and calcimagnesic soils, 8: Complex soils (Poorly developed brown soils- calcimagnesic soils), 9: Undeveloped soils with raw minerals, 10: Brown soils with raw minerals, 11: Dam, 12: Brown soils with raw minerals-ferralitic soils).

Model parameters. The Erosion Potential Method (EPM) is a model for assessing soil loss that integrates several components, each quantifies distinct erosion processes and their interconnections. This model quantitatively estimates erosion intensity, sediment production, and sediment movements. It is mainly utilized for predicting long-term yearly soil loss rates, such as sheet erosion, gully erosion, and surface sediment deposition. Additionally, the EPM may be used to mitigate losses caused by wind erosion and other forms of soil erosion. The IntErO model, developed by Spalevic, is an improvement over prior watershed measurement tools since it integrates Gavrilovic's EPM into its algorithm. This model requires only 25 input parameters to generate 22 output parameters, making it highly useful for managing large datasets. As a result, it provides a reliable and comprehensive method for examining runoff and erosion in many environmental contexts.

The IntErO model estimates erosion intensity and sediment discharge using several equations based on the Erosion Potential Method (EPM). The important parameters and their formulae are given below:

The annual volume of sediments (Wyear): Evaluate the volume of sediment removed by soil erosion and was calculated using the following equations:

$$\text{Wyear} = \text{T} \times \text{Hyear} \times \pi \times \sqrt{\text{Z}^3} \times \text{F}$$

Where T is the temperature coefficient, which is determined as follows:

$$\text{T} = \sqrt{(t/10} + 0.1)$$

Where F is the watershed area (km^2), and H-year is the yearly average rainfall from 2002 to 2022 in mm.

The Z coefficient, which can be classified based on the degree of erosion (Table 2), shows the strength of the erosion process and is computed as follows:

$$Z = Xa \times Y \times (\emptyset + \sqrt{Isr})$$

Where:

- The variable (Xa) indicates the degree of soil protection. Xa considers land use and the amount of vegetation cover. This coefficient ranges typically between 0.05 and 1, with values close to zero suggesting inadequate soil protection and values close to 1 indicating high soil protection. The Xa values were determined by assigning classes proposed by the EPM approach and comparing the watershed's LULC map to previous research.
- The soil erodibility coefficient (Y) is a dimensionless factor that measures soil erosion resistance and is determined by the basin's pedological and lithological properties (Figure 4). The Y factor was assessed in this study utilizing lithological data from the study area. Values for each soil type were then assigned using EPM guidelines and previous research. Values less than 0.25 indicate moderate erodibility, whereas values more than 2 indicate extremely erodible formations.
- The coefficient $\emptyset$ is a one-dimensional component whose values range from 0.1 to 1. This variable relates to active erosion and was estimated using the erosion pattern map of the El Makhazine basin. Values were subsequently assigned to each erosion type based on recommendations from prior studies. Furthermore, using DEM (DTM-ASTER-GDEM), the average percentage of basin slope Isr in the study area was determined (Figure 4) .

Given that some sediments are redeposited in watercourses and other catchments, the specific sediment production (Gsp) in $m^3\ km^{-2}\ year^{-1}$ should be determined. This can be achieved by multiplying the average yearly sediment production (Wyear) with a Ru coefficient:

$$Gsp = Wyear \times Ru$$

Where:

$$R = \sqrt{o \times d} / (0.25 \times (Lv + 10))$$

With: o is the extent of the catchment area, d is the average height of the basin in the final section, and Lv is the length of the main river.

Table 2. Ranges of the Z coefficient in the Erosion Potential Method (EPM) (Gavrilovic 1972, Spalevic 2011).

Z value class	Mean Z value	Erosion type	Erosion intensity
1.51 1.21–1.50 1.01–1.20	1.25	Deep Mixed Surface	Excessive
0.91–1 0.81–0.90 0.71–0.80	0.85	Deep Mixed Surface	Strong
0.61–0.70 0.51–0.60 0.41–0.50	0.55	Deep Mixed Surface	Medium
0.31–0.40 0.25–0.30 0.20–0.24	0.30	Deep Mixed Surface	Low
0.01–0.19	0.10	Deep Mixed Surface	Very low

Modeling and Simulation. The IntErO model, which simulates erosion and sediment discharge in the watershed, has been updated with data collected. To represent the environment, soil, climate, and geomorphology, data had to be entered. To better represent the special characteristics of the watershed, key parameters, including Z, WSP, and G, have been adjusted. Scenarios, along with other previously stated equations, were then used to compute erosion indices. The study investigated and reproduced the current condition of the watershed to examine the impact of variables such as land use and land cover on erosion.

The simulation findings were cross-checked with historical observations, field data, and other research conducted in the same area and in adjacent regions to validate the model. The data were evaluated spatially, and the area's most vulnerable to erosion were identified using GIS technologies. To gain a better understanding of the erosion dynamics in the Oued El Makhazine watershed, the results were evaluated. specific soil and water management recommendations were provided, such as reforestation and other conservation measures (Table 3).

Table 3. Input data used for the IntErO model in the El Makhazine watershed.

River basin area	F	1806,18	km²
The length of the watershed	O	3309,36	km
Natural length of the main watercourse	Lv	62,48	km
The distance between the fountainhead and mouth	Lm	52,9	km
The length of the main watercourse with tributaries	ΣL	2510,11	km
Basin length measured by a series of parallel lines	Lb	82,47	km
The area of the bigger river basin part	Fv	1020,66	km²
The area of the smaller river basin part	Fm	785,52	km²
Altitude of the first contour line	h0	79	m
Equidistance	Δh	100	m
The lowest river basin elevation	Hmin	21	m
The highest river basin elevation	Hmax	1678	m

NOTE : *The contour line lengths in the El-Makhazine watershed range from 401.35 km to 2.89 km, while the areas between neighboring contour lines vary from 120.61 km² to 0.35 km², showing a clear decrease in both metrics with elevation intervals : l iz (km), 401,35 - 898,7 - 1188,88 - 895,66 - 523,07 - 374,08 - 246,78 - 143,72 - 71,2 - 53,08 - 51,02 - 48,71 - 40,63 - 33,75 - 17,88 - 2,89; f iz (km²), 120,61 - 352,94 - 374,62 - 325,03 - 199,12 - 140,73 - 100,36 - 64,13 - 36,86 - 21,40 - 18,51 - 16,42 - 14,32 - 11,07 - 6,57 - 3,14 - 0,35*

A part of the basin with very permeable rocks	fp	0,17	
A part of the basin with medium permeable rocks	fpp	0,47	
A part of the basin with of poor water permeability	fo	0,36	
A part of the river basin under forests	fš	0,15	
A part of the river basin under grass, meadows, pastures and orchards	ft	0,74	
Bare land, plough-land and without grass	fg	0,11	
The volume of the torrent rain	hb	75,46	mm
Incidence	Up	50	years
Average annual air temperature	t0	20,86	°C
Average annual precipitation	Hyear	869,07	Mm
Types of soil products and related types	Y	1,3	
Coefficient of the river basin planning	Xa	0,51	
Visible and clearly exposed erosion process	φ	0,42	

RESULTS

The IntErO model predicted sediment yield and peak discharge in the Oued El Makhazine watershed. The table presents the results, highlighting several key basin characteristics. The symmetry coefficient (A) of 0.26 indicates that enormous flood waves may occur in the river basin. The G coefficient of 1.39 suggests a dense hydrographic network. The Isr rating of 27.64% indicates that steep slopes dominate the river basin. The Z coefficient of 0.631 ranks the river basin in the third category of destruction. The erosion process is moderate in intensity, classified as intrusive erosion. According to Gavrilovic, the river basin's sediment yield of 1870.06 m³/km²/year placed it in the second category, indicating intense surface-type erosion (Table 4).

Table 4. Results generated by the IntErO model in the El Makhazine watershed

Coefficient of the river basin form	A	10,33	
Coefficient of the watershed development	m	0,41	
Average river basin width	B	21,90	km
(A)symmetry of the river basin	a	0,26	
Density of the river network of the basin	G	1,39	
Coefficient of the river basin tortuousness	K	1,18	
Average river basin altitude	Hsr	359,39	m
Average elevation difference of the basin	D	338,39	m
Average river basin decline	Isr	27,64	%
The height of the local erosion base	Hleb	1657,00	m
Erosion energy basin's relief coefficient	Er	80,91	
Coefficient of the region's permeability	S1	0,76	
Coefficient of the vegetation cover	S2	0,79	
Water retention in inflow	W	0,7195	m
Energetic potential of flow during torrents	2gDF^½	3462,88	m km s
Maximal outflow from the river basin	Qmax	15433,65	m³/s
Temperature coefficient of the region	T	1,48	
Coefficient of the river basin erosion	Z	0,631	
Production of erosion material of basin	Wyear	36576358573	m³/year
Coefficient of the deposit retention	Ru	0,923	
Real soil losses	Gyear	3377659,34	m³/year
Real soil losses per km2	Gyear/km²	1870,06	m³/km² year

The soil protection degree is defined by the Xa parameter, which ranges from 0.05 to 1 (Table 5). A considerable amount of the watershed required adequate protection, with 11.49% of the region having Xa values more than 0.8, notably in bare soils and ploughlands. Lower Xa values were found in areas of old dense reforestation, dense scrubland, and dense deciduous forests, which covered 36.5% of the basin. This indicates that approximately a third of this region is managed, which helps reduce erosion. Pasture forests comprise the remaining 52.01% of the watershed, characterized by intermediate Xa values.

Table 5. Values of the coefficient Xa.

LULC	Xa value	%
Mountain pastures	0.6	52,01%
Meadows	0.4	21,90%
Well-constituted forests	0.05	14,60%
Plough-lands	0.9	9,02%
Bare lands	1	2,47%

The erodibility coefficient Y, which is influenced by soil type and lithology, is utilized by the IntErO model to assess soil erodibility. The research area's lithological and soil maps were categorized using terms from the IntErO program. This watershed's soils show low erodibility over 26.95% of the basin, very high erodibility over 36.89% of its surface, and intermediate erodibility over 36.16% of the basin (Table 6). The erosion process is represented numerically in this model by the parameter φ, which reflects the extent of erosion forms. The values that Gavrilovic had assigned to this parameter were used.

Table 6. Values of the coefficient Y

Types of soil products	Y value	%
Sand, gravel and incoherent soil	2.0	36,89%
Serpentines, Red sandstone, Flysch deposits	1.1	30,75%
Chernozems and alluvial well-structured deposits	0.5	19,61%
Solid and Schist limestone, Terra Rosa and Humic soil	0.9	7,34%
Decomposed limestone and marls - cement rocks	1.2	5,41%

The parameter Φ varied between 0.1 and 0.8 when the values attributed to this factor by Gavrilovic (Citation 1988) were adapted (Table X). Surface erosion affects 20% of the watershed, with a Φ coefficient of 0.3, accounting for 38% of the total impact, which indicates significant soil loss in a small area. Gully and rill erosion, which is more intense (Φ = 0.8), affects 50% of the basin but represents a significantly lower percentage of the total impact (34%). This is likely concentrated in larger, steeper sections. Forested and perennial vegetation regions, which occupy 24.4% of the basin, have a low erosion potential (Φ = 0.1) and perform an important protective role. Minor landslides in streambeds (Φ value = 0.2) affect just 3.6% of the area, making them a less problematic form of erosion (Table 7). Overall, surface and gully erosion are the primary causes of deterioration; however, forest vegetation serves as an effective erosion barrier, highlighting the importance of preserving and managing vegetated regions to maintain watershed stability.

Table 7. Values of the coefficient Φ.

Erosion forms	Φ value	%
20% of the river basin under surface erosion	0.3	38%
50% of the river basin under rill and gully erosion	0.8	34%
The river basin under forests and perennial vegetation	0.1	24,40%
There are smaller slides in the watercourse beds	0.2	3,60%

The erosion rates determined by the EPM model integrated into the IntErO program are presented in the table. The average sediment yield is 1870.06 m^3/km^2/year (29.03 t/ha/year). According to Gavrilovic, this suggests that the river basin belongs to category II, a zone of severe erosion, with surface erosion being the most common form. This uniform conversion aims to compare the results with erosion research undertaken in Morocco's Rif region. The majority of these research reports result in t/ha/year, and the EPM-IntErO models are not extensively utilized in Morocco.

DISCUSSION

The IntErO model provides a comprehensive assessment of sediment yield for the entire basin, rather than focusing solely on the spatial distribution of erosion rates. While empirical models such as RUSLE, USLE, and MUSLE are effective for estimating soil loss, IntErO offers a more extensive analysis by calculating key hydrological and geomorphological parameters. These include maximum river discharge, basin asymmetry, shape coefficients, watershed development, sinuosity, regional permeability, and vegetation cover—factors that are crucial in evaluating soil loss across the landscape (Chalise *et al.* 2019). One of IntErO's primary advantages over other models is its ability to determine both the sediment delivery ratio and the actual sediment output. In contrast, models such as RUSLE only predict cumulative erosion rates, which may not adequately reflect the quantity of soil leaving the basin because not all eroded material is carried out of the catchment. IntErO's sediment yield calculation reflects the actual volume of sediment leaving the river basin. IntErO also considers the coefficient and extent of other erosion forms, as opposed to RUSLE and USLE, which focus on sheet erosion. The majority of sediment delivered to reservoirs, however, is generated by gully and rill erosion, making IntErO's technique more applicable in these situations. That is, IntErO takes into consideration the contributions of several geomorphological phenomena common in the research area, such as landslides, bank and channel erosion, mega-rills, and gullies (Figure 5), all of which have a significant impact on soil loss (Borrelli *et al.* 2014). IntErO includes these additional processes, which distinguish it from models that only consider sheet erosion and provide a more comprehensive analysis of erosion dynamics.

Figure 5. Examples of erosion forms in the watershed
(moderately deep ravines and shallow landslides)

Figure 6. Types of management practices in the watershed
(threshold gabions in streams and along roadbanks).

A variety of factors influence soil erosion in the El Makhazine watershed, including the severity of gullying, the geographical location (Rif region) where eroded materials are easily transported and deposited in watercourses, the composition and steep slopes, the structure of the lithological formations, and human activity (Figure 6). In combination, these factors cause a wide range of negative effects on ecosystems, soils, water resources, and local communities. Some of the most notable negative consequences for the study area include:

-Risk of flooding: The model's results indicate that recent land use changes will probably cause more intense floods. According to the study's findings, the watershed has a high erosion rate, with surface erosion being the most common form, and is classified as belonging to the second category of destruction. The increase in peak flow and sediment yield in different regions of the basin can be attributed to the expansion of agricultural land, deforestation, and forest degradation (Figure 7). In addition, the asymmetry coefficient and the G coefficient value of 1.39 indicate a high density of the hydrographic network, suggesting that large flood waves could develop in the hydrographic basin.

-Soil quality: Topsoil loss has a considerable impact on soil quality since it is the most fertile and organic matter-rich layer. This loss affects soil fertility, alters its structure, decreases water retention capacity, and makes it unsuitable for plant growth (Figure 8). The intensity of surface runoff reduces soil quality by removing important minerals required for agriculture and plant development. This results in high values of surface runoff (Qmax equal to 15433.65 m^3/s and the permeability coefficient is 0.76) accelerated by steep slopes (Isr equal to 27.64%). Erosion also causes sedimentation in water bodies, which can lead to pollution, habitat degradation, and biodiversity loss.

-The process of sedimentation, which happens when sediments build up in rivers and dams (the production of erosion material in the river basin equal to 3657635,857 m^3/year, and the coefficient of the deposit retention is 0.923), affects the quality of water and upsets the equilibrium of aquatic ecosystems. One of the primary effects is an increase in water turbidity, which reduces light penetration and prevents algae and aquatic plants from photosynthesizing, thereby reducing habitat quality and biodiversity. Reservoir management is severely hampered by soil erosion and the subsequent sedimentation (Real soil losses equal to 3,377,659.34 m^3/year), which affects reservoir functionality and capacity.

-Reservoir storage capacity is steadily decreased by sedimentation, which limits the amount of water available for irrigation, hydropower generation, flood control, and water delivery. Additionally, this sediment buildup damages the reservoirs' ability to function efficiently, shortening their lifespan, increasing maintenance expenses, and requiring costly dredging projects.

Figure 7. Examples of protected areas with low sediment yield in the study area

The data and results obtained from this research are consistent with those observed in other Rif regions of Morocco with similar characteristics, indicating a relative reliability of the findings in this study. In the Rmel watershed in northern Morocco, which is well-managed but affected by quarrying activities, the IntErO model estimated soil losses of approximately 13 t/ha/year. Scenarios involving changes in land use indicated that reforestation could reduce erosion by 4.78

t/ha/year while converting quarries into agricultural land might decrease erosion by 1 t/ha/year (Ouallali *et al*., 2024).

Figure 8. Unprotected areas with high sediment yield in the study area.

A similar approach was used to predict the Arbaa Ayacha watershed's response to surface runoff, indicating an average erosion loss of 28 t/ha/year (Ouallali *et al.,* 2020). Other quantitative and qualitative erosion models used in the Rif produced comparable results: the RUSLE model indicated average losses of 16.53 t/ha/year in the Raouz watershed (Ed-daoudy *et al.*, 2023), 25.77 t/ha/year in the Arbaa Ayacha watershed (Ouallali *et al*., 2016), and 22 t/ha/year in the Sahla watershed (Sadiki *et al.,* 2009).

In the Nakhla basin (Moukhchane *et al*., 1998) and the Moulay Bouchta basin (Zouagui *et al*., 2012), environmental magnetism techniques such as magnetic susceptibility and radioisotopes (^{137}Cs and ^{210}Pb) also revealed loss values of approximately 39.6 t/ha/year, with losses reaching up to -140.36 cm according to the Tillage-Homogenization model in the Arbaa Ayacha region (Ouallali *et al.* 2023). Moreover, in Northwestern Morocco, land use and land cover substantially impact soil erosion because they influence soil stability, flow patterns, and vegetation cover, all of which may aggravate or improve erosion processes (Acharki *et al*. 2022).

CONCLUSION

The Rif region of Morocco has undergone considerable land-use changes in recent decades. The El Makhazine watershed is one of the most degraded areas, and it is significant because it supplies surface water to the El Makhazine dam, one of Morocco's largest dams. The loss of forested areas, urban growth, and the conversion of pastureland to cultivated land have all increased soil deterioration and surface erosion. The IntErO model, used for predicting surface runoff, soil erosion, and sediment yield in the watershed, suggests that recent changes in land use are likely to increase flood severity. According to the study, the watershed falls into the second category of destruction, indicating that the erosion process is severe and predominantly characterized by surface erosion. The degradation of forest lands, growth of agricultural land, and conversion of pastures to rain-fed agriculture all contribute to increased peak flow and sediment yield in the El Makhazine watershed.

The use of the IntErO model in the Makhazine watershed will help implement sustainable management strategies appropriate to this vulnerable area and offer insightful information on local dynamics. The protection of dams and the sustainability of water supplies in the face of climate change depend on developing effective strategies for soil conservation and water resource management, which this study aims to support. However, to better prevent soil erosion and improve environmental sustainability in similar environments, future research should focus on examining the long-term effects of current land use practices in the context of changing climate conditions.

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