

Article

Assessment of the Erosion and Outflow Intensity in the Rif Region under Different Land Use and Land Cover Scenarios

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Abstract: The port of Tangier Med is essential due to its strategic location, as it is an important trading center linking Europe, North America, and Africa. However, the increased rates of downstream sediment transportation put pressure on the sustainable future of the port. Thus, assessing the existing erosion rates and future improvement scenarios is imperative for planning sustainable management at the catchment level. We utilize the Erosion Potential Model (EPM) combined with the Intensity of Erosion and Outflow (IntErO) algorithm to assess the erosion and outflow intensity and to distinguish the sediment-producing areas in the R'mel watershed. The port's proximity at the bottom of the slope opposite the R'mel Dam is relevant in this context. Initial results show an average erosion rate of 13 t/ha/year. Quarry operations were identified as the primary sediment source, as indicated by the factors contributing to erosion. The qualitative PAP/RAC (Priority Actions Program/Regional Activity Center) model was used to assess the development trends in the watershed, confirming a clear tendency toward irreversible degradation in the quarry areas. Considering that the mined carbonate lithology represents 23.77% of the total area of the catchment, the situation in the region could deteriorate if quarry operations continue. The simulation of quarry rehabilitation scenarios through land use and land cover change (LULC) with IntErO shows that reforestation of quarries can significantly reduce erosion rates (4.78 t/ha/year) compared to their conversion to agricultural land. This study underlines the effectiveness of IntErO, based on the EPM model, in quickly and effectively mapping and quantifying water erosion.

Keywords: Intensity of Erosion and Outflow (IntErO) algorithm; Erosion Potential Model (EPM); quarry operations; reforestation; R'mel watershed

1. Introduction

The northern region of Morocco, geographically known as the Rif, is highly vulnerable to water erosion risk. Numerous recent and long-term studies have highlighted the high erosion rates in the Rif watersheds [1,2]. This increased susceptibility to erosion is mainly due to the relatively young age of the lithological formations, which consist primarily of friable material dominated by marl and clay [3]. The rugged topography and steep slopes that characterize the Rif area further facilitate the detachment and mobilization of sediments [4]. The adverse effects of erosion are particularly noticeable regarding water and soil resources, as the storage capacity of the hydraulic infrastructure has decreased significantly in recent years. Soil resources are exposed to the leaching of organic and mineral matter due to erosion [5,6], which leads to progressive soil degradation and threatens the food security of all living beings, including humans [7,8].

The scientific community and public and private institutions have been intensively involved in studying water erosion and erosion control for many years. The aim is to improve the understanding of this phenomenon and to develop appropriate erosion control measures that would ensure the sustainability of water and soil resources for as long as possible. As a result, numerous quantitative and qualitative models have been developed over the years. For example, some models are based on radioactive tracers such as Caesium-137 (¹³⁷Cs) [9,10], Pb Lead-210 (²¹⁰Pbex) [11], and Beryllium-7 (7B) [12,13]. These techniques have been widely criticized, mainly because of the high costs associated with laboratory analysis, the short half-life of these isotopes [14,15], and their inability to account for specific parameters that control the erosion process [16].

In addition, methods based on hydrological modeling have been developed, with the Soil and Water Assessment Tool (SWAT) model being one of the most widely used worldwide [17,18]. This model facilitates the assessment of sediment and water supply with optimal sensitivity parameters, and its main strength lies in ensuring the connectivity of hydrological systems within catchments. However, its application in Morocco is limited by the need for data measured by hydrometric stations over relatively long periods [19,20]. Other methods are based on a geographic information system (GIS) and remote sensing, such as the Revised Universal Soil Loss Equation (RUSLE) [21], Modified Universal Soil Loss Equation (MUSLE) [22], RUSLE-3D [23], and the Erosion Potential Method that is known as EPM [24] and which is a frequently used empirical model across the Balkan area, North Africa, and Europe along with the Middle East [25]. These models differ in terms of the type of data used.

EPM is one of the most used models by researchers as it considers various factors of water erosion [26–28]. It also assesses the effects of erosion forms and lithological substrates when evaluating the erosion process [29]. It has been integrated into an intensity of Error and outflow algorithm called IntErO (Intensity of Error and outflow) [30]. The integration of EPM into IntErO has facilitated the execution and application of EPM and has led to the international dissemination of the EPM method. However, in Morocco, the application of EPM still needs to be further improved [29,31]. This limitation can be overcome with IntErO, as it allows a fast and practical simulation of the physical catchment parameters. Previous studies have been conducted in the Arbaa Ayacha watershed using IntErO to assess erosion potential and show the influence of geomorphologic factors on soil erosion [29,30]. The successful implementation of previous studies has shown great potential for applying IntErO for advanced lithological applications in the Rif region.

IntErO is also a practical tool for qualitative erosion assessment. Previous studies have shown the importance of qualitative and holistic assessment methods for erosion prediction in risk mitigation measures in North African landscapes [32,33]. The qualitative method differs from the quantitative method in that it assigns weights to geographical units corresponding to soil erosion intensity [34]. The qualitative and quantitative models consider the same erosion factors, such as land use and land cover, soil type, slope gradient, and precipitation [35]. However, in the qualitative approach, each erosion control factor is given a specific weight depending on the researchers' assessment or understanding of the local erosion

processes and the importance of each parameter in controlling the phenomenon [35–37]. The PAP/RAC method [38] is one of the most used qualitative approaches in Morocco. The main objective of this method is the management of the Mediterranean coastal areas and the evaluation of the condition of the soil surfaces concerning their susceptibility to erosion. The PAP/RAC enables the visualization of erosion conditions, the analysis of water erosion relationships, and the assessment of risk trends in different catchment sizes [32].

An essential objective of this study is to adapt the IntErO model to the environmental conditions of the Moroccan Rif region to study erosion and runoff. The choice of the study area is not arbitrary but essential for several reasons. First, a reservoir in the downstream watershed of the R'mel serves as the primary source of drinking water for the city of Ksar Essghir. Directly opposite the reservoir is the most critical national coastal structure, the international port of Tangier Med [39]. This vital infrastructure must be protected from flooding and the damaging effects of water erosion. In addition, the basin's soils must be safeguarded through land management, especially as agriculture is the most important source of economic activity for the local population. In addition, the assessment of the current state of the R'mel catchment shows that land use has changed significantly and rapidly over time. The anthropogenic influence in this catchment is particularly pronounced and can be seen above all in the extensive quarrying activities concentrated in the central region of the catchment. The economies of many Mediterranean countries have benefited from the extraction of raw materials. Unfortunately, many quarries in Mediterranean countries caused severe damage to the environment and landscape [31,40,41]. Numerous studies have demonstrated the direct impact of operating or abandoned quarries on soil, water quality, and siltation of dams [42,43]. Therefore, soil conservation practices must be implemented to ensure soil protection and reduce the direct impact of the quarry on the ecosystem. Among these practices, the transformation of quarries to forests or vegetated areas, commonly known as afforestation, is of great scientific importance in the efforts to combat climate change, preserve biodiversity, stabilize soils, prevent erosion, and protect reservoirs as natural filters that retain sediments and pollutants before they enter the reservoirs [44]. In addition, reforestation helps to stabilize soils by strengthening their structure and water retention capacity, thus reducing the risk of erosion. Soil conservation is essential to maintain the fertility of adjacent agricultural land and prevent soil degradation.

The goal of this study is to determine the rate of erosion and the amount of sediment moving downstream of the basin using an efficient but not widely used model across the country. Sediment sources were identified and analyzed with respect to land use change scenarios in the region. Two scenarios regarding quarry surfaces were simulated utilizing the IntErO tool to assess the reliability of quarry rehabilitation and its impact on reducing erosion rates and sediment yield to the reservoir. Finally, the influence of erosion control factors on the erosion process was evaluated by incorporating qualitative aspects to determine the development trends of erosion in the region.

This study demonstrates the importance of quarry rehabilitation for environmental protection and ecosystem sustainability, highlighting the priority areas where erosion control measures are needed. Proactively managing these issues is essential to protect water and soil resources while maintaining the integrity of ecosystems in the region.

2. Materials and Methods

2.1. Study Area

The water catchment area of the R'mel lies in the northern Rif region of Morocco. It belongs to the province of Ksar Essghir, located in the Tangier-Tetouan Elhoceima region. The watershed covers an area of 34 km². Its altitude ranges from 12 to 572 m (Figure 1a).

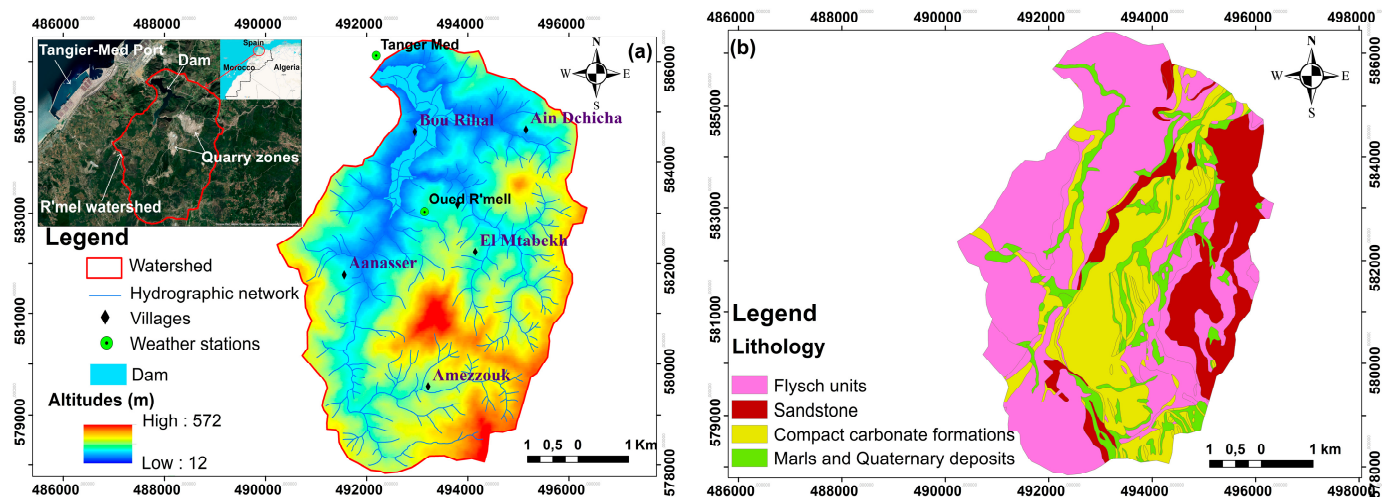


Figure 1. Geographical location of the (a) R'mel watershed and the Tanger Med port in Northern Morocco, (b) lithological map of the study area.

The topographic data for this watershed were extracted from the ASTER digital terrain model (DTM) downloaded from the Earth Explorer website (<https://earthexplorer.usgs.gov>) (accessed on 27 August 2023)). In the central and upstream parts of the watershed, the two highest points are located at the villages of Annasser and Amezzouk. However, the lowest elevations are downstream of the watershed where the R'mel Dam was built. This dam collects water from the surrounding slopes and surface runoff through the hydrographic network.

The study area has a Mediterranean sub-humid climate with an average annual precipitation of about 820.3 mm, calculated based on a 12-year precipitation data series measured at the meteorological station of the catchment area. Land use and land cover (LULC) data were obtained using geospatial remote sensing by processing a Landsat OLI8 image downloaded from the United States Geological Survey (USGS) website (<https://www.usgs.gov/>) (accessed on 27 August 2023)) and processed with ENVI software version 5.5.2 [45]. This software facilitated the supervised classification of the different LULC classes within the watershed, with in-depth field checks performed for specific classes. The resulting map illustrates that most of the watershed is covered by dense scrubland, followed by open scrubland, which is detailed in the Results and Discussion section. On the other hand, dense natural forests are limited to the southern and northeastern parts of the watershed. Arable land is generally located in the central part of the watershed and near the villages and accounts for 22.7% of the total watershed area. The watershed's unvegetated areas include rocks, bare land, and quarry areas (Table 1).

Table 1. Percentage of land use land cover (LULC) classes in the study area.

LULC	Area (km ²)	%	LULC	Area (km ²)	%
Dam	1.1	3.1	Dense forest	0.3	0.9
Quarrying areas	1.4	4.2	Moderately dense forest	1.1	3.1
Bare lands	0.5	1.5	Clear forest on dense scrublands	1.5	4.5
Rock outcrop	1.5	4.4	Dense reforestation	1.1	3.3
Agricultural land	4.8	13.9	Clear reforestation	0.04	0.1
Association: agricultural and built land	3.0	8.8	Dense scrubland	8.9	25.8
			Clear scrubland	91	26.4

The lithological data of the basin were taken from the geological map at a scale of 1:50,000, inspired by successful previous studies with aligning research objectives [46,47]. The basin has a variety of lithological formations (Figure 1b). The flysch formations, mainly located in the western part of the basin, cover about 49.77% of the basin's total area. In the

eastern part of the basin, sandstone formations dominate, covering approximately 15.25% of the site. Marl and quaternary deposits are mainly found on the banks of the gorge and make up 11.21% of the basin's area. Finally, compact carbonate rock outcrops in the central part of the basin make up about 23.77% of the total area. This carbonate formation was mined on a large scale, mainly for the construction industry.

We engaged a specialist pedologist from our authors' team, who conducted a comprehensive field visit in collaboration with our team. Drawing on the insights gained from this fieldwork and in conjunction with the data obtained from the prior geological survey, our team, comprising specialist pedologists and geologists, derived numerical values needed for the IntErO calculations in relation to the soils of the river basin. These values were then instrumental in the evaluation of the soils within the basin.

2.2. Intensity of Erosion and Outflow Assessment

2.2.1. IntErO Model Description and Implementation

EPM models [24] use multiple components to obtain a global estimate of soil loss. Each factor quantifies one or more processes and their relationships [30,39]. EPM quantitatively estimates erosion intensity, sediment production, and sediment transport [48]. Most models are used to predict long-term annual rates of soil loss to crops due to sheet erosion, gully processes, sediment transport, rill erosion, and deposition on the soil surface. The EPM model predicts the extent of erosion due to sheet or gully erosion and accounts for additional soil losses due to gully erosion, wind erosion, or soil erosion [49,50]. The IntErO model of Spalevic [24,51,52] integrates Erosion Potential Model (EPM) of Gavrilovic [24] into its algorithm. It is an improvement over the previously used river basin and area/distance measurement programs [29,53]. The method is useful and can handle large amounts of data. It requires only 25 input parameters to generate 22 output parameters (Table 2).

The IntErO model program package of Spalevic [54] takes six elements into account: soil type and lithology are represented by the coefficient Y, land use data represents Xa, temperature is linked to the parameter t, and erosion patterns are represented by the coefficient Q [51]. These coefficients must be thoroughly evaluated in various processes, including data collection, fitting, analysis, and integration into the model equations. The annual volume of sediments 'Wyear' eroded because of soil erosion was calculated using the following equations, Equations (1) and (2).

$$W_{\text{year}} = T \times H_{\text{year}} \times \pi \times \sqrt{Z^3} \times F \quad (1)$$

where F is the watershed area (km²), and T is the temperature coefficient derived as follows:

$$T = \sqrt{\left(\frac{t}{10} + 0.1\right)} \quad (2)$$

Hyear is the yearly average rainfall between 2007 and 2022 in mm. The Z coefficient, which can be categorized according to the degree of erosion (Table 3), represents the strength of the erosion process, and is calculated as follows in Equation (3):

$$Z = X_a \times Y \times \left(\emptyset + \sqrt{I_{\text{sr}}}\right) \quad (3)$$

The variable (Xa) represents the degree of soil protection. Xa considers land use and the extent of vegetation cover. With values close to 0, indicating low soil protection, and values around 1, indicating strong soil protection, this coefficient typically varies between 0.05 and 1 [20,55,56]. The Xa values were obtained by assigning the classes suggested by the EPM technique and comparing the LULC map of the watershed with previous studies [51,57].

Table 2. Input data used for the IntErO model in the R'mel watershed.

Parameters	Symbols	Values	Units
The watershed's length	F	34.4	km ²
The length of the main watercourse	O	25.7	km
The quickest path from the mouth to the fountainhead	Lv	12.3	km
The entire length of the primary watercourse, including tributaries of classes I and II	Lm	7.3	km
A set of parallel lines indicates the length of the river basin.	ΣL	110.1	km
The more significant portion of the river basin	Lb	9.3	km
The region of the shorter river basin	Fv	23	km ²
The watershed's length	Fm	11.4	km ²
Length of contour lines	Liz	50-100-150-200-250-300-350-400-450-500-550	km
The area between two adjacent contour lines	fiz	0.3-2.23-3.9-4.32-5.8-6.44-5.06-3.13-1.84-0.91-0.38-0.09	km
The first contour line's altitude	h0	50	m
Equidistance	Δh	50	m
The lowest elevation in the river basin	Hmin	12	m
The highest elevation in the river basin	Hmax	572	m
The portion of the river basin comprises a highly porous rock product (limestone, sand, and gravel).	fp	0.14	
The portion of the river basin comprises moderately permeable rocks (slates, marls, and brownstone).	fpp	0.18	
The portion of the river basin comprises low-permeability rocks (thick clay, compact eruptive).	fo	0.68	
The area of the river basin is covered with forests	fš	0.64	
The portion of the river basin covered in grasslands, meadows, and orchards	ft	0	
The section of the river basin is bare land, plowland, or ground devoid of grass vegetation.	fg	0.36	
The torrential rain's volume	hb	61.13	mm
Incidence	Up	100	years
Annual average air temperature	t0	17.5	°C
Annual precipitation average	Hgod	677.02	mm
Soil product categories and associated types	Y	1.1	
River basin planning, river basin planning coefficient	Xa	0.53	
Numeral equivalents of visible and exposed erosion processes	φ	0.32	

Table 3. Ranges of the Z coefficient in the Erosion Potential Method (EPM) [24,54].

Erosion Intensity	Erosion Type	Z	Mean Value Z
Excessive	Deep	1.51	1.25
	Mixed	1.21–1.50	
	Surface	1.01–1.20	
Strong	Deep	0.91–1	0.85
	Mixed	0.81–0.90	
	Surface	0.71–0.80	
Medium	Deep	0.61–0.70	0.55
	Mixed	0.51–0.60	
	Surface	0.41–0.50	
Low	Deep	0.31–0.40	0.3
	Mixed	0.25–0.30	
	Surface	0.20–0.24	
Very low	Deep	0.01–0.19	0.1
	Mixed		
	Surface		

The soil erodibility coefficient Y is a dimensionless factor that reflects the erosion resistance of the soil and depends on the pedological lithological characteristics of the basin [20]. The Y factor was evaluated in this study using lithological data from the study area. Values for each soil type were then assigned based on EPM recommendations and previous studies [20,55,56]. Values below 0.25 indicate moderate erodibility, while values above 2 indicate extremely erodible formations [56,58].

The coefficient ϕ is a one-dimensional component with values between 0.1 and 1. This parameter is related to active erosion and was calculated using the erosion pattern map of the R'mel basin. Values were then assigned to each erosion type using the recommendations of the previous studies [20,56,58]. Finally, the average percentage of basin slope I_{sr} in the study area was calculated using DEM (DTM-ASTER-GDEM). Calculating the specific sediment production (G_{sp}) was undertaken in $\text{m}^3 \text{ km}^{-2} \text{ year}^{-1}$ as some sediments are re-deposited in rivers or other catchments. This can be achieved using the following equation, Equation (4):

$$G_{sp} = W_{year} \times Ru \quad (4)$$

This can be accomplished by multiplying the average yearly sediment production (W_{year}) by an R coefficient (delivery ratio), Equation (5):

$$R = \frac{\sqrt{O \times D}}{0.25 \times (L_v + 10)} \quad (5)$$

The parameters O and D are given in kilometers, where O is the extent of the catchment area, D is the average height of the basin in the final section, and L_v is the length of the main river.

2.2.2. Land Cover Change Scenarios and Effect of Geomorphological Conditions

The investment directed toward implementing anti-erosion practices, along with their subsequent production, has the potential to yield satisfactory economic efficiency. This indicates that the allocation of resources to these measures can result in favorable returns, balancing both the financial aspect and the effectiveness of mitigating erosion-related challenges [59,60]. In this study, two scenarios were simulated in quarry areas using the IntErO algorithm to assess the reliability of quarry rehabilitation and its impact on erosion rates and sediment yield in the reservoir. This simulation involves utilizing the methodology outlined in Table 2 and Equations (1)–(5), incorporating alterations to the Xa coefficient within Equation (3). In the initial scenario, the land use and land cover (LULC)

category associated with quarries has been substituted with a vegetation zone. In contrast, quarries have been reclassified as cultivated land in the second scenario.

To analyze the effect of geomorphological conditions on the erosive process, we created an intersection between the individual erosion factors and the erosion rate map to illustrate the influence of crucial erosion variables on sediment formation. This link was created through a GIS process between the files in vector format. This method requires two vector layers for the slope factor: one for erosion classes and one for slope classes [29]. To create the low, medium, high, and excessive classes in the resulting EPM model map, we first divided the slope map into four categories: 0–15%, 15–30%, 30–45%, and above 45%. The two files were then overlaid using the ArcGIS 10.8 intersect command to determine the erosion rate for each slope class. To determine the proportion of low, moderate, high, and excessive erosion classes, we used a map showing the erosion rates for each slope class generated by this process. The contribution of each factor to sediment production was indicated using the same methods for other factors and maps illustrating lithological, land use, and erosion features [29,52]. The slope map and sediment production map classes are sliced from each map using the same ArcGIS 10.8 commands and tools.

2.3. Evolutionary Trends of Erosion in the Basin and Its Qualitative Assessment

Several organizations (UNEP, FAO, and DGCONA) have mapped and measured the erosion processes caused by rainfall in the Mediterranean regions [32]. The PAP/RAC approach was developed to analyze the sensitivity of water erosion [33,61]. It is based on the interrelationships and interdependence of water erosion risk variables. Specific procedures are required to map each element of the approach, primarily the processing, intersection, and analysis of the data sets.

Generally, the technique can be divided into three main steps. The first step is the predictive approach to assign values to water-eroding variables such as lithology and soil type, LULC, slope, and vegetation density. In this phase, a map of the erosive state is created (Figure 2), and the catchment is prioritized according to the degree of erosion. The second step is the descriptive stage based on a map of the erosion forms and patterns of the site and its erosion risk.

The third step is the integration phase, which is the culmination of the previous two processes. It overlays the map of erosion forms with the map of erosion conditions (Matrix 4 in Figure 2). An interactive map of water erosion is displayed. It helps to identify development trends in the catchment areas concerning erosion risk. Using a systematic approach, the PAP/RAC method examines the potential risk of soil erosion by emphasizing conservation measures and implementing effective erosion control methods. The PAP/RAC method for measuring soil erosion risk in Mediterranean regions includes the following steps:

- Data collection: The first step is to collect data on the many factors that influence the risk of soil erosion, including rainfall, soil type, lithology, LULC, and vegetation cover. This data can be collected through surveys, remote sensing, or existing databases.
- Data preparation involves digitizing and arranging the data obtained in a geographic information system (GIS) to process and prepare them for analysis.
- Erosion risk assessment: The next step is to assess the erosion risk by summarizing the information on the different aspects using a matrix technique. Under the matrix approach, each element is given a score based on how much it contributes to erosion risk. These scores are then added together to provide an overall erosion risk score for each area (Tables 4 and 5).

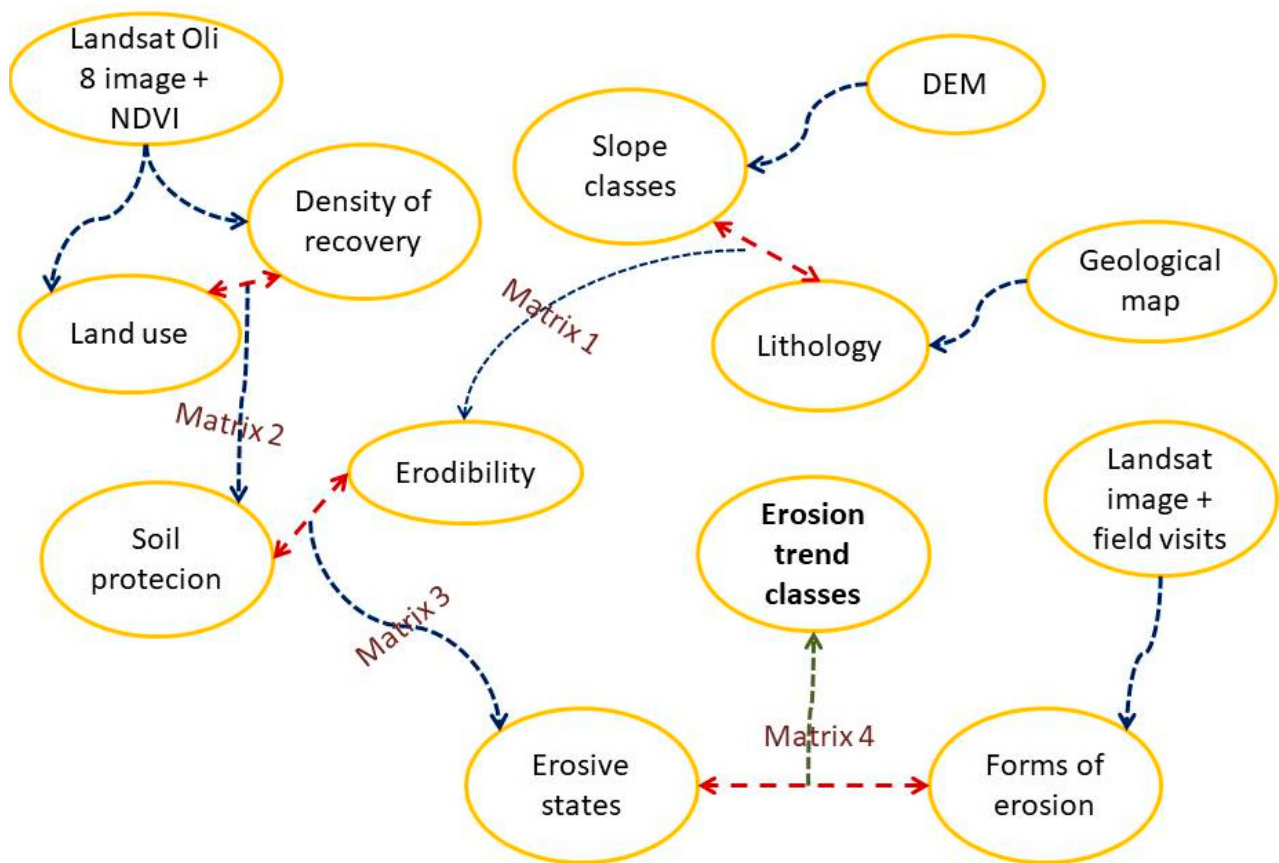


Figure 2. Methodology for assessing erosional trends in the basin using the PAP/RAC method [62].

Table 4. Matrices for assessing soil erodibility and soil protection degree.

Classes of Slope	Lithofacies Classes				Density of Recovery					
	a-1	b-2	c-3	d-4	Land Use	1 (<25%)	2 (25–50%)	3 (50–75%)	4 (>75%)	5 (dam)
1	1: EN	1: EN	1: EN	2: EB	1	2: M	1: A	1: A	1: A	0
2	1: EN	1: EN	2: EB	3: EM	2	3: B	2: M	1: A	1: A	0
3	2: EB	2: EB	3: EM	4: EA	3	4: MB	4: MB	3: B	2: M	0
4	3: EM	3: EM	4: EA	4: EA	4	4: MB	4: MB	3: B	2: M	0
5	4: EA	4: EA	5: EX	5: EX	5 (dam)	0	0	0	0	0

Matrix 1: Degrees of erodibility
EX: Extreme, EA: High, EM: Medium, EB: Moderate, EN: Low

Matrix 2: Degree of protection of the soil
MB: Very low, B: Low, M: Medium, A: High

Table 5. Matrices for assessing erosive states and erosion trends.

Soil Protection Classes	Erodibility Classes					Erosion Forms		
	1-EN	2-EB	3-EM	4-EA	5-EX	Erosive States	Minor Forms of Erosion (SP, L, D)	Major Forms of Erosion (M, C, Cx, Lx)
1 (A)	1	1	1	2	2	1	1	3
2 (M)	1	1	2	3	4	2	1	3
3 (B)	1	2	3	4	4	3	2	4
4 (MB)	4	4	5	5	5	4	2	4
5 (Dam)	0	0	0	0	0	5	2	4

Matrix 3: Erosive states
5: Very High, 4: High, 3: Notable, 2: Low, 1: Very low

Matrix 4: Erosion trends
(*): (1), (2), (3), (4)

(*) 1. Erosion processes tend to stabilize, retreat, or limit their spatial expansion. 2. Erosion processes tend to extend or intensify locally. 3. Erosion processes have a typical tendency to expand or increase. 4. A general trend toward irreversible degradation.

- Erosion risk mapping uses erosion risk scores to show where there is a high risk of erosion. This allows you to prioritize protection measures and visualize the areas at risk of erosion.
- Selection of conservation measures: Appropriate soil conservation measures can be selected for each erosion-prone area based on the erosion risk mapping. These measures may include terracing, contour plowing, improved plant cover, soil management techniques, and engineering structures.
- Finally, the selected protective measures are implemented, monitored, and tested for their effectiveness in minimizing erosion risk.

3. Results and Discussion

3.1. Erosion Potential Assessment

The IntErO model calculates the sediment supply and the maximum discharge in the R'mel catchment area. Table 6 shows the results obtained after applying this model. According to the symmetry coefficient A (0.67), the catchment can experience large flood waves. The coefficient G of 3.20 indicates that the drainage network is very dense. The Isrvalue of 479.65% suggests the catchment has almost vertical slopes. The Z-value of the catchment area of 1.424 indicates that it is damage category I. The erosion process is excessive due to the type of erosion; in this case, it is mixed erosion. According to Gavrilovic, a watershed with a value of 1101.36 m³/km² is classified as category III, which indicates moderate to severe surface erosion.

Table 6. Analysis of the current situation using IntErO.

Parameters	Symbols	Values	Units
The river basin shape coefficient.	A	0.41	
Watershed development coefficient.	m	0.59	
The average breadth of a river basin.	B	3.7	km
The river basin A's symmetry.	a	0.67	
The density of the basin's river network.	G	3.2	km/km ²
The tortuousness of the river basin.	K	1.68	
Average river basin elevation.	Hsr	255.19	m
The river basin's average elevation difference.	D	243.19	m
Decrease in the typical river basin.	Isr	479.65	%
The elevation of the river basin's local erosion base.	Hleb	560	m
Coefficient of the river basin relief's erosion energy.	Er	73.6	
Coefficient of permeability in the area.	S1	0.86	
Coefficient of the cover of vegetation.	S2	0.74	
Water retention in influx is presented analytically.	W	0.7704	m
Water flow's potential for energy during torrential downpours.	2gDF ^{1/2}	405.14	m km s
Maximum outflow in the river basin.	Qmax	81.51	m ³ s ⁻¹
Coefficient of temperature.	T	1.36	
Coefficient of erosion in the river basins.	Z	1.424	
Erosion material produced in the river basin.	Wgod	169,137.6047	m ³ /god
Coefficient for the retention of deposits.	Ru	0.224	
Actual losses in soil.	Ggod	37,886.82	m ³ /god
Actual losses of soil per km ² .	Ggod/km ²	1101.36	m ³ /km ² god

The degree of soil protection is assessed using the parameter Xa. The values for the soil protection coefficient Xa range from 0.05 to 0.9. A significant part of the catchment area had to be adequately protected, as 35.69% of the area had values for Xa on bare soils and plowed fields above 0.8. Lower Xa values correspond to some units of old dense afforestation, dense scrubland, and dense deciduous forest, which account for 34.5% of the basin. This value shows that one-third of this catchment is developed, slightly reducing erosion. Degraded forests and scrubland represent mean values of Xa in the remaining catchment (29.61%). Using the erodibility coefficient Y, the IntErO model evaluates the erodibility of the soil. The soil type and the lithology influence the soil erodibility (Y). The study region's lithological

and pedological maps were classified according to the terminology of the IntErO program. The soils of this catchment have an average erodibility in 50% of the catchment, a high erodibility in 43.26%, and a very high erodibility in 6.74% of the catchment. The parameter ϕ in this model expresses how far the erosion forms extend. It is a numerical representation of an evident and exposed erosion process. The values assigned to this component by Gavrilovic [63] have been applied. At the same time, forests and permanent vegetation cover 56.84% of the surface, 32.6% of the basin is subject to surface erosion, 2.34% to erosion by creeks and gullies, and 8.22% to deep erosion.

The erosion rates determined with the EPM model integrated into the IntErO program are shown in Figure 3. The average sediment production is $1101.36 \text{ m}^3/\text{km}^2/\text{year}$ (Figure 3a) or 13.22 t/ha/year (Figure 3b), with minimum and maximum values between 5 and 300 t/ha/year . This uniform conversion is intended to compare the results with erosion studies in the Moroccan Rif region. Most of these studies give the results in t/ha/year , while the EPM-IntErO models are not widely used in Morocco [20,64].

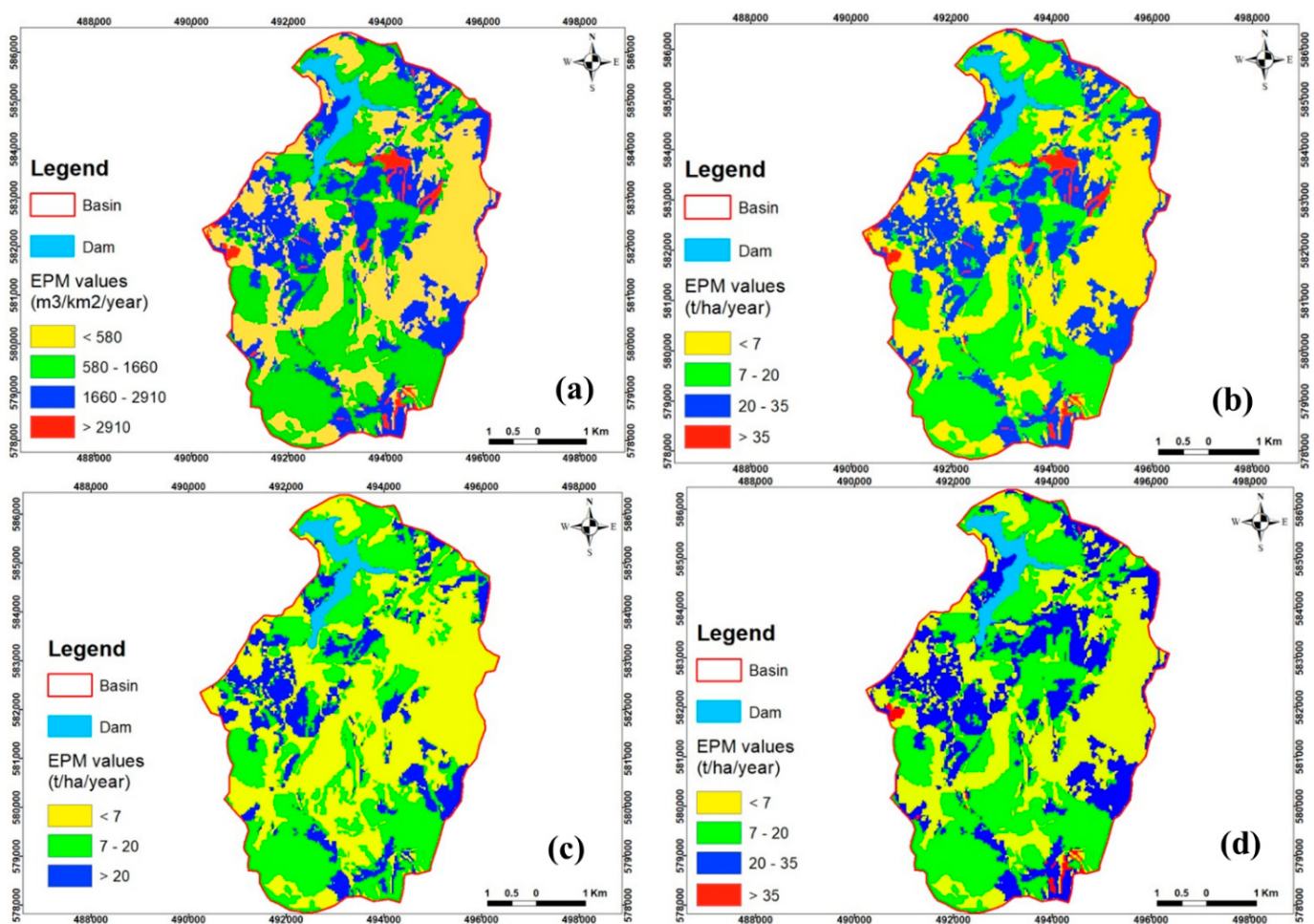


Figure 3. Erosion rates were obtained for the current situation in (a) $\text{m}^3/\text{km}^2/\text{year}$, (b) t/ha/year , (c) for reforestation in Scenario 1, (d) cropping and plowing in Scenario 2 Compared to other sections of the Moroccan Rif, the average erosion rate in the R'mel basin is low. For example, the average rate in the Nakhla catchment is 38.7 t/ha/year [65], while the RUSLE and SWAT models in the Arbaa Ayacha catchment showed 25.77 t/ha/year and 28.09 t/ha/year , respectively [29]. Erosion in the Raouz catchment area is estimated at 26.6 t/ha/year using remote sensing [66] and 16.53 t/ha/year using the RUSLE model [67]. These differences are mainly explained by the characteristics of the catchment area and the numerous interventions and developments carried out in the R'mel catchment area to maintain the dam and the downstream port.

The LULC parameter plays an important role. Over 60% of the R'mel catchment is covered by land uses that limit erosion, including dense and moderately dense forests, scrubland, and afforested areas. Moreover, the lithological substrate of the basin is mainly composed of fractured and compact erosion-resistant rocks such as tight carbonate rocks, sandstones, and flysch. In contrast, only a tiny part of the basin contains friable lithologies like marls and fluvial deposits. Consequently, anthropogenic activities, such as quarrying, are assumed to be the leading cause of erosion rates and the source of sediments moving downstream from the basin. These results highlight the need to analyze the basin's physico-chemical characteristics and assess each parameter's impact and contribution to erosion rates.

3.2. Effect of Basin Geomorphological Conditions

Bare areas and quarries, mainly located in the central zone of the basin, are the leading cause of excessive erosion (Figure 4a). The dense vegetation largely contributes to the low sediment input (34%). Open scrublands and agricultural land are essential in developing moderate erosion processes [68,69]. These observations also become apparent when analyzing the impact of erosion forms on sediment production (Figure 4c). Indeed, the areas exploited by quarries have the highest percentage in the excessive erosion class. Conversely, the regions stabilized by dense vegetation and afforestation mitigate the spread of erosion processes and ensure the stability of a considerable part of the basin (30%).

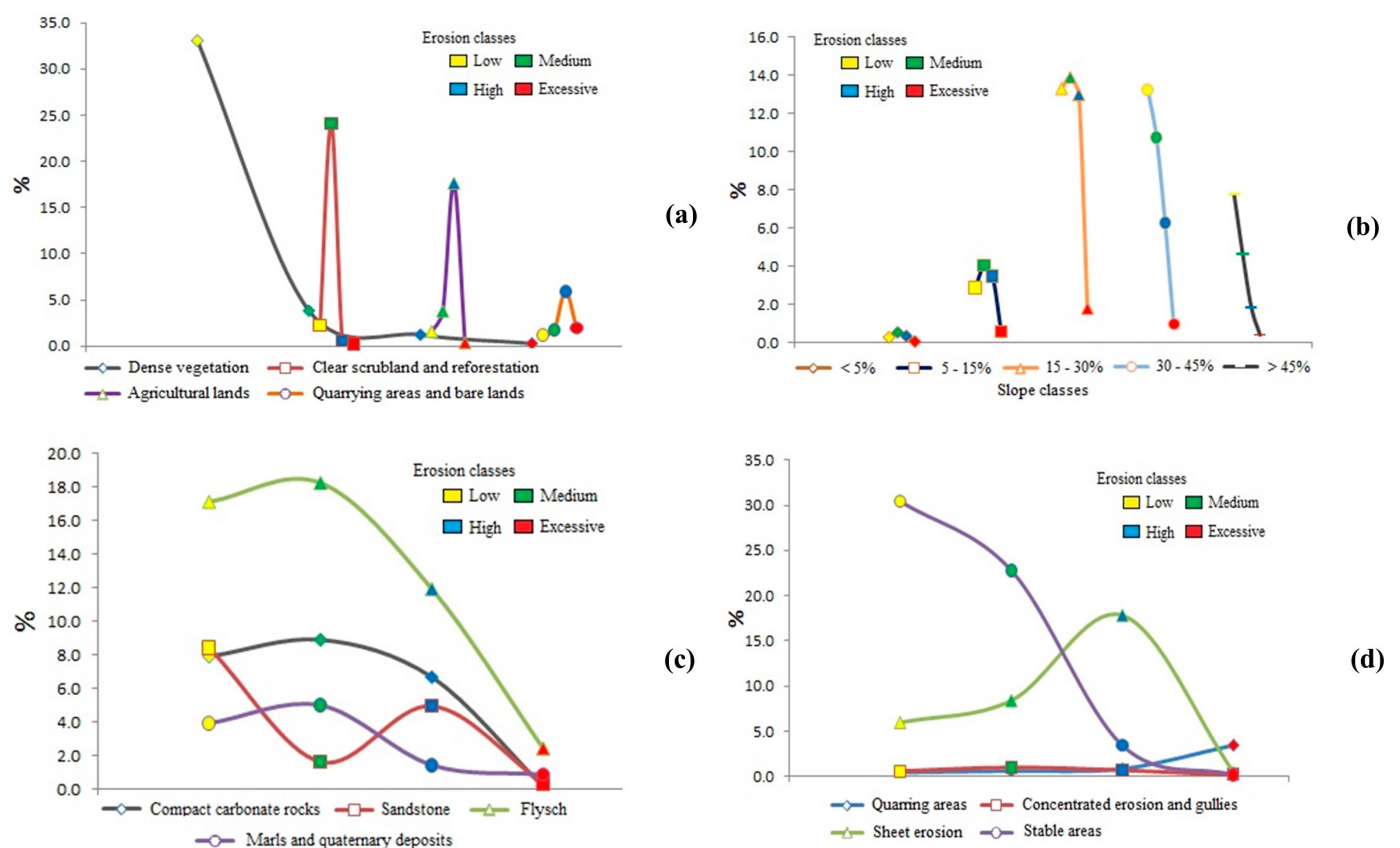


Figure 4. Analysis of erosion-contributing factors to the erosion rate, (a) LULC, (b) slope classes, (c) lithology, (d) forms of erosion.

The other erosion classes generate more particles in the study area than the slope class (0 to 15%). Due to the combination of this component and other variables that determine the amount of sediment production, areas with a slope of 15 to 30% are most likely to be affected by erosion (Figure 4b). This slope class is associated with poorly developed, highly erodible soils in the basin's center and downstream. The lithology in this part of the

basin is essentially marble and clay, and all formerly vegetated areas have been replaced by agriculture.

All these features favor large amounts of sediment and accelerate the erosion process. However, slopes with more than 45% inclination, especially upstream in the basin, favor small amounts of sedimentation. In this area, erosion is limited by the extensive regeneration of matorral shrubs, deciduous vegetation, lithosols, and sandstones. The erosion-limiting effect is known for these lithologies and land use patterns [29,70]. The steep slope, dense vegetation, and hard rock limit sediment production in this case.

3.3. Soil Erosion Scenarios

Analyzing factors controlling erosion in the catchment has shown that quarries are the primary activity responsible for erosion and the main sediment source. Two simulation scenarios were investigated to mitigate the impact of the quarry on the erosion process in the study area. The first scenario (Table 7), which involved replacing the quarries with dense vegetation through afforestation, resulted in a significant reduction in erosion rates, which decreased from 13.22 to 8.44 t/ha/year, a decrease of 4.78 t/ha/year (Figure 3c).

Table 7. Analysis of Scenario 1 (reforestation) using IntErO.

Parameters	Symbols	Values	Units
The river basin shape coefficient.	A	0.41	
Watershed development coefficient.	m	0.59	
The average breadth of a river basin.	B	3.7	km
The river basin A's symmetry.	a	0.67	
The density of the basin's river network.	G	3.2	
The tortuousness of the river basin.	K	1.68	
Average river basin elevation.	Hsr	255.19	m
The river basin's average elevation difference.	D	243.19	m
Decrease in the typical river basin.	Isr	479.65	%
The elevation of the river basin's local erosion base.	Hleb	560	m
Coefficient of the river basin relief's erosion energy.	Er	73.6	
Coefficient of permeability in the area.	S1	0.86	
Coefficient of the cover of vegetation.	S2	0.69	
Water retention in influx is presented analytically.	W	0.7704	m
Water flow's potential for energy during torrential downpours.	2gDF ^{1/2}	405.14	m km s
Maximum outflow in the river basin.	Qmax	75.72	m ³ /s
Coefficient of temperature.	T	1.36	
Coefficient of erosion in the river basins.	Z	1.056	
Erosion material produced in the river basin.	Wgod	10,7971.3	m ³ /god
Coefficient for the retention of deposits.	Ru	0.224	
Actual losses in soil.	Ggod	24,185.57	m ³ /god
Actual losses of soil per km ² .	Ggod/km ²	703.06	m ³ /km ² god

According to the asymmetry coefficient A, severe floods are possible in the watershed. The drainage network is highly dense according to the G value of 3.20. The watershed's slopes are steep and nearly vertical, according to the Isr value of 479.65%. Based on a Z-value of 1.056 (Scenario 1) and 1.366 (Scenario 2), the watershed is classified as Destruction Category I. The erosion strength is considerable, and the type of erosion is surface erosion (Scenario 1) and mixed erosion (Scenario 2). Gavrilovic classifies the basin as category IV, i.e., an area of low erosion, with a value of 703.74 m³/km²god (Scenario 1), and as category III, a region of medium erosion, with a value of 1035.62 m³/km²god (Scenario 2).

It should be noted that reforestation requires a lot of time until the trees reach full maturity and can develop their protective effect. The second scenario (Table 8), which involves the conversion of quarries to cropland, also reduced erosion rates slightly by almost 1 t/ha/year, from 13.22 to 12.42 t/ha/year (Figure 3d). Although this approach is less practicable than reforestation, it has the advantage that it takes less time to convert

quarries into agricultural land. The conversion of quarries into arable land is less effective than afforestation in erosion control. However, it has the advantage that the conversion and restoration of quarry areas take less time.

Table 8. Analysis of Scenario 2 (cropping and plowing) using IntErO.

Parameters	Symbols	Values	Units
The river basin shape coefficient.	A	0.41	
Watershed development coefficient.	m	0.59	
The average breadth of a river basin.	B	3.7	km
The river basin A's symmetry.	a	0.67	
The density of the basin's river network.	G	3.2	
The tortuousness of the river basin.	K	1.68	
Average river basin elevation.	Hsr	255.19	m
The river basin's average elevation difference.	D	243.19	m
Decrease in typical river basin decrease.	I.sr	479.65	%
The elevation of the river basin's local erosion base.	Hleb	560	m
Coefficient of the river basin relief's erosion energy.	Er	73.6	
Coefficient of permeability in the area.	S1	0.86	
Coefficient of the cover of vegetation.	S2	0.74	
Water retention in influx is presented analytically.	W	0.7704	m
Water flow's potential for energy during torrential downpours.	$2gDF^{1/2}$	405.14	mkms
Maximum outflow in the river basin.	Qmax	81.51	m ³ /s
Coefficient of temperature.	T	1.36	
Coefficient of erosion in the river basins.	Z	1.366	
Erosion material produced in the river basin.	Wgod	158,888.9	m ³ /god
Coefficient for the retention of deposits.	Ru	0.224	
Actual losses in soil.	Ggod	35,591.11	m ³ /god
Actual losses of soil per km ² .	Ggod/km ²	1034.62	m ³ /km ² god

Both scenarios are critical to reducing erosion, protecting the downstream dam and harbor from the adverse effects of erosion, and promoting the restoration of regional ecosystem balance through reintroducing native fauna and flora. The combination of these approaches would enable more sustainable management of the quarry while maintaining water quality and biodiversity and helping to protect vital infrastructure.

3.4. Quantitative Analysis of Erosion Trends in the Basin

To assess these trends and anticipate potential impacts, the applied PAP/RAC method allowed us to simulate future regional developments regarding degradation or stabilization [32,33,61]. The findings of this study show that the areas occupied by quarries (Figure 5a,b) exhibit a pronounced trend toward irreversible degradation, mainly concentrated in the central and upstream sections of the watershed where unprotected rocks predominate (Figure 6).

A widespread trend of widening or intensification of erosion was observed in areas with deep gullies, especially downstream of the basin. The zones around the dam are also moderately threatened (Figure 5c), indicating a localized trend of widening or intensifying erosion processes and highlighting the need for erosion control measures in this location. In contrast, the rest of the watershed appears to be relatively well preserved, with low erosion conditions and a trend toward stabilizing and regressing the spatial distribution of erosion processes (Figure 6).

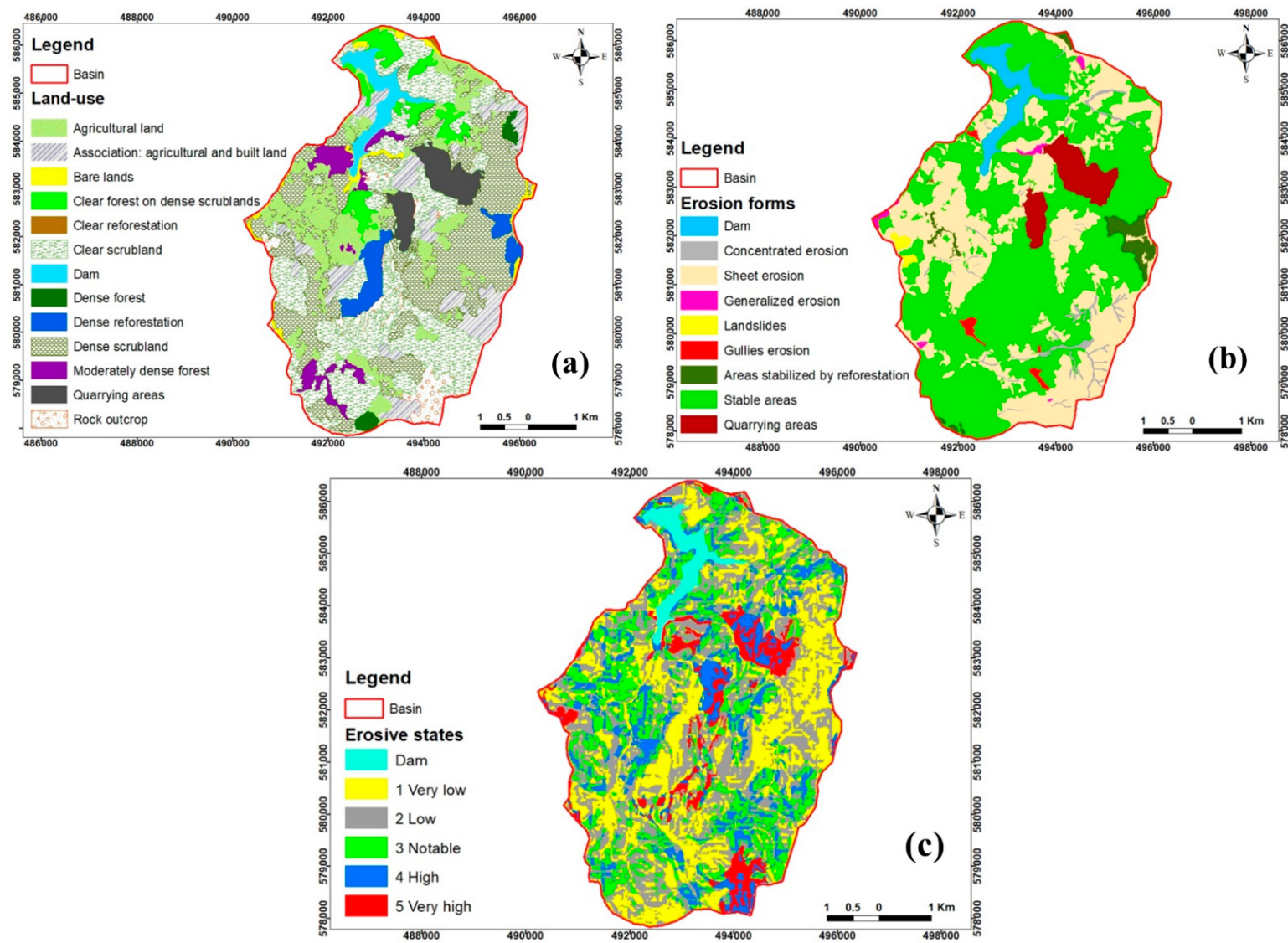


Figure 5. Results of erosion trends: (a) LULC map, (b) forms of erosion, and (c) states of erosion.

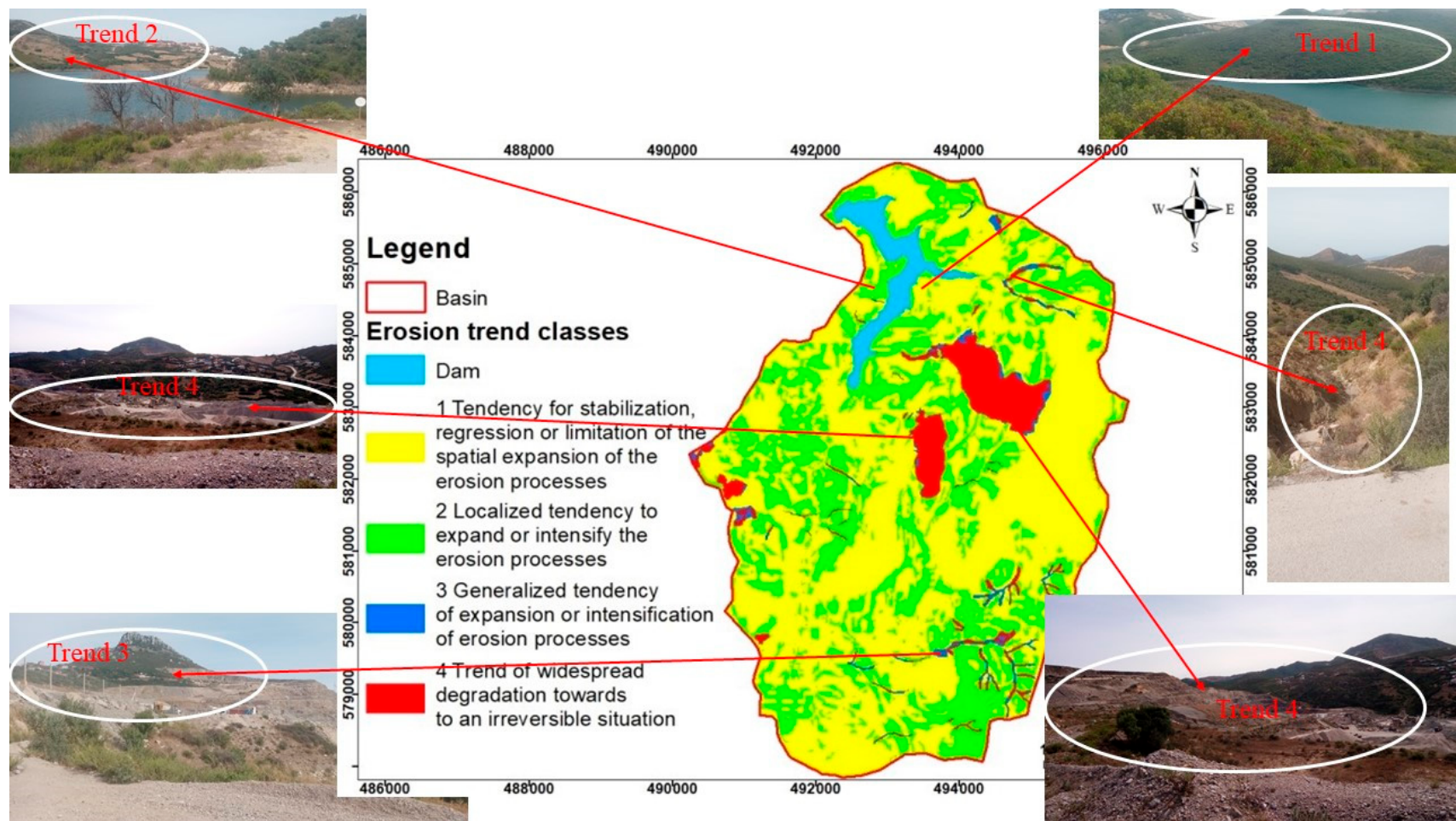


Figure 6. Erosion trend classes map in R'mel watershed.

4. Conclusions

Applying the IntErO algorithm based on the EPM model has proven to be a valuable tool for assessing sediment production under Moroccan environmental conditions. The study showed an average sediment production rate of 13.22 t/ha/an. Quarry areas were identified as the main contributors to sediment production, significantly influencing erosion and deposition downstream. These results are consistent with the qualitative model used by PAP/RAC, which shows a worrying trend of irreversible degradation in the quarry areas. In addition, the analysis has demonstrated that IntErO's ability to simulate quarry rehabilitation scenarios supports reforestation as an effective strategy to mitigate erosion. This approach helps control erosion, promotes ecosystem restoration, and contributes to the recovery of local flora and fauna in the catchment. The study found that several factors influence sediment mobilization within the catchment, including land use, lithology, erosion forms, slopes, and rainfall. The results highlight the robustness and effectiveness of the IntErO algorithm in erosion studies and sediment assessment under Morocco's unique environmental conditions. This research provides valuable insights for informed decision-making and promoting sustainable regional land management practices. By facilitating the conservation and restoration of critical ecosystems, the study contributes to the global scientific community and has broader implications for land management and erosion control research.

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