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# MEASUREMENT AND MODELLING OF SOIL EROSION USING THE IntErO AND GAVRILOVIC MODEL (EPM) BY USING GIS WITHIN ASSIF MELLOUL BASIN, CENTRAL HIGH ATLAS, MOROCCO

## SUMMARY

Water erosion is a major environmental threat that contributes to soil degradation, reduced land productivity, and damage to infrastructure, particularly in mountainous and semi-arid areas. The High Atlas of Morocco represents a critical erosion hotspot, where steep slopes, heterogeneous lithology, and complex hydrological networks amplify erosion susceptibility. Despite its vulnerability, no spatially explicit erosion modelling has previously been applied to the Assif Melloul basin, making this study a novel contribution to erosion assessment in the region. This research presents the first integrated application of the IntErO and Erosion Potential Method (EPM) by using GIS techniques in this basin to quantify soil loss, identify the driving factors, and generate erosion severity maps. The methodology combines morphometric analysis, thematic factor integration (e.g., slope, rainfall erosivity, soil sensitivity, vegetation cover), and field validation. The IntErO and EPM models generated spatial maps of erosion intensity (W), supported by coefficients such as erosion dynamics (φ), threshold index (Z), and vegetation protection (Xa). Results show that nearly 90% of the basin is affected by severe to excessive erosion, with the "very severe" class covering 38%. Production of erosion material exceeds 16,000 m³/km²/year, predominantly in high-altitude, poorly vegetated zones. Furthermore, NDVI-based land cover

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analysis between 1991 and 2021 reveals persistent vegetation loss, with bare soil occupying 76% of the area, significantly lowering the Xa and Y factors and intensifying erosion in steep terrain. This study also conducted a correlation analysis, revealing strong relationships between soil loss and slope (r = 0.80), soil sensitivity (r = 0.80), and erosion dynamics (r = 0.80), while vegetation protection showed a moderate negative correlation (r = -0.60). These results compared with Mediterranean erosion trends but represent a new contribution through detailed risk classification maps and a validated spatial framework for erosion forecasting. As an innovative step, this study introduces a classification of soil loss rate domains, offering a novel approach to precisely delineate zones that are most vulnerable to erosion processes. The findings highlight the urgent need for adaptive soil conservation, land-use planning, and ecological restoration efforts in Morocco's high mountain environments.

**Keywords:** Soil loss rate, IntErO model, Erosion Potential Method, Vegetation cover dynamic, Assif Melloul basin, High Atlas, Morocco, GIS

## INTRODUCTION

Soil erosion is a critical environmental issue in mountainous and semi-arid regions, where steep topography, fragile lithology, irregular rainfall, and sparse vegetation collectively contribute to land degradation and the depletion of natural resources (Sabri *et al*., 2022). In Morocco, particularly within the Central High Atlas; soil erosion presents a serious threat to ecosystem stability, agricultural productivity, and water resource sustainability (Ouakhir *et al*. 2023; 2025; Sabri *et al*., 2022). The situation continues to worsen in Moroccan mountainous zones, where specific soil erosion rates range between 500 and 1000 t/km²/year (Nait Taleb., 2025). This degradation predominantly affects the uppermost soil horizons, which are rich in organic matter, leading to a decline in soil fertility, crop yields, and ultimately resulting in land impoverishment (Modeste *et al*. 2016; Ennaji *et al*. 2024). The Assif Melloul basin, situated in the Central High Atlas, demonstrates such vulnerability; it is marked by rugged terrain, erodible lithology, and intense precipitation events, all of which make it highly susceptible to severe soil loss processes.

This basin is particularly sensitive to erosion and flooding, which negatively affect both natural ecosystems, and human activities (Goumih *et al*. 2022). The consequences are evident in the reduction of arable land, already limited in extent and quality, and the accelerated sedimentation of hydraulic and transport infrastructure downstream (Amraoui *et al*., 2024). These challenges raise concerns about the effectiveness of conventional management approaches, which often rely on short-term mechanical interventions that fail to address the root causes of soil degradation. They also highlight the urgency of developing more innovative, sustainable, and locally adapted solutions. Thus, this study is part of a broader effort to identify effective strategies to combat erosion, conserve soil resources, and restore the ecological balance of the Imilchil valley. Consequently, the quantification and mapping soil erosion risk is important for creating an effective soil and water conservation strategies. Several models have been developed to assess erosion intensity, including empirical, statistical, and physically based approaches. Among them, the IntErO Model and the Gavrilovic method, also known as the Erosion Potential Method (EPM), has been widely applied in various Mediterranean and mountainous environments due to its simplicity, adaptability, and capacity to integrate diverse environmental parameters (Gavrilovic, 1972; Gavrilovic, 1988; Dragicevic *et al*. 2011; Ennaji *et al*. 2022). The IntErO and EPM model considers factors such as land use, lithology, slope, erosion processes, and vegetation cover to estimate the annual sediment yield, and categorize erosion risk levels (Ouakhir *et al*. 2022; Spalevic *et al*., 2020).

The integration of Geographic Information Systems (GIS) with the IntErO and EPM model has greatly enhanced the spatial analysis of erosion-prone areas. GIS facilitates the handling of spatial distributed data and supports the visualization and interpretation of model outputs, enabling a more accurate and efficient assessment of erosion patterns (Bazzoffi *et al*. 2010; Nadia *et al*. 2024, Mohammadi *et al*., 2021). Thus, the IntErO and the EPM model is applied within the Assif Melloul basin, provided a valuable tool for evaluating the spatial distribution of soil erosion and informing land management practices.

The main purpose of this paper is to assess soil erosion within the Assif Melloul basin by using the IntErO and the Erosion Potential Method (EPM) integrated with remote sensing and GIS techniques. The specific objectives are to: (i) identify and analyze the key environmental factors influencing soil erosion in this mountainous watershed; (ii) estimate the potential annual soil loss; and (iii) map the spatial distribution of erosion risk zones. This is the first erosion modeling conducted in the Assif Melloul basin, situated in the Central High Atlas of Morocco; an area marked by complex geomorphology, diverse lithology, and acute environmental sensitivity. The originality of this work lies in its integration of multi-source geospatial data (including NDVI, DEM, and geological maps), long-term vegetation dynamics (1991–2021), and field-based validation within the IntErO model based on the EPM framework. Furthermore, the study delivers a set of newly developed erosion severity maps, providing detailed spatial zoning of soil loss and enabling quantitative forecasting in previously unmapped terrain. By linking morphometric, climatic, and ecological indicators, this research advances erosion modeling in Mediterranean mountainous environments and supports the design of targeted, data-driven soil conservation strategies aimed at sustainable land and water management in the High Atlas.

## MATERIAL AND METHODS

**Study area.** The Assif Melloul basin is strategically located in the axial boundary between the Central High Atlas, and the Eastern High Atlas of Morocco, which gives it notable hydrological and geomorphological importance (Figure 1). Besides, Assif Melloul River is the main tributary of the Oued El Abid through the Ahançal river. The studied basin plays an important role in the fluvial system of the big Oued Oum Err Bia River. The basin is situated between longitude x, 428000

W and 500000 E, and latitude y, 132000 S and 177000 N, placing the basin in a well-defined geographical context (Figure 1). The basin covered a total area of approximately 1773 km², and constitutes an important section of the upper part of the Oum Err Bia watershed. The study area is surrounded by three major hydrological basins: The Ziz-Ghris to the southeast, the Dadès basin to the south, and the Oum Er Bia basin to the north and west.

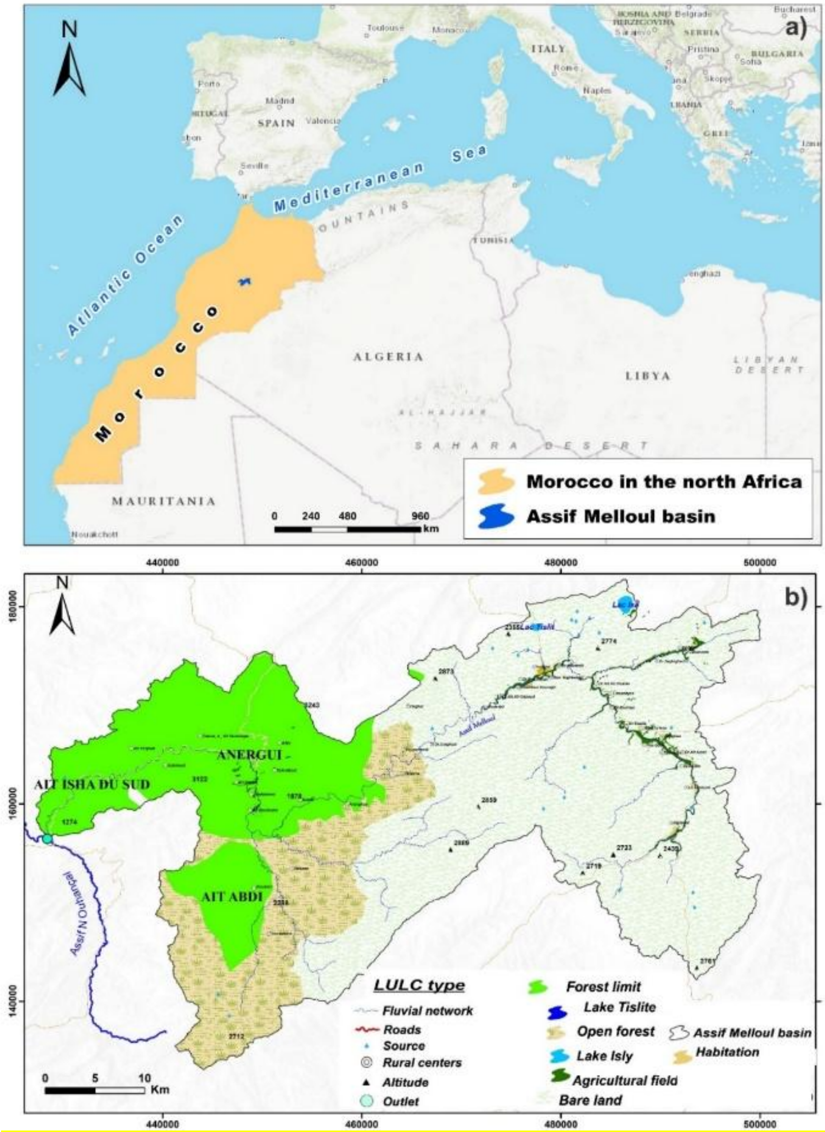


Figure 1. a) Presentation of study area in Morocco and b) land use land cover dynamic of Assif Melloul basin

This geographical situation provides to this area a role as a hydrological intersection, integrating the contributions of mountain precipitation and influencing the downstream river regimes (Ouakhir & El Ghachi, 2023). This basin is characterized by complex topography, varied geological formations, and a diverse hydrographic network. Geological formations are ranged from the Upper Triassic to the Quaternary, reflecting the complex geological evolution of the study area.

**Data Sources and preprocessing.** The datasets employed for applying the IntErO and the Erosion Potential Method (EPM) in the Assif Melloul basin, as outlined in Table 1, offer a robust and multidisciplinary basis for accurately modelling soil erosion dynamics. These include topographic inputs derived from a 30-meter resolution Digital Elevation Model (DEM), which facilitated the extraction of key morphometric parameters such as slope gradient (Ja), elevation, and drainage patterns. Furthermore, climatic variables; specifically, long-term averages of temperature and precipitation spanning the period 1988–2021 were sourced from the Hydro-Agency of Oum Er-Rbia (HAOMERB). These data were crucial for computing the temperature coefficient (T), a parameter that captures the influence of climatic aggressiveness on erosion intensity across the study area.

Table 1. Sources and characteristics of the used Data for the IntErO & EPM model

| Data | Description / Characteristics | Source |
|---|---|---|
| Digital Elevation Model | 30 m resolution; slope, height, drainage | SRTM DEM (processed in GIS) https://www.usgs.gov |
| Climatic Data | Rain gauge stations of Tilouguit, Zouit Ahenssal, Ait Ouchene, Louggagh, Sggat, Tabouazamt (1988–2021) | HAOMERB (Beni Mellal /Morocco) http://abhoer.digiup.ma/ |
| Land Use / Vegetation Index (NDVI) | Derived from Landsat 8; 30 m; Xa factor | USGS Earth Explorer https://earthexplorer.usgs.gov |
| NDVI Formula | NDVI = (NIR - RED) / (NIR + RED); NIR=Band 5, RED=Band 4 | Tucker (1979) |
| Landsat TM8 | Bands: RED (B4), NIR (B5); 30 m; NDVI & land use | USGS Earth Explorer https://earthexplorer.usgs.gov/ |
| Geological Map | Sheets: Imilchil, Zaouiat Ahansal, etc.; 1:100,000 scale | Ministry of Energy, Mines, Morocco https://www.environnement.gov.ma/ |
| Field Survey Data | Validation of slope, vegetation, lithology, erosion forms | Field Campaigns (2022–2023) |

Vegetation cover and land use were assessed using satellite imagery from Landsat 8 OLI/TIRS (TM8), with a 30 m spatial resolution, allowing the calculation of the soil protection factor (Xa) based on the Normalized Difference Vegetation Index (NDVI).

The NDVI is computed using the formula (Eq.1):

$$NDVI = \frac{NIR-RED}{NIR+RED} \quad (1)$$

where NIR corresponds to Band 5 and RED to Band 4 of Landsat 8.

This index provides a quantitative measure of vegetation density, which is critical for evaluating erosion resistance. Geological data were derived from detailed 1:100,000-scale geological maps of Imilchil, Zaouiat Ahansal, Tounfit, Tinghir, Tinjdad, and Beni Mellal, which informed the classification of lithology and sediment retention factors. Finally, extensive field surveys conducted between 2022 and 2023 provided validation for the spatial datasets and allowed ground-based assessment of erosion forms, slope conditions, and vegetation degradation.

Together, these datasets support a robust, spatially explicit analysis of erosion risk across a complex mountainous watershed, as presented in Table 1.

**Methodological approach of the IntErO and the EPM model**. Several quantitative and qualitative models have been developed to assess potential water erosion, including RUSLE, PAP/CAR, and SWAT. Among them, the Erosion Potential Method (EPM), developed by Gavrilovic in the 1950s, has been widely adopted, particularly in the Mediterranean region for its reliability in mountainous and data-scarce environments (Gavrilovic, 1959; Bazzoffi, 2014; Chalise *et al*. 2019; Aleksova *et al*., 2023). In this study, we employed the classical empirical approach proposed by Gavrilovic (1972), and new IntErO model (Spalevic, 2011) which combines qualitative indicators (e.g., slope, vegetation cover, soil sensitivity, land use) with quantitative parameters (e.g., precipitation, elevation, and temperature) to calculate the erosion coefficient (Z) and ultimately estimate annual soil loss (W) (Spalevic, 2019).

As explained in Figure 2, the adopted approach was implemented within a GIS environment, allows to derive and map each IntErO and EPM factor spatially; including slope gradient (Ja), soil sensitivity (Y), land cover protection (Xa), erosion dynamics (φ), and the threshold coefficient (Z).

The integration of these layers led to the generation of final outputs such as the soil loss (W) map and erosion risk zoning map. This modelling strategy was selected based on its proven suitability for rugged mountainous watersheds, such as the Assif Melloul basin, and its ability to produce reliable erosion estimates even in areas with limited ground-based data. The geospatial implementation further enhances the model’s capacity to visualize erosion dynamics and support targeted soil conservation planning.

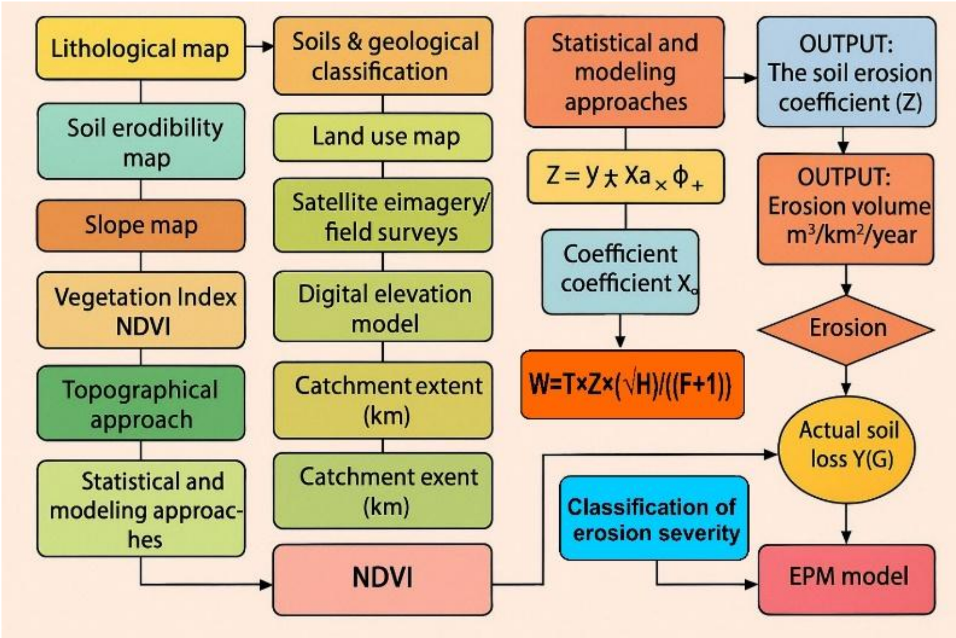


Figure 2. Flowchart for applying the IntErO and EPM model under GIS environment

This modelling considered as a system enhances the understanding of its functioning and allows for the prediction of its future developments in response to various issues (Dresch *et al*., 2015). It is crucial in environmental studies, particularly for assessing soil water erosion. The proposed diagram illustrates the method for studying the dynamics of water erosion in the Assif Melloul Watershed (B.V.A.M) using the IntErO (Spalevic, 2011) and the Erosion Potential Model EPM (Gavrilovic, 1972; Chaaouan *et al*. 2013). This models are based on two approaches: a qualitative evaluation, which relies on coefficients (γ, Xa, φ, Ja) to estimate an erosion coefficient (Z) and determine potential erosive states, and a quantitative evaluation, which uses coefficients (P, T°, C, Z) to calculate an erosion coefficient (W), allowing for the quantification of soil loss in m³/km²/year.

The LS factor is a topographic parameter that quantifies the combined effects of slope length (L) and slope steepness (S) on soil erosion potential. This factor is critical in hydrological and erosion models as it reflects how terrain configuration influences surface runoff and sediment transport. In this study, the LS factor was calculated using Moore and Wilson’s (1992) revised equation, which is well-suited for digital terrain analysis in mountainous environments. The formula used is (Eq.2):

$$LS = (0.4 + 1) \times \left(\frac{Flow\ Accumulation\ \times Cell\ Size}{22.13}\right) 0.4\ \times (\frac{Sin\ (Slope)^{1.3}}{0.0896} \quad (2)$$

The flow accumulation and slope values were derived from a high-resolution 12.5-meter DEM obtained from the USGS Earth Explorer, which allowed for detailed morphometric analysis across the rugged terrain of the Assif Melloul basin. This formulation accounts for how both long hillslopes and steep gradients intensify erosion by increasing runoff velocity and erosive force. Higher LS values are typically concentrated in concave slopes, convergent flow zones, and escarpments areas where water gathers and accelerates downslope.

These combined approaches provide a comprehensive assessment of water erosion risks in the studied watershed (Kosmas *et al*. 1997). The Erosion Potential Model (EPM), developed by Gavrilovic in the 1950s, and after modernized in use IntErO model by Spalevic (2011) are widely used empirical approaches for estimating soil loss due to water erosion, particularly in mountainous and Mediterranean environments (Panagos *et al*., 2015). The models integrate both qualitative and quantitative assessments of erosion risk by incorporating climatic, geological, land use, and topographical parameters. The central formula for calculating soil loss is (Eq. 3):

$$W = T \times Z \times \frac{\sqrt{H}}{(F+1)} \quad (3)$$

where W represents the annual soil loss ($m^3/km^2/year$), T is the temperature coefficient (reflecting climatic aggressiveness).

The temperature factor (T) is a critical climatic variable within the IntErO and EPM models, reflecting the influence of thermal conditions on erosion processes, particularly in mountainous Mediterranean regions where seasonal contrasts are marked. In this study, the T coefficient was derived using a combination of meteorological data obtained from the Hydraulic Agency of Oum Er-Rbia (HAOMERB) and thermal infrared bands from Landsat 8 satellite imagery.

Ground-based temperature records were collected from surrounding weather stations covering a long period (i.e., > 30 yr; from 1988 to 2021) and interpolated to represent the spatial variation within the Assif Melloul basin. In parallel, Landsat 8 Thermal Infrared Sensor (TIRS) data were processed to retrieve surface land temperature, supporting spatial calibration across topographic gradients. W classification as explained by Gavrilovic, (1988) at regional scale especially in Mediterranean contexts; is presenting in Table (2) below.

Table 2. Classification of erosion severity based on W factor

| W value ($m^3/km^2/yr^{-1}$) | Erosion severity class |
|---|---|
| < 5000 | Very low erosion |
| 5000 – 8000 | Low erosion |
| 8000 – 12000 | Moderate erosion |
| 12000 – 16000 | High erosion |
| > 16000 | Very High/ Catastrophic erosion |

The annual temperature coefficient (T) was calculated using the following empirical formula, derived from remote sensing and climatological research (Eq.4):

$$T = 0.1 = t_0) + 0.1 \quad (4)$$

where $t_0$ represents the average annual temperature in °C.

This formulation provides a more accurate representation of the temperature's impact on erosion intensity, especially in high-altitude terrains of the Central High Atlas. Higher values of T are associated with greater climatic aggressiveness, which typically leads to increased runoff and surface erosion, particularly in areas with limited vegetative protection. Z is the erosion coefficient, derived from qualitative factors such as vegetation cover, soil resistance, and human activity. H is the average slope height, and F is the sediment retention factor. The coefficient Z is calculated using the formula (Eq.5):

$$\mathrm{Z} = \mathrm{Y} \times \mathrm{Xa} \times (\varphi \times \sqrt{\mathrm{Ja}}) \quad (5)$$

where Y is a coefficient reflecting soil protection, Xa is related to soil erodibility, φ reflects the influence of land cover and human intervention, and Ja is the slope gradient coefficient. This dual approach enables the model to simulate both potential erosion risk and actual soil loss, making it particularly effective for land use planning and conservation practices (Gavrilovic, 1988; Chaaouan *et al*. 2013; Bazzoffi, 2014). Besides, the soil protection factor (Xa) plays a central role in the IntErO and EPM models as it quantifies the ability of vegetation and land cover to reduce erosion. This coefficient integrates both plant cover and land use characteristics, reflecting the resistance offered by the surface to erosive forces. In this study, Xa was estimated using NDVI-derived vegetation data from Landsat 8 and the following empirical equation proposed by Gavrilovic (1972) and adapted by Hembram *et al*. (2019) (Eq.6):

$$Xa = XaNDVI - 0.61) \times (-1.15) \quad (6)$$

where XaNDVI is the Normalized Difference Vegetation Index, which was calculated using the Landsat 8 TM. Based on the EPM classification scheme (Gavrilovic 1972; Lazarevic 1996), the Xa values were interpreted using the following scale, as presented in Table 3.

Table 3 : Xa classification within the IntErO and the EPM model

| Soil cover coefficient | Xa factor levels |
|---|---|
| Dense, mixed, thin and grove forest | 0.05 – 0.20 |
| Scarce bushes, shrubs, and little grove vegetation | 0.20 – 0.40 |
| Deforested and open vegetation, pasture | 0.40 – 0.60 |
| Rained crops, and cultivated areas, damaged pasture | 0.60 - 0.80 |
| Bare land | 0.80 – 1.00 |

Higher Xa values indicate lower protection against erosion, as seen in degraded lands, agricultural plots, and bare slopes. In contrast, lower Xa values correspond to dense vegetative cover with high protective capacity. The Xa map produced in this study allows for spatially explicit identification of erosion-prone zones and supports the formulation of land-use policies aimed at erosion control.

**Validation, correlation and Interpretation.** Field observations were used to validate the IntErO and the EPM model outputs by directly identifying various forms of erosion across the Assif Melloul basin, including gullies, landslides, bank undercutting, sheet erosion, rill erosion, and karstic subsidence features. These ground-truth observations confirmed the spatial relevance of the modelled erosion severity classes.

In addition to field validation, a correlation matrix was constructed using the key factors: slope gradient (Ja), soil sensitivity (Y), vegetation protection (Xa), erosion dynamics (φ), threshold coefficient (Z), and estimated soil loss (W). This matrix was developed in order to assess the statistical relationships among these variables. The analysis helped quantify the degree of influence each factor exerts on overall erosion outcomes and provided valuable insights into potential overlaps or synergies within the structure of the subject models. The matrix revealed strong positive correlations between W, Z, Ja, Y, and φ, confirming that topography, soil erodibility, and erosive dynamics are primary drivers of soil loss in the basin. In contrast, Xa showed a negative correlation with W, reflecting the protective role of vegetation cover.

These findings support the robustness of the models and its relevance for mountainous Mediterranean catchments, where erosion processes are highly influenced by slope morphology and land cover conditions.

## RESULTS AND DISCUSSION

**Soil sensitivity to erosion process (Y).** Precipitation is among the primary factors influencing water erosion, from the initial raindrops to surface runoff and eventually to the main drainage channels (Hao *et al*. 2019). In the absence of a comprehensive database detailing precise rainfall values within the studied basin, we utilized the average annual precipitation values collected and organized from a meteorological station located in central Imilchil, as well as from additional stations situated around the basin's perimeter. These data span a climatic cycle of 30 years. The IntErO and the EPM also relies on this same dataset for the development of the erosion zone map. To avoid redundancy, we briefly explain here the coefficient (P) used in this mode.

The Y factor map of the Assif Melloul basin illustrates the spatial variability in soil sensitivity to water erosion (Figure 3). The basin is predominantly characterized by low to very low sensitivity zones ($Y < 0.4$), particularly in its central and western parts, indicating relatively stable soils with limited susceptibility to erosion. However, several critical areas exhibit high (1.1–1.4) to very high ($Y > 1.4$) sensitivity, especially along steep slopes, ridgelines, and near the fluvial network, notably in the north-eastern, southern, and western fringes of the basin. These high-sensitivity zones are often associated with steep gradients, sparse vegetation, and concentrated surface runoff, making them particularly vulnerable to erosive processes. The figure also shows a strong correlation between altitude and erosion risk, with elevated terrains and areas surrounding major river channels showing increased sensitivity. This spatial analysis underlines the need for targeted soil conservation strategies in erosion-prone sectors, particularly through slope stabilization, reforestation, and sustainable land use practices to reduce land degradation and maintain watershed stability.

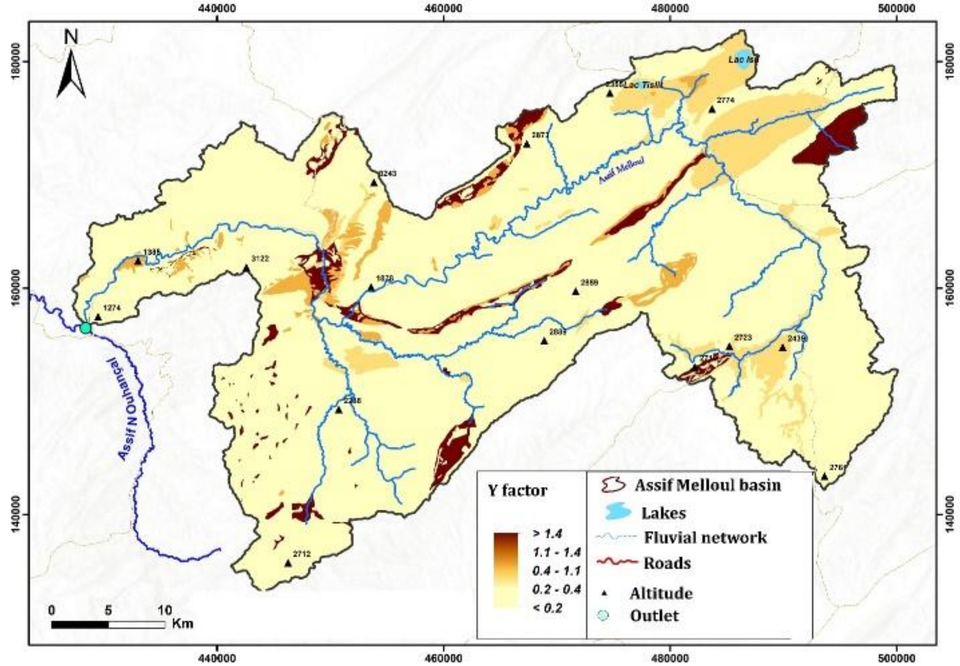


Fig 3. Coefficient (Y) of soil sensitivity to water erosion

**Effect of slope on soil erosion dynamic (Ja).** The Ja factor map illustrates the spatial distribution of slope steepness across the Assif Melloul basin, with values categorized into five classes ranging from flat to very steep terrains (Figure 4).

The highest slope values shown in dark brown, are concentrated primarily along the main ridge lines, mountain flanks, and river incisions, particularly in the central, north-eastern, and south-eastern parts of the basin. These areas reflect extremely rugged topography, where steep slopes contribute significantly to erosion risk and runoff acceleration. In contrast, the flatter areas indicated in light brown to beige, are sparsely distributed and mostly found along valley bottoms and plateau regions, especially around Anergui center, Agoudal, and parts of the outlet zone (1274 m).

The map demonstrates a strong topographic control on hydrological processes within the basin, where steep slopes dominate a large portion of the landscape, amplifying surface runoff, sediment transport, and potential for mass movements. These geomorphological conditions underline the importance of incorporating slope-related factors into soil erosion modelling and watershed management strategies, particularly in the steeply dissected zones of the High Atlas (Figure 4).

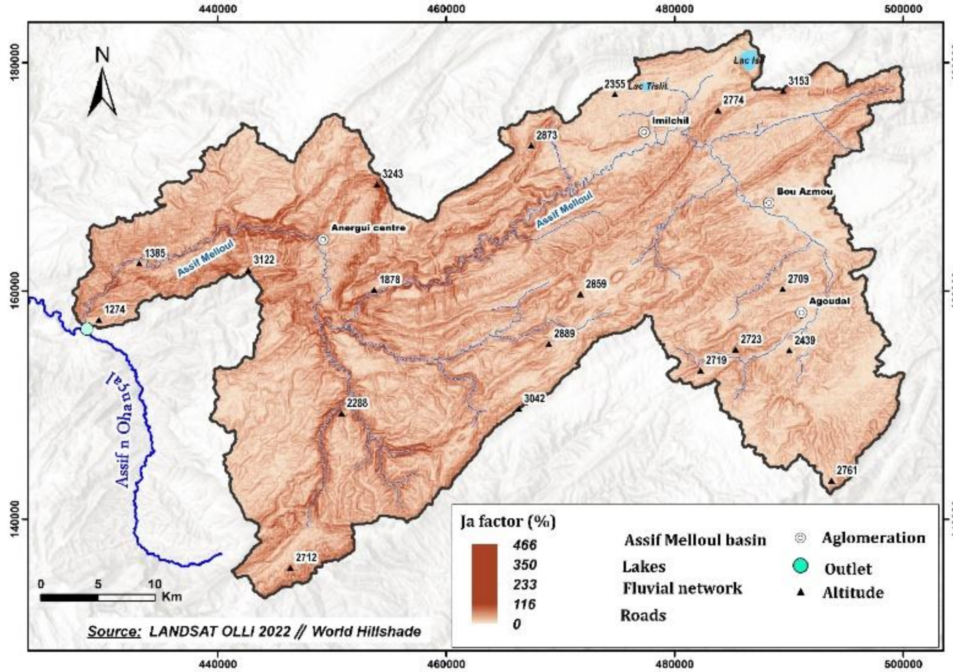

Figure 4. Ja factor of IntErO and EPM model

**Soil conservation and protection (Xa).** The Xa factor map reveals the spatial distribution of soil conservation capacity throughout the Assif Melloul basin (Figure 5). This factor, ranging from -0.09 to 0.45, evaluates the extent to which land cover and vegetation contribute to soil protection against erosion. Higher Xa values (in green and yellow) denote better soil protection, commonly associated with dense vegetation, forested areas, and permanent land cover, while lower or negative values (in purple and pink) indicate poor protective cover and thus higher susceptibility to erosion. The map shows that areas with high Xa values are mainly concentrated along riverbanks, forest patches, and agricultural terraces, particularly in the north-western part of the basin (around 1274–1385 m), and in localized zones near Anergui and Imilchil.

In contrast, widespread low Xa values dominate the southern, central, and eastern parts of the basin, reflecting sparse vegetation and degraded or exposed soils, especially around steep terrain and urban fringes near Agoudal and Bou

Azmou. These patterns suggest a pressing need for targeted soil conservation interventions; including reforestation, sustainable land use, and erosion control measures in zones where protective cover is minimal.

This factor plays a crucial role in controlling soil erosion, as areas with higher Xa values reduce the kinetic energy of raindrops and surface runoff, thereby minimizing soil detachment and transport. Conversely, low Xa zones accelerate erosion processes due to the absence of effective vegetative barriers and root systems that stabilize the soil. Overall, the map highlights the critical role of vegetation in mitigating soil loss and guiding land management strategies within the Assif Melloul watershed (Figure 5).

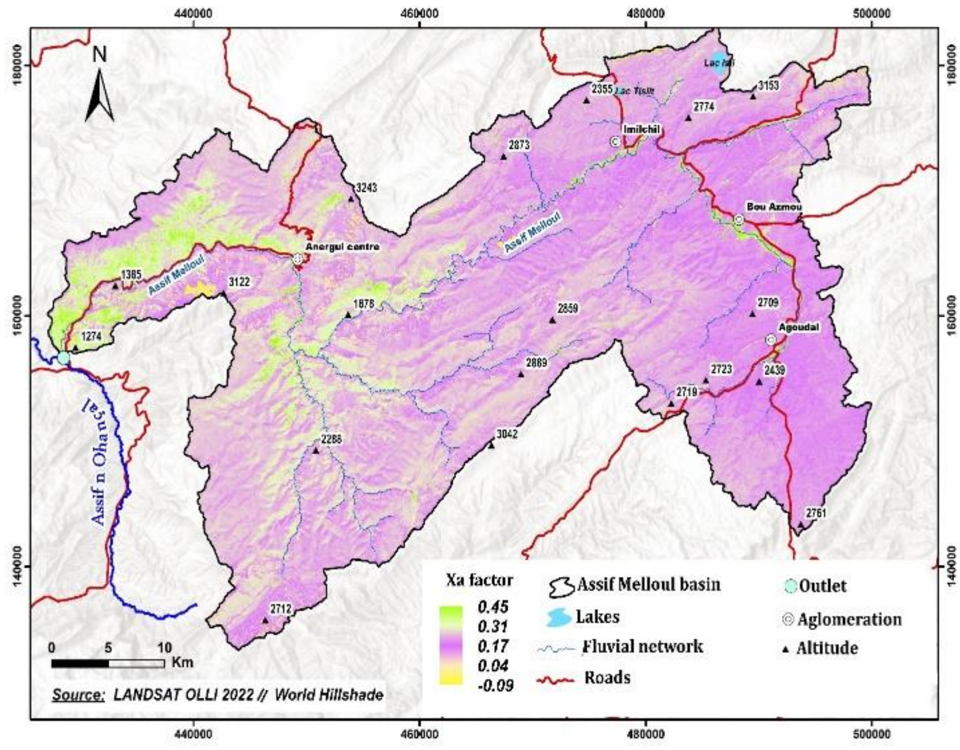


Figure 5. Soil protection factor (Xa)

**Dynamic of soil erosion coefficient (φ).** The φ factor map illustrates the spatial variability of the soil erosion dynamic index across the Assif Melloul basin. This index reflects the combined effects of topographic, climatic, and land cover conditions on the temporal and spatial intensity of erosion processes. The φ values range from 0.30 to 1, with the highest levels (shown in red to orange) indicating areas of intense and persistent soil erosion activity, while the lower values (in blue to light blue) correspond to zones of reduced erosion dynamics.

The most erosion-active zones (φ > 0.80) are concentrated along steep slopes, converging flow paths, and river incision lines, particularly in the central and south-eastern regions of the basin, as well as near Agoudal, Imilchil, and around the high-altitude peaks. These zones are highly vulnerable due to their rugged terrain, minimal vegetative protection, and strong hydrological connectivity. On the other hand, the less dynamic areas (φ < 0.50) are generally associated with valley bottoms, plateaus, or densely vegetated regions, particularly in the western and north-western parts of the watershed.

This factor is critical for understanding the rate and aggressiveness of soil loss over time. High φ values signify not only intense current erosion but also a high likelihood of future degradation, especially during extreme rainfall or flood events. In the broader context of the Atlas Mountains of Morocco, such patterns are common due to the region's complex geomorphology, intense seasonal rainfall, and land use pressures (e.g., overgrazing, deforestation, and poor agricultural practices). The φ factor thus helps pinpoint erosion hotspots where interventions are urgently needed to stabilize slopes, reinforce vegetation cover, and implement soil and water conservation measures.

Thus, the φ factor map highlights both the spatial concentration of active erosion zones and their potential evolution, offering a valuable tool for prioritizing erosion control strategies in both the Assif Melloul basin and similar fragile catchments throughout the Moroccan Atlas mountainous.

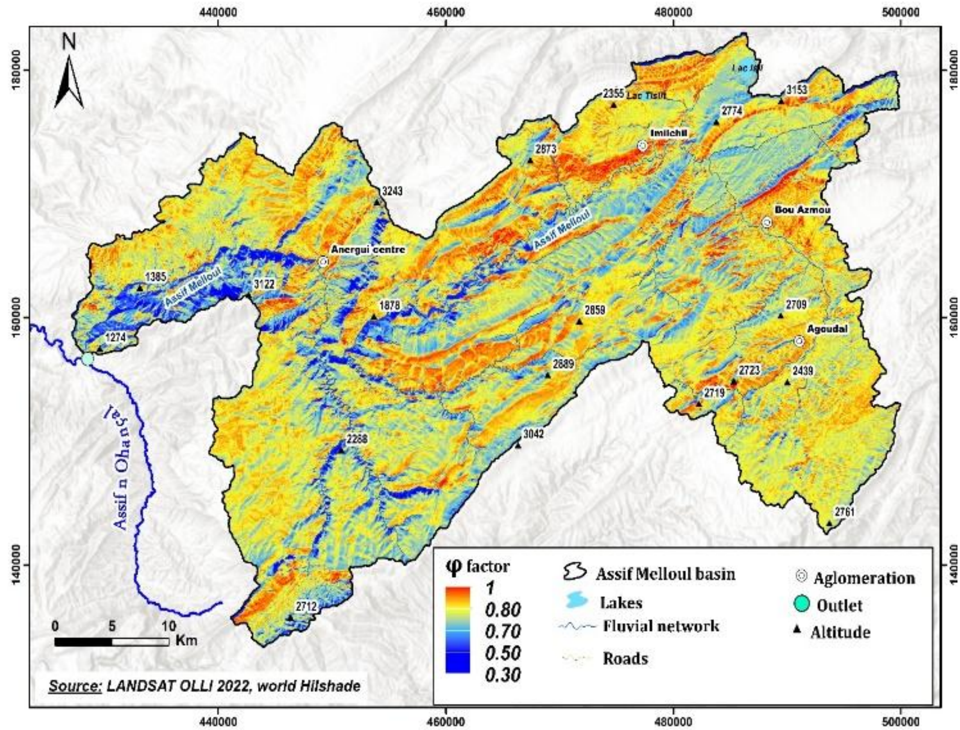

Figure 6 . Map of Soil erosion dynamic coefficient (φ)

**Temperature coefficient (C°).** The T factor map displays the spatial distribution of mean annual temperature across the Assif Melloul basin, with values ranging from 2°C to 14°C. The highest temperatures (12–14°C), represented in orange to light yellow, are predominantly concentrated in the lower altitudes, particularly in the western part of the basin around the outlet zone (1274–1385 m). In contrast, the lowest temperatures (2–4°C), shown in blue, dominate the higher altitude regions of the eastern and south-eastern zones, including areas surrounding Imilchil, Agoudal, and Bou Azmou, where elevations exceed 2700 m (Fig. 7).

Temperature plays a crucial role in soil vulnerability through its influence on vegetation cover, soil moisture retention, freeze-thaw cycles, and microbial activity. In warmer zones, elevated temperatures often enhance vegetative productivity, which may contribute to better soil protection. However, they can also lead to higher rates of organic matter decomposition, reduced soil structure stability, and increased evapotranspiration, thereby promoting soil dryness and erosion susceptibility, especially when vegetation is sparse. Conversely, in colder high-altitude areas, low temperatures reduce biological activity and slow down vegetation regeneration, while freeze-thaw processes contribute to soil fragmentation, increasing the risk of detachment and surface erosion (Figure 7).

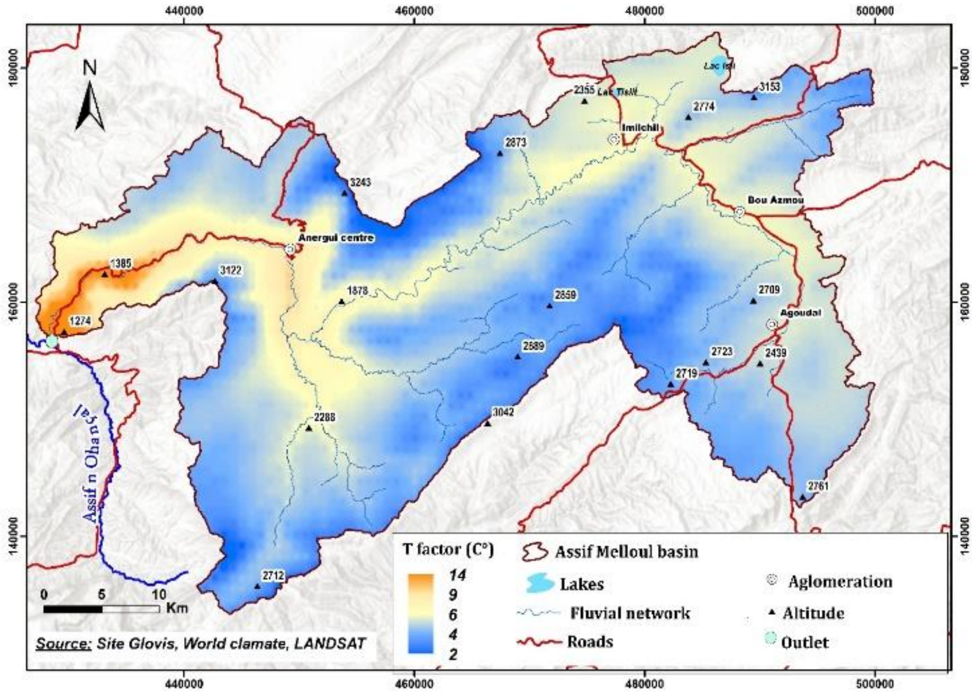


Figure 7. Temperature coefficient map

Overall, the temperature gradient within the Assif Melloul basin indicates diverse erosion dynamics with thermal stress and aridity increasing erosion risk in lowlands, and mechanical weathering processes enhancing vulnerability in highlands. These findings underscore the need to incorporate thermal conditions into erosion modelling and land management plans, especially in mountainous contexts like the High Atlas, where temperature variability significantly modulates soil stability (Figure 7).

**Rainfall erosivity coefficient (P).** The P factor map illustrates the spatial variation in rainfall erosivity, a key climatic determinant of soil erosion, across the Assif Melloul basin (Fig. 8).

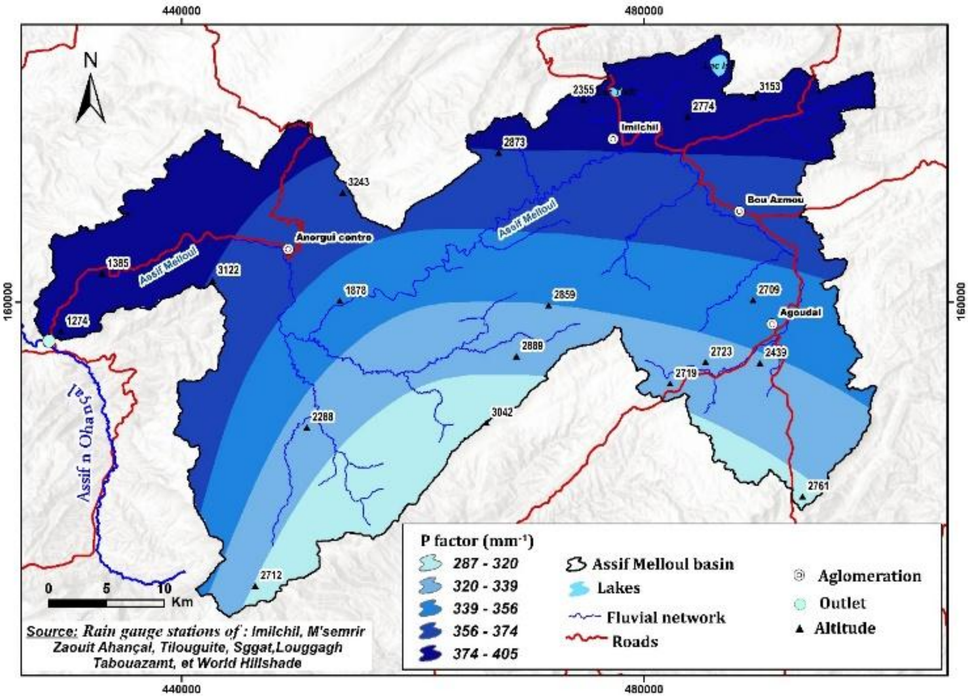

Figure 8. Map of Rainfall erosivity factor

Values range from 287 to 405 mm$^{-1}$, with higher values (shown in dark blue) concentrated in the northern and north-western parts of the basin, particularly around Imilchil, Lac Tislit, Anergui, and near the outlet zone (1274–1385 m). These areas are exposed to more intense and erosive rainfall events, which substantially increase the potential energy of raindrops, contributing to soil particle detachment and runoff-driven transport. In contrast, southern and south-eastern zones, including Agoudal, Bou Azmou, and southern ridges, show lower erosivity values (287–320 mm$^{-1}$), indicating comparatively weaker erosive forces.

In the context of the IntErO and the EPM, the P factor serves as a critical input representing the climatic aggressiveness that influences the overall erosion potential (Y). Areas with higher P values exhibit a greater likelihood of active erosion, especially when combined with steep slopes, erodible lithology, and poor land cover. Within the broader framework of the Atlas Mountains, such erosivity gradients reflect regional climatic contrasts, where northern and mid-altitude regions are more affected by intense rainfall and consequently more prone to hydric erosion.

This spatial representation of rainfall erosivity thus offers valuable insights for erosion risk assessment within the IntErO and EPM model, highlighting the necessity for preventive soil conservation practices; such as vegetative buffers, slope stabilization, and water harvesting structures, particularly in zones subject to high erosive rainfall energy (Ahalli *et al*. 2025) (Figure 8).

**Threshold of the erosive state coefficient (Z).** Figure 9 present the threshold of the erosive state within Assif Melloul basin, this map indicates a high variability of soil erosion state from upstream to downstream.

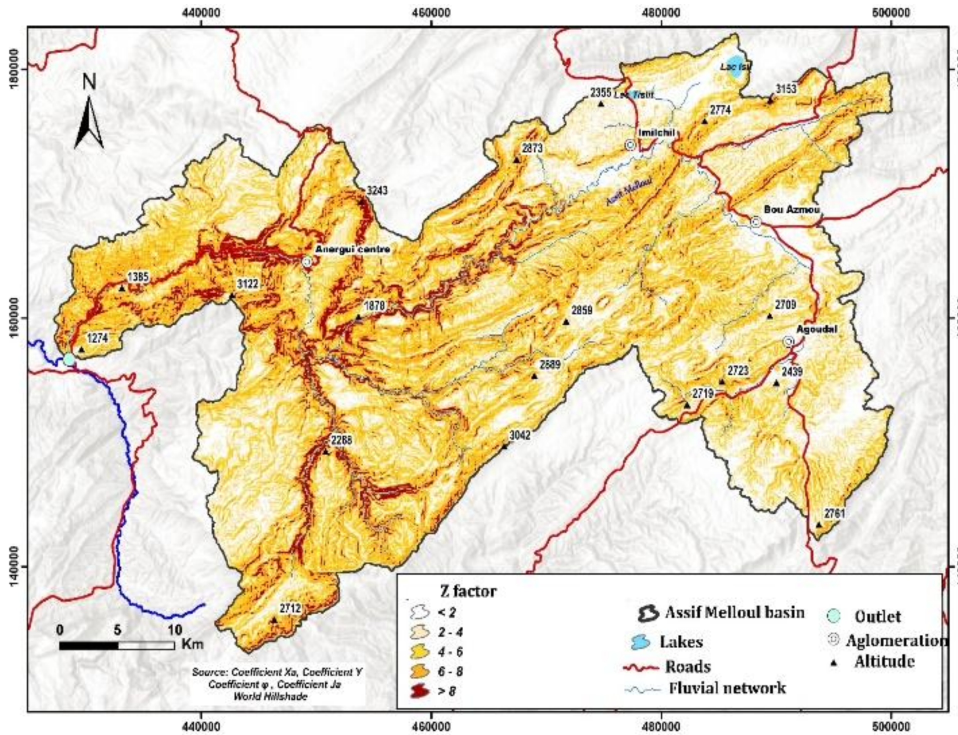


Figure 9. Threshold of the erosive state map

This composite index results from the integration of several key erosion-influencing factors, including slope steepness (Ja), soil protection (Xa), erosion sensitivity (Y), and erosion dynamics (φ). The Z values are classified into five categories: very low (< 2), low (2–4), moderate (4–6), high (6–8), and very high (> 8). Areas shaded in dark red, particularly along steep mountain ridges, fluvial corridors, and convergent slopes, indicate zones with very high erosion risk, where natural resilience thresholds are exceeded, making the soil highly susceptible to degradation (Farhan *et al*. 2015).

The central and western parts of the basin, especially around Anergui, Imilchil, 3122 m and 3243 m peaks, and the outlet slopes near Assif Ouhansal, are dominated by Z values > 8, marking them as critical erosion hotspots. These zones are characterized by the coincidence of steep slopes, low vegetation cover, high rainfall erosivity, and active geomorphological dynamics. In contrast, the southern and eastern sectors, particularly around Agoudal, Bou Azmou, and 2719–2761 m altitudes, show lower Z values (< 4), suggesting a more stable soil system with reduced susceptibility to active erosion processes.

In the context of the IntErO and the EPM, the Z coefficient is central to determining whether erosion processes will remain within a natural equilibrium or shift into an accelerated and irreversible state. A high Z value reflects a landscape where the erosive forces (e.g., rainfall, slope, surface runoff) surpass the buffering capacity of the terrain (e.g., vegetation, soil cohesion), resulting in intensified rill/gully erosion, landslides, and badlands formation.

This map serves as a vital planning tool for prioritizing soil conservation actions. It suggests that urgent intervention is needed in high Z areas to mitigate soil loss through techniques such as reforestation, check dams, terracing, and erosion barriers. Within the broader Atlas Mountains of Morocco, the Z factor reveals the complex interaction between natural vulnerability and anthropogenic pressures, offering insight into the landscape’s tipping points and helping guide sustainable watershed management (Figure 9).

**Soil loss coefficient (W).** Figure 10 presents the soil loss map of Assif Melloul basin which show a high significance of soil loss rate especially near to the Assif Melloul River.

This soil loss map (W) of the Assif Melloul basin represents the estimated volume of eroded soil in $m^3/km^2$/year, calculated by using the IntErO and the EPM based on factors such as rainfall erosivity (P), temperature (T), and the threshold erosive coefficient (Z). The erosion intensity is classified into five classes, ranging from less than 7,783 $m^3/km^2$/year to more than 16,000 $m^3/km^2$/year.

The most severely affected areas (in dark red and brown) are concentrated in the central and western zones, notably around Anergui, the outlet near Assif Ouhansal (1274–1385 m), and high-relief areas near 3122 m, where erosion exceeds 16,000 $m^3/km^2$/year. These hotspots coincide with regions of steep slopes, low vegetation cover, and high rainfall erosivity, making them highly vulnerable to water-driven soil loss. Conversely, the eastern and south-eastern parts, particularly around Agoudal and Bou Azmou, exhibit lower soil loss rates (< 7,783 $m^3/km^2$/year), benefiting from more moderate terrain and protective vegetative cover (Figure 10).

When compared to other Mediterranean mountain environments, the estimated soil loss rates in the Assif Melloul basin appear to be highly significant, often aligning with or surpassing the erosion levels documented in similar geomorphic-climatic contexts.

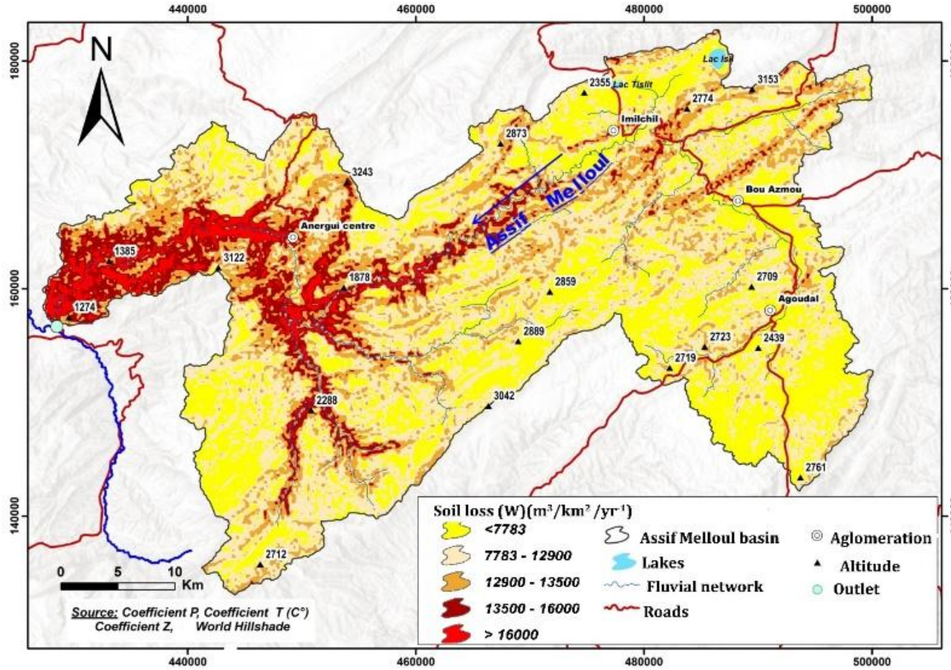


Figure 10. Map of final Soil loss coefficient (W) within Assif Melloul basin

In the Lebanon Mountains, for instance, average annual soil loss values range from 7,000 to 12,000 m³/km²/year, with localized hotspots exceeding 15,000 m³/km²/year due to intense seasonal rainfall and poor land management practices (Nasr *et al*., 2008). Similarly, in northern Algeria, the Cheliff basin exhibits soil erosion rates estimated between 8,000 and 13,000 m³/km²/year, particularly in steep agricultural regions lacking adequate vegetation cover (Benaabidate *et al*. 2003).

In the Middle Atlas of Morocco, Ennaji *et al* (2022) applied the EPM model to the Ouaoumana basin and reported values ranging between 9,500 and 17,000 m³/km²/year, which reflect comparable geomorphological and climatic constraints as observed in the Assif Melloul catchment. Furthermore, in southern Spain, the Guadalentín basin, a well-documented Mediterranean erosion hotspot, has shown high spatial variability in soil loss, with several sectors recording values that frequently exceed 14,000 m³/km²/year, especially in severely degraded and gullied terrains (De Vente & Poesen 2005).

These regional comparisons clearly position the Assif Melloul basin within the upper range of erosion severity encountered across the Mediterranean basin. The convergence of steep topography, rainfall erosivity, and limited vegetative protection intensifies the vulnerability of the landscape, highlighting the urgent need for erosion control and sustainable land management to prevent further soil degradation and ecological instability.

**Discussion of the influence of erosion factors on substrate loss: correlation analysis.** The correlation matrix and correlogram provide a comprehensive overview of the interrelationships between the various factors involved in the IntErO model and Erosion Potential Method and their combined influence on soil loss (W) in the Assif Melloul basin (Fig. 11).

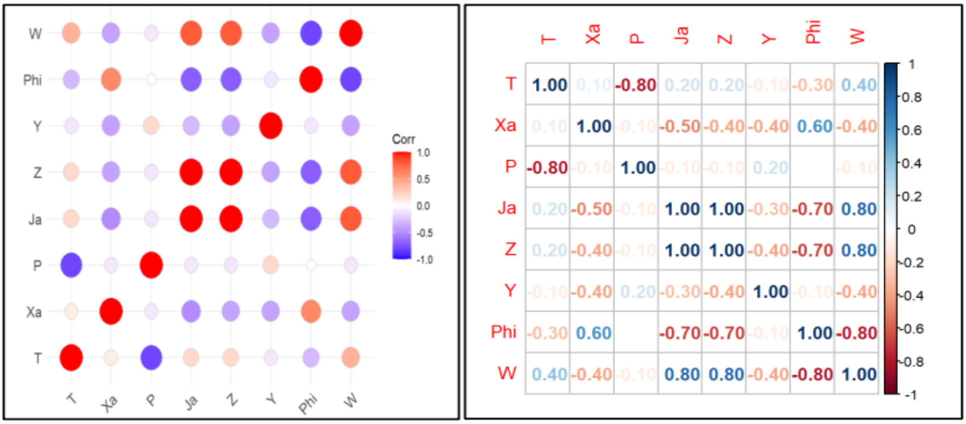

Figure 11. Correlation matrix among EPM coefficients and factors

The analysis reveals a strong positive correlation between soil loss (W) and several key factors, most notably Ja (slope factor, r = 0.80), Z (threshold erosive state, r = 0.80), Y (soil sensitivity, r = 0.80), and φ (erosion dynamic coefficient, r = 0.80). These strong relationships underscore the significant contribution of topography and dynamic erosion behavior in controlling sediment detachment and transport. In contrast, rainfall erosivity (P) and temperature (T) show moderate correlations with soil loss (r = 0.40 each), while Xa (soil protection factor) is negatively correlated (r = -0.60), confirming the mitigating effect of vegetation cover on erosion.

Notably, the strong internal correlations between Z, Y, φ, and Ja (all r ≥ 0.70) indicate that these variables are interdependent in defining erosion-prone zones. Similar findings have been reported in other basins within the Middle and High Atlas of Morocco, where studies (e.g., Ennaji *et al*. 2022; El Garouani *et al*. 2014) have demonstrated that slope and lithological fragility, combined with land cover degradation, are the primary drivers of erosion risk. Comparable trends are also observed in Mediterranean basins in northern Algeria, southern Spain, and Lebanon, where topographic and land use factors consistently emerge as the most significant predictors of soil loss (Nasr *et al*. 2008; De Vente & Poesen 2005).

In summary, the results from the Assif Melloul basin reaffirm the dominant influence of morphometric and land degradation variables on erosion dynamics in mountain environments. These correlations emphasize the importance of slope stabilization, vegetation restoration, and land cover management as critical strategies for erosion control in both Moroccan and Mediterranean mountainous regions.

**Classification of thresholds of the potential soil loss areas - Domaine of notable erosion (3%).** The figure provides visual evidence of active and severe erosion processes affecting the upstream sector of the Assif Melloul basin, particularly in zones characterized by high geomorphological vulnerability.


Figure 12. (a) Bank undercutting and slope failures in the upstream part of the Ouirghane sub-basin (Taghighacht sector). (b), (c), and (d) Deep gully incision and vertical bank retreat in the Tingagou area (Lakes Plateau), illustrating progressive channel deepening and lateral erosion

Photo (a) clearly illustrates bank undercutting and slope failure along the Taghighacht sector in the Ouirghane sub-basin, where lateral erosion and mass wasting are facilitated by unconsolidated material and steep slopes. This area lies within the Tilmi syncline depression, which has been identified as part of the notable to severe erosion domain (class 3%). The terrain's structural configuration, combined with low vegetation cover and hydrodynamic pressure during runoff events, intensifies slope instability.

Images (b), (c), and (d) depict the Tingagou area, located near the Lakes Plateau, where deep gully incision, vertical bank retreat, and channel entrenchment are dominant. These features are representative of advanced fluvial erosion stages, where concentrated runoff has carved narrow, deep channels into fine-grained sedimentary or alluvial deposits. These gullies are frequently found along structural depressions and fault-aligned valleys, where the erosive energy is not dissipated due to the absence of protective vegetation and flat terrains. Notably, the Tingagou region corresponds to one of the karstified zones of the Ait Abdi plateau, which includes dolines and ovals; karst landforms that further weaken the substratum and enhance surface and subsurface erosion.

Overall, this figure captures the geomorphodynamic instability of the notable to severe erosion domain (3%), which is controlled by both tectonic depressions (e.g., synclines), karstic features, and the absence of vegetation in the upper basin. These observations align with the IntErO and EPM-based erosion assessments and stress the urgent need for stabilization measures, especially in structurally sensitive areas where both lithology and topography amplify erosion processes (Sestras *et al*. 2023) (Figure 12).

**Domaine of severe erosion (22%).** This domain is occupied an area of 22% in the whole basin. Figure 13 displays a series of photographs (a–d) illustrating severe linear erosion features occurring across the mid-slope sectors of the Assif Melloul valley - Aqqa-N'Oueuenza tributary system.

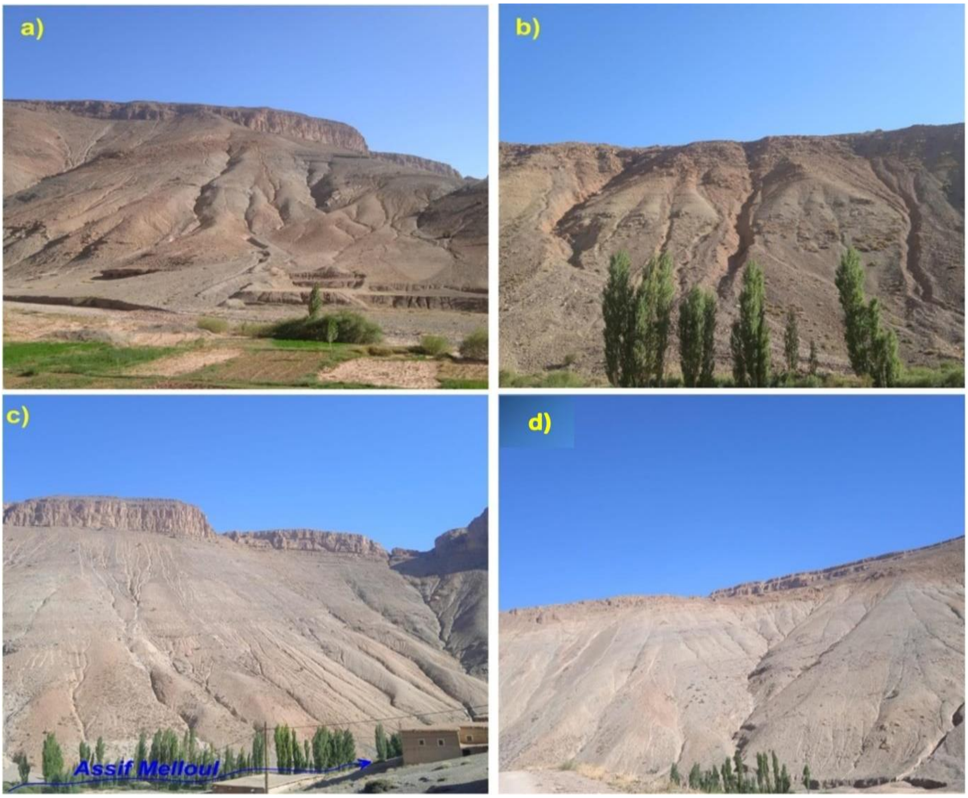


Figure 13. Visual Evidence of Severe Hillslope Erosion and Sediment Transfer Toward Cultivated Fields in the Aqqa-N'Oueuenza Sector, Assif Melloul Basin

These forms are characteristic of the severe erosion domain (22%), which, according to field observations, stretches along the entire length of the valley flanks, from the upper to the lower basin, but is particularly concentrated in the middle section.

In panels (a) and (b), we observe clearly developed rill and gully systems dissecting the steep hillslopes, where rainfall runoff concentrates along preferential flow paths. The scarification of the slope surface reflects both the lack of vegetative cover and the erodibility of the substrate, facilitating the formation of deep channels and incised vallons. These erosional structures actively channel water and sediments toward the lower elevations.

Images (c) and (d) further highlight the cumulative effects of this erosion. The steep, un-vegetated slopes serve as major sources of sandy sediments, which are transported by runoff into the agricultural fields located at the slope foot, near the Assif Melloul channel. This sediment accumulation leads to the asphyxiation of crop roots, affecting soil porosity and moisture retention, which eventually results in the decline or complete loss of vegetable cultivation in the area. The photos also underscore the lack of protective measures, such as terraces or vegetation buffers, which allows erosion to intensify seasonally.

In summary, this figure 13 effectively illustrates the geomorphological degradation resulting from severe, unchecked erosion processes within the middle reaches of the Assif Melloul basin. The resulting sediment flux from these degraded slopes poses a serious threat to downstream agricultural productivity, calling for the urgent implementation of soil conservation strategies, including slope reforestation, check dams, and sediment traps to safeguard both the landscape and local livelihoods.

**Domaine of very severe erosion (38 %).** The fig 14 (a–d) clearly depict landscape features associated with very severe erosion processes (38%), distributed across high-altitude regions and ridgeline slopes of the Assif Melloul basin. These zones, such as Tizi n'Ouanou, Tadghmamt, and the crests surrounding the Tilmi syncline, are typified by exposed slopes, fragile lithological layers, and intense runoff activity.

Photo (a) presents a classic example of gully incision forming at the base of a barren slope, with sediment transport channels emerging from minor convergence zones. Image (b) highlights a collapsed slope segment with a cracked depositional surface, indicating active surface sealing and post-flood sediment drying, commonly seen after high-intensity rainfall events. In photos(c) and (d), parallel incision patterns along steep slopes are visible, interpreted as differential erosion and subsurface flow phenomena. These formations, described as "berges denticulées" (toothed banks), result from a combination of surface runoff and hypodermic flow; where water infiltrates and exits the slope subsurface along specific pathways. The tunnel-like erosional features suggest that water has exploited natural fractures or less cohesive layers, resulting in multiple parallel drainage outlets. These signs of underground piping and rill convergence are typical of structurally unstable zones with layered or fractured substrates.

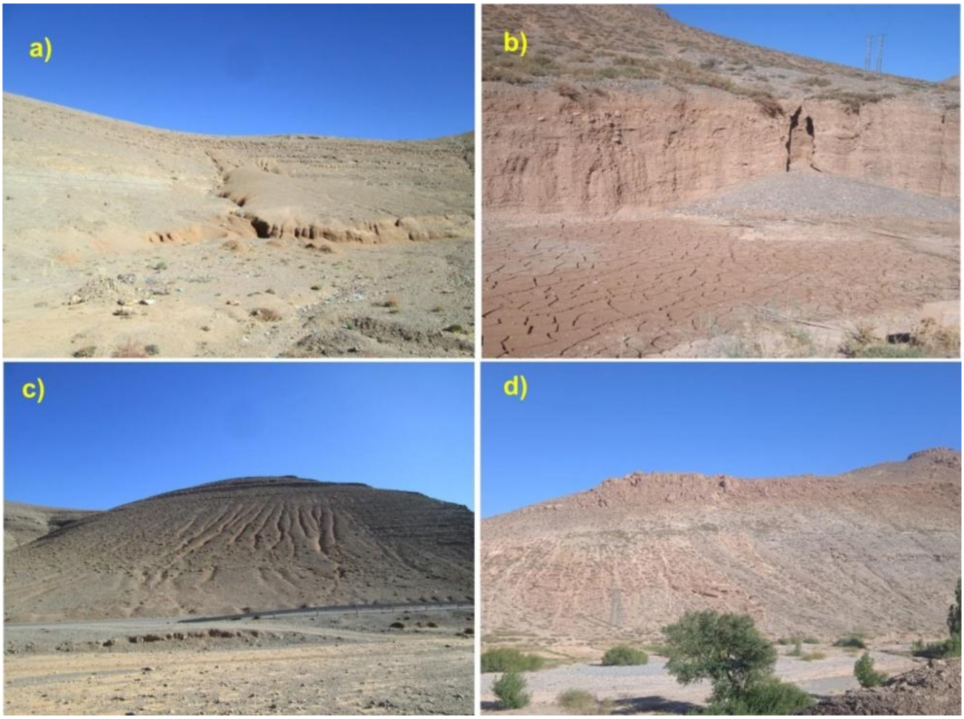


Figure 14. Illustrations of very severe erosion features in high-altitude zones of the Assif Melloul Basin—formation of denticulate banks and subsurface tunnels in Tizi n'Ouanou and Tadghmamt ridges

This very severe erosion domain poses significant geomorphological and ecological risks, accelerating slope retreat and sediment flux into downstream canyons such as those of Anergui and Akhachan. The advanced degradation stage visible here necessitates urgent soil stabilization, re-vegetation, and possibly structural erosion control interventions (Fig.14).

**The excessive erosion domain (28%).** The six sub-images (a–f) in figure 15 illustrate a variety of excessive erosion features that characterize approximately 28% of the Assif Melloul basin, particularly affecting the mid- to high-altitude areas. This domain includes a wide range of erosion forms, notably sheet erosion, rill and gully formation, bank undercutting, and intermittent ravines, often constrained by the outcropping of bare rocky substrates.

Image (a), taken near Agoudal, provides a wide overview of slope-surface degradation dominated by sheet and rill erosion, where runoff has carved shallow channels into soft sedimentary layers. Image (b) illustrates a deep gully system, a typical form of ravinement, which reflects prolonged water concentration and channelization on exposed hillslopes. The steep walls and V-shaped profile are indicative of active incision intensified by the absence of vegetative cover.

Images (c) and (d) show surfaces stripped of topsoil, affected by intense surface runoff and sheet flow. In particular, the pattern of shallow rills and flow accumulation marks, combined with rocky outcrops, suggest that erosion is being modulated by the presence of compacted or resistant lithological layers that limit deeper incision but accelerate lateral detachment (Rizki *et al*. 2025).

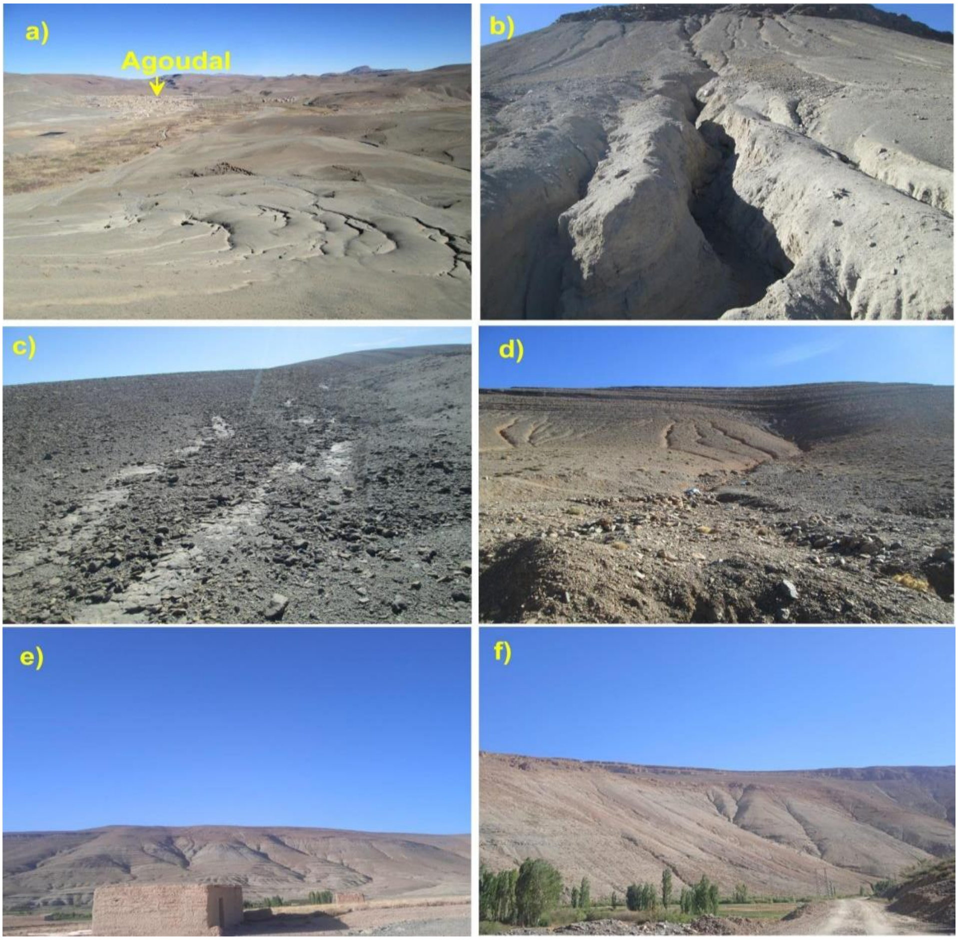


Figure 15.Some representative features of excessive erosion (28%) across the Assif Melloul basin: ravines, rills, sheet erosion, and bank undercutting in high-elevation zones

In photos (e) and (f), we observe the transitional zones between degraded hillslopes and agricultural valley floors, where bank undercutting and sheet wash processes contribute to the displacement of sediment toward cultivated lands. Despite the proximity of vegetation and fields, the uncontrolled upstream runoff remains a threat to soil quality and hydrological stability.

This domain is defined by high-intensity surface runoff, particularly in upper elevation zones, where the slope gradient, rainfall concentration, and bare soil exposure converge to enhance erosion risk. Although some forms such as gullies are constrained by lithological resistance, the landscape continues to evolve under excessive hydric pressure, making this a high-priority zone for erosion monitoring and mitigation.

**The catastrophic erosion domain (9%).** The four images (a–d) effectively document field evidence of catastrophic erosion processes, which affect approximately 9% of the Assif Melloul basin. This domain is primarily located along the high-altitude ridgelines exceeding 3000 meters, especially in the downstream portion of the basin, and extends into several structurally vulnerable depression zones. The terrain is composed mainly of Triassic clay-marl facies, known for their high erodibility and susceptibility to mass movement and deep gullying under concentrated runoff and gravitational forces.

Image (a) reveals deeply dissected hilltops and ridge flanks, where fragile sedimentary formations have been extensively incised by runoff. The smooth, rounded ridges and heavily stripped surface layers indicate long-term erosion combined with intense surface flow on unconsolidated materials. Image (b) depicts a collapsed slope front, possibly an old landslide headwall, with active rill development extending from steep highlands into a degraded agricultural terrace system.

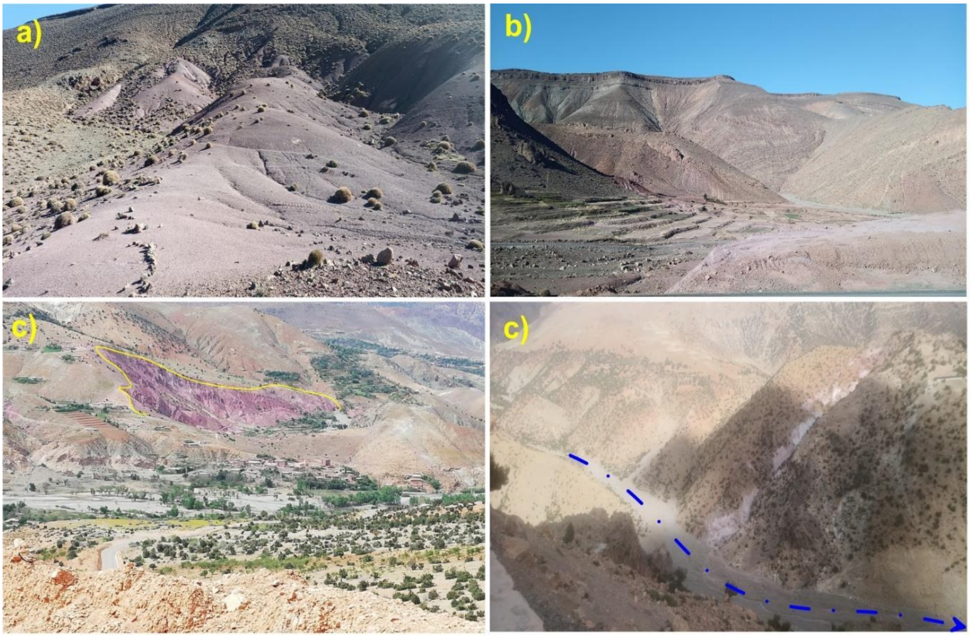


Figure 16. Visual evidence of catastrophic erosion processes (9%) in high-altitude and marl-clay Triassic zones of the Assif Melloul basin

Photo (c) (top-down view) shows a massive landslide scar outlined in yellow, affecting a Triassic clay-rich depression, typical of accumulation zones where slope material is destabilized by subsurface saturation and structural weaknesses (Ouallali *et al*. 2020). The proximity to cultivated lands underscores the threat of catastrophic sediment displacement into human-occupied areas. Image (d) presents a dramatic case of linear slope retreat and slope-channel interaction, with visible debris flows or landslide scars affecting a steep ravine system, likely initiated by a combination of subsurface water accumulation and surface runoff on impermeable marl layers.

This erosion class is considered the most hazardous within the basin due to the scale and intensity of geomorphic transformations, frequently resulting in large sediment discharges, infrastructure damage, and land loss. It calls for strict monitoring, slope stabilization, and upstream water management in order to reduce the triggering of such catastrophic events.

The enhanced box plot clearly demonstrates the dominance of very severe and excessive erosion classes in the Assif Melloul basin, covering 38% and 28% of the area, respectively. This distribution highlights a landscape under significant environmental stress, where nearly 90% of the basin is exposed to high erosion risk. The severe erosion class (22%) also contributes to widespread degradation, while catastrophic erosion (9%), though limited in spatial extent; represents extreme land instability in high-altitude and structurally fragile zones.

This alarming erosion pattern is consistent with findings from other Mediterranean-climate mountainous regions. For instance, Ben Slimane *et al*. (2018) reported that in the Kessab watershed in northern Tunisia, very severe erosion affected up to 40% of the basin due to steep slopes, sparse vegetation, and intense runoff.

In Algeria, Bouanani *et al*. (2010) found that the Tafna basin exhibited soil loss exceeding 20,000 $m^3/km^2$/year in more than 30% of the area, mainly in steep agricultural lands with degraded cover. In the High Atlas of Morocco, Chaker *et al*. (2020) quantified excessive erosion across 35% of the Oued Zat catchment, driven by fragile marly lithology and seasonal runoff pulses. Similarly, Ait Hssaine and Bridgland (2009) observed the effects of catastrophic gully erosion in the Ouzoud area of the Central Atlas, exacerbated by heavy rainfall events and anthropogenic pressure on terraced hillslopes.

Comparable results were reported by García-Ruiz *et al*. (2013; 2010) in the Ebro Basin of Spain, where very high erosion risk covered nearly 30–40% of marginal lands subjected to historical land abandonment and reduced infiltration capacity (Garcia-Ruiz 2010).

These findings confirm that the Assif Melloul basin is not an isolated case, but rather part of a broader pattern of severe erosion in Mediterranean mountainous contexts, where a combination of steep topography, erodible substrates, seasonal rainfall, and land use degradation converge to intensify soil loss. The figure underscores the urgent need for basin-scale conservation planning, including vegetation restoration, slope stabilization, and adaptive land management across the most vulnerable zones.

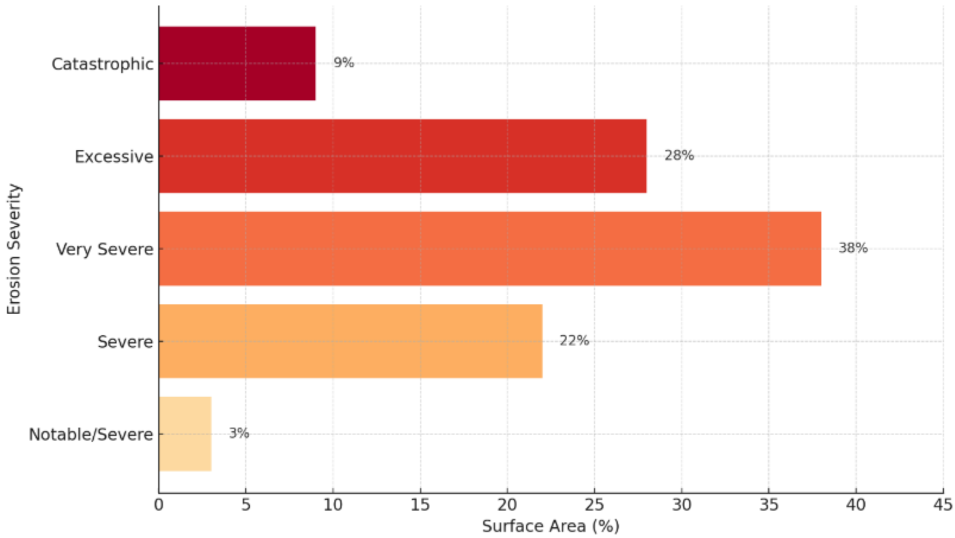


Figure 17. Enhanced box plot representation of erosion severity classes based on surface area proportions in the Assif Melloul basin

**Impact of land use and land cover on soil erosion process.** The analysis of vegetation cover dynamics in the Assif Melloul watershed between 1991 and 2021 reveals a significant regression of vegetated areas. Bare soil currently dominates approximately 76% of the basin, while only 14% remains under vegetative cover. The remaining land shows limited ecological change, with 4% exhibiting regression and 6% progression, indicating minimal vegetation recovery. This trend is particularly alarming in mountainous environments such as the High Atlas, where vegetation plays a crucial role in intercepting rainfall, slowing runoff, and protecting the soil against erosion (Morgan, 2005; Prosser *et al*., 2001). The absence of adequate vegetative cover increases the erosive power of surface runoff and contributes to rapid soil detachment and transport during intense precipitation events (Pavlova-Traykova *et al*. 2023).

This situation is consistent with observations in other Moroccan catchments. For instance, Bouguerra *et al*. (2020) reported that vegetation degradation in the Rmel watershed (northern Tunisia) led to severe erosion risks, with annual soil losses exceeding 50 t/ha/year, particularly in zones affected by agricultural encroachment and overgrazing. Similarly, Khanchoul *et al*. (2009) demonstrated a strong correlation between vegetation regression and increased sediment yield in the Oued Laou basin, noting a marked decline in soil retention capacity in deforested zones.

In another study, Ennaji *et al*. (2024) found that sparse vegetation in steep catchments of the Middle Atlas contributed to erosion rates exceeding 65 t/ha/year. These findings align with our results from Assif Melloul, where the dominance of bare soil reflects a heightened vulnerability to erosion, particularly under conditions of seasonal flash floods and high rainfall intensity, which are characteristic of the region's Mediterranean mountain climate (Liébault *et al.* 2005).

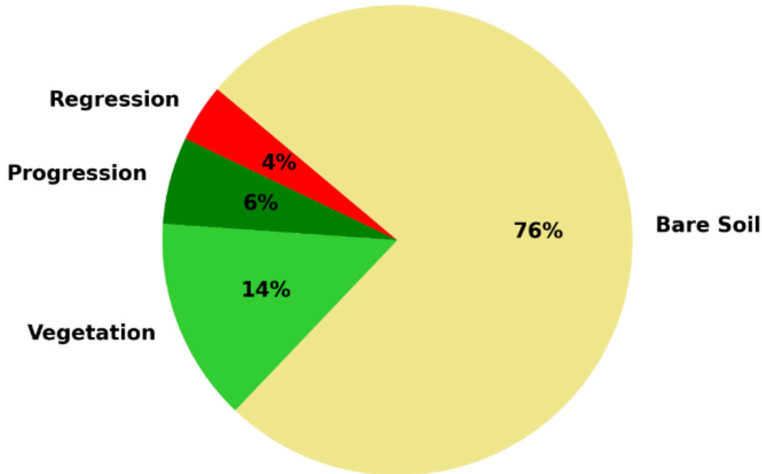


Figure 18. Vegetation cover dynamic in the Assif Melloul basin (1991 – 2021)

Furthermore, a regional synthesis by Chahboun *et al.* (2024) on land degradation in the Central and Eastern Atlas confirmed that vegetative decline, driven by both climatic stress and human activities; has significantly accelerated the pace of surface erosion (Omar *et al.*, 2024). These trends are particularly evident in steep-slope terrains, where the absence of plant roots reduces infiltration rates and intensifies sheet and rill erosion processes (Kosmas *et al.*, 2023).

The IntErO model and the EPM method, applied in this study, further supports the relationship between reduced vegetative cover and increased erosion coefficients (Z and W). Vegetation regression reduces the protective coefficient (Y) and increases the erodibility factor (Xa), both of which elevate the final soil loss estimate in $m^3/km^2/year$. As Ezzine *et al.* (2023) have shown, this model is particularly effective in simulating soil loss under variable vegetation scenarios, especially in semi-arid and montane contexts such as Assif Melloul.

In conclusion, the dynamic of vegetation regression in the Assif Melloul basin aligns with broader national patterns, and its direct impact on soil erosion is evident both quantitatively and qualitatively. Restoration strategies should focus on reforestation, regulated grazing, and sustainable land use to reduce the erosive footprint, especially in erosion-prone sub-watersheds. Such interventions are critical to safeguarding soil productivity and hydrological balance in the High Atlas and similar mountain environments.

## CONCLUSION

The comprehensive assessment of soil erosion dynamics in the Assif Melloul basin, located in the Central High Atlas of Morocco, reveals a worrying level of land degradation resulting from the interplay between natural and human-induced factors. Through the application of the IntErO model of Spalevic (2011) and the Erosion Potential Method of Gavrilovic (1972), supported by detailed field validation, spatial modeling, and morpho-climatic analysis; the study successfully delineated the watershed into five erosion severity classes: notable/severe, severe, very severe, excessive, and catastrophic. Notably, the very severe and excessive categories account for more than 65% of the basin's surface, underscoring the acute vulnerability of this mountainous environment. The combined effects of steep slopes, fragile lithological formations (especially Triassic marls and clays), irregular rainfall patterns, and sparse vegetation significantly contribute to elevated soil loss and ongoing geomorphological instability.

Spatial analysis indicates that erosion is not uniformly distributed but rather concentrated in structurally sensitive areas, including synclinal depressions, high-altitude ridges (e.g., Tizi n'Ouanou, Tadghmamt), and valley slopes adjacent to the canyons of Anergui and Akhachan. These regions are especially prone to advanced forms of erosion such as deep ravines, denticulated banks, piping tunnels, and gully systems, often intensified by concentrated surface and subsurface runoff. Correlation analysis further demonstrated strong positive associations between soil loss (W) and key morphometric and dynamic parameters, namely slope (Ja), soil sensitivity (Y), threshold coefficient (Z), and erosion dynamics (φ), highlighting the dominant role of terrain morphology and substrate fragility in sediment mobilization. In contrast, the soil protection factor (Xa) exhibited a strong negative correlation with erosion severity, reaffirming the critical importance of vegetative cover in mitigating the erosive impact of hydrological forces.

When compared to erosion dynamics in other Mediterranean mountain regions such as the Ebro Basin in Spain, the Tafna basin in Algeria, the Oued Zat and Ouaoumana basins in Morocco, and the Kessab watershed in Tunisia, the Assif Melloul basin ranks among the most critically affected landscapes. With estimated soil loss volumes reaching and often exceeding 16,000 $m^3/km^2$/year in several locations, the basin fits the profile of a geomorphologically active and highly vulnerable system, similar to those found throughout semi-arid Mediterranean terrains experiencing land pressure and hydroclimatic extremes. These international parallels confirm that the patterns observed in Assif Melloul are not isolated, but are part of a broader regional dynamic driven by the Mediterranean climate, fragile in lithology, and unsustainable land use practices.

In light of these findings, the study strongly recommends the urgent implementation of integrated watershed management strategies. Priority should be given to slope stabilization, reforestation of degraded areas, reinforcement of agricultural terraces, and the construction of erosion control structures (such as check dams and sediment traps), particularly in the zones classified under catastrophic and excessive erosion risk. Furthermore, continuous monitoring, the development of participatory land management with local communities, and the integration of remote sensing for early-warning systems will be crucial for mitigating erosion and ensuring long-term landscape resilience. Ultimately, this research contributes to the growing body of knowledge on soil degradation in the Atlas Mountains and reinforces the need for science-based decision-making in the face of increasing environmental pressures in Mediterranean mountain ecosystems.

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