Mathematical models and geographic information systems in the service of monitoring the spatial dynamics of water erosion: Case study of mediterranean watershed using the PAPCAR Model

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ABSTRACT

Water erosion is a major threat to land resources and agricultural productivity in semi-arid Mediterranean environments. This study aimed to identify the main factors driving water erosion in the Nfifikh watershed (Morocco) and to assess spatial variations in erosion susceptibility using a combination of the PAP/CAR qualitative model and geographic information systems (GIS). Spatial data, including ASTER-DEM, land use, vegetation cover, and lithological maps, were analyzed alongside field observations to map erosion vulnerability. The PAP/CAR methodology was applied in three stages – descriptive, predictive, and integration – to classify the watershed into stable and unstable zones and to evaluate areas at low, moderate, high, and very high erosion risk. Results indicate that 55.96% of the watershed exhibits high to very high erosion potential, primarily concentrated in downstream agricultural areas and slopes exceeding 20%. Sheet erosion dominates (87.77% of the basin), while rill and gully erosion occur in areas with sparse vegetation and moderates to steep slopes. Approximately 35% of the watershed is highly sensitive, while protective vegetation covers less than 35% of the area, failing to coincide with the most vulnerable zones. High erosion risk areas overlap with regions of intensive agriculture and higher population density, confirming that erosion susceptibility is driven by both natural factors and human activities. These findings provide a reproducible spatial framework for targeted soil and watershed management interventions. The integration of GIS with the PAP/CAR model enables the identification of priority zones for conservation, contributing to sustainable land use planning. This study offers new insights into the spatial dynamics of water erosion in semi-arid Mediterranean watersheds and demonstrates the value of combining cartographic modeling with field verification for environmental management.

Keywords: Nfifikh watershed, spatial dynamics, water erosion, geographic information systems, PAP/CAR mathematical model.

INTRODUCTION

Water erosion constitutes a real threat to the sustainability of land resources and their productive capacity worldwide, particularly in the Mediterranean basin, which is an area of long-standing human settlement (Ait Haddou et al., 2024; Bensiali et al., 2024; Bouiss Eddine et al., 2024; Ait Maamare et al., 2025). Consequently, this phenomenon represents an obstacle to the establishment of sustainable agriculture and population stability (Charef et al., 2025; Ed-Daoudy et al.,

2024). Morocco is part of this Mediterranean domain, which is experiencing a remarkable expansion of water erosion, attributable to the combination of complex processes involving rainfall aggressiveness, loss of vegetation cover, soil fragility, and the impact of human activities (Ed Daoudy et al., 2025; Layan et al., 2025; Hamouch et al., 2024a; Hamouch et al., 2024b).

Recent studies in Morocco indicate that rates of water erosion vary significantly between basins. In the Issen Basin (central-western Morocco), RUSLE models showed that soil loss rates range from 8 to 22 tons/hectare/year, depending on slope and land use (Ait Haddou et al., 2024). In an applied study in the Mezir Basin in the Berrechid region, soil loss rates of 10 to 25 tons/hectare/year were observed on agricultural lands with fragile soils, using RUSLE and GIS models (Hanane et al., 2024).

In contrast, other studies in the Raouz Basin (north-central Morocco) showed that the use of modified models, such as PAP/RAC, combined with ^137Cs isotope analysis, revealed heavily affected areas exceeding 20 tons/hectare/year, while areas with dense vegetation cover were less affected (Ed-Daoudy et al., 2024). Studies in the Targa-n-Touchtka Basin also showed that interventions, such as agricultural terraces, reduced soil loss rates from approximately 25 to less than 15 tons/hectare/year in treated areas compared to untreated areas (Taira et al., 2024).

These statistics show that areas with steep slopes, fragile soils, and intensive land uses — particularly agricultural land — are most vulnerable to water erosion, highlighting the need to implement soil conservation strategies appropriate for each type of natural and human condition to ensure the sustainability of land resources.

Water erosion hinders economic and social development, as the degradation of the production base has negative impacts on all sectors. For example, studies in the Issen Basin in central-western Morocco indicate that soil loss ranges from 8 to 22 tons/hectare/year, depending on slope and land use type, which directly affects agricultural productivity (Ait Haddou et al., 2024). In an applied study in the Mezir Basin in the Berrechid region, soil loss rates of 10 to 25 tons/hectare/year were observed on fragile agricultural lands using RUSLE and GIS models, leading to reduced agricultural yields and decreased land value (Hanane et al., 2024).

Furthermore, water erosion causes irreparable environmental damage, such as the degradation of natural habitats, a decline in biodiversity, and the extinction of certain species. For example, studies in the Targa-n-Toshtka Basin have shown that agricultural interventions, such as terraced farming, reduced soil loss from approximately 25 to less than 15 tons/hectare/year, contributing to the conservation of biodiversity and the mitigation of environmental risks (Taira et al., 2024; Abdelhamid Tawfik et al., 2025).

Furthermore, soil degradation has direct implications for agricultural productivity on the one hand, and for the value of agricultural land on the other, particularly in areas with steep slopes and fragile soils. As a result, these areas become unattractive to residents, prompting them to migrate to large and medium-sized cities, which leads to social decline in rural areas and the emergence of multiple crises in future urban centers (Tawfik et al., 2025). In the Rauz Basin in northern Morocco, studies using the PAP/CAR model and ^137Cs isotope analysis revealed that some areas experienced soil loss exceeding 20 tons/hectare/year, while areas covered by dense vegetation were less affected, underscoring the need for soil protection interventions (Ed-Daoudy et al., 2024).

Since human settlement in any area has historically depended on the availability of water and soil, ensuring their continuity requires that these resources remain in a good natural condition (Tawfik et al., 2025; Taira et al., 2024). This can only be achieved through planning and management that enable each fragile environment to respond to any internal or external change or impact (Hamouch et al., 2025; Limame et al., 2025). The issue is not always purely natural (climate, geology, topography, etc.) but has increasingly become linked to human behavior and patterns of land use, which may ultimately lead to negative land evolution and the disruption of general environmental balances. For example, deforestation and expansion of agricultural lands on fragile slopes in the Issen Basin (central-western Morocco) have led to significant soil loss and land degradation (Ait Haddou et al., 2024; Hanane et al., 2024), while similar human activities in the Traw and Oum Er-Rbia Basins (northern and central Morocco) have increased erosion rates, with soil loss ranging between 15 and 28 tons/hectare/year (Limame et al., 2024; Saouita et al., 2026). Given this strong and coherent interconnection between the elements of the environmental system and the components of the geographical space, water erosion results in a

real imbalance that paralyzes the ecosystem (Eddine et al., 2024; Charef et al., 2025).

River basins constitute true laboratories for studying this type of geomorphological phenomenon, as the activity of erosive processes leads to soil truncation, depletion, and a reduction in fertility, resulting in productivity loss in upstream areas and impacts on hydraulic structures and infrastructure downstream (Strahler, 1957; Walling and Webb, 1983). For this reason, the Oued Nfifikh river basin was selected, as it is characterized by a high degree of natural fragility and a strong sensitivity to water erosion due to the combined effect of various natural and human factors. Previous studies in Morocco have highlighted the ecological and hydrological characteristics of Oued Nfifikh, including the assessment of water quality and diatom indices, which reflect both natural conditions and anthropogenic impacts on the river (Haidar et al., 2025; Haidar et al., 2025). These studies provide detailed observations on sediment transport, soil degradation, and vegetation cover in the basin, confirming its vulnerability to water erosion and the importance of integrated watershed management.

River basins have historically been areas of human settlement and centers for the concentration of natural resources, which humans have exploited over time (Haddadi and Hadiya, 2024; Limame et al., 2024). Although river basins may be similar in terms of resources regardless of their proportions, they differ in terms of dynamics, whether among humid river basins themselves or between humid and arid ones (Roose et al., 2023; Saouita et al., 2026). In general, however, these basins share the same nature of crisis, especially those subjected to climatic variability and intensive human exploitation (Sebbar et al., 2023; Senhaji et al., 2024).

The Nfifikh watershed is part of the small Atlantic river basins, characterized by a semi-arid climate and intensive human exploitation, particularly since agriculture constitutes the backbone of the local economy (Ed-Daoudy et al., 2024; Zongo and Diallo, 2025). The watershed is characterized by pronounced environmental fragility and a high degree of susceptibility to erosion, resulting from the combined influence of natural factors (Tawfik et al., 2025; Taira et al., 2024). Among these, particular importance is attributed to the aggressiveness, irregular distribution, and concentration of rainfall within a limited number of days during the wet season (Hamouch et

al., 2025; Limame et al., 2025). This vulnerability is further accentuated by marked lithological diversity. Impermeable formations of the ancient basement, predominantly schists and quartzites, prevail in the upstream sector; the middle course is largely underlain by Secondary-era formations, mainly clay deposits; and near the outlet, Nfifikh river incises recently formed sediments composed essentially of silt and alluvial clay (Ait Haddou et al., 2024; Bensiali et al., 2024). Such geological conditions have favored the development of skeletal and weakly evolved soils, primarily poorly structured, hydromorphic, and immature soils, most of which constrain infiltration processes (Bouiss Eddine et al., 2024; Charef et al., 2025).

Beyond these natural determinants, anthropogenic pressures significantly contribute to the acceleration of erosional dynamics (Ed-Daoudy et al., 2024; Ed Daoudy et al., 2025). The rural sectors of the watershed are undergoing sustained demographic growth, prompting transformations in local livelihoods and the adoption of unsustainable agricultural production systems, accompanied by modifications in farming practices (Hamouch et al., 2024a; Hamouch et al., 2024b). In addition, forest ecosystems have experienced substantial degradation and have been converted into agricultural lands established on structurally degraded soils, a situation that frequently promotes surface runoff and intensifies erosion processes (Haddadi and Hadiya, 2024; Limame et al., 2024). This situation raises several critical questions regarding the dynamics of water erosion in the Nfifikh watershed: Which factors are primarily responsible for the degradation or stability of land resources, and to what extent do these factors individually or interactively control erosion processes? Although previous studies have highlighted certain determinants of soil erosion in semi-arid Moroccan landscapes, a comprehensive, spatially explicit assessment combining both natural and anthropogenic factors using the PAP/CAR model integrated with GIS remains lacking. Consequently, the patterns, intensity, and spatial distribution of erosion across the watershed are not yet fully understood, and the relative contributions of climate, lithology, topography, and human activities remain quantitatively unverified. Addressing these gaps is essential for developing reliable predictive tools and actionable maps that can inform sustainable land management strategies in the region.

Despite the recognized importance of understanding water erosion in semi-arid Moroccan watersheds, comprehensive analyzes that integrate both natural and anthropogenic drivers at the watershed scale remain scarce. In particular, the relative influence of lithology, slope gradients, rainfall patterns, soil characteristics, and human activities on the spatial variability of erosion in the Nfifikh watershed has not been systematically quantified. This knowledge gap limits the ability to predict erosion patterns accurately and hinders the development of effective strategies for soil conservation and sustainable land management.

The objective of this study is to quantitatively characterize the spatial patterns and driving factors of water erosion in the Nfifikh watershed using the PAP/CAR model combined with geographic information systems (GIS), thereby revealing previously undocumented relationships between natural and anthropogenic determinants of erosion. We hypothesize that the interaction of geological, climatic, topographic, and land-use factors produces heterogeneous erosion patterns across the watershed, and that GIS-based mapping can identify hotspots of degradation and areas of relative stability. By filling this gap, the study generates new scientific insights into the geomorphological functioning of semi-arid watersheds and provides a validated methodological framework for assessing erosion risk, which can inform both ecological research and practical land management decisions.

STUDY AREA

The Nfifikh watershed is located within the Atlantic coastal basins of Morocco and forms part of the Meseta region, extending from the Central Plateau (N33°17'47.42'' W6°51'56.99'') through the Chaouia to the coastal zone (N33°43'10.80'' W7°20'33.12''), with a general orientation from southeast to northwest. The watershed covers an area of 788.79 km² and has a main channel approximately 71 km long (digital elevation model (DEM) Processing Using GIS), originating in the Central Plateau and discharging into the Atlantic Ocean northwest of the city of Mohammedia. The Nfifikh River forms a natural boundary between the urban areas of Mohammedia and Mansouria. The watershed spans the provinces of Mohammedia, Benslimane, Settat, and Khouribga, encompassing 16 local administrative units, including four urban and twelve rural communes (n° 2.15.716, 23 septembre 2015, Maroc).

Geologically, most of the watershed is part of the ancient basement complex, exhibiting high lithological diversity. The area includes both easily erodible formations and more resistant rock types, which influence flow concentration, velocity, and consequently the erosive power of water. The dominant lithologies in the upstream sector consist of impermeable schists and quartzites, while the clay middle and lower sectors are underlain by Secondary-era and alluvial deposits [Add a map or source of geological data]. Soils in the watershed are generally shallow, poorly developed, and poorly structured, which enhances runoff and susceptibility to erosion, particularly on plateau surfaces and along riverbanks. Quantitative data on soil depth, texture, and erodibility are required to reproduce erosion assessments accurately (The geological map of Casablanca–Mohammedia and the Phosphate Plateau (1:100,000 scale), and the geological map of Morocco (1:1,000,000 scale)).

The watershed has been subject to long-standing human settlement, with population distribution varying according to topography and proximity to urban centers. Settlements are concentrated in valleys and flat areas, particularly in Mohammedia and other urban zones. Population growth, agricultural expansion, and other economic activities have increased the exploitation of natural resources, further intensifying erosion processes, population density exceeds 7500 inhabitants/km² in the lower urban sector near Mohammedia, while it is generally less than 45 inhabitants/km² in the upper rural part of the watershed (HCP, 2014/2024); land-use changes over the past decade include expansion of irrigated agriculture, urbanization along major transport corridors, and conversion of forested areas into agricultural lands (USGS, 2020; ESA, 2022; FAO, 2021). The main land uses include : rainfed agriculture (mainly cereals and legumes), irrigated agriculture in valley bottoms, grazing pastures, scattered forest and shrub vegetation, and expanding urban and peri-urban areas around Mohammedia and main transport corridors, each contributing differently to soil degradation and runoff dynamics. Historical and recent land-cover changes should be documented to support reproducibility and interpretation of erosion patterns, sources may include Landsat and Sentinel satellite imagery, national land-use statistics, and regional planning reports (USGS, 2020; ESA, 2022; FAO, 2021).

Overall, the Nfifikh watershed represents a complex interplay of natural and anthropogenic factors, including diverse lithology, fragile soils, semi-arid climate, topography, population pressure, and intensive land use. These characteristics make it an ideal site for studying water erosion dynamics, evaluating susceptibility, and testing the applicability of the PAP/CAR model integrated with GIS tools geospatial datasets used for reproducibility may include DEM, geological maps, soil maps, rainfall data, and land-use maps derived from remote sensing (USGS, 2020; ESA, 2022; FAO, 2021).

TOOLS AND METHODOLOGY

This study employed a combination of remote sensing, GIS, field surveys, and the PAP/CAR model to assess water erosion dynamics in the Nfifikh watershed. The watershed's topography was derived from the ASTER digital elevation model (DEM) with a spatial resolution of 30 meters, which was used to delineate the drainage network and define watershed boundaries using ArcGIS 10.8.2 software (ASTER-DEM source: NASA LP DAAC, accessed 20 March 2024). Complementary spatial data for 2024 were obtained from Google Earth and SAS Planet to support the mapping of land cover, settlements, and vegetation distribution (Figure 2a) (coordinates and links: Google Earth imagery, Longitude 6°50′W – 7°25′W; Latitude 33°10′N – 33°45′N; SAS Planet download, accessed 2024). Topographic maps at a scale of 1:50,000 and geological maps, including the Casablanca-Mohammedia produced in 1987 and Phosphate Plateau maps at 1:100,000 produced in 1956 and the national geological map of Morocco at 1:1,000,000 produced in 1985 (Figure 2, B), were used to identify spatial elements such as roads, rivers, and lithological units. Field verification was conducted with a global positioning system (GPS) to validate selected features, including erosion patterns (Figure 12), slopes, and land-use boundaries (50 points visited across the watershed, fieldwork conducted from 2020/2024). GIS and remote sensing tools were used to produce a series of thematic maps, including slope, elevation, land-use, and vegetation cover, which formed the basis for assessing the watershed's sensitivity to water erosion. These maps were further processed and integrated into the PAP/CAR modeling framework to qualitatively assess erosion risk.

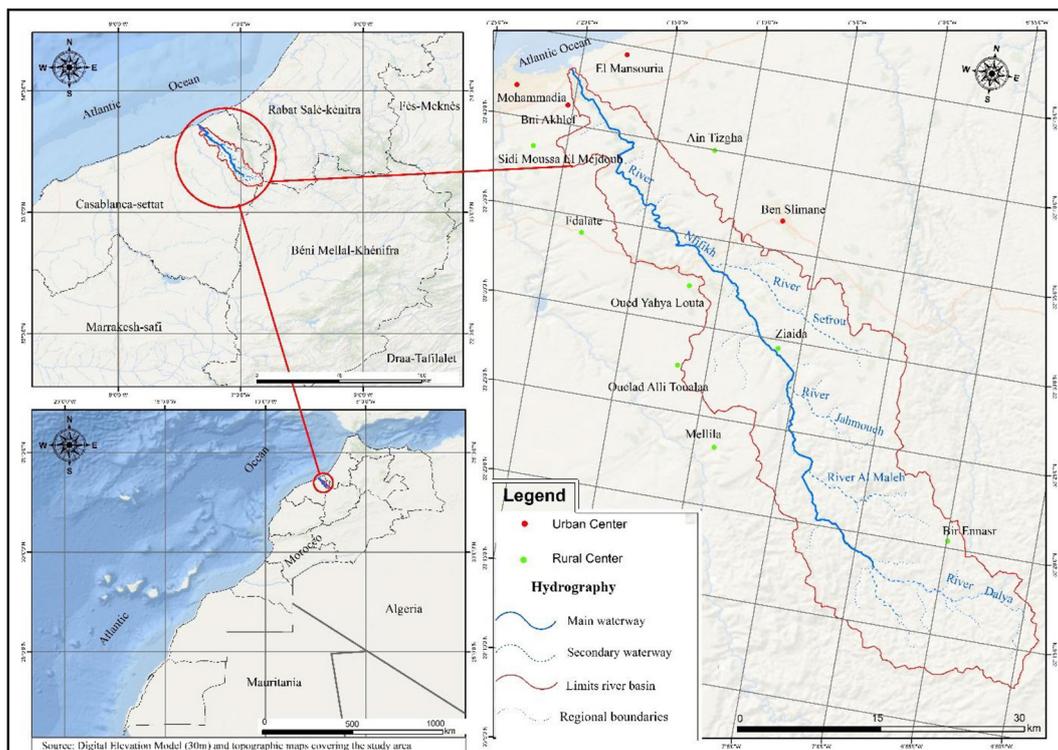The PAP/CAR model was selected due to its widespread application in Mediterranean

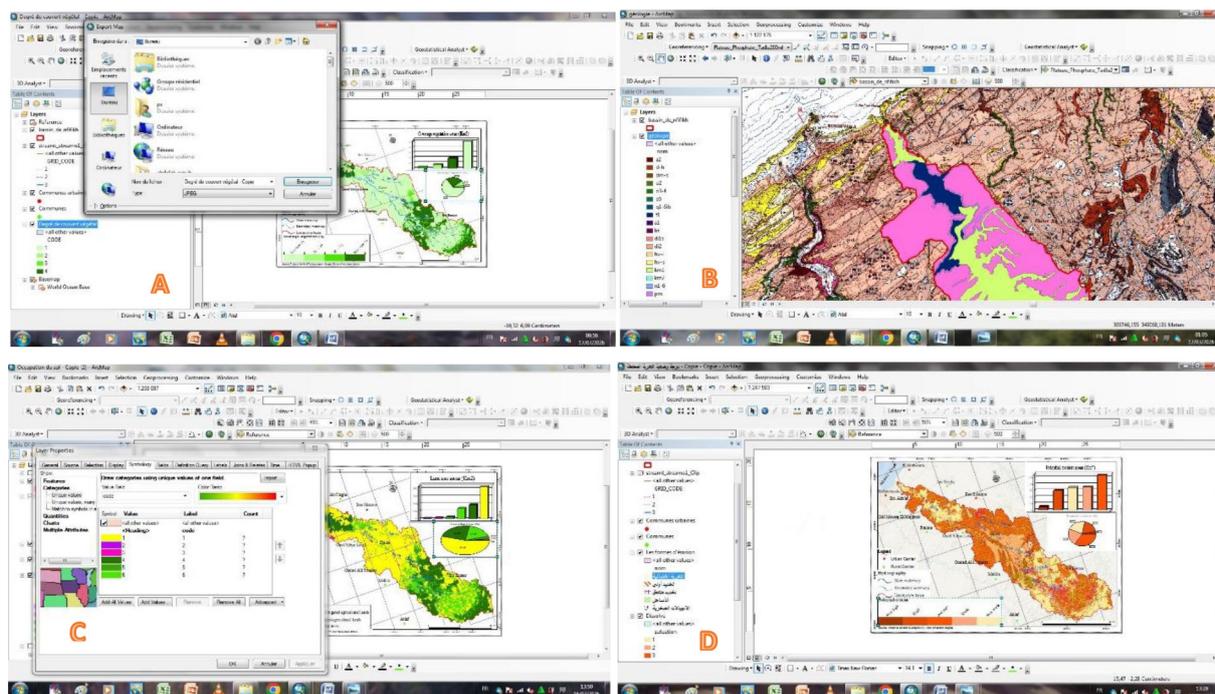**Figure 1.** Location of the Nfifikh watershed

Figure 2. Examples of the integration of remote sensing and geographic information systems (GIS) in the processing of the PAP/CAR model

watersheds and its ability to integrate natural and anthropogenic factors influencing erosion. The model enables the identification of both current and potential erosion areas (Figure 2c), as well as prioritization of zones for intervention. In this study, the cartographic component of PAP/CAR was applied, consisting of three main stages:

Descriptive stage: This stage involves documenting and evaluating current erosion forms and processes to classify the study area into stable and unstable environments. Field observations and remote sensing imagery were used to verify erosion features, including rill and gully formations on plateau slopes and riverbanks, sheet erosion on agricultural lands, and sediment deposition zones along the main channel (verified with GPS and high-resolution satellite imagery, 1:25,000 scale).

Predictive stage: This stage employs thematic maps to identify, evaluate, and integrate controlling factors, such as lithology, slope gradients, land use, and vegetation cover. Preliminary hypotheses about areas of high erosion risk were generated based on these factors. Factor weights were determined using expert judgment and literature values, with slope and land-use intensity receiving higher scores (Ait Haddou et al., 2024; Hamouch et al., 2024).

Integration stage: In this final stage, all qualitative information from the descriptive and predictive stages is consolidated to produce a comprehensive erosion map (Figure 1d), highlighting areas of high vulnerability and stability. This map serves as a key tool for watershed management and planning. Map outputs were prepared at 1:50,000 and 1:25,000 scales, with legends detailing erosion severity, land-use categories, and slope classes. Digital map files were exported in JPEG and shapefile (Figure 2a) formats to ensure reproducibility and compatibility with GIS platforms (Figure 3).

RESULTS

The degree of slope plays an important role in directing natural dynamics.

Our cartographic work shows that the slopes of the Nfifikh watershed remain very steep, exceeding 15° in 32.44% of the area, covering more than 255.84 km². This gives the water flow high morphodynamic energy, thereby increasing the volume of erosion, soil displacement, and transport on the slopes, especially since the dynamic energy of the stream increases in relation to the amount and concentration of rainfall in time and space. Most of these slopes are in the upper watershed, which largely falls within the Upper
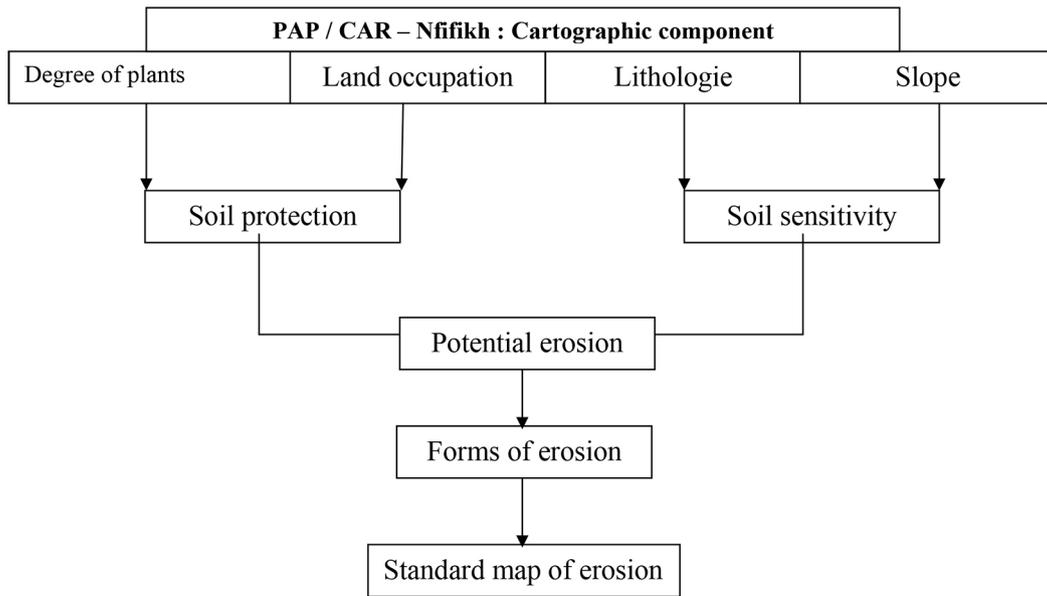
Figure 3. Methodology adopted for the erosion mapping using PAP/RA

Chaouia region, where terraced hills have developed along deep and wide valleys**.**

The length of slopes in the plateaus of the Nfifikh watershed exceeds three meters in most cases, representing 45.51% of the area and covering more than 359.01 km². These slopes are mainly distributed in the upstream part of the watershed, along the valleys in the middle course, and in the downstream area. In some cases, the average slope length reaches up to 50 meters along the main channel of Nfifikh river. However, the influence of slope length on erosion dynamics remains less pronounced than that of slope gradient, as confirmed by Roose (1994) through studies conducted in western North Africa. (Figure 4).
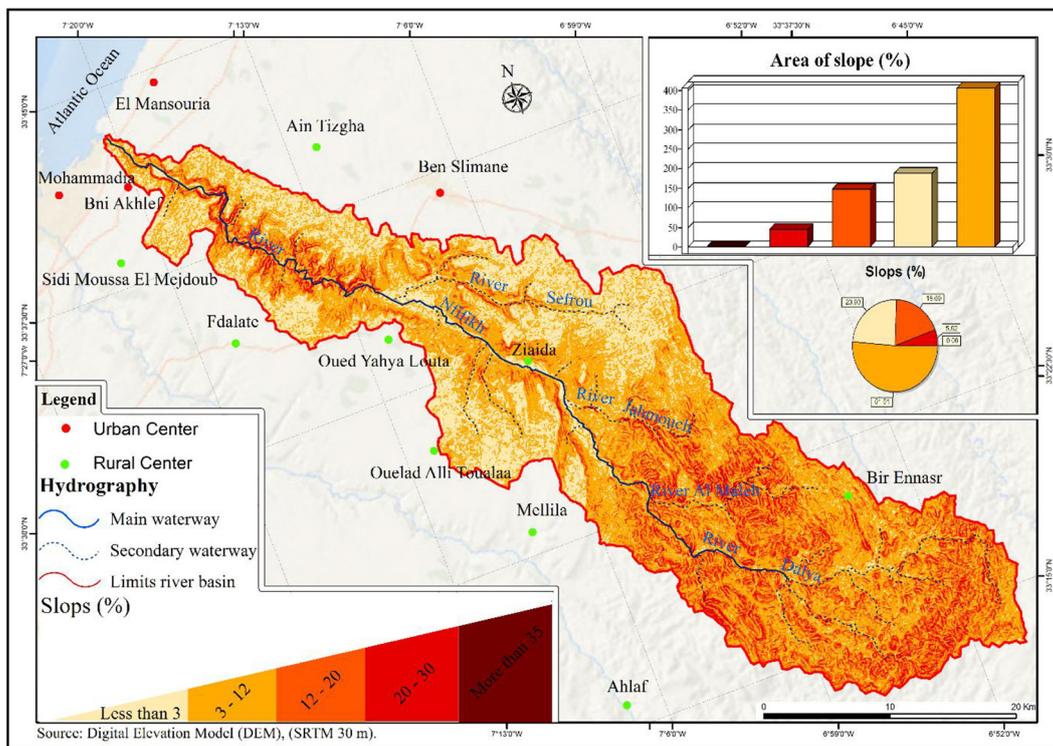

Figure 4. Map of the slopes of the Nfifikh watershed

Weak to moderately permeable lithological formations and erosion risk

Surface formations analysis using the PAP/CAR methodology indicates that 323.8 km² (40.96% of the watershed) consists of alluvial, sandy clay, red clay, brown silt, and fluvial gravel deposits. These formations have weak to moderate permeability and high erodibility, making them the most vulnerable areas to water erosion, especially outside the upstream zone and main riverbanks (geological map of Casablanca-Mohammedia and the Phosphate Plateau at a scale of 1:100,000 and field observations).

Quartzite, dolomitic basalt, sandstone, and alternating sandstone-quartzite sequences cover 224.59 km² (28.47%) and exhibit weak to moderate permeability with low to moderate erodibility. Moderately to weakly consolidated rocks, including gray and black schist, extend over 205.48 km² (26.05%), showing moderate susceptibility to erosion. Highly fractured and weakly weathered formations, such as clay-limestone alternations, occupy 26.63 km² (4.51%) and are highly vulnerable due to their low resistance to weathering (geological map of Casablanca-Mohammedia and the Phosphate Plateau at a scale of 1:100,000 and field observations). These lithological distributions provide a spatial framework for identifying erosion-prone areas. The combination of weakly resistant soils and erodible deposits highlights zones requiring priority management interventions and informs further analysis of slope, land use, and vegetation impacts on erosion. (Figure 5).

Soil sensitivity to water erosion

Application of the PAP/CAR model indicates that a substantial portion of the Nfifikh watershed exhibits high susceptibility to water erosion, particularly on plateau slopes. Approximately 280.64 km² (35.58% of the watershed) are classified as highly erodible, with erosion hotspots concentrated along the El Malah and Dalia Rivers in both upstream and downstream sectors. These areas are predominantly located on slopes exceeding 20%, where soil fragility and low structural stability exacerbate erosion processes (sensitivity map and slope map).

In contrast, areas with low susceptibility to erosion cover roughly 64.42% of the watershed and are mainly found on upper plateau surfaces, as well as on flatter sections in the middle and lower reaches. These zones are typically associated with more resistant lithologies, such as dolomitic basalt and quartzite, occurring both on plateau surfaces and in river bottoms characterized by gentle slopes (sensitivity map and geological map). The
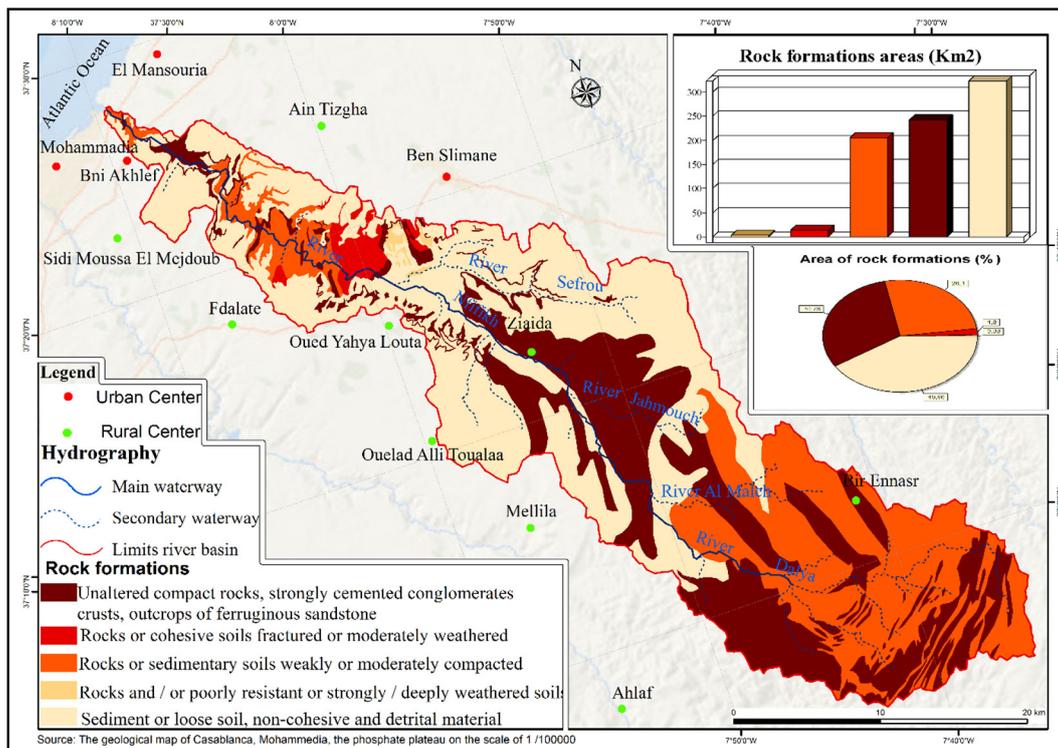

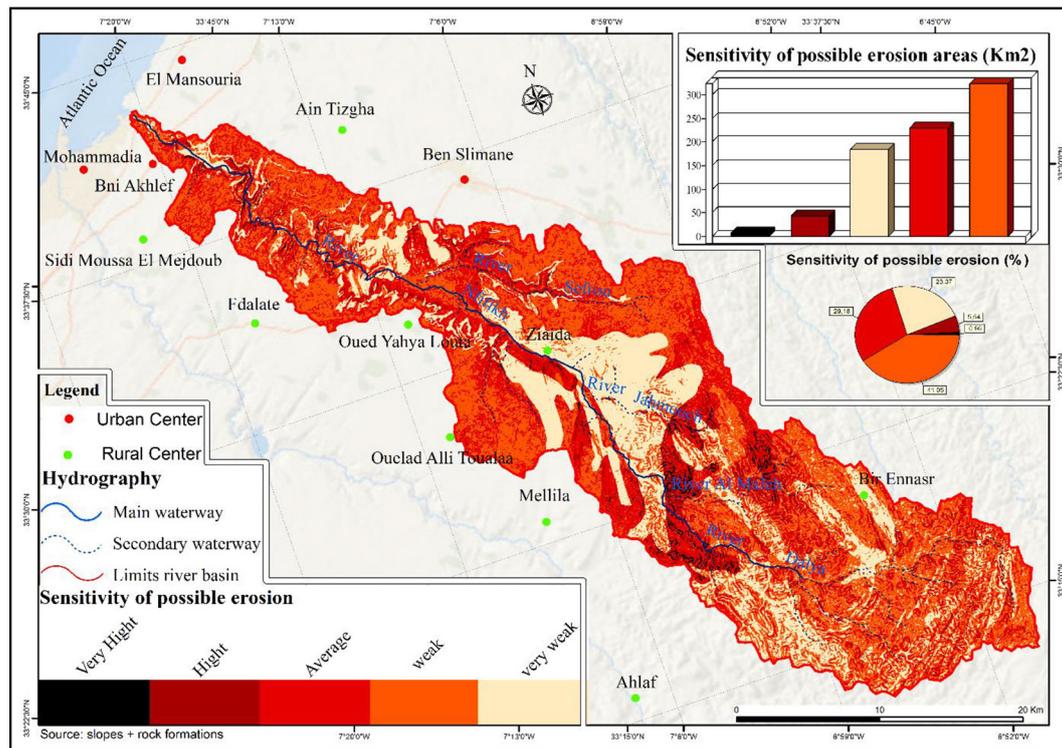**Figure 5.** Lithological map of the Nfifikh Watershed

Figure 6. Sensitivity map of the Nfifikh Watershed

spatial distribution of soil sensitivity highlights the heterogeneous nature of erosion risk within the watershed. The identification of highly vulnerable areas provides a scientific basis for prioritizing soil conservation measures and planning interventions. Stakeholders and local authorities can use this information to focus efforts on areas where slope, soil fragility, and lithology interact to generate the highest erosion potential (Figure 6).

Spatial distribution of land use according to area and type

There is a strong correlation between land use, demographic pressure, water erosion, and soil impoverishment in areas characterized by natural fragility. The watershed falls within this framework, as it contains several types and forms of land use by the local population. In accordance with the PAP/CAR methodology, and based on the use of Google Earth and SAS. Planet images as well as field observations, a classification of these uses has been established, which are relatively consistent in terms of density and level of exploitation, as follows:

Forested areas: Forests cover 185.24 km² of the total watershed area, representing 23.48%. They are mainly located in the downstream part of the watershed, particularly along valley slopes, disappear in the middle part, and reappear in the upstream area. The forest cover consists primarily of native species such as cork oak, thuja, juniper, and Aleppo pine, as well as introduced species like eucalyptus, which was planted during the French colonial period to drain wetlands in the basin and facilitate agricultural activities.

Dense matorral: This formation covers an area of about 23.89 km², accounting for 3.03% of the total watershed area, and is mainly found in the upstream zone. It consists of sparse trees associated with shrublands and steppe vegetation covering the ground. This area is characterized by low population density, where grazing constitutes the main activity, with large numbers of sheep, in addition to firewood collection for heating and other uses. In recent decades, farmers have tended to uproot trees to expand cultivated fields due to the fertility of the soils.

Open rangeland: covers 136.37 km² and represents 17.29% of the watershed area. It is located in the headwaters of Nefifikh river and then in the center of the basin to a lesser extent due to intensive human exploitation. It consists mainly of wild olive trees, sidra trees, and doum palms. Its soil is poor and barren, and surface crusts have

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begun to appear in some parts after the upper soil layers have been stripped away. Some grasses and herbaceous plants grow on it, which are used for grazing by the local inhabitants.

Rain-fed agricultural land: consists of various types of land that depend primarily on rainfall, covering an area of 429.77 km² and representing 54.48% of the watershed area. It is located in the center of the basin, particularly in the commune of Zayda, due to its flat surface and deep soil rich in organic matter, which is conducive to agricultural activity. Rain-fed agriculture predominates, relying exclusively on rainfall for irrigation. Most of this land is used for various crops, but cereals and legumes remain the most important. The majority of the land in these areas is subject to crop rotation, whether a cereal–legume cycle or a rotation of cereal crops followed by a fallow period to restore soil fertility.

Irrigated agricultural land: occupies 9.61 km² of the watershed area, representing 1.22%. It is distributed across the central part of the basin, particularly in the western and eastern parts of the Ziaida commune, then scattered throughout the lower watershed, while absent from the upper watershed. It is used for various crops intended mainly for marketing. The extent of these areas reflects the level of investment in the basin

aimed at increasing yields and productivity, involving irrigation through pumping from wells that have been in use since the French occupation of these lands.

Irrigated agricultural areas are generally characterized by relatively regular, clustered housing. As for the types of products grown in these areas, they include vineyards, vegetables, and fodder crops. However, these units have undergone changes over the last two decades that have negatively affected the land due to intensive exploitation, resulting in the decline and degradation of large areas of agricultural land.

Fruit trees: represent the smallest proportion of the total watershed area, covering 3.91 km² and accounting for no more than 0.5% of the total area. They consist mainly of olive trees, scattered in the lower and middle parts of the watershed (Figure 7).

Vegetation cover is of great importance in protecting soil against erosive factors

The study of vegetation cover is of utmost importance because it provides information about soil protection against erosion factors, as vegetation cover plays an important role in shaping and stabilizing the surface and creating balance. The
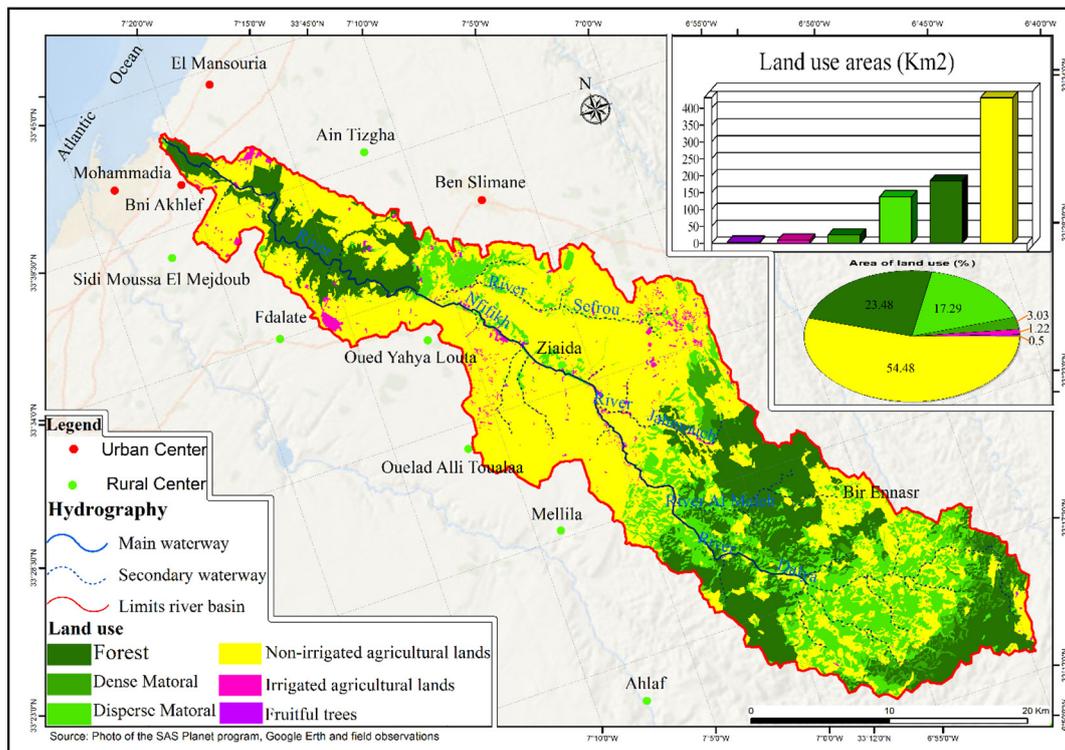

Figure 7. Land use map of the study area

morphology and external shape of trees protect the surface against various forms of erosion by preventing direct impact from raindrops and preventing the formation of crusts and the depletion of the soil of fine particles. Grass cover also contributes to improving soil resistance to erosion by increasing surface roughness and hindering runoff. Thus, the growth of this plant community after the first rainfall relatively limits the frequency of erosion and soil degradation, while in its absence, surface runoff is violent and results in the erosion of the upper soil layers.

The vegetation cover density map of the Nfifikh watershed reveals the dominance of unprotected areas (less than 5%), represented mainly by agricultural lands and bare areas. This situation results from the combined effect of several factors, including natural factors related to climatic variability and the decrease in rainfall amounts, as well as human intervention through burning, cutting, and overgrazing aimed at expanding agricultural areas. In contrast, areas with high vegetation cover exceeding 75% account for only 186.43 km², representing no more than 23.64% of the basin area, and are mainly concentrated in the Nfifikh river forest in the downstream area and in the Khatouat forest in the upstream area (Figure 8).

Degree of soil protection in the Nfifikh watershed

The overlay of the land-use map and the vegetation cover density map shows that most soils of the basin plateaus remain very weakly protected against water erosion. Areas with low soil protection cover approximately 569.52 km², representing about 72.2% of the total watershed area. Consequently, areas with good soil protection do not exceed 185.92 km², accounting for 23.57% of the basin's total area. This situation exposes the soils of plateau surfaces and slopes to direct rainfall aggressiveness and direct solar radiation, which inevitably accelerates the morphodynamic processes of their environmental settings, particularly on slopes that experience a significant decline in soil protection due to the widespread presence of grazing areas and the low density of vegetation cover, especially in the upper plateaus forming the river watershed.

The low level of soil protection on flat plateaus is also due to the nature of land use patterns, which are dominated by rain-fed agriculture and do not provide adequate protection throughout the year against heavy winter rains or summer solar radiation. This variation in soil protection across the basin plateau area corresponds to a variation in the
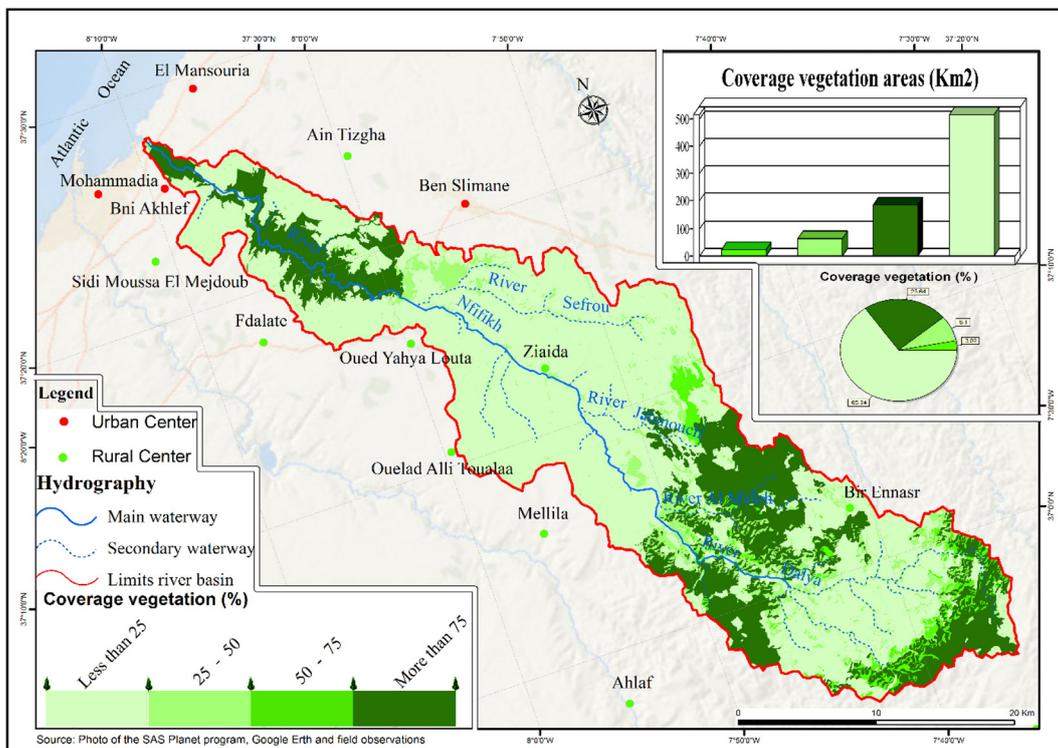

Figure 8. Vegetation cover density in the Nfifikh watershed according to PAP/RAC

distribution of water erosion activity, as areas with poor protection experience significant erosion, unlike well-protected areas, which theoretically experience limited erosion, except where fragile rocks coincide with steep slopes (Figure 9).

Spatial distribution of potential water erosion in the Nfifikh watershed

The results obtained by applying the PAP/CAR model show a high degree of correlation between areas of potential severe erosion, which cover 55.96% of the basin's plateau area, with a significant concentration in the lower watershed, particularly in agricultural areas underlain by fragile rock formations. In the upper plateaus, the main factors contributing to erosion are steep slopes, weak vegetation cover, and the spatial distribution of impermeable rock outcrops, which limit the spatial expansion of forest cover in favor of the predominance of agricultural areas, especially arable land. All these factors combined are responsible for the high potential for severe erosion in the plateau areas of the Nfifikh watershed.

Most of the areas prone to erosion are used for agriculture, particularly seasonal farming, meaning that the development of water erosion in these areas leads to continuous soil loss and a reduction in soil fertility, which in turn threatens food security and population stability. According to the PAP/CAR guidelines for unstable areas, improving the condition of these lands depends on the implementation and effectiveness of conservation and protection measures by various local and regional stakeholders (Figure 10).

Spatial distribution of water erosion forms in the Nfifikh watershed

Figure 11 shows the various forms of water erosion in the Nfifikh watershed, based on direct field observations and 2024 satellite images, with the aim of identifying and mapping the different forms of water erosion present in the watershed.

The analysis and interpretation of the water erosion forms map of the Nfifikh watershed reveal the widespread occurrence of sheet erosion, which occupies 87.77% of the watershed area. In contrast, the combined proportions of initial and deep rill erosion do not exceed 5.68% of the total area, while gullies account for 4.93%, mainly observed on slopes with steep to very steep gradients where forest cover is absent. Rockfalls, for their part, occupy approximately 1.59% of the watershed area (Figures 11 and 12).
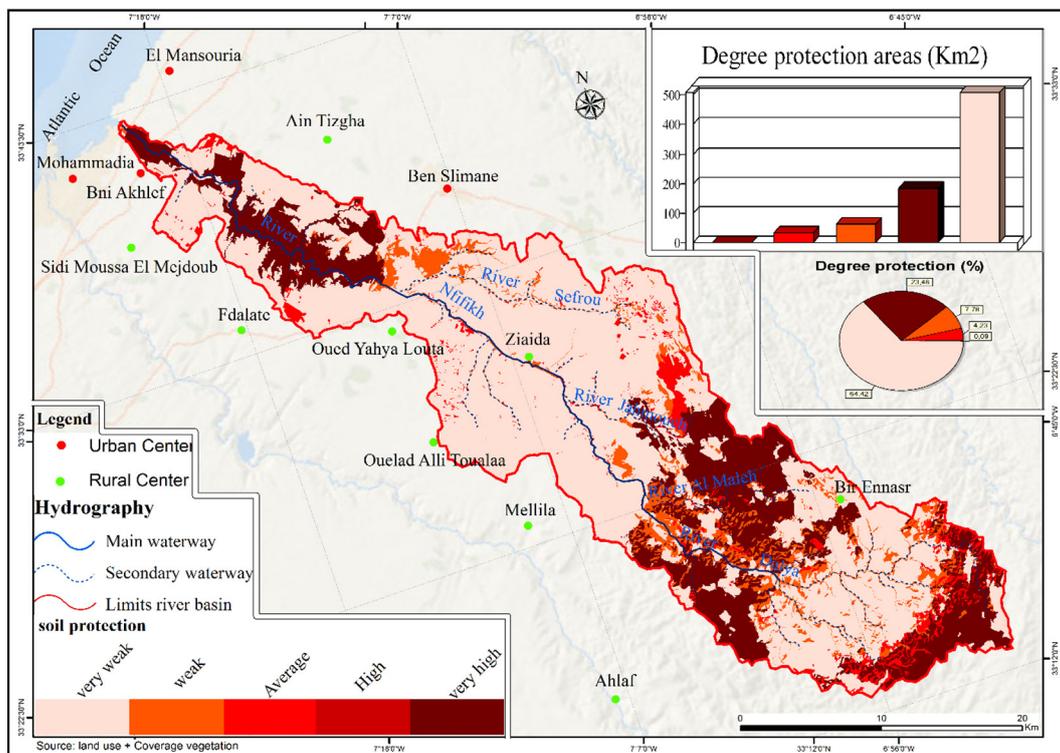

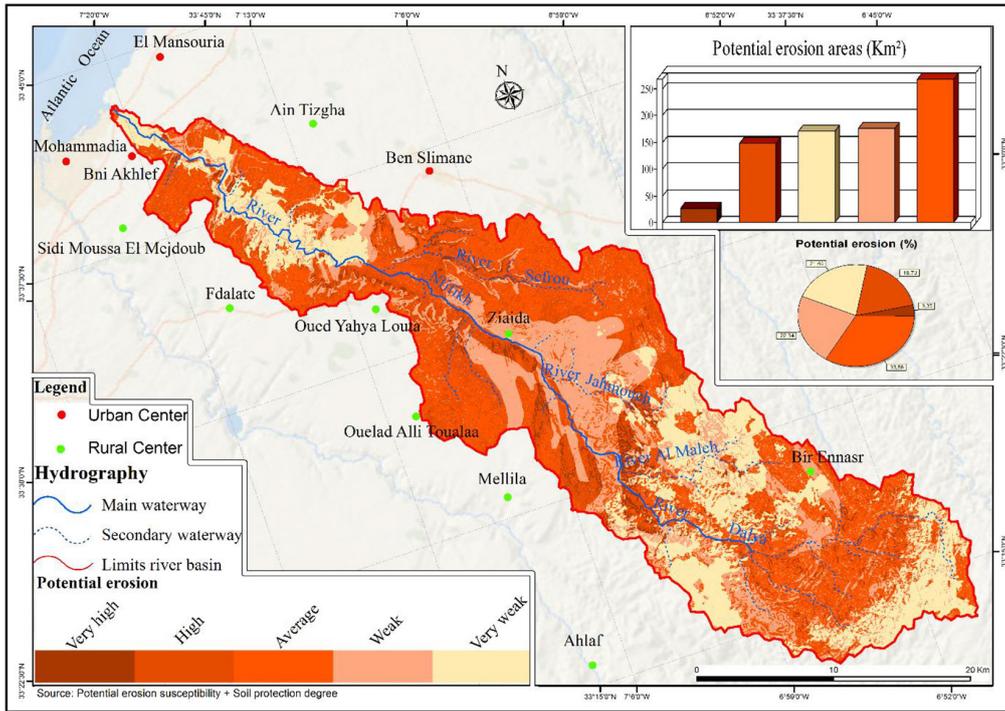**Figure 9.** Soil protection map of the Nfifikh watershed

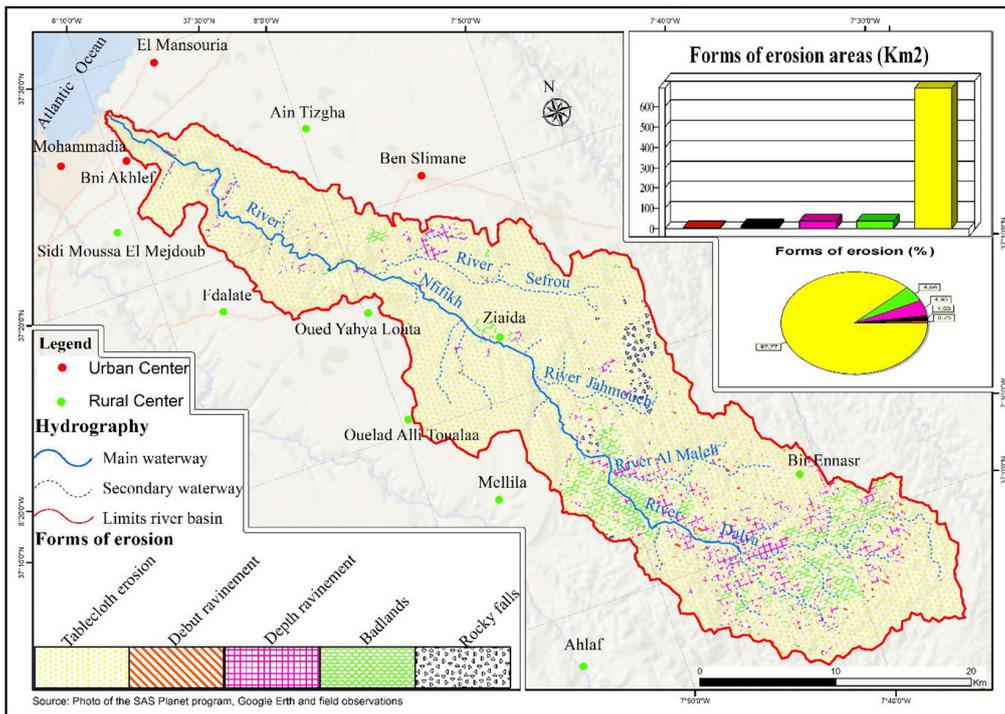**Figure 10.** Map of the erosive states of the Nfifikh watershed

Figure 11. Map of erosion forms in the Nfifikh watershed

DISCUSSION

The cartographic analysis of water erosion in the Nfifikh watershed, integrating GIS and the PAP/CAR model, reveals a strong spatial correspondence between areas of high and very high erosion potential, which together occupy approximately 55.96% of the watershed. These areas are notably concentrated in the downstream sectors, particularly in rainfed agricultural zones underlain by fragile lithological formations (El-badaoui et al. 2023; Ed-Daoudy et al. 2024).

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Figure 12. Forms of water erosion in the Nfifikh watershed: (a) Debut ravinement, (b) depth ravinement, (c) badlands, (d) rocky falls
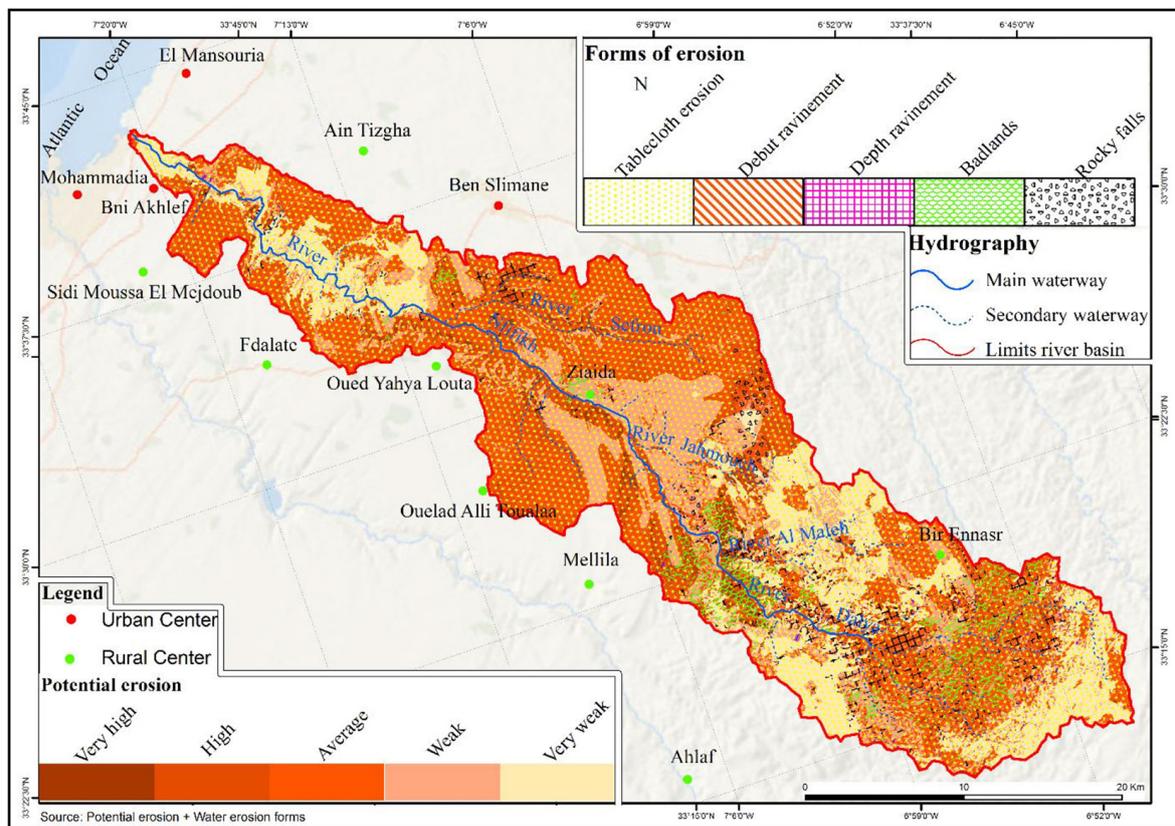

Figure 13. Consolidated map of water erosion risk in the Nfifikh watershed

In these locations, multiple erosion-inducing factors converge, including steep to very steep slopes, sparse vegetation cover, and impermeable lithologies in the upstream portions of the watershed (Peñuela, 2026).

In the middle and downstream sections, the combination of fragile lithology, limited forest cover, and predominance of rainfed agriculture emerges as the main driver of elevated erosion potential (El Amarty, 2021). These findings are consistent with patterns reported in similar Mediterranean semi-arid watersheds, where the interaction of topography, land use, and lithological vulnerability significantly shapes erosion dynamics.

According to the PAP/CAR framework, areas undergoing active erosion are classified as unstable zones, whereas stable zones constitute approximately 44.04% of the watershed. These stable areas are largely located in the upstream sector, where gentle to moderate slopes coincide with dense vegetation, enhancing resistance to erosive processes (Elbadaoui et al., 2023). Conversely, the most erosion-prone areas are dominated by agricultural land, particularly seasonal cropping zones. This suggests that current agricultural practices amplify soil loss, reduce cultivable land, and pose risks to food security and local population stability. The spatial patterns identified in this study highlight the complex interplay of natural and anthropogenic factors driving erosion. They also emphasize the need for targeted interventions – conservation measures, reforestation, and sustainable land management practices should prioritize areas of high and very high erosion potential. Moreover, the integration of GIS-based mapping with the PAP/CAR methodology provides a robust framework for identifying priority zones, supporting evidence-based decision-making for watershed management and soil conservation (Figure 13).

CONCLUSIONS

This study achieved its objective of identifying the main factors driving water erosion in the Nfifikh watershed and assessing spatial variations in erosion susceptibility using the PAP/CAR methodology combined with GIS. The results provide a detailed map of erosion vulnerability, classifying areas from very low to very high susceptibility, which directly addresses the research goal. Analysis of the watershed's natural and anthropogenic

components confirms that its characteristics – steep to very steep slopes, widespread semi-bare areas, and extensive coverage of impermeable or weakly permeable lithologies – create conditions highly favorable to water erosion. Sheet erosion was the dominant form, affecting approximately 87.77% of the watershed, while initial and deep rill erosion, as well as gullies, were concentrated in areas with sparse vegetation and moderate to steep slopes.

The study demonstrates that more than 35% of the watershed is highly sensitive to erosion, while protective vegetation covers less than 35% of the area and is unevenly distributed relative to the most vulnerable zones. High to very high erosion risk areas coincide with concentrated agricultural land and regions with higher population density, confirming the hypothesis that erosion susceptibility results from the combined effect of natural fragility.

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