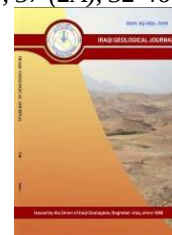




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Modeling and Mapping Water Erosion Risk via GIS, Remote Sensing, and the PAP/RAC Model - Case of Tamdroust Watershed, Morocco

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Abstract

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Water erosion remains the main form of land degradation globally, with a particularly high sensitivity in Morocco. This study aims to assess and map areas at risk of water erosion in the Tamdroust watershed (Settat Plateau, Morocco) using the PAP/RAC model combined with Geographic Information Systems (GIS) and remote sensing. This comprehensive approach integrates several factors influencing erosion, such as topography, lithology, vegetation density, and land use, to identify erosion-prone areas. The methodology comprises three phases. The first, "predictive" phase generates a synthesized map illustrating the distribution of erosion states. The second phase spatializes different forms of erosion. Finally, the third phase integrates the results of the first two phases. The first phase reveals an abundance of moderate erosion covering 52% of the area, with significant erosion observed in about 7% of the watershed, indicating a trend towards increased erosion without intervention. The subsequent phases identified several forms of erosion such as sheet erosion, gully erosion, solifluction, and Badlands, mainly in areas with steep slopes and low vegetation cover. These results underline the need for interventions to prevent further deterioration of the Tamdroust watershed, highlighting the importance of sustainable land and water resource management in the region.

Keywords: GIS; Remote Sensing; PAP/RAC; Water erosion; Tamdroust watershed

1. Introduction

Water erosion stands as the predominant cause of agricultural land degradation across various global regions. This ongoing process is acknowledged as the principal threat to soil functionality, posing a risk to 40% of lands (FAO and ITPS, 2015). Specifically, the Mediterranean region is identified as a climate "hotspot" experiencing notably aggressive climatic occurrences during autumn and winter (IPCC, 2013). Furthermore, over 40% of Moroccan agricultural land are severely threatened, and this phenomenon has a direct impact on the reduction of water quality due to sediment, nutrients, chemicals, and transported fertilizers, as well as siltation of reservoirs and the destruction of water bodies, primarily water reservoirs (Chevalier et al., 1995). It also leads to a reduction in fish stocks in hydrosystems (Namr and Mrabet, 2004).

Recently, there are indicators based on evidence of significant changes in land use (Borreli et al., 2017) that trigger accelerated soil erosion with dramatic implications for nutrient and carbon cycles, land productivity, and, consequently, global socio-economic conditions (Keesstra et al., 2016). For these

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reasons, since the early 1960s, Morocco has embarked on a sensible process of surface water mobilization by constructing several dams to mitigate the continuous decrease in precipitation and frequent flooding due to climate change (Goufri et al., 2020).

Quantifying and mapping soil loss risks involve two approaches: direct and indirect measures. Direct measurement of erosion, as indicated by Duarte et al. (2021), is a complex and resource-intensive process for evaluating soil loss. In contrast, the indirect method relies on equations and mathematical models, continually evolving over the past fifty years due to technological advancements. Various models, including empirical ones, factor in parameters like precipitation, lithology, topography, and vegetation cover. The Universal Soil Loss Equation (USLE) and its adaptations stand out among the widely used empirical models.

The integration of remote sensing and Geographic Information Systems (GIS) has significantly facilitated the cost-effective modeling and spatial representation of water erosion (Akalai et al., 2014). Several researchers have applied the Priority Actions Programme/Regional Activity Centre (PAP/RAC) approach, demonstrating its efficacy in mapping and modeling water erosion. Studies by (Attia et al., 2005; Elbouqdaoui et al., 2006; Bachaoui et al., 2007; Sadiki et al., 2012; El Aroussi et al., 2013; Akalai et al., 2014; Mesrar et al., 2015; Iaaich et al., 2016; Ousmane et al., 2017; Lakhili et al., 2017; Tahouri et al., 2019; Hmamouchi et al., 2020; and Sadouki et al., 2023) have highlighted the reliability of the PAP/RAC method in Moroccan watersheds. This method aims to incorporate human influence on the environment using GIS and remote sensing technologies for processing spatial data. These tools are pivotal for spatial analysis, allowing the cost-effective and timely mapping and analysis of extensive geographical data.

The objective of this study is to map regions prone to water erosion, employing the PAP/RAC model's principles that incorporate natural influencers like land use, slope, lithology, and vegetation cover. Integrating the PAP/RAC guidelines with spatial remote sensing and GIS techniques in the Tamdroust river basin, the goal is to develop a thematic map identifying priority areas vulnerable to erosion. This map aims to aid decision-makers in selecting preventive measures crucial for mitigating the adverse effects of erosion risk on the population, their assets, and the environment.

2. Study Area

The present study focuses on the Tamdroust watershed, which is part of the Settât Plateau in Morocco (Fig. 1). It covers an area of approximately 656 km² with a perimeter of 194 km. The altitude within the basin varies, with the minimum altitude being 809 m and decreasing to 287 m at the outlet. Administratively, it belongs to the Settât province and includes the rural municipalities of Tamdroust, Ras el Ain, Sidi Hajjaj, Lamrarga, Ouled chlih, and Ben Ahmed. The geology consists of Hercynian basement rocks, folded and granitized, which outcrop in the northern and southwestern parts of the plateau (Archambault et al., 1975). These rocks are covered by subtabular overlying formations, relatively undeformed by the Alpine phases (Mahdioui et al., 2015). The Quaternary superficial formations in the region result from the combined action of climatic conditions and tectonic movements influenced by the withdrawal of the Moghrebiein (El Bouqdaoui, 1995).

The Tamdroust basin represents a vulnerable environment to degradation. It is characterized by the predominance of soft lithological formations (marl, shale, clay, etc.) that are easily erodible. The topography features steep slopes (>35%) that are cultivated. The natural vegetation cover has been significantly degraded due to inappropriate anthropogenic activities. Consequently, water erosion in this basin has reached critical stages (El Assaoui et al., 2023). The study area is situated in a Mediterranean climate context, with an average annual rainfall of approximately 530 mm. Seasonal and interannual variations in precipitation are notable, with a recent trend toward drought. This has a significant impact on water resources, soil quality, and vegetation.

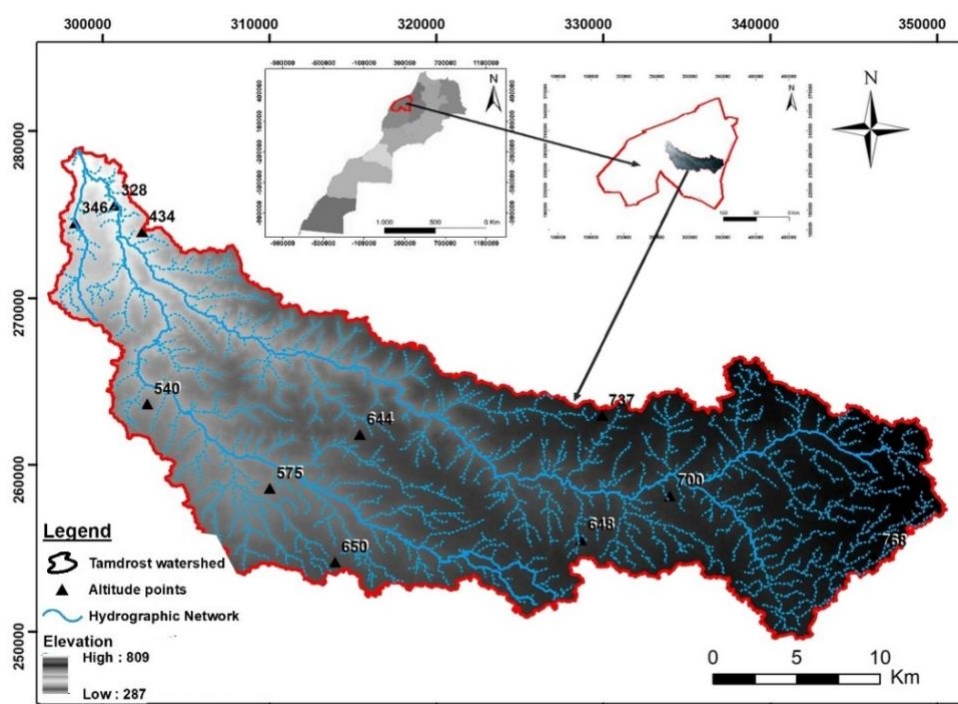


Fig.1. Situation of the Tamdroust watershed

3. Materials and Methods

The PAP/RAC model seeks to conduct a qualitative evaluation of water erosion sensitivity by examining how risk factors are interconnected and interdependent, aiming to comprehend this phenomenon. Given the interlinked nature of these factors, employing a RACtographic approach becomes essential to execute multiple intersection, processing, and data analysis operations. The classic iteration of the model (PAP/RAC, 1998; advocates a methodological framework that integrates these tasks into three complementary phases: reconciling benefits, employing diverse techniques, conducting data processing, and executing tographic modeling. The qualitative PAP/RAC method is grounded in three distinct approaches.

Predictive Phase: This phase involves identifying, evaluating, and integrating all physical parameters such as slope, lithology, and vegetation cover to make preliminary assumptions about erosion risk. The goal of this phase is data processing through a sequence of several operations, including the development of slope and lithofacies class map, erodibility map, land cover map, soil protection map, and erosive state map.

Descriptive Phase: This phase aims to identify and evaluate current erosion processes at the site, as well as different degrees of exposure to erosion and evolving trends. It is carried out through fieldwork (recognition and monitoring of forms) and satellite image processing, using the predictive map of potential erosive states as a cartographic and thematic reference framework. The combined procedure of field observation and process identification consists of three operations.

Integration Phase: This phase combines the results of the previous two approaches by overlaying the erosion form map with the erosive state map. It provides a consolidated, synthetic map of water erosion. (Fig. 2) illustrates the methodological scheme for applying the PAP/RAC guidelines in the Tamdroust watershed.

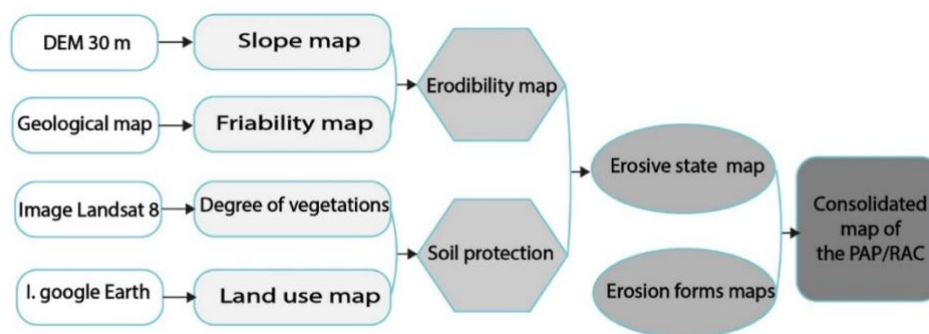


Fig.2. Methodology adopted for the erosion mapping using PAP/RAC

To assess the susceptibility of soils to water erosion in the Tamdourst basin, a qualitative model was employed. This model relied on topographical, geological, and vegetation cover data, utilizing satellite imagery (Landsat 8 from March 22, 2022 and Google Earth), an ASTER GDEM-type digital elevation model with a 30-meter resolution, topographic maps of the study area (Ali_moumen, Ben Ahmed, Melgou, Mgarto, Ras El Ain at a 1:50,000 scale), the geological map of Morocco (1/1M), as well as field observations. These data were used to define the study area and generate various thematic maps using remote sensing software (Erdas imagine, Envi) and Geographic Information Systems (GIS). The data were georeferenced to the coordinate system of Morocco.

4. Results and Discussions

4.1. Predictive Approach

The initial predictive phase encompasses seven sequential data processing steps. These steps culminate in the delineation of uniform units representing erosion states, ultimately serving as the foundation for mapping the potential and overall patterns of soil water erosion.

4.1.1. Slope Map

Slope is a topographic feature of the watershed that has a significant influence on the rate of erosion. It is, therefore, one of the important factors in soil erosion. Its influence on erosion is more pronounced than on runoff, especially when the soil is not fully covered. For soils bearing the same crops, runoff increases with the slope. Steep slopes with fast runoff are generally responsible for excessive erosion and the emergence of various erosion forms, such as Badlands, the extent of which depends on geology, soils, and vegetation cover protection. The classification of slopes on the watershed map is done according to the classes defined in the PAP/RAC guidelines, which are based on the following Table 1.

Table 1. Slope classes according to the PAP/RAC (1998) model and their spatial distribution in the watershed

PAP/RAC CODE	Class	Area	
		Km ²	Percentage (%)
1.	Nulle to low (0-3%)	83,79	12,77
2.	Moderate (3%-12%)	473,23	72,16
3.	Abrupt (12%-20%)	81,57	12,43
4.	Very abrupt (20%-35%)	16,90	2,55
5.	Extreme (>35%)	0,61	0,09

The obtained results show a percentage of 12.77% and 72.16% for the strata with low and moderate slopes, respectively. Steep and very steep slopes are located in the northeastern part of the basin due to the topographical nature of the region, representing a percentage of 12.43% and 2.55%. The analysis of the slope table and map (Fig. 3) indicates the prevalence of moderate slopes in our basin. Therefore, our basin has a relatively gentle relief, which will enhance the flow of water and promote sheet erosion in the basin. Ablation will significantly outweigh accumulation since slopes with less than 3% inclination occupy only 12.77% of the watershed.

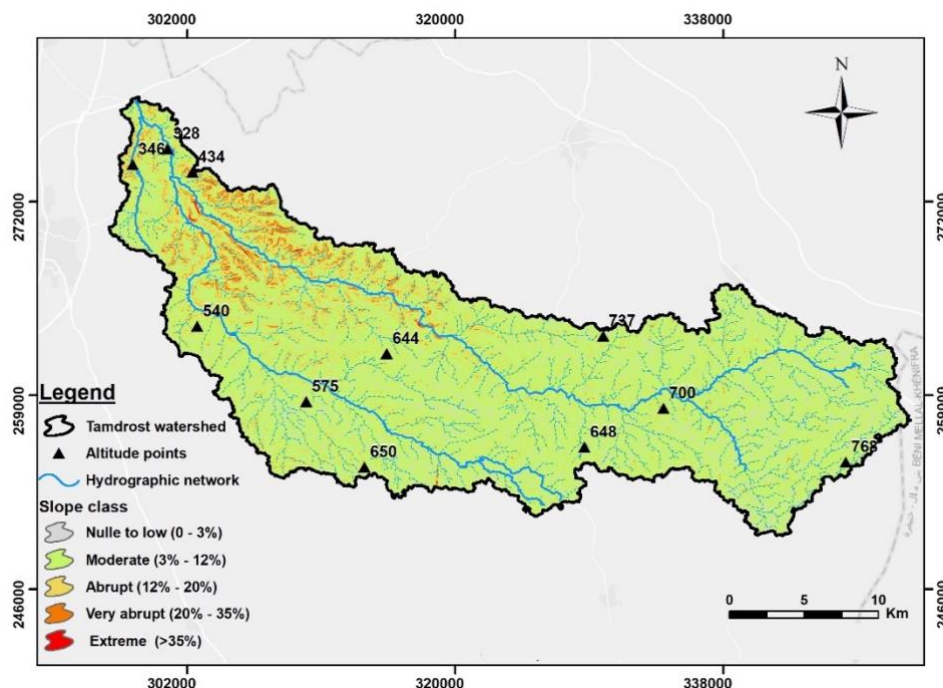


Fig.3. Map of the slopes of the Tamdroust watershed

4.1.2. The lithofacies map and friability map

The lithofacies map provides information about the degree of substrate friability and its vulnerability to erosive risk. It is from the lithological map that rocks can be classified according to their geological formation and mechanical resistance, which are factors directly affecting water erosion. It was created based on the processing of geological data (1/1M geological map of Morocco). The legend of the lithofacies map includes the classes presented in (Table 2), which contain descriptive abbreviations of the types used in the PAP/RAC guidelines.

Table 2. Lithofacies classes according to the PAP/RAC model and their spatial distribution in the watershed

Class of lithofacies	Degree of soil cohesion	Area	
		Km ²	(%)
1(a)	Unweathered compacted soils, strongly cemented conglomerates, crusts, outcrops of ferruginous sandstones (massive limestones, strongly rocky soil, igneous or eruptive rocks, locally encrusted soils).	195,59	30, 9
2(b)	Fractured or moderately weathered cohesive rocks or soils	35,89	5
3(c)	Low to moderately compacted sedimentary rocks or soils (slate, shale, marl, etc.).	78,88	17
4(d)	Rocks and/or soils that are not very resistant or that have been strongly/deeply altered (marl, gypsum, clayey slate, etc.).	234,43	37
5(e)	Loose, non-cohesive sediments or soils and detrital material.	39,74	10, 10

The lithofacies map of the Tamdroust watershed (Fig. 4) shows that this basin is predominantly characterized by lacustrine limestone rocks, while siliceous rocks and conglomerates cover an area of 30.9%. Additionally, marl and phosphate rocks extend over 37% of the basin, corresponding to the central part of the phosphate plateau. Dune facies cover 17% of the total area and are located at the extremities of the study basin. Alluvial or fluvial terrace class occupies nearly 10%, and the lacustrine facies class, as well as the mixture of sandstone, limestone, marl, and clay, cover 5% of the basin.

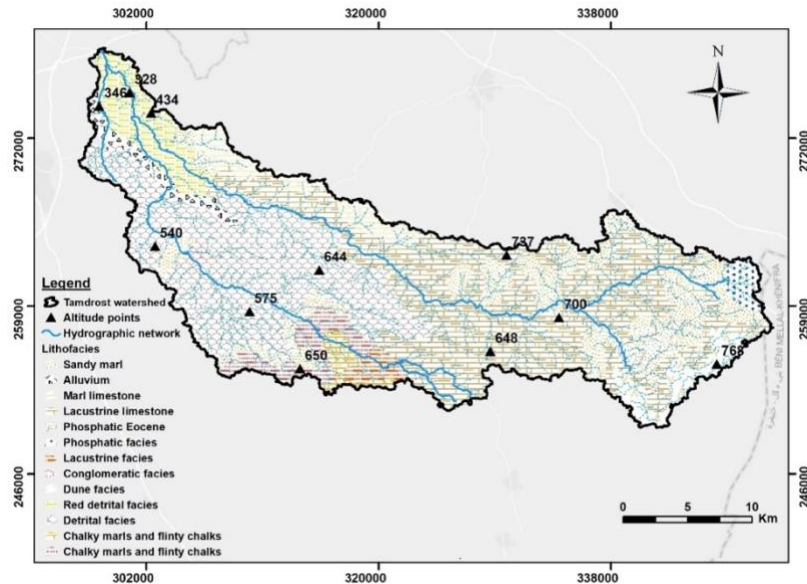


Fig.4. Lithological Map of the Tamdroust Watershed (Source: Geological Map of Morocco, 1/1 000 000)

The various substrates from the lithological map are then grouped into five classes to obtain the map of friability or material resistance to erosion. An analysis of the map (Fig. 5) regarding the degree of soil resistance to erosion reveals that classes with low (d) to very low (e) resistance cover 47.10% of the basin, while the class with medium resistance (c) occupies 17% of the total area. The classes with strong (b) to very strong (a) resistance represent 35.9% of the watershed's surface.

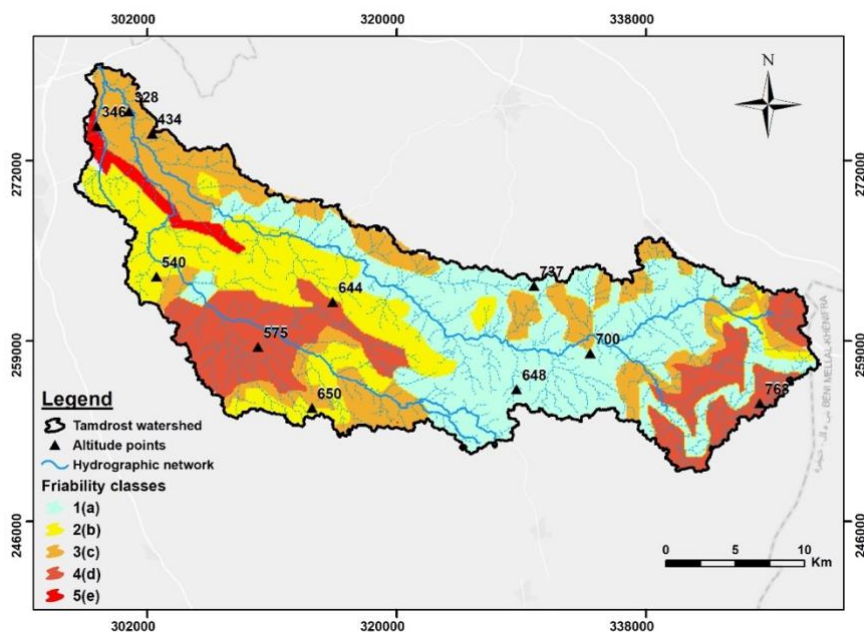


Fig.5. Friability Map of the Tamdroust Watershed

4.1.3. Erodibility map

It is the outcome of combining data from the map of surface formations with that of the slope map. Five classes are derived, with each class corresponding to different erosion susceptibility levels, necessitating specific measures (Rafla et al. 2005). The erosion susceptibility map of the Tamdroust watershed results from the overlay of the slope map and the lithofacies map. Polygons resulting from the overlay of these two reference maps are categorized according to the matrix presented in the following table, (EN) very low, (EB) low, (EM) moderate, (EA) high, and very high (EX) Table 3.

Table 3. Soil erodibility matrix according to PAP/RAC (1998)

Classes of slope	Classes of lithofacies				
	1(a)	2(b)	3(c)	4(d)	5(e)
1	1(EN)	1(EN)	1(EN)	1(EN)	2(EB)
2	1(EN)	1(EN)	2(EB)	3(EM)	3(EM)
3	2(EB)	2(EB)	3(EM)	4(EA)	4(EA)
4	3(EM)	3(EM)	4(EA)	5(EX)	5(EX)
5	4(EA)	4(EA)	5(EX)	5(EX)	5(EX)

Figure 6, representing the erodibility degree map, highlights that when the slope is steep and/or the terrain exhibits low resistance, erodibility is consistently high. However, it also shows that nearly 94% of the watershed has a moderate to medium erodibility degree, while poorly erodible soils cover approximately 53 km², accounting for about 8% of the area.

Conversely, highly to extremely erodible soils represent only 5% of the watershed's total area. Analyzing the erodibility map and the different classes in the database, it is evident that the watershed is predominantly of medium erodibility. However, population growth, vegetation cover degradation, and climate changes may increase the degree of terrain erodibility. In the absence of a preventive and protective basin strategy, it is likely that the terrain will become increasingly erodible.

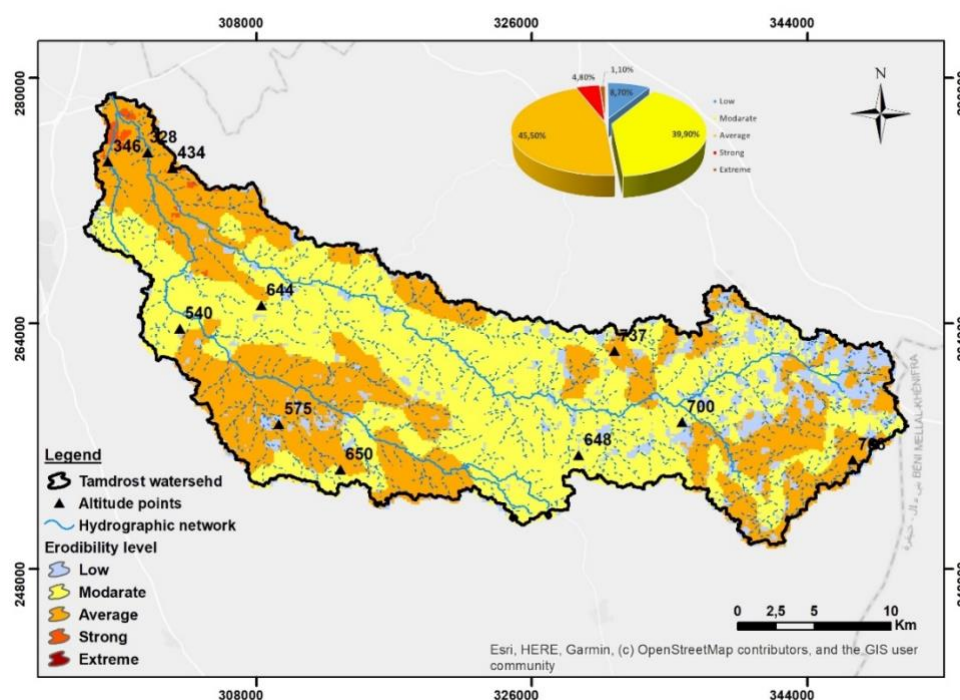


Fig.6. Erodibility map of the Tamdroust watershed.

4.1.4. Land use map

Land use provides insight into the physical land cover types and their structures on emerged land. It encompasses natural or planted vegetation and is of significant importance as it enables us to understand current and future trends, identify high-risk areas susceptible to degradation, and areas earmarked for development. Our land use map was created based on a Landsat 8 satellite image from March 13, 2022, with a 30-meter resolution. This means that each pixel in the image represents an area on the ground that is 30 meters by 30 meters in size.

From the analysis of the map (Figure 7), it is evident that the Tamdroust watershed is extensively impacted by human activities. Agricultural land expansion covers approximately 66% of the basin's surface. These lands are predominantly used for cereal cultivation, with minimal soil cover during the rainy season, often on steep slopes with fragile soils. Natural forests cover only 2.33% of the area, primarily located in the upper part of the basin, influenced by altitude and precipitation. These forests are generally in decline due to expansion and increased deforestation.

Irrigated land has significantly expanded in the study area, covering 14% of the total surface, thanks to government projects such as the Green Morocco Plan and the Regional Development Program (PDR). Olive trees dominate arboriculture at altitudes above 1000 meters, either as pure plantations with or without management or as mixed plantations with fig trees or annual crops (cereals, legumes).

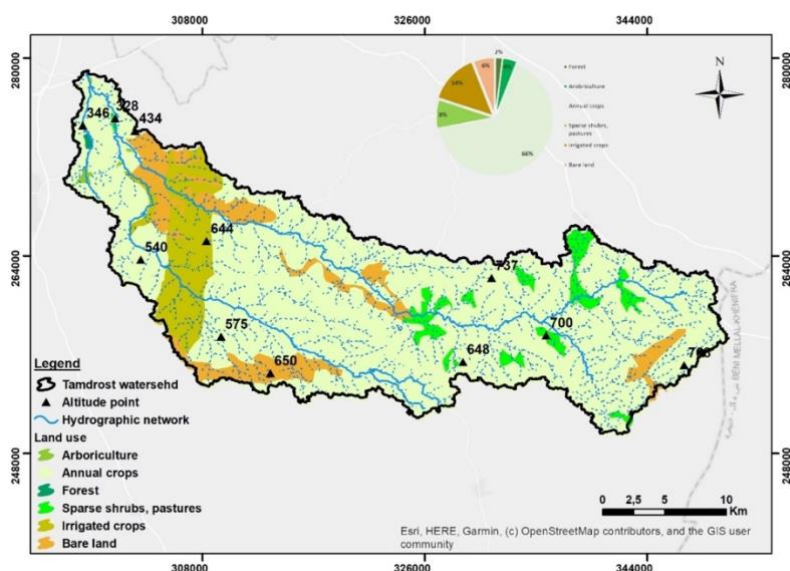


Fig.7. Land use map of the study area

4.1.5. Vegetation cover map

Vegetation cover is one of the paramount factors that affect the condition of soils. In fact, the risk of erosion increases when the soil is bare. An area protected by vegetation provides raindrop impact mitigation, slows down surface runoff, and enhances infiltration.

A dense vegetation cover is even more effective in reducing erosion as it dissipates the energy of raindrops, slows down surface water flow, and maintains good surface porosity, preventing surface crusting (Roose 1996, Sabir and Roose 2004).

The creation of the vegetation cover density map in the Tamdroust watershed is accomplished through the transformation and classification of a Landsat 8 satellite image from March 22, 2022, using the NDVI (Normalized Difference Vegetation Index), representing the density of vegetation cover according to the PAP/RAC classification. High NDVI values (approximately 0.43-0.52) correspond to areas with dense tree cover. Elevated values (0.33-0.43) represent vegetation areas, while moderate

vegetation density is represented by values between 0.14-0.23. Low values (0.04-0.14) correspond to cultivated lands. The PAP/RAC model categorizes vegetation cover levels into four categories Table 4.

Table 4. Classes of the Degree of Vegetation Cover in the Tamdrost Watershed According to the PAP/RAC

Classes	Degree of vegetation cover	Area in %
1	Inférieur à 25%	23
2	25% - 50%	32
3	50% - 75%	40
4	Supérieur à 75%	5

The analysis of the database and the synthetic map obtained from (Fig. 8) and (Table 6) show the distribution of vegetation cover values. Areas with a vegetation cover value of less than 25% occupy an area of 23%, while nearly 32% of the total area has a vegetation cover density between 25 and 50%. The third class does not exceed 40% of the watershed area, and areas with a vegetation cover degree greater than 75% cover approximately 5% of the total watershed.

Comparing the map in Figure 8 to the actual land use map, it is evident that the percentage of well-protected areas has decreased. This change can be attributed to the transition of cultivated land to bare land in the central and northeast parts of the study area, likely due to the summer season when the satellite image was captured. The areas along the riverbanks also exhibit a high level of vegetation, which corresponds to natural lands and reforested areas.

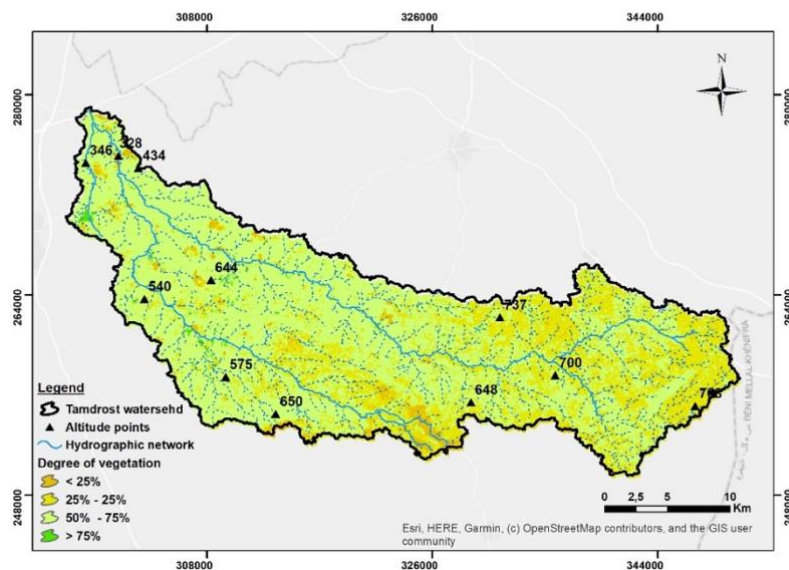


Fig.8. Vegetation Cover density in the Tamdrost watershed according to PAP/RAC

4.1.6. Soil protection map

A soil well protected by vegetation is less susceptible to degradation by erosive agents such as raindrop energy and runoff. The map of soil protection degrees was created by overlaying the land use map and the vegetation cover density map using the matrix presented in the table. This matrix consists of five classes of soil protection degrees: very low (MB), low (B), moderate (M), high (A), and very high (MA).

The purpose of this map is to rank the Tamdroust watershed into polygons based on the degree of protection. This step is essential as it helps identify areas with low or high protection, including critical areas that require urgent reforestation efforts to stabilize and protect the soil.

Table 5. Matrix generating the soil protection degree (PAP/RAC, 1998)

Land use	Cover density			
	1	2	3	4
1	5(MB)	5(MB)	4(B)	4(B)
2	5(MB)	5(MB)	4(B)	3(M)
3	3(M)	2(A)	1(MA)	1(MA)
4	4(B)	3(M)	2(A)	1(MA)
5	5(MB)	4(B)	3(M)	2(A)

Table 6. Soil protection degree (PAP/RAC, 1998)

Classes	Soil Protection Degrees	Area in %
1	Very high (MA)	15
2	High (A)	13
3	Notable (M)	42
4	Low (B)	13
5	Very Low (MB)	7

The Analysis of the results obtained and the soil protection map allowed for the visualization of different soil protection classes and their spatial distribution. The very low protection class (MB) is located in the northwest of the watershed in areas that contain marl and phosphate lithofacies and low slopes. It covers an area of 7%. The low protection in the study area is due to severely degraded vegetation cover, resulting from high land use for agriculture and overgrazing.

The medium protection class (M) extends over an area of 42%, scattered randomly throughout the basin. The high and very high protection classes cover 28% of the total area and are found in irrigated areas and part of the watercourse in the northeast of the basin. Areas with high and very high erosion correspond to areas with significant human activity and relatively large human populations.

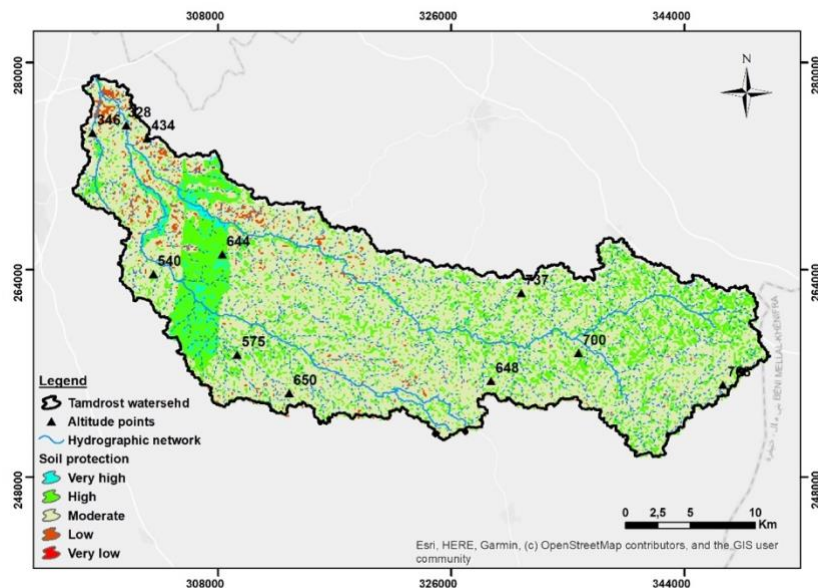


Fig.9. Soil protection map of the Tamdroust watershed

4.1.7. Erosive state map

The erosive state map (Figure. 9) is the final product of the predictive phase, resulting from the overlay of the erodibility map and the soil protection map based on the erosive state matrix of the PAP/RAC model Table 7.

Table 7. Matrix of soil erosive based on soil protection degrees and erodibility degrees (PAP/RAC, 1998)

Degree of soil protection	Degree of erodibility				
	1(EN)	2(EB)	3(EM)	4(EA)	5(EX)
1(MA)	1	1	1	2	2
2(A)	1	1	2	3	4
3(M)	1	2	3	4	4
4(B)	2	3	3	5	5
5(MB)	2	3	4	5	5

Table 8. Soil erosive degree (PAP/RAC, 1998)

Classes	Degree of soil erosive	Area in %
1	Very low	4,11
2	Low	35,46
3	Notable	52,30
4	High	7,63
5	Very high	0,5

The erosive state map of the Tamdroust basin reveals that the predominant categories are low and notable erosion, covering approximately 87.76% of the basin's surface (refer to Fig. 9 and Table 8). Meanwhile, high and very high erosion classes collectively represent 8.13% of the study area. Conversely, areas exhibiting very low erosion constitute a minimal portion, approximately 4.11% of the study area. Analysis depicted in Figure 8 indicates concentrated erosion in the northwestern and upstream regions, with intermittent affected zones throughout the basin. This pattern is largely attributed to steep slopes, inadequate vegetation cover, and the presence of loosely structured sedimentary formations, all contributing factors fostering soil erosion.

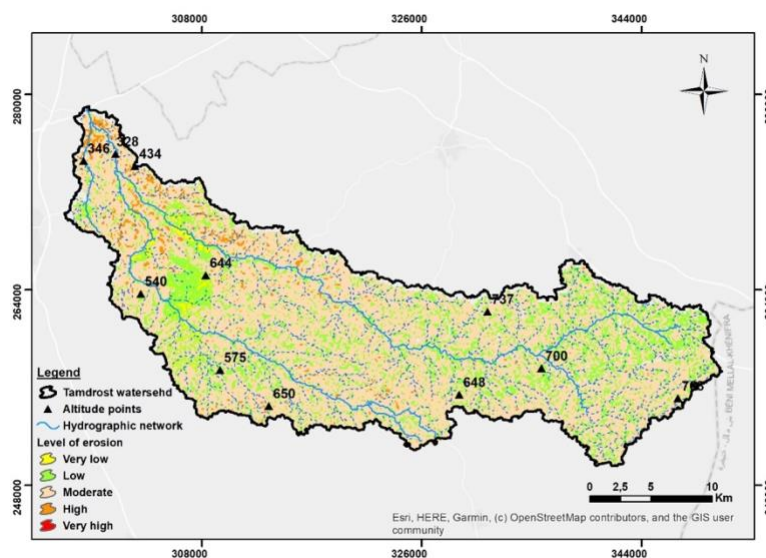


Fig.9. Map of the erosive states of the Tamdroust watershed

The downstream regions show predominantly very low to low levels of erosion, which can be attributed to the presence of dense vegetation cover and gentle slopes. In contrast, significant erosion is scattered throughout the study area, influenced by the rugged topography of the upper Tamdroust basin and limited vegetation cover. Interestingly, certain areas display low to very low erosion levels despite having sparse vegetation and steep slopes. This anomaly is explained by the presence of erosion-resistant geological formations, such as metamorphic rocks and conglomerates, which act as protective layers, reducing erosion in areas with low vegetation cover and steep terrain. slopes

4.2. Descriptive Approach

The erosion forms map is generated using satellite images and fieldwork. It was observed that, based on the conducted research, the erosion forms in the study area are less abundant compared to other regions in Morocco, such as the Rif region. Various erosion forms were identified, ranging from elementary to advanced forms. This variation is controlled by several factors, with climate (temperature and rainfall) being a crucial driving factor in the dynamics of water erosion. The lithology also plays a guiding role in the spread of erosion forms.

The Tamdroust watershed experiences a moderate-intensity erosive dynamic with relatively less diverse modes. The distribution of erosion forms varies from one area to another based on physical and anthropogenic conditions.

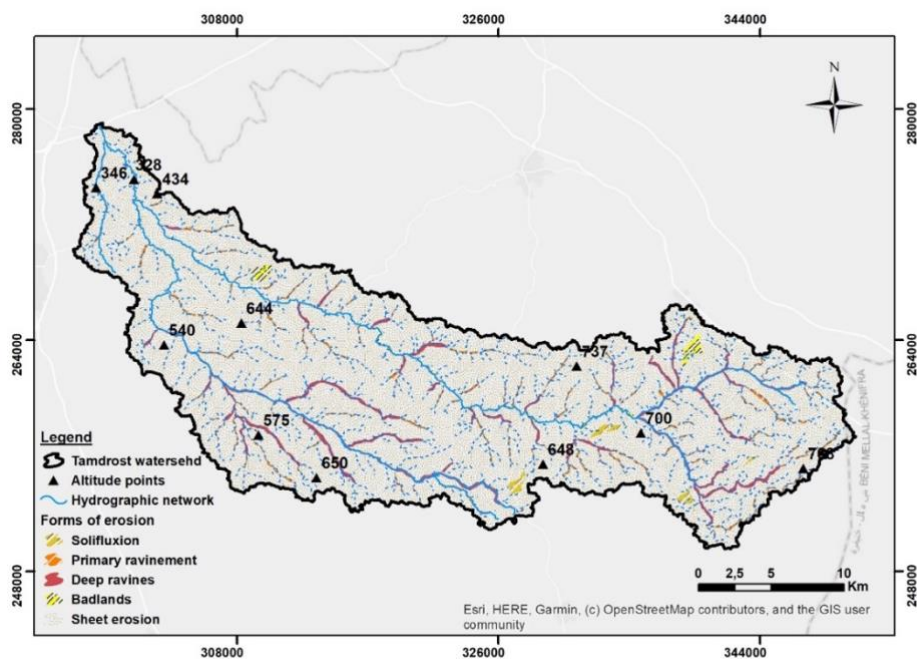


Fig.10. Map of erosion forms in the Tamdroust watershed

The analysis of the map and the database shows that the most prevalent form of erosion in our study area is sheet erosion, which is widespread throughout the watershed, covering approximately 81% of the basin. This type of degradation directly threatens land productivity. On the other hand, Badlands, representing the ultimate stage of land degradation, cover about 1.15% of the total area. Additionally, there are moderately deep gullies and shallow ravines, covering 8% of the watershed. This can be explained by intense rainfall, steep slopes in this area, and impermeable terrain (marls and phosphate rocks), while human practices have accelerated erosive dynamics in the basin.

All these conditions contribute to the initiation, detachment, and easy movement of materials on the slopes. Areas affected by deep gullies cover 6.85% of the basin and are mainly located on the north

or northwest-facing slopes of high sandstone and flyschic massifs, where vegetation is relatively dense and still plays its protective role. Solifluction features are located on the south and southwest slopes, with their extension in the basin being relatively limited, occupying about 3% of the watershed. The development of these erosion forms can lead to various damages, including reduced crop yields, a decrease in the agricultural land area, and an acceleration of reservoir siltation rates, thereby reducing the quantity and quality of available water. They also lead to the degradation of road infrastructure and other problems.

4.3. Integration approach: consolidated PAP/RAC erosion map

This stage represents the ultimate culmination of the prior phases, seeking to enhance the outcomes acquired from the predictive phase by incorporating the subsequent descriptive phase. The resultant product yields a finely detailed RACtographic assessment, presenting an exact portrayal of soil degradation's status and the diverse facets of erosion.

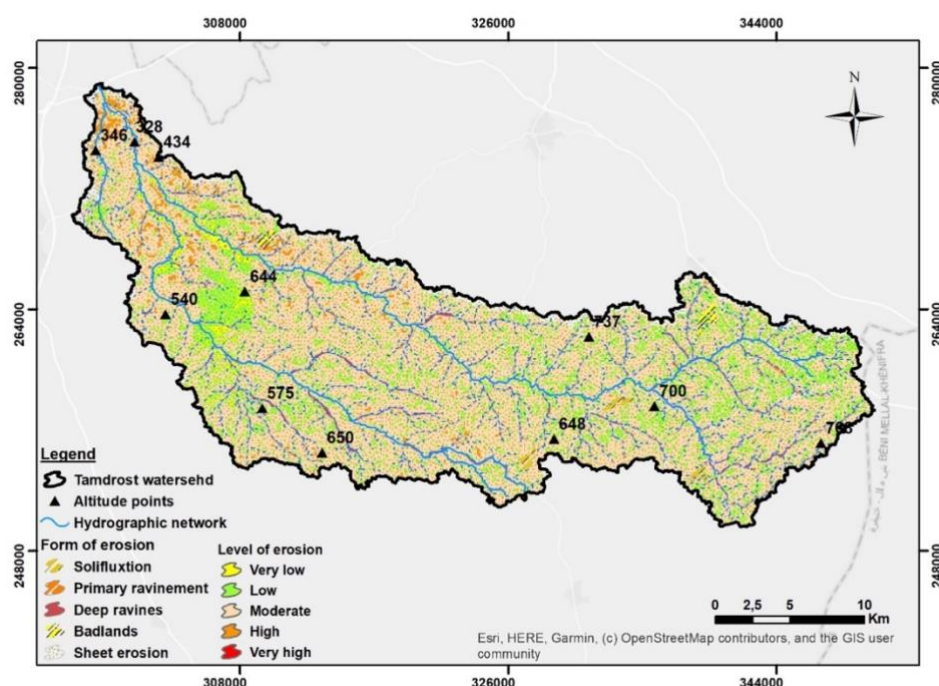


Fig.11. Consolidated map of water erosion risk in the Tamdrost watershed.

The integrated map (Fig. 11), derived from combining the erosion forms map (Fig. 10) and the erosive states map (Fig. 9), represents a qualitative depiction. This map highlights the prevalence of sheet erosion and diffuse runoff forms in the basin, which align with areas exhibiting a low to very low degree of water erosion within the study area. Conversely, the central region showcases various water erosion manifestations, including Badlands, medium-deep gullies, and solifluction, indicating a high to very high degree of water erosion. This occurrence can be attributed to the susceptibility of marl and marl-clay soils, coupled with inadequate vegetation cover in those areas.

5. Conclusions

The application of the PAP/RAC method to map and estimate water erosion in the Tamdrost watershed has facilitated a comprehensive analysis and understanding of erosion risk evolution. The initial phase, termed the predictive phase, encompasses seven interconnected steps, progressively generating a map depicting erosive states. This map offers valuable insights into the current state of soil

degradation, notably highlighting the dominance of the notable class. Factors such as lithology, slope, land use, and vegetation cover greatly influence this classification, with areas of strong and very strong erosion occupying relatively smaller portions within the watershed.

The subsequent descriptive phase illustrates that the watershed faces erosion risks due to various forms of erosion spread across a significant area. However, these erosion forms exhibit less development compared to other regions in Morocco, like the Rif, for example.

The integration phase, serving as the culmination of our research, complements the predictive phase by incorporating descriptive erosion process data. Its primary aim is to generate a final map that identifies and assesses both potential erosion (Erosive Status) and ongoing erosion in diverse forms, intensities, and evolutionary trends. The consolidated erosion map reveals that around 88% of the watershed is affected by low to moderate-intensity water erosion, while 8% experiences high to very high-intensity water erosion, and approximately 4% encounters very low water erosion. Notably, sheet erosion, representing the initial stage of water erosion, covers 81% of the total surface. Furthermore, the presence of shallow and deep rills is observed in areas where slope and lithology favor water erosion.

Lastly, the trend map, a product of the integration phase, outlines the anticipated evolution of erosion across various parts of the watershed. It stands as a vital tool guiding decisions concerning land use planning and agricultural practices aimed at mitigating water erosion risks within this watershed.

References

- Akalai, N., Hlila, R., El Imrani, M., 2014. Risk of water erosion in coastal watersheds north of Tetuan (Internal Rif, northern Morocco): Evidences from GIS-based spatial approach. *International Journal of Innovation and Applied Studies*, 8(4), 1735-1751.
- Archambault, C., Combe, M., Ruchard, J.P., 1975. Le plateau des phosphates : ressources en eau. Notes et Mémoires du Service. Géologique du Maroc, 231, 239–258
- Attia, R., Sadok, A., Hédi, H.I., 2005. Application des Directives RAC/PAP pour la formulation d'un programme de gestion de contrôle de l'érosion et de la désertification Cas du bassin versant de l'Oued Rmel. – Programme d'Actions Prioritaires, Centre d'Activités Régionales, Tunisie, 72.
- Bachaoui, B., Bachaoui, E.M., El Harti, A., 2007. Cartographie des zones à risque d'érosion hydrique : exemple du Haut Atlas marocain. *Revue Télédétection*, 7(1), 393-404.
- Boerrelli, P., Robinson, D.A., Fleische, L.R., Lugato E., Ballabio C., Alwell, C., Panagos, P., 2017. An assessment of the global impact of 21st century land use change on soil erosion. *Nature Communications*. 8(1), 1–13.
- Chevalier, J., Pouliot, J., Thomson, K., Boussema, M.R., 1995 : Systèmes d'Aide à la Planification Pour la Conservation des Eaux et des Sols (Tunisie). Systèmes d'Information Géographique Utilisant les Données de Télédétection. Actes du Colloque Scientifique International, Hammamet, Tunisie, 4-12.
- Duarte, L., Cunha, M., Teodoro, A.C., 2021. Comparing Hydric Erosion Soil Loss Models in Rainy Mountainous and Dry Flat Regions in Portugal. *Land*, 10(6), 554. DOI: 10.3390/land10060554.
- El Aroussi, O., El Garouani, A., Jabrane, R., 2013. Modelling and mapping of soil erosion on the Oued El Malleh catchment using remote sensing and GIS. *Journal of Urban and Environmental Engineering*, 7(02), 302-307.
- El Assaoui, N., Bouiss, C., Sadok, A., 2023. Assessment of Water Erosion by Integrating RUSLE Model, GIS and Remote Sensing – Case of Tamdrost Watershed (Morocco). *Ecological Engineering & Environmental Technology*, 24(3), 43–53.
- El Bouqdaoui, K., 1995. Etude géologique et géotechnique de la Ville de Settat : cartographie géotechnique et substance utile de la Province de Settat, Thèse de Doctorat Géologie, Université Mohammed V, Rabat.
- Elbouqdaoui, K., Ezzine, H., Zahraoui, M., 2006. Évaluation du risque potentiel d'érosion dans le bassinversant de l'Oued Srou (Moyen Atlas, Maroc). *Science et changements planétaires/Sécheresse*, 17, 3, 425-431.
- FAO and ITPS, 2015. Status of the World's Soil Resources (Main Report). Fao.
- Goufri, A., Daoui, L., De vente, J., 2020. A new simple approach to assess sediment yield at a large scale with high landscape diversity: an example of Morocco. *Journal of African Earth Sciences*, 168, 103871.

- Hmamouchi, M., El-Fengour, M., El-Fengour, A., Houari, A., 2020. The assessment of erosion in Aoulai watershed (central Rif mountains, Morocco) based on the PAP-RAC guidelines application. *territorium* 27 (I), 2020, 17-23.
- Iaich, H., Moussadek, R., Baghdad, B. et al., 2016. Soil erodibility mapping using three approaches in the Tangiers province–Northern Morocco. *International Soil and Water Conservation Research*, 4(03), 159-167.
- Namr, K. I., Mrabet, R., 2004. "Influence of agricultural management on chemical quality of a clay soil of semi-arid Morocco, *Journal of African Earth Science*, 39 (3–5), 485–489.
- IPCC (Intergovernmental Panel on Climate Change), 2013. "Summary for Policymakers. In *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge: Cambridge University Press.
- Keesstra, S.D., Bouma, J., Wallinga, J., Tittonell, P., Smith, P., Cerdà, A., Fresco, L.O., 2016. The significance of soils and soil science towards realization of the United Nations Sustainable Development Goals. *Soil*. 2(2), 111–128.
- Lakhili, F., Benabdelhadi, M., Chaoui, A., Bouderk, N., Lahrach, A., 2017. Cartographie de l'érosion qualitative des sols du bassin versant de Beht (Maroc). *American Journal of Innovative Research and Applied Sciences*, 4(5), 174-185.
- Mahdioui, L., Charchari, H., Allali, H., Naja J., Bakkali, A., 2015. Characterization and development of agricultural land the watershed the Oued Bou Moussa, high Chaouia, Settati, Morocco, *IRACST - Engineering Science and Technology: An International Journal (ESTIJ)*, 5(2).
- Mesrar, H., Sadiki, A., Navas, A., Faleh, A., Quijano, L., Chaaouan, J., 2015. Modélisation de l'érosion hydrique et des facteurs causaux, Cas de l'oued Sahla, Rif Central : *Zeitschrift für Geomorphologie*, 2015.
- Ousmana, H., El Hmaidi, A., Essahlaoui, A., Bekri, H., El Ouali, A., 2017. Modélisation et RACtographie du risque de l'érosion hydrique par l'application des SIG et des directives PAP/RAC. Cas du bassin versant de l'Oued Zgane (Moyen Atlas tabulaire, Maroc). *Bulletin de l'Institut Scientifique, Rabat, Section Sciences de la Terre*, 2017, 39, 103-119.
- PAP/RAC, 1998. Directives pour la cartographie et la mesure des processus d'érosion hydrique dans les zones côtières méditerranéennes. [Section du livre]. [s.l.]: PAP-8/PP/GL.1. Split, Centre d'activités régionales pour 870 le Programme d'actions prioritaires (PAM/PNUE), en collaboration avec a FAO, 1998
- Rafla, A., Agerbaoui, S., Hamrouni, H., 2005. Application des Directives CAR/PAP pour la formulation d'un programme de gestion de contrôle de l'érosion et de la désertification. Cas du bassin versant de l'Oued Rmel. Split.
- Roose, É., 1996. Méthodes de mesure des états de surface du sol, de la rugosité et des autres caractéristiques qui peuvent aider au diagnostic de terrain, des risques de ruissellement et d'érosion, en particulier sur les versants cultivés des montagnes. *Bull. Réseau Érosion*, 16, 87-97.
- Sabir, M., Roose, É., 2004. Influence du couvert végétal et des sols sur le stock de carbone et les risques de ruissellement et d'érosion dans les montagnes méditerranéennes du Rif occidental, Maroc. *Bulletin du Réseau Érosion*, 23, 144-154.
- Sadiki, A., Mesrar, H., Faleh, A., Chaaouan, J., 2012. Modélisation et cartographie des risques de l'érosion hydrique: cas du bassin versant de l'oued Larbaa, Maroc. *Papeles de geografía* 55-56: 179-188.
- Sadouki, D., Benzougagh, B., Amine, A., Aassoumi, H., Lakhili, F., Mihraje, A., 2023. Mapping of Zones Vulnerable to Water Erosion Using PAP/RAC and GIS Method Upper the Ait Moulay Hmad Dam, Northeast of the Central Massif, Morocco. *The Iraqi Geological Journal*, 181-197.
- Tahouri, J., Sadiki, A., Karrat, L., 2019. Using PAP/RAC model and GIS tools for mapping and study of water erosion processes in the Mediterranean environment: Case of the Asfalou watershed (Oriental Rif, Morocco).