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Modelling and mapping of soil erosion risk based on GIS and PAP/RAC guidelines in the watershed of Tassaoute (Central High Atlas, Morocco)

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Abstract. Morocco watersheds, which provide many ecosystem services necessary for the socio-economic life of rural communities, are experiencing significant change and environmental problems. Hence, a thorough analysis of potential soil erosion is crucial in addressing the significant problem that soil erosion poses in the highlands of Moroccan, enabling us to identify and prioritize areas with severe erosion. Thus, the present study aimed to evaluate and map areas at risk of water erosion in the upstream Tassaoute watershed (central High Atlas, Morocco), using the Priority Action Program/Regional Activity Center (PAP/RAC) method associated with Geographic Information Systems (GIS) and remote sensing. The PAP/RAC approach consisted of integrating the natural factors that influence water erosion, namely slope, lithology, vegetation cover and land use. This method provided an accurate cartographic product that reflects the reality of the state of soil degradation and the qualitative assessment of erosion. The map generated to assess erosion risk in the study area has unveiled a worrisome threat posed by erosion to this basin, especially in the middle and downstream, such that 40% of the basin surface has significant erosion and the high and very high degrees of erosion represented 27% of the total surface of the study area. The resulting maps generated by the PAP/RAC model, validated through comparison with actual outcrop data, demonstrate the reliability of the model in assessing and mapping water erosion risks in the upstream Tassaoute basin.

Key words:
water erosion,
PAP/RAC,
GIS,
remote sensing,
soil mapping,
erosive states,
Tassaoute watershed,
Morocco

Introduction

Soil erosion is the most widespread form of land degradation in the Mediterranean area, mainly due to the unpredictable nature of the region's climate, the increased anthropic activity that changes the structure of the vegetation cover, and the intrinsic vulnerability of its soil (Rhouma et al. 2018). According to Hudson (1990), the soil situation continues to deteriorate in Morocco: 40% of the land is threatened by water erosion. In Morocco, according to the High Commission for Water and Forests and the Fight against Desertification, water erosion affects 23 million ha, and specific soil degradation varies from 500 $t \cdot km^{-2} \cdot year^{-1}$ in the Middle Atlas to more than 5000 $t \cdot km^{-2} \cdot year^{-1}$ in the Rif (HCEFLCD 1996). In the literature, the soil degradation is expressed by a decrease in vegetation density, a loss of soil (loss of long-term productivity), a loss of organic matter and retention capacity, and by an increase in mineralization of the landscape (Faleh and Maktite 2014; El Jazouli et al. 2019; Barakat et al. 2022; El Jazouli et al. 2022; Mosaid et al. 2022). Therefore, erosion phenomena require an integrated analysis and evaluation. In this context, many studies have been carried out on soil degradation by water erosion and landslides in Morocco and given acceptable quantitative and qualitative results (Merzouki 1992; Bonn 1998; Aït Brahim et al. 2003; Damnati et al. 2004; Moukhchane 2005; Sadiki et al. 2009; Faleh and Maktite 2014; Tahiri et al. 2014; Barakat et al. 2017; Elaloui et al. 2017; El Jazouli et al. 2017; El Jazouli et al. 2019; El Jazouli et al. 2022). The literature has shown that remote-sensing and geographical information system (GIS) techniques were widely applied and more efficient for modelling water erosion hazards at global, regional, and local levels. Utilizing the power of remote sensing and GIS, some models were applied, such as USLE/RUSLE (Wischmeier and Smith 1978; Risse et al. 1993; Renard et al. 2017), WEPP (Laflen et al. 1991; Pruski and Nearing 2002; Boardman 2006), and SWAT (Arnold et al. 1998a; Arnold et al. 1998b); each of these has its unique features and range of applications for assessing soil loss rates. In the Mediterranean coastal areas, the Priority Actions Program/Regional Activity Centre (PAP/RAC), coordinated by UN Environment, developed a PAP/RAC model to provide basic instructions for a methodology of erosion mapping. The PAP/RAC model is designed to predict soil loss by integrating factors influencing water erosion, such as topography, river system, soil type, lithological material, and land cover types (reflecting farming systems) (Ousmana et al. 2017; Chikh et al. 2019; Tahouri et al. 2022). This model has been successfully employed in various Mediterranean countries and has demonstrated its effectiveness in numerous scientific studies (Hassan et al. 2013; Faleh and Maktite 2014; Mesrar et al. 2015; Hili et al. 2017). Hence, it was decided to apply the PAP/RAC model to identify the land potentially exposed to erosion problems in the upstream watershed of the Tassaoute located in the central High Atlas.

The choice to study the Tessaoute basin of the Moulay Youssef dam is justified by several reasons. Firstly, this basin has been classified as a fourth-order priority by the national plan of watershed management (PNABV) due to the significant erosion observed in the area (HCEFLCD 1996a). Additionally, the Tassaoute River is considered the most important tributary of the Oum Er-Rbia River. Furthermore, this basin plays a crucial role in meeting the water supply and irrigation needs in the Marrakech region. The main current challenge in this region is linked to excessive human pressure – in particular, increasing rates of deforestation and the intensification of agricultural and grazing activities, which are exacerbated by climate stress. According to this, the present study focused on water erosion assessment and modelling. Selection of an appropriate approach to soil erosion evaluation is critical, the PAP/RCA model is chosen due to its adaptability for the management of Mediterranean coastal areas, its low requirement for direct measurement data (slope, hydrographic network, soil type, lithological material, and type of vegetation cover), and its satisfactory results. Previous studies conducted in various countries: Morroco (Faleh and Maktite 2014; Mesrar et al. 2015; Boukrim et al. 2016; Elaloui et al. 2017; Hili et al. 2017; LakHili et al. 2017; Ousmana et al. 2017; Ait Yacine et al. 2019; Labbaci et al. 2020; Tahouri et al. 2022), Tunisia (Ben Rhouma et al. 2018; Chokri 2020) and Algiers (Khallef et al. 2020b) encourage the use of this model. The second reason is that the water erosion problem in this watershed was studied by applying other models (Elaloui et al. 2017; Barakat et al. 2022), but the PAP/RAC model has not been used for this watershed. Therefore, the work was carried out through the three approaches (or phases) of the PAP/RAC qualitative model: the predictive phase, the descriptive phase, and the integration phase. The final product of this method is mapping the erosive state of the Tassaoute upstream basin to determine the priority areas that require intervention.

The main objective of this study was to assess the spatial distribution of eroded areas in the upstream Tassaoute basin using the PAP/RAC model in combination with advanced geographic information system (GIS) techniques. The aim was to provide valuable information for developing effective land management and conservation strategies in the study area, in order to reduce the adverse effects of soil erosion.

Materials and methods

Soil erosion is the most widespread form of land degradation in the Mediterranean area, mainly due to the unpredictable nature of the region's climate, the increased anthropic activity that changes the structure of the vegetation cover, and the intrinsic vulnerability of its soil (Rhouma et al. 2018). According to Hudson (1990), the soil situation continues to deteriorate in Morocco: 40% of the land is threatened by water erosion. In Morocco, according to the High Commission for Water and Forests and the Fight against Desertification, water erosion affects 23 million ha, and specific soil degradation varies from 500 t·km^{-2}·year^{-1} in the Middle Atlas to more than 5000 t·km^{-2}·year^{-1} in the Rif (HCEFLCD 1996). In the literature, the soil degradation is expressed by a decrease in vegetation density, a loss of soil (loss of long-term productivity), a loss of organic matter and retention capacity, and by an increase in mineralization of the landscape (Faleh and Maktite 2014; El Jazouli et al. 2019; Barakat et al. 2022; El Jazouli et al. 2022; Mosaid et al. 2022). Therefore, erosion phenomena require an integrated analysis and evaluation. In this context, many studies have been carried out on soil degradation by water erosion and landslides in Morocco and given acceptable quantitative and qualitative results (Merzouki 1992; Bonn 1998; Aït Brahim et al. 2003; Damnati et al. 2004; Moukhchane 2005; Sadiki et al. 2009; Faleh and Maktite 2014; Tahiri et al. 2014; Barakat et al. 2017; Elaloui et al. 2017; El Jazouli et al. 2017, 2019, 2022). The literature has shown that remote-sensing and GIS techniques were widely applied and more efficient for modelling water erosion hazards at global, regional, and local levels. Utilizing the power of remote sensing and GIS, some models were applied, such as USLE/RUSLE (Wischmeier and Smith 1978; Risse et al. 1993; Renard et al. 2017), WEPP (Laflen et al. 1991; Pruski and Nearing 2002; Boardman 2006), and SWAT (Arnold et al. 1998a, b); each of these has its unique features and range of applications for assessing soil loss rates. In the Mediterranean coastal areas, the Priority Actions Program/Regional Activity Centre (PAP/RAC), coordinated by UN Environment, developed a PAP/RAC model to provide basic instructions for a methodology of erosion mapping. The PAP/RAC model is designed to predict soil loss by integrating factors influencing water erosion, such as topography, river system, soil type, lithological material, and land cover types (reflecting farming systems) (Ousmana et al. 2017; Chikh et al. 2019; Tahouri et al. 2022). This model has been successfully employed in various Mediterranean countries and has demonstrated its effectiveness in numerous scientific studies (Hassan et al. 2013; Faleh and Maktite 2014; Mesrar et al. 2015; Hili et al. 2017;). Hence, it was decided to apply the PAP/RAC model to identify the land potentially exposed to erosion problems in the upstream watershed of the Tassaoute located in the central High Atlas.

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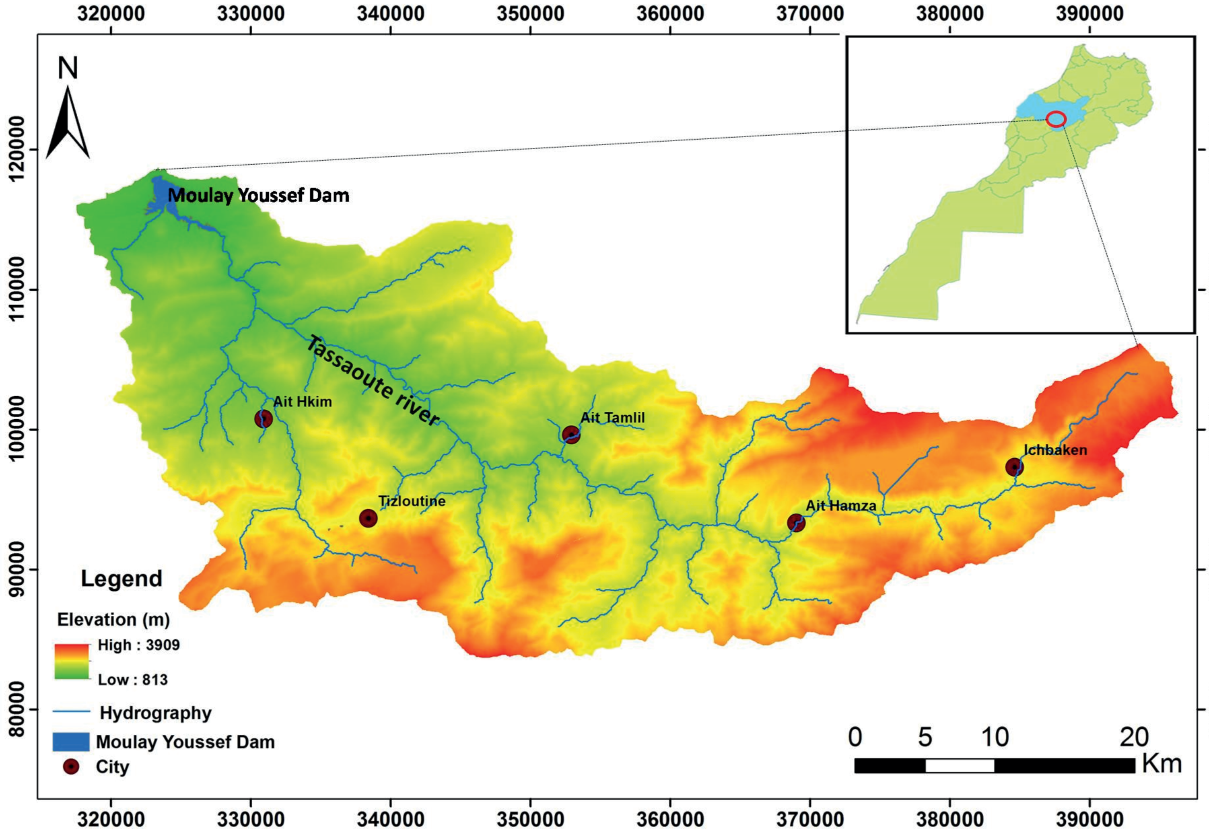

Fig. 1. Location and elevation map of the upstream Tassaoute watershed

Materials and methods

Study area

The watershed of the upstream Tassaoute of the Moulay Youssef Dam (Fig. 1), our study area, is part of the large watershed of Oum Er Rbia and is located in the western part of the central High Atlas (Morocco). The watershed is bounded in the north by the Jbilets belt, in the east by the watershed of Oued Lakhdar, in the west by the basin of Oued Tensift, and in the south by the foothills of the High Atlas and the summits of Ait Ouar-Jdid, Anghoumar and Ouadaker, whose southern slopes belong to the watershed of Oued Draa. It covers an area of 1418.35 km^2. It is located 70 km from Marrakech city and lies between 31°33’56” N and 31°64’47” N and 6°48’40” W and 7°33’40” W. The elevation ranges from 813 m to 3909 m a.s.l., with a steep slope of 21.5%. The sparse vegetation cover of the watershed occupies mainly its downstream area. The climate has semi-arid characteristics with an average annual precipitation of about 344 to 568 mm, and an average annual temperature of 12.6°C. The highest mean temperature was recorded in July (23.2°C) and the lowest was during January (3.7°C).

Geologically, the upstream Tessaoute watershed is an integral part of the western part of the central High Atlas (Atlas of Demnate) (Roch 1939). The most highly represented geological series in the watershed (Fig. 2) are the Permo-Triassic and the Lias, while later series, other than the Quaternary, occupy only a few synclines (Elaloui et al. 2017). The substratum comprises mainly sandstone and permeable limestone from the Triassic and Lias sedimentary formations. The watershed downstream comprises the schist, clay, and dolomite rocks in the Triassic sedimentary series (Couvreur 1988).

Data collection

The qualitative model used to map the sensitivity of soils to water erosion in the upstream Tassaoute watershed requires the use of data relating to topography, geology, vegetation cover, and field observations.

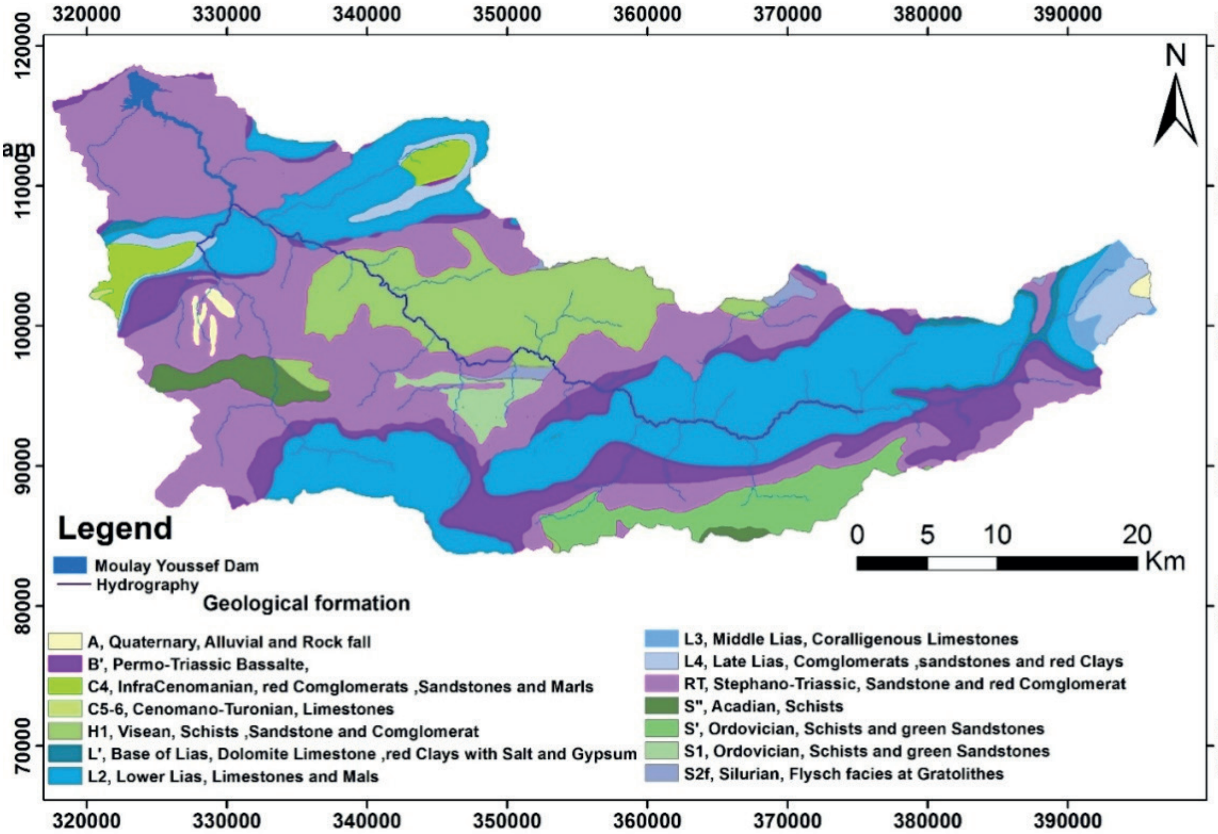

Fig. 2. Geological map (from geological maps of Demnate and Telouete 1:200000) of the study area.
Source: (Termier 1941)

The digital terrain model (DTM) from SRTM radar images of 30-m resolution were downloaded from the website of United States Geological Survey (USGS) (http://gdex.cr.usgs.gov/gdex); the geological map of Demnate and Telouete at 1:200,000, Landsat 8 satellite images are obtained from the USGS Earth Explorer website (accessed on May 15, 2019), and Google Earth, and the observations on the ground, allowed the delimitation of the study area and the realization of the different thematic maps, with the help of software dedicated to remote sensing and GIS.

Methodology

The method adopted for this study is the PAP/RAC (Fig. 3), which was developed in 1988 by the Regional Activity Center for the Priority Actions Program (PAP/CAR) of the United Nations Environment Program's Mediterranean Action Plan, in collaboration with the Directorate-General for Nature Conservation (DGCONA) of the Spanish Ministry of Environment and the Land and Water Development Division (AGL) of the Food and Agriculture Organization (FAO) of the United Nations.

The PAP/RAC model is a qualitative model of water erosion that allows for the classification of the watershed surface into distinct units based on vulnerability to erosion and identifies the most fragile areas. This method comprises three approaches

The predictive approach

The predictive approach controls erosion based on thematic mapping of factors (slope, lithology, land use and degree of vegetation cover). This approach uses a sequence of data processing operations to obtain an erosive state map that assesses the degree of erosion over the whole area.

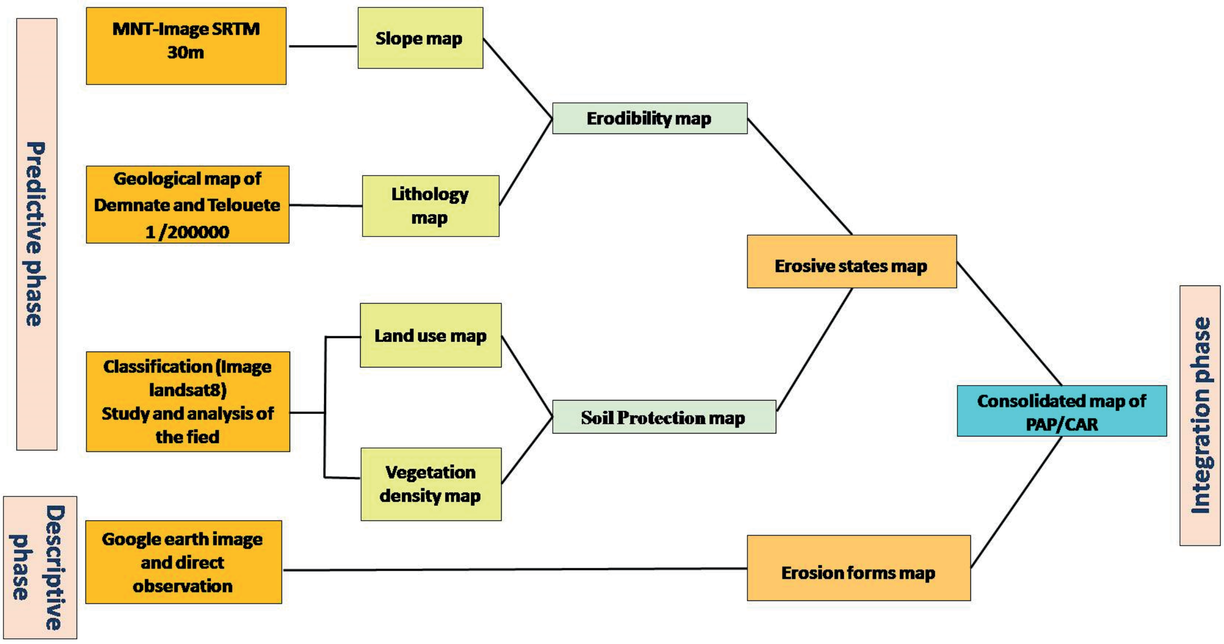

Fig. 3. Methodological flowchart of the application of the method PAP/RAC

Development of the erodibility map

Soil erodibility is a measure of the soil's sensitivity to water erosion, based on its properties such as composition, structure and texture. These characteristics determine the soil's response to erosive agents (Wischmeier and Smith 1978; Sheridan et al. 2000; Khallef et al. 2020a). The erodibility parameter is determined by the nature of the substrate, which influences the likelihood of producing friable materials and its predisposition to facilitating substrate mobility through erosion. To generate the erodibility map, slope and lithology (lithofacies) maps were created and overlaid. The slope is one of the major factors contributing directly to water erosion, as investigated in several case studies (Hessel et al. 2014; El Jazouli et al. 2019; Yared et al. 2020; Tairi et al. 2021; Barakat et al. 2022; Echogdali et al. 2022; Mosaid et al. 2022). It gives runoff the energy necessary to dislodge and move soil particles (Chaplot and Le Bissonnais 2000). The slope map of the study area (Fig. 4) was developed from the Digital Elevation Model provided by the USGS with a resolution of 30 m. This map was classified according to the guidelines of PAP/CAR (Table 1). Meanwhile, the lithofacies map identifies different types of rocks or surface sediments/soils based on their degree of mechanical resistance and is classified according to the relative degree of cohesion and mechanical resistance to erosion (Ben Rhouma et al. 2018). The lithology map (Fig. 5) of the studied basin was created using the 1:200,000 geological maps of Demnate and Telouet. The distribution of the depicted terrains on the map was coded based on their degree of friability and mechanical resistance, divided into five classes according to the PAP/CAR model (Table 2), to obtain the friability map (Fig. 6).

In order to generate the erodibility map (Fig. 7), the lithology and slope maps were overlaid using the soil erodibility matrix from the PAP/RAC model (Table 3). This PAP/RAC model allows for the classification of terrains based on their degree of erodibility, ranging from low to moderate, medium, high and extreme, as illustrated in Table 4.

Development of the soil protection map

Vegetation plays a crucial role in protecting soil against erosion in two ways. Firstly, it reduces the energy of erosive agents and, secondly, it decreases the energy of rain erosion by intercepting raindrops through the aboveground parts of plants (Rey et al. 2004). At the soil level, vegetation helps to combat runoff by improving water infiltration (Cerda 1998). The impact of vegetation may vary depending on the type of plant formations and land use (Kim and Jeong 1998).

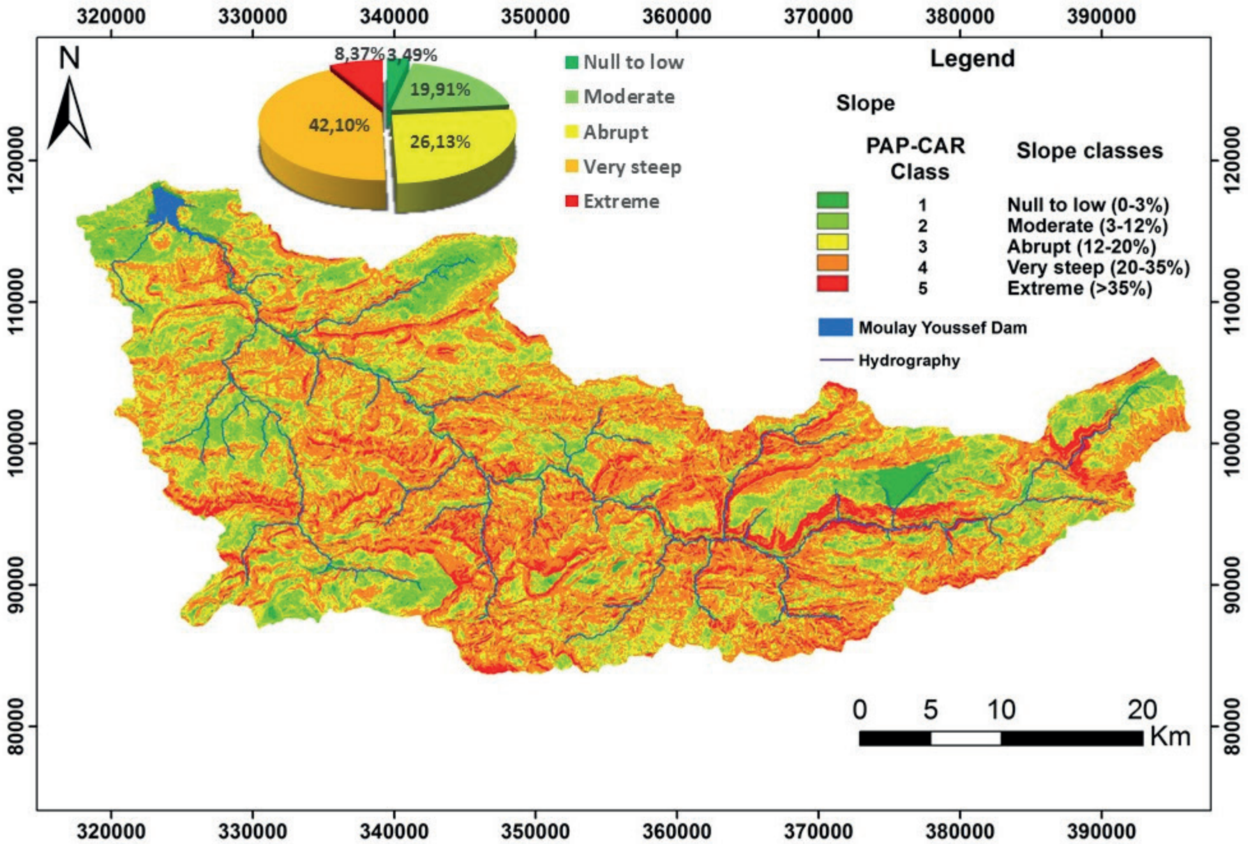

Fig. 4. Slope map of the study area

Table 1. Slope classes according to PAP/RAC (1998)

Slope	Class (%)	PAP-RAC Code
Null to low	0-3	1
Moderate	3-12	2
Abrupt	12-20	3
Very steep	20-35	4
Extreme	>35	5

After generating land use and vegetation density maps for the watershed, a protection map was obtained by superimposing these factors. Land use and land cover constitute an important factor that can affect soil erosion through rainfall and surface runoff (Yalcin et al. 2011). The LULC of the upstream Tassaoute watershed (Fig. 8) was prepared from the LANDSAT 8 satellite image at 30-m resolution, taken on May 15, 2019 from the USGS (United States Geological Survey) website (http://earthexplorer.usgs.gov). The image was processed to have an atmospheric correction and then classified using supervised classification in the maximum likelihood algorithm procedure. GIS environment was employed to prepare a land use category map of the study area, considering field data used to verify and validate the classified images.

According to the PAP/RAC model guidelines, five classes were considered to produce the LULC map, as seen in Table 5. The second canopy density map in the upstream Tassaoute watershed (Fig. 9) was evaluated using Landsat 8 satellite image dated May 15, 2019, acquired from the USGS using the Normalized Difference Vegetation Index (NDVI) (Carlson and Ripley 1997) derived from Landsat 8 image dated May 15, 2019. To delineate the NDVI along the study area, the reflectance ratio of red (R) and near-infrared (NIR) sunlight radiated from plants is used, following Equation (1) (Yengoh et al. 2015; Gascon et al. 2016).

$$\mathrm{NDVI} = (\mathrm{NIR} - \mathrm{R})/(\mathrm{NIR} + \mathrm{R}) \qquad (1)$$

The soil protection map (Fig. 10) is obtained by overlaying the land use map and the vegetation cover density map according to the soil protection matrix of the PAP/RAC model (Table 7). This map allowed to classify into units the study area according to the degree of protection and to delineate non- and less-protected areas requiring rapid intervention to fix and stabilize the soil (Direction de l'aménagement

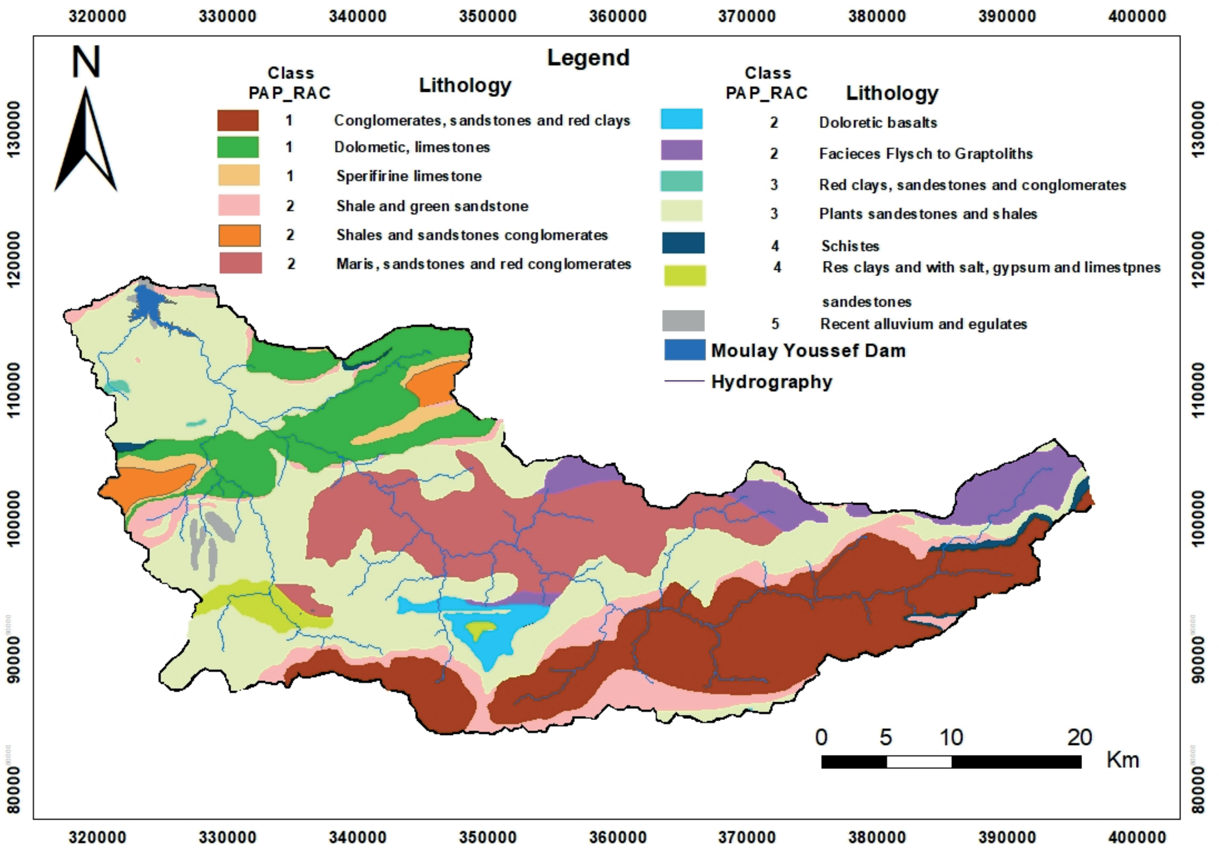

Fig. 5. Lithofacies map of the study area

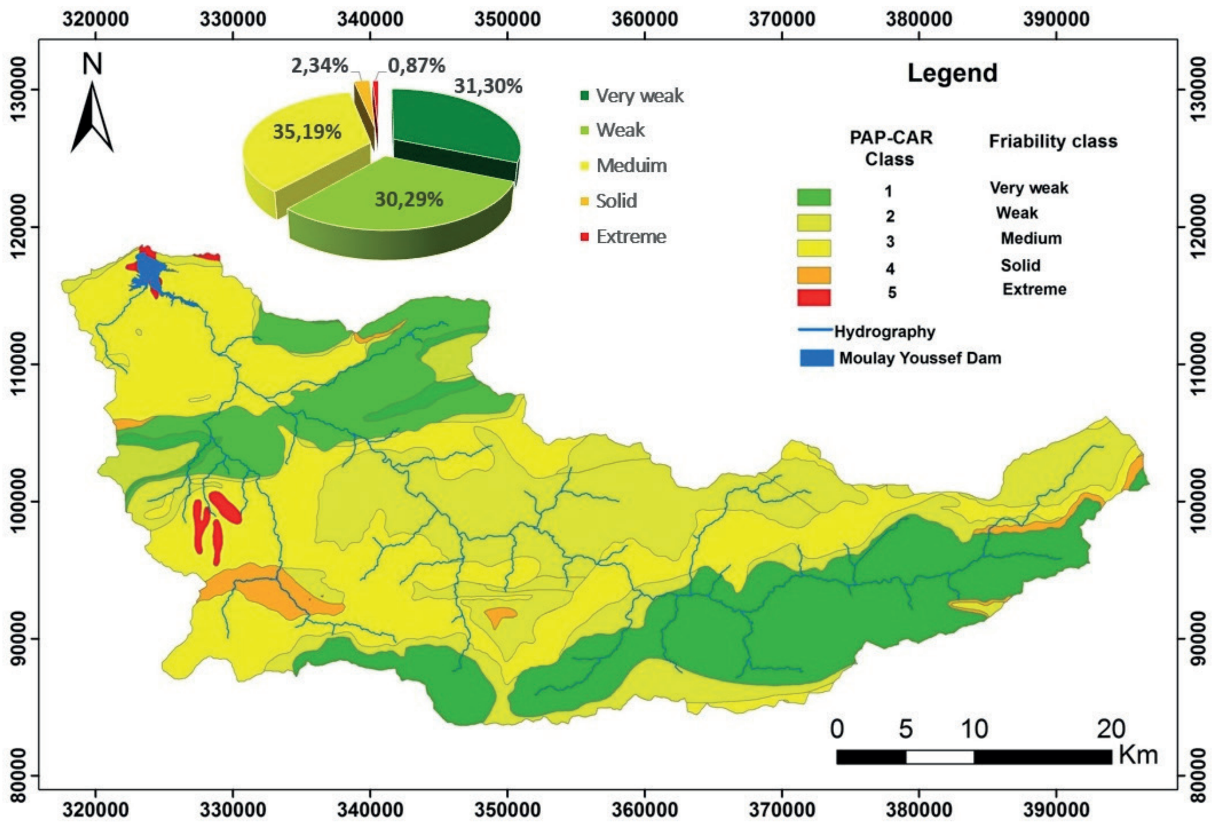

Fig. 6. Friability map of the study area

Table 2. Classes of relative degree of cohesion and mechanical resistance to erosion according to PAP/RAC (1998)

Lithofacies Class	Type of Materials
1	Weathered compact rocks, strongly cemented conglomerates, outcrops of limestone or igneous or eruptive rocks.
2	Fractured or moderately weathered cohesive rocks or soils
3	Sedimentary rocks or weakly or moderately compacted soils (marl, marl-limestone)
4	Rocks with little resistance and strong alteration (gypsum, shale, tuffaceous crusts, molasses...)
5	Loose, non-cohesive sediment or soil and detrital material

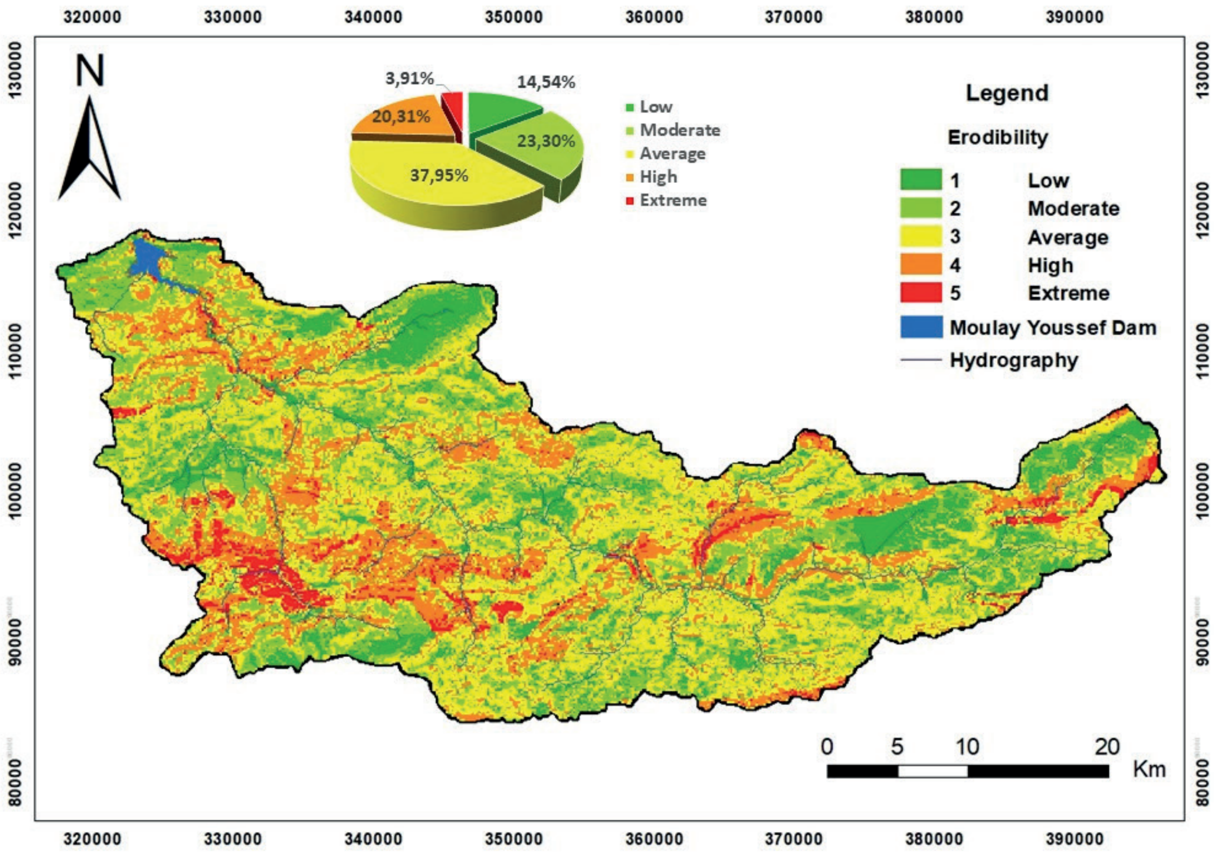

Fig. 7. Erodibility map of the study area

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

Slope classes	Lithofacies classes				
	1	2	3	4	5
1	1	1	1	1	2
2	1	1	2	3	3
3	2	2	3	4	4
4	3	3	4	5	5
5	4	4	5	5	5

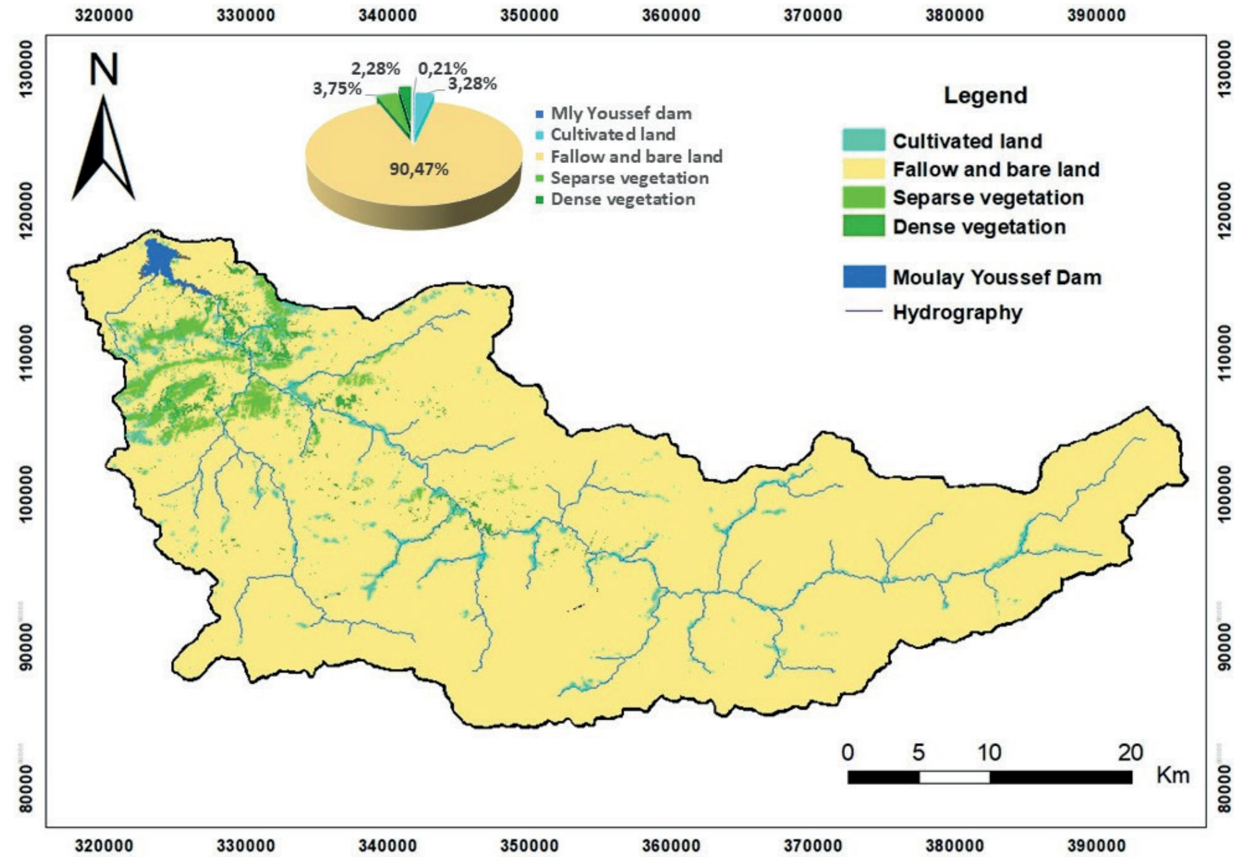

Fig. 8. Land use map of the study area

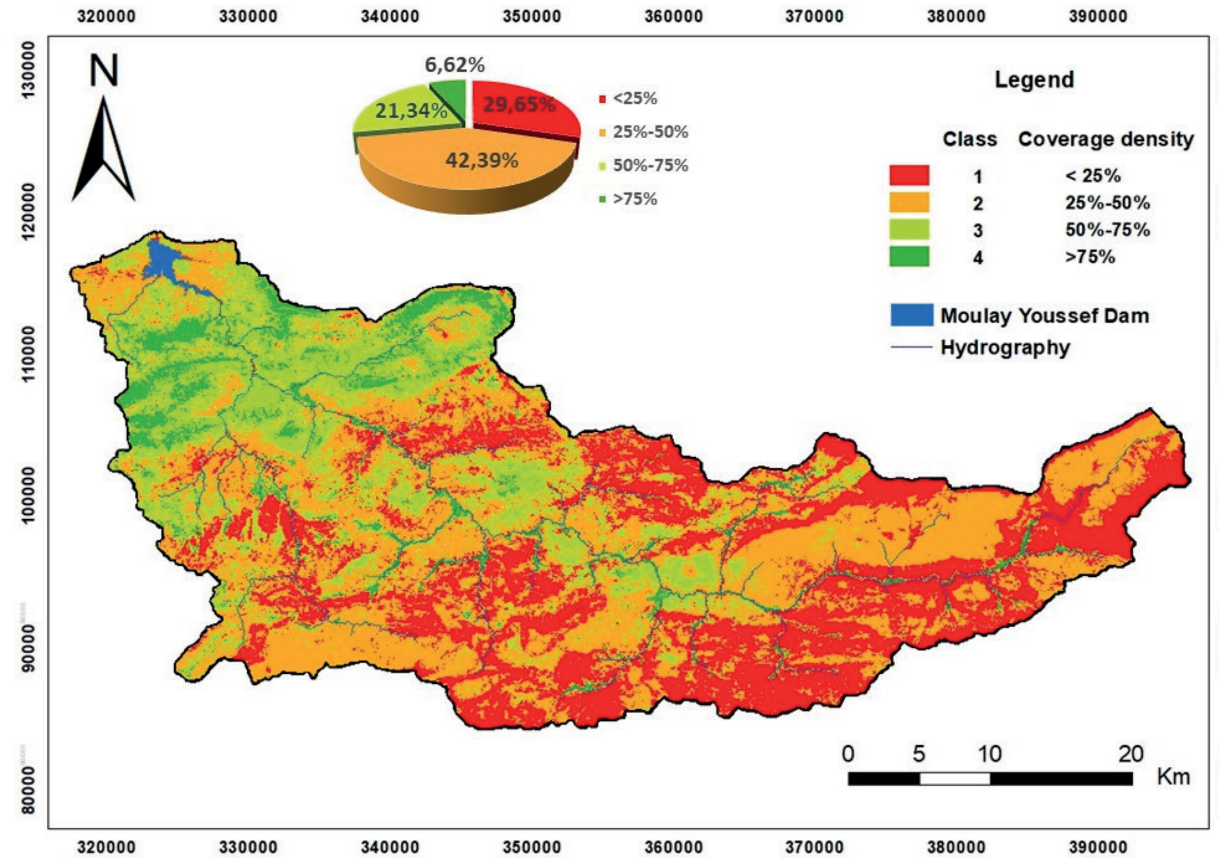

Fig. 9. Degree of vegetation cover map of the study area

Table 4. Erodibility according to PAP/RAC (1998)

Class	Degree of erodibility
1	Low
2	Moderate
3	Average
4	High
5	Extreme

Table 5. Land use classification according to PAP/RAC (1998)

Class	Land Occupation
1	Dry farming or bare ground
2	Arboriculture and Reforestation
3	Intensive cultivation near housing
4	Natural forest
5	Dense Covered Matorrals

Table 6. Classification of the vegetation cover density according to PAP/RAC (1998)

Class	Cover density degree (%)
1	<25
2	25-50
3	50-75
4	>75%

Table 7. Matrix generating the soil protection degree (PAP/RAC 1998)

Land use	Cover density			
	1	2	3	4
1	5	5	4	4
2	5	5	4	3
3	3	2	1	1
4	4	3	2	1
5	5	4	3	2

Table 8. Matrix of soil erosive conditions (PAP/RAC 1998)

Degree of soil protection	Degree of erodibility				
	1	2	3	4	5
1	1	1	1	2	2
2	1	1	2	3	4
3	1	2	3	4	4
4	2	3	3	5	5

du Territoire 2002). Those units corresponded to very low, low, medium, high and very high levels of soil protection.

Development of the erosive state map

The result of the predictive approach is the erosive state map (Fig. 11) generated by overlaying the erodibility map and the soil protection map. This map is particularly valuable as it classifies the catchment area into polygons based on the level of erosion risk, utilizing a matrix recommended by the PAP/RAC guidelines (Table 8).

The descriptive approach

The descriptive phase is the second step of the PAP/RAC model, allowing to identify and evaluate the real erosion processes (detachment, transport and sedimentation) on the ground. This phase, considered complementary to the predictive phase, provides the actual state of erosion in the study area by mapping the erosion patterns. The map of erosion patterns (Fig. 11) was generated by using the high-resolution Google Earth imagery, which allowed the digitization of these erosion patterns, corrected by field observations.

The integration approach

The integration phase is the last step of the PAP/RAC model. This phase is the product of two previous steps. The superposition of the map of erosive states and the map of erosion forms provided us with an exact cartographic product called the PAP/RAC consolidated erosion map (Fig. 12), reflecting the reality of the state of soil degradation and the future evolution of erosion. It results in a final cartographic product identifying and evaluating potential erosion (erosive status) and current erosion in various forms, intensities and evolutionary trends (Ousmana et al. 2017).

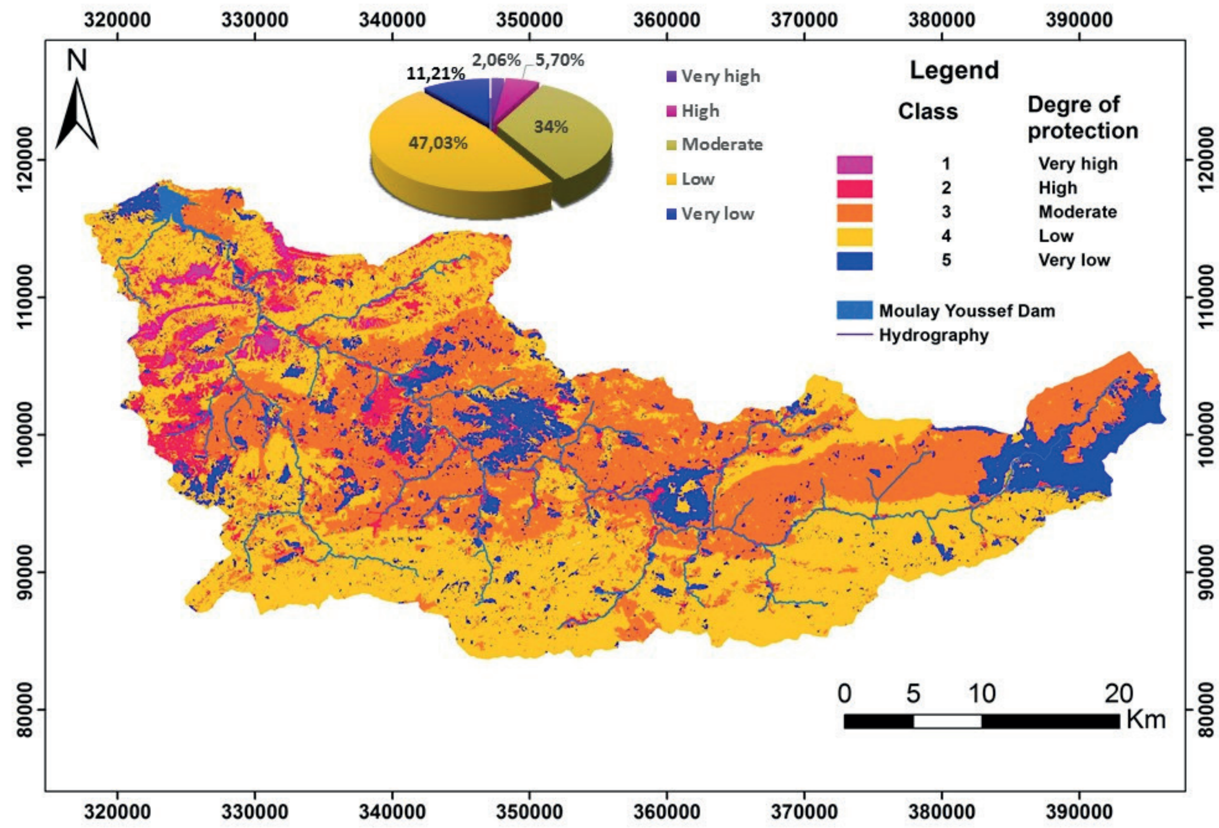

Fig. 10. Soil Protection Map of the study area

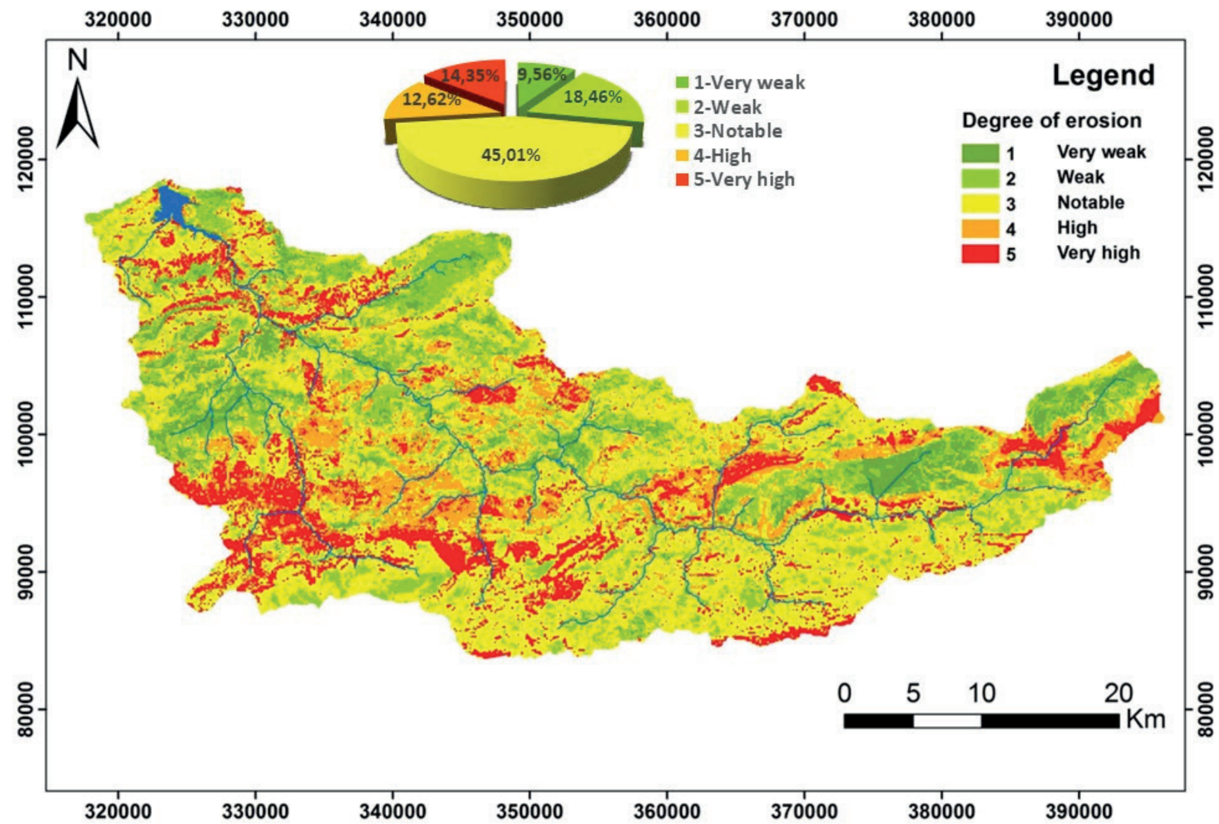

Fig. 11. Map of erosive states of the study area

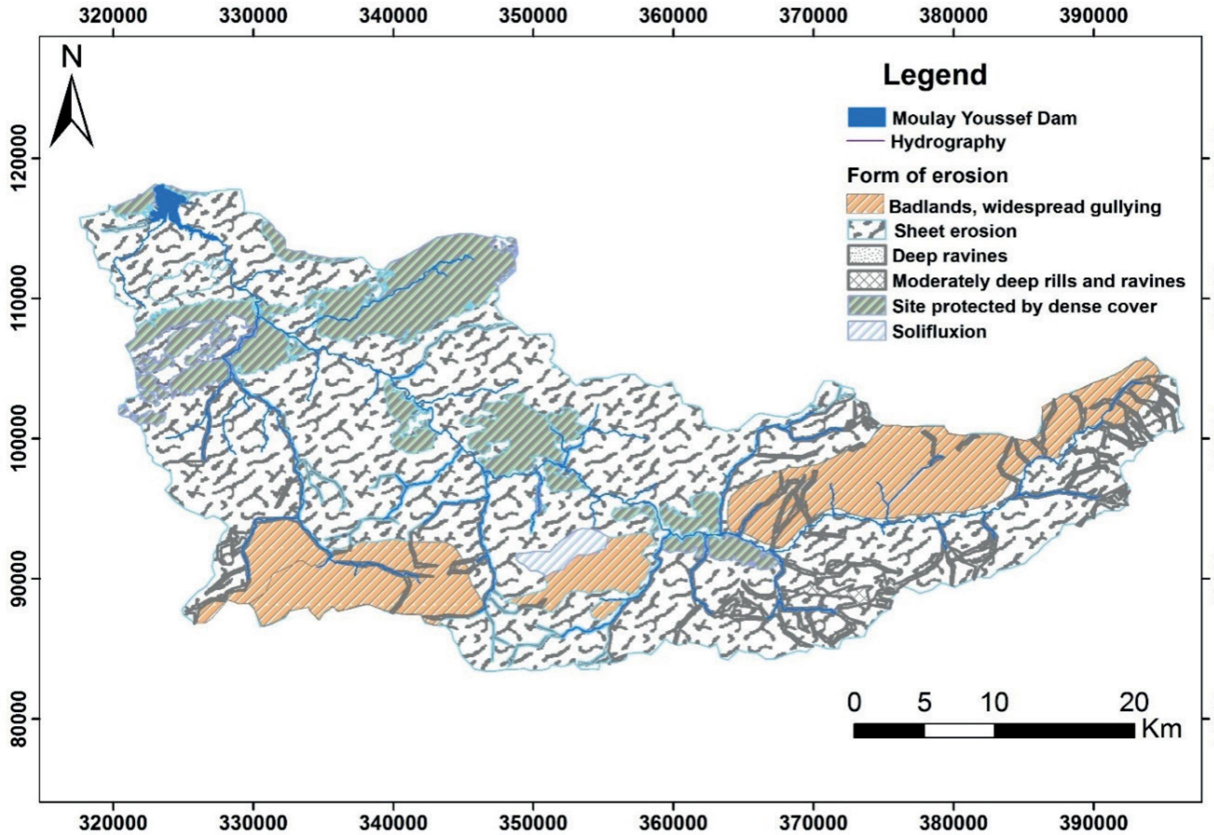

Fig. 12. Map of erosion forms of the study area

Results and discussions

Predictive approach

Erodibility map

The soil erodibility is a measure of the soil's sensitivity to water erosion, based on its properties such as composition, structure and texture. These characteristics determine the soil's response to erosive agents (Wischmeier and Smith 1978; Sheridan et al. 2000; Khallef et al. 2020a). The erodibility parameter is determined by the nature of the substrate, which influences the probability of producing friable materials, as well as its predisposition to promote substrate mobility through erosion. In order to generate the erodibility map, the lithology and slope maps were overlaid using the soil erodibility matrix from the PAP/RAC model (Table 3). This PAP/RAC model allows for the classification of terrains based on their degree of erodibility, ranging from low to moderate, medium, high and extreme, as illustrated in Table 4.

Based on the erodibility map (Fig. 7), the erosion susceptibility in the upper Tassaoute River watershed is influenced by both slope and the cohesive properties of the lithological facies. The PAP/CAR model indicates that areas characterized by steep slopes and low resistance are highly prone to erosion. The regions exhibiting strong and extreme erodibility are primarily located in the south-western section of the basin, extending partially into the upstream area, where slopes exceed 30%. The most prevalent erodibility class, moderate erodibility, covers approximately 37.95% of the basin's surface and is predominantly distributed in the upstream and middle sections. On the other hand, the low and very low erodibility classes occupy the north-western part of the basin, as well as a small portion of the upstream area, representing approximately 14.54% of the total upstream Tassaoute River area. The topographic and lithological factor combination showed that 65.16% of the study area had medium, high and extreme erodibility, while 34.84% of the area showed weak to moderate eroded soil. These results are related to the rugged topography of the upstream Tassaoute watershed, such that 76.6% of the watershed has a slope greater than 20%, and the formations have a low to medium resistance to water erosion. High to extreme erodibility lands are steeply sloping lands with low erosion resistance.

The combination of topographic and lithological factors reveals that 65.16% of the study area exhibits moderate, strong and extreme erodibility, while 34.84% of the surface consists of soils with low to moderate erosion. These results are attributed to the rugged topography of the upstream Tassaoute River watershed, where 76.6% of the basin has slopes exceeding 20% and the lithological formations have low to moderate resistance to water erosion. Areas with strong to extreme erodibility are characterized by steep slopes and low resistance to erosion.

Soil protection map

The produced soil protection map of the upstream Tassaoute basin given in Figure 10 showed that 58.24% of the upstream Tassaoute watershed is poorly protected as the basin is very low to very poorly protected; rangeland and bare land predominate there. Figure 10 also showed that 34% of the total watershed is moderately protected, and only 7.76% (specifically located in the downstream part of the basin) is most protected. The degradation of soil protection in the large portion of the Tassaoute watershed highlights the importance of implementing measures to reduce erosion and enhance vegetation cover.

Erosive state map

The produced map of the erosive states of the Tassaoute upstream basin showed the dominance of the class of moderate and low notable erosion (Fig. 11); it occupies 40.01% of the basin surface. The high and very high erosion classes represented 26.97% of the study basin. Compared to the other classes, the very low and low erosion degree classes are weakly represented, with about 9.56% and 18.46% of the study area, respectively.

As seen in Figure 11, we noted that the most eroded areas are concentrated in the south-western and upstream parts and a few in the middle areas of the study watershed. This can be explained by the slope steepness, the lack of vegetation cover, and the outcrop of relatively loose sedimentary formations considered as factors promoting soil erosion. In the downstream part, we notice the dominance of areas of very low to low degrees of erosion; this may be due to the dense vegetation cover and low slopes. The significant erosion class is scattered throughout the study area and may be related to the rugged topography of the entire upstream Tassaoute watershed and low vegetation cover. In some areas, despite the low vegetation cover and steep slopes, the degree of erosion is low to very low due to the outcropping of geological formations that are more resistant to erosion, such as metamorphic rocks and conglomerates. These geological formations, when exposed in regions with limited vegetation cover and steep slopes, serve as a protective layer that effectively reduces erosion.

Descriptive approach (erosion form map)

The produced map of the erosion forms showed that the upstream Tassaoute watershed was represented by different forms of erosion such as in slicks, gullies, and ravines (Fig. 12). These forms of erosion are generally combined over the entire area of the basin. Still, based on the abundance-dominance approach, it is possible to attribute to each geographical area the form(s) of erosion that dominated it (Ait Yacine et al. 2019).

The map analysis at this stage revealed that approximately 30% of the study area is characterized as stable due to the presence of dense vegetation cover, while the remaining 70% is considered unstable. The instability of the upstream Tassaoute basin is evident through various processes of water erosion. These erosive processes contribute to the loss of soil in different ways. Sheet erosion and scouring are the predominant forms of erosion, posing a threat to approximately 90% of the basin. The gullying or badlands threatened mainly marl and limestone, with steep slopes located in the upstream and center of the basin. The medium-deep gullies and ravines affected 2.21% of the land; they are mainly located in the southern part of the upstream part of the basin; they appear on non-exploitable land with loose materials and steep slopes. The deeper gullies affected no more than 1% of the study area, located between the upstream and the center of the basin in hilly areas with low vegetation cover.

However, the risk of periodically flooded or alluvial areas, characterized by flooded depressions during floods and heavy precipitation, is mainly localized in the center of the basin and occupies less than 0.5% of the surface area. The different forms of erosion and their distribution in the upstream Tassaoute basin can be explained by the

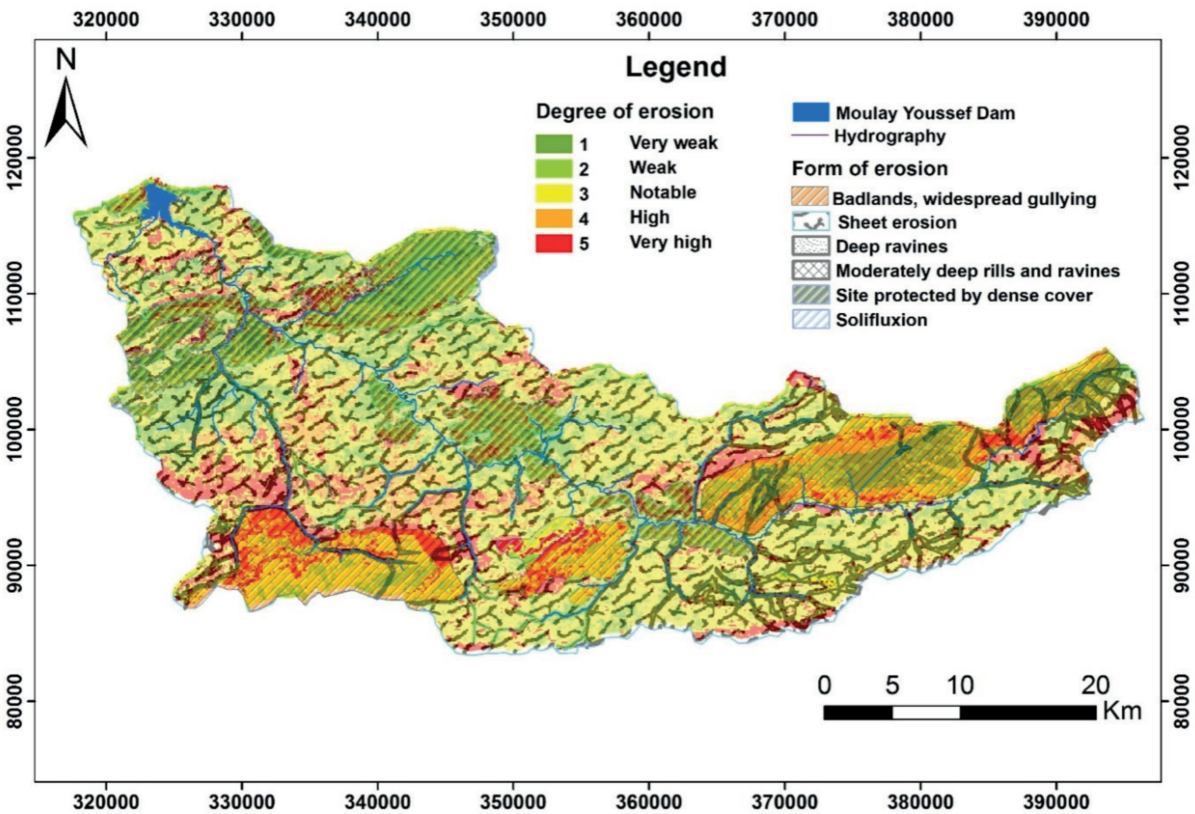

Fig. 13. Consolidated map of PAP/RAC of the study area

vulnerability of the terrain, the slope of the land, the action of watercourses, and human practices.

Integration approach (consolidated PAP/RAC erosion map)

The analysis of the consolidated erosion map (Fig. 13) allows us to deduce that the areas characterized by weak and notable erosion coincide with the form of sheet erosion. The areas where erosion is weak to very weak coincide with the areas protected by the dense cover. It is also noted that the areas where erosion is notable to high coincide with badlands where there is widespread gullying; the low density of vegetation cover explains this. In some places, the combination of sheet forms, gullies and ravines is found, concentrated mainly in the upstream part of the basin and coinciding with areas that suffer a low to high degree of erosion. These areas generally correspond to rugged terrain with a relatively high rate of soil friability and a very low density of vegetation cover. The overlay of the predictive and descriptive states confirms that the vulnerability of the upstream Tassaoute watershed from high to very high erosion is essentially located in the middle and upstream part of the study area.

Conclusion

The qualitative modelling of water erosion by the PAP/RAC method in the upstream Tassaoute watershed integrated several causal factors (slope, lithology, land use, density of vegetation covers and actual erosion patterns). The mapping and estimation of water erosion using the PAP/RAC method in the study area allowed an analysis and understanding of the erosion risk in the study area. The results obtained in this qualitative study are considered satisfactory in comparison to another study on erosion conducted in the upstream Tassaoute basin by (Elaloui et al. 2017), who did a quantitative study of water erosion by the universal soil loss equation (‘USLE) and found results on the extent of erosion in this study area. The map of the predictive approach, which is based on the degrees of influence of the different factors controlling water erosion, shows that about 72% of the land has significant high to very high erosion, and 28% has very low to low erosion. The descriptive phase, which consists of the accurate erosion map, shows the presence of different forms of erosion, simple and combined, with the dominance of sheet erosion and scouring, followed by generalized gullying or badlands. The gullies, medium-deep gullies and deep gullies appeared in the upstream and middle parts of the basin. In the integration phase, the superposition of the predictive and descriptive phases showed that the gully erosion pattern and gullying coincided with areas of significant erosion. The badlands coincided with medium to high erosion areas with steep slopes and friable land. The deep gully is visible in the midstream of the basin in a few areas showing significant erosion. The stable areas corresponded to soils with dense vegetation cover and/or low slopes, mainly located in the downstream part of the basin.

The areas most affected by erosion are distributed in the central part of the basin's downstream, corresponding to friable land with steep slopes and less dense vegetation cover. In contrast, the least eroded are areas located downstream of the basin that exhibit low slopes and less friable land better protected by vegetation cover. This confirmed the important role of slope, lithology and vegetation cover in protecting the soil from water erosion.

Given the increasing degree of erosion caused by climate change and the threats to natural resources and consequently to the economic and social quality of life of the inhabitants, it is necessary to intervene to combat this phenomenon with an integral and reliable approach that will provide a global overview of the extent of soil vulnerability in watersheds. Thus, the methodology adopted can help decision-makers better target the priority areas of intervention and minimize the costs and time related to management studies for any anti-erosion development.

Disclosure statement

No potential conflict of interest was reported by the authors.

Author contributions

Study design KZ, AB, AE, MN; data collection KZ, AE; statistical analysis KZ, AE; result interpretation KZ, AE, MN; manuscript preparation KZ, AB, AE; literature review: AB, AE, MN, MO.

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