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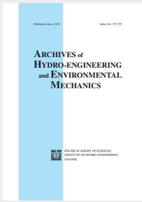

Analysis and Mapping of Water Erosion Vulnerability Using GIS for the Mghila Watershed, Northwest of Algeria

Abdelkader Ratiat[1,3], Ali Haddad[2*], Ilham Bouaichi[1,3], Chahrazed Naziha Matene[1]

[1]University Djillali Bounaama, Khemis Miliana,44225 Algeria, e-mails: a.ratiat@ensh.dz; i.bouaichi@ensh.dz; c.maten@univ-dbkm.dz; [2]Laboratory of Protection and Preservation of Water Resources, Department of Water Sciences and Environment, Faculty of Technology, Blida 1 University, 9000 Blida Algeria, [3]2Water and Environmental Engineering Laboratory, National Higher School for Hydraulics (ENSH), 9000 Blida, Algeria; [*]corresponding author: e-mail: haddad.ali.hydr@gmail.com;haddadali@univ-blida.dz

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Abstract. Intensification of extreme rainfall-runoff events in arid and semi-arid regions because of climate change induce the water erosion that contributes considerably to the loss of vegetal layers of soils and reduce the storage capacity of dams by silting of transported sediments from the watershed to the impoundment. This paper aims at proposing means for protecting the Mghila dam against silting by identification and delimitation of vulnerable areas to water erosion. This dam, built in the North-West of Algeria, ensures irrigated cultivation. Topographical, geological, and land use characteristics of the watershed were analyzed using the geographic information system (GIS). Analysis of results has allowed the identification by area percentage four-vulnerability classes with sensitivity to the water erosion: low (18.89%), medium (13.08%), high (65.05%) and very high (8.38%). The spatial distribution of the lithological substratum friability, the vegetation cover and slope degrees have led to the development of an efficient strategy for the watershed management in order to reduce the effect of water erosion on soil degradation and silting of the Mghila dam.

Key words: water erosion, silting, extreme rainfall-runoff, arid regions, sediment transport

1. Introduction

The development of any state or nation throughout the world depends essentially on mobilizing their natural resources, such as their cultural activities. Countries in arid and semi-arid regions face serious challenges in feeding their populations because of the scarcity of water resources and the degradation of agricultural soils. The changing of the hydrologic cycle in these regions has induced the extension and persistence of dry periods. The exposition of soils to high temperatures increases their fragility, and during extreme rainfall-runoff events, the sediment particles could be eroded and transported.

Erosion of soils is currently causing serious problems for agricultural production, where the yield per hectare remains very low. The seriousness of this phenomenon seems to exceed all efforts made so far to curb the various erosion processes (Morsli et al 2004). According to Mostephaoui et al (2013), 50 million hectares in Algeria are threatened by desertification and water erosion.

Several countries have been affected by erosion. For example, the Sahel is one of the most affected regions in the world by soil water erosion, with an annual average of 1.54 t $ha^{-1}year^{-1}$ of potential soil loss due to water erosion (Adamou et al 2022). In Algeria, many authors have published various values of specific soil erosion rates in catchment areas, such as in the case of the Kebir watershed with 57.2 t $ha^{-1}year^{-1}$ (Khanchoul et al 2012) as well as the Oued Bellah watershed with 61 t $ha^{-1}year^{-1}$ (Elahcene et al 2013). 14 million hectares of mountain areas in the North part of the country were degraded by water erosion (Touahir et al 2018).

The silting of dams has affected numerous dams in Algeria. According to the declaration of the National Agency of Dams and Transfers in 2021, 80 large dams are in operation with a total storage capacity of 8.6 billion m^3. The actual capacity is reduced by 15 percent (1.29 billion m^3) because of silting. The main cause of silting remains the high rate of sediments eroded and transported by extreme floods to the impoundment of the dam. In the Boukerdane dam, the rate of soil erosion was assessed to be 4.46 t $ha^{-1}year^{-1}$ as well the volume of sediment accumulated in the lake was about 11.104 million m^3 during the period of 1993 to 2013 (Tadrist et al 2016). With an average annual specific erosion varying between 20 and 40 t ha^{-1}, Algeria is classified among the countries with the most erodible soils in the world. Over all, water erosion poses serious social and economic problems by reducing the useful agricultural surface and pushing the rural population to renounce agricultural jobs (Touaibia 2010).

Geographic Information Systems (GIS) are a practical tool for the modeling of development and analysis. This tool allows the creation, management, analysis, and mapping of all types of data. It integrates the location data with all types of descriptive information. Many researchers throughout the world have used GIS to model and forecast soil degradation by water erosion. Bensekhria and Bouhata (2022) have applied the GIS approach combined with the universal soil loss equation (USLE) to assess and map the soil erosion on the Oued El Hai watershed in the Northeast of Algeria. Mosaid et al (2022) have used the GIS with its integrated erosion potential model to map and evaluate the vulnerability of the Oued Srou watershed (Morocco) to water erosion and its impact on the silting of Ahmed El Hansali dam. Afera et al (2018) have studied the erosion sensitivity using GIS and multi-criteria decision approach with parameters of influencing factors in Ribb Watershed (Ethiopia). Drzewiecki et al (2013) used GIS for quantitative and qualitative assessment of soil erosion risk in Malopolska (Poland), where satellite remote sensing technology and the object-based image analysis (OBIA) approach were applied in order to characterize the erosion risk levels of agricultural lands. Bilal et al (2021) used a GIS-based multi-criteria decision approach for mapping the soil erosion susceptibility zones in the Chitral district (Pakistan). According to this study, several different factors such as lithology, slope, elevation, plain curvature, lineaments, land cover, rainfall, drainage density, NDVI (Normalized Difference Vegetation Index), and NDWI (Normalized Difference Water Index) were considered, and weights have been assigned to each factor. The generated map obtained from the combination of all maps showed degrees of soil erosion in five different classes.

The purpose of this paper is to propose means for protecting the Mghila dam against silting through the identification and delineation of vulnerable zones to water erosion. The collection and elaboration of thematic maps for the study area will be necessary in order to study the effect of water erosion phenomena on the soils of the Mghila watershed. The different maps will be cross-referenced using the Geographic Information System (GIS). The resulting maps will be analyzed in order to establish the soil vulnerability map to water erosion and thereafter to propose an adequate strategy for protection and management of the Mghila watershed in order to curb the effect of water erosion on soil losses and silting of the Mghila dam.

2. Methodology

2.1. Study Area

The Mghila watershed is located in Tissemsilt province in the Northwest part of Algeria (Fig. 1). It extends over 315 137 hectares of surface. It is limited by geographical coordinates: X1 = 1°0′0″ E, Y1 = 35°20′0″ N; X2 = 2°0′0″ E, Y2 = 36°0′0″ N. It is divided into three distinct surface parts: plains in the south (25%), transitional mountains in the center (31%) and mountains (44%). The climate of the study area is semi-arid with relatively low annual rainfall ranging from 300 to 600 mm. It is characterized by a cold and wet winter and a hot and dry summer, with temperatures varying between 0° and 6°C in winter and 32° to 36°C in summer. According to the lithology map, the Mghila watershed reveals a wide range of surface formations, dominated by clay soils from marl formations.

The mean annual rainfall in the study area is about 547 mm, and more than 98% of it occurs between September and May. In autumn and winter, the study area receives an equal amount of rain. Nevertheless, the seasonal distribution is quite irregular because it rains half as much in spring as it does in winter. In addition, it rains much less in summer, with barely 6% of the total annual average precipitation. Fig. 2 shows the annual distribution of precipitation and average monthly rainfalls over the period of the years 2010 to 2021.

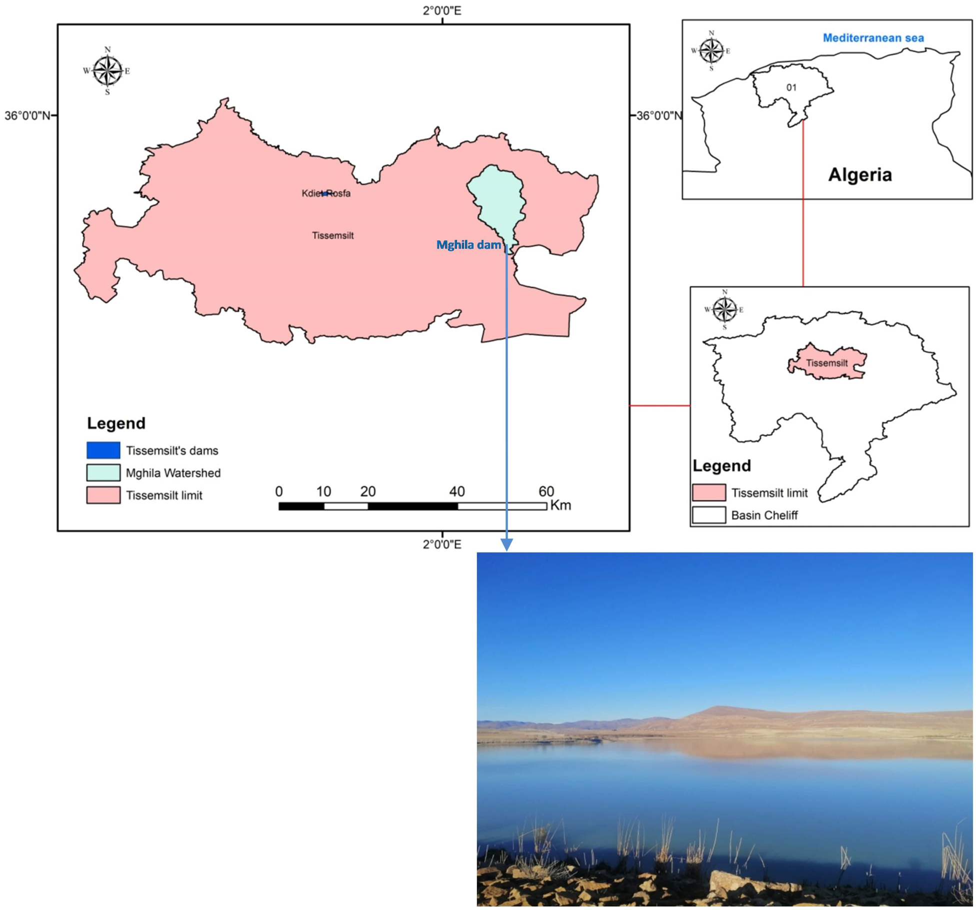

Fig. 1. Study area

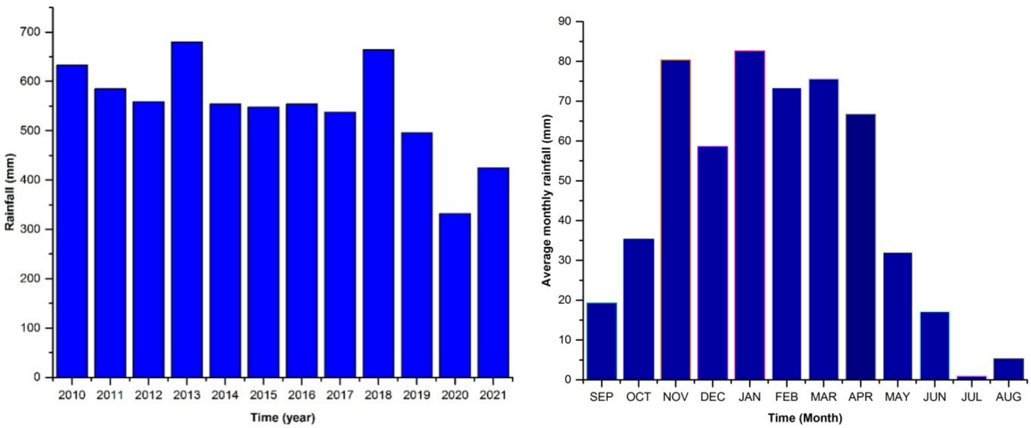

Fig. 2. Annual rainfall distribution (left); Average monthly rainfall (right)

2.2. Extreme Rainfalls

Analysis of precipitation data collected from the national agency for water resources has shown that extreme rainfalls occurred frequently over the Mghila watershed, with total precipitation values ranging from 30 to 90 mm. The storms of September 29 to October 2, 1994, and October 24, 2000, were the most important, with respectively 90 and 83 mm of precipitation. These resulted in extreme flooding that caused nine deaths and extensive material damages.

2.3. Hydrographic Network

The Mghila watershed presents a strong density of hydrographic networks (Fig. 3), which is explained by the high rate of steeper slopes and less permeable land formations. The sensitivity to linear erosion (gulling) over the Mghila watershed is defined by the parameters of drainage density and torrential coefficient. The first parameter (Eq. 1) that is expressed as the total length of the mainstreams over the watershed area gives a drainage density of 1.2. This value indicates that the study area is highly drained by a ramified hydrographic network.

$$D_d = \frac{\sum_{i=1}^{n} L_i}{A}. \tag{1}$$

where D_d is the drainage density; L_i is the length of the stream number i, n is the total number of streams, and A is the watershed surface.

The second parameter gives information about the torrentiality of the watershed (Eq. 2). It takes into account both the density of drainage and elementary streams (Eq. 3). With a density of elementary streams of 0.78, the drainage density is about 0.93, which is explained by the large number of tributaries (see Fig. 3).

The average number of tributaries (Fig. 3) results in a considerable value of the torrential coefficient.

$$CT = F_1 \times D_d, \tag{2}$$

$$F_1 = \frac{N_1}{A}, \tag{3}$$

where CT is the coefficient of torrentiality; F_1 is the density of elementary streams; and N_1 is the number of elementary streams.

2.4. Approach

The approach used in this paper for the analysis and mapping of water erosion sensitivity is an assessment that relies on weighting each factor before overlaying them. The overall difference between all the qualitative models using the GIS approach is in the weighting of the different factors. Each factor behaves differently in different areas

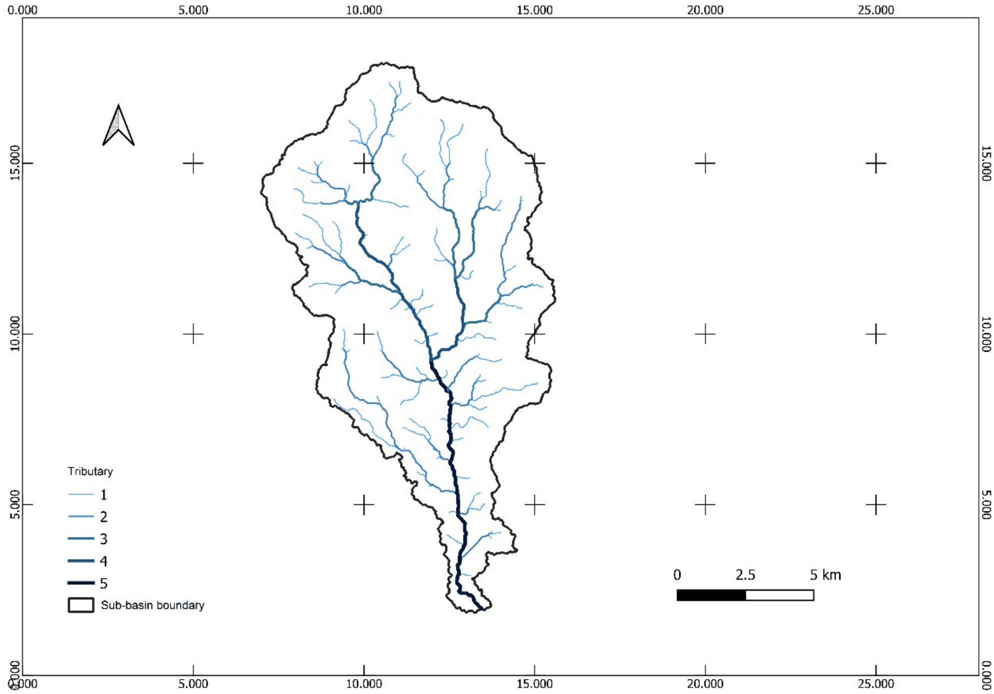

Fig. 3. Hydrographic network of the Mghila watershed

of the watershed. Factors such as lithology, slope, and land use and their weightings are chosen from several experiments conducted in the study area. In fact, the approach was focused on two steps. The first consists in the elaboration of thematic maps for the study area. The resulting maps are then cross-referenced by using a Geographic Information System (GIS). The use of this technique gives us the possibility of studying different themes by mapping and visualizing the different data. After all databases have been merged (Fig. 4), possible scenarios is considered in order to establish the soil vulnerability map to water erosion.

2.5. Soil Occupation Map

The vegetation cover of the Mghila watershed was mapped using satellite images and data obtained from the organization of agricultural and forestry conservation in the Tissemsilt province. Several types of land use are represented in Fig. 5. According to Roose (1977), the capacity of protection against water erosion is assigned into four classes. The first is non-protective, which corresponds to completely bare and uncultivated soils. The second class is not very protective and includes rangelands. The third class is low protective, with annual crops such as cereals and extensive agriculture. The fourth class is highly protective and consists of forests, reforestation, arboriculture, and viticulture. The land cover map was obtained using the maximum

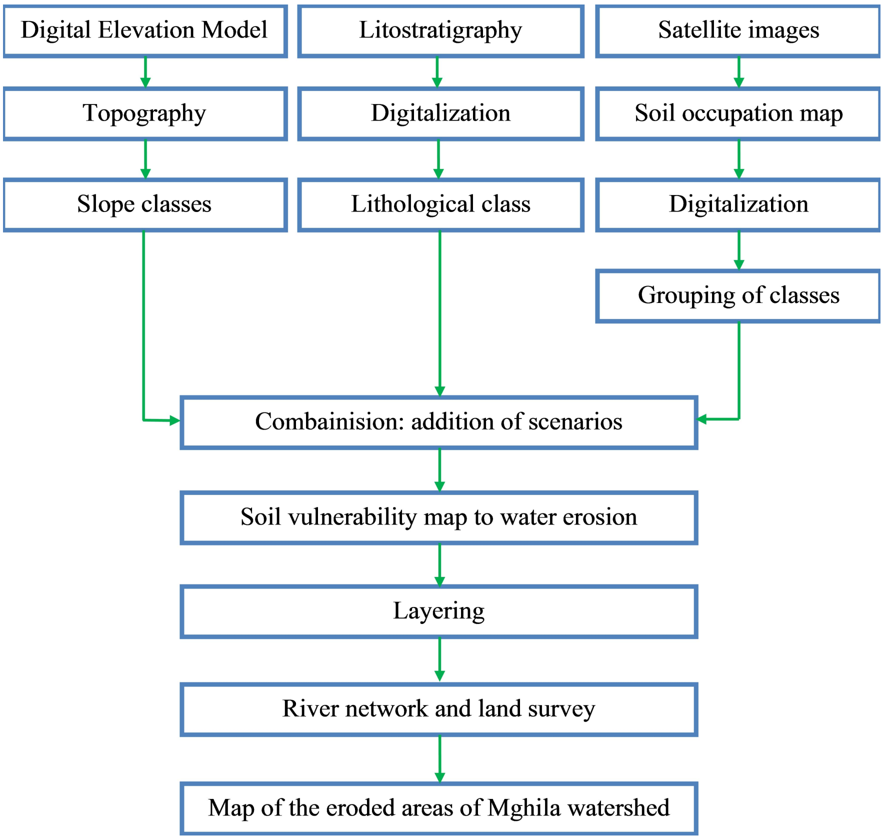

Fig. 4. Methodological approach

likelihood technology-driven classification based on direct observation of land cover types. This technique presents the land cover as cropland, dry land, very dense vegetation, sparse or medium-dense vegetation, and urban areas. Each class is assigned a value between 1 and 4 (Tab. 1), with 1 being assigned to the least vulnerable class and 4 to the most vulnerable class (Roose 1977). Using these classifications, the vegetation cover of the Mghila watershed was classified into three appropriate classes: (1) permanent vegetation cover, which represents forest cover, forest reforestation, arboriculture and vineyard plantation; (2) temporary cover, which consists of cereals, arable lands, extensive and semi-intensive agriculture; (3) incomplete vegetation cover, which includes degraded pasture and bare soil.

2.6. Lithology Map

The lithological map of the Mghila watershed reveals a wide range of surface formations, which are dominated by clay soils derived from marl formations. The characteristics of the soils, as well as their susceptibility to hammering and cracking, are used

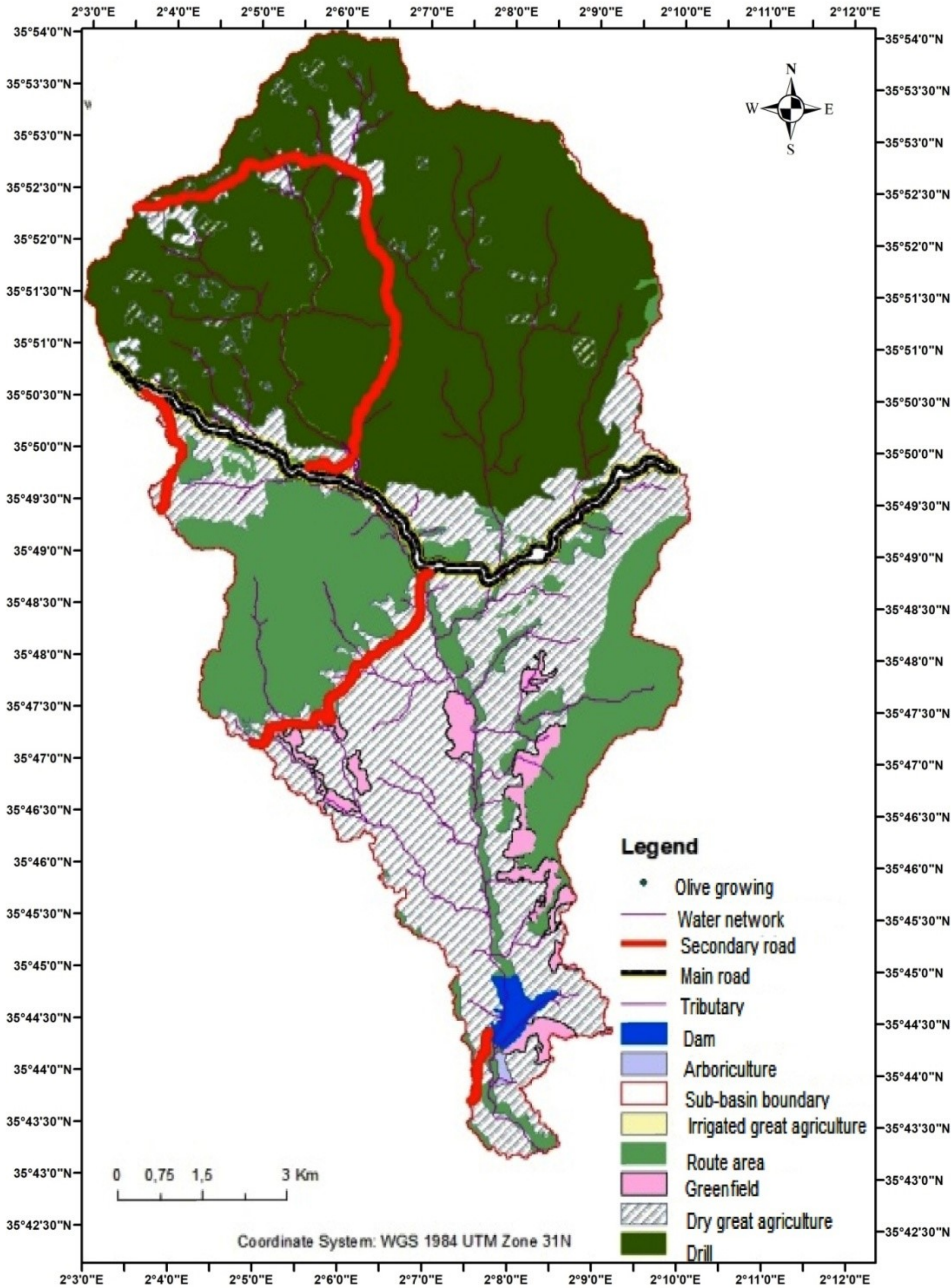

Fig. 5. Soil occupation map of the Mghila watershed

Table 1. Classes of vegetation cover sensitivity to erosion

Value or cost	Level	Classification
1	Resistant	Forest
2	Medium resistant	Tree cultivation + dry field crop
3	Low resistant	Olive growing
4	Very low resistant	Water areas + park area +bare soil zone + water network

to assign susceptibility grades to each soil type (Tab. 2). The susceptibility classification comprises four classes with percentages of basin areas arranged in descending order. This soft and fragile lithology certainly generates dynamic erosive activity, as shown on the lithological map (Fig. 6), which demonstrates that the highly sensitive soil classes represent one percent of the entire surface.

Table 2. Classification of soils according to different characteristics

Type of soil	Resistance	Class of sensibility
Lower Cretaceous + Upper Cretaceous	High resistance	1
Lower Jurassic + Paleocene	Medium resistance	2
Oligocene	Low Resistance	3
Lower Miocene + Quaternary + Upper Miocene	Very low resistance	4

2.7. Slope Map

The slope map is generated from the digital elevation model (DEM), where for each slope the class is assigned an index varying between one and four and a percentage of the total watershed surface (Tab. 3).

Table 3. Indices and surfaces of Slope classes

Indices	Slope %	Surface %
1	40–60	4.33
2	20–40	9
3	10–20	39.41
4	0–10	46.91

3. Results and Analysis

The methodology developed in this study uses quality rules for the evaluation and prioritization of factors interfering with water erosion and land use (Fig. 5), slope degree (Fig. 7), and lithology (Fig. 6). All these data have been integrated into the Geographic Information System for better information management.

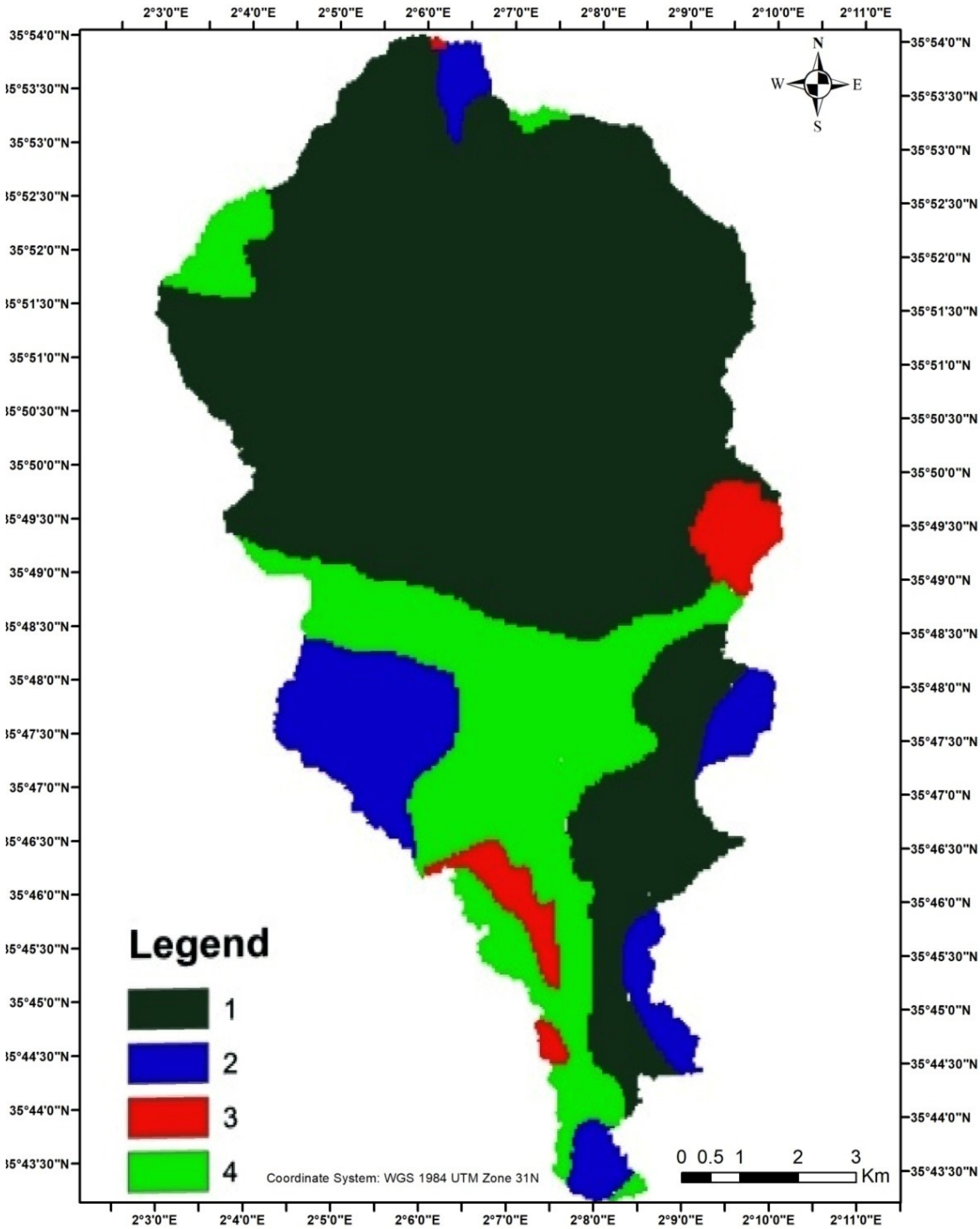

Fig. 6. Lithological map of the Mghila watershed

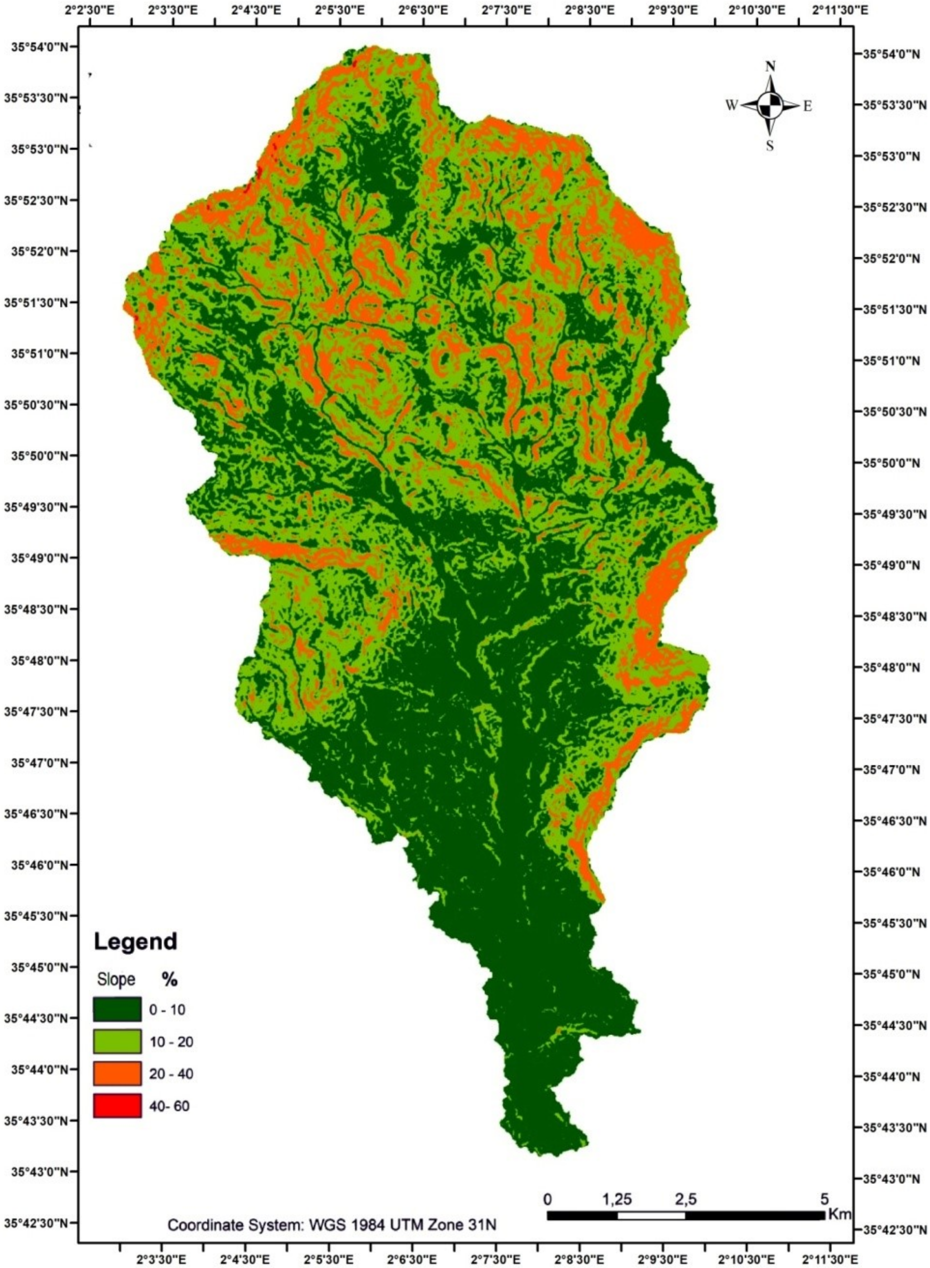

Fig. 7. Slope map of the Mghila watershed

3.1. Land Fragility Map

In order to elaborate the land fragility map, we have adopted quality rules for processing and analyzing the degree of land fragility. In fact, four land fragility classes were considered and assigned by indices from one to four (Tab. 4).

Table 4. Land fragility classes

Indices	Land fragility class
1	Very fragile land
2	Quite fragile land
3	Moderately fragile land
4	Not fragile land

The land-use map was cross-referenced with the lithological map for the elaboration of the land fragility map (Fig. 8). The cross-referencing was done through an appropriate matrix (Tab. 5) where the crossing of a low-resistance soil class with a low vegetation cover class gives a low fragility class. The resulting map shows four land fragility classes: 1 – very fragile land (24.16%), 2 – quite fragile land (56.21%), 3 – moderately fragile land (1.33%), and 4 – not fragile land (18.25%). The very fragile and fragile lands represent more than 80.37% of the watershed surface.

Table 5. Decision rules for land fragility

Plant cover	Lithology			
	1	2	3	4
1	1	1	1	2
2	1	2	2	3
3	2	2	3	4
4	3	4	4	4

3.2. Map of Soil Sensitivity to Water Erosion

The assessment of the vulnerability of soils to water erosion requires the use of quality rules for analysing the degree of sensitivity. Each of the four sensitivity classes we have selected has an index between one and four (Tab. 6).

Table 6. Classes of sensitivity to water erosion

Indices	Sensitivity classes to water erosion
1	Very high
2	Relatively high
3	Medium
4	Low

The soil sensitivity map for water erosion is generated by intersecting the soil fragility map with the slope map. For example, according to the matrix of decision

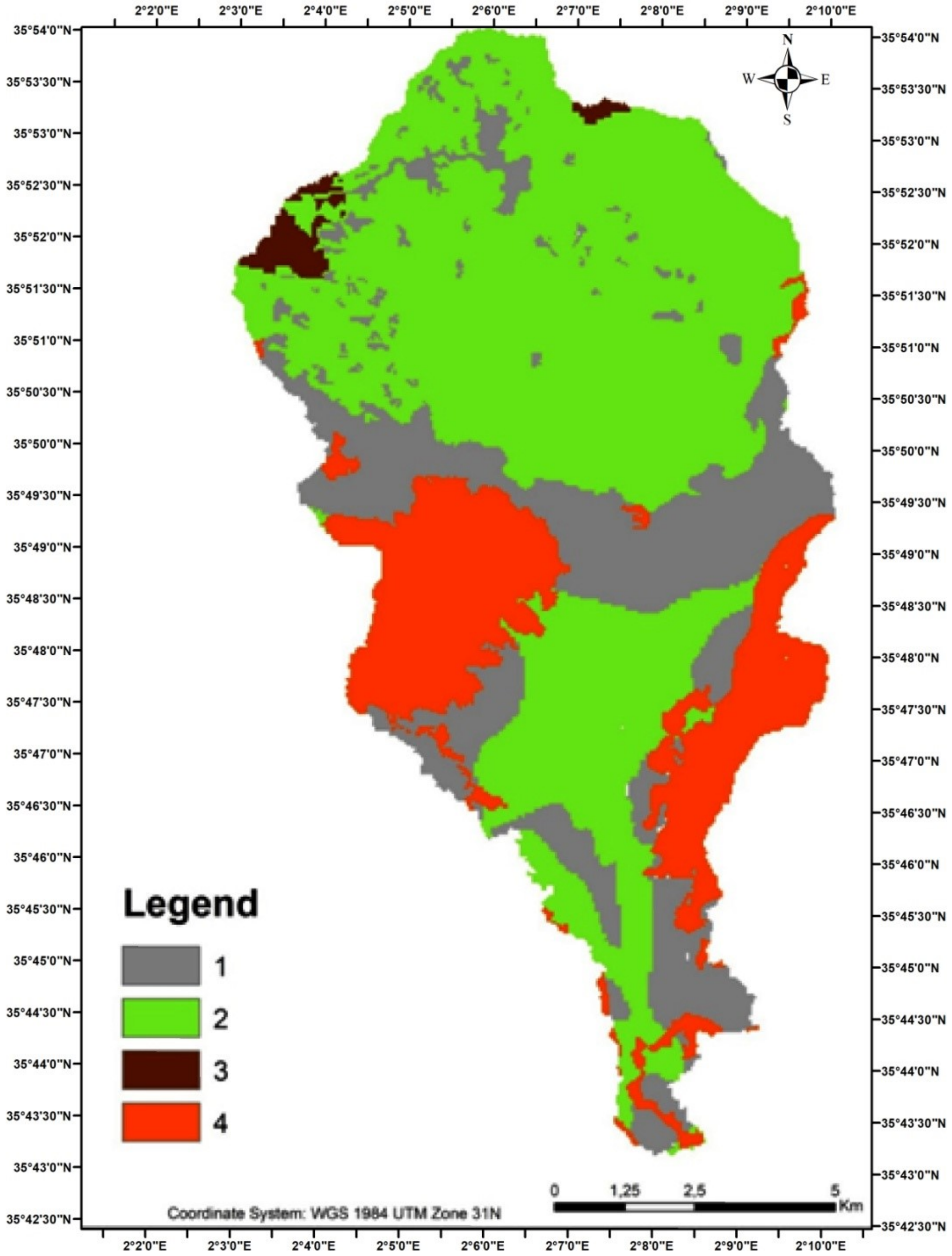

Fig. 8. Fragility map of the Mghila watershed

rules (Tab. 7), the intersection of a very fragile soil (class 1) with a steep slope (class 1) gives a very high erosion sensitivity (class 1). In fact, there are four main classes of sensitivity to water erosion (Fig. 9) expressed in percentage of the watershed surface: 1 – very high (8.38%), 2 – relatively high (65.05%), 3 — medium (13.08%), and 4 – low (12.89%). Although the southeast part of the watershed is very favourable to the phenomenon of water erosion, the northern part, with steep slopes (> 40°), is not. For the other parts where the slope ranges between 5° and 15°, the soils are less vulnerable to water erosion.

Table 7. Decision rules for erosion sensitivity

Slope	Land fragility			
	1	2	3	4
1	1	1	1	2
2	1	2	2	3
3	2	2	3	4
4	3	4	4	4

4. Conclusions

The mapping by the GIS is an approach used to deal with erosion hazards to analyze the risk of water erosion in any watershed. The approach adopted in this study uses quality rules for the assessment and prioritization of factors interfering with water erosion. It is based on the specific weighting of each factor before overlaying it. Land use, lithology, and slope are considered as factors that influence the degradation of soils. The analysis of these factors by using GIS has enabled us to draw a global map of areas vulnerable to water erosion. The sensitive sites were classified, from the most to the least sensitive, into four categories. The most sensitive areas are those nearest to the Mghila dam. First, the fragility map was created by combining lithology and land use maps. More than 80% of the watershed surface is classified as quite to very fragile soils, and less than 20% represents moderately to lowly fragile soils. Second, the vulnerability map to water erosion was created by combining the fragility and slope maps. Areas with low to medium erosion sensitivity cover 26% of the watershed surface, and the areas with high to very high erosion sensitivity are about 74%. According to these findings, it is strongly advised to implement an effective watershed protection and management strategy as soon as possible in order to reduce the impact of water erosion on soil degradation and silting of the Mghila dam. Several solutions could be adopted for reducing the risk of soil erosion over the Mghila watershed. In arid and semi-arid regions, mechanical and biological techniques for anti-erosion protection, such as the adaptation of agricultural practises, reforestation, fruit plantations, torrential correction, drains, outlets, and re-vegetation, are very practical solutions.

However, the analysis and mapping of water erosion vulnerability using qualitative rules remains proportional and cannot be regarded as a universal method that can be

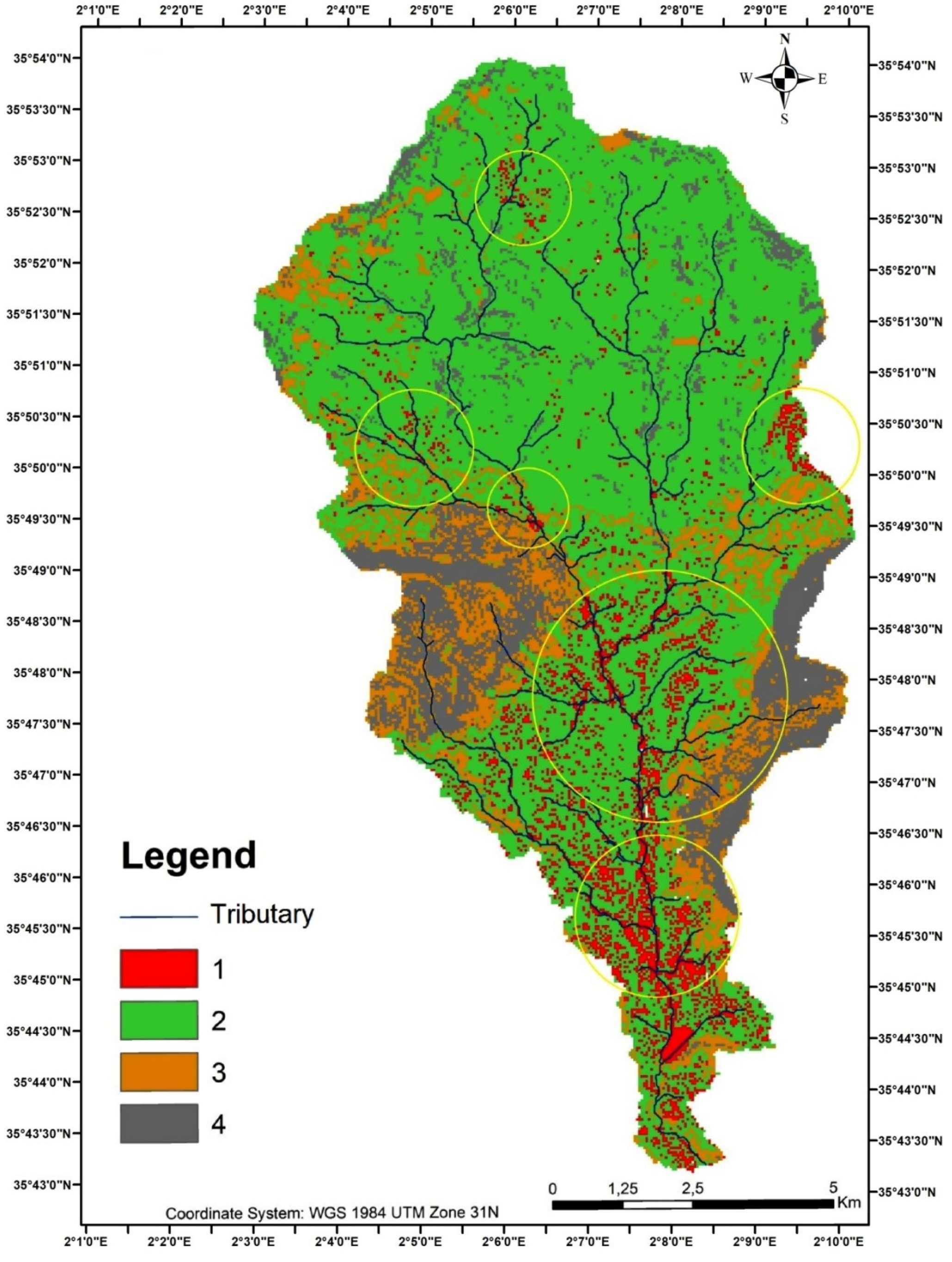

Fig. 9. Water erosion sensitivity map for the Mghila watershed

applied to any kind of watershed because, according to the qualitative decision rules, the soil sensitivities to water erosion are classified by their consequence from high to low. This classification could change considering the degree of interference among the specific watershed characteristics such as land use, lithology, and slope. Meanwhile, the quantitative assessment of soil loss due to water erosion over the watershed should also be considered in order to accurately determine the most vulnerable areas and, therefore, quantify the sediments that could be eroded and transported towards the Mghila dam; thereby reducing its storage capacity.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

References

Adamou S. N., Gourfi A., Touré A. A., Daoudi L. (2022) Water erosion in southwestern Niger: Impacts of natural and anthropogenic factors on soil loss [Érosion hydrique au Sud-Ouest du Niger: Impacts des facteurs naturels et anthropiques sur les pertes en sols], *Géomorphologie: Relief, Processus, Environnement*, https://doi.org/10.4000/geomorphologie.16744.

Afera H., Asirat T., Ermias S., Mihret D. (2018) Erosion Sensitivity Mapping Using GIS and Multi-Criteria Decision Approach in Ribb Watershed Upper Blue Nile, Ethiopia, *International Journal of Energy and Environmental Science*, **3** (6), 99–111. doi:10.11648/j.ijees.20180306.11.

Bensekhria A.; Bouhata R. (2022) Assessment and Mapping Soil Water Erosion Using RUSLE Approach and GIS Tools: Case of Oued el-Hai Watershed, Aurès West, Northeastern of Algeria, *ISPRS Int. J. Geo-Inf.*, **11**, 84, https://doi.org/10.3390/ijgi11020084.

Bilal A., Ahsen M., Wesam S. A., Muhammad A. M., Talha J., Ahmed Z. (2021) Soil erosion susceptibility mapping using a GIS-based multi-criteria decision approach: Case of district Chitral, Pakistan, Ain Shams, *Engineering Journal*, **12** (2), 1637–1649, ISSN 2090-4479, https://doi.org/10.1016/j.asej.2020.09.015.

Drzewiecki W., Wężyk P., Pierzchalski M., Szafrańska, B. (2013) Quantitative and Qualitative Assessment of Soil Erosion Risk in Małopolska (Poland), Supported by an Object-Based Analysis of High-Resolution Satellite Images, *Pure and Applied Geophysics*, SpringerLink. https://doi.org/10.1007/s00024-013-0669-7.

Elahcene O., Terfous A., Remini B., Ghenaim A., Poulet J.-B. (2013) Study of sedimentary dynamics in the watershed of Oued Bellah (Algeria) [Etude de la dynamique sédimentaire dans le bassin versant de l'Oued Bellah (Algérie)], **58** (1), 224–236, http://dx.doi.org/10.1080/02626667.2012.742530.

Khanchoul K., Boukhrissa Z. E. A., Acidi A., Altschul R. (2012) Estimation of suspended sediment transport in the Kebir drainage basin, Algeria, *Quaternary International*, **262**, 25–31, DOI:10.1016/J.QUAINT.2010.08.016.

Morsli B., Mazour M., Mededjel N., Hamoudi A., Roose E. (2004) IInfluence of land use on the risks of runoff and erosion on the semi-arid slopes of northwestern Algeria [Influence de l'utilisation des terres sur les risques de ruissellement et d'érosion sur les versants semi-arides du nord-ouest de l'Algérie], *Sécheresse*, **15** (2), 96–104.

Mosaid H., Barakat A., Bustillo V., Rais J. (2022) Modeling and mapping of soil water erosion risks in the Srou basin (Middle Atlas, Morocco) using the EPM model, GIS and magnetic susceptibility, *Journal of Landscape Ecology*, **15** (1), 126–147, https://doi.org/10.2478/jlecol-2022-0007.

Mostephaoui T., Merdas S., Sakaa B., Hanafi M., Benazzouz, M. (2013) Mapping of water erosion risks by applying the universal soil loss equation using a geographic information system in the watershed of Al Hamel (Boussaada) Algeria [Cartographie des risques d'érosion hydrique par l'application de l'equation universelle de pertes en sol a l'aide d'un systeme d'information geographique dans le bassin versant d'Al Hamel (Boussaada) Algerie], *Journal Algérien des Régions Arides*, **12** (1), 131–147, https://www.asjp.cerist.dz/en/article/76912.

Roose E. (1977) *Erosion and runoff in West Africa, twenty years of measurements in experimental plots* [Erosion et ruissellement en Afrique de l'Ouest, vingt années de mesures en parcelles expérimentales], Paris: ORSTOM, 108 p. (Travaux et Documents de l'ORSTOM; 78). ISBN 2-7099-0480-2.

Tadrist, N., Debauche, O., Xanthoulis, D. (2016) mpact of erosion on dam siltation, coastal groundwater recharge and marine intrusions in the semi-arid Mediterranean zone: Case of the Boukourdane dam (Algeria) [Impact de l'érosion sur l'envasement des barrages, la recharge des nappes phréatiques côtières et les intrusions marines dans la zone semi-aride méditerranéenne: Cas du barrage de Boukourdane (Algérie)], *Biotechnologie, Agronomie, Socieetë et Environnement*, **20** (4), DOI:10.25518/1780-4507.13281.

Touaibia, B. (2010) Problems of erosion and solid transport in Northern Algeria [Problématique de l'érosion et du transport solide en Algérie septentrionale], *Sécheresse*, **21** (4), 333–335, doi: 10.1684/sec.2010.0281.

Touahir, S., Asri, A., Remini, B., Saad, H. (2018) Prediction of water erosion in the watershed of Oued Zeddine and siltation of the Ouled Mellouk dam (North-West Algeria) [Prédiction de l'érosion hydrique dans le bassin versant de l'Oued Zeddine et de l'envasement du barrage Ouled Mellouk (Nord-Ouest Algérien)], *Géomorphologie: Relief, Processus, Environnement*, **24** (2), 167–182.https://doi.org/10.4000/geomorphologie.12083.