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Evaluating the impact of soil management measures on erosion in the upstream part of Nebhana watershed using MEDALUS and RUSLE models

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ABSTRACT: Water erosion is a serious threat to the environment, sustainability of agriculture and socio-economic development. It is widespread in the Mediterranean regions, particularly in Tunisia. The upstream watershed of the Nebhana dam (855 km2), located in central Tunisia, is among the regions most affected by this global issue. The objective of this study is to estimate and spatially assess water erosion in the basin, produce an erosion risk map and identify priority areas to facilitate the intervention of decision makers and managers in developing appropriate policies for conserving soils and protecting the upstream Nebhana-dam against sedimentation. The adopted methodology uses the Revised Universal Soil Losses Equation (RUSLE) and the MEDALUS approach in a GIS environment. The obtained results showed that RUSLE model was efficient in quantifying the average soil loss in the basin, given that estimated value (10.94 t/ha/year) was very close to the value obtained from bathymetric measurements in the dam reservoir (11.25 t/ha/year). Furthermore, RUSLE estimated that 34% of the total area is suffering from an erosion risk exceeding the soil loss tolerance which is in agreement with results found by MEDALUS approach revealing that 30% of the total area were vulnerable to erosion and were considered as areas with highest priority for land management intervention.

KEYWORDS: Vulnerability, Soil, Modeling, GIS, Management.

1 INTRODUCTION

Water erosion is a natural phenomenon widespread in Mediterranean countries and is becoming a serious environmental problem that threatens the sustainable agricultural productivity, water resource mobilization and reservoir storage capacity [1]. Climatic conditions, geomorphology, soil type, vegetation, and human activities are the main factors responsible for soil degradation [2].

North Africa is among the most affected areas, notably Tunisia, where water erosion causes the loss of 15,000 ha/year of arable land [3] and the reduction of the storage capacity of reservoirs by about 17.7% [4], [5]. Soil degradation is increasingly accentuated on bare and fragile soils, which is the case of the upstream watershed of Nebhana, in central Tunisia. The choice of this site was dictated by the presence of a rugged terrain, the density of the hydrographic network, the dominance of friable lithological formations and the poverty of soils in organic matter. Combined with an aggressive semi-arid climate, these conditions make the study area more vulnerable to erosion and the Nebhana Dam more exposed to siltation.

A quantitative and spatial assessment of water erosion is of major importance in order to develop the best strategies for sustainable water and soil management. In this context, many hydrological and erosion models have been developed and applied in different regions of the world, ranging from empirical to physical process-based models [6], [7].

The complexity and magnitude of data requirements have limited the application of spatialized physical models and prompted the use of the Universal Soil Loss Equation (USLE) [2], which was initially designed for small agricultural plots. Nevertheless, the evolution of spatial technologies and geographic information systems has improved the use of this equation at large scales. Thus, the integration of RS Remote Sensing combined with GIS in the USLE has made this model an effective tool for forecasting erosion on large watersheds, for spatial analysis of the most vulnerable areas, and for monitoring the evolution of this scourge in the long term [8], [9], [10], [11], [12], [13]. The revised version of USLE is RUSLE [14], it has been widely applied in the Mediterranean context and has given quite interesting soil loss estimation results in several countries and especially in Tunisia [8], [10], [11].

The objective of the present study is to quantitatively and spatially assess water erosion in the Nebhana upstream watershed and identify prioritized areas for intervention based on RUSLE model and MEDALUS (Mediterranean Desertification and Land Use) approach. This approach determines the most sensitive areas to erosion and desertification through a sensitivity index calculated by combining physical (soil quality), environmental (vegetation quality), climatic (climate quality) and social (management quality) variables related to the study area. This approach is simple but robust and its performance has been judged in different Mediterranean watersheds [15], [16], [17].

2 MATERIELS ET METHODES

2.1 STUDY AREA

The Nebhana watershed is located in central Tunisia. It represents one of the three major watersheds in the region draining southeast flanks of the Tunisian Dorsale. The study area is the downstream of the Nebhana watershed draining an area of 855,4km2. It belongs to three governorates which are Kairouan, Siliana and Zaghouan. This catchment is characterized by a semi-arid Mediterranean climate, with a hot dry summer with average value above 30°C and cool wet winter with a minimum of 7°C in February. Precipitation is irregular generally of short duration and high intensity, the average annual value for the period 2003-2013 is 405 mm.

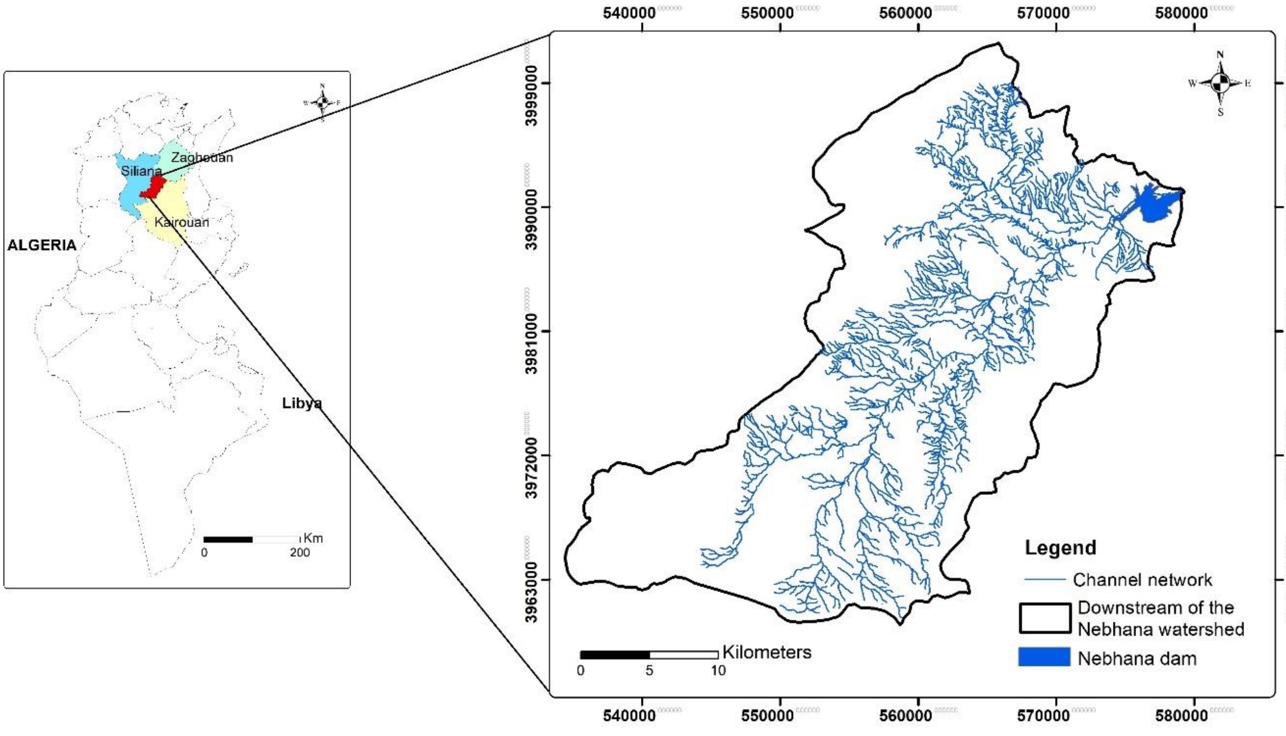

Fig. 1. Location of the study area

2.2 METHODOLOGY

This study aims to quantify and spatialize soil vulnerability to water erosion in the upstream watershed of Nebhana. Given the scarcity of data in this region, we chosen two empirical approaches (RUSLE and MEDALUS) that have been successfully used in soil and water conservation planning studies in Tunisia [8], [10], [11]. These two models have been integrated under a Geographic Information System (GIS) to allow a comprehensive modeling and mapping of the erosion process and to be able to propose the best water and soil conservation strategies. Fig. 2 shows the methodological flowchart adopted in this study.

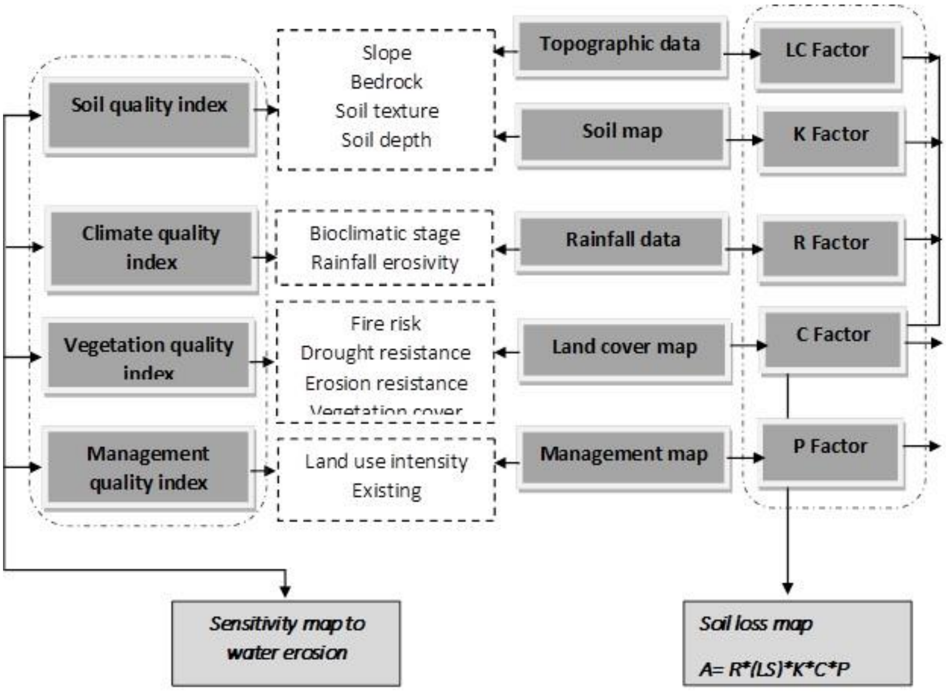

Fig. 2. Methodological flowchart of the study

2.2.1 RUSLE MODÈL

The RUSLE model [18] is the Revised version of the Universal Soil Loss Equation USLE. It allows the prediction of the average annual soil loss by multiplying the five factors controlling water erosion [2], [14]. It is calculated using the following formula in Eq. 1

$$A=R_{RUSLE}*K*LS*C*P \qquad \text{(Eq.1)}$$

Where A is Annual Soil Loss (t.ha-1.yr-1); R is Rainfall Erosivity Factor (MJ.mm.ha-1.hr-1.yr-1); K is Soil Erodibility Factor (t.ha.hr-1.MJ-1.mm-1); LS is Topographical Factor (L in m and S in %); C is Vegetation Cover Factor and P is Land management practices Factor.

- **Rainfall erosivity factor (R)**

Erosivity is an index of rainfall aggressiveness and its ability to produce erosion [19]. According to Wischmeier and Smith (1978) [2], erosivity is defined as the product of rainfall kinetic energy (E) and its maximum intensity during 30 min (I30). Since data on rainfall kinetic energy and intensity are not always available, alternative formulas have been developed based on annual and monthly rainfall [20, 21, 22]. In this case study, to overcome this lack of data, we opted for the formula of Arnoldus (1980) [21]. which correlates well with the erosivity index of Wischmeier and Smith. The R-factor equation is expressed as follows (Eq. 2):

$$R=0.3\times\left(\sum_{i=1}^{12}\frac{P_i^2}{P}\right)^{1.93} \qquad \text{(Eq.2)}$$

Pi is the monthly precipitation (mm) and P is the annual precipitation (mm). The thematic map of climatic aggressiveness for the studied area was obtained based on interpolation of R values using the Kriging in ArcGIS which was the most appropriate interpolation method for our context. According to the spatial distribution of R factor, the highest erosivity values were recorded in the upstream part of the watershed. The generated map shows that R values in the study area are ranging from 286 to 890 MJ mm/ha h year (Fig. 3).

- **Soil erodibility factor (K)**

The soil erodibility factor K characterizes the sensitivity or susceptibility of a soil to erosion expressed in t/h/ha. MJ.mm [19]. It is a function of soil texture and structure, permeability and organic matter content. Soil erodibility was determined by referring to the equation of Wischmeier and Smith (1978) [2] (Eq. 3):

$$K=2.1*M^{1,4}*10^{-6}*(12\text{-mo})+0{,}0325*(S-2)+0{,}025*(C-3) \qquad \text{(Eq.3)}$$

K is the soil erodibility factor (t.h/MJ.mm); mo is the percentage of organic matter; M = (% fine sand + % silt) × (100 - % clay) and S and C are respectively the soil structure and permeability codes. This factor was determined for each soil unit of the watershed based on Cormary and Masson (1964) [23] study in Tunisia.

- **Topographic factor (LS)**

The topographic factor (LS) has a significant influence on soil erosion [24], it is a combination of the slope length factor (L in m) and slope inclination (S in %) which are estimated from the Digital Elevation Model (DEM) of the study area at a resolution of 30 meters. The formula proposed by Wischmeier and Smith (1978) [2] was used to calculate this factor from a GIS processing of the DEM (Eq. 4):

$$LS=\left(\frac{\lambda}{22.13}\right)^{m}*\left(0{,}065+0{,}045*S+0{,}0065*S^2\right) \qquad \text{(Eq4)}$$

λ: length of slope; S: slope inclination (%); m: exponent that depends on the degree of slope of the land, m = 0.5 when the slope < 10%

- **Land cover factor (C)**

The land cover determines the degree of soil protection against climatic aggressivity. It improves infiltration by maintaining good soil porosity and dissipates the energy of raindrops. The Land cover factor (C) is assigned to each type of land use, it varies from 0.001 under dense forest to 1 on bare soil. In this study, the values of the C factor were determined according to the researches done in Tunisia by Collinet et al. (2001) [25] in a similar agro-climatic context.

- **Anti-erosive practices factor (P)**

This factor expresses the impact of agricultural practices and anti-erosion management on soil protection, it varies from 0.1 for a low slope and very well managed soil to 1 for unmanaged soils. In the area studied, the existing managements are essentially bench terraces, stone lines and dry-stone sills.

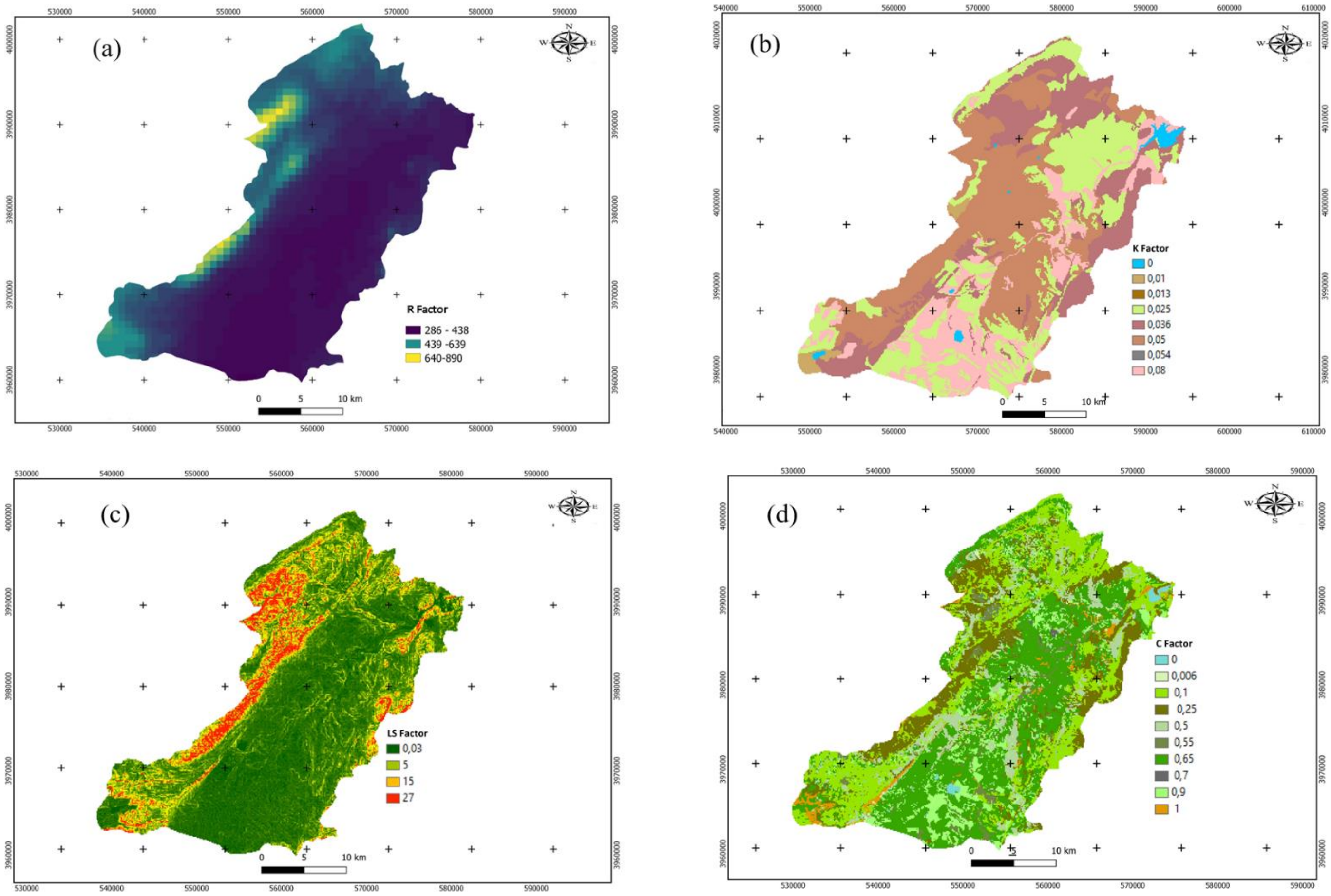

Fig. 3. Areal Distribution of Rainfall erosivity factor (a), Erodibility factor (b), Topographic factor (c) and Land cover factor (d)

2.2.2 MEDALUS APPROCH

The MEDALUS approach was adopted to evaluate the sensitivity of the upstream of Nebhana watershed to water erosion. This method is based on the calculation of the Desertification Sensitivity Index (DSI) which results from the combination of the Climate Quality Index (CQI), the Soil Quality Index (SQI), the Vegetation Quality Index (VQI) and the Land Use Quality Index (LQI):

$$\mathrm{DSI}=(\mathrm{CQI}\times\mathrm{SQI}\times\mathrm{VQI}\times\mathrm{LQI})^{1/4} \qquad \text{(Eq. 5)}$$

2.2.2.1 CLIMATE QUALITY INDEX (CQI)

This index was calculated based on rainfall, aridity index and orientation, which have a great influence on water availability for plants. In this case study, due to lack of accurate data, the climate quality index was calculated from the bioclimatic stage of the area (BS) and the rainfall aggressivity (RA) according to Eq. 6:

$$\mathrm{CQI}=(\mathrm{BS}*\mathrm{RA})^{1/2} \qquad \text{(Eq.6)}$$

RA is calculated using Eq.7, where IF is the Fournier's index and RCI is the rainfall concentration index:

$$\mathrm{RA}=(\mathrm{IF}*\mathrm{RCI})^{1/2} \qquad \text{(Eq.7)}$$

2.2.2.2 SOIL QUALITY INDEX (SQI)

The soil quality index was evaluated based on four measurable parameters that have a strong influence on the sensitivity to erosion: the bedrock (B), the soil texture (T), the slope (S) and the soil depth (D). The soil quality index (SQI) is given by the following expression (Eq.8):

$$\text{SQI} = (B*T*S*D)^{1/4} \qquad \text{(Eq.8)}$$

2.2.2.3 VEGETATION QUALITY INDEX (VQI)

he vegetation quality index of the studied watershed was elaborated based on the vegetation cover score map and the erosion protection score map.

2.2.2.4 MANAGEMENT QUALITY INDEX (MQI)

The management quality index (MQI) was evaluated using the score assigned to the management status of agricultural land. It is a function of the intensity of land use (ILU) and the management policies (PA) engaged to control the erosion phenomenon.

$$\text{SQI} = (B*T*S*D)^{1/4} \qquad \text{(Eq.9)}$$

In fact, well maintained lands are considered as well protected against erosion, however, area with degraded land management practices is considered as moderately to poorly protected. Thus, the areas threatened by erosion and not yet managed are considered very sensitive to erosion and need to be spatially for future interventions.

Pour déterminer ces zones on tient compte des zones hors aménagement qui sont constituées essentiellement par les plaines, les forêts, les broussailles, les terres incultes, les plans d'eau (sebkha, barrage) et les zones urbaines.

3 RÉSULTS AND DISCUSSION

3.1 SOIL LOSS ESTIMATION BEFORE WATERSHED MANAGEMENT

3.1.1 SOIL LOSS ESTIMATION USING RUSLE

The quantitative evaluation of erosive risk in the upstream watershed of Nebhana dam was carried out using the RUSLE method which is based on the integration of five factors (R, K, LS, C and P). Each of the RUSLE factors with associated attribute data is digitally encoded in a GIS database to eventually produce five thematic layers, that were superimposed to ensure the spatial distribution of soil loss map. The impact of land management practices on water erosion was performed by generating an erosive risk map without considering the anti-erosive practices factor by assigning to P a value of 1 (Fig. 4).

The obtained results showed that average soil loss rate is about 10.94 t/ha/yr, 65.6% of the basin area is affected by an erosion rate less than 8 t/ha/yr, while 28.4% of the area revealed a high sensitivity to erosion (>25 t/ha/yr). Area where specific erosion is higher than 40 t/ha/yr presented about 6%. The different erosive risk classes and sensitivity index adopted in this study are presented in Table 1.

The comparison of soil loss estimated by RUSLE method (10.94 t/ha/yr) and soil loss calculated based on bathymetric measurements at Nebhana dam (11.25 t/ha/yr) [5, 26], showed that values are very close, and RUSLE reproduced properly the water erosion of the watershed.

Tableau 1. Erosive risk classes and sensitivity index adopted by RUSLE and MEDALUS

RUSLE	Erosion risk classes	MEDALUS	
Soil loss (t/ha/yr)		Classes	SI
0-5	Very low	1	1 <ISE< 1,61
5-8	Low	2	1,61 <ISE< 1,65
8-25	Medium	3	1,65 <ISE <1,69

25-40	High	4	1,69 <ISE <1,72
>40	Very high	5	1,72<ISE < 2

SIE: Sensitivity Index to Erosion

At the sub-basin level, the spatial distribution of soil loss revealed that subbasin 2, occupying 134 km^{2,} about 15.6% of the total area of the watershed, is the most vulnerable to erosion. It was found that 61% of its area is subject to an erosive risk exceeding the tolerable limit (>8 t/ha/yr) of which 16.3% suffered from a very high erosion (>40 t/ha/yr). The remaining area (39%) is affected by low and very low erosion. For SBV 7 (51.5km^2), results showed that it is the most protected sub-basin with about 80% of its area is subject to erosion less than or equal to 8 t/ha/year, while 1% is under strong erosive risk and only 0.6% are affected by erosion greater than 40 t/ha/r (Fig. 4).

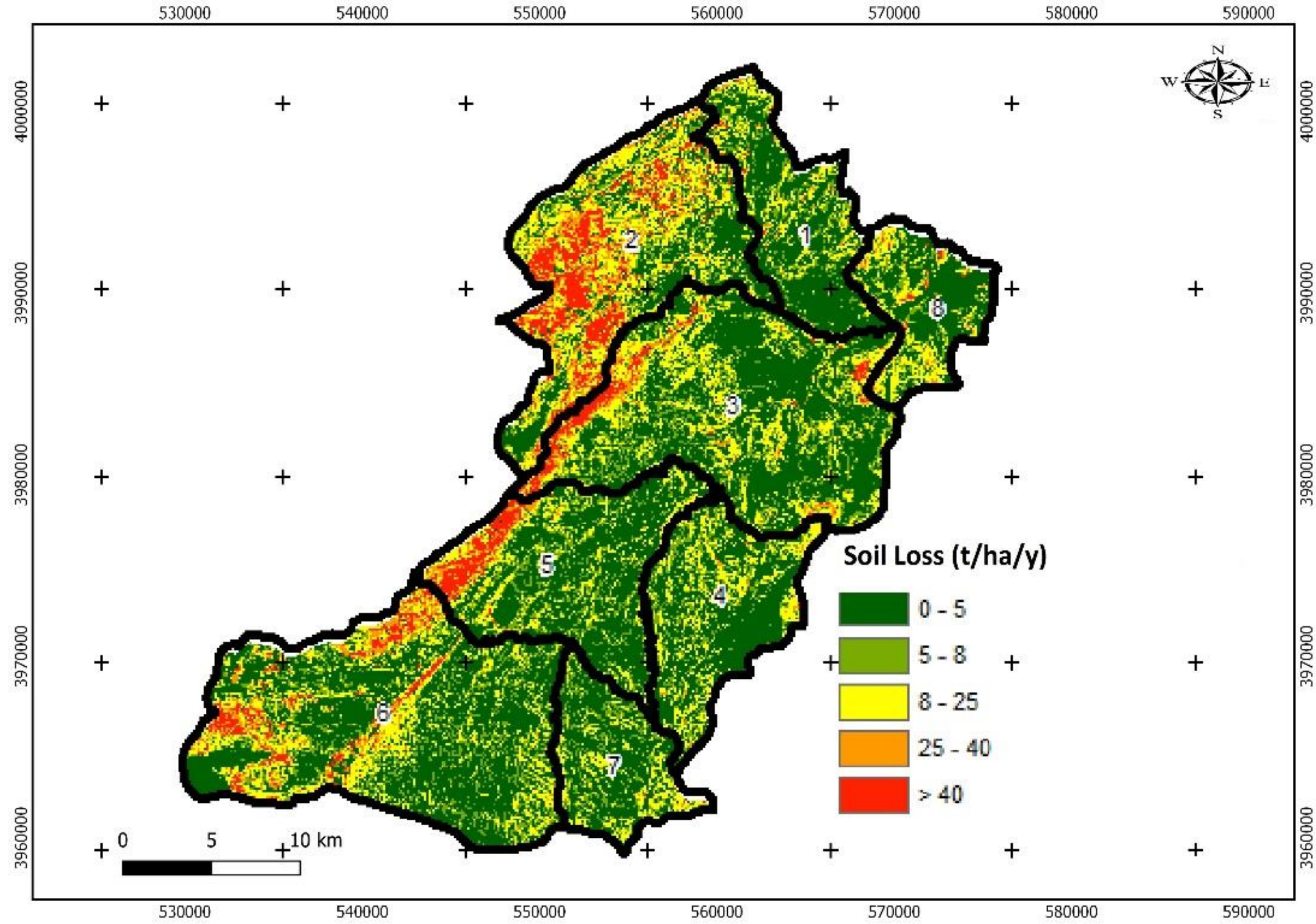

Fig. 4. Spatial distribution of soil loss in the Nebhana watershed before management using RUSLE

3.1.2 SOIL LOSS ESTIMATION USING MEDALUS

According to MEDALUS approach, the erosion sensitivity map is obtained by crossing the four indices related to soil (SQI), vegetation (VQI), climate (CQI) and management (MQI) using QGIS software.

The impact of land managements on water erosion was assessed by estimating the sensitivity indexes in the unmanaged Nebahana watershed. Based on founded results, 30.6% of the total area are suffering from a very high erosive risk and are the most prioritized for management interventions. These areas corresponded generally to sloping lands and loose soils with intensive surface stripping and generalized and hierarchical gullying.

The rest of the basin consisted of areas slightly affected by erosion and which are generally cultivated lands with gentle slope and very limited surface gullying. As shown in Fig. 5, the most sensitive subbasins are SBV 2 followed by SBV 3, with high sensitivity indexes.

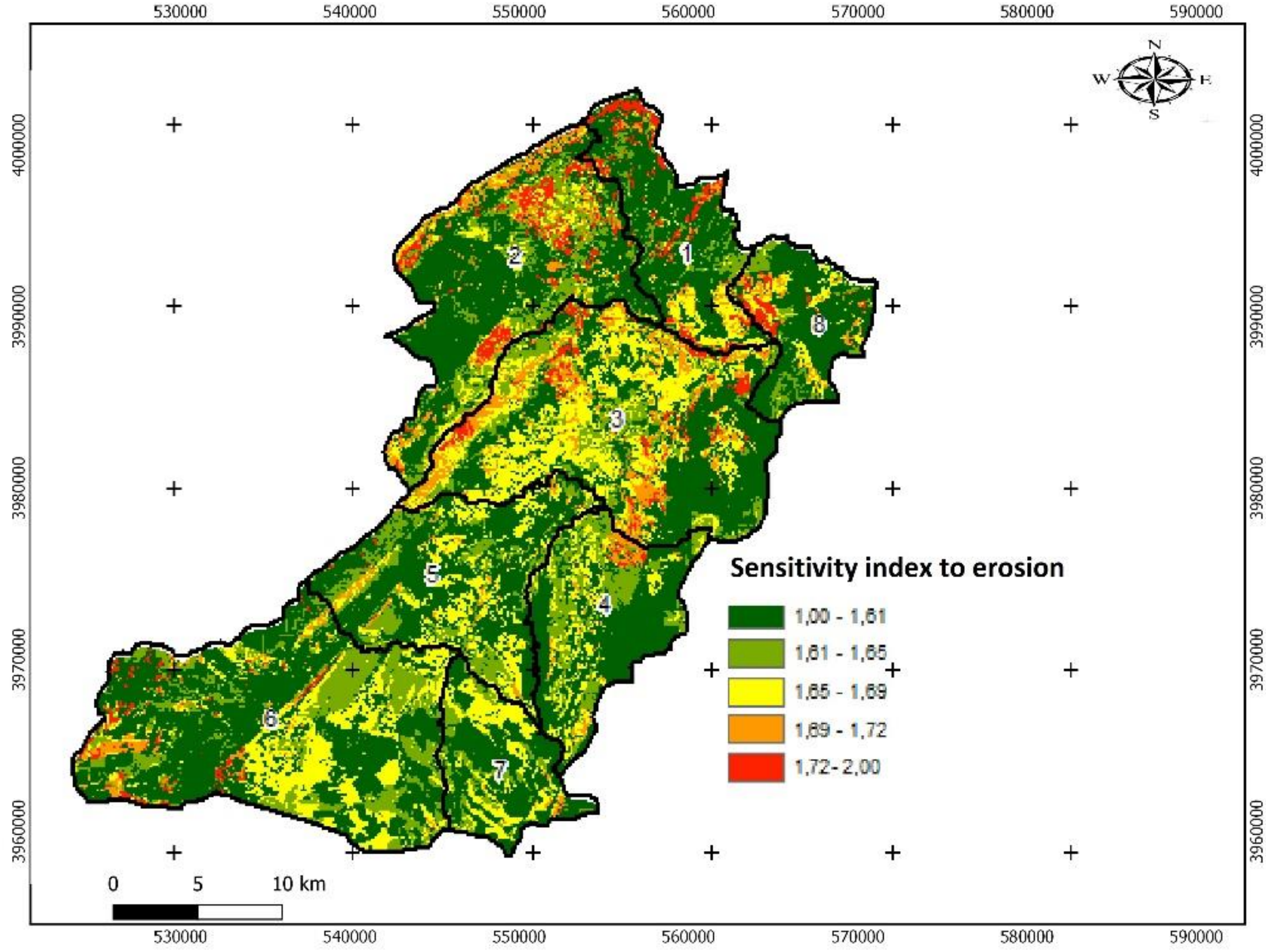

Fig. 5. Spatial distribution of sensitivity index in the Nebhana watershed before management using MEDALUS

3.2 SOIL LOSS ESTIMATION AFTER WATERSHED MANAGEMENT

The existing managements in Nebhana watershed have been inventoried from data available in the Water and Soil Conservation Directorate, from Google Earth images and from field surveys. According to these data, the implemented conservation measures corresponded mainly to manual or mechanical bench terraces that extend over an area exceeding 28 km^{2,} stone lines, dry stone sills as well as rainwater spreading and recharge structures.

3.2.1 SOIL LOSS ESTIMATION USING RUSLE

The implementation of anti-erosion managements in the Nebhana watershed resulted in a reduction of average soil loss estimated by RUSLE to 7.64 t/ha/yr. Each erosion risk class has undergone a change in the occupied area as presented in Fig. 6. We note that 71.7% of the total area of the watershed is affected by erosion less than or equal to 8 t/ha/yr, while 23.1% of the area reveals a high erosion risk (>25 t/ha/year), the rest of the watershed where the specific erosion is greater than 40 t/ha/yr presents only 5.2%.

3.2.2 SOIL LOSS ESTIMATION USING MEDALUS

The elaborated erosion sensitivity index map for the managed watershed showed that area occupied by each sensitivity index class has also changed for MEDALUS (Fig. 7). In fact, 20% of the total area suffered from high and very high erosion and are considered as priority areas for management.

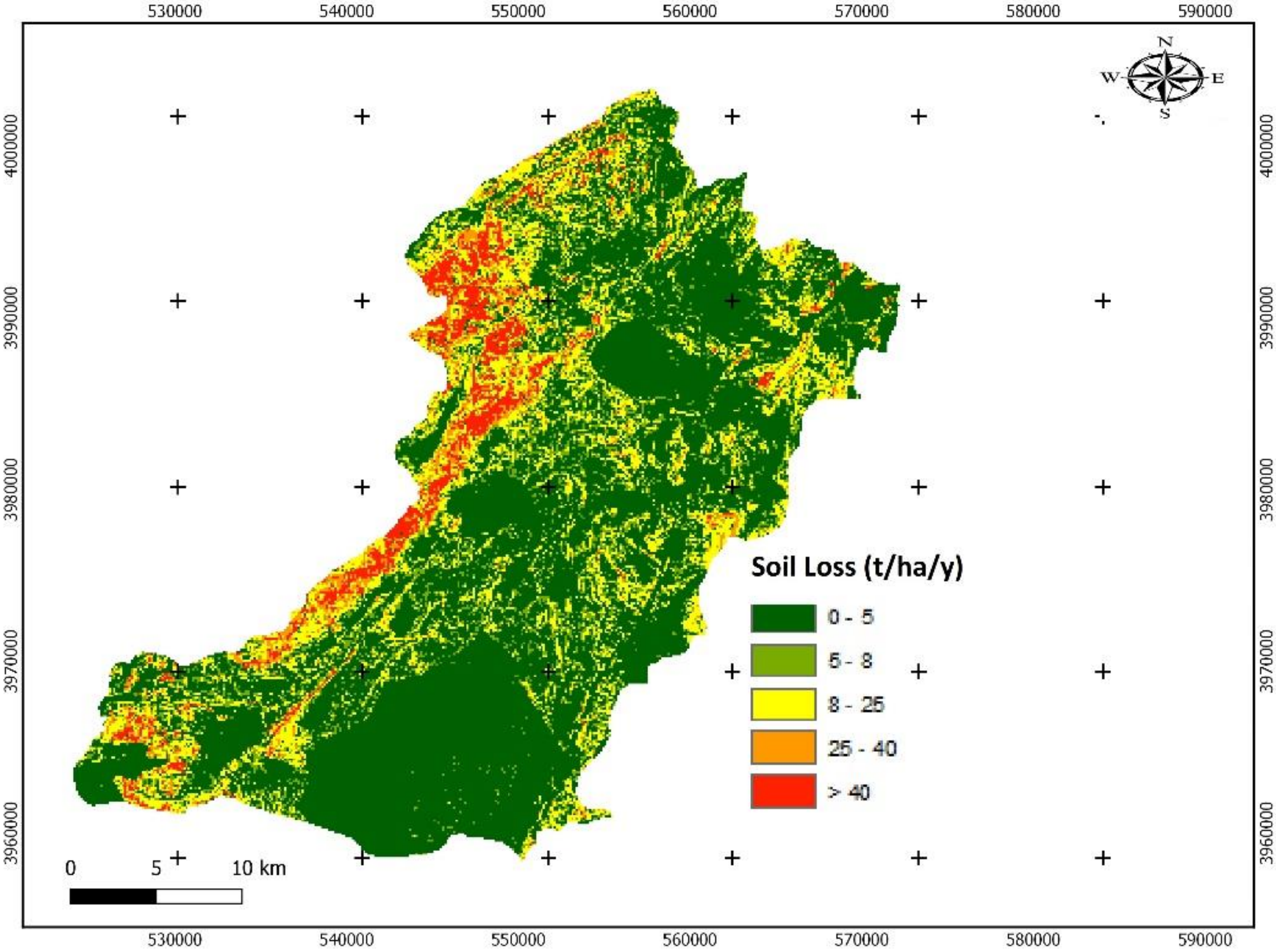

Fig. 6. Spatial distribution of soil loss in the Nebhana watershed after management using RUSLE

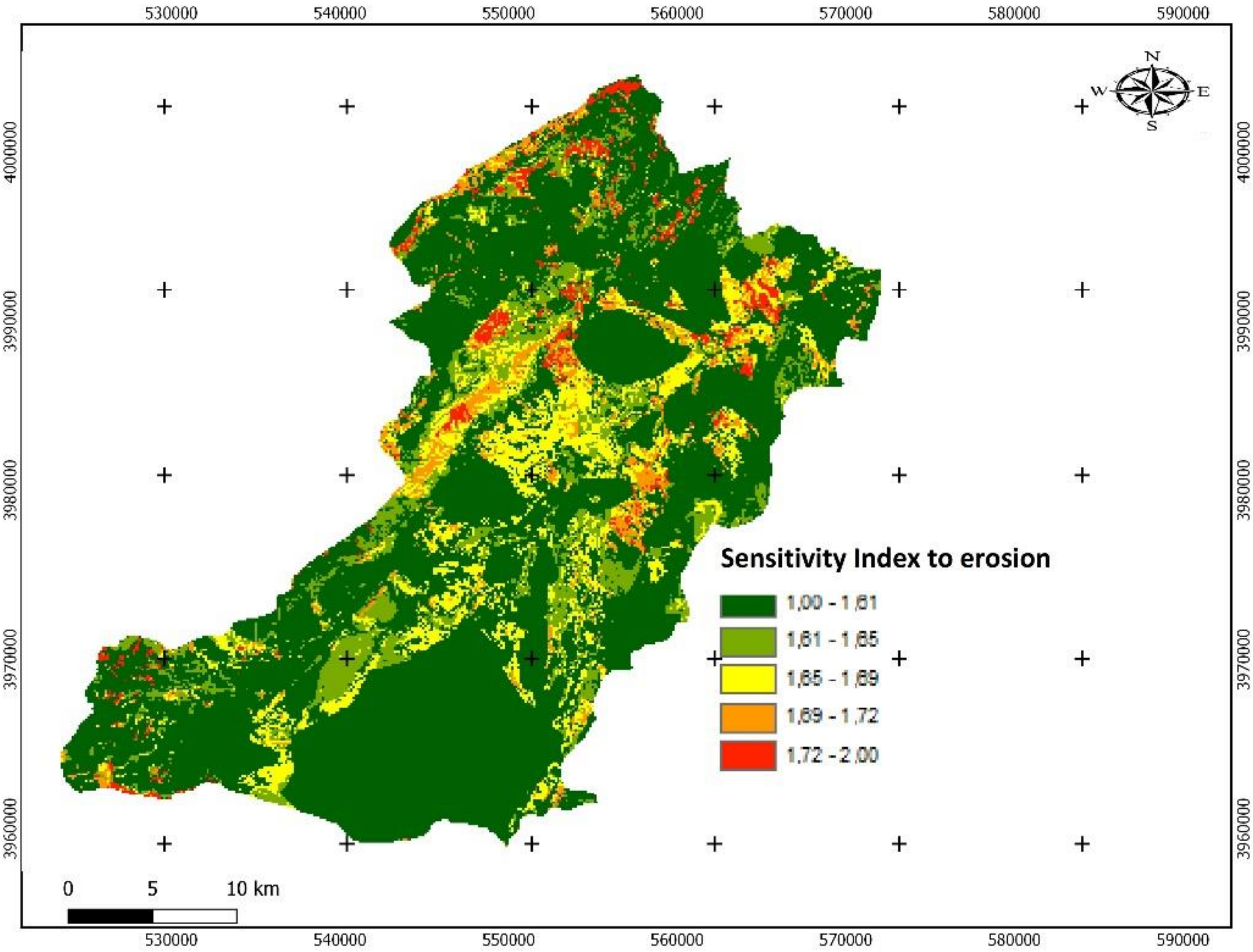

Fig. 7. Spatial distribution of sensitivity index in the Nebhana watershed after management using MEDALUS

3.3 COMPARATIVE ANALYSIS OF RESULTS

The comparative analysis of obtained results from RUSLE and MEDALUS is based on the comparison of areas affected by each erosion risk class. Results showed that there is a significant correspondence between the two models before and after watershed management. The most vulnerable areas requiring management intervention are practically the same for RUSLE and MEDALUS. Thus, the empirical model RUSLE is verified by MEDALUS approach.

Fig. 8. showed that erosion risk classes estimated with these two methods matched well. In fact, for both RUSLE and MEDALUS, the very low erosion class is dominant. Based on RUSLE model, this class represented 50,3% and 60.2% of the total area, respectively before and after watershed management. According to MEDALUS, the very low erosion class is about 51,6% and 67.5% of the total area, respectively before and after the watershed management.

High and very high erosion risks before watershed management occupied very close areas for the two adopted models, about 11.4% for RUSLE and 11.2% for MEDALUS. After watershed management, this class of erosion was reduced, and results are also in agreement with 9.9% for RUSLE and 8.4% for MEDALUS. Furthermore, the remaining risk classes estimated by RUSLE and by MEDALUS occupied also nearby areas.

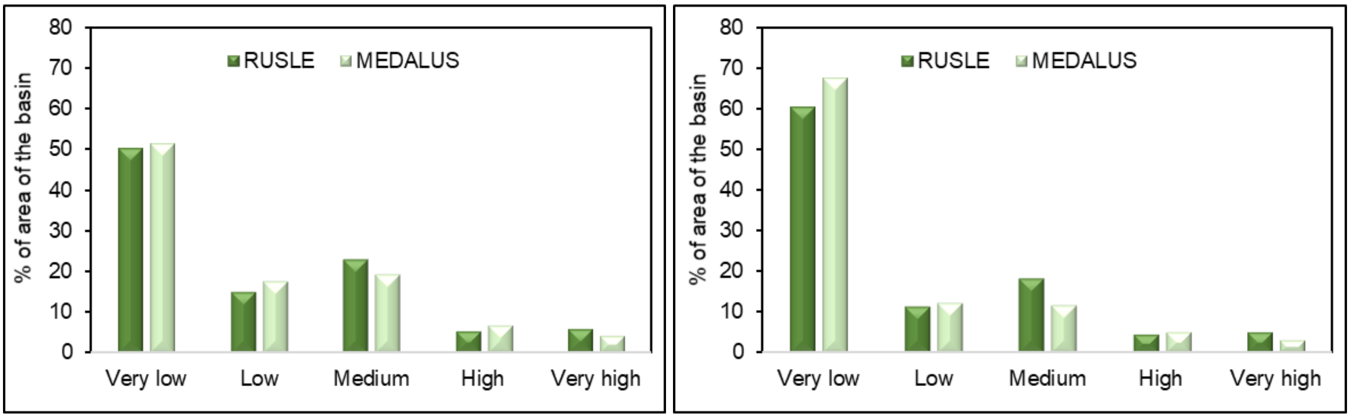

Fig. 8. Distribution of soil loss classes before (on the left) and after watershed management (on the right)

3.4 VALIDATION

The Effective validation of obtained results requires some similarity between the visible effect of erosion in the field and the estimation of RUSLE and MEDALUS models. Thus, a multitude of randomly distributed points were marked on the generated soil loss map. It was found that, according to RUSLE and MEDALUS, the most sensitive areas are mainly located in the upstream part of the basin where slopes are very steep, lands are rugged, scrubland are mostly degraded, and human activities are intensive, these areas are suffering from a generalized and very hierarchical gullying. Points on the map with low to very low erosion corresponded to protected lands or no sensitive lands to erosive processes.

Validation process revealed that there is a good agreement between simulated results and ground truth. The bathymetric measurements consolidates this agreement and showed that the quantification and the spatial distribution of soil loss in the upstream watershed of Nebhana dam using RUSLE and MEDALUS presented a satisfactory reliability to identify the most vulnerable areas and to deal with data scarcity in Mediterranean watersheds

4 CONCLUSION

The assessment of water erosion in the upstream watershed of Nebhana Dam using RUSLE and MEDALUS models coupled with QGIS software, was based on the integration of several factors such as topography, land use, pedology, lithology and climate. These empirical models, which do not require many input parameters, are increasingly used for land management planning of semi-arid catchments. These models allow the quantification of soil loss and the identification of most vulnerable areas to erosion, which helps decision makers to better plan their strategies and to install the most appropriate soil and water conservation measures.

The application of RUSLE model showed its ability to reproduce well the average annual soil loss rate which is about 10.94 t/ha/yr against a value of 11.25 t/ha/yr from the available bathymetric measurements in the Nebhana reservoir. Before the watershed management, 34% of the total area suffered from erosion exceeding the tolerable limit (8 t/ha/year). After the installation of land management practices, the area concerned is reduced to 28.3%, a value that is still not satisfactory and it is wise to propose the necessary interventions to reduce high erosion by acting on the anti-erosion practices factor. The most affected areas are concentrated in the upstream part of the basin which correspond to bare soils with steep slopes. According to MEDALUS approach, 30% and 22% of the watershed had high sensitivity index before and after management respectively. Thus, these areas are the most sensitives and the most prioritized for management intervention. The comparison of these two models showed that RUSLE is verified by MEDALUS.

Indeed, according to RUSLE, 51% of the area are requiring land management practices measures, based on MEDALUS, this part of the basin requires also management. To contribute to the protection of Nebhana watershed against water erosion, land management plan was proposed with the objective of reducing upstream runoff, protecting the Nebhana dam, extending the life of the reservoir, and improving yields.

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