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B – data collection
C – statistical analysis
D – data interpretation
E – manuscript preparation
F – literature search

Predicting water erosion in arid lands using the GIS-based RUSLE model: A case study of Bedour catchment, central Tunisia

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Abstract

This study was conducted with a view to quantifying soil erosion in arid lands of Tunisia. To do this, we have opted to use the RUSLE model based on geographic information systems. By collecting data on rainfall, soils, vegetation, slopes and conservation practices separately as a layer and determining the pixel values for each of these factors, a quantified assessment of erosion in the basin is obtained. The data superposition and computing, following the model equations and protocol, allowed us to know the spatialized water erosion values at the pixel level. For the whole catchment, the study showed values oscillating between 0 and 163 $\mathrm{Mg \cdot ha^{-1} \cdot year^{-1}}$ with an average annual rate of 3 $\mathrm{Mg \cdot ha^{-1} \cdot year^{-1}}$. With such a low R (rainfall erosivity) factor (between 21.43 and 21.88 $\mathrm{MJ \cdot mm \cdot ha^{-1} \cdot h^{-1} \cdot year^{-1}}$) itself related to low monthly and annual rainfall amounts, the region experiences locally very high annual erosion rates. Soil protection through conservation practices has saved the basin from even higher erosion. While plains cultivated and equipped with contour benches often suffer from low rates of erosion (less than 2 $\mathrm{Mg \cdot ha^{-1} \cdot year^{-1}}$), unused slopes are neglected without protection, resulting in significantly high rates of erosion.

Key words: *arid lands, GIS, RUSLE, Tunisia, water erosion*

INTRODUCTION

Soil erosion is a serious problem that constrains planners in all countries. The loss of arable and even fallow land is often a loss of richness and resources for the people who live there. It is for this reason that the concern to quantify soil erosion is still topical among decision-makers when choosing conservation techniques. Among the first models to fill this gap is the USLE (universal soil loss equation) model introduced by the U.S. Department of Agriculture (USDA) [WISCHMEIER, SMITH 1965]. Later it was revised [RENARD *et al.* 1997] and renamed to RUSLE (revised universal soil loss equation). This model has benefited from constant improvements by the initiators but also by the users who are always looking for more precision and realism in the calculation of the various factors. Thus, the rainfall erosivity factor (R) for rain aggressiveness has seen a multiplication of formulas designed to replace the initial formula, which is difficult to apply under all conditions. Similarly, the topographic factor (LS) has seen improvements to account for other water behaviour outside of sheet erosion. Tunisia is known as a land of water erosion and attempts to quantify it have not ceased multiplying [ANDERSSON 2010; AVENARD 1965; CORMARY, MASSON 1964; JEBARI 2008; JEBARI *et al.* 2009; 2010; MASSON 1971; ZANTE *et al.* 2003]. If the northern regions of Tunisia have benefited from some studies using the RUSLE model, the arid regions have not known such studies to our knowledge despite the real advantages of having quantified studies available. The arid regions, in spite of the weakness, the short and violent character of their precipitations, have very remarkable erosion phases as the field inspection shows. This has led us to attempt to quantify soil erosion in these areas using the RUSLE model based on GIS.

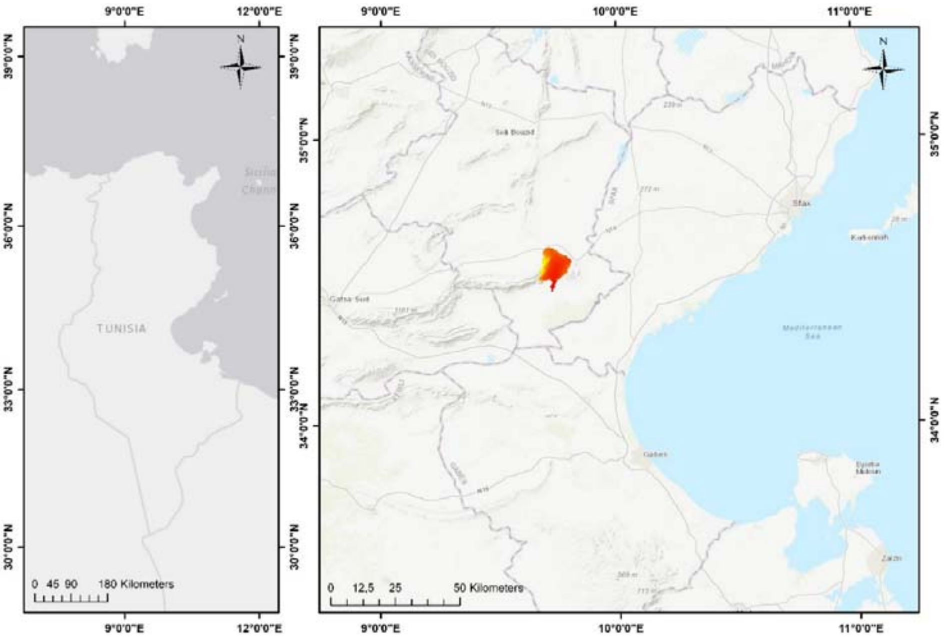

Fig. 1. Location of the study area; source: own elaboration

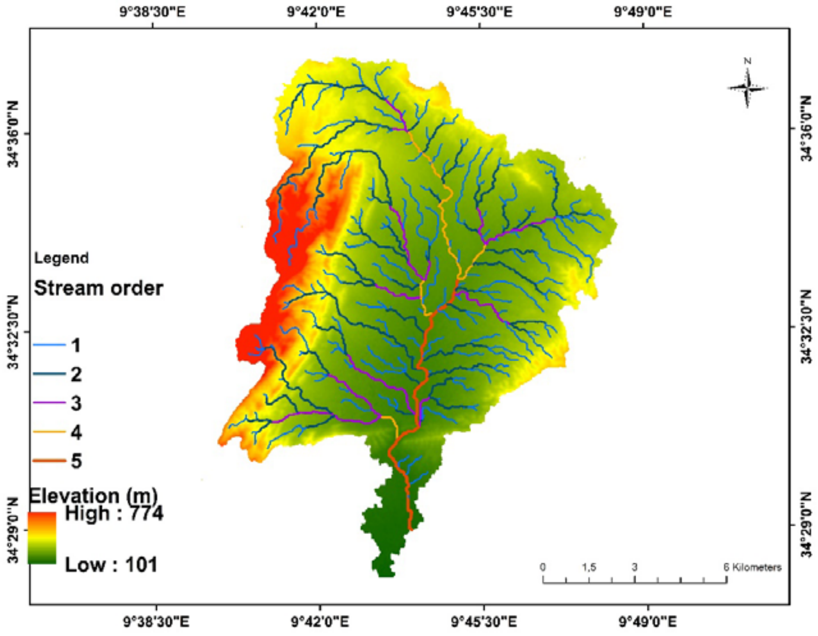

Fig. 2. Digital elevation model and streams of study area; source: own elaboration

STUDY AREA

The Bedour catchment is located in central Tunisia between 9°38'E to 9°49'E and 34°36'N to 34°29'N (Fig. 1, Fig. 2). It corresponds to a depression surrounded by mountainous reliefs (Fig. 3): the Bouhedma-Boudouaou chain to the West, the Chaabita-Chetatil jebels to the South, the Jebel Njilet to the South–West and by Kef Nsour to the North. The altitudes are between 130 and 160 m in most of the central plain and attain 774 m in the relief surrounding the catchment. The outcropping terrains are Cretaceous limestone and marl in the small relief of the North of the basin. In the West, the relief of Boudouaou is composed of Cretaceous limestone, marl and clay, tertiary sandstone and

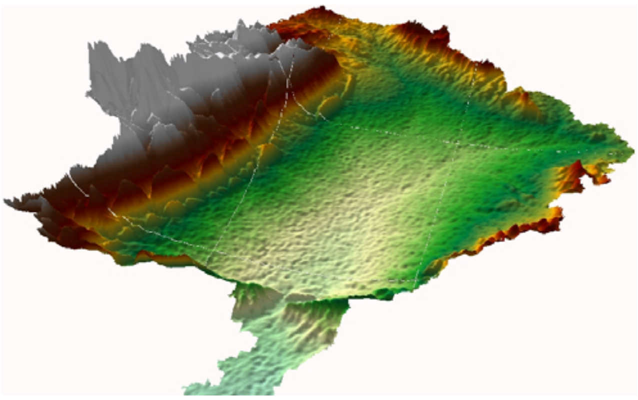

Fig. 3. 3D map of study area; source: own elaboration

Neogene conglomerates. The small heights of the southwest are composed mainly of gypsum and clay (Triassic). Their piedmonts are covered with gypsum crusts. The North-West and West piedmonts are occupied by quaternary calcareous crusts. The Bedour catchment belongs to the cool lower arid climate stage with the exception of the western mountainous part which belongs to the temperate upper arid stage. The average rainfall of the stations surrounding the catchment is 193 mm·year^{-1}. The vegetation in the watershed is very weak and sparse. It is composed by xerophytic species largely degraded by overgrazing.

MATERIALS AND METHODS

The RUSLE soil erosion quantification and assessment model is based on 5 independent factors whose calculation in simple multiplication allows to obtain the total annual soil loss rate (A): Fig. 4:

$$A = R \cdot K \cdot C \cdot P \cdot LS \tag{1}$$

Where: A = annual rate of soil loss (Mg·ha^{-1}·year^{-1}), R = rainfall erosivity factor, K = soil erodibility factor, C = crop cover factor, P = practice support factor, LS = topography factor.

Methodology of flow chart is shown in the Figure 4.

The rainfall erosivity factor (*R*): this factor means the kinetic energy delivered during rainy periods and volume of water mobilized for runoff. The higher is rainstorm intensity, the greater is the erosion potential. The R factor initially presented by WISCHMEIER and SMITH [1978] is the product of the kinetic energy of a storm and its maximum intensity during an interval of 30 minutes:

$$EI_{30} = Ec \cdot I_{30} \tag{2}$$

Where: EI_{30} = the erosivity index for an event (MJ·mm·ha^{-1}·h^{-1}·year^{-1}), Ec = the total rain kinetic energy (MJ·h^{-1}), I_{30} = the maximum rain intensity in 30 min (mm·h^{-1}).

However, the conditions required by this equation are rarely available and need high-resolution data. This is why and since the constraints posed by this equation many RUSLE users have proposed alternative formulas. Some of them are founded on the annual rainfall average. Others, however, are based on the monthly average. After tests of several of these formulas, we opted for use of the Fournier index modified by ARNOLDUS [1980] (Modified Fournier Index – *MFI*) (Eq. 3). This choice was made to prevent values overestimation and to allow potential comparisons.

$$R = \sum_{i=1}^{12} \frac{(Pi)^2}{P} \tag{3}$$

Where: Pi = the monthly rainfall average, P = the annual average.

Soil erodibility factor (*K*): K factor means the erodibility of soils in a particular region. The K factor defined by WISCHMEIER and SMITH [1978] is based on soil texture, organic matter quantity and porosity:

$$K = A \cdot B \cdot C \cdot D \cdot 0.1317 \tag{4}$$

Where:

$$A = [0.2 \cdot 0.3 \exp(0.0256\, sand\,(1 - silt/100))]$$

$$B = \left(\frac{silt}{clay + silt}\right)^{0.2}$$

$$C = 1.0 - \frac{0.25\, clay}{clay + \exp(3.72 - 2.95 clay)}$$

$$D = 1.0 - \frac{0.70\, sand1}{sand1 + \exp(-5.41 + 22.9\, sand1)}$$

In this study, we used the soil map provided by the national "Carte Agricole" project of the Ministry of Agriculture [2001]. After extracting soil map polygons, we assigned the values of K from literature in the region.

Crop management factor (*C*): C factor means the ability of vegetation cover to reduce soil erosion. It ranges from 0 (total protection) to 1 (no protection). Values are assigned from RUSLE tables or other based on plots experimental studies. In this study, we performed a supervised classification of the 10 m resolution Sentinel 2 image (downloadable from Copernicus Open Access Hub [undated]) to extract a land use map. C values were then assigned according to the tables used in regional and international studies.

Conservation practice factor (*P*): P factor means the role of conservation practices in reducing soil erosion. It vary from 0 (total protection) to 1 (no protection). In this

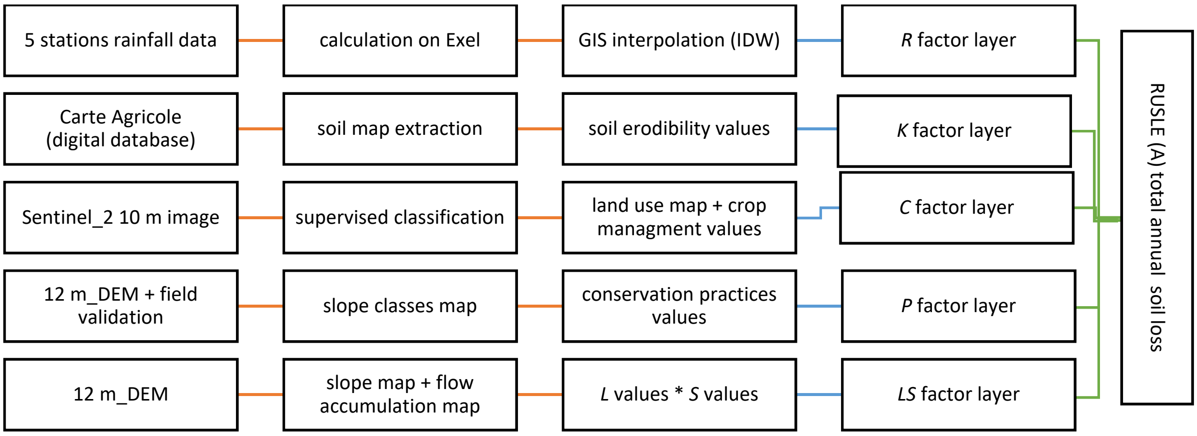

Fig. 4. Methodology flow chart; L = slope length factor, S = steepness factor, R = rainfall erosivity factor, K = soil erodibility factor, C = crop management factor, P = conservation practice factor, LS = slope length and steepness factor; source: own elaboration

study, we proceeded to generate the percentage slope map on which we assigned the values, by slope class, of the conservation practices most used in the study area, namely the contour benches according to available table.

Slop length and steepness factor (LS): LS factor means the role of the slope length (L) and its steepness (S) in soil erosion. To obtain the LS value map we applied the following equations (McCool *et al.* [1987]; Desmet and Govers [1996]):

$$LS = L \cdot S \tag{5}$$

Where:

$$L = \left(\frac{\lambda}{22.13}\right)^{m}$$

$$m = \frac{F}{1+F} \qquad \text{(Mc Cool } et\ al. \text{ [1987])}$$

$$F = \frac{\sin\beta\ 0.01745/0.0896}{3\left(\frac{\sin\beta}{0.01745}\right)^{0.8} + 0.56}$$

m = index of slope's length factor

$$L_{(i,j)} = \frac{1\left[A_{(i,j)}+D^2\right]^{M+1} - A(i,j)^{M+1})}{x^M\ D^{M+2}(22.13)^M} \qquad \text{(Desmet, Govers [1996])}$$

Where: β = slope layer in arcgis (°), A = flow accumulation layer (arcgis), D = grid cell size (m), x = coefficient that corrects the length of flow way through a raster cell.

S factor (McCool *et al.* [1987])

When $\tan\beta_{(i,j)} < 0.09 \quad S_{(i,j)} = 10.8 \sin\beta_{(i,j)} + 0.03$

When $\tan\beta_{(i,j)} \geq 0.09 \quad S_{(i,j)} = 16.8 \sin\beta_{(i,j)} - 0.5$

At the end of this part, we would like to notice that working with a 12 m DEM and 10 m satellite image seems to be optimal for this kind of work. Larger than this resolution, processing data especially merging polygons would require a lot of memory resources and computing capacity.

RESULTS AND DISCUSSION

***R* factor**: the data used in this study are records of 10 years from 2002 to 2011. This choice was determined by the numerous gaps in rainfall data at the different stations. The only years where there are no gaps in all stations are those selected for this study (Tab. 1). The R factor calculated for the 5 rain weather stations neighbouring the Bedour watershed shows, after extraction, a gradient of values evolving between 21.43 and 21.88 MJ·mm·ha^{-1}·h^{-1}·year^{-1} from East to West of the basin (Tab. 1, Fig. 5).

Table 1. Annual average rainfall (2002–2011) and rainfall erosivity factor (R) factor for weather stations in the study area

Station	Longitude E	Latitude N	Annual average rainfall	R factor
Bir Ali	10.095789	34.740684	186.68	20.61
Skhira	10.069900	34.299882	187.87	22.26
Mezzouna	9.842230	34.580594	182.79	21.45
Meknassy	9.602237	34.604781	197.52	22.29
Bouzayane	9.427244	34.573043	210.85	27.23

Source: rainfall data: Direction des eaux... [2018].

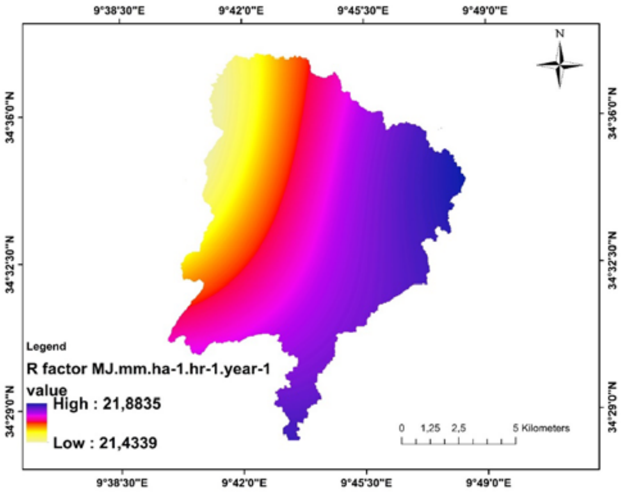

Fig. 5. R factor; source: own elaboration

***K* factor**: the K factor oscillates in the Bedour watershed between 0.044 and 0.06. The majority (22.58%) of the land in the catchment is mineral soils (Table 2). Then come the calcareous soils and the rendzines with respectively 23.7 and 23.37%. Afterwards we find the less evoluated soils with 17.7% and the complex soils with 12.55% (Fig. 6).

Table 2. Soil erodibility factor (K) values for different soil types

Soil	K factor value
Mineral soils$^{1)}$	0.060
Calcareous soils$^{1)}$	0.046
Rendzines$^{1)}$	0.055
Less evaluated soils$^{1)}$	0.044
Isohumic soils$^{1)}$	0.046
Complex$^{2)}$	0.050

Source: own elaboration based on literature: $^{1)}$ Ben Cheikha and Gueddari [2008], $^{2)}$ Andersson [2010].

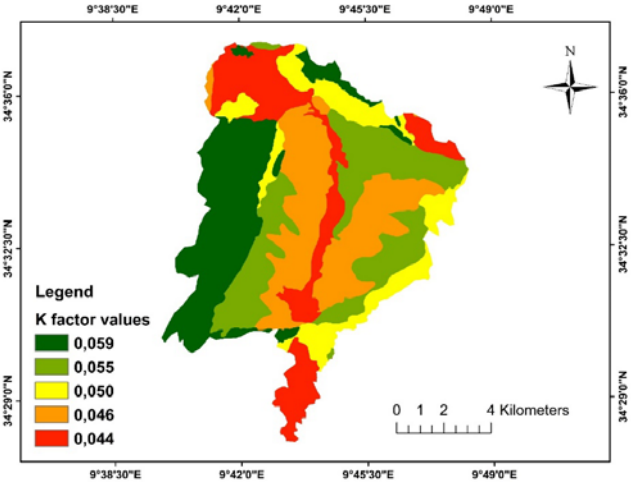

Fig. 6. K factor in the study area; source: own elaboration

***C* factor**: the C factor in the Bedour catchment shows three classes of values: bare land (C = 1) represents 34% of the watershed. The land covered by young olive trees and fruit trees, often spaced apart due to insufficient rainfall

(C = 0.9), occupies 45% of the total surface. Intensively cultivated plots (cereals, vegetables, drop by drop irrigation, legumes, etc.) or well-preserved tufts of natural vegetation (C: 0.4) cover 19% (Tab. 3, Fig. 7).

Table 3. Crop management values for different types plots

Plot type	*C* factor value
Bare soil	1.0
Young olive, fruit trees	0.9
Intensively cultivated plots (cereals, vegetables, legumes)	0.4

Source: MASSON [1971].

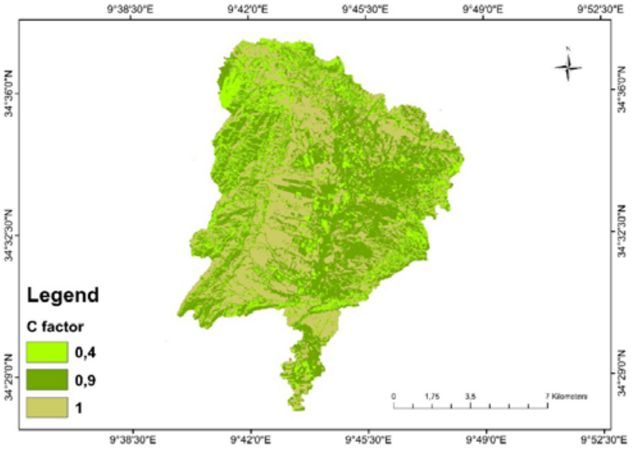

Fig. 7. *C* factor in the study area; source: own elaboration

***LS* factor**: the *LS* factor in the Bedour basin shows values between 0 and 155. Most of the land in the catchment (65%) is less than 1. 33% of the lands are between 1 and 5. Land with *LS* values above 5 represents only 1.44% (Fig. 8).

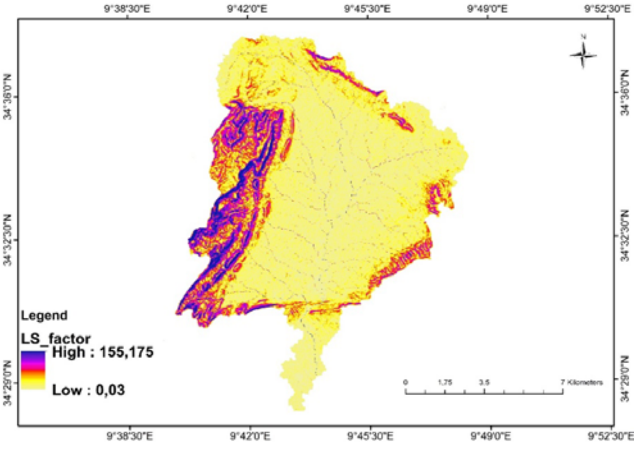

Fig. 8. *LS* factor in the study area; source: own elaboration

***P* factor**: In the Bedour watershed, the water and soil conservation practices used are essentially contour benches. The efficiency of this practice varies according to the slope value (Tab. 4). We applied the values cited in SHIN [1999] for contouring (Fig. 9).

The contour benches are completely useless on slopes higher than 26% (P = 1) which represent 12.48% of the basin. They become more efficacious as the slope weakens.

Table 4. *P* factor values for different slope classes acc. to SHIN [1999] and their percentage share in studied area

Slope classes	*P* factor (contouring)	Share (%)
0.0–7.0	0.55	49.00
7.0–11.3	0.60	18.96
11.3–17.6	0.80	11.15
17.6–26.8	0.90	8.42
>26.8	1.00	12.48

Source: own study.

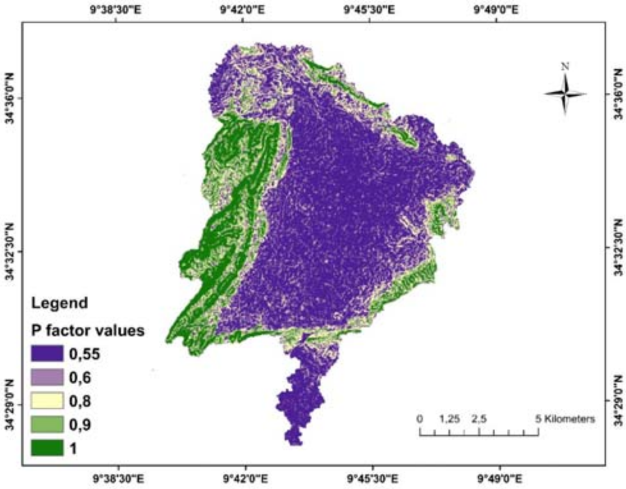

Fig. 9. *P* factor in the study area; source: own elaboration

The reliefs surrounding the Bedour catchment escape to any protection from erosion. Whereas the piedmonts with moderate slopes are weakly protected by the benches (0.6 to 0.8). These represent 30% of the watershed. The lands in the centre of the catchment (49%) have better protection (0.55).

RUSLE *A* factor (annual soil loss): The results of the application of the RUSLE erosion model in the Bedour Basin are significant. Indeed, the final factor varies between 0 and 163 $\mathrm{Mg \cdot ha^{-1} \cdot year^{-1}}$ with an annual rate of 3 $\mathrm{Mg \cdot ha^{-1} \cdot year^{-1}}$ (Fig. 10).

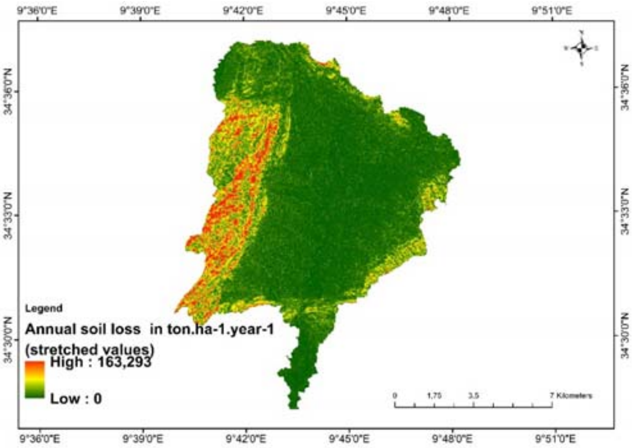

Fig. 10. Annual soil loss with stretched values in the study area; source: own elaboration

The distribution under usual classes of soil erosion of the factor A gives a predominance of erosion lower than 1 $\mathrm{Mg \cdot ha^{-1} \cdot year^{-1}}$, which concerns the major part of the basin (77%). Then comes the class 1–5 Mg·ha^{-1}·year^{-1} which characterizes 21% of the catchment and which corresponds approximately to the piedmonts of the reliefs and the moderate slopes (Tab. 5). The 5–15 Mg·ha^{-1}·year^{-1} class concerns 1% of the catchment and concerns steep slopes and highly erodible soils. Rates above 15 Mg·ha^{-1}·year^{-1} represent only 0.02% of the basin. This means that 98.77 of the land in the watershed is less than 5 Mg·ha^{-1}·year^{-1}.

Table 5. Soil annual loss under standard classes in the study area

Class	ha	%
<1	8 430	77.63
1–5	2 295	21.13
5–15	128	1.17
15–25	3.46	0.03
15–50	1.46	0.01
>50	0.46	0.004

Source: own elaboration.

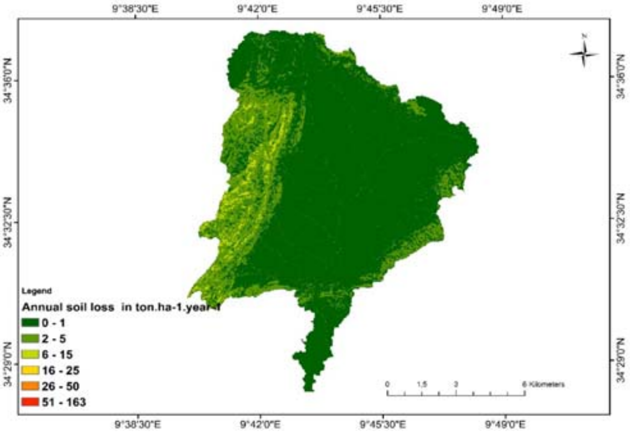

Fig. 11. Annual soil loss under standard classes in the study area; source: own elaboration

While the commonly used classification shows that most of the land is in the low erosion class, a second classification according to the MASSON [1971] classification for the erosion conditions of semi-arid lands in Tunisia has been realized to examine the details of these percentages (Fig. 12, Tab. 6).

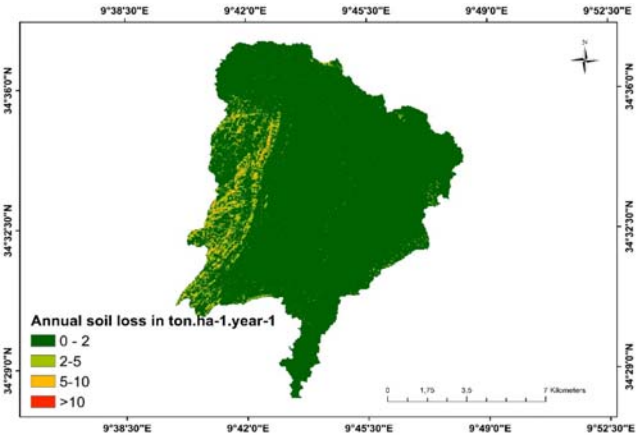

Fig. 12. Annual soil loss under MASSON [1971] classes for Tunisian semi-arid lands; source: own elaboration

Table 6. Annual soil loss under MASSON [1971] classes for Tunisian semi-arid lands

Class	ha	%
0–2	1 0158	93.54
2–5	567	5.22
5–10	122	1.12
>10	11.28	0.10

Source: own elaboration based on MASSON [1971].

Thus, 10 158 ha of the catchment's land (93.54%) have been affected by erosion in the range of 0 to 2 Mg·ha^{-1}·year^{-1}, 567 ha or 5.22% of the total land suffers from erosion rates between 2 and 5 Mg·ha^{-1}·year^{-1}. 122 ha (1.12%) have rates between 5 and 10 Mg·ha^{-1}·year^{-1}. The highest rates in the basin, i.e. above 10 Mg·ha^{-1}·year^{-1}, concern 11.28 ha or 0.1% of the land.

The spatial distribution shows that:

- the mountainous areas in the western part of the basin are the sectors that suffer most from soil loss and that's because they record the highest values of the watershed; they correspond in fact either to areas made up of bare rock or poor soils with a high erodibility factor; these are the slopes of Bou Douaou mountain where clay, sand and marl banks are omnipresent (Fig. 10);
- the zones corresponding to the small reliefs bordering the basin of the North sides and especially the South–East and South sides are experiencing erosion due to the soft rocks (clays and gypsum) and poor vegetation cover;
- streambeds represent areas of moderate erosion due to soft and friable materials that cover them in addition to the role of grazing in these areas.

The soil loss map is very close to the *LS* factor map. Because steep slopes are the first erosion factor in our study watershed. The importance of protection in arid zone basins is also demonstrated since the maximum RUSLE value rises to 181 Mg·ha^{-1}·year^{-1} instead of the current 163 Mg·ha^{-1}·year^{-1} in the case where the *P* factor is not computed.

The comparison with the few studies realized in Tunisia shows that the annual erosion rate increases with the latitude i.e. with the increase in rainfall. This study is among the rare studies conducted out in the arid zones of Tunisia. It shows that the *R* factor is the first determinant in the final erosion rate.

The comparison with studies realized in neighbouring regions in Tunisia or in other regions of North Africa assumes that the different studies used similar formulas. However, it should be noted that while the number of studies using the RUSLE model is important, the methodologies used are very varied, especially concerning the choice of *R* factor and the *K* factor equations, which makes the results comparison insignificant. Both of these factors must be considered very carefully if results are to be compared over time or space. In this study, all cases cited have *K* factor values similar to our area and *R* values normally increasing with latitude where precipitation is more abundant going northward. Thus, ZANTE *et al.* [2003] recorded an average erosion rate of 4.12 Mg·ha^{-1}·year^{-1} in the Abdessadok basin (Tunisian Dorsal). Similarly, ANDERSSON

[2010] found comparable rates in small basins of Mrichet and Sadine (Tunisian Dorsal) respectively 11.4 and 24.5 $Mg \cdot ha^{-1} \cdot year^{-1}$. Ben Cheikha and Gueddari [2008] observed an average erosion rate of 14.8 $Mg \cdot ha^{-1} \cdot year^{-1}$ in the Jannet catchment (Tunisian Dorsal). In northeastern Tunisia (Cap Bon) Gaubi *et al.* [2017] concluded an average rate estimated at 24 $Mg \cdot ha^{-1} \cdot year^{-1}$. Furthermore, in North-East Algeria, Bouguerra *et al.* [2017] reported average erosion rates of 11.18 8 $Mg \cdot ha^{-1} \cdot year^{-1}$ in the Bouhamdane basin.

At the end of our work, and to verify the accuracy of the results of the used model, we attempted to choose a number of pixels from the final erosion map of RUSLE. Then with their GPS coordinates, we examined them on field. Overall, the pixels selected do correspond to areas of potential erosion and the presence of gullies in most cases supports this idea (Tab. 7).

Table 7. Selected pixels examined on field

Pixel id	Localization	Pixel value ($Mg \cdot ha^{-1} \cdot yr^{-1}$)	Condition
1	34,540723 9,738086	8	bare fields ploughed
2	34,604867 9,719029	21	gully
3	34,515047 9,734666	57	gully
4	34,563125 9,797973	5	gully bed
5	34,573914 9,776423	0	encrusted interfluve
6	34,595150 9,721674	10	clayey piedmont
7	34,516727 9,717600	7	ploughed plot
8	34,560132 9,735690	13	ploughed fields in stream bed
9	34,498713 9,731875	6	gully that destroyed a bench
10	34,510245 9,726795	16	gully

Source: own elaboration.

CONCLUSIONS

The study conducted in the Bedour watershed showed that the arid regions of Tunisia, despite their low annual rainfall totals, are experiencing significant rates of water erosion. In addition to the usual gullying, this is manifested in a loss by sheet erosion demonstrated here by the RUSLE model. The use of a 12 m DEM at the base of the work allows an appropriate and even an optimal level of precision for the quantification of erosion at the pixel level. On the other side, to avoid any overestimation of the R factor values, we opted for the use of the modified Fournier index. The superposition of the different layers of the model allowed us to compute the different parameters and to obtain an annual rate oscillating between 0 and 163 $Mg \cdot ha^{-1} \cdot year^{-1}$ with an average rate of 3 $Mg \cdot ha^{-1} \cdot year^{-1}$. The spatial distribution of erosion shows that the slopes that are often denuded and devoid of any management or crops are the most affected by erosion in the study area. While the plains, which constitute the major part of the watershed, experience a low erosion often less than 2 $Mg \cdot ha^{-1} \cdot year^{-1}$ due mainly to the widespread protection action encouraged by the authorities. It is also shown that this protection is relatively effective since it saves the lands of the basin from erosion that can be much higher. The comparison with previous studies done in Tunisia concluded that the results obtained here are in consistent with some studies that used similar formulas if we take into account the normal variation of the R factor.

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Chokri BEDOUI

Przewidywanie erozji wodnej na obszarach klimatu suchego za pomocą modelu RUSLE z wykorzystaniem GIS – przykład zlewni Bedour w środkowej Tunezji

STRESZCZENIE

Badania prowadzono, aby ilościowo ocenić erozję gleby na suchych obszarach Tunezji. W tym celu wykorzystano model RUSLE bazujący na systemie informacji geograficznej. Zbiór danych, ich nakładanie i obliczenia prowadzono zgodnie z równaniami i protokołem modelu umożliwiły poznanie erozji w przestrzeni na poziomie pikseli. Badania wykazały, że w całej zlewni nasilenie erozji zmieniało się od 0 do 163 $\mathrm{Mg \cdot ha^{-1} \cdot rok^{-1}}$ ze średnią równą 3 $\mathrm{Mg \cdot ha^{-1} \cdot rok^{-1}}$. Mimo małego współczynnika R (erozyjność opadu), mieszczącego się w granicach 21,43–21,88 $\mathrm{MJ \cdot mm \cdot ha^{-1} \cdot h^{-1} \cdot rok^{-1}}$, który odzwierciedla niewielkie miesięczne i roczne opady, badany region doświadcza lokalnie bardzo wysokiego tempa erozji. Ochrona gleby poprzez odpowiednie działania uratowała zlewnię przed jeszcze większą erozją. Podczas gdy równiny uprawiane z ziemnymi ławami biegnącymi wzdłuż poziomic ulegają mniejszej erozji (mniej niż 2 $\mathrm{Mg \cdot ha^{-1} \cdot rok^{-1}}$), nieuprawiane stoki są pozbawione takiej ochrony, co skutkuje wysokim tempem erozji.

Słowa kluczowe: *erozja wodna, GIS, obszary suchego klimatu, RUSLE, Tunezja*