Quantifying water erosion hazard in central Tunisia A case study: the Leben watershed

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Received 10 May 2018; Revised 22 October 2018; Accepted 3 November 2018

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ABSTRACT

This study was performed in order to quantify soil erosion in the arid lands of central Tunisia. To do this we used geographic information systems, remote sensing and the RUSLE prediction model. While the study area is characterized by reduced rainfall quantities and therefore a low *R* factor, other factors such as high soil erodibility, low vegetation cover and steep slopes resulted in locally high erosion rates. Indeed, the calculation of RUSLE factors revealed values between 0 and 731 $\text{tones} \times \text{ha}^{-1} \times \text{year}^{-1}$ with an average of 3.84 $\text{tones} \times \text{ha}^{-1} \times \text{year}^{-1}$. Whereas most catchment lands have low levels, the relief surrounding the catchment has relatively high rates due to the high value of slopes, the skeletal soils that compose them, but also due to the absence of protection, reforestation or crop management. This study also showed that despite their small extension compared to the watershed, main streams sectors, and especially their banks, record the highest erosion rates mainly due to the flow accumulation in the downstream sectors. Relative protection of the piedmont, which has saved them from higher erosion, can only be considered efficient and sustainable if the upstream hillsides are also protected. The comparison with previous studies carried out in Tunisia shows similarities in the results of some of them, considering the natural geographical variation of the *R* factor.

KEYWORDS

Water erosion; RUSLE; Tunisia; arid lands

1. Introduction

Soil water erosion is one of the main threats to arable lands sustainability. Tunisia is one of the Mediterranean countries most affected by this hazard. Combating land erosion in Tunisia is an old phe-

nomenon and has become over time more widespread and more technical. Although studies on soil erosion have multiplied over time, the arid regions of Tunisia have not, to our knowledge, been of particular interest for this type of study. This is probably

due to low precipitation that suggests low erosion, which this study is trying to contradict. Indeed, the scarcity of rainfall does not mean that central Tunisia lands are not affected by water erosion. On the contrary, precipitations in these regions follow wet cycles and less wet or even dry cycles. During wet periods, rainfalls often cause flooding with runoff and erosion values comparable to the more humid regions of northern Tunisia. Studies to quantify soil erosion began a few decades ago, but spatialization and mapping techniques were unreliable and resource-intensive. Today, this work is made easier by tools such as geographic information systems, remote sensing and digital models that can be integrated into them. This study intends to use these tools to attempt to quantify erosion based on the RUSLE model. This model is established on experimental studies plots and it is in continuous improvement (Wischmeier et al., 1965; Renard et al., 1997). The objective of such a model is not to stop erosion but to know the high-risk areas and then to

act on the controllable factors such as slope length (shortening it by contouring or terracing), or by well choosing crops and protection types (Masson, 1971).

2. Study area

The study area, with an area of 1470 km², is located in central Tunisia between 9°10' to 9°50'E and 34°29' to 34°51'N (Fig. 1). Altitudes vary from 115 m in the central plains to 986 m in the relief bordering the watershed. The Meloussi and Majoura mountains border the catchment on the north and west sides, the South Bouhedma Mountain and the Mehiri-Zebbeus mountain on the east side (Fig. 2). The major part of the basin corresponds on the contrary to vast plains which are disturbed only locally by Kodiât Ouled Amara plateau. These reliefs generally correspond to anticlines bordering two large synclines, partially separated to the west by a small anticline convexity.

Figure 1 Location of the study area

Figure 2 Digital elevation model and stream

The outcropping rocks on the reliefs are essentially Cretaceous limestone and dolomite except the reliefs of the east where they are composed by gypsum and clay–gypsum layers. Clay outcrops are particularly present in the south–eastern part of Dribika and Nadour of Triassic constitution. Neogene deposits (clay, conglomerate, sand) often occupy the northern and eastern piedmonts with gypsum or calcareous crusts. Inherited or actual sand accumulations litter the relief of the southern limit of the catchment. Most of the central plains are alluvial layers from the Upper Pleistocene and Holocene. The study area belongs mainly to the upper arid climate stage, a small part to the south–east to the cool lower arid and a band corresponding to the Majoura Mountain (north–west of the basin) belongs to the temperate lower semi–arid stage. The relief surrounding the watershed is covered by a degraded scrubland of *Phoenicia juniper*. While the western piedmonts are covered by an esparto steppe, the southern piedmont is the site of a sandy jujube steppe. The eastern and north–eastern gypsum lands are covered with halophile vegetation.

3. Materials and methods

Presentation of RUSLE model: This model consists of five independent parameters which, multiplied according to the following equation result in the final soil loss rate (Eq. 1) (Fig. 3).

$$A = R \times K \times C \times P \times L \times S \quad (1)$$

where, A = annual rate of soil loss in $\text{tonnes} \times \text{ha}^{-1} \times \text{year}^{-1}$, R = rainfall erosivity factor, K = soil erodibility factor, C = crop cover factor, P = practice support factor, LS = topography factor.

The rainfall erosivity factor R , as defined by Wischmeier and Smith (1978) (Eq. 2), means the rain kinetic energy E multiplied by the maximum rainfall intensity (I_{30}) for 30 min. This index represents the potential erosive risks in a specific region. In our study, given the impossibility to apply the Wischmeier and Smith equation, we opted for the formula developed by Renard and Freimund (1994) based on the modified Fournier index (MFI) which establishes the relationship between the MFI and the R factor with a high determination coefficient ($r^2=81$) (Eq. 3a) (Renard and Freimund, 1994). The MFI reflects both annual and monthly average and

will avoid overestimating of R factor values in a region characterized principally by its aridity (Eq. 4) (Arnoldus, 1980). The MFI and R factor were calculated on the rainfall data of 7 stations located around but also inside the catchment area, for the period from 2002 to 2011. This period was chosen because it has no data gaps.

$$R = (E_c) \times (I_{30}) \quad (\text{Wischmeier and Smith, 1978}) \quad (2)$$

where, R is the erosivity factor for an event in $\text{MJ} \times \text{mm} \times \text{ha}^{-1} \times \text{hr}^{-1} \times \text{year}^{-1}$, E_c is the total rain kinetic energy in MJ/h and I_{30} is the maximum rain intensity in 30 minutes in mm/h .

$$R = 0.07397 \times F^{1.847} \text{ when } F < 55 \text{ mm} \quad (3)(a)$$

$$R = 95.77 - 6.081F + 0.477 \times F^2 \text{ when } F > 55 \text{ mm} \quad (b)$$

where F is the Modified Fournier Index

$$F = \sum_{i=1}^{12} \frac{(P_i)^2}{P} \quad (4)$$

where P_i is the monthly rainfall average and P is the annual average.

The soil erodibility factor K is a function of organic matter, texture, permeability and soil profile structure. The initial equation of Wischmeier et al., 1978 (Eq. 5) has often been used to define tables containing soil k values. The higher this index, the higher the soil erosive potential. In our study we extracted the soil map from the *Carte Agricole* (agricultural map, digital database) of the ministry of agriculture. Then we assigned the k values available in literature from Tunisia or elsewhere (Ben Cheikha et al., 2008; Andersson, 2010; Zante, 2003; Kort, 2013; Leguedois, 2003).

$$K = A \times B \times C \times D \times 0.1317 \quad (5)$$

where:

$$A = [0.2 \times 0.3 \exp(0.0256 \text{ sand}(1 - \text{silt}/100))]]$$

$$B = \left[\frac{\text{silt}}{\text{clay} + \text{silt}} \right]^{0.2}$$

$$C = \left[1.0 - \frac{0.25 \text{ clay}}{(\text{clay} + \exp[(3.72 - 2.95 \text{ clay}]))} \right]$$

$$D = \left[1.0 - \frac{0.7 \text{ sand } 1}{(\text{sand } 1 + \exp[(-5.41 + 22.9 \text{ sand } 1)])} \right]$$

The topographic factor LS is a function of both slope length L and slope steepness S . It means the slope contribution to increase erosion potential in the study area. To obtain LS value map we applied the following equations: McCool et al., 1987; Des-

met et al., 1996 (Eq. 6). We used the 28 m resolution Astgdem digital elevation model. This choice was dictated by the relatively large area of the catchment but also the absence of a more detailed DEM covering the basin.

$$LS = L \times S \quad (6)$$

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

$$m = \frac{F}{1+F}$$

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

m = index of slope's length factor

$$L_{(i,j)} = \frac{[A_{(i,j)} + D^2]^{m+1} - A_{(i,j)}^{m+1}}{X^m D^{m+2} (22.13)^m}$$

where: β = Slope layer in ArcGis (in degrees), A = Flow accumulation layer (ArcGis), D = grid cell size (meters), X = coefficient that corrects the length of flow way through a raster cell.

S-factor

$$\text{when } \tan \beta_{(i,j)} > 0.09 \quad S_{(i,j)} = 10.8 \sin \beta_{(i,j)} + 0.03$$

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

Crop management factor C refers to the role of vegetation in protecting soils from erosion. It includes both natural and cropland vegetation. Today, remote sensing makes it much easier to study crop cover. In our study we used a Sentinel_2_1C image with a resolution of 10 m. Image processing and field confirmation allowed us to make a supervised classification. This has permitted us to have land use classes to which we have assigned the C factor values from literature (Masson, 1971).

The conservation practice factor P considers man-made facilities and agricultural practices (ploughing, crop rotation, etc.) used to reduce runoff and erosion. This factor varies from total protection (0) to no protection (1). In our study we firstly digitized conservation practices from Google Earth. Then we exported polygons to ArcGis where we integrated them into the class slope map in percentages. Afterwards we extracted and pasted them with the untreated area and assigned P values to these polygons according to the slope classes. The untreated area was given a value of 1.

Figure 3 Methodology flow chart

4. Results and discussion

After the data collection phase, we proceeded to calculate model factors, one by one, then to multiply them in the math algebra tool of the ArcGis software. The results are as follows:

– Rainfall erosivity factor R : after interpolation with the Idw tool and extraction in the ArcGis software, the study region shows an R factor evolving between 20.58 and 32.59 $\text{MJ}\times\text{mm}\times\text{ha}^{-1}\times\text{hr}^{-1}\times\text{year}^{-1}$ (Table 1) (Fig. 4). These values are very low com-

pared to other regions but are consistent with their climate and the amount of rainfall the region receives. Moreover, some studies cite R values comparable to these. They particularly are in concordance with the results of Zante et al., (2003). This author recorded for Abdessadok watershed (Tunisian dorsal, Siliana region, 345 mm) values of 64 $\text{MJ}\times\text{mm}\times\text{ha}^{-1}\times\text{hr}^{-1}\times\text{year}^{-1}$ as average with values of 25 for the dry year and 93 $\text{MJ}\times\text{mm}\times\text{ha}^{-1}\times\text{hr}^{-1}\times\text{yr}^{-1}$ for the very rainy year.

Table 1 Weather stations, annual rainfall average and R factor for 2002–2011 period

Stations	LONG	LAT	Rainfall Annual average (mm)	Modified Fournier index	R factor
Bir Ali	10.095789	34.740684	186.68	20.61	19.77
Skhira	10.0699	34.299882	187.87	22.12	22.53
Mezzouna	9.84223	34.580594	182.79	21.90	22.13
Meknassy	9.602237	34.604781	197.52	21.06	20.59
Bouzayane	9.427244	34.573043	210.85	24.11	26.42
Sidi Bouzid	9.483061	35.037113	308.11	33.17	47.63
Gafsa	8.784391	34.422414	193.6	14.53	10.37

– The soil erodibility factor K : this factor was determined first by extracting the soil map as polygon files from the Carte Agricole (national agricultural mapping program) and then by assigning K values from studies performed in Tunisia or elsewhere. According to experimental work by Dumas (1965), (Table 3), soils constituting the study area belong to soils with high erodibility and very high erodibility (between 0.04 and 0.075 $\text{tones}\times\text{ha}\times\text{h}/\text{MJ}\times\text{mm}\times\text{ha}$) (Fig. 5) (Table 2). Soils very sensitive to erosion are confined in the moun-

tain belt surrounding the catchment. These are mainly raw mineral soils and low developed soils. But the rest of the land in the watershed is also composed of highly erodible soils. The spatial distribution of the different soil types shows the diversity of the formations occupying the basin. Thus, low developed soils are the most widespread in the catchment (33%). Then we find complex soils with 15%, followed by isohumic soils with 18% of the watershed. Raw mineral soils and rendzine occupy respectively 13% and 8% of the total surface.

Table 2 Soil types, K factor values and sources

Soil type	K factor values	ha	%	Source
Rendzine	0.05	12394.2	8.42	Ben cheikha et al.(2008)
Raw mineral soils	0.075	19895.47	13.52	Ben cheikha et al.(2008)
Low developed soils	0.055	49720.27	33.80	Ben cheikha et al.(2008)
Brown calcareous soils	0.046	9699.305	6.59	Ben cheikha et al.(2008)
Iso humic brown soils	0.042	27289.38	18.55	Kort (2013)
Halomorphic soils	0.04	4620.358	3.14	Kort (2013)
Complex soils	0.05	22274.69	15.14	Andersson (2010)
Stream bed	0.046	1172.018	0.79	Zante (2003)

Figure 4 R factor

Figure 5 K factor

Figure 6 *C* factor

Table 3 Soil erodibility classes according to Dumas (1965) after conversion to SI units system (Foster et al., 1981)

Values classes	Erodibility classes
$K < 0.0065$	very lowly erodible soil
$0.0065 < K < 0.0131$	slightly erodible soil
$0.0131 < K < 0.0263$	moderately erodible soil
$0.0263 < K < 0.0526$	highly erodible soil
$0.0526 < K < 0.079$	very highly erodible soil

– Crop management factor *C*: this factor was first determined from a Sentinel 2 satellite image classification and the identification of the different homogeneous land use zones. Then the *C* values available in the literature were assigned to these areas (Masson, 1971) (Table 4). The following values are given: 0.9 for olive groves which occupy 35% of the catchment area, 0.4 for intensively cultivated areas, i.e. 15% of the catchment area, and 1 for bare soil which represents approximately half of the catchment area (Fig. 6) (Table 5).

– The conservation practices factor *P*: this factor was first created by digitizing the treated areas,

essentially by contour benches from Google Earth. Then, polygons were integrated with slope map classified in percentages. Afterwards, they were extracted from the unprotected area. While the maximum value 1 has been assigned to these, the values of the treated areas depend on their slope class. Results are as follow: untreated area represents the major part of the watershed: 89%. The remaining 10% has *P* values oscillating between 0.55 and 0.9 (Fig. 8) (Table 6).

Table 4 *C* factor table according to Masson (1971)

Vegetation type	<i>C</i> factor
Bare land, fallow land	1
Fruit arboriculture	0.9
Winter wheat	0.7
Cereal crop rotation	0.4
Forages	0.2
Cereal crop rotation + fodder	0.1 to 0.01
Improved pastures	0.01

Table 5 Crop management values and sources

Crop management	C factor values	ha	%	Source
Bare soils, bare rocks	1	71240.50154	48.44	Masson (1971)
Olive groves	0.9	51497.14704	35.01	Masson (1971)
Irrigated crops and intensive plots	0.4	23343.46525	15.87	Masson (1971)
Built-up areas	0	971.1252788	0.66	–

Table 6 P factor values and sources

Slope classes	P factor values (contouring)	ha	%	Source
0–7	0.55	9232.803	6.27	Shin (1999)
7–11.3	0.6	4069.721	2.76	Shin (1999)
11.3–17.6	0.8	2005.117	1.36	Shin (1999)
17.6–26.8	0.9	467.7729	0.31	Shin (1999)
>26.8	1	131296.4	89.27	Shin (1999)

Figure 7 LS factor

Figure 8 *P* factor

– The slope length and steepness factor *LS*: The watershed values vary between 0 and 836 and they are closely linked to the slope map values, i.e. the mountain areas are those with the highest *LS* values, whereas the central plains have the lowest (Fig. 7). The spatial distribution of the *LS* factor shows that most of the catchment (87%) has values below 2, followed by the moderate slopes, low-reliefs and plateau (7%) which have values between 2 and 5 (Table 7). Then we find the areas of steep slopes of the mountainous border (3.79%) which have values between 5 and 10. Mountain cornices and main rivers (0.41%) have values greater than 10.

Table 7 Classified *LS* factor values

LS factor values classes	Area in ha	%
0–2	129405.10	87.98
2–5	11495.49	7.82
5–10	5570.16	3.79
>10	607.65	0.41

– RUSLE annual total erosion

Seen as a whole, annual soil loss values are evolving between 0 and 731 $\text{tonnes} \times \text{ha}^{-1} \times \text{year}^{-1}$ with an average erosion of 3.84 and a standard deviation of 5.08 $\text{tonnes} \times \text{ha}^{-1} \times \text{year}^{-1}$.

Erosion map in stretched values based on standard deviation clearly shows a location of elevated values on the mountains of the north, north-west and secondarily of the south of the watershed (Fig. 9). This is logical since the regions mentioned include important mountain systems with narrow inter-mountain depressions and often steep slopes.

Representation of erosion values under the standard RUSLE classification shows the 5–15 $\text{tonnes} \times \text{ha}^{-1} \times \text{year}^{-1}$ class as the most characteristic of mountainous regions (4.93%) while the 0 to 1 class is the most widespread in the watershed terrain (78%) followed by the 1 to 5 $\text{tonnes} \times \text{ha}^{-1} \times \text{year}^{-1}$ class (15.53%) (Fig. 10) (Table 8).

But when we use the Masson (1971) classification for the semi-arid regions of Tunisia we can see more details in erosion spatial distribution (Fig. 11) (Table 9). Therefore, lands experiencing erosion between 0 and 2 $\text{tonnes} \times \text{ha}^{-1} \times \text{year}^{-1}$ represent the

major part of the basin (86.34%). Those losing between 2 and 5 $\text{ton} \times \text{ha}^{-1} \times \text{year}^{-1}$ represent 8.02%, followed by lands suffering soil loss between 5 and 10 $\text{ton} \times \text{ha}^{-1} \times \text{year}^{-1}$ (5.41%). The most critical erosion (above 10) concerns only 1.92%. If we combine the two central classes, we obtain 13.43 (19448.48 ha) of the lands affected by erosion between 2 and 10 $\text{ton} \times \text{ha}^{-1} \times \text{year}^{-1}$.

Table 8 Soil annual loss under standard classes

Erosion classes ($\text{ton} \times \text{ha}^{-1} \times \text{year}^{-1}$)	ha	%
0–1	114139.27	78.84
1–5	22477.60	15.53
5–15	7143.24	4.93
15–50	1009.31	0.70
50–200	10.54	0.01
> 200	1.27	0.0008

Figure 9 Erosion map in stretched values based on standard deviation

Figure 10 Annual soil loss under standard classes

Figure 11 Annual soil loss under Masson (1971) classes for Tunisian semi-arid lands

Figure 2 Enlargement of erosion map in the main stream

Figure 3 Enlargement of the erosion map at the Meloussi Mountain

Figure 4 Enlargement of the erosion map along the Leben banks

Table 9 Annual soil loss under Masson (1971) classes for Tunisian semi-arid lands

Erosion classes ($\text{tonnes} \times \text{ha}^{-1} \times \text{year}^{-1}$)	ha	%
0–2	124998.74	86.34
2–5	11618.13	8.02
5–10	7830.35	5.41
> 10	2780.37	1.92

The relatively high erosion values recorded on the relief of the catchment borders are clearly related to the presence of soil types with very high erodibility (K above 0.052) which are raw mineral soils, low-developed soils and soils with high erodibility (rendzine). They are also explained by the often high LS values recorded there. On the other hand, reliefs of the catchment margins are rarely cultivated or covered by a vegetal cover. On the contrary, they are experiencing significant overgrazing due to a livestock that is inappropriate with attempts to reforest and improve grazing areas remaining below requirements. Protection against erosion is almost absent in the mountains surrounding the catchment. Reforestation does not seem to succeed and slopes are often denuded denouncing multiple failures: inefficiency of reforestation and protection efforts but also multiple and repeated aggressions by abusive overgrazing.

Comparison with previous studies on erosion quantification may be interesting if authors had used similar formulas and same unit system. Therefore Zante et al., (2003) obtained in the Abdessadok watershed (Tunisian dorsal, Siliana region, 345 mm) an average soil loss of $4.12 \text{ tonnes} \times \text{ha}^{-1} \times \text{year}^{-1}$ with a minimum value of 1.75 (the driest year) and a maximum value of 6.03 (the wettest year). These values seem to be concordant with the values recorded here given the similarities between the two catchments.

Moreover, Albergel et al. (2003) reported, at the end of the Hydromed project (study of water erosion in selected basins in the Mediterranean area) and during the annual observation of soil losses, values in the order of $1.8 \text{ tonnes} \times \text{ha}^{-1} \times \text{year}^{-1}$ in the Gouazine catchment (Tunisian dorsal, jebel Bargou, 400 mm), $12.2 \text{ tonnes} \times \text{ha}^{-1} \times \text{year}^{-1}$ in the Mrichet watershed (Tunisian dorsal, jebel Bargou, 450 mm), $17.5 \text{ tonnes} \times \text{ha}^{-1} \times \text{year}^{-1}$ in the Es Senega basin (central Tunisia, Sbiba region, 250 mm), $24.2 \text{ tonnes} \times \text{ha}^{-1} \times \text{year}^{-1}$ in the Fidh Ali catchment (central Tunisia, Kairouan region, 300 mm) and $32 \text{ tonnes} \times \text{ha}^{-1} \times \text{year}^{-1}$ in the Kamech basin in northeast Tunisia (Table 10).

Later, Ben Chaika et al. (2008) recorded in the Jannet watershed (Tunisian dorsal, Siliana region, 400 mm) a value of $14.8 \text{ tonnes} \times \text{ha}^{-1} \times \text{year}^{-1}$ for an average year, with values in the order of $6.5 \text{ tonnes} \times \text{ha}^{-1} \times \text{year}^{-1}$ for a dry year and a value of $20 \text{ tonnes} \times \text{ha}^{-1} \times \text{year}^{-1}$ for a very wet year.

Table 10 Soil loss in some catchments in Tunisia after Alberger et al., (2003)

Watersheds	Location	Catchment area (ha)	Year of survey	Soil loss ($\text{tonnes} \times \text{ha}^{-1} \times \text{year}^{-1}$)
El Gouazine	Central Tunisia, valley in alluvium Pleistocene crusts. (Isohyet 400 mm)	1810	1990	1.8
Es Sénega	Central Tunisia, Cretaceous Mountains. Limestone and gypsum marls (Isohyet 250 mm)	363	1991	17.5
Fidh Ali	Central Tunisia, Eocene anticline. Marls gypsum and lumachelles (Isohyet 400 mm)	238	1991	24.2
Kamech	Central Tunisia, Cap Bon Anticline. Limestone, sandstone and marl (Isohyet 650 mm)	245.5	1993	32.0
M'Richet	Central Tunisia, Bargou anticline. Marls and Cretaceous limestone (Isohyet 450 mm)	158	1991	12.2

Andresson (2010) obtained values of 11.4 and $24.5 \text{ tonnes} \times \text{ha}^{-1} \times \text{year}^{-1}$ respectively in the Mrichet and Sabine basins. Gaubi et al., (2017) recorded in the Lebna catchment (North-East of Tunisia) a value

of $24 \text{ tonnes} \times \text{ha}^{-1} \times \text{year}^{-1}$. The disparities in erosion values mentioned here are mainly attributable to geographical variations in the R factor. Indeed, rainfall in Tunisia is increasing towards the north-west.

The study of the final erosion map shows that the main streams are not only considered to be areas of high erosion but also have the highest rates of erosion in the basin (Fig. 12). Indeed, if the mountainous sectors record values between 0 and 49 $\text{tonnes} \times \text{ha}^{-1} \times \text{year}^{-1}$, (Fig. 13) main streams have values ranging from 0–731 $\text{tonnes} \times \text{ha}^{-1} \times \text{year}^{-1}$, the highest in the catchment as shown on the enlargement maps legend. This can be explained by the role of *LS* factor based on slope accumulation and particularly flow accumulation from upstream to downstream of the catchment area. This means that at the level of the main streams and especially their downstream segments, the flows accumulation is maximum, resulting in a maximum of erosion. Thus, the model revision and *LS* factor formulas multiplication have resulted in a consequent improvement in of erosion assessment. Similarly, the enlargement shows that in watercourses the pixels with the most erosion values most often correspond to the banks more than the bed (Fig. 14). This is related to the abrupt change in elevation and slope recorded by the model interpreting it as a flow and material movement.

5. Conclusion

In this study, the objective was to use the RUSLE prediction model to quantify erosion in the Leben catchment. While *R* factor values are significantly low (between 20.58 and 32.59 $\text{MJ} \times \text{mm} \times \text{ha}^{-1} \times \text{hr}^{-1} \times \text{year}^{-1}$), the *K* factor values are substantially high or very high (between 0.04 and 0.075 $\text{tonnes} \times \text{ha} \times \text{h} / \text{MJ} \times \text{mm} \times \text{ha}$). Similarly, the watershed is dominated by bare soils (48%) or olive groves (35%), which do not provide much soil coverage; soil conservation practices have only concerned the piedmont sectors in the catchment. The *LS* factor, closely related to slope maps, reveals mountainous areas as more susceptible to erosion.

Superposition of the different model factors allowed us to compute erosion values and revealed erosion rates ranging between 0 and 731 $\text{tonnes} \times \text{ha}^{-1} \times \text{year}^{-1}$ with an average erosion of 3.84 $\text{tonnes} \times \text{ha}^{-1} \times \text{year}^{-1}$. The relatively elevated rates of erosion are mainly found in the relief surrounding the catchment because of the high values of slopes, the skeletal soils which often compose them, but also be-

cause of absence of protection, reforestation or crop management. This means that the process of relief erosion that began in the Tertiary Era continues, taking advantage of soil and vegetation degradation and overgrazing. It means also that, if the mountain slopes are not protected and reforested, erosion will not decrease in the watershed while protection of the piedmont remains relative.

Comparison with previous studies carried out in Tunisia shows similarities in the results with some of them considering the geographical variation of the *R* factor. Analysis of the results at the pixel level showed that the streams and especially their banks record the highest erosion values and this was related to the flow accumulation in the downstream sections.

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