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Assessment of Soil Erosion Using the Universal Soil Loss Equation (USLE) and GIS: a Case Study of the Sbaihya Wadi Catchment Area in Northern Tunisia

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Abstract: The purpose of this study was to investigate the spatial distribution of annual soil loss in Sbaihya Wadi catchment using USLE model. The Sbaihya Wadi catchment's in central of Tunisia is characterized by a semi-arid climate. Rare and irregular rains, generally of stormy character, combined with an important deforestation, cause severe erosion. Soils are degraded and the sediments resulting from this erosion contribute to silt up the dam's reservoir in downstream. Integration of thematic maps of the Universal Soil Loss Equation (USLE) factors into ArcView-GIS and their databases allowed, to disentangle complexity and the interdependence between factors in erosion risks analysis and to better determine the impact of each factor and to evaluate its contribution to soil loss. Crosscutting of thematic maps and the application of the ULSE formulas to assess on a classified basis the catchment area by producing a synthetic map of sensitivity degrees to erosion, to evaluate the average rate of the sheet erosion (10 t/ha/yr) and to identify the decisive factors which controlling erosion by order of importance. Those factors are the Slope, the soil erodibility and the vegetable cover. Thus, the USLE model was used in a GIS environment to identify regions susceptible to water erosion and needing immediate soil conservation planning and application in Sbaihya Wadi catchment.

Key words: Tunisia • Erosion • Sbaihya wadi • Geographical information system • Universal soil loss equation

INTRODUCTION

Water erosion of soils is a widespread phenomenon in Mediterranean countries (map of worldwide erosion) and one which continues to grow in importance, especially on soils with steep slopes, a fragile substratum and not much vegetative cover. According to FAO studies [1], water erosion affects 50% of lands in Turkey, 35% in Greece and 40% in Morocco. In Algeria, it affects 45% of the Tellienne area, or one million hectares [2]. In Tunisia, 45% of the country's surface area is threatened by erosion [3]. These figures clearly demonstrate the alarming situation, one which requires immediate intervention through necessary measures and adequate means to fight the problem.

In Tunisia, several studies have been done to try to understand the different mechanisms which govern water erosion [4-11]. The first studies were done by Cormary and Masson [4] who studied water erosion at several sites in the Tunisian Dorsal based on the Universal Soil Loss Equation (USLE). In central Tunisia, Baccari *et al*. [11] studied the influence of the topographic factor, slope and length of slope (LS) and the runoff factor (R) of rainwater in producing sediments.

In order to evaluate the risk of erosion of the soils in the catchment area, numerous factors involved in the erosion process had to be mapped out and analyzed, including intensity of rainfall or runoff (R), slope and its length (LS), erodibility of the soil (K), vegetative cover (C) and cultural practices (P). Each factor is different in the various areas of the catchment basin, thus providing a multitude of data to map out, store, structure and process in a rational way.

The Geographic Information System (GIS) makes it possible to cross maps with different themes, merge their databases and apply mathematical equations to the digital values of the erosion factors.

The Universal Soil Loss Equation (USLE) by Wischmeier and Smith [12] remains, by far, the model the most often used of all of the mathematical models predicting sheet erosion. Integrating thematic maps of the factors of this model into the GIS made it possible to

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define the impact of each factor on soil loss, rank the factors by order of importance with respect to areas of erosion and quantify soil loss.

This Study Has the Following Objectives: Group together and map out the different factors involved in the erosion process using the GIS;

Create an interactive database of the factors of erosion which includes geostandard and structured data of the major factors involved in the erosion process;

Locate areas which are susceptible to producing sediments and evaluate the quantity of soil loss per hectare by integrating Wischmeier & Smith's [12] Universal Soil Loss Equation (USLE) into the GIS.

MATERIALS AND METHODS

Study Area: The catchment area of Sbaihya Wadi, with a surface area of 354 ha, is situated in semi-arid northern Tunisia (Figure 1). It has mild winters and an average annual rainfall of 436 mm. Rainfall most often occurs as short, violent storms, according to the weather data provided by the DG/ ACTA and the IRD [13].

The catchment area is located 12 km north of Zaghouan and 35 km south of Tunis. The geographical coordinates of a small dam built in 1993 at the outlet are as follows: (528471,500; 355644,8) in the Lambert Conformal Conic projection. The altitude of the catchment area ranges from 473 m in the north and 200 m in the south, at its outlet. Its average altitude is 386 m. The average longitudinal slope is 7.7%. Its cross slope, much higher than its longitudinal slope, often exceeds 15%. From a lithological point of view, 5% of the catchment surface area is covered by a marl-limestone and massive white limestone formation, 89% by a gray marl formation, 3.5% by alternating layers of marl and gray marl limestone and 2.5% by layers of gray marl with swelling clay and quartzite. As for the types of land use most often found in the catchment area, there are annual crops (cereal crops), forests, scrublands, rangelands and bare soil.

Method: The methodological approach presented here is based on the use of both the GIS and the Universal Soil Loss Equation (USLE) as well as multiple sources of data in order to model the spatial and temporal dynamics of the sensitivity of the soil to water erosion in an agricultural catchment area.

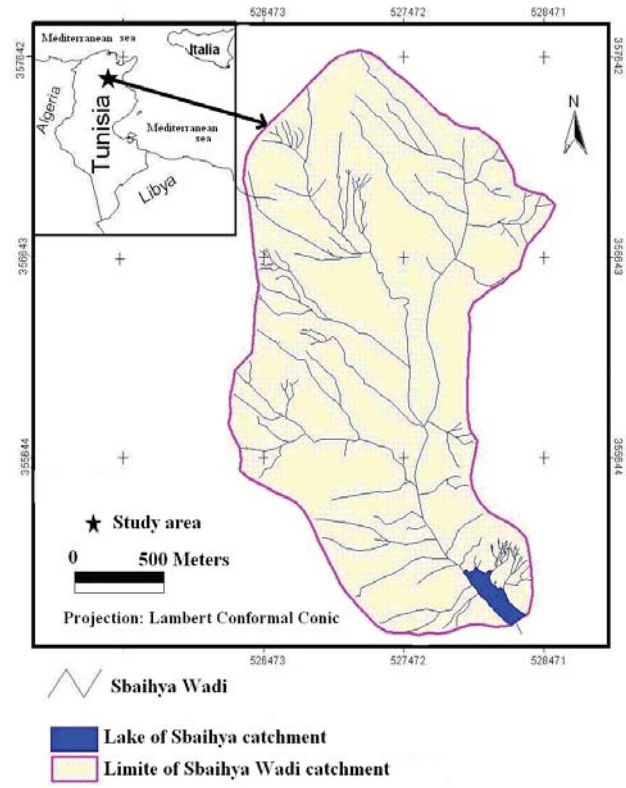

Fig. 1: Location of the Sbaihya Wadi catchment area in Tunisia

The Universal Soil Loss Equation [12] was applied to quantify soil loss by sheet erosion. The equation is a multiplicative function of five factors which determine water erosion: climatic intensity, erodibility of the soil, gradient and length of slope, land use and anti-erosion practices.

In order to apply the USLE to the Sbaihya Wadi catchment area, the different factors of the universal equation had to be assessed over the entire surface area of the catchment basin and mapped out thematically. These maps were categorized and based on FAO standards [1] for erosion cartography. They were then integrated into the ArcView Geographic Information System (GIS).

The different polygons obtained for each map were combined with their databases. Combining the maps using the GIS "Geoprocessing" model and applying the mathematical equations of Wischmeier & Smith's [12] model made it possible to assess the rate of erosion at every point in the catchment area and draw up a synthetic map of the soil loss.

According to Wischmeier and Smith [12], erosion (A) is a multiplicative function of the following factors and can be expressed as such:

$$A = R \times K \times LS \times C \times P$$

Where:

A : Amount of soil eroded, expressed in tons per hectare
K : Erodibility factor of the soil (t/year)
R : Rainfall intensity factor
L : Length of the slope
S : Gradient of the slope
C : Vegetative cover factor
P : Water and soil conservation factor

Factors L, S, C and P are relationships that have no dimension.

This empirical method was applied in Tunisia in 1970 by Masson, in 1992 by Boussema et al. (SAGATELE) and in 2008 by Baccari.

Rainfall and Runoff Factor (R): The erosion factor of rainfall and runoff (R) defined by Wischmeier [12] is equal to the kinetic energy of the rainfall (E) multiplied by I30 (the maximum intensity of rainfall for 30 minutes) according to the following equation [5]:

$$R = \alpha E \times I_{30}$$

Where:

α is the coefficient from the System of Units (in the International System of Units $\alpha = 1/685$)
E is expressed in joules per square meter
I30 is expressed in mm per hour

For small catchment areas less than 20 km^2, the rainfall intensity factor practically does not change in the catchment area but does vary over time [5], on an interannual and seasonal scale. The average interannual value will be used here, which is 117 meters ton / ha / year in the Sbaihya catchment area, determined over the period of 1994 to 2004 for the same basin.

Erodibility of the Soil (K): The erodibility of the soil (K) represents the rate of soil loss per surface unit. It is a function of organic matter content, soil texture, soil permeability and structure of the surface soil.

Calculation of the value of K is based on five parameters, commonly characterized using standard descriptions of pedological profiles and laboratory analyses. These five parameters are as follows:

- The percentage of silt and very fine sand (from 0.05 to 0.1 mm),
- The percentage of sand greater than 0.1 mm,
- Organic matter content,
- Structure,
- Permeability.

The value of K for a soil can be calculated using the following formula [12]:

$$1000\, K_{us} = 2.1\ 10^{-4}\ (12 - \%OM)\ M^{1.14} + 3.25\ (b - 2) + 2.5\ (c - 3)$$

Where:

M = (percentage of silt + very fine sand) x (100 - percentage of clay)
OM = Percentage of organic matter
b = Soil structure code used to classify soils
c = Category of permeability of the profiles

In order to determine the K factor in the Sbaihya Wadi catchment area, analyses of the granulometry and organic matter were done on 28 samples taken from the loose formations which could be pushed by erosion (soil, alluvia and colluvia) and which covered the different geological formations shown on the surface of the basin. In order to limit the influence of the other factors, an average of 3 or 4 of the values of K was used for each lithological formation. The values for the factor of erodibility were obtained by using the Wischmeier and Smith [12] formula.

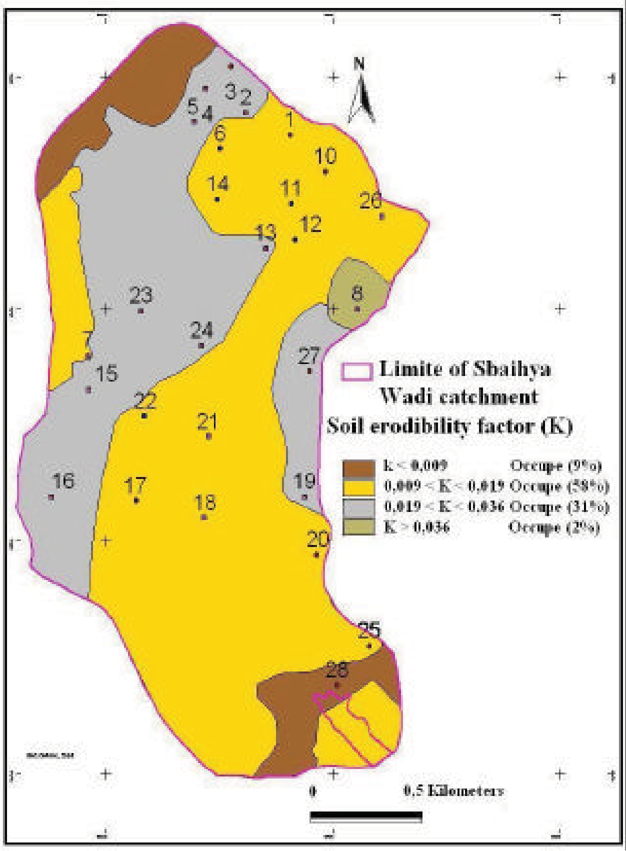

Fig. 2: Spatial distribution map of soil erodibility factor (k) in the Sbaihya Wadi catchment area

Figure 2 shows the map of the categories of erodibility of the Sbaihya Wadi catchment area and pinpoints the places from which the samples were taken.

The following five categories of erodibility were noticed:

Ksi< 0.0089 with a very low erodibility, corresponding to the marl-limestone and limestone formations at the far north end of the catchment area and to the marl and gray marl-limestone formations at the far south end (sample 28), 0.0089<Ksi<0.019 with a low erodibility, corresponding to the two main lithological formations of the catchment area: marl and greenish-gray marl with limestone intercalations for soils with a clay or silty clay texture (samples 1, 6, 7, 10, 11, 12, 14, 17, 18, 20, 21, 22, 25 and 26), 0.019<Ksi<0.036 with a medium erodibility, corresponding to the two lithological formations of the catchment area: marl and greenish-gray marl with limestone intercalations for soils with a silt or clay loam texture (samples 2, 3, 4, 5, 13, 15, 16, 19, 23, 24 and 27), Ksi> 0.036 with a high erodibility, corresponding to soils with a silt texture on greenish-gray marl (sample 8).

Topographical Factor (LS): In order to determine the LS factor, 1/25,000 topographical maps of Bir Mcherga and Grombalia were used for the Sbaihya catchment area. The topographical factor takes into account two parameters: the gradient S and the length L for segments of the basin having the same slope.

Each slope unit on the map was divided by superimposing the slope map with those showing contour lines and the hydrographic network in such a way that topographic units with the same slope and slope length could be drawn. The LS factor is determined from the formula proposed by Wischmeier and Smith [12] by considering that each unit has the same slope and the same slope length.

For the USLE, the LS equation for a uniform slope is as follows:

$$LS = (\lambda/22.13)^m \, (65.41 \sin^2 \theta + 4.56 \sin \theta + 0.065)$$

Where:

λ corresponds to the length of the slope at the site (in meters) θ corresponds to the gradient of the slope

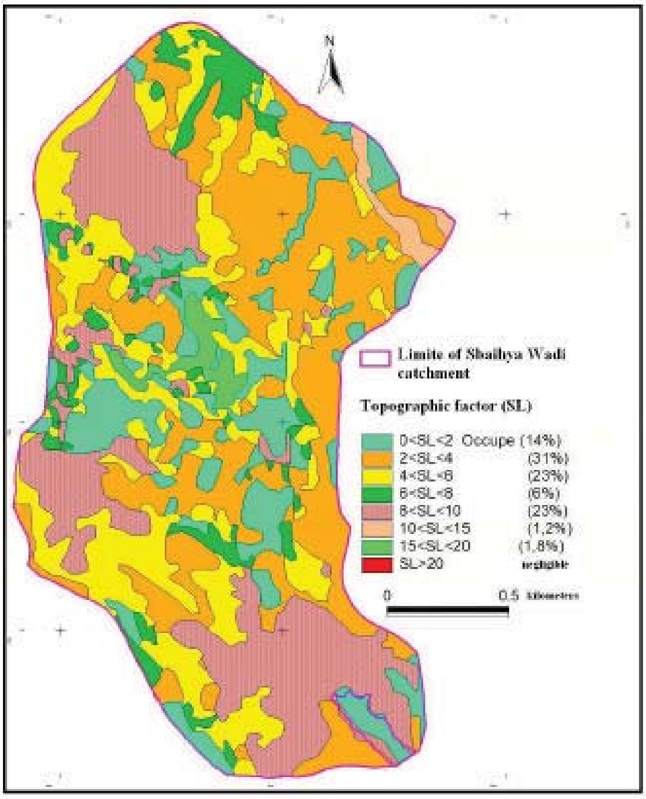

Fig. 3: Spatial distribution map of topographic factor (LS) in the Sbaihya Wadi catchment area

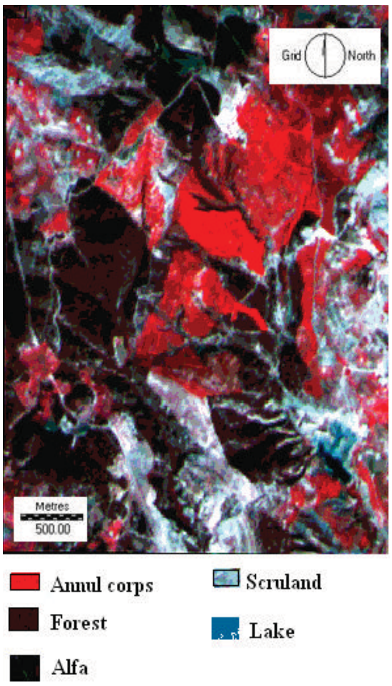

Fig. 4: SPOT 4 composite image of Sbaihya Wadi catchment area, 04/16/ 2000

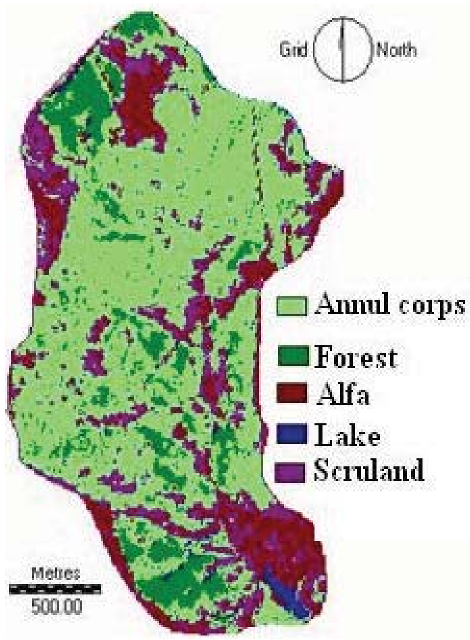

Fig. 5: Supervised classification of Sbaihya Wadi catchment area Land use from SPOT 4 composite image

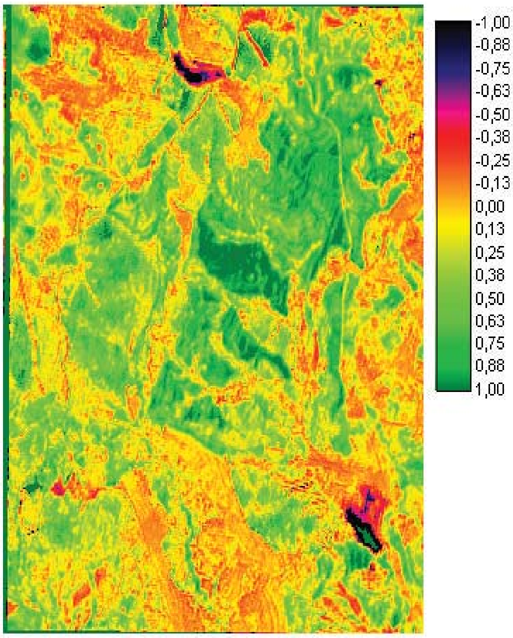

Fig. 6: Vegetation factor (NDVI) of Sbaihya Wadi catchment area to the 04/16/2000

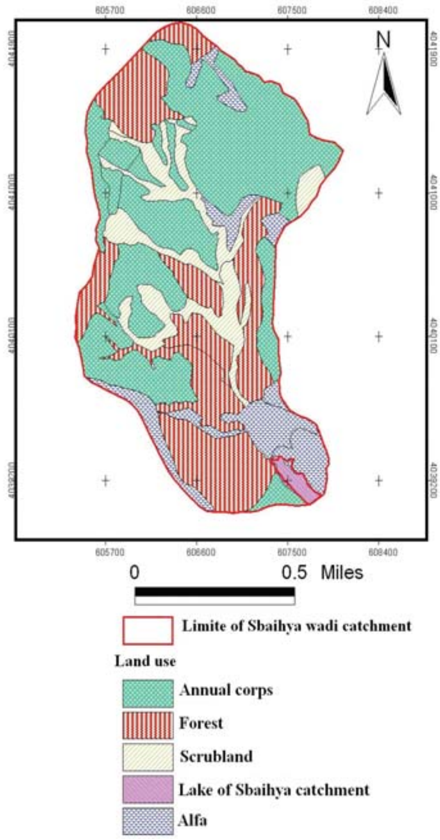

Fig. 7: Map of land use of Sbaihya Wadi catchment area

(in degrees) m corresponds to a coefficient linked to the relationship between rill and inter-rill erosion equal to 0.5 for slopes of 5% or more, 0.4 for slopes from 3.5 to 4.5%, 0.3 for slopes from 1 to 3% and 0.2 for slopes less than 1% (all of the slopes were estimated to the nearest 0.5%).

The LS factor therefore depends on both the length of the slope and its gradient. Its values vary between 0.1 and 5 in most crop farm locations and can get up to 20 in the mountains.

The topographical map of the LS factor of the Sbaihya catchment area (Figure 3) quantifies the risk of erosion linked to incline (slope) and extent (slope length). This map also sums up the respective percentages of each category of the LS factor compared to the surface area of each catchment basin. A look at this map shows that 14% of the surface area of the basin has a very low LS factor (0<LS<2). Over half of the basin's surface area has a slope factor of between 2 and 6 (a low to medium factor) and more than 20% has a high slope factor (8<LS<10). Thus, 32% of the Sbaihya catchment area surface area shows a medium to high slope factor (LS>6).

As for the slope and its length, the Sbaihya catchment area shows a medium to high vulnerability to erosion.

Vegetative Cover Map (C): The C factor corresponds to the relationship between erosion of a plot of land partially or entirely covered by vegetation and erosion of one that has the same topographical and pedological characteristics but that has bare soil with standard treatment. The risk of erosion increases when the soil has little vegetative cover or crop residue.

In order to determine the C factor, two types of satellite images with a spatial resolution of 20 m on the ground were used: one HRV(XS) image from SPOT-4 acquired on April 16, 2000 (Figure 4) and aerial Ortho images.

Once these images are processed and classified (Figure 5), they are then integrated into the GIS to map out the vegetative cover (Figure 7).

The main characteristics of the images used are presented in Table 1.

In the Sbaihya Wadi basin, a value for the C factor was attributed for each type of land use. In fact, a supervised classification approach of the SPOT 4 image was applied in order to plot the land use map. This map was checked by on-site observations and aerial Ortho-images. In addition, by thresholding the vegetative

Table1: Characteristics of the images used

Type of image	Spatial resolution	Number of bands	Date acquired
HRV(XS) from SPOT-4	20	4	4/16/2000
Aerial Ortho images	2	1: 10 000	6/14/2001

factor, a map of the vegetative cover density could be drawn [14]. These maps were used to infer how much protection the soil was getting from the vegetative cover (the C factor). This was done in fact by analogy from work done in the region by Masson [5] and Boussema [15] for each of the different crops and land uses for the C factor values.

RESULTS AND DISCUSSION

The Risk of Erosion Map

Map of Sensitivity to Erosion in the Sbaihya Catchment Area: In order to draw the map of sensitivity to erosion map, three maps were combined: erodability (K), slope and slope length (LS) and rainfall and runoff intensity (R). By multiplying the average values of each category, it was thus possible to obtain the sensitivity to erosion map. Each of these three factors was stored in the geographic database in the GIS. Combining these maps resulted in a map showing cartographic units corresponding to categories defining the degrees of sensitivity to erosion.

This sensitivity to erosion map thus corresponds to erosion of bare soils. Figure 8 corresponds to the sensitivity to erosion map in the Sbaihya catchment area. In order to draw the risk of erosion map, four categories of risk were defined:

- Very low, with erosion less than 1 ton/ha/year,
- Low, with erosion between 1 and 5 tons/ha/year,
- Medium, with erosion between 5 and 10 tons/ha/year,
- High, with erosion between 10 and 20 tons/ha/year.

The risk of erosion map was obtained by crossing the sensitivity to erosion map and the land use map to which were attributed the values of the vegetative cover factor (C) for each land use category. This factor most often contributes to reducing erosion because it takes into

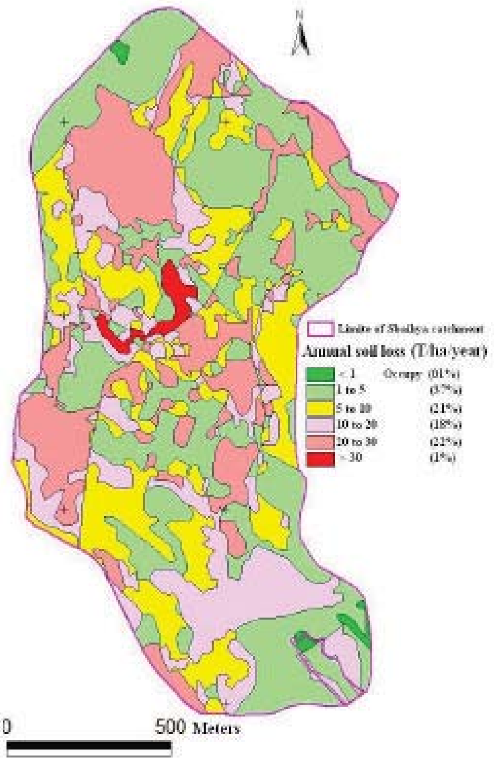

Fig. 8: Spatial distribution map of soil sensitivity to erosion in the Sbaihya Wadi catchment area

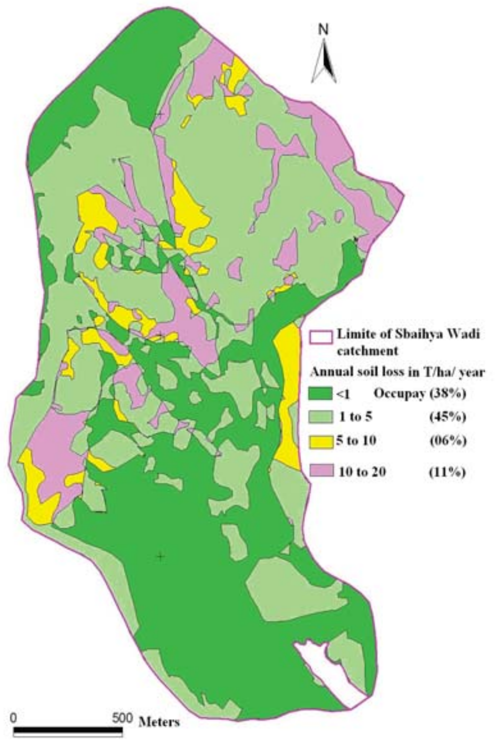

Fig. 9: Spatial distribution map of the risk of erosion in the Sbaihya Wadi catchment area

Table 2: C factor values of the vegetative cover in the Sbaihya catchment area

	C factor	Surface area of the Sbaihya catchment area (in %)
Forest	0.030	43.3
Scrubland	0.150	15.0
Annual crops in Sbaihya	0.523	42.7
Riverbed	0.200	1.0

Table 2: Risk of erosion of the soil in the catchment area

Risk of erosion categories	Surface area (in %)
Very low < 1 T/ha/year	38
Low 1 to 5 T/ha/year	45
Medium 5 to 10 T/ha/year	6
High 10 to 20 T/ha/year	11

account vegetative cover and its role in protecting the soil. For forests, the erosion value was divided by 100 for a dense forest, by 20 for a thin forest and by 6 for reforestation. For cereal crops, which cover around 40% of the surface area of the catchment area, soil erosion was reduced by half compared to bare soil. Orchards, on the other hand, with their continuously worked soil, hoed several times throughout the year, protected the soil very little and only seem to reduce erosion by 10% compared to bare soil.

The results of crossing the sensitivity to erosion map with that of land use, attributing an average value to the vegetative cover factor for each category of land use, are presented in Figure 9 for the Sbaihya catchment area. Table 2 sums up the results obtained.

Table 2 shows that 17% of the surface area of the Sbaihya catchment area was characterized by a medium to high risk of erosion.

The most threatened areas, those with the highest erosion factor, were those which had herbaceous vegetation or a degraded vegetative cover, were plowed on sloped ground and had a loose surface layer formation of silt and clay. This was the case for the soils in the upstream part of the left bank, a part of the right bank and those in the confluence areas of the tributaries. Certain units corresponded to outcrops of limestone, to limestone ruts, or to soil held by vegetative cover.

Based on these different sensitivities to erosion, different types of anti-erosion measures could be used to fight soil erosion. For very low, low or medium sensitivity to erosion, in other words less than 5 t/ha/year, anti-erosion measures do not need to be considered. For medium sensitivity to erosion, priority should be given to developing crop conservation techniques in the cultivated areas. However, biological techniques for soil conservation could also be applied in non-cultivated areas of known soil degradation. For high to very high sensitivities to erosion, priority should either be given to physical measures taken in and upstream of the cultivated areas or to adapted crop techniques such as direct sowing or no plowing.

Anti-Erosion Practices (P): The values of P were less than or equal to 1. The value 1 was attributed to those lands where none of the practices mentioned were used. There were no anti-erosion measures in the entire Sbaihya Wadi catchment area and farmers did not use anti-erosion crop practices. Most of the crops were cereal and plowing was rarely done parallel to contour lines. Given this situation, the value of P=1 was assigned to the whole surface area of the basin.

CONCLUSION

This note outlines the results of applying the Universal Soil Loss Equation using a Geographic Information System in the Sbaihya Wadi catchment area. The study showed that the catchment area lost an average of 10 t/ha/year. This value corresponded to high erosion that could not be tolerated by soils exposed to intensive climate conditions of little rainfall but stormy weather, which did not allow for the pedogenetic evolution that would compensate for soil loss. Wide surfaces of bare land, stripped of soil and affected by widespread gully erosion were witness to this. This serious situation was further worsened by the other factors which combine to accelerate erosion: high slopes (31% of the surface of the Sbaihya Wadi catchment area had slopes greater than 15%), very erodible soil (33% of the soils had a K factor > 0.019) and an alarming degradation of the vegetative cover.

The mathematical model for evaluating soil loss (USLE) integrated into a GIS made it possible to manipulate several criteria and parameters. In addition, a statistical analysis was done in order to emphasize the correlations between rates of erosion and the different factors of this process. The results obtained showed that average soil loss varied mostly according to land use and slope.

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