

EVALUATION OF THE ECONOMIC EFFECTS OF SOIL EROSION RISK ON AGRICULTURAL PRODUCTIVITY USING REMOTE SENSING: CASE OF WATERSHED IN TUNISIA

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ABSTRACT:

Soil erosion by water is a major environmental problem in the developing countries in particular. It has economic, social and environmental implication due to both on-site and off-site effects. The objective of this study is to assess the effects of soil erosion by water on-site and off-site on agriculture productivity at farm level using a combination between environmental and economic approaches and applied in a watershed in Tunisia. The environmental method is a combination between the Revised Universal Soil Loss Equation (RUSLE), remote sensing and Geographic Information System (GIS). Furthermore, multi-temporal satellite images and Transformed Adjusted Vegetation Index (TSAVI) are used to estimate the accurate the Crop management factor (C factor) with taking into account the phenology of the crops. Moreover, the economic model which is built using mathematic programming is used to assess the economic value of soil erosion by water. The comparison between baseline scenario (without erosion) and alternative scenarios where the soil erosion risk is incorporated shows that the total income of the watershed reduced with the effect of soil erosion. The approach proposed in this study is helpful for the decision makers to plan suitable strategies and measures to preserve water and soil resources. Indeed, the environmental method is useful to identify vulnerable areas with mapping soil erosion risk. In addition, the economic value of soil erosion can be used by the decision maker to prioritize areas of soil conservation.

L'érosion hydrique des sols est considérée comme un problème environnemental. En faite, le processus d'érosion des sols a de graves conséquences sur les ressources naturelles et sur l'environnement. Donc, l'objectif de ce travail est d'estimer la valeur économique de l'érosion hydrique des sols en utilisant un couplage d'un modèle environnemental et d'un modèle économique de programmation mathématique appliqué à l'échelle d'un bassin versant en Tunisie. Le modèle environnemental est basé sur la combinaison entre le modèle d'érosion hydrique RUSLE, la télédétection et le Système d'Information Géographique (SIG). Au cours de cette étude, le facteur de végétation de RUSLE (C facteur) a été déterminé en utilisant une relation entre des images satellitaires correspondant aux différentes périodes du cycle végétatif des plantes et l'indice de végétation (TSAVI). Le modèle économique de programmation mathématique a été utilisé pour établir des simulations pour l'estimation de la valeur économique de l'érosion hydrique. Ainsi, le résultat de la comparaison entre les simulations a montré que le revenu global au sein du bassin versant diminue avec l'intégration de l'érosion dans le modèle. Ainsi, cette méthodologie basée sur le couplage d'un modèle environnemental et d'un modèle économique peut être bénéfique pour l'établissement des stratégies de conservation des eaux et des sols efficaces.

1. INTRODUCTION

Environmental problems are a preoccupation of countries all over the world. Consequently, the protection of the environment and the natural resources for the future generations are their main challenge. In order to plan a better environmental decision-making policy, the economic valuation of environmental problems is important. For this reason, soil erosion by water which is considered as a major environmental threat to the sustainability and productivity of agriculture (Pimentel et Al, 1995) is the main focus of many countries. This phenomenon is defined as the process of detachment, transport and deposition of soil particles by flowing water. Through its damages caused, the effect of soil erosion is divided into two categories, on-site and off-site effects (Eaton, 1996). Soil erosion refers to a loss in soil productivity due to physical loss of topsoil, reduction in rooting depth, removal of plant nutrient

and loss of water (Lal, 2001). Therefore, the loss of soil productivity is the main onsite effect and sedimentation and eutrophication of waterways and reservoirs are offsite effects (Alfsen et al, 1996).

In addition, soil erosion has far-reaching economic, political, social and environmental implications (Ananda and Herath, 2003). Due to its economic implication, farmers should be aware of this problem and of the necessity of implementing conservation measures (Martinez-Casasnovas and Ramos, 2006). Indeed, the cost of erosion can be used to prioritize implementation of soil conservation (Clark, 1996).

Because of its negative consequences to the farmers and the societies, several researchers attempted to estimate the economic value of soil erosion. In the literature, there are many studies that deal with the valuation of the on-site effects

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(Martinez-Casasnovas and Ramos, 2006; Williams and Tanaka, 1996). Some others researchers used a combination between a biophysical model and a mathematical programming model (Donaldson et al., 1995 ; Mimouni et al., 2000). However, few papers pointed out the off-site effects (Moore and McCarl, 1987).

Furthermore, the assessment of the economic value of soil erosion required information from field. Therefore, there are many models used to predict soil loss such as the Universal Soil Loss Equation (USLE) (Wischmeier and Smith, 1978) or the Revised Universal Soil Loss Equation (RUSLE) (Renard et al., 1997). In order to increase the accuracy of erosion assessment and to predict the spatial location of soil erosion risk, many researchers combined erosion models with Remote Sensing tools and Geographic Information System (GIS) (Fistikoglu and Harmancioglu, 2002 ; Kefi et al., 2009 ; Yoshino and Ishioka, 2005).

In addition to researchers, like many countries, Tunisia, with a semi-arid climate and an irregular rainfall, is threatened by soil erosion by water. For this reason, the Tunisian government adopted different strategies of water and soil conservation. Therefore, the objective of this study is to assess the effect of soil erosion by water on-site and off-site on agriculture productivity at farm level using a combination between environmental and economic approaches and applied in watershed in Tunisia. This assessment can be helpful for a better environmental policy making. Furthermore, the environmental approach is based on erosion model, remote sensing and GIS. The economic model is built using mathematic programming.

2. MATERIALS AND METHODS

In this study, a method consists of a combination of environmental and economical model was applied in Boulabbouz watershed in Tunisia. The environmental approach is based on soil erosion model, remote sensing and GIS. The economical method is built using mathematic programming. Figure 1 shows the flowchart of the methodology.

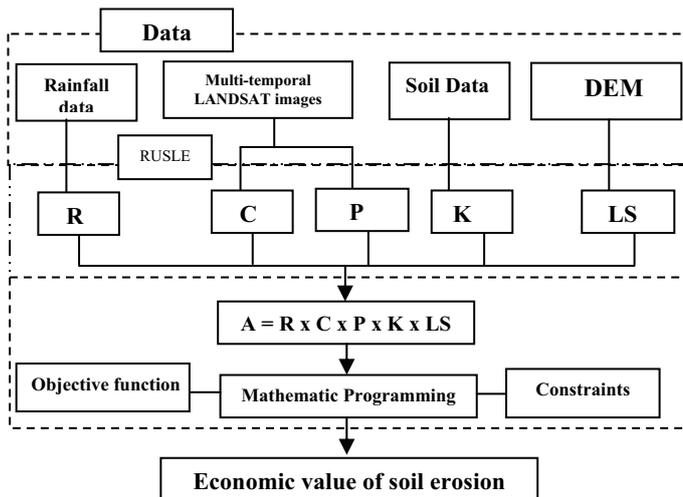


Figure 1 : Flowchart of the methodology

2.1 Study area

The watershed of the hillside dam Boulabbouz is located in Zaghouan between 36°14.404' to 36°16.9' N latitude and 10°10.833' to 10°10.868' E longitude (Figure 2). Its area is about 1435 ha covered by rangeland and agricultural land

suitable for cereal. The annual average rainfall is about 365 mm. The capacity of the hillside dam's reservoir is about 1 610 000 m³. The water available is used for the irrigated perimeter. Its area is about 34 ha.

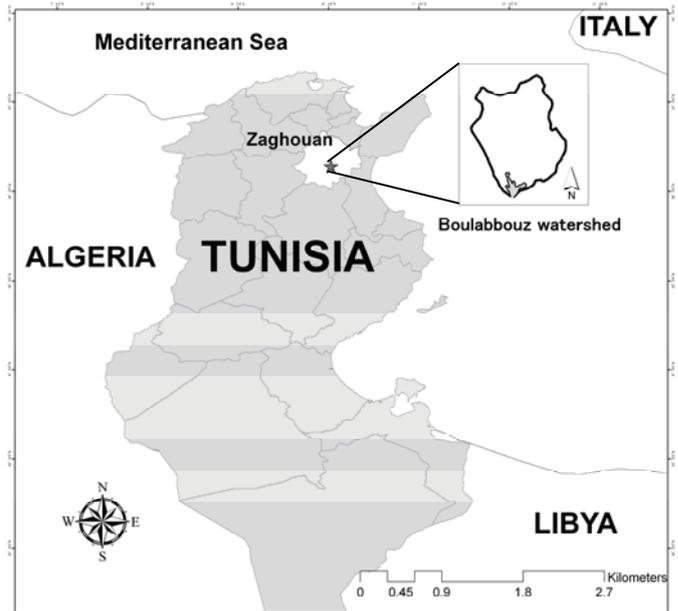


Figure 2 : Study area location

2.2 Environmental approach

The Revised Universal Soil Loss Equation "RUSLE" model aims at predicting soil loss from agricultural lands due to soil erosion by water. It is based on 5 factors related to rainfall, soil characteristics, topography, land use and land cover management. It can be written as

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

where A is the annual land loss (Ton/ha/year). R represents the rainfall erosivity factor (MJ.mm/ ha.Hr.year). K is the erodibility factor (Ton.ha.hr/ha.MJ.mm). C is the crop management factor. P is the supporting practices factor and LS is the slope length and slope inclination factor. C, P and LS are dimensionless.

In this study, these 5 factors are represented on a raster with a cell resolution of 5 x 5 m and geo-referenced to the Universal Transverse Mercator (WGS 84 Zone 32 N). They are computed using suitable datasets and appropriate software such as ERDAS imagine, Arcgis 9.2 and Arcview 3.2.

2.2.1 Rainfall Erosivity factor (R factor)

The rainfall erosivity factor (R factor) represents the erosive potential of rainfall. The R factor is the result of the sum of the total kinetic energy (E) for a storm and the storm's maximum 30 minutes intensity (I₃₀). The R factor formula can be written as follows:

$$R = \sum_{j=1}^n (E_k \cdot I_{30})_j \quad (2)$$

where R is the average rainfall erosivity factor (MJ.mm/ ha.Hr.year), E_k is the Total Kinetic energy of the storm, I₃₀ is

the storm's maximum 30 minutes intensity and j is the number of storms in the series. The Kinetic energy is expressed as follows (Foster et al. 1981):

$$E_k = 0.1119 + 0.0873 \cdot \text{Log}_{10}(I) \quad (3)$$

Rainfall data is obtained from the Zeckoune weather station. It is the closest weather station to the study area. These data are received from the Directorate of water and soil conservation (DG/ACTA) in Tunisia.

2.2.2 Soil Erodibility factor (K factor)

The erodibility factor K represents the susceptibility of the soil to erosion. It is calculated using the following relationship (Wischmeier and Smith 1978), which is a combination of the soil's texture, organic matter, structure and permeability.

$$K = 2.8 \times 10^{-7} \times (12 - \text{OM}) \times M^{1.14} + 4.3 \times 10^{-3} \times (s - 2) + 3.3 \times 10^{-3} \times (p - 3) \quad (4)$$

where K is the soil erodibility factor. OM is the percent of organic matter content. p is the soil permeability code which can have one of 6 code values: 1 refers to "Fast", 2 from "Moderate to fast", 3 to "Moderate", 4 from "Slow to moderate", 5 to "Slow" and 6 to "Very slow". s is the soil structure code ranging from 1 to 4. "Friable" is 1, "Fine polyhedral" is 2, "Medium to coarse polyhedral" is 3 and "Solid" is 4. M is the particle size parameter and can be written as:

$$M = (\% \text{ silt} + \% \text{ very fine sand}) \times (100 - \% \text{ clay}) \quad (5)$$

In order to analyze K factor, several datasets obtained from FAO soil classification, soil map of Tunisia and soil information of the study area are used. Therefore, different soil types are recognized.

2.2.3 Crop management factor (C factor)

It is used to reflect the effect of cropping and management practices on the erosion rate. The C factor ranges from near 0 for high density of vegetation to 1 for barren land. In this current study, a regression analysis between C factor and vegetation indices is used. In order to obtain C factor, three Landsat satellite images which are download from (<http://glovis.usgs.gov/>) are used. Table 1 shows the required information regarding to the images.

N°	Path / Row	Sensor	Acquisition Data
1	191 / 35	Landsat 5 TM	31/12/2006
2	191 / 35	Landsat 5 TM	22/04/2007
3	191 / 35	Landsat 5 TM	25/06/2007

Table 1 : Satellite images used

The main objective of using these images is to obtain an average of C factor by taking into account the phenology cycle of the crops. Furthermore, prior to image analysis, the atmospheric and radiometric effects on the image have been corrected using the real time of the sun elevation angle and the sun-earth distance. Then, supervised classification using the maximum likelihood algorithm is used to determine different land use classes in the study area (Lillesand and Kiefer 1994). In order to get the most accurate result of C factor of the each land use, a regression analysis based on its relation with

vegetation indices is employed. The Normalized Difference Vegetation Index (NDVI) is widely used to assess vegetation cover (Rouse et al, 1973). However, in semi arid and arid areas when the vegetation cover is sparse, NDVI can have problems of accuracy due to the influence of the background soil. For this reason, Huete (1988) proposed the Soil Adjusted Vegetation Index (SAVI) which minimizes spectral variance due to the background soil type. Further, Baret et al. (1989) proposed the Transformed Soil Adjusted Vegetation Index (TSAVI) for more accuracy. In this study, TSAVI is used. The TSAVI is based on soil line slope and intercept. It can be written as:

$$TSAVI = \frac{a(NIR - aR - b)}{aNIR + R - ab + X(1 + a^2)} \quad (6)$$

Where a: slope of the soil line, b: intercept of the soil line, NIR : Near Infrared Band or Band 4 and R : Red band or Band 3. X : Adjustment factor to minimize soil noise.

The soil line is a linear relationship between the bare soil reflectance observed in two different wavebands (Baret et al. 1993). It can be built by establishing a relationship between the reflectance of the NIR band and Red band. It is written as follows:

$$NIR_{soil} = a \cdot RED_{soil} + b \quad (7)$$

Where NIRsoil is the soil reflectance in the Near-Infrared Band, REDsoil is the Soil reflectance in the Red Band and a and b represent the parameters of the soil line.

2.2.4 Topographic factor (LS factor)

The Topographic factor is a combination of two factors, L and S, where L is the slope length factor, representing the effect of slope length on erosion and S is the slope steepness, representing the effect of slope steepness on erosion. In this study, LS factor is produced using TOPOCROP which is an extension of Arcview 3.2 (Schmidt and Persson 2003). This method is based on the use of Digital Elevation Model (DEM) which is got from ASTER Global Digital Elevation Model (ASTER GDEM) with a 30 m resolution and downloaded from (<http://www.gdem.aster.ersdac.or.jp/index.jsp>). Indeed, in this current study, a subset of Aster DEM 36 – 010 is utilized.

2.2.5 Supporting practice factor (P factor)

This factor represents the practices and measures used to control soil erosion by water such as counter ridges or terraces (Wischmeier and Smith, 1978). The value of P factor depends on the soil management measures which are related to the slope of area. In addition P value is attributed as 1 in area without erosion control practice, 0.11 in area with slope (0-5%), 0.12 with a slope (5-10%), 0.14 with a slope (10-20%) and 0.19 with a slope (20-30%). Erosion control measures are recognized using satellite images and aerial photos of Boulabbou watershed and supplemented by some observations in the field.

2.3 Economical method

The mathematic programming which is based on Objective function and constraints is used for farm level planning. The basic model can be written as below :

Optimize Objective function:

$$Z = C \cdot X$$

Constraints

$$\text{Subject to } AX \leq b$$

$$X \geq 0$$

(8)

Where :

- Z is the objective function to be optimized
- C is objective function coefficients
- X is vector of decision variables
- A is the matrix of technical coefficients
- b is a vector of constraint coefficients

In order to assess the impact of soil erosion, a soil loss constraint is added to the model. Therefore, the effect of soil erosion by water is evaluated by comparing the baseline scenario to two alternative scenarios where erosion is incorporated.

The baseline model is the optimal situation using the current production plan of the farmers. Indeed, this scenario is to maximize the total net income of the watershed under several constraints related to irrigated and rainfed areas, labor, irrigation water, crop rotation, rangeland and olive trees areas. In addition, the area under rangeland and arboriculture should not change.

Moreover, the first scenario consists of the valuation of soil erosion effect on-site. Indeed, a soil erosion constraint is added to the model. The total soil erosion and erosion effects by crops are obtained from the environmental approach.

The second scenario is to evaluate the economic value of soil erosion on-site and off-site. Due to lack of data, the off-site effect of soil erosion is limited of the effects of reservoir sedimentation in particularly. To do so, the soil erosion constraint will be kept and it is supposed that 10 years of sedimentation will reduce the water available for irrigation.

In order to get the required data and information about the price, crops 'yield and input (fertilizer use, labor, water, land,...) a socio-economic survey was conducted in the watershed.

3. RESULTS AND DISCUSSION

In order to obtain the economic value of soil erosion by water, the annual soil loss of the watershed using RUSLE model is estimated. This value is then incorporated in the mathematic programming as a constraint.

3.1 Environmental approach

RUSLE erosion model is composed of 5 factors and the finding of each one is presented below.

3.1.1 R factor

The R factor is considered as the most important factor for soil erosion by water. In this work, the average of R factor is about 396.77 MJ.mm/ ha.Hr.year which can be considered as a low value of erosivity (Foster et al.,1981).

3.1.2 K factor

The mean value of K factor is 0.032 Ton.ha.hr/ha.MJ.mm which is recognized as a moderate soil erodibility.

3.1.3 C factor

C factor depends on the land use. Moreover, the supervised classification indicated that the watershed is covered especially by rangeland, dry farming land such cereal, olive tree and

irrigated crops such as melon and watermelon in summer and bean in winter. The finding is shown in table 2.

Class	Land occupation	Area (%)
1	Rangeland	52.08
2	Arboriculture	3.87
3	Dry land	21.20
4	Irrigated land	1.20
5	Bare land	19.94
6	Water	1.70

Table 2 : Land occupation distribution

Furthermore, the relationship between the C factor and the TSAVI is obtained using a statistical regression. This regression is based on the correlation of the C factor value of each land use and the mean value of the TSAVI's pixels. This vegetation index is acquired by estimating the soil line. Table 3 shows the characteristics of the soil line.

N°	scene date	Slope (a)	intercept (b)	R ²
1	31/12/2006	0.95	0.033	0.84
2	22/04/2007	1.19	0.013	0.77
3	25/06/2007	1.11	0.098	0.92

Table 3 : soil line characteristics

In this study, three satellite images with different periods of phenology cycle of the crops are used. Indeed, the image of December shows the beginning of the growing cycle of cereals and winter irrigated crops. April image represents the growing period of cereal and the harvest season of winter crops and beginning of cycle of summer crops. June image indicates the harvest period of cereal and growing period of summer crops. Additionally, The best-fit regression equation of the relationship between C factor and TSAVI is an exponential equation which can be written as follows.

$$C = \alpha \cdot e^{-\beta \cdot TSAVI} \tag{9}$$

Where α and β are respectively 1.02 and 14.25
Furthermore, the result of this relation is shown in table 4

Class	Land occupation	C factor
1	Rangeland	0.21
2	Olive trees	0.33
3	Cereals	0.30
4	Market garden	0.42
5	Bare land	1

Table 4 : C factor attribution

These datasets are used to establish the C factor map useful to map soil erosion by water for the watershed.

3.1.4 LS factor

The results show that LS value is high in mountain area. Indeed, about 6 % of the watershed has an LS factor more than 5 which indicated high slope steepness and consequently, a high vulnerability to erosion. However, about 39% of the watershed particularly the area close to the reservoir of the hill dams has an LS factor lower than 1. It represents the flat land of the watershed.

3.1.5 P factor

In this watershed, the mean of P factor is 0.967 which is close to 1. This value indicates that the erosion control measures in this watershed are very low and quite inexistent.

3.1.6 Soil erosion by water

The soil loss obtained from the product of the 5 factors. The spatial distribution of soil loss is presented in figure 3.

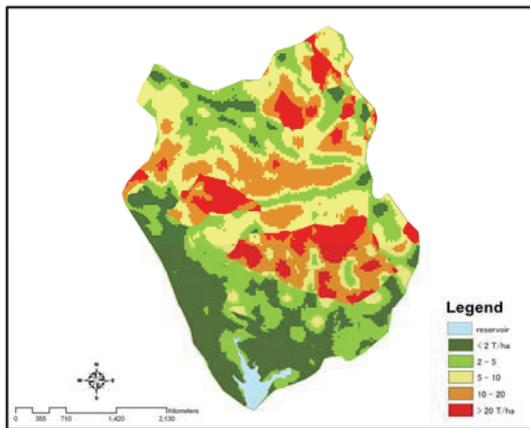


Figure 3: Spatial distribution of Soil erosion risk

This map of soil erosion by water shows that soil loss is ranging from lower than 2 T/ha to more than 20 T/ha. The finding of this distribution is presented in Table 5.

Class	Soil loss value (T/ha.year)	Erosion risk classes	Area (%)
1	< 2	Very Low	21.85
2	2 - 5	Low	25.82
3	5 - 10	Moderate	24.24
4	10 - 20	High	17.94
5	> 20	Very High	10.15

Table 5 : Distribution of erosion risk

The results show that the erosion risk increases in particular from mountainous areas to gentle areas. Erosion risk occurs in areas with steep slope, poor vegetation, high soil erodibility and no erosion control. Moreover, land use and management practices are the deciding factor in determining the extent of soil erosion and erosion induced degradation (Eaton, 1996). In addition, the identification of areas at high-risk of erosion is of prime importance in soil conservation planning (Zhou et al, 2008). Moreover, understanding specific problem and formulate suitable measures requires a detailed knowledge of not only the biophysical nature of degradation but also its economics effects on farms (Gretton and Salma, 1997).

3.2 Economic model

In order to estimate the value of soil erosion by water, a baseline scenario is compared to alternative scenarios where soil erosion effects are incorporated. Furthermore, scenario 1 deals with the estimation of soil erosion effects on-site and the second scenario consists of the estimation of both effects on-site and off-site. In this study, the off-site effect is obtained from the

estimation of the reduction of water available for irrigation due to the sedimentation of the reservoir.

The results of land occupation and the total income of the watershed are presented in table 6.

Land use	Baseline scenario	Scenario 1	Scenario 2
Rangeland (ha)	748	748	748
Olive trees (ha)	56	56	56
Rainfed crops (ha)	204.35	82.3	85.71
Irrigated winter crops (ha)	26.25	26.25	26.25
Irrigated summer crops (ha)	17.5	17.5	5.92
Total Income (DT)	273 739	225 796	186 355

Table 6 : Scenarios results

The findings show that soil erosion by water has a negative impact in the agriculture productivity. Indeed, the first scenario shows that total income is reduced with about 17 % and the total area for rainfed crops is decreased. Regarding to this comparison, the on-site effect is about 34 DT/ha. Furthermore, the results indicate that the farmers try to preserve their land and to decrease the effect of soil erosion by changing their crops activities. Indeed, dry agricultural lands are very sensitive to soil erosion and need good management practices.

Furthermore, the second scenario shows that total Income of the watershed is reduced with about 32%. In addition, farmers modified also their activities by diminishing the irrigated areas because the water available is not enough especially in summer season. The erosion effect value for this scenario is about 61 DT/ha. Hence, the estimation of economic value of soil erosion is helpful for the farmer and decision makers to recognize the problem and to implement conservation measures (Martinez-Casasnovas and Ramos, 2006). The economic model proposed acceptable results but it can be improved by adding some constraints.

4. CONCLUSION

Soil erosion is a major environmental problem. It affects agriculture productivity (Gretton and Salma, 1997). Therefore, in this current study, a method based on the combination of environmental and economic approaches is proposed to assess the effects of soil erosion by water.

Furthermore, the environmental approach consists of the integration of RUSLE erosion model with remote sensing data and GIS. In addition, the use of multi-temporal satellite image and TSAVI are useful to estimate the accurate C factor with taking into account the growing cycle of the crops. In addition, the mapping of soil erosion risk is useful to identify vulnerable areas.

Moreover, the economic model which is based on objective function and constraints is helpful to assess the behavior of the farmers to minimize soil erosion effect. Indeed, in order to prevent natural resources, farmers reduced crops with high sensitivity to soil erosion by water from their lands.

This approach can be helpful for the decision makers to determine whether it is economical to allow erosion to occur without conservation or to do erosion control to reduce it.

However, this method which provides a framework to estimate the cost of erosion needs some improvements.

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