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INTEGRATING GIS AND AHP METHOD FOR EROSION VULNERABILITY DETERMINATION FOR LABIOD WATERSHED (EASTERN ALGERIA)

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Abstract: The LABIOD Watershed is a space of high vulnerability to soil erosion which causes an irreversible situation of desertification. This study illustrates the combination of analytic hierarchy process (AHP) with geographic information systems (GIS) to resolve the complicatedproblem of soil erosion in this semi-arid area. In this paper, pair-wise comparisonmatrixes and consistency ratio in a multi-criteria analysis method are computed in IDRISI Selva software by using GIS with Revised Universal Soil Loss Equation (RUSLE) model. As the result, consistency ratio (CR) was very significant and highlights the advantages of this application in the determination of vulnerability to erosion which constitutes a decision making toolfor adjusting necessary protection measures.

Keyword: AHP, decision making tool, erosion vulnerability, GIS, LABIOD watershed, RUSLE.

1. INTRODUCTION

Recently, there is a growing interest on the use of geographic information systems (GIS) as a decision support tool in multi criteria analysis (MCA) for the various benefits that presents. At present, Algeria knows very complex process of soil degradation where 50 million hectares are affected by desertification and water erosion. However, LABIOD watershed is facing dynamic process of erosion due to its local terrain and vegetation cover reduction. The GIS was found practical when used for modeling natural risks. The RUSLE model is one of the most widely-used to predict soil erosion (Renard et al., 1997; Wischmeier & Smith, 1978). In this model, the following criterion has to be considered as influencing erosion process such as of rainfall erosivity, topographic factor, soil erodibility and crop management and agrotechnics.

The objective of this study is carried out in order to identify study area vulnerability to erosion integrating GIS and AHP approach (Saaty, 1980; 2004); to develop a decision making tool for erosion risk and formulate soil conservation actions.

2. THE STUDY AREA

LABIOD watershed is situated East of Algeria in the oriental part of the Saharian Atlas between northern latitude 34°52' - 35°24' and eastern longitude 5°54' - 6°35’.

It is a basin of the big hydrological Basin of Chott Melrhir and extends a 1300 km². It is composed of 3 main valleys: LABIOD, Chenaoura and T’kout forming by their confluence Ghassira valley. It is created by the meeting of torrents with abrupt slopes of Chelia Mountain which represents the highest summit with 2326m generating longitudinal and transverse slopes along its exposure.

After crossing tighten stream of Ghassira, it is steep-sided in Ghoufi canyons and M’Houneche gorge then opens a way towards Saharian plain until Foum El Gherza dam. The study area is characterized by a semi-arid climate and tamed river system which crosses alternate stratum between limestone and marl or red clay and sand in the south bend on antyclinal and synclinal series with north-east / south west general exposure.

3. MATERIALS AND METHODS

The analytic hierarchy process (AHP) was introduced in 1980 by Saaty in aim to resolve complex problems in a hierarchical model and it has also been recognized as an effective Multi criteria decision system (Malczewski, 2006). It is a decision-making approach which simplifies complicated problems related to land use planning (Chandio & Bin Matori, 2011) and presents the most appropriates approach for soil erosion predicting model Revise Universal Soil Loss Equation (Renard et al., 1997) using GIS. The important criteria correspond to RUSLE model factors as shown in equation (1) and identified by discussions with experts.

$$A = R^* K^* LS^* C^* P \qquad (1)$$

Where:
A: is the predicted long-term average soil loss (ton/ ha /yr)
R: rainfall–runoff erosivity factor (MJ. mm ha^{-1})
K: soil erodibility factor (ha. MJ.mm)
LS: slope length–steepness factor (dimensionless);
C: crop management factor (dimensionless);
P: is the land management practice factor (dimensionless, ranging between 0 and 1).

4. ASSESSMENT OF THE SOIL EROSION CRITERION

4.1 Criteria weights and standardization:

In aim to perform this study, a research process consists of a choice of components where each one influences erosion process and centers establishing set of standardized criteria then assign ranks and choices by expert's view to compareeachelement in the corresponding leveland calibrated them on the numerical pair-wise comparison scale (Table1). Ratings are usually converted to numerical weights on a scale 0 to 1 with overall summation of 1. To make comparisons possible we set the suitability values of the factors to a common scale. Then, to standardize the criterion FUZZY membership functions are used and linear membership were adopted to convert input data into corresponding criterion layers. The linear method used is shown in the following equation:

$$\mu (x) = (x - min) / (max - min) \qquad (2)$$

Where:
min and max are input data.
$\mu (x) = 0$ if $x < min$
$\mu (x) = 1$ if $x > max$

AHP pair-wise comparison matrix is constructed, where each criterion is compared with the other criteria to get relative weights expressed in numerical scale as follows:

$$\omega = (\omega_1, \omega_2, \ldots, \omega_n) \qquad (3)$$

The sum of weights must be 1 and is used to derive (CR) which is given by the following equation:

$$CR = CI / RI \qquad (4)$$

Where:
CI: consistency index.
RI: random consistency index.
The consistency index is calculated as follows:

$$CI = (\lambda_{max} - n) / (n - 1) \qquad (5)$$

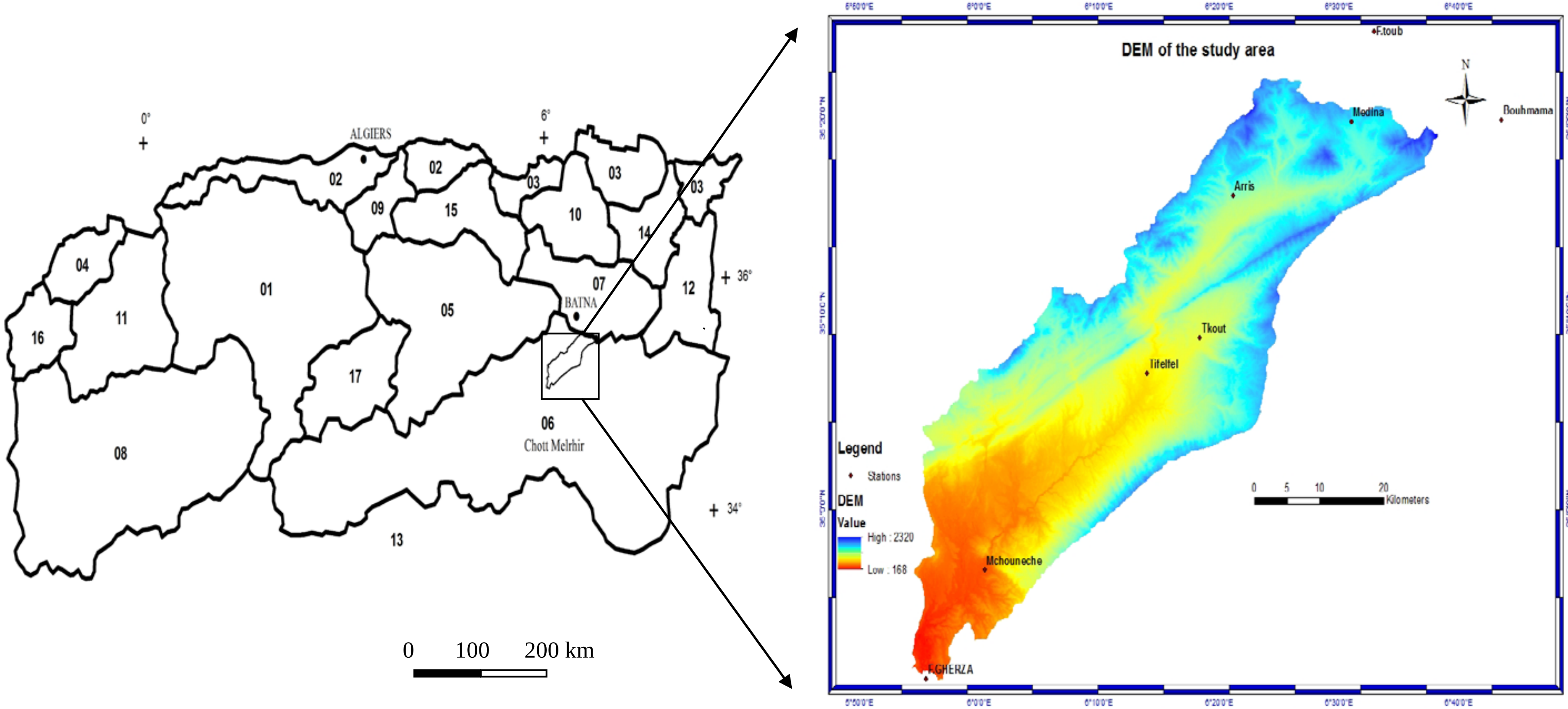
Where:
λ_{max}: Eigen value, sum of the products between each element of the Eigen vector and column totals.
n: number of factors.

This step of stage is computed automatically using IDRISI Selva 17 software.

For the (RI), Saaty (1980) proposed that this index is used by comparing it with the appropriate one and he arbitrarily generated reciprocal matrix using numerical scale.

Table 1. Pair-wise comparison scale for AHP preferences

Intensity of relative importance	Definitions
1	Equal importance
2	Equal to moderate importance
3	Moderate importance
4	Moderate plus
5	Strong importance
6	Strong plus
7	Very strong demonstrated importance
8	Very very strong
9	Extreme importance



The study area

01: Cheliff 02: Côtiers algérois 03: Côtiers constantinois 04: Côtiers oranais
05 : Chott Hodna 06 : Chott Melrhir 07 : Hauts Plateaux constantinois
08 : Hauts Plateaux oranais 09 : Isser 10 : Kebir-Rhumel 11 : Macta
12: Medjerda 13: Sahara 14: Seybouse 15: Soummam 16: Tafna 17: Zahrez

Figure 1. Location of the study area

The average Random Index of sample size 7 matrices is shown in table 2.

Table 2. Average Random consistency Index (RI)

Matrix size	1	2	3	4	5	6	7
RI	0	0	0.58	0.9	1.12	1.24	1.32

Finally, Criteria weights were automatically computed in decision support tool using IDRISI Selva17 software in GIS where 0.40, 0.15, 0.0731, 0.135 and 0.242 are respectively (R), (K), (LS), (INDVI) and (P) weights.

The Consistency Ratio (CR) determined through IDRISI Selva 17 software is 2% less than 10%which mean that the judgments are acceptable and we don't need to reconsider some pair wise values.

4.2 Rainfall erosivity

Rainfall erosivity (R) is defined as the potential ability of precipitation to cause erosion and is a function of the physical characteristics of rainfall.

Various experimental and statistical based rainfall erosivity determination equations exist for different regions of the world (Roose, 1987; Wischmeier & Smith, 1978; Renard & Freimund, 1994; Ferro et al., 1999; Van Leeuwen & Sammons, 2003; Diodato, 2004). It can be concluded that there is no acceptable standard formulation for the determination of R.

The rainfall erosivity component in the case of the widely used RUSLE soil erosionmodel is computed using the equation given by Wischmeier & Smith (1978). The estimation of the factor R requires the product of rain event kinetic energy (Ec) and maximum 30-minute intensity (I_{30}).

$$R = Ec * I_{30} \quad (6)$$

Where:

Ec: total kinetic energy of rain (MJ / hour);

I_{30}: maximum 30-minute intensity (mm / hour).

In the case of LABIOD watershed, the rainfall intensity is not recorded at the meteorological stations and there is an even more sporadic availability of long term continuous rainfall data which is a prerequisite to compute the R-factor.

According to Wischmeier & Smith (1978), the annual erosivity index (R) is computed using the following equation.

$$R = (k*C)^n \quad (7)$$

Where:

k = 0.751 corresponding to semi-arid area and n = 0.80 corresponding to semi-arid and sub humid index.

$$C = h_1 * h_{24} * H \quad (8)$$

Where:

h_1: height of rain fallen in one hour (cm).

h_{24}: height of rain fallen in 24 hours (cm).

H: Annual average height of rains (cm).

The gauging station rainfall data from 1973 to 2010 are obtained from National Agency of Water Resources (NAWR) for the 8 ground stations, 5 in and 3 out the river Basin. Rainfall data for the ground stations were statistically adjusted with Gumbel distribution.

After standardized rainfall erosivity values between 0 and 1 are ranged in 3 categories: low, medium and high erosivity according to LABIOD watershed characteristics where value is higher than 125 t/ha in the northern portion and lower than 19 t/ha in the southern area.

4.3 Soil erodibility criterion

The study area is found to be dominated mostly by a clayey and silty type of soil which is reported to be highly fragile and susceptible to water erosion.

The soil erodibility factor is computed as a function of soil properties such as texture, organic matter content, permeability and structure.

RUSLE model use a restrictive and applied definition of soil erodibility and it is considered as the change in the soil per unit of applied external force or energy, when viewed from a fundamental standpoint (Renard et al., 1997).

The soil erodibility factor is computed by the following formula (Wischmeier & Smith, 1978; Renard et al., 1997):

$$100\,K = 2.1 * M^{1.14} * 10^{-4} (12 - OM) + 3.25 (s - 2) + 2.5 (p - 3) \quad (9)$$

Where:

M: (% silt + very fine sand %) * (100 - % clay)

OM: percentage of organic matter.

s: soil structure code (1 : very fine granular, 2 : fine granular, 3 : coarse granular, and 4 : platy, massive, or blocky),

p: permeability class (1: rapid, 6.0-20.0 in/hr; 2: moderate to rapid, 2.0 -6.0 in/hr; 3: moderate, 0.6-2.0 in/hr; 4: slow to moderate, 0.2- 0.6 in/hr; 5: slow, 0.06 - 0.2 in/hr; 6: very slow, less than 0.06 in/hr).

Where:

1 inch = 25.4 mm

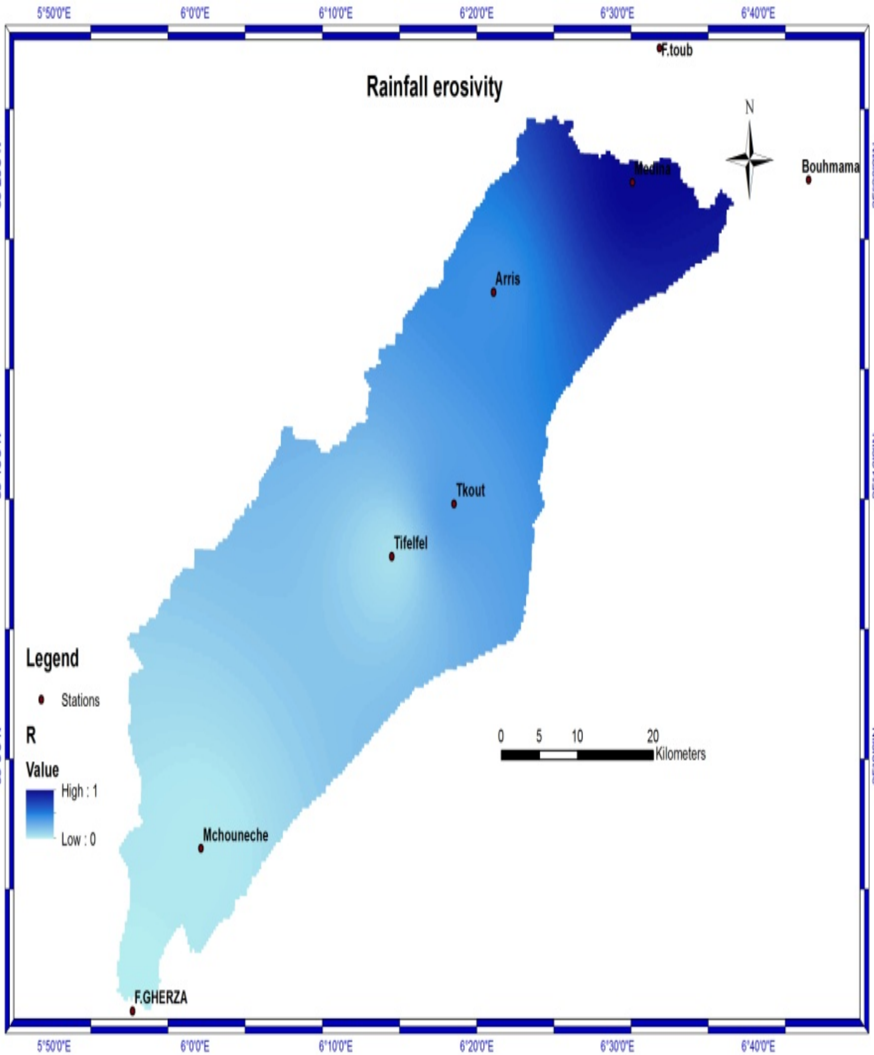


Figure 2. Rainfall erosivity

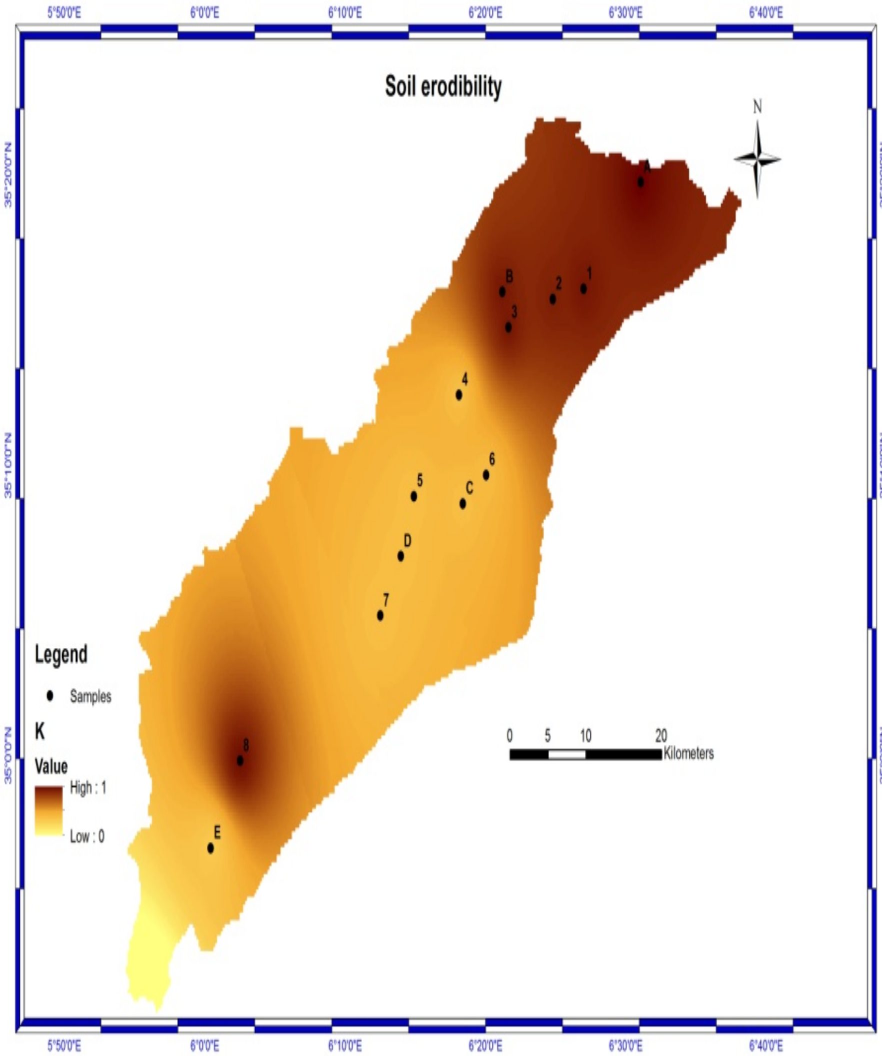


Figure 3. Soil erodibility

For conversion to international system (SI), K values are divided by 7.59 because K is in US customary units.

As the erodibilty factor is crucial to be determined in the whole study area where few studies exist for LABIOD watershed, K was computed on the basis of Kati (2012) and SONATRACH (2000) studies for which soil particle size analysis and hydro geological properties data are available.

For physical analysis, the pipette method of Robinson (1922) was applied for13 soil samples taken in the A horizon from different parts of the study area to determinate the finer fractions andthis method requires that the soil suspension be completely dispersed before sedimentation begins. For soil pH, it was fluctuated between 7.37 and 8.85 after chemical analysis with electrometric method.

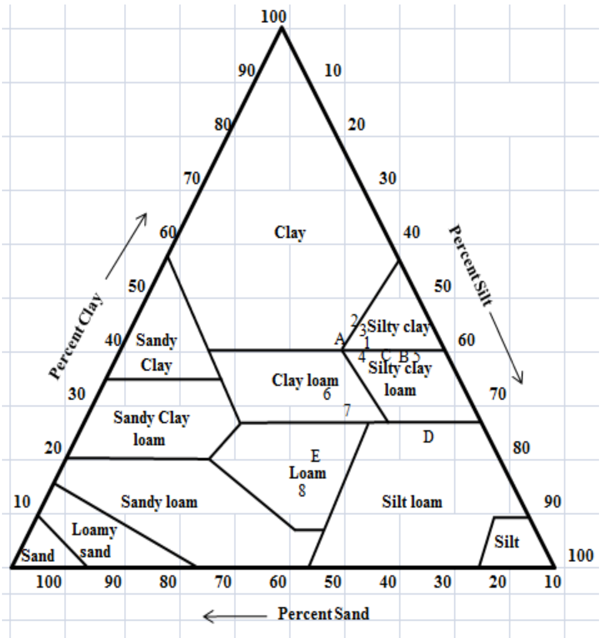


Figure 4. Soil samples texture

Soil permeability was estimated by determining infiltration so that low infiltration signifies slow permeabilityon the bases of water balance equation as follows:

$$P = R_f + E_V + I \qquad (10)$$

Where:
P: precipitation (mm)
R_f: runoff (mm)
Ev: evapotranspiration (mm)
I: infiltration (mm)

R_f and ETc were calculated as follows:

$$R_f = P^3 / 3 * ETc^2 \qquad (11)$$

$$ETc = 16 * (10 * T / I)^a \qquad (12)$$

Where:
T: monthly average temperature (°c)
I: thermal index

$$I = (0.09 * T)^{1.5} \qquad (13)$$

a: temperature index

$$a = 0.049239 + 1.792 * 10^{-2} * I - 7.71 * 10^{-5} * I^2 + 6.75 * 10^{-7} * I^3 \qquad (14)$$

It is important to know that useful available water (UAW) depends of precipitation, soil saturation and (P - ETc) surplus.
If P > ETc then ETr = ETc which means that UAW is affected by (P - ETc) surplus until it is complete.
If P < ETc then ETr = P and UAW = 0

For real evapotranspiration (ETr), it was calculated as follows:

$$ETr = P / (0.9 + P^2 / L^2)^{0.5} \qquad (15)$$

Where:
ETr: real crop evapotranspiration (mm)
L: annual average temperature (°c)

$$L = 300 + 25 * T + 0.05 * T^3 \qquad (16)$$

$$DI = ETc - ETr \qquad (17)$$

Calculated water balance parameters are shown in table 4.

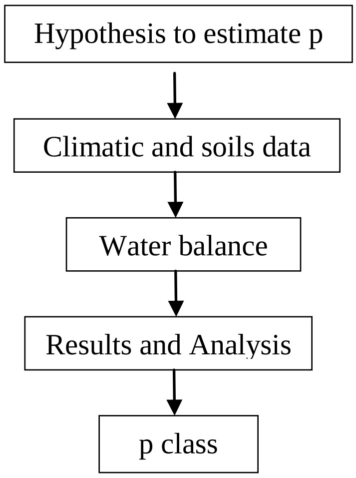


Figure. 5 Estimating soil permeability organigram

The calculated infiltration was 13.5 mm which means that soil permeability is slow to moderate but this evidence should take into account the interannual variations of precipitation and soil saturation.

The category of low erodibility corresponds to limestone Formations; medium is corresponding to limestone intercalations with marl and for high and very high erodibility it corresponds to marl with a silty clay loam, clay and clay loam texture.

Table 3. Samples physico-chemical properties

Samples	Horizon (cm)	Clay (%)	Silt (%)	Sand (%)	Texture	OM	pH
A	20	41.5	37.7	16.8	C	3.75	8.46
B	20	37.8	53.4	7.4	SCL	2.30	8.55
C	20	34.5	50.7	8.9	SCL	2.10	7.37
D	20	23.1	45.6	10.4	SL	1.98	8.56
E	20	20.7	31.0	40.2	L	1.76	8.15
1	20	40.3	41.6	13.2	SC	1.61	8.65
2	20	42.4	31.7	10.1	C	2.72	8.85
3	20	41.8	41.1	13.1	SC	1.74	8.50
4	20	38.9	46.7	8.3	SCL	1.34	8.46
5	20	38.5	51.2	7.7	SCL	1.83	8.44
6	20	31.3	35.4	27.2	CL	3.02	7.90
7	20	26.9	32.8	23.9	CL	1.57	7.68
8	20	18.1	26.3	41.5	L	2.75	7.90

Texture: C= Clay, CL=clay loam, SC= silty clay, SCL= silty clay loam, L= loam, LC= loamy clay, SL= silt loam, OM: % of organic matter, pH: in saturation soil paste (H_2O)

Table 4. Water balance of Medina and M'chouneche stations (ANWR, 2002; Mebarki, 2006)

Station	Months											
Medina	September	October	November	December	January	February	March	April	May	June	July	August
P	48.5	38.4	42.2	37.4	36.1	29.1	40.1	39.2	39.8	25.4	8.6	32.6
ETc	92.1	56.0	26.6	11.6	11.0	14.0	25.7	51.4	79.5	125.6	158.1	143.7
UAW	0.0	0.0	15.6	25.8	25.1	15.1	14.3	0.0	0.0	0.0	0.0	0.0
ETr	48.5	38.4	26.6	11.6	11.0	14.0	26.7	39.2	39.8	25.4	8.6	32.6
DI	43.6	17.6	0.0	0.0	0.0	0.0	0.0	0.0	39.7	100.2	149.5	111.1
R_f												38.3
M'chouneche												
P	9.2	13.4	13.0	14.6	11.4	10.3	19.0	13.4	9.5	4.2	1.2	2.5
ETc	168.6	84.3	33.0	14.6	14.0	21.0	36.2	69.7	135.4	210.8	305.5	272.8
UAW	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
ETr	9.2	13.4	13.0	14.6	11.4	10.3	19.0	13.4	9.5	4.2	1.2	2.5
DI	159.4	70.9	20.0	0.0	2.6	10.7	17.2	56.3	125.9	206.6	304.3	270.3
R_f												0.27

P: precipitation (mm), ETc: potential crop evapotranspiration (mm), UAW: useful available water (mm), DI: deficit irrigation (mm), ETr: real crop evapotranspiration (mm), R_f: runoff

The standardized K values are ranged in 4 categories where water erosion vulnerability level from K factor is insignificant when K is under 0.039, moderate when K is between 0.039 and 0.053 and high when K is between 0.053 and 0.066 and very high when K is higher than 0.066.
The result of samples analysis shows some anomalies in the soil structure and organic matter percentage which is probably due to the irrational use of fertilizers or the expiration of the used dispersion agents.

4.4 The topographic criterion

Though, the incorporation of digital elevation models (DEM) into GIS, a topographic factor LS can be determined.

The accuracy with which topographic factor LS can be estimated depends on DEM resolution (30m) in this case.

The topographic factor (LS) was calculated on the basis of Moore & Burch, (1986) formula using DEM:

$$LS = (\text{Flow accumulation} * \text{resolution} / 22.13)^{0.5} * (\sin ß / 0.0896)^{1.3} \qquad (18)$$

Where:
ß: slope in degrees.

The flow accumulation was calculated using the spatial analyst extension after slope deriving from DEM using hydrological tools.

Then, flow direction determined by sinks is derived to obtain flow accumulation.

As the other criteria standardized values are ranged in 3 categories: low, medium and high.

4.5 The NDVI criterion

The source data for representing the vegetation cover of the study area is obtained from the LANDSAT satellite's TM data.
Normalized Difference Vegetation Index (NDVI) which is basically a remote sensing based vegetation index is used here to reflect the vegetation cover characteristic of the region.

The values are computed as the ratio of the measured intensities in the visible red and the near-infrared spectral bands of the electromagnetic spectrum using the following formula:

$$NDVI = (NIR - VR) / (NIR + VR) \qquad (19)$$

Where:
NIR: near infrared band
VR: visible red band

De Jong (1994) determined the following function to estimate USLE-C factor from NDVI and revised by (De Jong et al., 1994).

$$C = 0.431 – 0.805 * NDVI \qquad (20)$$

Where:
C: crop management factor

The function presents a modest correlation and C values were low and doesn't exceed 0.43 that is why NDVI is taken in this study.

Incorporation of vegetation increase and its varieties in the form of NDVI map allow us greater information about spatial vulnerability to erosion and values are ranged in 3 categories: low vegetation is under 0.29, medium is from 0.3 to 0.53 and high vegetation when NDVI is higher than 0.53.

4.6 Land conservation practice factor:

The land conservation practice is considered as a reducing soil erosion factor.
We have assigned values for each conservation practices as seen in study areas; 0.25 for crop land to 1 for area with no conservation practices.

Table 5. Conservation practices and P values (Wischmeier & Smith, 1978)

Conservation practice	P values
No conservation	1.00
Transverse sloping culture	0.75
Culture following contour lines	0.50
Culture in alternates bands	0.38
Culture in alternates bands and in contour line	0.25

When all RUSLE model thematic layers are determined, the vulnerability to erosion is obtained by using the Fuzzy Overlay tool operator in ArcGIS10.1 software.

The erosion vulnerability was ranged in 4 categories according to FAO, PNUD, and UNESCO (1980) classification of soil degradation by water erosion: low is under 10 t/ha/yr, medium is between10 and 50 t/ha/yr, and high is between 50 and 200 t/ha/yr and very high vulnerability is higher than 200 t/ha/yr.

5. RESULTS AND DISCUSSION

From the first sight, it appears that LABIOD watershed is really vulnerable to soil erosion. Rainfall erosivity is considered as one of the important criteria that influences the soil erosion processes and detachability of soil particles depends on soil and rainfall characteristics while overland flow with or without rill systems and their characteristics, governs transportability.

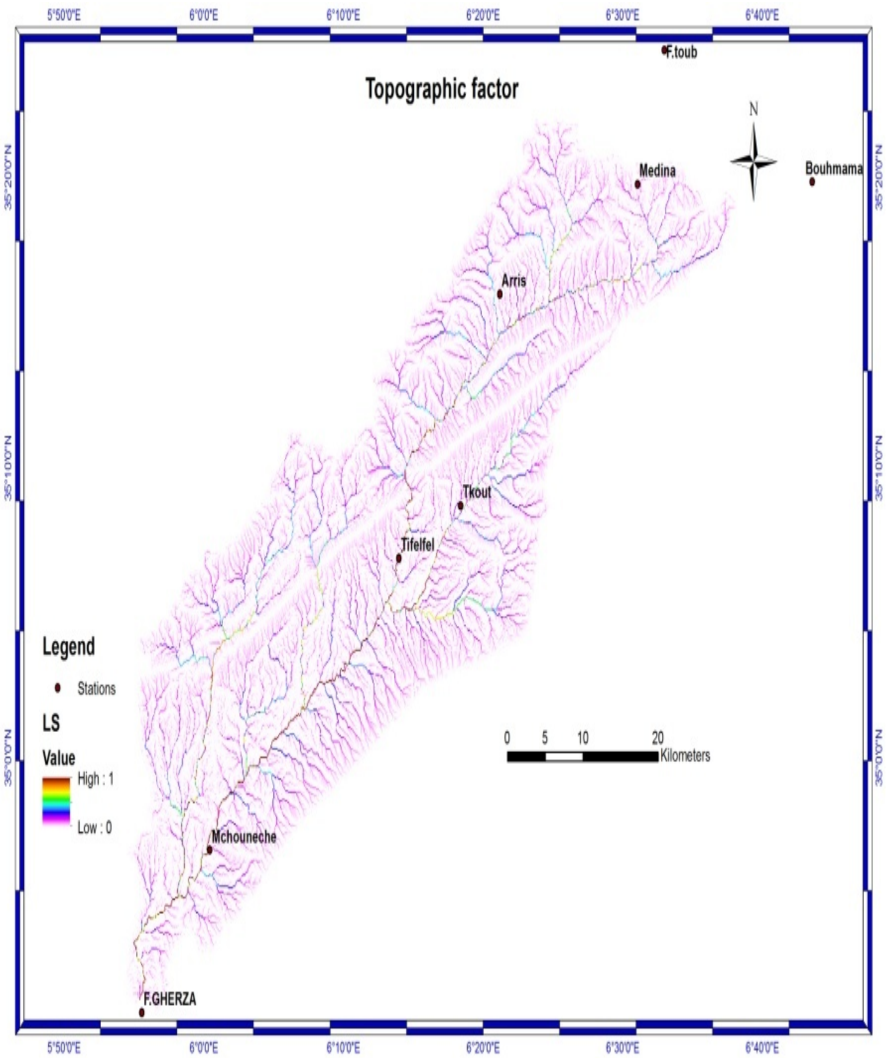


Figure 6. Topographic factor

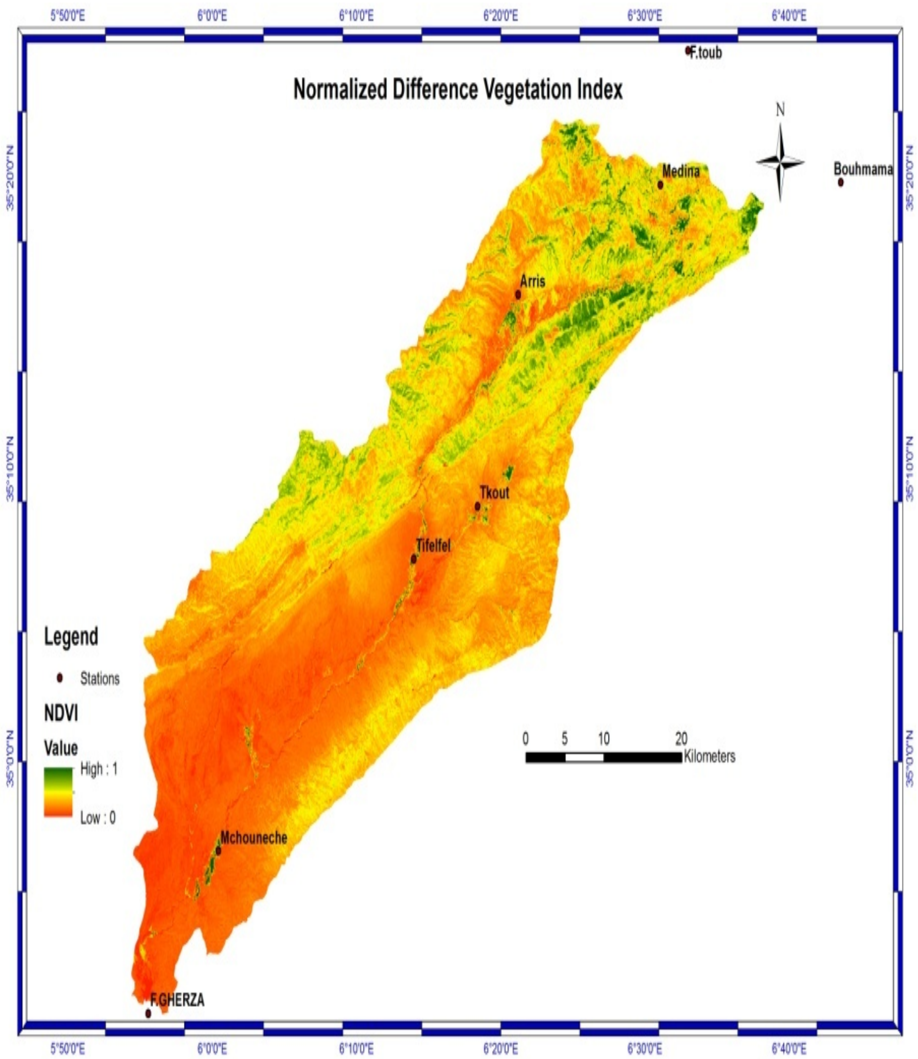


Figure 7. Normalized Difference Vegetation Index

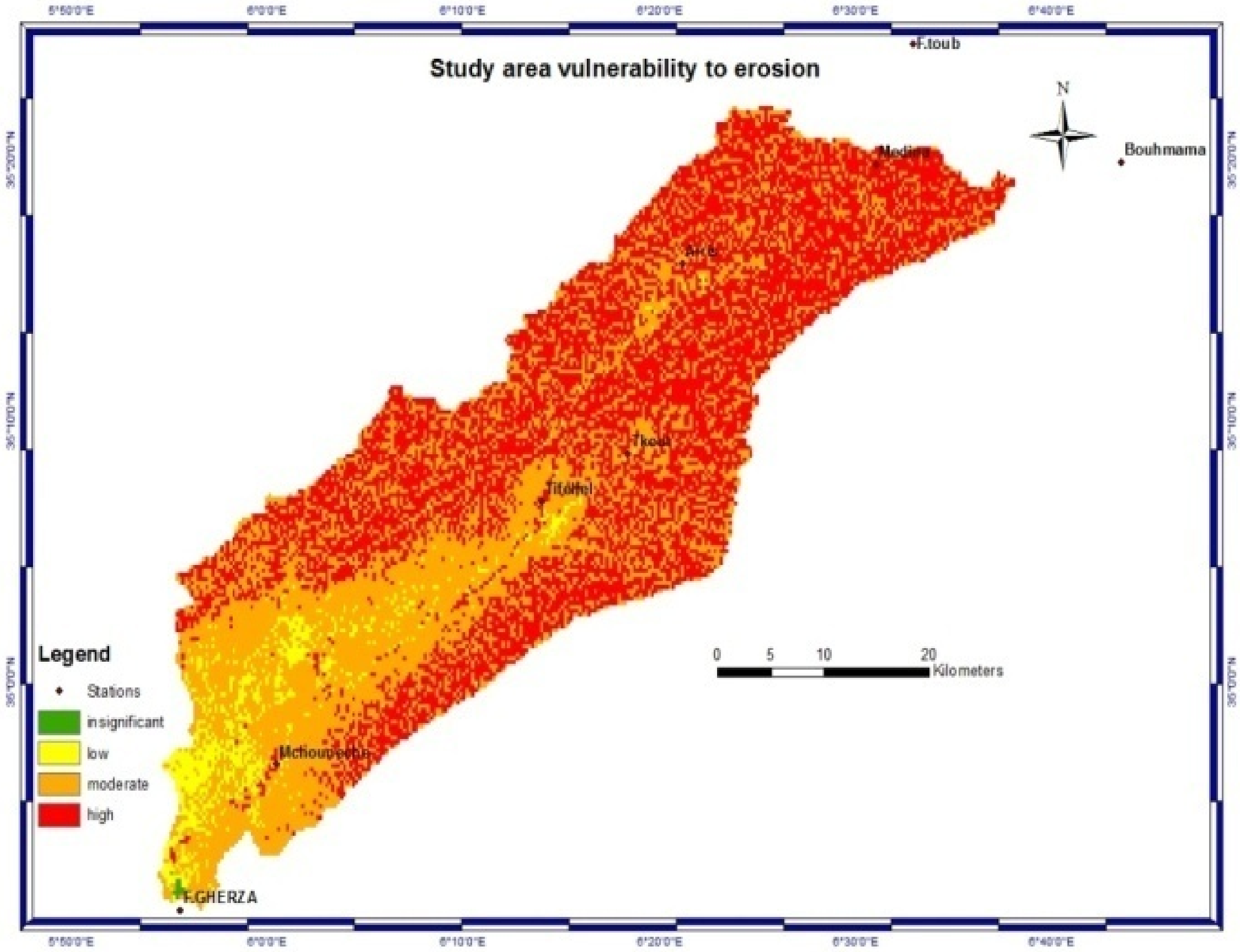


Figure 8. Study area for vulnerability to erosion

The higher vulnerability to erosion corresponds to mountainous zones with maximum value of 307 t/ha/yr which means that soil degradation is more than 13.3 mm/yr; due to erosivity aggressiveness, vegetation cover reduction in addition to the erodibility processes which consist of soil detachment and transport by raindrop impact and surface flow, due to topography especially slopes and no infiltration of rainwater into the soil which is favoring the development of deep cracks and causes the departure of gullies in sensitive silty clayey texture resulting in the production of diffuse runoff.

From McGillivray & Donovan (2007) study, slopes less than 11 % (5°) are reported to be depositional and slope higher than 45 % (20°) as erosional and it is also found that the effect of slope can be greatly reduced by vegetation cover.

For that purpose, we suggest some measures to reduce vulnerability to erosion in this watershed portion such as reforestation, perfecting the drain system and ecological restoration of stream by protection of banks.

Areas of low vulnerability to erosion correspond to the lowlands of study area which are sediments deposit zones characterized by arid climate which is favorable for irrigated cultures.

The low values registered in south portion of the watershed reveals that it is a deposit sediment zone which causes Foum EL Gherza dam mudding where only 14 million m^3 are stocked from a total capacity of 47 million m^3 (Remini et al., 2009).

According to the results, soil vulnerability to erosion increases with erosivity aggressiveness, topographic factor; soil erodibility and vegetation cover properties validating Taabni & Kouti (1993) study which reveals that 45% (1 million hectares) of Tellienne areas in Algeria are affected by erosion.

The application of conservation practices factor should be taken with care when applied for watershed with no conservation practices.

In spite of the results, the accuracy of some data remains influenced by many conditions such as the erodibility factor which is extremely prejudiced by the use of fertilizers in arboriculture and causing degradation of soil properties or the erosivity factor which didn't take into account the interannual variations of precipitations which means that it is suitable to take seasonal precipitation for more precision adding to this, the period of insecurity that Algeria knew since 1990 and which caused social and environmental problems in this marginalized region such as the rural exodus or ecosystem degradation.

These complicated conditions can be resolved by incorporating the result of this paper in local authorities policy as a decision making tool.

6. CONCLUSION

The model described in this paper provides the case of LABIOD watershed (east of ALGERIA) and constitutes a contribution to the erosion studies.

The integrated GIS and AHP approach in soil erosion analysis is advocated to identify vulnerable zones to erosion.

Pair-wise comparison matrix was constructed using AHP method and priority weights were calculated in decision support IDRISI Selva software.

This research can be used as a decision making tool which help local authorities in incorporating their policy.

The advantages of an integrated GIS are the development of a coherent support for the predicting soil erosion and the establishment of the level of the study area vulnerability.

This study can also be strength to a new approach for decision-makers, reducing future natural hazards on the LABIOD watershed.

However, it is a sustainable approach; it permits to take soil conservation actions at early stages to control the dynamic of erosion.

The result of the present study identifies spatial distribution of vulnerability to erosion and localizes high risks area requiring priority conservation measures such as physical measures in upstream and biological treatments in non cultivated zones.

As few studies exist for the study area, this paper is considered as a contribution to natural risk analysis in LABIOD watershed using the integrated GIS and AHP which present a more practical approach for adjusting appropriate intervention for soil conservation.

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