EROSION MODELING AT THE RMIL WATERSHED IN NORTHERN TUNISIA USING THE USLE AND THE SWAT MODELS

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Abstract. The objective of the research is to assess the soil erosion in the Rmil watershed using the SWAT and the USLE models. Laboratory analyses was conducted for determining texture and organic matter. The USLE model with light management like forest and agricultural practices represented by P factor indicated that about 28 % of soil loss rate in the Rmil watershed was between 5 and 10 t. ha^{-1}. y^{-1}. The soil loss rate more 10 t. ha^{-1}. y^{-1} represented over 12 %. The annual average soil loss arte is 5.12 t. ha^{-1}. y^{-1}. The integration of erosion control measures, represented by the P factor, shows an average soil loss rate of 3.85 t ha^{-1}. y^{-1}. The calibration of the monthly runoff showed an acceptable performance. The simulated soil loss using SWAT model varied from 0 to more than 20 t. ha^{-1}. y^{-1} with an annual average of 6.18 t. ha^{-1}. y^{-1}. The USLE method is able to spatially resolve the soil loss rate at a pixel and determine the prone area. Globally, the two models give a comparable estimates value of annual average soil loss rate. These spatial soil loss rates can be considered by decision-makers for planning management strategies to reduce soil loss.
Keywords: *soil loss rate, hydrological modelling, soil loss map, runoff, soil samples analyses, SWAT-CUP*

Introduction

Soil degradation refers to the decline in soil quality and productivity caused by various human activities and natural processes (FAO, 2020; Wheeler et al., 2024). This degradation is a significant global concern particularly in the Mediterranean countries (Ferreira et al., 2022). Thus, soil degradation poses risks to agriculture sector, ecosystems, water quality and overall soil sustainability (FAO/ ITPS, 2015; Al-Mamari et al., 2023; Senanayake et al., 2024). Further, soil erosion negatively impacts agricultural productivity and leads to dam siltation (Jebari et al., 2010; Kondolf et al., 2014; Boukari et al., 2019; Panagos et al., 2024). Multiple factors, including climate, topography, soil properties and human activity, have led to the unsustainability of soils in the Mediterranean region (Trimble and Crosson, 2000; Boukari et al., 2019; Telo da Gama, 2023). The rise in soil erosion rates in these areas is attributed to the extensive history of

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human activities, which affects economic growth and ultimately societal health and sustainability (García-Ruiz, 2013). Several authors revealed that the land use/land cover is among the principal factors of soil erosion at various scales and an optimization of land use structuring is essential for erosion management (Regasa et al., 2023; Parajuli and Nepal, 2024; Mnasri et al., 2024; Qiao et al., 2024). Therefore, soil resources are considered as fundamental for human life sustainability by providing agriculture production (Alewell et al., 2019; Nasir Ahmad et al., 2023). Ensuring sustainability of life on Earth and achieving food security requires the preservation of soil resources to support agricultural development and ecosystem functions (United Nations, 2013; Pozza and Field, 2020; Hou, 2023). In addition, among the 17 UN Sustainable Development Goals, soil protection has drawn a lot of attention by effective actions (Dazzi and Lo Papa, 2022). Soil degradation is a significant global issue in the Mediterranean countries (Alitane et al., 2022; Ferreira et al., 2022; Gonzalez-Romero et al., 2023). As a part of the Mediterranean region Tunisia has been affected by this phenomenon. Serbaji et al. (2023) demonstrated that 6.43% of the Tunisian territory experiences a very high soil loss rate exceeding 30 t/ha/year, while 4.2% of its area is impacted by high mean annual soil losses, ranging from 20 to 30 t/ha/year estimated by the RUSLE method.

Evaluating soil erosion is an important first step in preserving soil resources against degradation in soil fertility and siltation in dams. It is a primary global concern to evaluate soil loss rate in order to help decision makers in implementing effective management practices for reducing soil degradation. Scientists have created models based on the physical characteristics of landscapes to track the pace of soil loss in order to better understand the mechanics of soil erosion (Borrelli et al., 2021; Donovan, 2022). The soil erosion modelling is a good tool to determine and to prioritize the prone area for implementing soil and water conservation management to reduce erosion risk (Borrelli et al., 2021).

Borrelli et al. (2021) developed a comprehensive database, named Global Applications of Soil Erosion Modelling Tracker (GASEMT) based on articles review and numerous studies on soil erosion models. The GASEMT database contains an extensive information about the application these models. Its purpose is to help forthcoming United Nations global soil erosion assessment on a country-specific basis, while contributing to the identification of research priorities in soil erosion by establishing a groundwork for focused and thorough analyses for the future. Several tools were developed to evaluate soil erosion, such as the Water Erosion Prediction Project (WEPP), the Soil and Water Assessment Tool (SWAT), the Universal Soil Loss Equation (USLE).

The USLE method is worldwide used to spatial the soil loss rate (Bezak, 2022; Serbaji et al., 2023). It comprises an empirical formula that computes average yearly soil loss rates. Pham et al. (2018) demonstrated that USLE model exhibited the highest level of sensitivity to the topographic factor (LS) for evaluating soil erosion. Further, the soil water conservation measures implemented in cultivated lands and mountains zones, presented by the support practices factor (P), are effective ways to assess soil erosion Pham et al. (2018). Further, innovative measurement and modeling, remote sensing image processing and geo-statistics deliver new data for enhancing water erosion processes modeling and parameter estimation (Svoray and Atkinson, 2013). The integrated water resources management requires a complex model to evaluate human activities impacts on water quality and quantity (Rickson, 2014; Vigiak, 2015). Hydrological models are seeing growing utilization for simulating soil erosion processes such as the SWAT model (Gassman, 2014; Aloui et al., 2023). Additionally, suspended sediments and nutrients

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transfers worsen the ecological condition of dam's fresh water (Fathali et al., 2011; Aouissi et al., 2014; Shi et al., 2014; Mosbahi and Benabdallah, 2020; Zeng et al., 2022) showed that land use change has strongly affected the erosion modeling in a watershed located in the High Atlas of Morocco.

In Tunisia, soil erosion for extreme rainfall events is a major factor of siltation in dams and hill lakes and reduction in soil fertility (Jebari et al., 2010; Ben Zaied et al., 2021). In the arid region in Tunisia the rainstorm generates the largest soil loss rate (Ben Zaied et al., 2021). It has major consequence for the economic welfare and the farming sustainability (Arbi et al., 2020; Ben Khelifa et al., 2021).

The USLE and SWAT models were used in this study. These models require specific efforts to collect and analyze data. Thus, the combination of GIS and models is an operable approach for evaluating soil erosion in Rmil watershed given the lack of monitoring and measurements. In addition, the evaluation of soil loss rate helps scientists and policymaker to identify the prone areas and the needed intervention for planning soil management strategies. In this paper, ground truth through soil analysis and use of two spatial tools to estimates soil erosion are investigated. The USLE method provides a global estimation of erosion while the SWAT models allows an estimation over a period of time used for the simulation taking into account the climatic variability from one year to another.

Materials and methods

Study area

The Rmil watershed, located at the Siliana governorate Northern Tunisia, covers approximately 231 km^2 (*Fig. 1*). It is a sub-basin of the Medjerda watershed, the most important and the only permanent flow river in Tunisia. Based on the digital elevation model, the altitude ranges between 266 and 808 m (*Fig. 1*). The basin receives an average annual rainfall of 450 mm for the period 2003-2013, with monthly temperature varying between 5 °C and 37 °C, whereas the average annual evaporation is 1600 mm during the period from 2003 to 2013. The rainfall data was obtained from the general directorate of water resources. The evaporation data was obtained from the General Directorate of Dams and Major Hydraulic Works. The watershed present moderate to steep slopes predominantly within the 5 to 15 % gradient ranges.

Land use data was derived from processing Landsat 5 satellite image with the 30 m resolution for the year 2000 and updated through field trip and surveys in 2011 (*Fig. 2a*). Cereal crops (rotation farm land) are the dominant land use accounting for 57 % and olive trees represent 23 % of the study area. The soil types were obtained from the national agriculture map (Min. Agr., 2002). The Rmil watershed is characterized by complexes units soil type (35%), calcosols (22%) and vertisols (12%) (*Fig. 2c*). The properties of soil (soil texture, organic matter (OM), hydraulic conductivity and bulk density) were determined through laboratory analysis of 67 soil samples revealing that clay loam is the predominant soil texture in the basin (*Fig. 2b*).

The observed climatic data including rainfall and weather parameters were obtained from the General Directorate of Water Resources. Four rain gauges were used in this study (*Fig. 1*). The names of the rain gauges are "Rmil", "Aroussa", "Siliana" and "Bouarada" with average annual rainfall of 465, 500, 498 and 370 mm, respectively.

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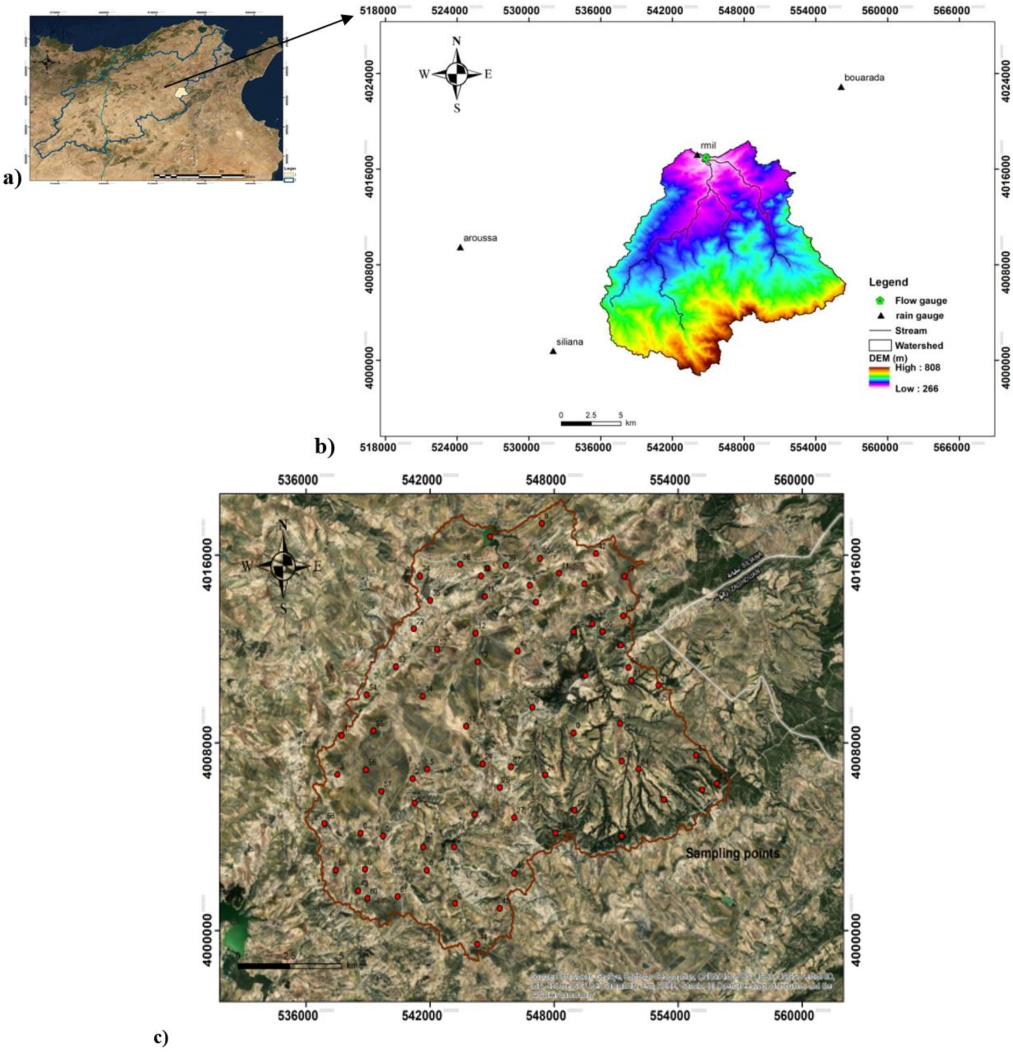

Figure 1. *a) Medjerda watershed, b) Rmil watershed and digital elevation model (DEM) and c) Soil samples location*

Monthly rainfall at the Rmil rain gauge varied from less than 5 mm to 35 mm for the period of 2003 to 2013 (*Fig. 3*). The maximal and minimal temperatures recorded at the Bouarada meteorological gauge were obtained from the National Institute of Meteorology of Tunisia for the period 2003 to 2013.

Methodology

Erosion modeling requires extensive data to accurately simulate the complexity of watershed system. Thus, multiple sources of data were consulted to prepare the database. In this study, spatial distribution of soil loss has been assessed using both the USLE equation and SWAT model methods (*Fig 4*).

DEM data was integrated in SIG to determine the (LS) factor. The estimation of LS factor is based on slope and contributing area. It is derived from DEM. The rainfall erosivity factor (R) was calculated using the rainfall data whereas the erodibility factor (K) was estimated using the sampled soil properties carried out in laboratory with the resulting soil class map integrated in the SWAT model. Land use data was employed to

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determine the C-factor for the USLE equation and as an input to the SWAT model. *Figure 4* illustrates the methodology flowchart developed in this study for the USLE equation and the SWAT model.

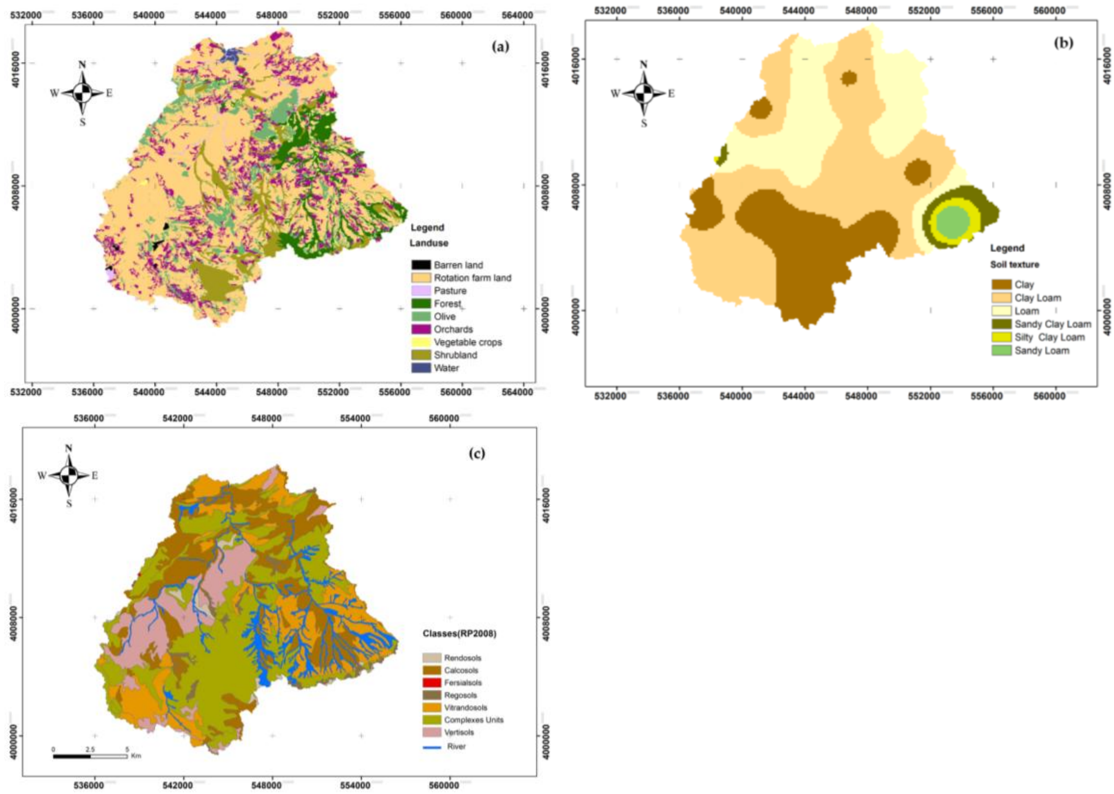

Figure 2. *The Rmil watershed land use (a), soil classes (b) and soil texture (c)*

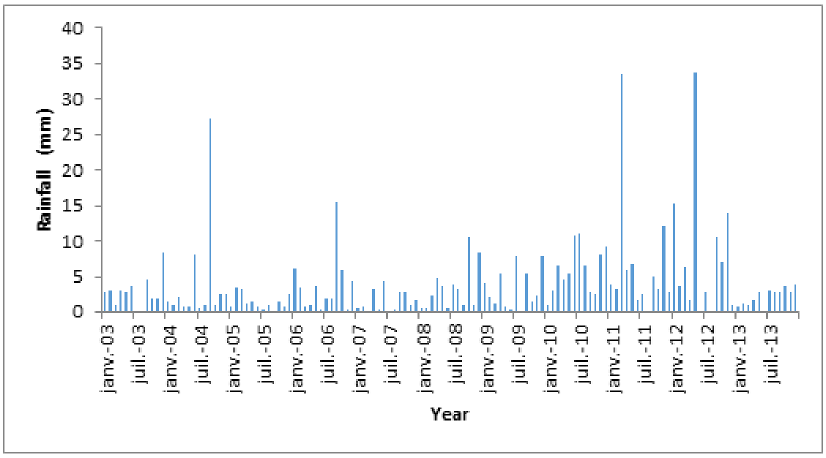

Figure 3. *Average monthly rainfall at the Rmil rain gauge (2003-2013)*

USLE model

The USLE model depends the physical characteristic of watershed and the rainfall intensity. It is estimated by the *Equation 1*.

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$$A = R \times K \times LS \times C \times P \qquad \text{(Eq.1)}$$

where:
A represents the quantity of soil erosion rate (t ha^{-1} y^{-1}),
R is a rainfall erosivity (MJ mm/ha.h.y),
K corresponds to soil erodibility (t ha h/ha MJ mm),
LS represents the slope length factor,
C corresponds to the land use index,
P corresponds to the anti-erosive management index.

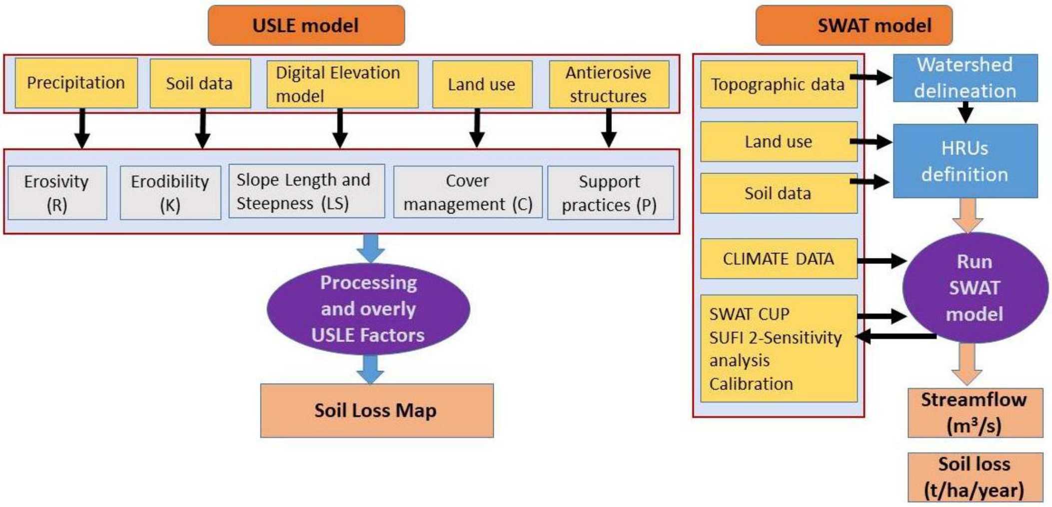

Figure 4. *Flowchart methodology*

Rainfall erosivity (R factor)

The rainfall erosivity presents the force of raindrop to detach soil (Wischmeier, 1978). Renard and Freimund (1994) proposed *Equation 2* for estimating R. The rainfall data was analyzed during 11 years over four rain gauges at the Rmil watershed.

$$R = 0.0483\ P^{1.61} \quad \text{if } P < 850 \text{ mm} \qquad \text{(Eq.2)}$$

where:
P: is the annual precipitation (mm),
R: is the annual rainfall erosivity (Mj.mm.ha^{-1}.h^{-1}. y^{-1}).

In this method, the R value is estimated from annual rainfall and it does not take into account the temporal variation on daily basis as it is the case for hydrologic models.

Soil erodibility (K)

The soil erodibility factor K is estimated by *Equation 3*:

$$K = 27.66\ m1.14 \times 10{-}8 \times (12 - OM) + [0.0043 \times (S - 2)] + [0.0033 \times (P - 3)] \times 0.1317 \qquad \text{(Eq.3)}$$

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where;
K is the soil erodibility factor (ton ha.hr ha^{-1} MJ^{-1} mm^{-1}),
m is the (silt % + sand %) × (100 − clay %),
OM is the % organic matter,
S is the structure code: (1) very structured or particulate, (2) fairly structured, (3) slightly structured, and (4) solid,
P is the profile permeability code: (1) rapid, (2) moderate to rapid, (3) moderate, (3) moderate to slow, (5) slow and (6) very slow.

67 soil samples were taken from the topsoil (0-30 cm) of the study area using a hand-held Edelman (*Fig. 1*). The location of soil sample points was determined using the “MAPS me” application. In the laboratory, the soil samples were dried and sieved at the Tunisian Central Laboratory. The texture of the soil was determined by sedimentation. (Pipette Robinson Method). The Walkley and Black chromic acid wet oxidation method was used to determine the organic matter (Komissarov et al., 2024).

LS factor

The topographic factor (LS) represents the factors related to slope length and gradient. The slope length factor was estimated by the SAGA-QGIS tool based on the DEM.

Land use index (C factor)

The C-factor is influenced by land cover. The C values varied from 0 to 1 (*Table 1*).

Table 1. *C factor values (Masson, 1971)*

Land caver type	C Factor
water	0
Forest	0.1
Shrubland dense	0.17
shrubland	0.36
Pasture	0.4
Cereal crops	0.4
vegetable crops	0.55
Orchards	0.9

The anti-erosive factor (P)

The P factor illustrates the impact of soil conservation management. *Table 2* presents the variation of P values for various slopes and management practices (Shin, 1999).

Table 2. *The anti-erosive factor (P)*

Slope (%)	Contour ridge	Buffer strip	Terraces
0.0 – 7.0	0.55	0.27	0.1
7.0 – 11.3	0.60	0.3	0.12
11.3 – 17.6	0.80	0.4	0.16
17.6– 26.8	0.90	0.45	0.18
> 26.8	1.00	0.5	0.2

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Hydrological modelling: SWAT model

In this study, the agro-hydrological model SWAT model was implemented. It is worldwide used to evaluate the impact of agricultural practices on water quantity and quality (Arnold et al., 1998; Neitsch et al., 2005). It is used to simulate hydrological and biogeochemical processes as well as the sediment transfer within a watershed with a heterogeneity of soil, topography, land use and land management. The watershed in SWAT model was divided in sub-basins based on Digital elevation model. Each sub-basin was divided in the hydrological response unit by overlaying land use, soil and slope classes. The hydrological processes in SWAT model followed two paths, land and channel cycles. The SWAT model simulated the overland fluxes of water, nutrient and sediment of the basin. The second cycle concern the routing of water, sediment and nutrient into the channel to the outlet of watershed (Neitsch et al., 2005; Gassman et al., 2014). The hydrologic water balance in SWAT model is estimated at the HRU unit by the *Equation 4*.

$$SW_t = SW_0 + \sum_{i=1}^{t}(R_i - Q_i - ET_i - P_i - Qr_i) \quad \text{(Eq.4)}$$

where:
SWt represents the ultimate soil moisture content (mm),
SW0 represents the initial moisture level of soil (mm),
Ri represents a daily rainfall (mm),
Qi represents a daily runoff (mm),
ETi represents a daily evapotranspiration (mm),
Pi represents the percolation on day i (mm),
Qri represents the return flow on day i (mm).

The sediment simulation in SWAT model is linked to the hydrologic processes. The soil loss rate and sediment transport in SWAT model is calculated for each HRU. It is estimated by *Equation 5*.

$$sed = 11.8 \cdot (Q_{surf} \cdot q_{peak} \cdot area_{hru})^{0.56} \cdot K_{USLE} \cdot C_{USLE} \cdot P_{USLE} \cdot LS_{USLE} \cdot CFRG \quad \text{(Eq.5)}$$

where,
sed represents the soil erosion load (tons),
Qsurf represents the runoff (mm ha^{-1}),
qpeak represents the peak runoff rate (cubic meter per second),
areahru is a hru surface (ha),
K_{USLE} represents the soil erodibility factor,
P_{USLE} represents the anti-erosive structures factor,
C_{USLE} represents the land use / cover factor,
LS_{USLE} represents the topographic factor,
CFRG represents the coarse fragment factor.

SWAT model is used to represent the complex interactions between the hydrological and sediment processes. The surface runoff is estimated using the SCS-CN method.

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SWAT input data and setup

The SWAT model is an over-parametrization model. A 30 m digital elevation model was used in this study obtained from NASA's Shuttle Radar Topography Mission (SRTM). It is used for watershed delineation. The land use of Rmil watershed was obtained from Landsat 5 satellite imagery for year 2002 and updated in 2011. The soil type map of the Rmil watershed at a scale of 1: 50000 was obtained from the national agricultural map of Tunisia. The database of soil types and properties was obtained from soil samples analyzed in the laboratory. Daily rainfall was collected from four rain gauges (*Fig. 1*) for the period of 2003-2013. The flow data at the outlet of Rmil watershed was obtained from the general directorate of dams in Tunisia. The Rmil watershed was delineated into 13 sub-basins. Each sub-basin was divided in the Hydrologic Response Units.

Mode sensitivity analysis and calibration using SWAT-CUP

A SWAT-CUP software was used to study the sensitivity analysis, calibration and validation of runoff simulation using the Sequential Uncertainty Fitting algorithm (SUFI-2) (Abbaspour et al., 2015). The Sequential Uncertainty Fitting Version2 (SUFI-2) algorithm is used in the SWAT Calibration Uncertainties Program (SWAT_CUP) (Abbaspour et al., 2018) for model calibration, validation and uncertainty analyses. The SWAT model output is imported into SWAT-CUP and analyzed. Fourteen parameters were used to study the sensitivity analysis for monthly runoff simulation (*Table 3*). The values of t-stat and p-value were used for evaluating the ranking of hydrological parameters according to the sensitivity degree. The parameter with high absolute value of t-stat and low value of p-value is the most sensitive in runoff simulation (Abbaspour et al., 2018). The p-value indicates the importance of a parameter's sensitivity, whereas the t-test measures the sensitivity of that parameter (Gyamfi et al., 2016).

Table 3. *Sensitivity parameter ranges*

Parameters	Operation	Min	Max	Adopted value
CN2.mgt	R*	-0.2	0.2	-0.07
alpha_bf.gw	V**	0	1	0.96
surlag.bsn	V	4	24	16.93
sol_awc .sol	R	-0.25	0.25	-0.01
esco.hru	V	0.01	1	0.59
EPCO.hru	V	0.01	1	0.87
USLE_P.mgt	R	0.1	0.9	0.10
SOL_K(..).sol	R	-0.25	0.25	0.23
CH_K1.sub	V	0.01	0.5	0.23
USLE_K(..).sol	R	0.01	0.5	0.35
SOL_Z(..).sol	R	-0.25	0.25	-0.19
SLSOIL.hru	R	-0.5	0.5	-0.34
GW_DELAY.gw	V	30	450	217.42
GWQMN.gw	R	0	2	1.39

Note: * R means an existing parameter value is multiplied by (1+ a given value). ** V means the existing parameter value is to be replaced by a given value.

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Out of the fourteen parameters used for the sensitivity analysis, four parameters (CN2.mgt, SOL_AWC(..).sol, GW_DELAY.gw and ESCO.hru) were identified as the most sensitive parameter for runoff simulation as indicated by the t-stat and p-value ($p < 0.05$) (Thavhana et al., 2018; Abbaspour et al., 2018). The overall results of the sensitivity analysis are presented in *Table 4*.

Table 4. *Parameter tests*

Parameters	t-stat	p-value
12:R__SLSOIL.hru	0.087	0.930
3:V__SURLAG.bsn	0.113	0.910
7:R__USLE_P.mgt	0.315	0.753
8:R__SOL_K(..).sol	0.670	0.504
6:V__EPCO.hru	0.738	0.461
14:R__GWQMN.gw	1.173	0.242
11:R__SOL_Z(..).sol	1.203	0.230
9:V__CH_K1.sub	1.276	0.203
10:R__USLE_K(..).sol	-1.333	0.183
2:V__ALPHA_BF.gw	-1.909	0.057
5:V__ESCO.hru	-2.033	0.043
13:V__GW_DELAY.gw	-2.184	0.030
4:R__SOL_AWC(..).sol	3.056	0.002
1:R__CN2.mgt	-13.971	0.000

Model performance criteria

The statistical index used for evaluating the SWAT model simulation are the Nash Sutcliffe (NS), the coefficient of determination (R^2) and the percent bias (PBIAS), presented by the *Equations 6, 7 and 8*.

$$NS = 1 - \frac{\sum_{i=1}^{n}(O_i - P_i)^2}{\sum_{i=1}^{n}(O_i - \overline{O})^2} \quad \text{(Eq.6)}$$

$$R^2 = \left[\frac{\sum_{i=1}^{n}(O_i - \overline{O})(P_i - \overline{P})}{\sqrt{\sum_{i=1}^{n}(O_i - \overline{O})^2 \sum_{i=1}^{n}(P_i - \overline{P})^2}}\right]^2 \quad \text{(Eq.7)}$$

$$PBIAS = \frac{\sum_{i=1}^{n}(O_i - P_i)}{\sum_{i=1}^{n} O_i} \times 100 \quad \text{(Eq.8)}$$

where, n is the number of data, Oi is the observed parameter, Pi is a predicted parameter by the model, $\overline{O_i}$ is the average observed parameter and $\overline{P_i}$ is the average predicted parameter.

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Results

USLE factors

The USLE method was used to evaluate the soil losses. Four maps were constructed in ArcGis software as an input to USLE equation (*Fig. 5*).

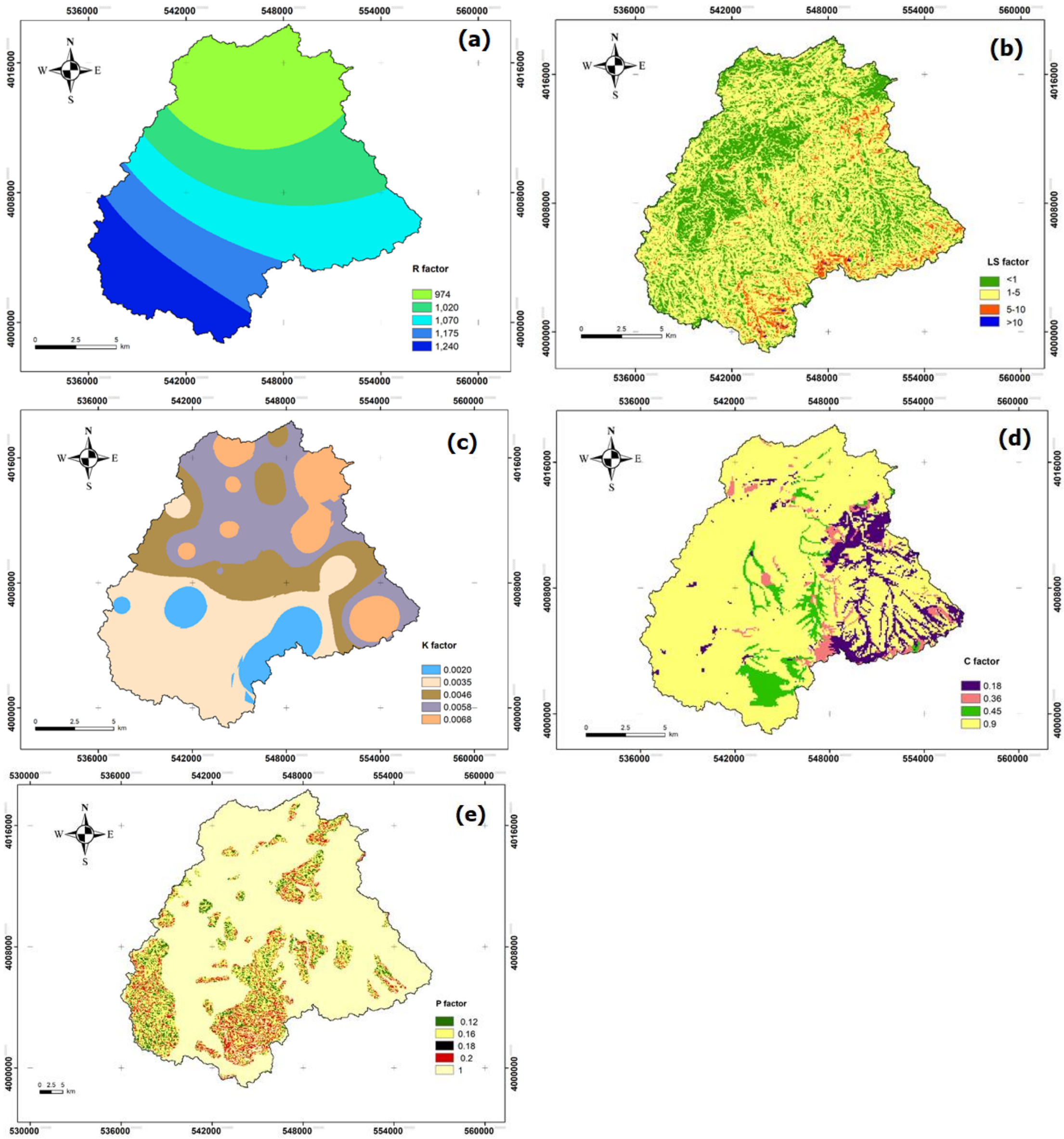

Figure 5. *Erosivity factor R (a), LS factor (b), erodibility factor K (c), land use/cover factor C (d) and anti-erosive factor P(e)*

Rainfall erosivity factor (R)

Fig. 5a shows the spatial distribution of the erosivity factor in the Rmil watershed during the period 2003-2013. The R values ranged from 974 to 1240 MJ·mm/(ha·hr·y), increasing from the upstream to the downstream on the Rmil watershed (*Fig. 5a*). The highest rainfall erosivity was estimated in the southern part of the Rmil watershed.

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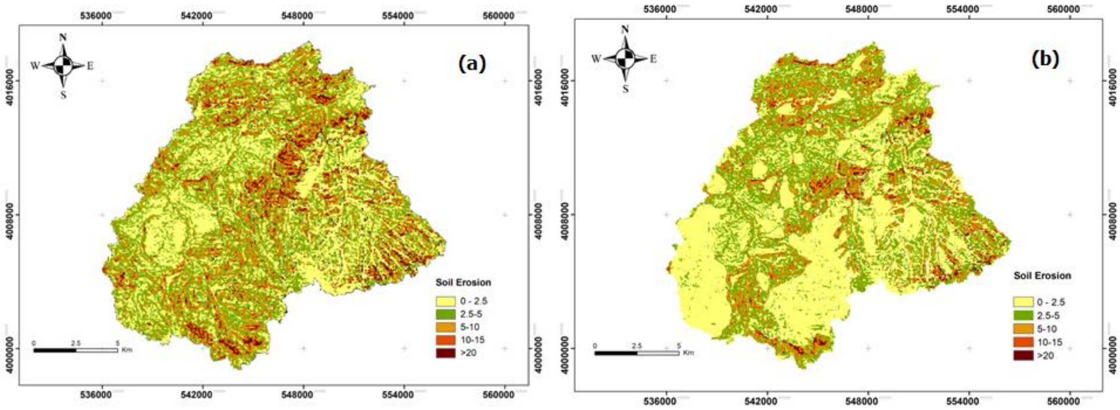

__Figure 6.__ Spatial soil loss distribution (t ha^{-1} y^{-1}) in the Rmil watershed (a) with light management and (b) with integration of soil and water conservation measures

Slope length (LS)

The LS value estimation is based on the topography. The LS factor in the Rmil watershed varied from less 1 to more than 10 (*Fig. 5b*). The steep slopes are located in the southern and eastern parts of the Rmil watershed, improving the soil erosion and runoff velocity.

The erodibility factor (K)

The erodibility factor estimation is based on the soil samples analysis in laboratory. The erodibility factor map is illustrated in the *Fig. 5c*. The K factor values varied from 0.002 to 0.0068.

The C factor

The C factor was derived from land use map (*Fig. 5d*). The management factor (C) in the Rmil watershed varied from 0.1 to 0.9. C factor values near 0 indicate well-protected land cover and effective conservation efforts, while values approaching 1 correspond to barren land and agricultural fields exposed to heavy rainfall.

The P factor

The soil loss by erosion is influenced by the type of land use, soil conservation management, agricultural practices and rainfall intensity. For farm land in sloped area, farmers adopt contour ridge for reducing the soil erosion rate. The P factor values of the Rmil watershed varied from 0.12 to 1 (*Fig. 5e*).

Erosion mapping using USLE model with light management

Fig. 6a illustrates the erosion mapping in the Rmil watershed with P factor represented a light management based on forest and agricultural practices (tillage operation). The soil loss rate varied from as low as 2.5 t ha^{-1} y^{-1} to over 20 t ha^{-1} y^{-1} with an annual average of 5.12 t ha^{-1} y^{-1}. *Fig. 6a* displays the spatial distribution of soil loss rate. In comparison to *Fig. 6b*, the benefits of soil and water conservation management, clearly show an improvement in the reduction of soil erosion.

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The rate of soil loss (*Table 5*) shows that 12.08% of total area was more than 10 t ha^{-1} y^{-1}. The low soil loss rate presents 28.04% of Rmil watershed. The rate of soil loss differed across land use types and the implemented anti-erosion measures. The average soil loss rate become 3.85 t ha^{-1} y^{-1}. The USLE simulation shows that 1.68 % of the study area presents a high prone area affected by soil erosion with a soil loss rate more than 20 t ha^{-1} y^{-1} according to Singh and Phadke (2006) classification.

Table 5. *Soil erosion distribution at the Rmil watershed using USLE equation with light management*

Score Scale	Soil Loss Class (t ha^{-1} y^{-1})	Area Percentage (%)	Indicator
1	<5	59.88	Very low
2	5-10	28.04	Low
3	10-20	10.4	Moderate
4	>20	1.68	High

Comparing our results to other studies using the same method in similar watershed in Tunisia shows close in some cases and some differences in others. Ben Rhouma et al. (2018) reported an average erosion loss of 1.9 t ha^{-1} y^{-1} for the El Gouazine basin in northern Tunisia. These results were attributed to the low LS factor and the forest land cover at the basin. The monitoring of 28 small hilly reservoirs catchment located in the mountains regions showed an average rate of soil loss equal to 14.5 t ha^{-1} y^{-1} (Jebari et al., 2010). The fluctuation in soil loss rates can be attributed to the R and K factors, main parameters controlling soil erosion. The application of USLE method for the Lebna watershed located in Cap-Bon, northeastern Tunisia showed an average soil erosion for 24 t ha^{-1} y^{-1} (Gaubi et al., 2016).

Runoff simulation using SWAT model

The monthly runoff simulation results before calibration showed that the values of the statistical index NSE, R^2 and PBIAIS were 0.42, 0.6 and -20%, respectively. The calibration step was based with the adjustment of the most sensitive parameters. For the period 2003 to 2009, the calibration procedure showed an improvement in the monthly runoff simulation with NSE, R^2 and PBIAS of 0.8, 0.84 and -10% respectively (*Fig. 7*). The monthly runoff simulation shows a high performance, which is explained by the acceptable ranges of the statistical index values.

The statistical model performance criteria NSE, R^2 and PBIAS for the validation of monthly runoff during the period from January 2010 to December 2013 (*Fig. 8*) were 0.6, 0.65 and 13%, respectively.

The results of the monthly runoff simulation show a satisfactory based on Moriasi et al. (2007). Satisfactory agreement between observed and predicted runoff is also shown by the statistical values. Furthermore, the PBIAS values for the calibrated and validated periods are -8% and 13%, respectively. They indicate that the model has an underestimation of 8% during the calibration period and an overestimation of 13% during the validation period. This difference is partially due to the fact that the validation period corresponds to dry years.

The hydrological calibrated and validated model was used to simulate the soil erosion in the Rmil watershed.

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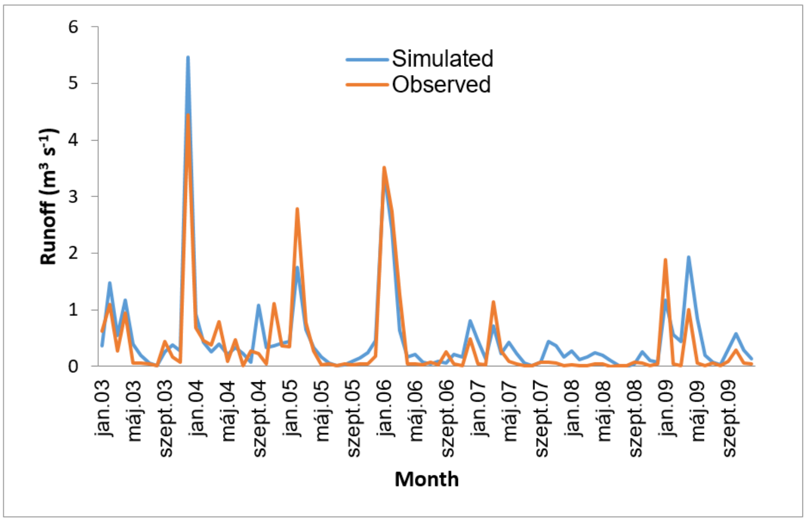

***Figure 7.** Monthly runoff predicted and observed at the outlet of Rmil watershed after calibration*

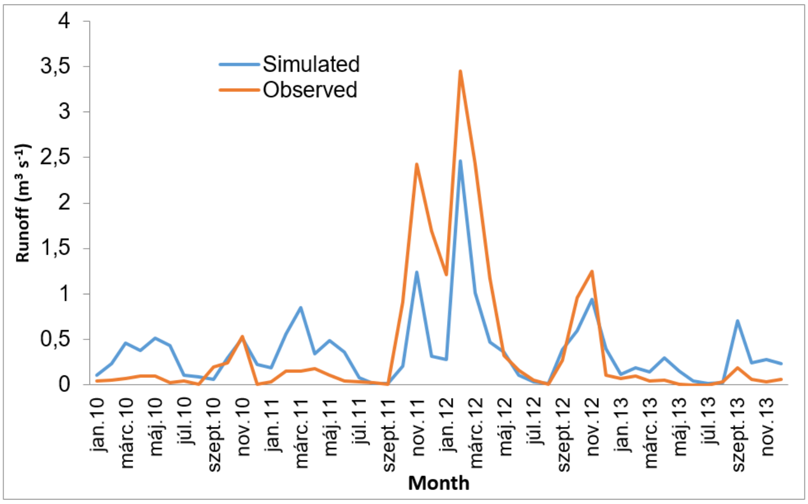

***Figure 8.** monthly runoff predicted and observed at the outlet of Rmil watershed during the validation period*

Sediment simulation using SWAT model

Sediment yield temporal variability

The temporal distribution of the sediment throughout these 11 years is outlined in *Figures 9a* and *9b*. Monthly sediment yield values varied from a minimum of 0.03 t/km^2 in the driest year, with a monthly runoff value of 0.01 m^3 s^{-1} to a maximum of 14.75 t/km^2 on December 2003 which was the wettest year with a runoff value of 5.5 m^3 s^{-1}. *Figure 9a* shows an agreement between the monthly simulated peaks of sediment yield and runoff. The simulated average annual sediment yield and runoff of the Rmil watershed is presented in *Figure 9b*. A close correlation between average annual runoff and sediment yield was found (*Figure 9b*).

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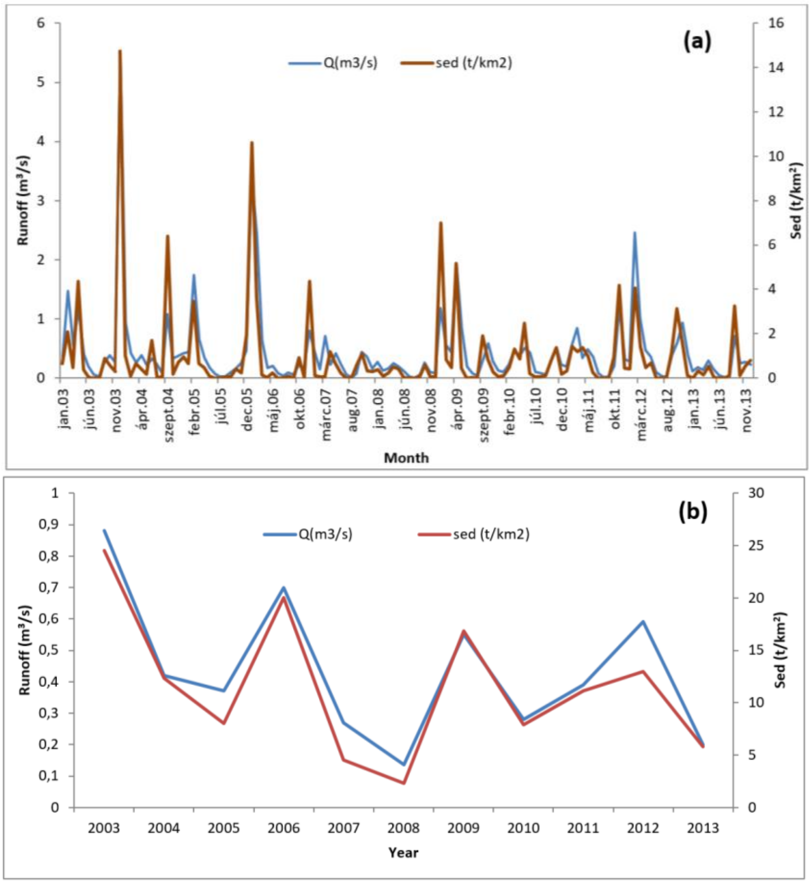

Figure 9. *a) monthly streamflow and sediment variation for the period 2003-2013, b)average annual sediment yield and strealflow for the period 2003-2013 in the Rmil Watershed*

There is a high correlation between monthly simulated runoff and monthly simulated sediment yield with a correlation coefficient of 0.81 (*Figure 10*). The strong correlation between streamflow and sediment yield has been demonstrated in numerous studies on soil loss estimation in Tunisia (Mosbahi et al., 2013; Mtibaa et al., 2018; Benrhouma et al., 2024).

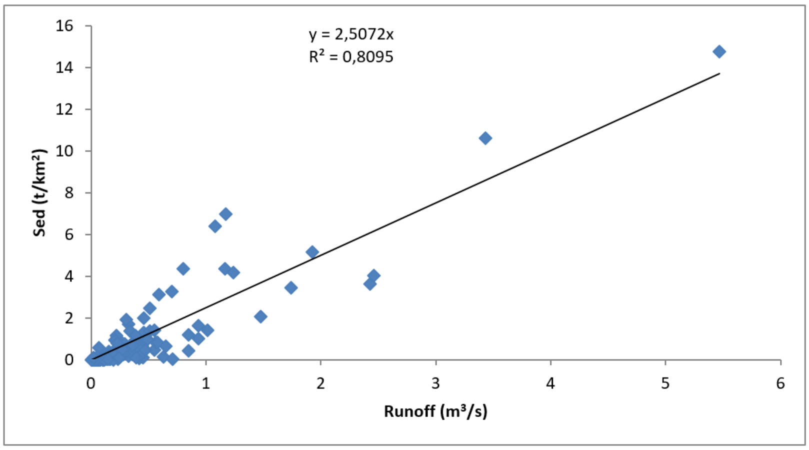

Figure 10. *Relating simulated sediment yield to simulated runoff*

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Spatial distribution of soil loss rate simulated by SWAT model

The soil erosion mapping using SWAT model indicated that the annual soil erosion rate varied from 0 to over 20 t ha^{-1} y^{-1} (*Fig. 11*) with an annual average rate for 6.18 t ha^{-1} y^{-1}. The highest rate of soil loss was simulated in the southern part of the watershed where the average of soil loss rate exceeds 20 t ha^{-1} y^{-1}. Areas with high to moderate soil erosion risk presents 18.8% and areas with the lowest erosion risk represents 23.43% of the watershed (*Table 6*).

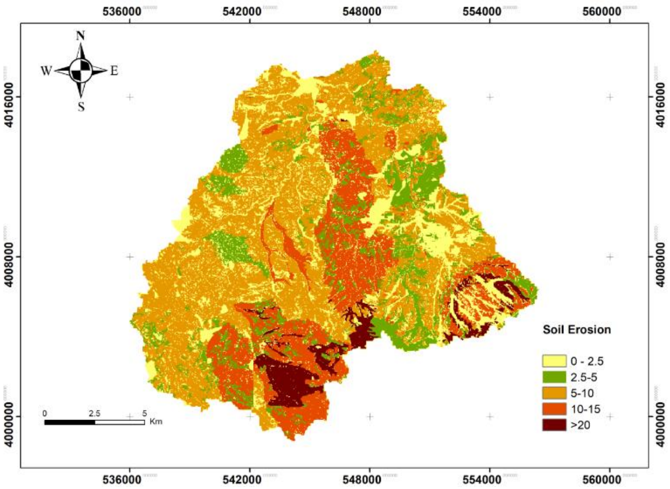

Figure 11. *Soil loss distribution (t/ha/year) simulated by SWAT model*

Table 6. *Soil erosion distribution in the Rmil watershed using SWAT model*

Score Scale	Soil Loss Class (t ha^{-1} y^{-1})	Area Percentage (%)	Indicator
1	<5	23.43	Very low
2	5-10	57.76	Low
3	10-20	18.52	Moderate
4	>20	0.28	High

The SWAT model present an effective support for determining priority areas for intervention for reducing soil erosion risk. However, the simulated sediment yield on the Rmil watershed is lower when contrasted with other investigations like Sarrath watershed, a sub-basin of the Medjerda River, where the rate of soil loss simulated by SWAT model application varied from 0.03 to 23.5 t ha^{-1} y^{-1} (Mosbahi et al., 2013).

Spatial comparison of soil loss rate using USLE and SWAT model

The annual average of soil loss rate estimated using the USLE and SWAT models were respectively 5.12 t ha^{-1} y^{-1} and 6.18 t ha^{-1} y^{-1}. The anti-erosive measures in the Rmil watershed were considered only in the USLE model (*Fig. 6b*).

Table 7 shows the spatial comparison analysis of soil loss rates estimated by USLE and SWAT models in the Rmil catchment. The results show that the rate of soil loss estimated by USLE and SWAT in the class <10 t ha^{-1} y^{-1} accounts for 87.92% and 81.2%, respectively (*Table 7*).

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Table 7. *Soil loss distribution at the Rmil watershed Results using USLE and SWAT models*

		USLE	SWAT
Soil Loss Class (t. ha^{-1}. y^{-1})	**Indicator**	**Area in Percentage (%)**	**Area in Percentage (%)**
<5	Very low	59.88	23.43
5-10	Low	28.04	57.76
10-20	Moderate	10.4	18.52
>20	High	1.68	0.28

Table 7 shows differences in the spatial distribution of areas with significant erosion, particularly where soil loss exceeds 10 t ha^{-1} y^{-1}.

The results may be influenced by the period used for the SWAT model runs, as the 11-year period may not fully represent the variability of dry and wet years. Longer period for SWAT model simulations may induce similar results. This presents challenges in selecting the most appropriate tool for assessing soil loss rates. Nevertheless, the use of both methods can still provide insights for soil erosion estimates, even though with certain level of uncertainty, which can help the decision makers to plan the necessary management for water and soil conservation.

Discussion

Water erosion is linked to the hydrological process like rainfall and runoff for soil detachment and transport. The consequences of soil erosion are the degradation of soil fertility, the decline of crop production and dam siltation. Three strategies for soil and water conservation have been implemented by the Tunisian government. The USLE method was used to spatial the soil loss rate in the Rmil watershed from the pixel unit to the entire watershed. Hermassi et al., 2023 show the limit of USLE to simulate the sediment delivery. Further, they used a sediment delivery distributed model for sediment load simulation in the Merguellil watershed located in the central of Tunisia. The limitations of USLE concept was presented by Alewell et al. (2019) based on an overview of the application of the ULE globally. The USLE method does not consider runoff for estimating soil erosion. The SWAT model considers the runoff processes for estimating sediment transport. The calibrated and validated runoff simulation using the SWAT model improves soil erosion modeling in the Rmil watershed. The SWAT model has the ability to model a temporal variation of soil erosion over time. The soil loss rate was simulated using the SWAT model at the HRU, sub-watershed and watershed scales. The Geographic Information System was used to produce the spatial analysis report for both the USLE and SWAT models. *Table 7* shows the results of the spatial distribution of the soil loss classes. According to the results, the value of the percentage of area affected by very low to low soil loss for the USEL and the SWAT models was 87% and 81%, respectively. Many studies in Tunisia were used SWAT and USLE model for simulating soil erosion. They show a high performance in runoff and soil erosion modelling (Mtibaa et al., 2018; Mosbahi et al., 2020; Ben Khelifa et al., 2021; Hermassi et al., 2023).

Soil erosion is a significant problem particularly in farmland that needs to be addressed. Sustainable agricultural practices and anti-erosion measures ensure control of soil erosion.

Conclusions

The USLE and SWAT models were implemented in the semi-arid Rmil watershed in Siliana, northern Tunisia, to evaluate e water erosion from 2003 to 2013. Numerous variables affect the erosion in the Rmil Watershed. Precipitation intensity is the first and most important factor, followed by soil erodibility and topography. In fact, the watershed steepness of slopes, the vegetation covers and the erosion control practices are all affected soil erosion processes. The accuracy of the USLE method was established by estimating soil erodibility from the field samples and laboratory analysis. The five parameters of the USLE model were developed in a GIS environment. Furthermore, the estimated erosion dynamics between treated and untreated circumstances were compared spatiotemporally through the use of the USLE approach, supporting the identification of prone areas. The major soil and water conservation measures have been implemted in the Rmil watershed is the contour ridges.

The SWAT model was calibrated and validated for runoff simulation. It has good performance in simulating runoff at the catchment scale, but has not been calibrated to simulate soil erosion as erosion management practices have not been considered in the SWAT model. Thus, it will be necessary in the future to give further consideration to the effects of erosion management practices on the transport of sediment. In the SWAT Calibration Uncertainties Program (SWAT_CUP), the sensitivities of 14 input parameters were analyzed using the SUFI-2 algorithm. For the Rmil watershed, four of the SWAT input parameters are the most sensitive, including those from CN2.mgt, SOL_AWC.sol, GW_DELAY.gw, and ESCO.hru. Satisfactory model performance was obtained during calibration and validation.

The results of soil loss rate estimated by USLE and SWAT models, show that there are differences in both models, which can be related to the model conceptualization and the modelling of hydrological and sediment processes The average annual soil loss rates estimated by USLE and SWAT models of the Rmil watershed were 5.12 and 6.18 t ha^{-1} y^{-1}, respectively. Soil water conservation structures (SWCS), which are represented by the P factor in the USLE equation, were used for reducing soil erosion risk. The results showed that the average annual rate of soil loss after the implementation of the SWCS was 3.85 t ha^{-1} y^{-1}. There was a 33% reduction in soil erosion after implementation of erosion control measures in the Rmil watershed using USLE method. There were significant differences in the geographical distribution of soil erosion, with lower levels in the forested areas and the flat alluvial plains in the north, and higher levels in the central and southern mountainous areas with higher altitudes and slopes.

The USLE parameters could be improved by field measurements and remote sensing. Monitoring of sediment concentration in the study area is necessary for the calibration and improvement of the sediment simulation using SWAT model. Soil erosion modelling plays an important role in assessing the rate of soil loss at spatial and temporal scales. It helps researchers and decision-makers to understand and plan strategies to protect soil and water.

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REFERENCES

[1] Abbaspour, K. C. (2015): SWAT-CUP: SWAT calibration and uncertainty programs-a user Manual. – Eawag: Swiss Federal Institute of Aquatic Science and Technology. https://swat.tamu.edu/media/114860/usermanual_swatcup.pdf.

[2] Abbaspour, K. C., Vaghefi, S. A., Srinivasan, R. (2018): A Guideline for Successful Calibration and Uncertainty Analysis for Soil and Water Assessment. A Review of Papers from the 2016 International SWAT Conference. – Water 10(1): 1. https://doi.org/10.3390/w10010006.

[3] Alewell, C., Borrelli, P., Meusburger, K. (2019): Using the USLE: chances, challenges and limitations of soil erosion modeling. – International Soil and Water Conservation Research 7(3): 203-225. https://doi.org/10.1016/j.iswcr.2019.05.004.

[4] Alitane, A., Essahlaoui, A., El Hafyani, M., El Hmaidi, A., El Ouali, A., Kassou, A., El Yousfi, Y., van Griensven, A., Chawanda, C. J., Van Rompaey, A. (2022): Water Erosion Monitoring and Prediction in Response to the Effects of Climate Change Using RUSLE and SWAT Equations: Case of R'Dom Watershed in Morocco. – Land 11: 93. https://doi.org/10.3390/land 11010093.

[5] Al-Mamari, M. M., Kantoush, S. A., Al-Harrasi, T. M., Al-Maktoumi, A., Abdrabo, K. I., Saber, M., Sumi, T. (2023): Assessment of sediment yield and deposition in a dry reservoir using field observations, RUSLE and remote sensing: Wadi Assarin, Oman. – Journal of Hydrology 617: 128982. https://doi.org/10.1016/j.jhydrol.2022.128982.

[6] Aloui, S., Mazzoni, A., Elomri, A., Aouissi, J., Boufekane, A., Zghibi, A. (2023): A review of Soil and Water Assessment Tool (SWAT) studies of Mediterranean catchments: Applications, feasibility, and future directions. – Journal of Environmental Management 326 (Part B): 116799. https://doi.org/10.1016/j.jenvman.2022.116799.

[7] Aouissi, J., Benabdallah, S., Lili Chabaâne, Z. (2014): Modeling water quality to improve agricultural practices and land management in a Tunisian catchment using the Soil and Water Assessment Tool. – J. Environ. Qual. 43(1): 18-25. https://doi.org/10.2134/jeq2011.0375.

[8] Arbi, C., Brahim, N., Slim Shimi, N. (2020): Mapping of water erosion by GIS/RUSLE approach: watershed Ayda river - Tunisia study. – Arabian Journal of Geosciences 13: 810. https://doi.org/10.1007/s12517-020-05774-0.

[9] Arnold, J. G., Srinivasan, R., Muttiah, R. S. (1998): Large area hydrologic modeling and assessment. Part I. Model development. – J Am Water Resour Assoc. 34(1): 73-89. https://doi.org/10.1111/j.1752-1688.1998.tb05961.x.

[10] Ben Khelifa, W., Strohmeier, S., Benabdallah, S. (2021): Evaluation of bench terracing model parameters transferability for runoff and sediment yield on catchment modeling. – Journal of African Earth Sciences 178(4): http://dx.doi.org/10.1016/j.jafrearsci.2021.104177.

[11] Ben Rhouma, A., Hermassi, T., Habaieb, H. (2018): Water Erosion modeling in a Mediterranean semi-arid catchment using USLE/GIS (El Gouazine, Central Tunisia). – Journal of New Sciences Agriculture and Biotechnology 50(7): 3071-3081. https://www.jnsciences.org/index.php?option=com_attachments&task=download&id=411.

[12] Benrhouma, A., Hermass, T., Jarray, F., Attia, R., Bouajila, K., Mechri, M., Aouissi, J., Kotti, M. L., Hashem, A., Avila Quezada, G. D., Abd_Allah, E. F., Harrouchi, F. (2024): Soil erosion assessment using SWAT, in relation with Land use, agricultural practices, and future climate change in a semi-arid catchment in Tunisia. – Environ. Res. Commun. 6: 105028. DOI 10.1088/2515-7620/ad85c8.

[13] Ben Zaied, M., Jomaa, S., Ouessar, M. (2021): Soil Erosion Estimates in Arid Region: A Case Study of the Koutine Catchment, Southeastern Tunisia. – Appl. Sci. 11: 6763. https://doi.org/10.3390/app11156763.

http://www.aloki.hu ● ISSN 1589 1623 (Print) ● ISSN1785 0037 (Online)
DOI: http://dx.doi.org/10.15666/aeer/2302_25412563

[14] Bezak, N., Borrelli, P., Mikoš, M. (2022): Outreach and Post-Publication Impact of Soil Erosion Modelling Literature. – Sustainability 14: 1342. https://doi.org/10.3390/su14031342.
[15] Borrelli, P., Alewell, C., Alvarez, P., Anache, J. A. A., Baartman, J., Ballabio, C., Bezak, N., Biddoccu, M., Cerdá, A., Chalise, D., Chen, S., Chen, W., De Girolamo, A. M., Gessesse, G. D., Deumlich, D., Diodato, N., Efthimiou, N., Erpul, G., Fiener, P., Freppaz, M., Panagos, P. (2021): Review Soil erosion modelling: a global review and statistical analysis. – Science of the Total Environment 780: 146494. https://doi.org/10.1016/j.scitotenv.2021.146494.
[16] Boukari, A., Benabdallah, S., Everbecq, E. (2019): Assessment Agriculture Pressures Impact on the Joumine River Water Quality Using the PEGASE Model. – Environmental Management 64(4): 520-535. https://doi.org/10.1007/s00267-019-01207-1.
[17] Dazzi, C., Lo Papa, G. (2022): A new definition of soil to promote soil awareness, sustainability, security and governance. – International Soil and Water Conservation Research 10: 99-108. https://doi.org/10.1016/j.iswcr.2021.07.001.
[18] Donovan, M. (2022): Modelling soil loss from surface erosion at high-resolution to better understand sources and drivers across land uses and catchments; a national-scale assessment of Aotearoa, New Zealand. – Environmental Modelling and Software 147. https://doi.org/10.1016/j.envsoft.2021.105228.
[19] FAO (2020): FAO Soils Portal Key definitions. – Food and Agricultural Organization of the United Nations (FAO). Accessed 19 October 2020.
[20] FAO, ITPS (2015): The Status of the World's Soil Resources. – Main Report, Rome. https://www.fao.org/3/i5199e/i5199e.pdf.
[21] Fathalli, A., Ben Rejeb Jenhani, A., Moreira, C. (2011): Molecular and phylogenetic characterization of potentially toxic cyanobacteria in Tunisian freshwaters. – Systematic and Applied Microbiology 34(4): 303-310. http://dx.doi.org/10.1016/j.syapm.2010.12.003.
[22] Ferreira, C. S. S., Seifollahi-Aghmiuni, S., Destouni, G., Ghajarnia, N., Kalantari, Z. (2022): Soil degradation in the European Mediterranean region: Processes, status and consequences. – Science of the Total Environment 805: 150106. https://doi.org/10.1016/j.scitotenv.2021.150106.
[23] García-Ruiz, J. M., Nadal-Romero, E., Lana-Renault, N. (2013): Erosion in Mediterranean landscapes: Changes and future challenges. – Geomorphology 198: 20-36. https://doi.org/10.1016/j.geomorph.2013.05.023.
[24] Gassman, P. W., Sadeghi, A. M., Srinivasan, R. (2014): Applications of the SWAT model special section: overview and insights. – J. Environ. Qual. 43(1): 1-8. http://dx.doi.org/10.2134/jeq2013.11.0466.
[25] Gaubi, I., Chaabani, A., Ben Mammou, A. (2016): A GIS-based soil erosion prediction using the Revised Universal Soil Loss Equation (RUSLE) (Lebna watershed, Cap Bon, Tunisia). – Nat Hazards 86(1): 219-239. https://link.springer.com/article/10.1007/s11069-016-2684-3.
[26] Gonzalez-Romero, J., Zema, D. A., Gianmarco Carrà, B., Neris, J., Fajardo, A., Plaza-Álvarez, P. A., Moya, D., Peña-Molina, E., de las Heras, J. (2023): Soil erosion modelling of burned and mulched soils following a Mediterranean forest wildfire. – Soil Use and Management 39(2): 881-899. https://doi.org/10.1111/sum.12884.
[27] Gyamfi, C., Ndamuka, J. M., Salim, R. W. (2016): Application of SWAT model to the Olifants basin: calibration, validation and uncertainty analysis. – Journal of Water Resource and Protection 8: 397-410.
[28] Hermassi, T., Kotti, M. L., Jarray, F. (2023): Soil Erosion in a Changing Environment over 40 Years in the Merguellil Catchment Area of Central Tunisia. – Appl. Sci. 13: 11641. https://doi.org/10.3390/app132111641.
[29] Hou, D. (2023): Sustainable soil management for food security. – Soil Use and Management 39(1): 1-7. https://doi.org/10.1111/sum.12883.

http://www.aloki.hu ● ISSN 1589 1623 (Print) ● ISSN1785 0037 (Online)
DOI: http://dx.doi.org/10.15666/aeer/2302_25412563

[30] Jebari, S., Berndtsson, R., Bahri, A. (2010): Spatial soil loss risk and reservoir siltation in semi-arid Tunisia. – Hydrological Sciences Journal 55(1): 121-137. http://dx.doi.org/10.1080/02626660903529049.

[31] Komissarov, M., Fomicheva, D., Zhidkin, A., Yudina, A. (2024): Variations in soil erodibility (K-factor) for the Chernozems depending on the method of texture determination. – MethodsX 13: 1-9. https://doi.org/10.1016/j.mex.2024.102876.

[32] Kondolf, G. M., Gao, Y., Annandale, G. W. (2014): Sustainable sediment management in reservoirs and regulated rivers: Experiences from five continents. – Earth's Future 2: 256-280. http://dx.doi.org/10.1002/2013EF000184.

[33] Masson, J. M. (1971): L'érosion des sols par l'eau en climat méditerranéen. Méthode expérimentale pour l'étude des quantités érodées à l'échelle du champ. – Thèse - Université des Sciences et Techniques de Languedoc, CNRS n°AO 5445, 213 p.

[34] Min. Agr. (Ministère de l'Agriculture) (2002): Cartes agricoles de la Tunisie. – Ministère de l'Agriculture, Tunis, Tunisia.

[35] Mnasri, H., Nunes, A., Sahnoun, H., Abdelkarim, B., Mahmoudi, S. (2024): Assessment of soil erosion in southern Tunisia using AHP-GIS modeling. – Euro-Mediterranean Journal for Environmental Integration 9: 223-234. https://doi.org/10.1007/s41207-023-00429-4.

[36] Moriasi, D. N., Arnold, J. G., Van Liew, M. W. (2007): Model evaluation guidelines for systematic quantification of accuracy in watershed simulations. – Trans. ASABE 50(3): 885-900. https://swat.tamu.edu/media/1312/moriasimodeleval.pdf.

[37] Mosbahi, M., Benabdallah, S., Boussema, M. R. (2013): Assessment of soil erosion risk using SWAT model. – Arabian Journal of Geosciences 6(10): 4011-4019. http://dx.doi.org/10.1007/s12517-012-0658-7.

[38] Mosbahi, M., Benabdallah, S. (2020): Assessment of land management practices on soil erosion using SWAT model in a Tunisian semi-arid catchment. – Journal of Soils and Sediments 20(16): 1129-1139. https://link.springer.com/article/10.1007/s11368-019-02443-y.

[39] Mtibaa, S., Hotta, N., Irie, M. (2018): Analysis of the efficacy and cost-effectiveness of best management practices for controlling sediment yield: A case study of the Joumine Watershed, Tunisia. – Science of the Total Environment 616-617: 1-16. https://doi.org/10.1016/j.scitotenv.2017.10.290.

[40] Nasir Ahmad, N. S. B., Mustafa, F. B., Muhammad Yusoff, S. Y. (2023): Spatial prediction of soil erosion risk using knowledge-driven method in Malaysia's Steepland Agriculture Forested Valley. – Environment, Development and Sustainability 26: 15333-15359. https://doi.org/10.1007/s10668-023-03251-8.

[41] Neitsch, S. L., Arnold, J. G., Kiniry, J. R. (2005): Soil and water assessment tool, theoretical documentation version 2005. – Grassland, Soil and Water Research Laboratory, Texas. https://swat.tamu.edu/media/1292/swat2005theory.pdf.

[42] Panagos, P., Matthews, F., Patault, E., De Michele, C., Quaranta, E., Bezak, N., Kaffas, K., Patro, E. R., Auel, C., Schleiss, A. J., Fendrich, A., Liakos, L., Van Eynde, E., Vieira, D., Borrelli, P. (2024): Understanding the cost of soil erosion: An assessment of the sediment removal costs from the reservoirs of the European Union. – Journal of Cleaner Production 434. https://doi.org/10.1016/j.jclepro.2023.140183.

[43] Parajuli, P., Nepal, D. (2024): Evaluation of the Effects of Potential Landuse Changes at a Watershed Scale. – Conference: ASABE Presentation # 2400139. At: Anaheim Marriott, Anaheim, CA.

[44] Pham, T. G., Degener, J., Kappas, M. (2018): Integrated universal soil loss equation (USLE) and Geographical Information System (GIS) for soil erosion estimation in A Sap basin: Central Vietnam. – International Soil and Water Conservation Research 6(2): 99-110. http://dx.doi.org/10.1016/j.iswcr.2018.01.001.

[45] Pozza, L. E., Field, D. J. (2020): The science of Soil Security and Food Security. – Soil Security 1: 100002. https://doi.org/10.1016/j.soisec.2020.100002.

[46] Qiao, X., Li, Z., Lin, J., Wang, H., Zheng, S., Yang, S. (2024): Assessing current and future soil erosion under changing land use based on InVEST and FLUS models in the Yihe River Basin, North China. – International Soil and Water Conservation Research 12: 298-312. https://doi.org/10.1016/j.iswcr.2023.07.001.
[47] Regasa, M. S., Nones, M. (2023): SWAT model-based quantification of the impact of land use land cover change on sediment yield in the Fincha watershed, Ethiopia. – Front. Environ. Sci. 11: 1146346. doi: 10.3389/fenvs.2023.1146346.
[48] Renard, K. G., Freimund, J. R. (1994): Using monthly precipitation data to estimate the Rfactor in the revised USLE. – J Hydrol 157: 287-306.
[49] Rickson, R. J. (2014): Can control of soil erosion mitigate water pollution by sediments? – Sci. Total Environ 468-469: 1187-1197. http://dx.doi.org/10.1016/j.scitotenv.2013.05.057.
[50] Senanayake, S., Pradhan, B., Wedathanthirige, H., Alamri, A., Parkmore, H-J. (2024): Monitoring soil erosion in support of achieving SDGs: A special focus on rainfall variation and farming systems vulnerability. – Catena 234: 107537. https://doi.org/10.1016/j.catena.2023.107537.
[51] Serbaji, M. M., Bouaziz, M., Weslati, O. (2023): Soil Water Erosion Modeling in Tunisia Using RUSLE and GIS Integrated Approaches and Geospatial Data. – Land 12: 548. https://doi.org/10.3390/land12030548.
[52] Shin, G. J. (1999): The analysis of soil erosion analysis in watershed using GIS. – Ph.D. Dissertation, Department of Civil Engineering, Gang-won National University.
[53] Simonneaux, V., Cheggour, A., Deschamps, C., Mouillot, F., Cerdan, O., Le Bissonnais, Y. (2015): Land use and climate change effects on soil erosion in a semi-arid mountainous watershed (High Atlas, Morocco). – Journal of Arid Environments 122: 64-75. http://dx.doi.org/10.1016/j.jaridenv.2015.06.002.
[54] Singh, R., Phadke, V. S. (2006): Assessing soil loss by water erosion in Jamni River Basin, Bundelkh and region, India, adopting universal soil loss equation using GIS. – Current Science 90(10): 25-27. http://www.jstor.org/stable/24091996.
[55] Svoray, T., Atkinson, P. M. (2013): Geoinformatics and water-erosion processes. – Geomorphology 183: 1-4.
[56] Telo da Gama, J. (2023): The Role of Soils in Sustainability, Climate Change, and Ecosystem Services: Challenges and Opportunities. – Ecologies 4(3): 552-567. https://doi.org/10.3390/ecologies4030036.
[57] Thavhana, M. P., Savage, M. J., Moeletsi, M. E. (2018): SWAT model uncertainty analysis, calibration and validation for runoff simulation in the Luvuvhu River catchment, South Africa. – Physics and Chemistry of the Earth, Parts A/B/C 105: 115-124. https://doi.org/10.1016/j.pce.2018.03.012.
[58] Trimble, S. W., Crosson, P. (2000): Land Use: U.S. soil erosion rates - Myth and reality. – Science 289(5477): 248-250. https://doi.org/10.1126/science.289.5477.248.
[59] UN (United Nations) (2013): Draft Resolution. – Submitted by the Vice-Chair of the Committee, Ms. Farrah Brown (Jamaica), on the Basis of Informal Consultations on Draft Resolution A/C.2/68/L.21; United Nations General Assembly: Washington, DC, USA.
[60] Vigiak, O., Malagó, A., Bouraoui, F. (2015): Adapting SWAT hillslope erosion model to predict sediment concentrations and yields in large Basins. – Science of the Total Environment 538(December 2015): 855-875. https://doi.org/10.1016/j.scitotenv.2015.08.095.
[61] Wheeler, B., Webb, N., Williams, J., Faist, A., Edwards, B. E., Herrick, J., Lepak, N., Kachergis, E., McCord, S., Newingham, B., Pietrasiak, N., Toledo, D. (2024): Integrating Erosion Models into Land Health Assessments to Better Understand Landscape Condition. – Rangeland Ecology & Management 96: 32-46. https://doi.org/10.1016/j.rama.2024.05.003.
[62] Wischmeier, W. C., Smith, D. D. (1978): Predicting rainfall erosion losses - A guide to conservation planning. – Agricultural Handbook No. 537. US Dept Agric., Washington, DC. https://handle.nal.usda.gov/10113/CAT79706928.

[63] Zeng, X., Huang, L., He, G., Wang, D., Wu, X., Fang, H. (2022): Phosphorus transport in the Three Gorges Reservoir over the past two decades. – Journal of Hydrology 609: 127680. https://doi.org/10.1016/j.jhydrol.2022.127680.

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