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Soil Erosion Analysis with GIS: A Case Study of Oued Sly Catchment, Northern Algeria

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Abstract: Soil erosion is a process that involves the detachment and transportation of soil particles by water, presenting notable challenges of the depletion of soil fertility, diminished agricultural productivity, and consequences for water reservoirs. The integration of Geographic Information System (GIS) and modeling techniques provides a valuable platform for assessing and addressing soil water erosion. This study specifically examines the risk of soil water erosion in the Oued Sly catchment within the Middle Cheliff watershed in northern Algeria. Employing the Universal Soil Loss Equation (USLE) and thematic maps, the research evaluates the key factors influencing erosion. Results reveal that the catchment generally experiences low to moderate erosion levels, averaging 23.4 to 40 t ha^{-1} yr^{-1} across 90.7% of the total area. However, around 9.3% of the catchment exhibits higher erosion rates exceeding 40 t ha^{-1} yr^{-1}. These findings offer valuable insights for informed watershed management and strategies to mitigate soil water erosion in comparable regions.

Key words: Erosion, solid particles, soil fertility loss, USLE model.

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Hydraulic erosion poses a significant threat to both people and infrastructure, particularly in watersheds and dams, with natural factors such as rainfall, relief, geological formations, and vegetation cover exacerbating the issue (Achite and Meddi, 2005; Belouchrani *et al.*, 2021). In Algeria, soil water erosion has become a major challenge impacting the economy and the environment, contributing significantly to sediment transport and deposition on dams, leading to substantial loss of storage capacity and agricultural lands (Kouli *et al.*, 2009; Assefa *et al.*, 2015; Amellah and el-Morabiti, 2021; Nehai *et al.*, 2021; Sun *et al.*, 2021). Siltation in Algerian dams led to a reduction of 16.5% in the initial total storage capacity by 2025 (Remini, 2017; Guenfoud *et al.*, 2021). However, specific dams have experienced even more significant decreases, such as the Sidi Yacoub dam in the middle Cheliff watershed, which lost 11.6% and 21.65% of its initial capacity in 2004 and 2020, respectively.

In this study, our objective is to mitigate soil water erosion in the Oued Sly watershed by integrating erosion-contributing factors of the Universal Soil Loss Equation (USLE) into a Geographic Information System (GIS). The research aims to quantify water erosion and emphasize the importance of the

Sidi Yacoub dam's silting rate as a crucial indicator of soil erosion in the region, thereby offering valuable scientific data for decision-makers.

Materials and Methods

The Oued Sly watershed, situated within the Ouarsenis mountain range of the Tell Atlas, spans a diverse natural landscape between the Cheliff plain in the north and the highlands of Tiaret in the south. Covering 927 km^2, the watershed exhibits varied altitudes, with the primary watercourse extending over 40.8 km, leading to the Sidi Yakoub dam. Administratively, the watershed spans 17 municipalities across Tissemsilt, Relizane, Cheliff, and Tiaret provinces. The region's geological and topographical features, characterized by diverse relief, render it highly susceptible to soil water erosion. This susceptibility arises from factors such as the reduction of protective vegetation cover, steep slopes, easily weathered lithological formations, and aggressive rainfall (Bouderbala, 2021).

The study employs the Revised Universal Soil Loss Equation (RUSLE) model to assess erosion, integrating climatic aggressiveness, soil erodibility, topography, land use, and erosion control practices. Despite criticisms, RUSLE remains a widely accepted approach for evaluating water erosion. Thematic maps within a Geographic Information System (GIS) are utilized to map and analyze factors influencing erosion in this region, allowing for the identification and quantification of soil loss in the Oued Sly watershed. This model provides a comprehensive view of the relationship between factors and soil erosion.

Methodologically, the study integrates climatic data, geological and pedological maps, vegetation cover maps, and satellite imagery for the evaluation of erosion factors. The meteorological data used in this study to estimate the rainfall erosivity factor (R) have been provided by the National Agency of Hydraulic Resources (ANRH). The soil erodibility factor (K) is derived from Landsat 8 ETM satellite imagery, while the topographic factor (LS) is calculated using the Shuttle Radar Topography Mission (SRTM) digital elevation model. The vegetation cover (C) is computed based on NDVI, and indicators of erosion control practices (P) are derived from land use patterns.

The final map of soil erosion in the Oued Sly watershed is obtained through the integration of parameters controlling water and soil erosion, enabling the mapping of vulnerable erosion zones within the watershed. Such a final map serves as a valuable tool for managing these zones to prevent future land degradation within the watershed.

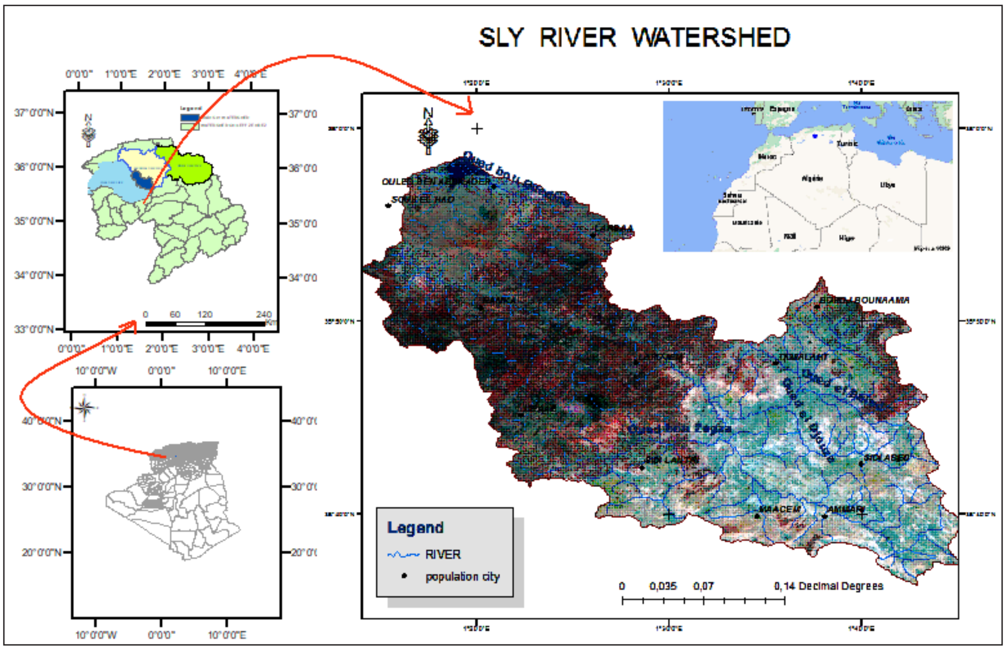

Fig. 1. Situation of Oued Sly watershed.

Results and Discussions

Rainfall-Runoff erosivity factor (R)

Rainfall erosivity, a key element in soil erosion assessment, was determined using the equation proposed by Renard and Freimund (1993): $R=0.0483 \cdot P^{1.6}$, where: R represents erosivity in t ha^{-1} yr^{-1} and P denotes annual precipitation in mm (Bouguerra *et al.*, 2017). Climatological data on average rainfall, sourced from meteorological stations situated within or in proximity to the Oued Sly watershed, serve as the foundation for estimating the rainfall erosivity factor (R). The average rainfall is interpolated throughout the entire watershed using the Topo to Raster interpolation tool.

The resulting map of the rainfall erosivity index R (Fig. 2) offers insights into the distribution of erosive rains within the watershed. Higher R values signify regions prone to highly erosive rains, while lower values indicate less erosive rainfall. The gradient observed from the northwest and southeast towards the northeast and central east highlights the varying erosive power of rainfall across the watershed. Emphasizing the importance of adequate vegetation cover on eastern slopes becomes apparent to mitigate the impact of raindrop splash and minimize particle detachment. This understanding of rainfall erosivity patterns aids in formulating targeted erosion control strategies for the study area. The erosivity map delineates regions exhibiting high to very high erosivity ($R \geq 600$ t ha^{-1} yr^{-1}), signifying an imminent threat of soil erosion and the potential for severe land degradation, particularly concentrated in the eastern section of the watershed. Conversely, moderate erosivity ($R < 600$ t ha^{-1} yr^{-1}) predominates in the western part of the watershed. Despite being categorized as moderately erosive, rainfall events in this area can still induce moderate soil erosion.

Topographic factor (LS)

The factor of slope plays an important role in assessing the possibility of breaking down and transporting soil particles into runoff, which directly affects erosion. Steeper slopes intensify erosion as runoff increases, while higher slopes increase soil loss. To calculate flux concentration, the slope length factor was replaced by the upstream drainage area, using the formula proposed by Mitasova *et al.* (1996).

The topographic factor map (LS) was established based on slope maps derived from a 30 m resolution digital elevation model (DEM) based on contour lines from 1/50,000 topographic maps, which is a combination of slope length (L) and steepness (S). The values in this map range from 0.03 to 28.63 (Fig. 3). Approximately 73.9% of the basin area exhibits slopes under 5%, while 23.9% features slopes ranging from 5% to over 18%. Steeper slopes exceeding 18% cover 2.32% of the area of the watershed. The slope values offer valuable insights into erosion behavior. The basin's topography, which is characterized by steppe plateau from southeast to northwest, includes

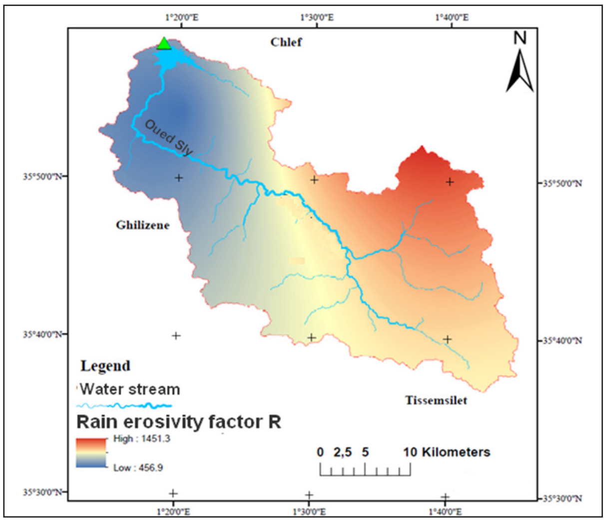

Fig. 2. Rainfall erosivity factor map R.

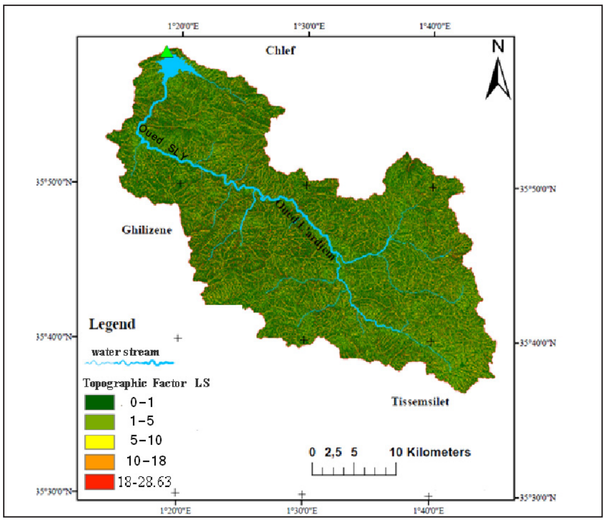

Fig. 3. Map of the LS topographic factor.

rugged topographic units with steep-sloped entities, contributing to erosion dynamics.

Soil erodibility factor K

Soil erodibility, a crucial factor in soil erosion evaluation, reflects the ease with which soil particles detach, influenced by factors such as structure, texture, grain size distribution, organic matter content, and permeability. In the Oued Sly watershed, the soil erodibility factor (K) was determined using the Wischmeier nomograph, incorporating data from pedological profiles (Sabir *et al.*, 2002; Zouagui *et al.*, 2018).

The K factor map reveals values from 0.0125 to 0.0243 across the Oued Sly watershed, indicating varying degrees of soil fragility and susceptibility to erosion (Fig. 4). Areas with values below 0.0195 are associated with erosion-resistant soils, while those around 0.022 signify erosion-prone soils. The map illustrates that 5.94% of the watershed area exhibits high erosion resistance, 12.15% has low to moderate erodibility soils, and approximately 81.92% consists of highly erodible soils. This comprehensive understanding of soil erodibility provides valuable insights into erosion dynamics and aids in developing targeted erosion control strategies in the study area.

Vegetation cover factor (C)

The vegetation cover factor, denoted as "C," is an important parameter in evaluating soil erosion vulnerability, reflecting the impact of vegetation on erosion processes. Vegetation acts as a natural safeguard against erosion by intercepting rainfall, slowing runoff, and enhancing soil stability (Bardadi *et al.*, 2021).

The high value "C=1" for bare soil, indicates no vegetation cover, suggesting a high risk of erosion, while the low value "C=0.01" indicates more effective vegetation cover, suggesting a lower risk of erosion. The "C" values for various land cover types in the Oued Sly watershed, were ranging from 0.03 for vegetation to 1 for bare soils. Dense vegetation cover, particularly in forests and shrubs, plays a vital role in reducing erosion by dissipating raindrop energy and maintaining good soil infiltration. Factor "C" values are determined through regression analysis using the NDVI, calculated as (NIR - R) / (NIR + R) for Landsat 8 images. The NDVI values range from -1.0 to 1.0, where higher values represent dense vegetation, and lower values indicate bare soil or water bodies.

The regression relationship C = exp [-α*(NDVI/(β-NDVI))] is utilized, with α = 2 and β = 1, to estimate "C" values based on NDVI. The spatial distribution of "C" is extracted from the vegetation cover map, reflecting the type of land vegetation cover. In the Oued Sly watershed, the Southeast region dominated by large crops exhibits higher "C" values (>0.1), indicating minimal soil protection. Conversely, the central basin with forests and shrubs showcases lower "C" values (<0.1, even <0.03), signifying better soil protection (Fig. 5).

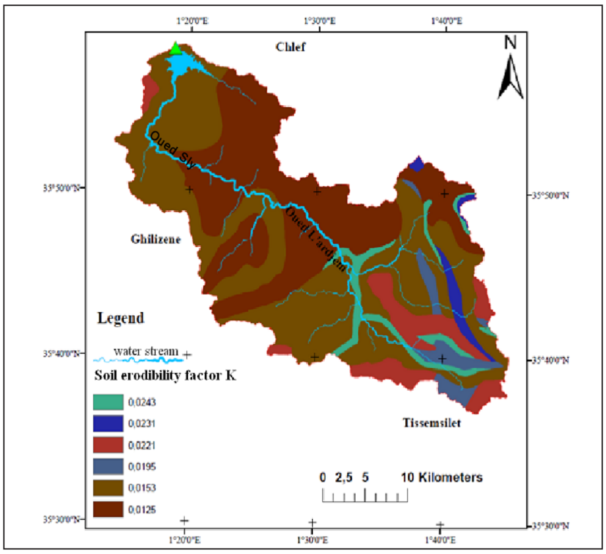

Fig. 4. Map of the soil erodibility factor K.

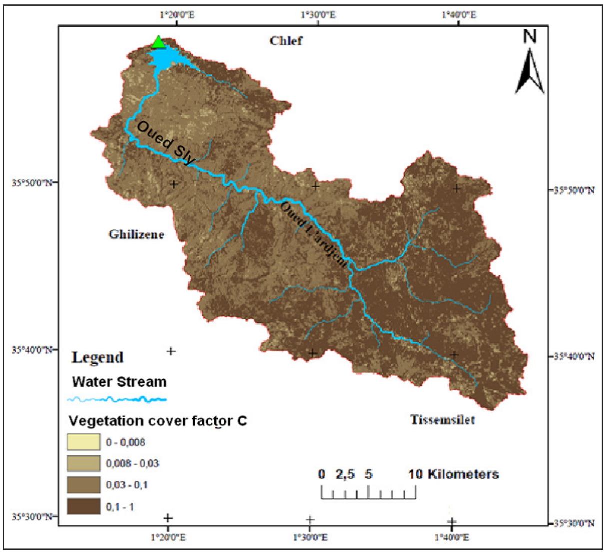

Fig. 5. Vegetation cover lands factor C.

Table 1. P-factor values (Wischmeïer and Smith, 1978)

Type of erosion control practice	Slope	Maximum length	P
Contour farming	1 à 8%	61 à 122 m	0.5
Contour farming	9 à 12%	36 m	0.6
Contour farming	13 à 16%	24 m	0.7
Contour farming	17 à 20%	18 m	0.8
Contour farming	21 à 25%	15 m	0.9
Contour farming with grass strips	1 à 8%	30 à 40 m	0.25 à 0.5
Contour farming with grass strips	9 à 16%	24 m	0.3 à 0.6
Contour farming with grass strips	17 à 25%	15 m	0.4 à 0.9

The vegetation cover factors provide valuable insights for identifying erosion-prone areas and formulating targeted soil conservation strategies in the Oued Sly watershed.

Erosion control practices factor (P)

The factor P, which represents erosion control practices, accounts for the combined effect of various support techniques employed to minimize soil loss. These practices often involve methods such as terracing, contour farming, and the implementation of strip cropping, among others. The table 1 shows the values of the P factor.

The P factor describes soil conservation practices implemented by human actions to mitigate water erosion. P values typically range from 0 to 1, depending on the adopted practice and the slope. Contour farming, strip cropping, terracing, reforestation with benching, and hilling are among the most effective soil conservation practices. The anti-erosion practices identified in the Oued Sly watershed mainly include bunds and boundary ridges, dry stone walls, terraces, and occasionally dry hedges around certain plots. The P-values range from 0.55 to 1, with higher values observed in the center of the watershed and lower values observed upstream (Fig. 6).

Final map of soil erosion in the Oued Sly watershed

The research methodology involves the integration of cartographic and descriptive data related to various erosion factors and parameters into a Geographic Information System (GIS). This empirical, quantitative erosion model employs the Revised Universal Soil Loss Equation (RUSLE) to estimate soil losses in t ha^{-1} yr^{-1} per unit area. The ArcGIS software facilitates the overlay of cartographic data, producing the erosion risk map. This detailed map provides perspectives into erosion potential at the pixel level throughout the Oued Sly watershed.

In the initial examination of the erosion class map, a scattered spatial distribution of erosion classes emerges, signifying the cumulative impact of diverse erosion factors in the region. Erosion values range from 10 t ha^{-1} yr^{-1} to a maximum of 125.64 t ha^{-1} yr^{-1}, prompting an analysis of physical parameter maps. The majority of the Oued Sly watershed experiences very low erosion classes (< 40 t ha^{-1} yr^{-1}), particularly in the southeast part with soil loss ranging from 10 t ha^{-1} yr^{-1} to 40 t ha^{-1} yr^{-1} in shrubland areas. Western regions exhibit higher erosion classes, varying from 40 t ha^{-1} yr^{-1} to 80 t ha^{-1} yr^{-1}. The northwest and middle of the watershed show the highest erosion class due to steep slopes and geological characteristics.

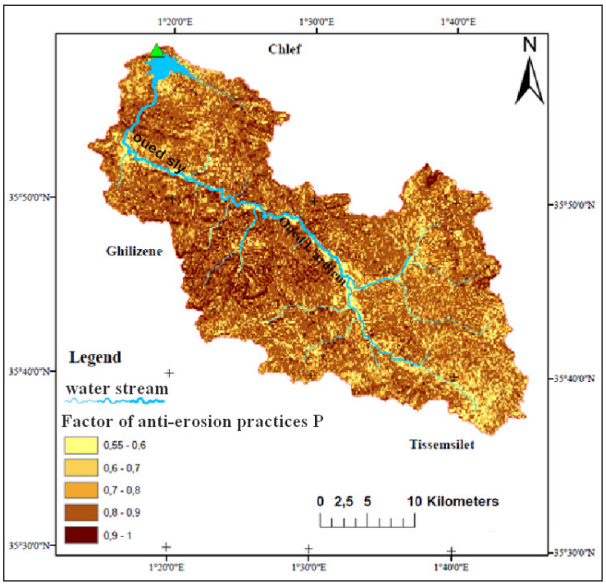

Fig. 6. Erosion control practices factor map (P).

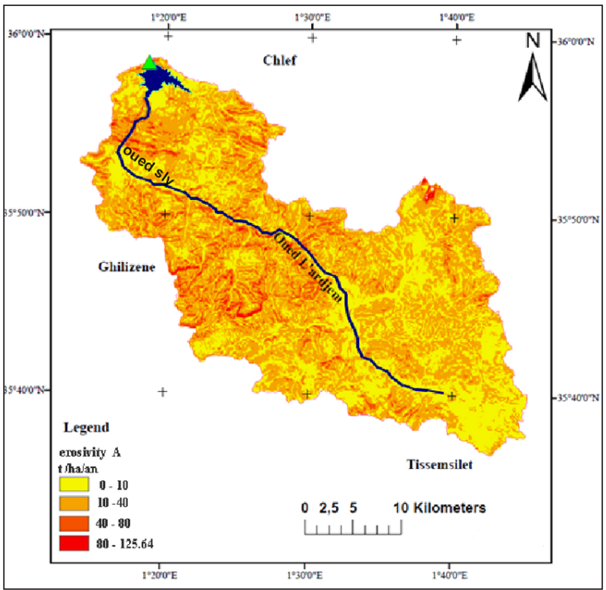

Fig. 7. Final soil erosivity map in (t ha^{-1} year^{-1}).

Rainfall-runoff erosivity, soil erodibility, slope length-steepness, vegetation cover, and erosion control practices significantly influence water erosion rates, contributing to overall soil loss in the Oued Sly watershed (Fig. 7).

Conclusion

This study aimed to utilize a Geographic Information System (GIS) for the spatialization of water erosion, employing the Universal Soil Loss Equation (USLE) model developed by Wischmeier and Smith. The integration of geological layer friability, vegetation cover, annual average rainfall distribution, and slope inclination into GIS provided comprehensive insights into the Oued Sly watershed, enabling the mapping of vulnerable erosion zones within the watershed. The delineation of erosion-prone areas revealed four sensitivity classes: low sensitivity (40.52%), moderate sensitivity (50.239%), high sensitivity (8.62%), and very high sensitivity (0.62%). The research found that there is an average annual soil loss of 23.4 t ha^{-1} yr^{-1}, signifying substantial downstream impacts that are observable through the siltation of the Sidi Yacoub dam. The dam experienced a 21.65% loss of its initial capacity based on a 2020 bathymetric survey.

The results indicated that rainfall erosivity, soil erodibility, and topographic factors are the primary drivers of soil erosion in the study area. Specifically, high and very high-risk erosion classes were found predominantly in agricultural areas and bare soil within the Oued Sly watershed. Implementing vegetative cover, alongside optimal cropping systems in this watershed, should be prioritized. Additionally, integrating techniques like terracing and ridging could further aid in reducing sediment yields to the Sidi Yacoub dam, thereby extending its lifetime.

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