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INTEGRATION OF THE USLE MODEL AND GIS TECHNOLOGIES IN SOIL EROSION ANALYSIS. CASE STUDY

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Abstract. *The paper presents the application of the Universal Soil Loss Equation (USLE) model, integrated within a GIS environment, for estimating the average annual soil loss in the Cigher River Basin, located in the central-eastern part of Arad County. The main objective was to assess erosion vulnerability in relation to natural factors (precipitation, relief, soil) and anthropogenic factors (land use, agricultural practices). The analysis was based on multi-annual climatic data, pedological information, a 25 m resolution Digital Elevation Model (DEM), and Sentinel-2 satellite imagery used to calculate the NDVI index. The five USLE factors - R (rainfall erosivity), K (soil erodibility), LS (slope length and steepness), C (cover management), and P (support practices) - were determined and integrated as raster layers to generate the final soil loss map. The results indicate average annual soil loss values ranging from 0 to over 41 t/ha/year, with an overall mean of 1.00 t/ha/year. Approximately 88% of the basin area falls within the very low-risk class (below 3 t/ha/year), while high-risk zones are located in the southern part of the basin, where steep slopes coincide with intensive agricultural use. The study confirms the effectiveness of integrating the USLE model with GIS technologies in the spatial analysis of erosion risk and highlights the need to implement conservation measures in critical areas to ensure sustainable soil resource management.*

Keywords: *USLE, GIS, soil erosion, spatial modeling.*

INTRODUCTION

Soil erosion represents one of the most significant land degradation processes worldwide, with major implications for the environment and agricultural activities (KIM ET AL., 2005; BORDEAN ET AL., 2013; ŠPALEVIĆ ET AL., 2020). The intensity of this phenomenon is determined by the complex interaction between natural factors (climatic, pedological, and geomorphological) and human activities. According to Balabathina et al. (2020), approximately 85% of the world's degraded lands are affected by erosion processes, which lead to soil fertility loss and the decline of crop productivity and grassland biodiversity (CALUSERU ET AL., 2013; SINGH, PANDA, 2017; COPĂCEAN ET AL., 2019; PATRICHE, 2023). Due to its scale and consequences, soil erosion is considered one of the major contemporary environmental issues.

In Romania, approximately 43% of agricultural land is susceptible to erosion, a process whose manifestation varies depending on local conditions such as topography, soil type, rainfall, and land use (NISTOR, NISTOR, 2002). The critical season generally occurs between May and August, a period characterized by torrential rains with a strong impact on the soil. Although numerous erosion control structures existed in the past, many have been abandoned or are currently in an advanced state of degradation, which intensifies soil loss and its effects on surface and groundwater, as well as on agricultural land (MAN, 2014).

Estimating soil loss at the watershed level through classical methods requires significant time and resources and is often constrained by the lack of necessary data. Under these conditions, the use of modern spatial analysis and modeling techniques computer-assisted

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offers an efficient alternative for estimating soil losses at various spatial and temporal scales (BORRELLI ET AL., 2015; TODISCO ET AL., 2022).

Among the most widely applied models globally is the Universal Soil Loss Equation (USLE), developed by the United States Department of Agriculture (USDA) and later improved in the RUSLE and RUSLE2 versions (PANAGOS ET AL., 2015). Integrating this model into a GIS (Geographic Information Systems) environment allows for the spatial analysis and representation of the factors involved in erosion processes, providing a solid foundation for risk assessment and the development of sustainable land management strategies (ESTIFANOS, 2014; MENGIE ET AL., 2019; SIMON ET AL., 2022; PATRICHE, 2023).

Given the increasing importance of assessing soil degradation processes through modern means, the integration of empirical models such as USLE within GIS environments represents an efficient approach to the spatial analysis of erosion risk. This combination enables the quantification of soil losses and the identification of vulnerable areas, contributing to the foundation of protective measures and the sustainable management of soil resources.

The objective of this study is the application of the Universal Soil Loss Equation (USLE) model, integrated within a GIS environment, to estimate the average annual soil loss in the Cigher River Basin (Arad County). The analysis aims to evaluate the degree of susceptibility to erosion based on natural factors (precipitation, relief, soil) and anthropogenic factors (land use, agricultural practices), as well as to identify critical areas requiring priority soil conservation measures.

MATERIALS AND METHODS

Study Area

The Cigher River Basin, located in the central-eastern part of Arad County (21°30′ - 22°05′ E, 46°05′ - 46°25′ N), is characterized by a diverse relief with elevations ranging from 95 to 792 m (Figure 1), including the Low Plain of the Criș Rivers, the Cigher Hills, and the northern sector of the Zarand Mountains.

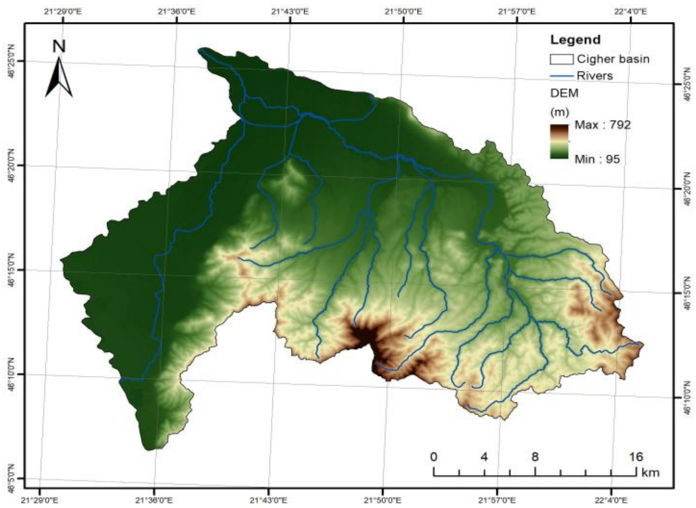

Figure 1. Location of the study area and Digital Elevation Model (DEM) of the Cigher River Basin (processed after GEOSPATIAL, 2022; EEA - EU-DEM, 2022)

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The climate is temperate-continental, with average annual temperatures of 10 - 11°C and precipitation ranging from 600 - 800 mm. The hydrographic network, dominated by the Cigher River, shows high density in the southern part of the basin. The soils are diverse, ranging from fertile chernozems in the lowland areas to erodible luvisols and regosols in the hilly and mountainous regions, while the vegetation varies from deciduous forests to grasslands and agricultural lands. This natural complexity gives the basin a differentiated susceptibility to erosion, which is more pronounced in areas with rugged relief and sparse vegetation cover.

Data and software used

The spatial analysis was carried out based on geospatial datasets integrated within a GIS environment. The following data were used: climatic data (multi-annual average precipitation for 2013–2024) from 11 meteorological stations (CLIMATIC DATABASE, 2023); vector-based soil data (GEOSPATIAL, 2022); a Digital Elevation Model (DEM) with a spatial resolution of 25 m (EEA, 2022); and Sentinel-2 satellite images from 2024 (COPERNICUS OPEN ACCESS HUB, 2023) used for calculating the NDVI index (HERBEI ET AL., 2012). Processing and analysis of the geospatial data were performed using ESA SNAP 9.0.0 for satellite image processing and ArcGIS 10.8 for spatial analysis and USLE modeling.

Research Methodology

The USLE model (Universal Soil Loss Equation), developed by Wischmeier and Smith (1978), estimates the average annual soil loss (A) as the product of five main factors, according to the following equation (SELMY ET AL., 2021; GE ET AL., 2023):

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

where: A - average annual soil loss (t/ha/year); R - rainfall erosivity; K - soil erodibility; LS slope length and steepness; C - vegetation cover; P - soil conservation practices.

Each factor was spatialized and converted into raster format (spatial resolution of 25 m), using the Stereo 1970 projection system.

The R factor, determined based on Hurni's (1985) formula (BALABATHINA ET AL., 2020):

$$R = 0.55 \times P - 4.7$$

where: R - rainfall erosivity (MJ mm $ha^{-1}h^{-1}year^{-1}$); P - mean annual precipitation (mm).

The K factor was calculated according to Wischmeier et al. (1971), based on soil texture, structure, permeability, and organic matter content (SELMY ET AL., 2021):

$$100K = 2.1M^{1.14} \times 10^{-4} \times (12 - a) + 3.25 \times (b - 2) + 2.5(c - 3)$$

where: K - soil erodibility (t $ha^{-1}MJ^{-1}mm^{-1}$); M - parameter calculated as [very fine sand (%) + silt (%)] × [100 − clay (%)]; a - organic matter content (%); b - soil structure code; c - soil permeability class.

The LS factor was derived from the DEM using the relationship proposed by Mitasova (1996) (ZISU, 2014), which correlates flow accumulation and slope angle for each pixel:

$$LS = \left(\frac{FA \times \text{cell size}}{22.13}\right)^m \times \left(\frac{\sin(\text{slope angle} \times 0.01745)}{0.9}\right)^n$$

where: LS - topographic factor (dimensionless); FA - flow accumulation; cell size - pixel dimension (spatial resolution) - 25 × 25 m; slope angle - slope map, in radians; m = 0.5; n = 1.3 - exponential values.

The C factor was obtained based on NDVI values derived from Sentinel-2 imagery, using the equation proposed by Van der Knijff et al. (2000) (BALABATHINA ET AL., 2020):

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$$C = \exp\left[-\alpha \times \frac{NDVI}{(\beta - NDVI)}\right]$$

where: C - cover management factor (dimensionless); NDVI, calculated using the formula (NIR − R) / (NIR + R); NIR - near-infrared band; R - red band; α = 2; β = 1.

Factorul P was estimated indirectly as a function of slope, according to the relationship proposed by Wener (2002) (ALLAFTA & OPP, 2022), due to the lack of data on actual conservation practices:

$$P = 0.2 + 0.03 \times S$$

where: P – support practice factor (dimensionless); S - slope (%).

The final result was a map of average annual soil loss, classified into five intensity classes: very low (0 - 3 t/ha/year), low (3.1 - 10 t/ha/year), moderate (11 - 20 t/ha/year), high (21 - 40 t/ha/year), and very high (>41 t/ha/year). This classification enabled the assessment of erosion vulnerability and the identification of areas requiring protective interventions.

RESULTS AND DISCUSSION

Soil erosion represents one of the major geomorphological processes that affect ecosystem balance and land productivity, being controlled by the complex interaction between climatic, pedological, geomorphological, and anthropogenic factors.

Within the Cigher River Basin, erosion risk estimation was carried out through the application of the USLE model in a GIS environment, which allowed the integration of spatial parameters and the quantification of average annual soil losses. The relief analysis, based on the DEM, revealed altitudinal variations between 95 m in the low-lying areas of the northern half and 792 m in the southern part of the basin, where fragmented landforms occur, with steep slopes and narrow interfluves. Based on these characteristics, the territory can be divided into three altitudinal subzones: the high zone (>600 m), characterized by high relief energy and strong erosion potential; the intermediate hilly zone (300–600 m), with moderate slopes and variable relief; and the low zone (<300 m), where gentle slopes limit erosional processes. This morphometric analysis provided the essential foundation for the spatial interpretation of erosion risk and for the subsequent modeling of the USLE factors.

Spatial Modeling of the Determinant Factors of Soil Erosion

The application of the USLE model within the GIS environment enabled an integrated analysis of the main natural and anthropogenic factors controlling the intensity and spatial distribution of erosion processes across the Cigher Basin. The five main parameters (R, K, LS, C, and P) were determined, processed, and integrated as raster layers with uniform resolution for the entire basin area. This approach facilitated a coherent spatial representation of the risk factors, providing a solid foundation for estimating the average annual soil loss.

R Factor (Rainfall Erosivity Factor) It expresses the climatic potential of rainfall to generate erosion processes and depends on the intensity, duration, and frequency of precipitation events, particularly torrential rains.

In the Cigher Basin, the values obtained for the R factor range between 275.85 and 432.57 MJ·mm/ha·h·year, showing a clear increasing trend toward the eastern and northeastern parts of the basin (Figure 2), where the pluviometric regime is more active. This distribution suggests a higher erosion potential in the low hilly areas, where intense rainfall favors surface runoff formation and soil particle detachment processes.

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K Factor (Soil Erodibility Factor) It quantifies the predisposition of soil material to be detached and transported under the action of rainfall and surface runoff. This factor depends on properties such as texture, structure, organic matter content, and permeability.

In the Cigher Basin, the K factor values range between 0 and 0.60 t·ha·h/ha·MJ·mm (Figure 3), with the 0.30–0.40 t·ha·h/ha·MJ·mm interval predominating, characteristic of soils with medium erodibility. Areas with higher values correspond to fine-textured, weakly structured soils with low permeability, which, when combined with steep slopes, become extremely vulnerable to erosion.

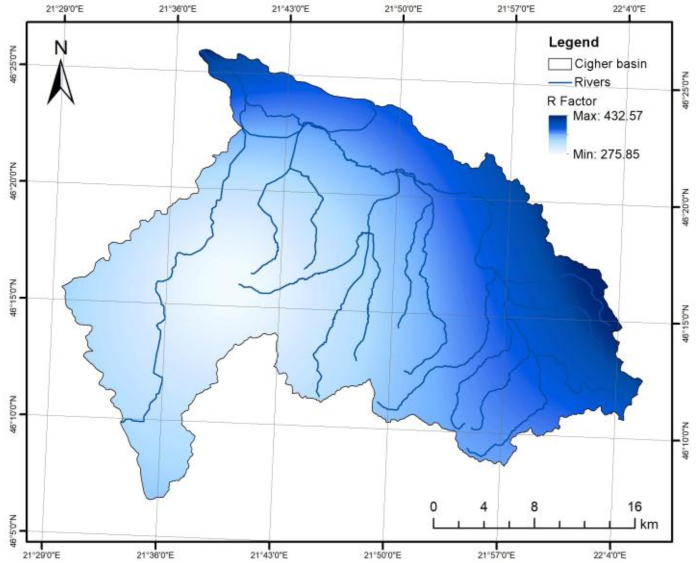

Figure 2. Spatial distribution of R factor values (rainfall erosivity) in the Cigher Basin

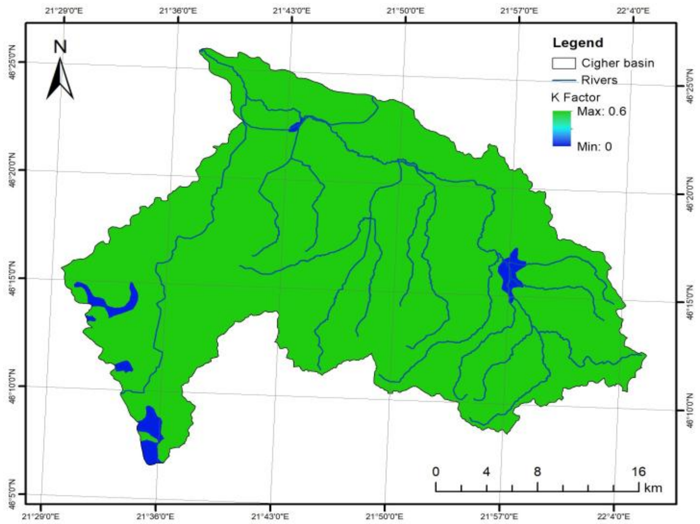

Figure 3. Spatial distribution of K factor values (soil erodibility) in the Cigher Basin

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The LS Factor (influence of terrain morphometry) reflects the role of topography in erosion processes by combining the effects of slope length (L) and slope steepness (S). The steeper the slope and the longer the hillside, the greater the surface runoff energy, which increases the transport capacity of soil particles.

Based on the DEM, LS values in the Cigher Basin range between 0 and 9.53, with maximum values recorded in the southern and southeastern parts of the basin (Figure 4), where the terrain is more fragmented and the slopes frequently exceed 25–30°. In contrast, the northern and northwestern parts of the basin show low values (<1), corresponding to areas with gentle slopes and a low risk of erosion.

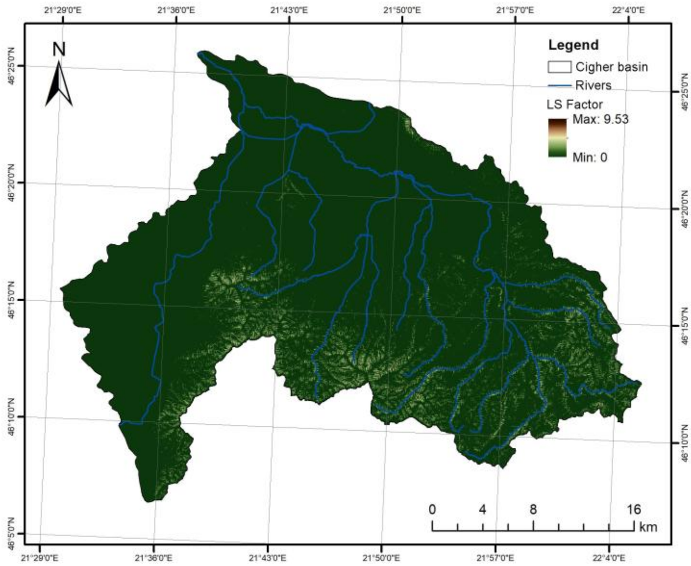

Figure 4. Spatial variability of the LS factor (slope length and steepness) in the Cigher Basin

The C Factor (Cover Management Factor) represents the effect of vegetation cover and land use on soil protection against the erosive action of water. Lower values of this factor correspond to surfaces well protected by vegetation (forests, grasslands), while higher values indicate reduced protection, typical of exposed arable lands.

In the Cigher Basin, C values range between 0.030 and 1.412 (Figure 5), reflecting a high diversity of land use types. The lowest values (<0.1) are found in the forested areas of the south and east, while agricultural lands, predominant in the central and northern parts, show higher values associated with an increased risk of soil loss.

The P Factor (Support Practice Factor) expresses the effectiveness of soil conservation techniques (terracing, contour farming, or vegetative strips) in reducing soil losses. In the absence of direct field data, P values were estimated based on the slope model and correlated with the likelihood of applying protection practices.

The obtained values range between 0.2 and 2.612 (Figure 6), indicating a wide range of conditions. Areas with low values (<0.5), located mainly in the northern half of the basin, benefit from a higher degree of protection, while areas with high values (>1.5), particularly in the south and southeast, indicate the absence of conservation measures and a high risk of erosion.

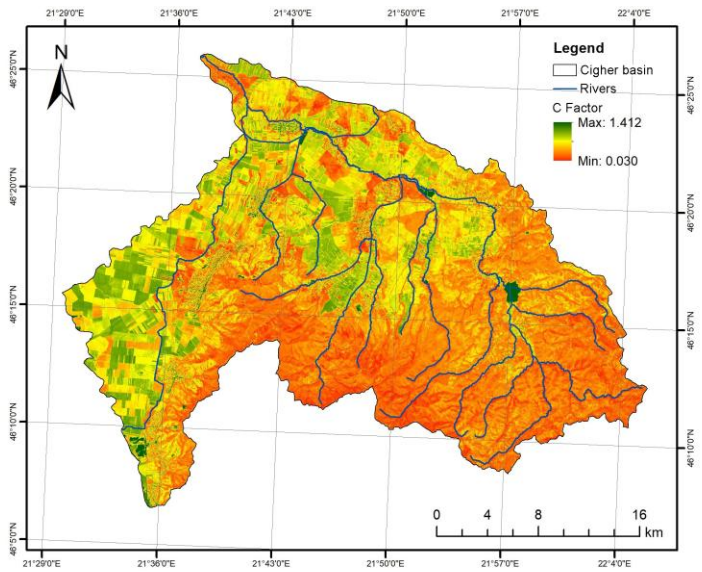

Figure 5. Spatial distribution of C factor values (Cover Management Factor) in the Cigher Basin

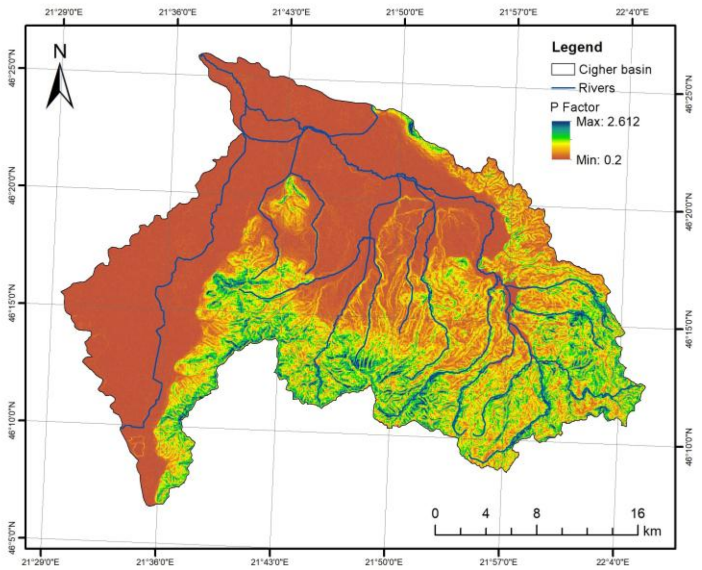

Figure 6. Spatial distribution of P factor values (Support Practice Factor) in the Cigher Basin Cigher

This stage of spatial modeling provided a detailed and multidimensional view of the potential erosion risk within the Cigher Basin. The overlap of high values of the **R**, **LS**, and **C** factors highlights critical areas in the southern and eastern parts of the basin, where soil conservation interventions should be prioritized. Integrating these factors into the GIS analysis offers an effective scientific tool for identifying vulnerable areas and supporting decision-making for sustainable land management planning.

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Estimation of average annual soil loss and identification of vulnerable areas

The spatial integration of the five USLE factors (R, K, LS, C, and P) within the GIS environment allowed the creation of a comprehensive map of average annual soil loss across the Cigher Basin (Figure 7). By multiplying the raster layers corresponding to each factor, the mean soil loss value was calculated, expressed in tons per hectare per year (t/ha/year). The result of this analysis provides a synthetic overview of the intensity of erosion processes and the spatial distribution of soil degradation risk.

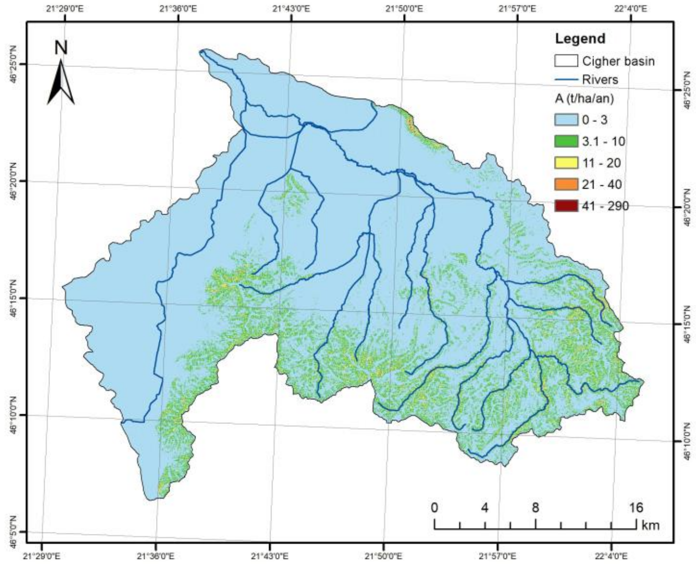

Figure 7. Estimation of average annual soil loss (t/ha/year) in the Cigher Basin, according to the USLE model

The obtained values range from 0 to over 41 t/ha/year, indicating considerable variation in soil loss depending on local characteristics such as relief, soil type, rainfall, and land use. For coherent interpretation, these values were classified into five vulnerability classes: very low (0–3 t/ha/year), low (3.1 - 10 t/ha/year), moderate (11 - 20 t/ha/year), high (21 - 40 t/ha/year), and very high (over 41 t/ha/year).

Statistical analysis showed that approximately 88% (74,131 ha) of the total basin area (84,473 ha) falls within the very low-risk category, reflecting a stable geomorphological equilibrium and a natural background erosion regime. The low-risk class covers about 10% (8,609 ha) of the area, typically corresponding to agricultural lands on gently sloping hillsides where erosion processes are moderate. Conversely, the moderate, high, and very high-risk zones, although limited in extent (about 1.8% of the total area), concentrate severe soil losses, with local values exceeding 40 t/ha/year. These vulnerable areas are mainly located in the southern part of the basin, where steep slopes, unstable soils, and unprotected agricultural lands coincide. In contrast, the northern and central regions, characterized by gentle relief and dense vegetation cover, show minimal soil losses, confirming the stabilizing role of vegetation and mild slopes.

Although the overall average soil loss for the entire basin is relatively low (≈ 1.00 t/ha/year), the extreme values observed in the southern part highlight the presence of localized accelerated erosion processes, which over time may lead to soil fertility decline, sedimentation of the hydrographic network, and degradation of agricultural lands.

CONCLUSIONS

The application of the USLE model within the GIS environment enabled an integrated assessment of erosion risk in the Cigher Basin by correlating the natural and anthropogenic factors that control soil loss.

The results show that relief plays a determining role in the distribution of erosion processes, with high LS factor values located in the southern part of the basin, where steep slopes increase the risk of land degradation. Rainfall erosivity (R) and soil erodibility (K) contribute secondarily, while land use (C) and agricultural practices (P) locally amplify soil loss.

The average annual soil loss is approximately 1.00 t/ha/year, indicating a generally low level of erosion; however, areas with high values exceeding 21 t/ha/year represent hotspots of severe erosion in the southern and southeastern parts of the basin.

Overall, the study confirms the effectiveness of combining the USLE model with GIS analysis for identifying vulnerable areas and supporting the implementation of soil conservation measures and sustainable land management strategies.

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