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SPATIAL MODELLING OF SOIL EROSION BY GIS TECHNIQUES, WITH APPLICATIONS IN LAND IMPROVEMENT

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Abstract: The aim of the research in this paper is to apply a complex spatial analysis model, based on GIS techniques, to identify areas susceptible to surface soil erosion and to determine the intensity of this phenomenon in different subareas of the Crişul Alb basin, in order to provide solutions for land improvement. The overall objective of the research was to identify and evaluate areas susceptible to soil erosion by applying a complex spatial analysis model based on GIS techniques, geospatial and remote sensing data, in order to determine the intensity of surface erosion in different subareas of the Crişul Alb basin and to propose solutions for the necessary land improvement.

1. INTRODUCTION AND GENERAL CONSIDERATIONS

Soil erosion is a natural process influenced by factors such as precipitation, topography, vegetation and human activities. It can have devastating effects on soil, affecting agricultural productivity, water quality and biodiversity. In the context of land improvement, soil erosion management is essential for maintaining soil fertility and protecting agricultural infrastructure. Spatial modelling of soil erosion using Geographic Information Systems (GIS) techniques provides a powerful tool for understanding and managing this phenomenon.

In this context, the importance of spatial modelling of soil erosion is materialized by:

a. Identification of vulnerable areas. Using GIS techniques, Digital Elevation Models (DEMs), spatial models of the factors involved and erosion models can be created, which allow the identification and classification of areas with different degrees of risk of erosion. These areas can be specifically monitored and managed to prevent soil loss.

b. Plan and implement control measures. GIS allows different soil management scenarios to be simulated, evaluating the effectiveness of control measures such as terracing, use of cover crops, and establishment of vegetative barriers. These simulations help to select the most effective intervention strategies.

c. Monitoring and impact evaluation of measures. GIS technologies allow continuous monitoring of the land and evaluation of the impact of implemented measures on soil erosion. Collected data can be analyzed to adjust and improve management strategies.

d. Integration of data sets from multiple sources. GIS can integrate data from various sources such as satellite imagery, climate data, land use data, and soil properties. This integration capability provides a holistic view of the factors influencing soil erosion.

The delimitation of the study area was done according to the Cressuri Water Basin Administration. To conduct the research and implement the workflow, i.e. territory characterization and calculation of factors involved in the estimation of vulnerability to surface soil erosion, the following key datasets were used:

- Climatic data, i.e. annual precipitation amounts from 2013 to 2022, recorded at 11 meteorological stations in the vicinity of the area of interest (Climatic Databases, 2023): Alba Iulia, Câmpeni (Bistra), Chişineu-Criş, Deva, Gurahonţ, Roşia Montană, Sânnicolau Mare, Sebeş (Alba), Şiria, Ştei (Petru Groza), Vărădia de Mureş;
- pedologic data in vector format (Geospatial, 2022);
- Digital Elevation Model (DEM), with 25 m spatial resolution (EEA, 2016), a hybrid product based on SRTM and ASTER GDEM data, From the DEM, the direction and accumulation of runoff and slope map were generated.
- Sentinel 2 satellite images, from 2021, from the months of March, May, July, October and November (Copernicus Open Hub, 2023); from these, the NDVI map was generated, with mean values, at the 2021 level.

The scientific data and information used in the research in this section were processed by various methods and software, as follows: satellite images were processed with ESA SNAP 9.0.0 software to obtain NDVI maps; ArcGIS 10.4 for Desktop and QGIS 3.24.1 Tisler software were used for geospatial data processing, overlay analysis and cartographic representation; the presentation of results was done with Microsoft Office 2016 and image editing with Adobe Photoshop CC 2018.

2. METHODS:

The Universal Soil Loss Equation (USLE) formulated by Wischmeier and Smith (1978) was used to estimate the average amount of soil lost annually by erosion and to generate the soil erosion susceptibility map for the analyzed territory. This equation assumes the product of five factors (Figure 1): rainfall erosivity

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(R), soil erodibility (K), topographic factor (LS), land cover management factor (C) and conservation support practice factor (P) [1,2,3]

The five USLE factors were spatialized in GIS as raster maps (Figure 1) with 25 m spatial resolution. The spatial resolution at which the results were obtained was conditioned by the available geospatial data, in particular DEM.

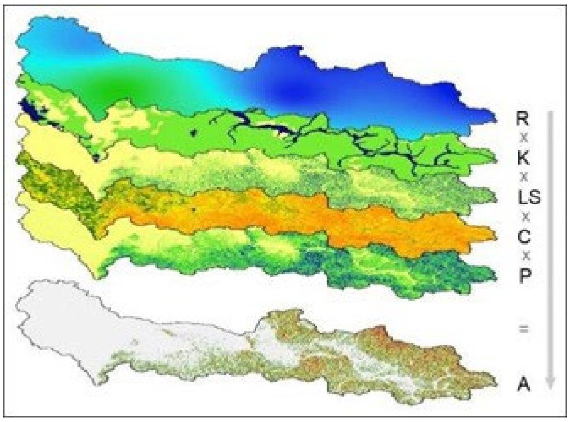

Figure 1. Research methodology

Spatial modeling of soil erosion is an essential tool for understanding, monitoring and managing this complex phenomenon. One of the most widely used models for estimating soil loss due to erosion is the Universal Soil Loss Equation (USLE). The application of this model provides a quantitative estimate of erosion by evaluating key factors contributing to the process, namely Rainfall erosivity (R), Soil erodibility (K), Topographic factor (LS), Land cover management factor (C) and Conservation Support Practice Factor (P).[4,8]

3. CASE STUDY:

The watershed of the Crișul Alb river, considered as a case study in this paper (Figure 2), belongs to the Crișuri Watershed and is located in the western part of Romania. It runs approximately SE - NW, its extreme points being 46°8'58.3"N, 23°6'18.3"E (near Tarnița); 46°2'28.1"N, 22°47'12. 7"E (near Dealu Mare locality); 46°30'8.2"N, 21°15'43.0"E (near Grăniceri locality), 46°38'17.6"N, 21°22'1.7"E (near Vârșand locality).

The Crișului Alb basin overlaps, for the most part, the county of Arad, and in the south-eastern part, the county of Hunedoara; in the east, on very small areas, it extends into the county of Alba, and in the north, also on a small area, it overlaps the county of Bihor. The basin area is 422798 ha and the perimeter 521965 m. [5,6,7]

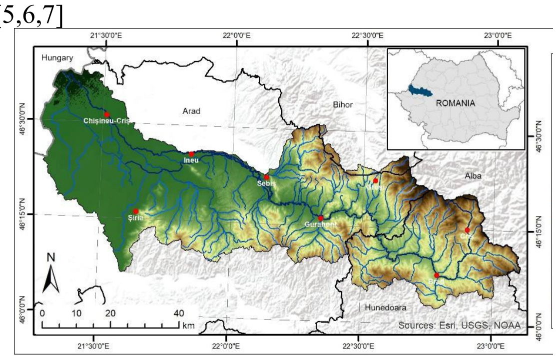

Figure 2. Localization and DEM

Based on the multi-year average precipitation values, the R-factor map was generated (Figure 3). It shows minimum values of 275.85 MJ mm mm ha-1h-1yr-1 in the southwest in the low plain area, suggesting that precipitation has a lower erosion capacity in these subareas. The maximum values of 571.59 MJ mm mm ha-1h-1yr-1, characterize the central part and the mountainous zone, which means that in these areas, precipitation is more intense and has a higher capacity to cause soil erosion.

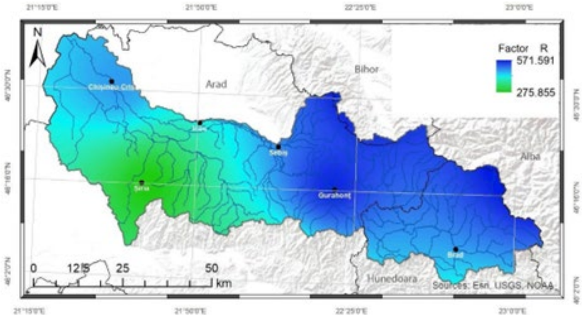

Figure 3. R-factor distribution map
(MJ mm ha-1 ha-1h-1yr-1)

In the analyzed territory, the R-factor can be influenced by both climatic patterns and topographic characteristics of the region. Eastern mountainous regions may have higher values due to steep slopes and higher precipitation.

The K-factor (soil erodibility) in the USLE and RUSLE equations is a key parameter for assessing soil vulnerability to erosion (Figure 3). The K-factor reflects the susceptibility of soil to detachment and transport processes of soil particles caused by raindrop impact and surface runoff.

The importance of the K-factor derives from the need to quantify how soil properties contribute to erosion. The K-factor is influenced by several parameters, including soil texture (percentage of sand, clay, and silt), organic matter content, soil structure, and soil permeability.

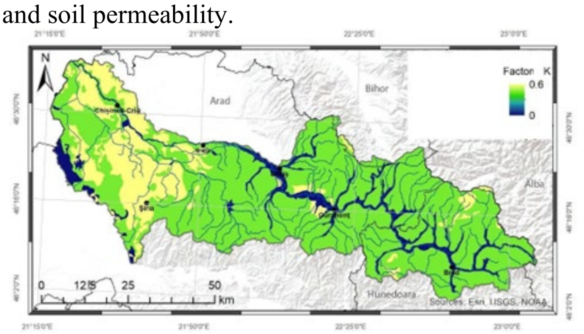

Figure 4. K-factor distribution map
(t ha-1MJ-1mm-1)

The soils of the analyzed area are distributed according to the physico-geographical factors: in the mountainous and hilly areas, districambosols and luvosols predominate, and in the lowlands, chernoz soils, eutricambosols and alluviols.

In the study area, K-factor values range from 0.04 t ha-1MJ-1mm-1 for sandy soils to 0.6 t ha-1MJ-1mm-1 for clay soils (Figure 4). The low values (0 - 0.2 t ha-1MJ-1MJ-1mm-1), predominate in the central and eastern part of the basin. Medium values (0.2 - 0.4 t ha-1MJ-1MJ-1mm-1) are sporadically distributed in different parts of the basin, while high values (0.4 - 0.6 t ha-1MJ-1MJ-1mm-1) are found mainly in areas close to the courses of main rivers and in mountainous areas.

The LS factor is an essential component in the USLE and RUSLE models used to estimate soil erosion and refers to the impact of topography on erosional processes. This factor reflects the influence of topography on erosion risk. Specifically, LS combines the effects of slope length (L) and slope steepness (S), both of which have a direct impact on the amount of soil lost to erosion. The longer and steeper the slope, the greater the risk of erosion (Liu et al., 2000; Lastoria et al., 2008), due to the increased kinetic energy of water flowing down the slope.

The LS factor is used to evaluate and compare different terrains according to their susceptibility to erosion. For example, lands with long and steep slopes have a higher LS factor and therefore a higher risk of erosion compared to flat or short and gently sloping lands. Accurate LS factor estimates are essential for planning soil conservation measures and implementing land management practices that reduce erosion.

The LS factor map (Figure 5) provides essential information about the potential for soil erosion due to topography in the catchment of the Crișului Alb.

In the study area, the relief is complex and varies between 82 - 1587 m, and the slope of the terrain ranges between 0 - 59º. Under these conditions LS has values between 0 - 16.56 (Figure 5).

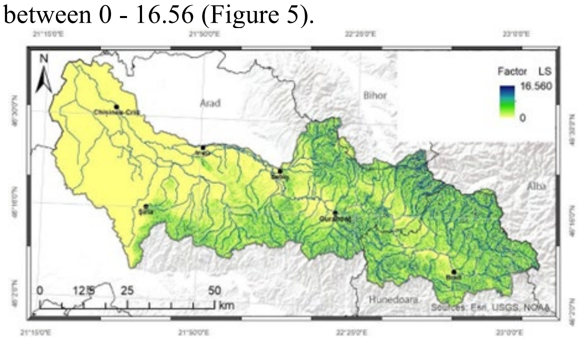

Figure 5. LS factor distribution map

The C-factor, or land cover management factor, is a crucial element of the USLE and RUSLE equations. This factor reflects the effect of land management practices and vegetation cover on soil erosion rates. It is one of the most variable and difficult to quantify factors in these equations, due to its sensitivity to spatio-temporal changes and the complexity involved in integrating several sub-factors.

The importance of Factor C lies in its ability to quantify the influence of different land use practices and vegetation on soil erosion. Agricultural practices, crop types, land management methods and vegetation cover are all aspects that can significantly alter the value of this.

In the Crișul Blanc basin in 2021, mean NDVI values ranged from -0.21 - 0.63. The minimum values are specific to areas not covered by vegetation (waters, roads or ploughed or harvested agricultural land), while the maximum values characterize forested areas, in mountainous areas.

The C-factor, calculated from satellite imagery, had values ranging from 0.03 - 1.41 (Figure 6). The maximum values of the C-factor correspond to lowland areas, dominated by agricultural land, with a lower degree of soil cover and thus lower erosion protection potential. The C values decrease towards higher altitudes, where forest floors predominate, offering a high degree of soil erosion protection.

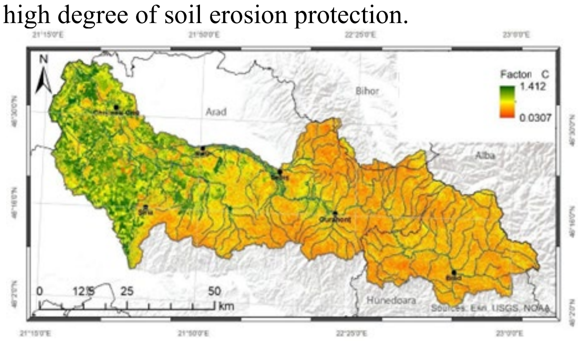

Figure 6. Distribution map of Factor C

The P-factor (Figure 7), also known as the Conservation Practices Factor, represents the effect of conservation practices applied on agricultural land to reduce soil erosion. Practices include strip farming, terracing and the use of vegetation strips, among others.

The P-factor defines the impact of land use and agricultural and non-agricultural practices on soil erosion, thus quantifying the influence of conservation strategies in the occurrence and manifestation of erosional processes.

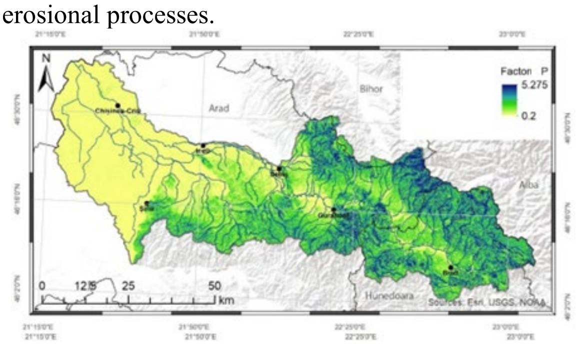

Figure 7. Distribution map of Factor P

Soil erosion is a major problem with multiple negative environmental and economic impacts. From an ecological point of view, erosion leads to the loss of fertile topsoil, which decreases agricultural productivity and affects biodiversity. It also pollutes rivers and lakes with various solid particles or non-specific substances, degrading water quality and affecting aquatic ecosystems. On a socio-economic level, soil erosion can lead to lower incomes for farmers, increased irrigation costs and the need to import food, with a negative impact on local and regional economies.

Globally, the use of the USLE model and its variants, such as RUSLE and MUSLE, has enabled the assessment and management of soil erosion in different regions. Studies have shown that erosion rates vary significantly depending on factors such as soil type, topography, climate and land management practices. In intensively farmed regions, such as parts of Asia, South America and Africa, erosion rates can reach 30 - 40 t/ha/yr, while in undisturbed forests these rates are much lower, between 0.004 - 0.05 t/ha/yr.

The assessment of the mean annual soil loss in the Crișul Alb basin (Figure 8) was made on the raster image with a spatial resolution of 25 m, resulting from the multiplication of the raster maps of the five USLE factors (R, K, LS, C and P) in ArcGIS 10.4.[9,10]

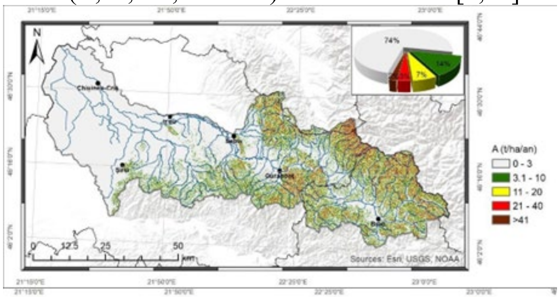

Figure 8. Soil erosion map (t ha-1year-1)

From Figure 8, it can be seen that 74% of the territory falls into the class of very low susceptibility to erosion (less than 3 t ha-1yr-1), land that is located in the low plain zone, in riverbeds and depressions at the base of slopes. In the low rate class (3.1 - 10 t ha-1yr-1), 14% of the land is classified; 7% was classified with moderate rates and 4% with high (21 - 40 t ha-1yr-1) and very high (over 41 t ha-1yr-1) erosion rates.

High rates of soil loss through erosion generally characterize areas with high precipitation, clay soils and steep slopes in premontane and montane areas.

The erosion risk map (Figure 8) shows that the spatial distribution of mean annual soil loss in the analyzed basin was variable, with minimum values in the western half of the basin, in the lowlands and low hills, and maximum values in the eastern half, in the uplands.

In terms of impact on settlements and infrastructure, the main settlements in the analyzed basin are located in areas with relatively low erosion, which could reduce the risk of major damage to infrastructure.

The localities of Ineu, Sebiș, and Gurahonț are located close to rivers, suggesting a possible influence of alluvial erosion, but the data do not indicate major erosion in these areas.

The distribution of soil erosion in the Crișul Alb basin is largely low, with concentrated areas of higher erosion in specific regions. The majority of the territory shows an erosion of 0 - 3 t/ha/year, indicating a relatively stable situation in terms of soil conservation. The data suggest that interventions to control erosion should be concentrated in identified areas of high erosion.

4. CONCLUSIONS

Spatial modeling of soil erosion is an essential tool for understanding, monitoring and managing this complex phenomenon. Using the Universal Soil Loss Equation (USLE) model allows the quantitative estimation of soil loss by assessing key factors: precipitation erosivity (R), soil erodibility (K), topographic factor (LS), land cover management factor (C) and conservation practices factor (P). These factors vary significantly depending on climatic, topographic and land use characteristics, influencing the susceptibility of soil to erosion.

In the Crișul Blanc catchment, precipitation erosivity varies between 275.85 and 571.59 MJ mm $ha^{-1}h^{-1}year^{-1}$, with maximum values in mountainous areas, indicating the need for increased conservation measures in these regions. Soil erodibility varies between 0.04 and 0.6 t ha-1MJ-1mm-1, being influenced by soil texture and structure. The topography of the terrain, expressed by the LS factor, shows higher values in areas with steep slopes, indicating an increased risk of erosion. The land cover management factor (C) reflects the influence of land use practices and vegetation, and the conservation practices factor (P) emphasizes the impact of applied conservation measures.

Soil erosion in the Crișul Alb basin is a significant problem, with negative effects on the local environment and economy. The assessment of erosion susceptibility using the USLE model revealed that most of the territory has a very low erosion rate (0-3 t/ha/year), a situation identified especially in the lowland areas and river floodplains, which indicates a relatively stable situation in terms of soil conservation. However, high erosion rates are concentrated in the pre-mountain and mountainous areas, where the topography and intense precipitation contribute to significant soil losses.

The impact on localities and infrastructure is reduced, due to their location in areas with low erosion. In order to maintain stability and prevent further degradation, it is essential to focus erosion control interventions in the regions identified with high erosion and to promote sustainable agricultural practices and soil conservation measures.

The implementation of a diversified set of measures to reduce and combat soil erosion in the Crișul Alb basin is essential for protecting soil resources and maintaining agricultural productivity.

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