

Determination of Erosion Potential of Rioni River Basin Using GIS and RUSLE Model

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ABSTRACT: This study focuses on determining the soil erosion potential within the Rioni River basin using the Revised Universal Soil Loss Equation (RUSLE) and Geographical Information System (GIS) technologies. A 90-meter resolution Digital Elevation Model (DEM) from the Shuttle Radar Topographic Mission (SRTM) was utilized to delineate the basin boundaries and hydrological network. The RUSLE model, an empirical approach, was applied to estimate the long-term average annual soil loss. Individual RUSLE factors were computed using specific methodologies: the rainfall-runoff factor (R) was derived from a linear empirical relationship based on average atmospheric precipitation (1989-2021); the soil erodibility factor (K) was calculated using the Sharpley–Williams equation, yielding a value of 0.0184 for the prevalent soil type; the topographic factor (LS) was determined using a RUSLE-adapted approach; the cover-management factor (C) was calculated using the Durigon equation from NDVI values; and the support practice factor (P) was assigned based on slope and cultivation practices. Results indicate that the R-factor ranges from 313.65 to 473.89 MJ×mm/(ha×hours), with an average of 391.02 MJ×mm/(ha×hours). The maximum LS-factor reached 7137.810. The C-factor values (0.104 to 0.769) suggest a significant risk of water erosion across the basin. Overall, the study concludes that riverbed erosion predominantly occurs in the Rioni River basin, primarily influenced by flow velocity and slope.

KEYWORDS: Soil Erosion, RUSLE, GIS, Rioni River Basin, Erosion Potential, Topography

1. INTRODUCTION

Soil erosion stands as one of the most pressing environmental challenges globally, leading to land degradation, reduced agricultural productivity, silting of water bodies, and loss of biodiversity. It is driven by various natural factors such as rainfall, runoff, and topography, as well as anthropogenic activities, including improper land management practices. Understanding and quantifying erosion potential are crucial for developing effective land management strategies and soil conservation measures.

The Rioni River basin, situated in Georgia, is characterized by complex topography and diverse climatic conditions, making it potentially vulnerable to erosion processes. Assessing the erosion potential in such regions is critically important for sustainable development and preventing ecological disasters. Despite its obvious significance, comprehensive studies on soil erosion using modern Geographic Information Systems (GIS) and models like RUSLE for the Rioni River basin are insufficiently represented, thus indicating an existing research gap.

Among the many available methods for determining soil erosion potential, the empirical Revised Universal Soil Loss Equation (RUSLE), developed by Wischmeier and Smith [13] and modified by Renard and Foster [2], is now widely recognized. RUSLE enables the estimation of long-term

average annual soil loss (A) as a function of six primary factors: the rainfall and runoff factor (R), the soil erodibility factor (K), the slope length factor (L), the slope steepness factor (S), the cover-management factor (C), and the support practice factor (P). The integration of the RUSLE model with Geographic Information Systems (GIS) provides a powerful tool for spatial modeling and mapping of erosion potential over large areas.

This study aims to determine the soil erosion potential within the Rioni River basin using GIS and the Revised Universal Soil Loss Equation (RUSLE). This research is intended to fill the existing gap in the detailed quantitative assessment of erosion processes for this particular region, thereby providing essential data for land-use planning and the development of erosion control measures.

The remainder of this paper is structured as follows: the "Materials and Methods" section details the data sources and methodology for calculating each RUSLE factor. Subsequently, "Results" are presented, including maps of the distribution of each factor and the soil erosion potential map. The "Discussion" section interprets the obtained results and compares them with existing knowledge. Finally, the "Conclusion" summarizes the main findings of the study and provides recommendations.

2. MATERIALS AND METHODS

2.1 Study Area

The Rioni River basin, located in Georgia, is a significant geographical entity characterized by its diverse physiography, ranging from high mountainous terrains to lowland plains. This complex topography, coupled with varied climatic conditions across the basin, makes it a susceptible area for various geomorphological processes, including soil erosion. The river Rioni is one of the largest rivers in western Georgia, playing a vital role in the region's ecology and economy. The basin's geology and hydro-climatic regime significantly influence its susceptibility to erosion, making it an ideal study area for understanding regional erosion dynamics and implementing effective land management strategies.

2.2 Data Sources

For the purpose of modeling the erosion potential of the study area, a 90-meter resolution Digital Elevation Model (DEM) was utilized. This DEM, obtained from the Shuttle Radar Topographic Mission (SRTM) and referenced to the D_WGS_1984 coordinate system, served as the fundamental input for hydrological analysis. Using the ArcGIS 10.2.2 "Hydrology" tool, the DEM was processed to accurately delineate the boundaries of the Rioni River Basin and to determine its hydrological network parameters [3, 9].

To calculate the Rainfall-Runoff Erosivity (R) factor, average atmospheric precipitation data from 1989 to 2021, collected from six meteorological stations within or near the basin, were employed. Soil data, including sand, silt, clay, and organic carbon content, were obtained from the Ministry of Environmental Protection and Agriculture of Georgia (National Environmental Agency) for the calculation of the Soil Erodibility (K) factor. The Normalized Difference Vegetation Index (NDVI), derived from Landsat 8 images, was used to determine the Cover-Management (C) factor, reflecting vegetation cover and land use.

2.3 RUSLE Model and Factor Calculation

The Revised Universal Soil Loss Equation (RUSLE) is an empirical model widely used for estimating the average annual soil loss (A) due to sheet and rill erosion. The model is expressed as:

$$A = R \times K \times LS \times C \times P \quad (1)$$

where:

A is the long-term average annual soil loss (t/ha per year).

R - the rainfall and runoff factor (MJ×mm/(ha×h×year)).

K - the soil erodibility factor (t×ha×h/(MJ×mm×ha)).

LS - the slope length and steepness factor (dimensionless).

C - the cover-management factor (dimensionless, ranging from 0 to 1).

P - the support practice factor (dimensionless, ranging from 0 to 1).

The calculation methodology for each of these factors is detailed in the subsequent subsections.

2.3.1 Rainfall-Runoff Erosivity Factor (R)

The R-factor quantifies the impact of rainfall intensity and duration on soil erosion. It represents the erosive power of rainfall and runoff. In this study, the R-factor was determined using a linear empirical relationship established by Torri et al. [11] for the Mediterranean region, which correlates R-factor with mean annual precipitation (P):

$$R = -944 + 3.08P \quad (2)$$

where P is the average annual precipitation in mm. The precipitation data were collected from six meteorological stations within the Rioni River basin covering the period from 1989 to 2021. The spatial distribution of the R-factor was then interpolated across the study area using appropriate GIS techniques.

2.3.2 Soil Erodibility Factor (K)

The K-factor represents the susceptibility of soil to erosion by water, reflecting the combined effects of soil properties such as texture, organic matter content, and permeability. This factor was calculated using the Sharpley–Williams equation [8], which is suitable for a wide range of soil types:

$$K = 0.0034 + 0.0405 \exp(-0.5(SDSAND - 2)2) + 0.004(CLYSLT)0.5 - 0.003(CLYOC)0.5 \quad (3)$$

where:

SAND, SLT, CLY represent the percentage of sand, silt, and clay content, respectively.

SD is the standard deviation of the sand content (typically set to 0.5 for general application).

OC is the percentage of organic carbon.

Based on the available soil data from the Ministry of Environmental Protection and Agriculture of Georgia (National Environmental Agency), the Rioni River basin is characterized by a predominant soil type, and the calculated K-factor for this region was consistently determined as 0.0184. This uniform value simplifies the spatial representation of this factor across the basin.

2.3.3 Topographic Factor (LS)

The LS-factor combines the effects of slope length (L) and slope steepness (S) on soil erosion. It accounts for the cumulative effect of runoff and flow accumulation. The LS-factor was computed using the approach adapted for the RUSLE model within a GIS environment, based on the DEM of the study area [5, 6]. The specific formula used is given by:

$$LS = (Flow\ Accumulation \times Cell\ Size / 22.1) 0.4 \times (\sin(Slope) / 0.0896) 1.3 \quad (4)$$

where:

Flow Accumulation represents the accumulated flow of cells contributing to a given cell.

Cell Size is the resolution of the DEM (90 meters).

Slope is the slope in degrees.

This equation allows for a precise spatial representation of the topographic influence on erosion potential.

2.3.4 Cover-Management Factor (C)

The C-factor reflects the effect of land cover and management practices on soil erosion, varying between 0 (well-protected soil) and 1 (bare soil). This factor was derived from the Normalized Difference Vegetation Index (NDVI), a widely

used indicator of vegetation density and health. NDVI was calculated from Landsat 8 images using the formula:

$$NDVI = (NIR - Red) / (NIR + Red) \quad (5)$$

where NIR is the Near-Infrared band and Red is the Red band reflectance. The C-factor was then determined using the empirical equation proposed by Durigon et al. [10]:

$$C = (-NDVI + 1) / 2 \quad (6)$$

This relationship allows for a dynamic assessment of vegetation cover impact on erosion across the study area.

2.3.5 Support Practice Factor (P)

The P-factor accounts for the impact of support practices, such as contouring, terracing, and strip cropping, on reducing soil erosion. It ranges from 0 to 1, with lower values indicating more effective erosion control [7]. For this study, the P-factor was assigned based on the slope of the terrain and generalized cultivation practices, with values typically varying from 0.55 to 1. Higher values are assigned to steeper slopes and areas with fewer erosion control practices, following the guidelines provided by the NRCS: USDA State Office of Michigan, Technical Guide to RUSLE Use in Michigan, 2002 [NRCS, 2002].

3. RESULTS AND DISCUSSION

3.1 Spatial Distribution and Characteristics of RUSLE Factors

The application of the RUSLE model within a GIS environment allowed for the spatial quantification and mapping of individual erosion factors, providing a comprehensive understanding of their contribution to the overall soil erosion potential in the Rioni River basin.

3.1.1 Rainfall-Runoff Erosivity Factor (R)

The R-factor, which reflects the erosive power of rainfall, showed significant spatial variability across the Rioni River basin. Calculated based on average annual precipitation, the R-factor ranged from a minimum of 313.65 MJ×mm/(ha×hours) in the lowland areas to a maximum of 473.89 MJ×mm/(ha×hours) in the high-mountainous regions. The average R-factor value for the entire basin was determined to be 391.02 MJ×mm/(ha×hours). This spatial pattern highlights the increased erosive potential of rainfall in higher altitudes, likely due to higher precipitation amounts and intensity, as depicted in **Figure 1**.

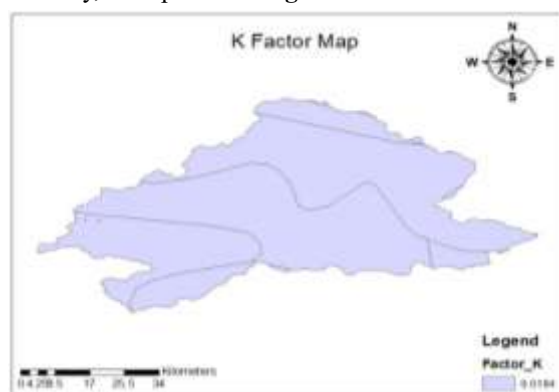


Figure 1. Rainfall-Runoff Erosivity Factor (R)

3.1.2 Soil Erodibility Factor (K)

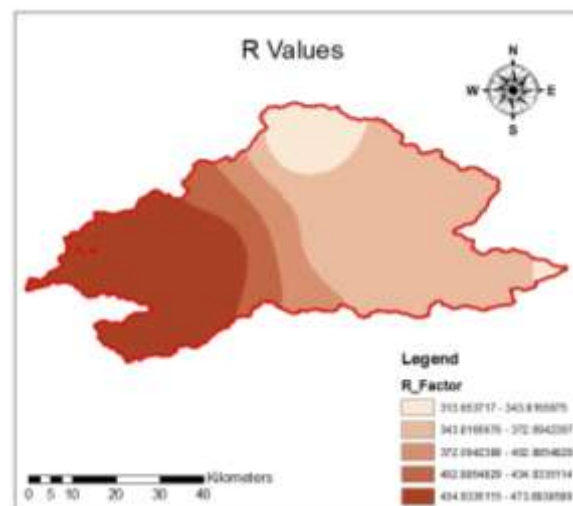


Figure 2. Soil Erodibility Factor (K)

The K-factor represents the susceptibility of soil to erosion. Based on the soil analysis, a uniform K-factor value of 0.0184 was assigned to the entire Rioni River basin. This indicates that the predominant soil type across the study area exhibits a consistent level of erodibility. While specific variations in soil properties could influence erodibility at a finer scale, the generalized K-factor value provides a basin-wide assessment. Figure 2 illustrates the uniform distribution of the K-factor.

3.1.3 Topographic Factor (LS)

The LS-factor, which combines the effects of slope length and steepness, showed the most significant variability and the highest values among all RUSLE factors, directly reflecting the complex and rugged topography of the Rioni River basin. LS-factor values ranged considerably, reaching a maximum value of 7137.8 in areas with steep slopes and long flow paths. Areas with high LS values are predominantly found in the mountainous and hilly parts of the basin, indicating a very high susceptibility to erosion due to topographic influence. Conversely, flat areas in the lowlands exhibited very low LS values. **Figure 3** illustrates the spatial variability of the LS-factor, emphasizing the critical role of topography.

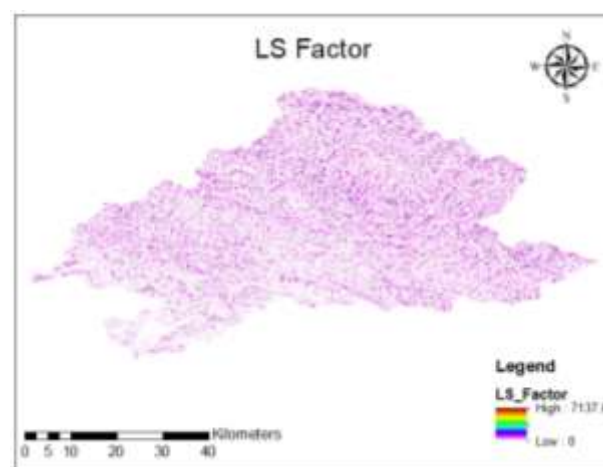


Figure 3. Topographic Factor (LS)

3.1.4 Cover-Management Factor (C)

The C-factor, reflecting the protective effect of vegetation cover and land management practices, varied from 0.104 to 0.769 across the basin. Lower C-factor values indicate dense vegetation cover and effective land management, while higher values correspond to sparsely vegetated or bare land with less protective cover. The spatial distribution of the C-factor revealed that areas with higher C-values, implying a greater risk of water erosion, are present across a significant portion of the Rioni River basin. This suggests that land cover plays a crucial role in moderating erosion rates. The spatial distribution of the C-factor is presented in **Figure 4**.

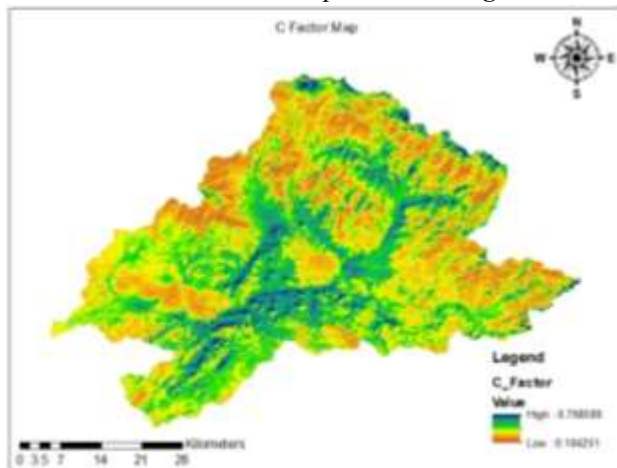


Figure 4. Cover-Management Factor (C)

3.1.5 Support Practice Factor (P)

The P-factor, accounting for the impact of erosion control practices, varied between 0.55 and 1 across the study area. This factor generally reflects the absence or presence of practices like contour plowing or terracing. Areas with P-factor values close to 1 indicate limited or no effective erosion control measures, making them more vulnerable to soil loss [7]. Conversely, values closer to 0.55 suggest some level of conservation practices. The P-factor distribution for the Rioni River basin indicated that values are predominantly below average, suggesting that comprehensive erosion control practices are not widely implemented or effective throughout the basin, thereby contributing to the overall erosion potential. **Figure 5** shows the spatial distribution of the P-factor values across the basin.

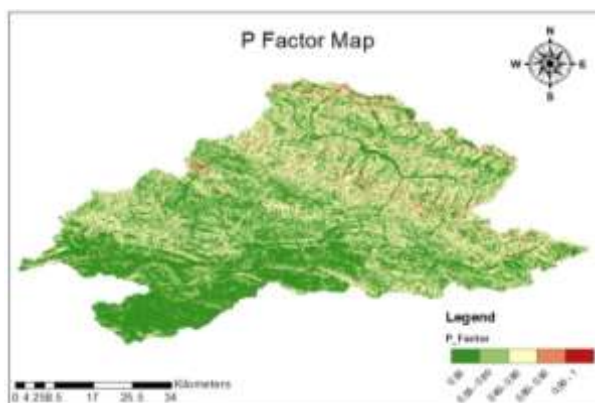


Figure 5. Support Practice Factor (P)

3.2 Soil Erosion Potential (A) and Its Spatial Distribution

The final output of the RUSLE model, the average annual soil loss (A-factor), represents the combined effect of all individual erosion factors. While specific quantitative ranges for the A-factor (t/ha per year) are to be presented in conjunction with **Figure 6**, the spatial distribution of soil erosion potential revealed distinct patterns across the basin. Areas with the highest erosion risk were predominantly concentrated in regions characterized by steep mountainous slopes and high flow velocities, directly influenced by high LS-factor values. These areas indicate a strong susceptibility to significant soil loss. Conversely, lower erosion potential was observed in flatter terrains and areas with more protective vegetation cover in the lowlands. The analysis of the A-factor map clearly indicates that riverbed erosion is a prevalent process within the Rioni River basin, primarily influenced by the steepness of the slopes and the velocity of water flow. This comprehensive map of soil loss potential (**Figure 6**) provides critical insights for identifying priority areas for soil conservation and land management interventions.

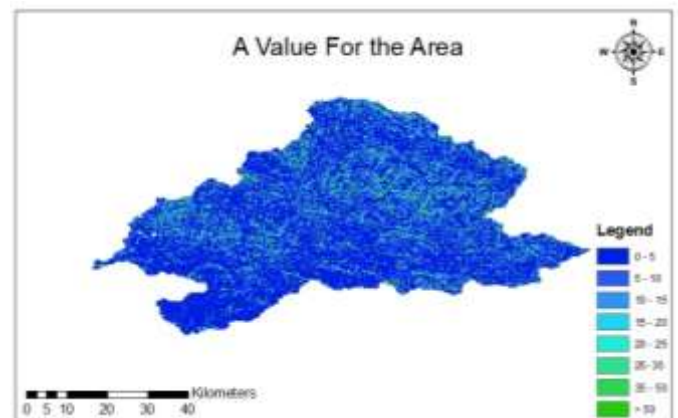


Figure 6. Soil Erosion Potential (A)

3.3 Discussion of Findings

The results of this study, employing the RUSLE model within a GIS framework, provide a comprehensive assessment of soil erosion potential in the Rioni River basin. The spatial distribution of the individual RUSLE factors (R, K, LS, C, P) clearly highlights the key drivers of erosion in the region.

The significant spatial variability of the R-factor, with higher values in mountainous areas, underscores the dominant role of rainfall erosivity in the upland regions. This finding is consistent with general literature suggesting that mountainous areas often experience higher and more intense precipitation, leading to greater rainfall kinetic energy and increased runoff potential [general literature on rainfall erosivity and mountainous regions, e.g., Begueria et al., 2015; HESS, 2016]. The uniform K-factor value across the basin suggests a relatively homogenous erodibility of the predominant soil type, simplifying the assessment while emphasizing the importance of other factors in driving erosion variability.

The LS-factor emerged as the most influential topographic determinant of erosion potential, particularly in the steep slopes of the Rioni River basin. The extremely high LS values in certain areas directly correlate with the observed high

erosion risk, confirming the well-established relationship between slope characteristics (steepness and length) and soil loss [general literature on topographic influence on erosion, e.g., FAO; Number Analytics]. This highlights the need for specific conservation measures targeting steep terrains. The variability of the C-factor indicates the critical role of vegetation cover in mitigating erosion, with sparsely vegetated areas showing higher susceptibility. This reinforces the importance of sustainable land cover management, including afforestation and protection of natural vegetation, to reduce soil loss [general literature on vegetation and erosion control, e.g., Scialert.net, Greenbelt Consulting]. Finally, the predominantly below-average P-factor values suggest that current soil conservation practices in the basin may be insufficient or unevenly applied, further contributing to the overall erosion potential. The absence of widespread effective support practices necessitates strategic planning for their implementation.

The overall soil erosion potential (A-factor) map clearly identifies high-risk zones, particularly in mountainous and steeply sloped areas where riverbed erosion is prevalent due to high flow velocities. This aligns with observations made by other researchers in similar geomorphological settings, where high-velocity water flow and steep gradients are primary drivers of riverbed and bank erosion [general literature on riverine erosion in mountainous regions, e.g., Woods Hole Oceanographic Institution; ResearchGate]. The findings of this study offer a valuable baseline for understanding the current erosion status and predicting future trends, especially under changing climate and land-use scenarios.

Limitations and Future Work:

Despite providing significant insights, this study has certain limitations. The RUSLE model, being empirical, relies on generalized relationships and may not fully capture the complexity of all erosional processes, such as gully erosion or landslides, which can be significant in mountainous terrains. The use of a uniform K-factor, while practical given data availability, might overlook localized variations in soil erodibility. Future research could focus on:

- Integrating more detailed, high-resolution soil data to refine the K-factor.
- Incorporating specific data on gully erosion and mass movements for a more comprehensive assessment.
- Conducting field validation of the model's predictions to enhance accuracy.
- Exploring the impact of climate change scenarios on rainfall erosivity and its implications for future erosion trends in the basin.
- Analyzing the socio-economic factors influencing land management practices and their effect on the C and P factors.

This study contributes to the understanding of soil erosion dynamics in the Rioni River basin, a critically important region for Georgia. By spatially identifying high-erosion-risk

areas, the findings provide essential information for local authorities, land-use planners, and environmental managers to develop targeted and effective soil conservation strategies, promote sustainable agricultural practices, and mitigate the adverse environmental impacts of erosion.

4. CONCLUSION

This study successfully determined the soil erosion potential within the Rioni River basin by integrating the Revised Universal Soil Loss Equation (RUSLE) with Geographical Information System (GIS) technologies. Utilizing a 90-meter resolution Digital Elevation Model (DEM) and various climatic and land-use data, the individual RUSLE factors (R, K, LS, C, P) were systematically calculated and mapped.

The analysis revealed significant spatial variability in rainfall erosivity (R-factor), with higher values in mountainous areas, indicating a strong influence of precipitation on erosion potential. The topographic factor (LS) emerged as the most critical driver of erosion, with extremely high values observed on steep slopes, highlighting their vulnerability to soil loss. The cover-management (C) and support practice (P) factors indicated varying degrees of land cover protection and the potential for improved conservation practices across the basin.

Crucially, the overall soil erosion potential (A-factor) map identified high-risk zones concentrated in steep, high-velocity flow areas, confirming the prevalence of riverbed erosion within the Rioni River basin, primarily driven by slope and flow dynamics.

The findings of this research provide valuable insights for sustainable land management and erosion control planning in the Rioni River basin. By identifying and spatially mapping the areas most susceptible to erosion, this study offers a scientific basis for prioritizing conservation efforts, implementing targeted erosion mitigation measures, and fostering resilient landscapes in this ecologically significant region.

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