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Soil Erosion Assessment Using the RUSLE Model in Rulindo District, Rwanda.

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Abstract

Soil is a crucial component of the earth's ecosystem, playing a vital role in various environmental functions. However, human activities and environmental stressors like population growth, deforestation, and overgrazing significantly contribute to soil degradation, particularly soil erosion. Soil erosion has several adverse effects, such as reduced soil fertility, diminished crop productivity, decreased reservoir capacity, degraded water quality, increased pollution and sedimentation in water bodies, and reduced biodiversity. The Revised Universal Soil Loss Equation (RUSLE) is a widely used model for estimating soil erosion due to rainfall and runoff. This model incorporates factors such as rainfall erosivity (R), soil erodibility (K), slope length and steepness (LS), land cover and management (C), and conservation practices (P). This study aims to assess soil loss in the hilly Rulindo District of Rwanda using GIS and the RUSLE model to aid in soil restoration and sustainable land management. The study employs the RUSLE model, integrated with GIS techniques, to calculate average annual soil loss in Rulindo District. The analysis revealed that sectors like Shyorongi, Masoro, Ngoma, and Murambi are at high risk of soil erosion due to factors such as intense rainfall, loamy soils, and steep slopes. Conversely, sectors like Bushoki, Base, Rusiga, and Cyungo exhibit lower erosion rates. These findings highlight the need for targeted soil conservation measures in high-risk areas to mitigate erosion, improve soil fertility, and ensure sustainable land management. The results provide valuable insights for policymakers and land managers to implement effective soil restoration strategies, contributing to environmental sustainability and agricultural productivity in the district.

Keywords: RUSLE Model, , GIS and Rulindo District.

1. Introduction

Soils are an essential component of earth system functions that facilitate the supply of essential ecosystem services (B.G. Jahun, R. Ibrahim, N.S. Dlamini & S. M. Musa; 2025). However, the soil may be degraded by human activities and environmental stressors. Population increases, deforestation, and overgrazing are the three major factors that cause and exacerbate soil erosion.

Erosion has many negative effects that are of real concern for a variety of reasons. Firstly, removal of the fertile top layer of soil (topsoil) by erosion affects soil fertility and crop productivity. Secondly, erosion diminishes reservoir capacity and operation and degrades downstream water quality (Wali, Umaru Garba, 2013). Thirdly, soil erosion causes a rise in pollutants and sedimentation in streams and rivers, resulting in the blockage of these waterways as well as a reduction in biodiversity. Fourthly, erosion also transports soil-laden water downstream, which may produce sediment layers that impede the flow of streams and rivers and ultimately cause floods. Lastly, erosion destroys the land that can host fewer plants capable of absorbing climate-warming carbon dioxide (Amare, Dessie; 2020). The estimation of soil loss can be determined by various model including RUSLE.

The Revised Universal Soil Loss Equation (RUSLE) is an advanced version of the Universal Soil Loss Equation (USLE), designed to estimate soil erosion caused by rainfall and its associated runoff. This model is widely used in agriculture, forestry, and land management to predict long-term average annual soil loss. RUSLE incorporates several factors to provide a comprehensive analysis such rainfall erosivity, soil erodibility, slope length and steepness, landcover and management, and conservation support practices factors to help decision-makers for optimal soil restoration planning and sustainable land management practices (Kaushik G & Santasmita Das B, 2020).

R-factor indicate more potential for erosion due to heavier and more frequent rainfall; K factor measures the susceptibility of soil particles to detachment and transport by rainfall and runoff. It is influenced by soil properties such as texture, structure, organic matter content, and permeability. Soils with high silt content are typically more erodible, while those with high clay or sand content are less so. The LS factor represents the effect of topography on erosion rates (Efthimiou, N; Evdoxia, L & Karavitis, C; 2014). The C factor accounts for the effect of vegetation, crop cover, and management practices on soil erosion. It reflects how well the soil surface is protected by plant cover, residues, and other surface treatments. The P factor represents the effectiveness of practices that help reduce the amount and rate of water runoff, these practices include contour farming, terracing, strip cropping, and the use of sediment control structures (Amare, Dessie; 2020).

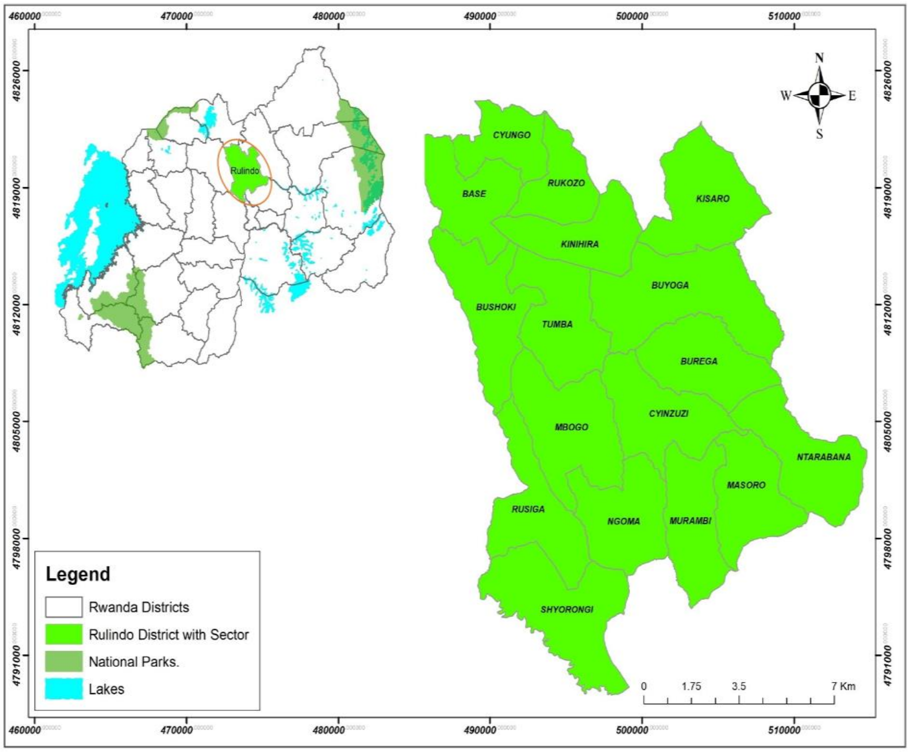
RUSLE remains the most suitable method for assessing soil erosion risk in various regions especially in the hilly region. In Rwanda, soil erosion is critical issue in land management especially in mountain region. Rulindo District as one of the districts with hills, Soil erosion and soil nutrient loss are major problems where it takes what would be the fertile soil to rivers and wetlands. In Rulindo District, Shyorongi Sector is the worst affected with an area estimated to 800 ha (22% of the land) at risk of erosion, followed by Rukozo Sector with 235 ha (17%), and Rusiga Sector with 466 hectares (16% of sector land at risk (IUCN, 2022).

Therefore, this assignment is aiming to assess soil loss in the Rulindo District using GIS, and the RUSLE model. This may be used by decision-makers for optimal soil restoration planning and sustainable land management practices.

2. Study Area Description

Rulindo District is one of the five Districts that make up the Northern Province. It is bordered by Nyarugenge and Gasabo Districts in the south, Gicumbi District in the east, Gakenke District in the west and Burera District in the north. The District has 17 administrative Sectors (Shyorongi, Rusiga, Bushoki, Base, Cyungo, Rukozo, Kinihira, Kisaro, Mbogo, Ngoma, Ntarabana, Cyinzuzi, Masoro, Burega, Buyoga and Murambi), with 71 Cells and 494 Villages (Imidugudu) and cover a surface area of approximately 567 km^2. The population of Rulindo District is 360,144, where 171,849 are males and 188,295 are females (NISR, 2022). Rulindo District is characterized by hills among which include Tare, Tumba and Cyungo hills with their altitude rising to 2,438 m.

Figure 1. ***showing geographical location of Rulindo District***



3. Methodology

The RUSLE is the most extensively used erosion method to forecast the average annual soil loss through computing the soil erosion parameters (Allafta, H.; Opp, C 2022). The RUSLE calculates the average annual soil loss in tons per hectare based on five parameters:

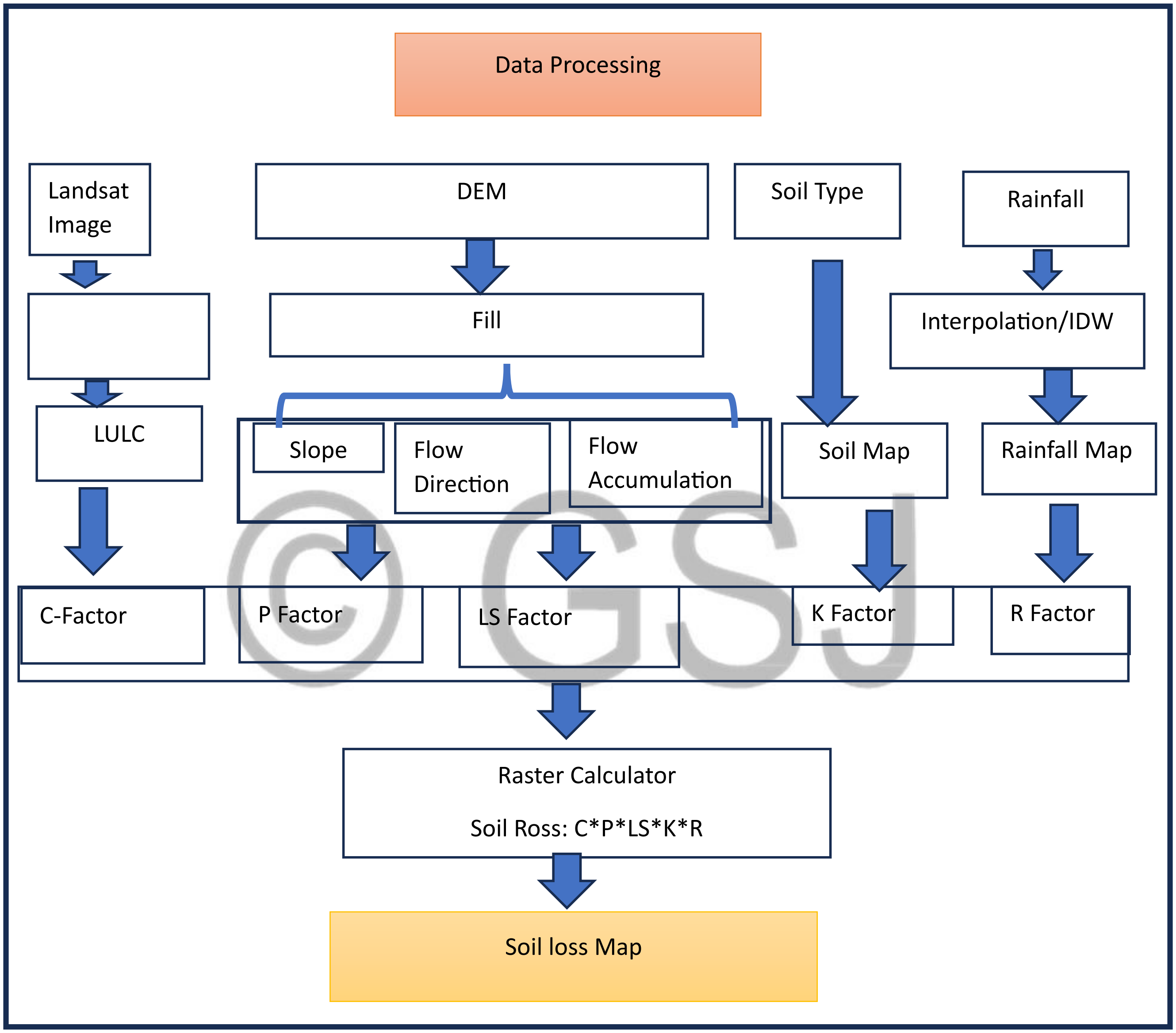
A = R*K*LS*C*P **where,**

A: stands for the average annual soil loss; R: is the rainfall erosivity factor, K: represents the soil erodibility factor; L: denotes the slope length factor; S: refers to the slope steepness factor; C: represents the Cover and management factor; and P denotes the conservation support practices factor. After calculating the RUSLE parameters, GIS was used to convert each parameter into raster format.

In this assignment, GIS was used to compute all five parameters as well as calculating the annular soil loss in Rulindo District. In this regard, LS -Factor were calculated using the Digital Elevation Model (DEM) in the ArcGIS 10.8, Slope length (L), K-factor was obtained using soil data from Ministry of Agriculture (MINAGRI), R-Factor was computed using climatology/annual rainfall data from Meteo station Rwanda using interpolation methods (Inverse Distance Weighted), a tool in “Spatial Analyst Tools”), Land Use Land Cover (LULC) produced by Esri Rwanda were used to calculate the C-Factor. Both LULC and slope of Rulindo District were used to compute P-factor.

GIS was used to convert each parameter/factor into raster format and to create the soil erosion map by using "Raster Calculator", which is a tool under "Spatial Analyst Tools" in ArcGIS to determine the interaction between above mentioned parameters (R, K, LS, C and P).

Figure 2. Data Processing



- ***Rainfall erosivity factor (R-factor)***

Rainfall erosivity (R) is a function of rainfall's ability to cause soil erosion by separating and moving soil particles. R calculation necessitates continual and thorough rainfall data (B. M. Mutua & A. Klik , 2004). In this assignment, point data of rainfall data from Meteo Rwanda stations spatially distributed in Rulindo District. The rainfall data of Rwagihuha, Rulindo, Rutongo, Cyohoha and Ruganda meteo stations are 1347mm, 1362mm, 1248mm, 1223mm and 681mm, the point data were interpolated using IDW methods to create the annual rainfall raster data of Rulindo District. Lastly, the Rainfall erosivity were calculated using the Hurni formula explored in 1985.

R= (0.526*P)-8.12 Where:

R= Rainfall erosivity factor

P= Mean Annual rainfall (mm/year)

- ***Soil erodibility factor (K-factor)***

Soil erodibility represents the intrinsic resistance of soil to erosion by rain and runoff, and it is a reflection of the interactions of physical and chemical features of soil that influence detachment, transportation, and infiltration capacity. The soil's texture, structure, organic matter content, permeability, and its iron, aluminum, and salt concentration are among the most important determinants of erodibility (Baig A. Al Shoumik, Md. Zul kar K & Md. Sanaul I; 2023). The following formulas were used to calculate the K values.

Fraction of orgnic carbon (F_OrgC)= (1-((0.0256*[OC topsol])/([OC topsol]+Exp(3.72-(2.95*[OC topsol])))))

Fraction of Silt (F_= (1-((0.7 *(1- [SAND] /100)) /((1- [SAND]/100) +Exp (-5.51 +22.9 *(1- [SAND] /100)))))

Fraction of Clay (F_clay)= ([silt top]/[clay top]+([Silt top])))^0.3

Fraction of Sand (F_sand)= (0.2+(0.3*Exp((-0.256*[sand top]*(1-[silt top]/100)))))

K Fcator: [F_orgC]*[F_sand]*[F_silt] *[F_clay]*0.1317

- **Slope length and steepness factor (LS-factor)**

The LS factor describes the impact of topography on erosion, which is directly proportionate to the slope's length and gradient (Hyeon Sik Kim , 2006). The LS factor map was generated using the Digital Elevation Model (DEM) using ArcGIS 10.8. The terrain effects on erosion are assessed using the LS parameter, which is the product of slope length (L) and slope steepness (slope angle)

(S). The escalating runoff accumulation towards the downslope increases the total soil erosion as the slope length (L) increases. Similarly, as the slope steepness rises, the runoff velocity and erosivity rise consequently. Using an ArcGIS Spatial analyst extension, the combined LS factor was calculated using the following equation, which was applied to a 10m DEM cell size:

LS= {FA*(Cell size/23.13)} ^0.4*{Sin (Slope of DEM*0.01745)/0.09} ^1.3*1.6

Where:

LS= Slope length and Steepness factor

FA= Flow Accumulation

- **Landcover and management factor (C-factor)**

The C factor describes how LULC types affect the soil loss rate. Calculating the C factor values within the RUSLE method necessitates information regarding the soil management condition, the function of crops and canopies residues as a soil cover, soil moisture condition, and soil surface unevenness (R Roslee & K Sharir; 2019). We used LULC classification produced by Esri Rwanda for C factor determination, The district was classified into the appropriate LULC categories, and the C parameter was derived from the district's LULC map. Then, we converted the raster map to vector format to provide the equivalent C factor for each LULC type. The table below tabulate land cover and its values used to determine the C-factor.

Table 1. Land Use Land Cover type and C factor

No	LULC type	C Factor
1	Cropland	0.24
2	Built-up	0.15
3	Forest	0.01
4	Wetland	0.24
5	Waterbody	0

- ***Conservation support practices factors (P-factor)***

The P factor quantifies the influence of conservation strategies, such as buffer belts of close-growing plants, contouring, and terracing on soil loss at a specific site. Adopting these supportive conservation practices reduces the P-value because they limit runoff volume and velocity and promote sediment deposition on the slope surface (Yusron S , Sus Mardiana & Eko Pradjoko, 2022). In this assignment, the slope and land use land cover were used to rate and determine the p-value with respect to the slope intervals.

Table 2. Slope interval and P factor

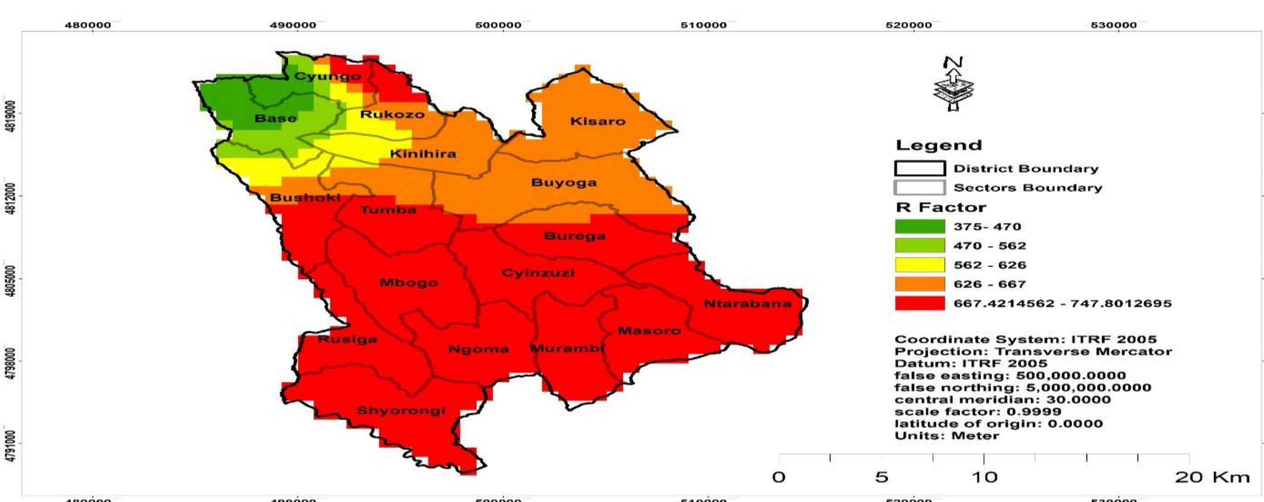
Land Use	Slope (%)	P Factor
Agricultural Land	0-5	0.10
	5-10	0.12
	10-20	0.14
	20-30	0.19
	30-50	0.25
	30-100	0.33
Other Land Use	All	1.00

4. **Results and Discussions**

4.1. Rainfall erosivity factor (R-factor)

The average annual rainfall data were used to compute the rainfall erosivity (R factor). Rainfall in Rulindo District varies between 681mm-1347mm. By calculation, the R values vary from 375 to 747.8. The prevailing pattern of the average annual rainfall in the Rulindo District area displays the highest values in the Southern portions of the district. Therefore, a high R factor is anticipated in the south parts of the district as R increases in such parts, while it decreases in the north part of the district. the map below shows the distribution of rainfall erodibility factor (R Factor) in Rulindo District.

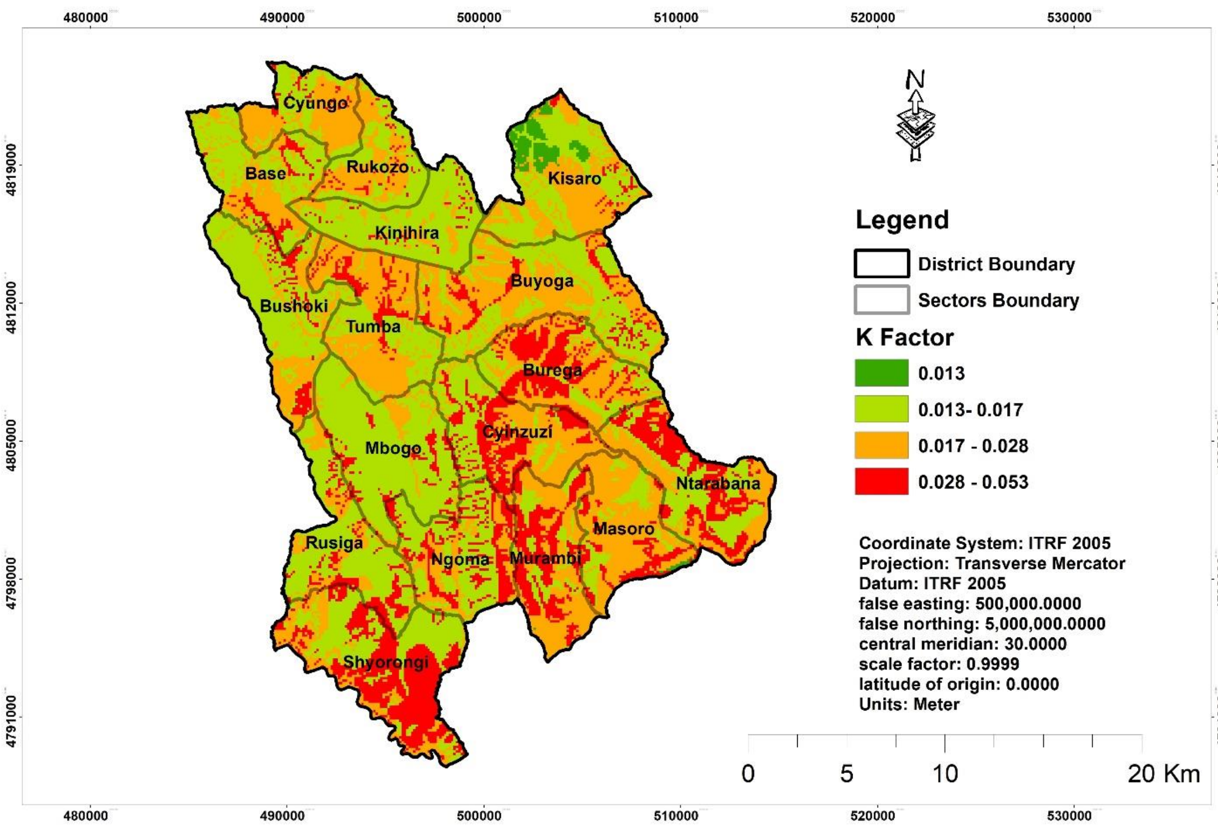
Figure 3. Distribution of rainfall erodibility factor (R Factor) in Rulindo District.



4.2. Soil erodibility factor (K-factor)

In Rulindo District, Clay-rich soils have low K values due to their resistance to separation. Coarse-grained soils, such as sandy soil, have a low K level due to their low runoff potential, although being readily disintegrated. The K value range from 0.013-0.053 in Rulindo District. Shyorongi, Murambi, Masoro, Ntarabana, Cyinzuzi, Ngoma and Burega sectors are associated with high K values campares to the sectors in the northern park including Kisaro, Rukozo, Cyungo, Base, Kinihira and Buyoga sectors. The map below shows K values distribution in Rulindo District:

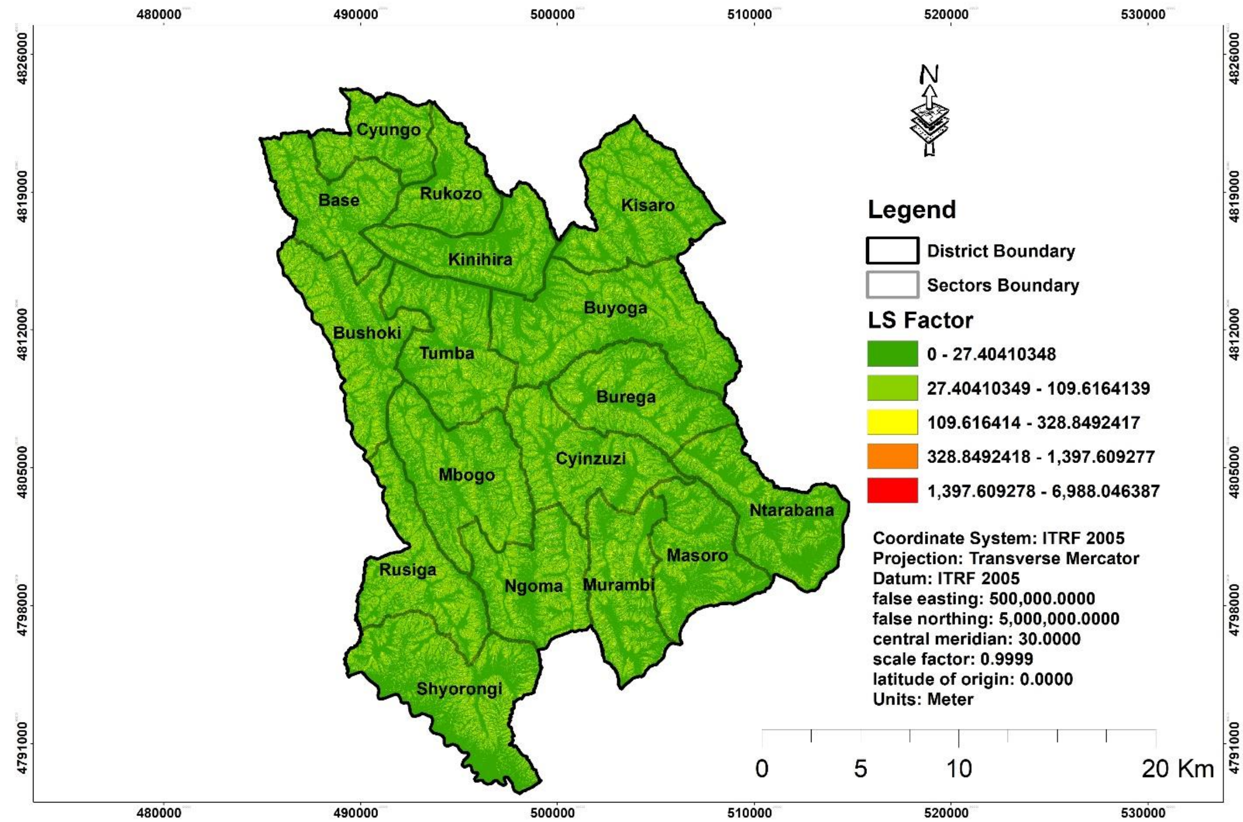
Figure 4. The map below shows K values distribution in Rulindo District.



4.3. Slope length and steepness factor (LS-factor)

The LS factor was calculated by considering the slope and flow accumulation as inputs, although it depends on slope more than on flow accumulation. The lowest LS values occupy the low-lying western lands, reflecting the slope effect on the LS outcomes. In contrast, the highest LS values are situated in the complex northern and eastern land forms of the study area. The LS factor of the district has four classes: 0, 0-0.01; 0.01 to 0.15; 15 to 24. Figure below indicates the distribution C factor in Rulindo District.

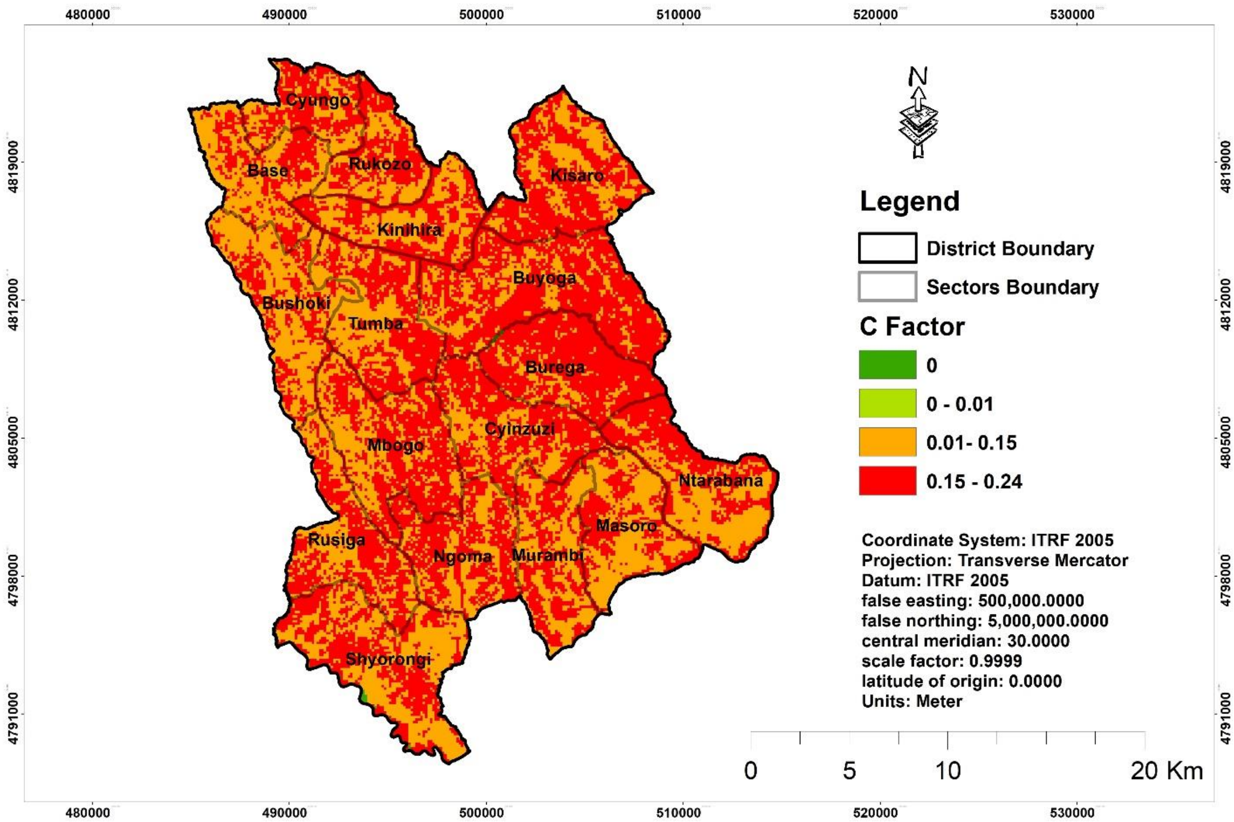
Figure 5. Showing LS factor distribution in Rulindo District.



4.4. Land Cover and management factor (C-factor)

The study area's primary land-use types are barren, cropland, and shrub land. Water/wetland and urban land use represent a small ratio of the land use categories in the basin. Based on the existing literature, the C factor values assigned to each LULC category were 0.5, 0.015, 0.65, 0.075, and 0 for bare land, shrub land, cropland, urban, and water/wetland, respectively (Figure 6). Cropland that prevails in the northern and middle parts of the basin has the highest C factor (i.e., 0.65). Likewise, bare land that extends over the southwestern parts of the study area has a high C factor (i.e., 0.50). Cropland, bare land, urban, shrub land, and water/wetland occupy 12.7, 50.5, 0.9, 35.1, and 0.7% of the basin's area, respectively.

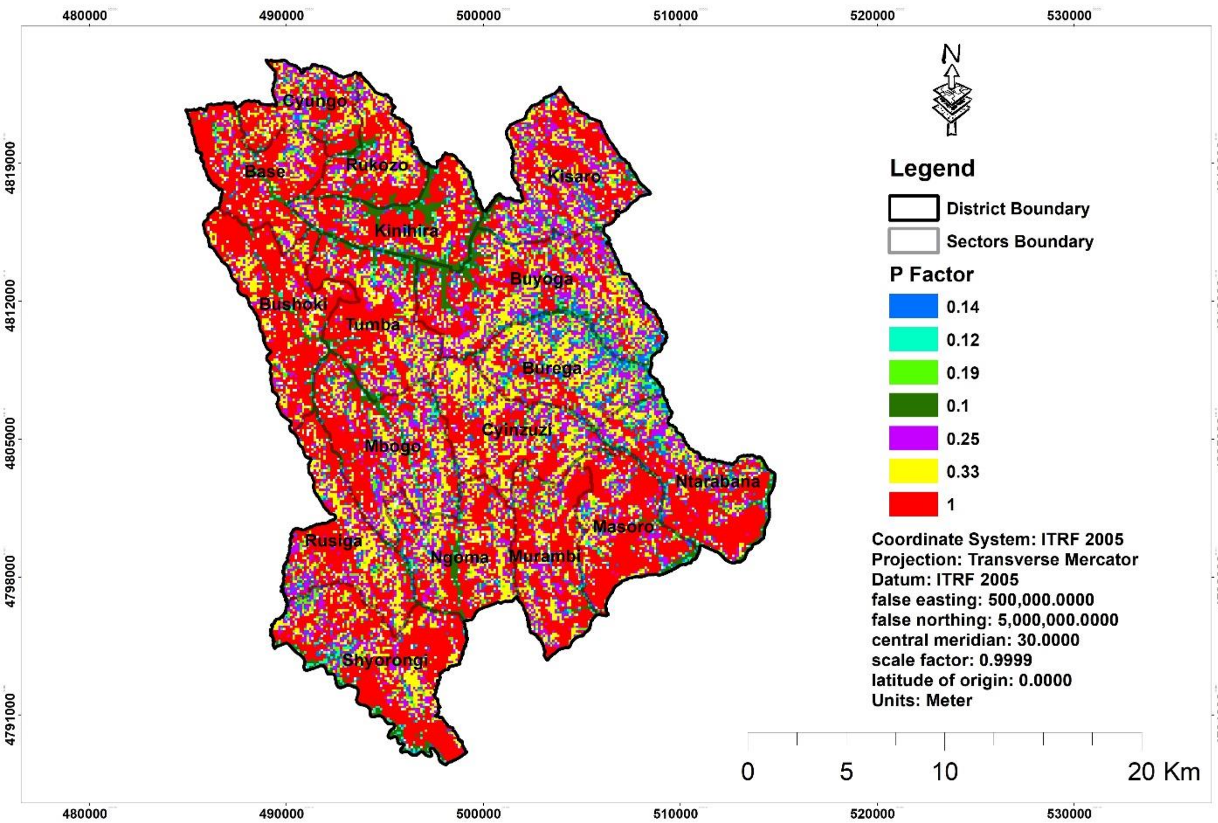
Figure 6. Map showing Land cover and management factor (C factor)



4.5. Conservation support practices factors (P-factor)

The P factor is controlled by the terrain slope. The overall slope pattern in Rulindo District demonstrates the steepest slope in the northern, Southern and western parts and decreases towards the East. Therefore, high P factor values are anticipated in the northern, Southern and western parts, and low values are in the Eastern parts of the district.

Figure 7. Showing Conservation support practices factors (P-factor)

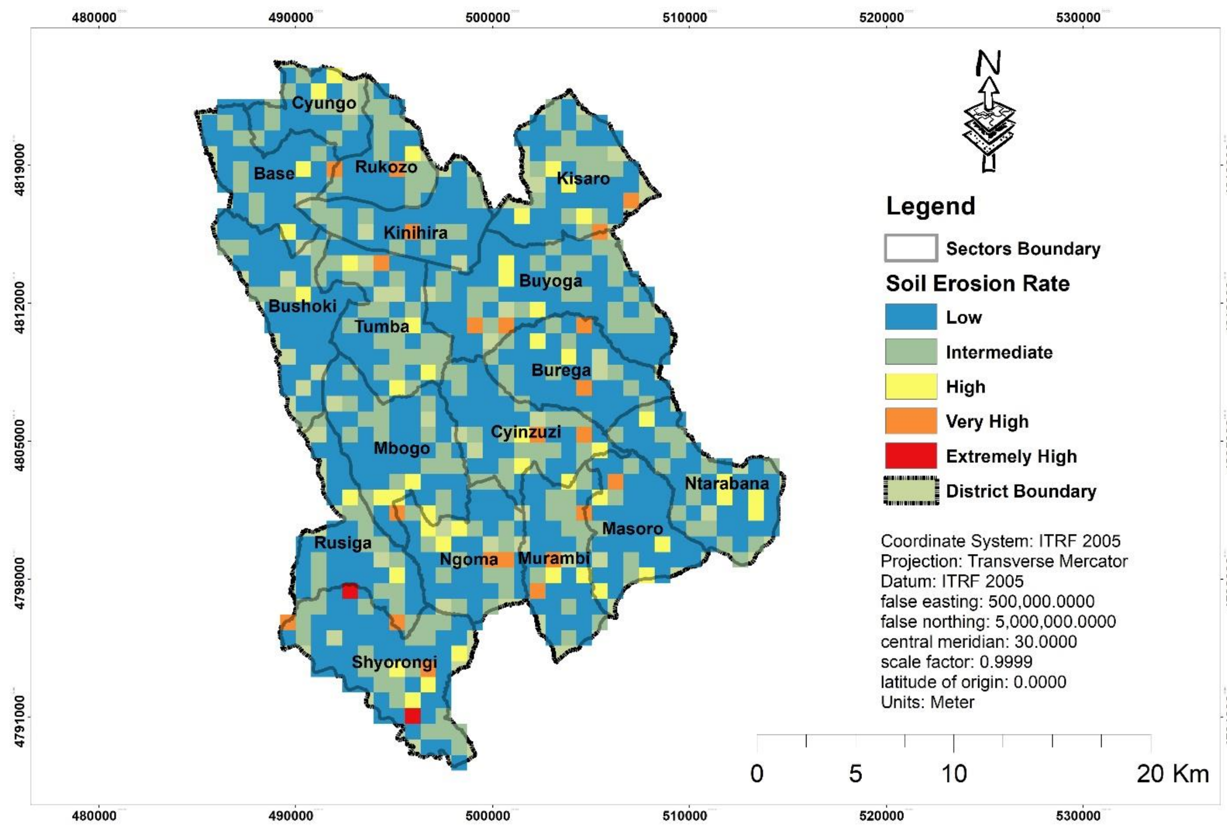


4.6. Estimation of Potential Soil Erosion

Rainfall erosivity, slope length and steepness, soil erodibility, land cover management, and soil conservation represent the main erosion contributors. Figures below illustrate the results of the modeling of these factors. The modeling of rainfall erosivity reveals that the higher the rainfall intensity, the higher its erosion potential. The soil erodibility parameter, which indicates both the soil's vulnerability to erosion and the rate of runoff, demonstrate that the least transport-resistant soils that generate large runoff had the highest values for K parameter. Modeling the slope's length and gradient reveal that the steeper the slope, the larger the runoff velocities and, thus, the greater the erosion. Similarly, slope improves the conservation support practice parameter, and thus erosion. The cover and management component that indicates how various LULC types affect soil loss rates reveal that farmland and bare land have the greatest values, while shrub land and urban land use have the lowest.

Although all five RUSLE parameters influence the ultimate soil erosion rate, these parameters have a different impact on the erosion rate in the current study. The analyses in this study reveal that such parameters vary in different magnitude which indicates that these parameters affect erosion rates in the same order. As a result of the final soil loss model, Figure below shows the annual erosion map of the study area, which helps to identify the areas that are prone to soil erosion. The high soil loss rates are linked to areas of high rainfall levels, loamy soil domination, elevated terrains/plateau margins with a steep side slope, and high cultivation activities. Clearly, the Shyrongi , Masoro, Ngoma and Murambi sectors are among the sector affected by high soil erosion while, Bushoki, Base, Rusiga, Cyungo where P values are concerned soil erosion are at low rate. Thus, these results may aid in decision making for improved land conservation and soil management. Public agencies should take the necessary measures to mitigate the influence of these influencing parameters.

Figure 8. Estimation of Potential Soil Erosion



5. Conclusion

The assessment of soil erosion in Rulindo District using the Revised Universal Soil Loss Equation (RUSLE) model has provided significant insights into the various factors influencing soil degradation. The RUSLE model integrates parameters such as rainfall erosivity, soil erodibility, slope length and steepness, land cover and management, and conservation practices. By using Geographic Information Systems (GIS), these parameters were effectively computed and visualized, highlighting areas at risk of severe soil erosion. The results indicate that sectors like Shyorongi, Masoro, Ngoma, and Murambi face higher erosion risks due to intense rainfall, loamy soil, steep slopes, and extensive cultivation activities. Conversely, areas with lower P-values, such as Bushoki, Base, Rusiga, and Cyungo, exhibit reduced erosion rates, showcasing the importance of effective land management practices.

This study underscores the critical need for targeted soil conservation strategies in Rulindo District. The identification of high-risk areas provides a foundation for implementing erosion control measures, such as terracing, contour farming, and the establishment of vegetation cover. Policymakers and land managers can utilize these findings to prioritize areas for intervention, ensuring sustainable land use and soil fertility preservation. Ultimately, the application of the RUSLE model combined with GIS technology offers a robust framework for assessing and mitigating soil erosion, contributing to environmental sustainability and agricultural productivity in Rulindo District.

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