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Estimating Soil Erosion to Highlight Potential Areas for Conservation Priority in Rukarara Catchment, South-western Rwanda

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Abstract

Soil erosion is one of the major environmental problems in tropical ecosystems; however, the lack of information on the amount of eroded soils in Rwandan mountainous watersheds hinders effective decision-making toward sustainable soil management. This study aimed at predicting soil erosion in the Rukarara River watershed, one of the mountainous watersheds in Rwanda, and identifying potential areas of high erosion risk using the revised universal soil loss equation (RUSLE) implemented in a GIS environment. The annual soil loss was estimated by computing and performing a spatial overlay analysis of relevant layers including rainfall erosivity (R), soil erodability (K), slope length and steepness (LS), cover management (C), and conservation practice (P) factors. The results indicate that the annual soil erosion varies from 54 to 134 t ha^{-1} year^{-1} (95% confidence interval) with a mean of 39.96 t ha^{-1} year^{-1}. The study area is generally characterized by very low and low soil erosion classes and the mean erosion correlated with literature results in the tropics. Agricultural lands are the hotspots of soil erosion with a mean of soil loss of 61.29 t ha^{-1} year^{-1}. The produced maps and soil loss estimates can facilitate informed decision-making toward sustainable soil management in mountainous areas of Rwanda, especially in the Rukarara River watershed.

Keywords: Soil erosion, Soil conservation, Rukarara River watershed, RUSLE & GIS

1.Introduction

Soil erosion is the dissolving, and removal of topsoil triggered by combined effects of natural and anthropogenic factors (Foster et al., 1972; Kuznetsov, et al., 1998; Belasri and Lakhouili, 2016). The natural factors include climate, topography, soil, and vegetation; the anthropogenic include for example tillage systems, soil conservation measures, overgrazing, and deforestation, etc. (Raissouni et al., 2012). Soil erosion detaches individual soil particles from the soil mass and transports them over variable distances (García-Ruiz et al., 2015). The transport of soil particles

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can take various forms of erosion such as splash, interrill, rill, and gully erosion and affects soil resources quality, soil fertility loss, soil matter export into natural waters, severe hazards, surface water flow on bare lands, and sedimentation (Blaikie and Brookfield, 2015, Ashiagbor et al., 2013, Ristić et al., 2012). All these impacts directly affect the environment and the economy of the countries (Navas et al., 2005). For example, the sediments affect reservoirs and dams and therefore increase the costs of their maintenance (Samaras and Koutitas, 2014).

Erosion has become a major environmental problem in many African countries (Byiringiro and Reardon, 1996) and is more pressing in highland regions (Kulimushi et al., 2021a). Rwanda, a country known as the land of thousand hills given the dominant mountainous landscapes, is one of Africa's most ecologically sensitive environments under severe pressure of soil degradation in the form of soil erosion (Byizigiro et al., 2020). In Rwanda, soil erosion is a result of a combination of several factors such as heavy rains, steep slopes, insufficient soil protection measures, inappropriate soil conservation techniques, and low awareness of the farmers and the local leaders on the erosion consequences, fragile soils for Rwanda (Byizigiro et al., 2020). In the country, highlands occupy more than half of its area and suffer from medium to very high water erosion (Bizoza, 2011; Nyssen et al., 2009). The highlands are naturally prone to erosion due to their steepness (Karamage et al., 2016), heavy rainfall, and poor land management under a high population density. In such highland ecosystems, soil erosion is the most hampering land-based livelihood challenge (Karamage et al., 2016; Labrière et al., 2015; Olson and Berry, 2003).

Soil erosion is causing serious threats to soil fertility, waters, national economy, and welfare in Rwanda. The soil losses are associated with increased acidity, reduced soil nutrients, and low organic carbon contents (Mupenzi et al., 2011), decline in soil fertility, soil incapacity to support plant growth, river or lake siltation and flooding (Bugenimana, 2017). Soil erosion in Rwanda results in soil losses of about 1.4 million tons of soil per year, equivalent to an economic loss of US $ 34,320,000, (Stockholm Environment Institute, 2009). The actual soil erosion by water was estimated at approximately 595 million tons per year with a mean soil erosion rate of soil losses, land and water resources will continue to degrade. This underlines the need to conserve soils in Rwanda to prevent or reduce water losses by runoff and associated soil losses (Bizoza, 2011; Posthumus and Stroosnijder, 2010). To create an environment with minimal erosion, Rwanda is implemented soil conservation measures including bench terraces, trenches, progressive terraces, contour cropping, grass strips, and agronomic management practices. These soil conservation measures are implemented by policymakers and land owners to prevent water erosion in Rwandan landscapes dominated by steep slopes (Adimassu et al., 2016; MINAGRI, 2017).

Rizinjirabake et al. (2018) indicated the concentration effect in the Rukarara River. The effect is attributed to the surface erosion, interflow, and direct precipitation that mobilize and transport materials into streams. The erosion in the Rukarara River watershed can cause both environmental and socio-economic problems. On one hand, erosion in the watershed can remove soil nutrients from agricultural lands; this can decrease agricultural production. On the other hand, the erosion in the study area can cause sedimentation of the river and reduce therefore hydroelectric production at Rukarara hydropower production stations (I to VI). The erosion increases river loads and damages mechanical equipment; it causes a wide range of environmental impacts. In fact, the source of the Rukarara is the overall source of the Nile (Brakspear, 2008; Dumont, 2009). The soil erosion in the watershed can cause serious environmental problems in downstream including Mwogo, Nyabarongo, Akagera, and Nile Rivers. However, few attempts have dealt with quantitatively assessing the soil erosion status in the Rukarara River watershed although such information is critical for the effective management of the watershed. The objectives of this study are (1) to estimate the RUSLE model parameters within the Rukarara River watershed, (2) to quantify the actual soil erosion rate in the study area, and (3) to develop a soil erosion risk map for the watershed. To achieve the above research objectives, the study used the Revised Universal Soil Loss Equation (RUSLE) model integrated into Geographical Information Systems (GIS). The study estimated the annual soil loss rates under various effects such as rainfall; soil types, topography, and land cover type, soil conservation practices, and land use. Assessing the annual soil loss rates is essential for the development of adequate erosion prevention measures for sustainable management of land and water resources in the study area and can be used as a scalable model for various mountainous watersheds.

2. Materials and Methods

2.1. Study Area

Rukarara River watershed is a drainage area of the Rukarara River, which together with Mwogo and Mbirurume are considered to be the sources of the Nyabarongo River and the source of the west Nile, which moves towards the north of Africa and flows into the Mediterranean Sea (Dumont, 2009). The watershed is about 6445 km^2, and its elevation is about 1544 m to 2924 m a. s. l, its annual precipitation is about 1300 mm to 1450 mm per year, and its average temperature is about 18°C. Its climate exhibits four distinct seasonal periods in the year: two rainy seasons (from mid-September to December and from March to June) and two dry seasons (from July to mid-September and January to March).

The watershed is characterized by angular hills jagged with irregular slopes ranging from 0° to 68° (Nduwayezu et al., 2015) making soils susceptible to soil erosion and degradation. In addition, the watershed soils are very poor and acidic (pH ranging from 3.6-5.7) (Cyamweshi et al., 2022). The soil acidity combined with soil erosion conditions and low soil nutrients in the Rakarara River watershed contributes to low agricultural productivity unless fertilizers are used. The watershed’s land cover land use includes a part of the Nyungwe National Park (NNP), as well as plantation forests and cropland with annual or perennial crops (Rizinjirabake et al., 2018). Rukarara River watershed itself is located in the Nyamagabe district and occupies a large part of the Nyamagabe district and encroaches on the boundaries of the Nyamasheke, Rusizi, and Nyaguguru districts (See Figure 1).

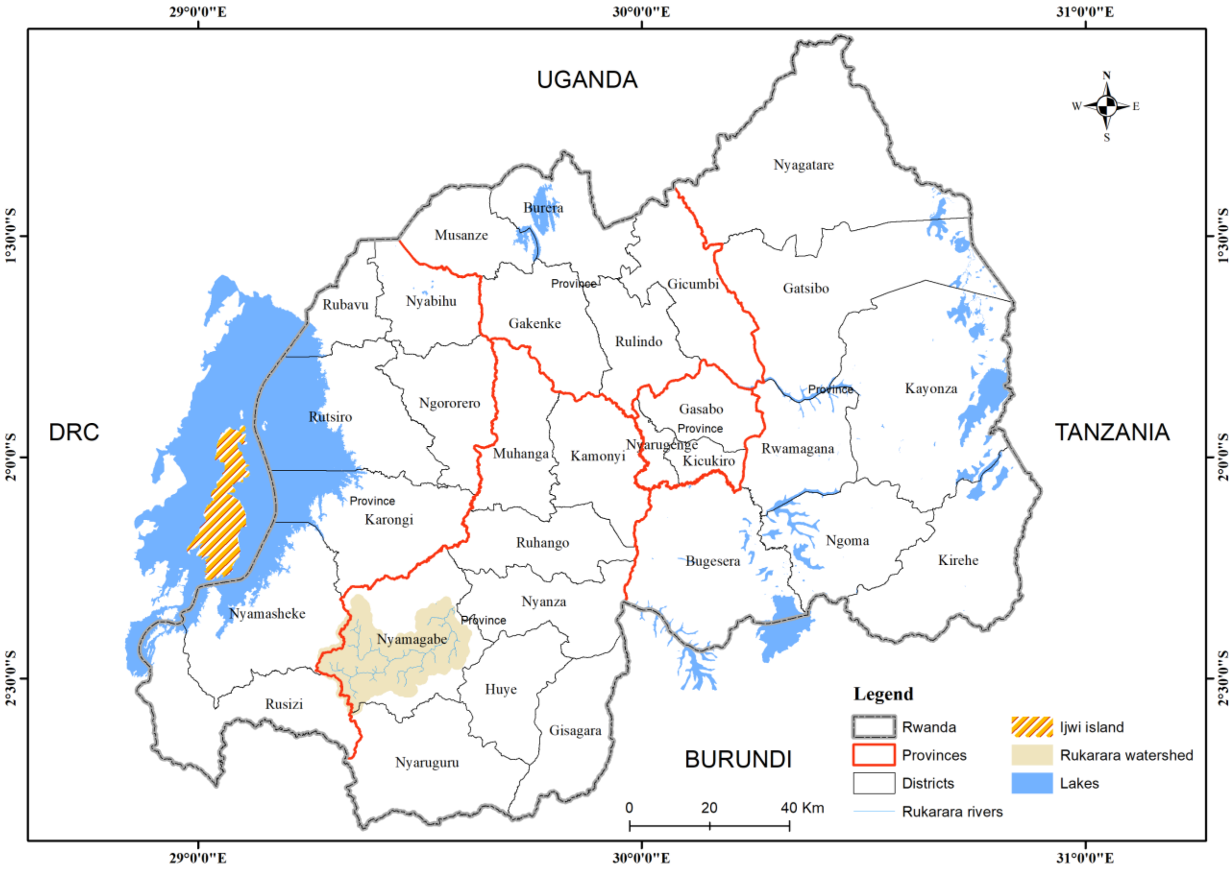

Figure 1: Localisation of the Rukarara River watershed in Nyamagabe District, Southern Province, Rwanda

2.2. RUSLE Model

The Revised Universal Soil Loss Equation (RUSLE) is the updated version of the basic Universal Soil Loss Equation (USLE). The RUSLE predicts the mean rate of rill and interrill soil erosion due to the combined effects of rainfall, soil, topography, land use, and soil conservation practices (Koirala et al., 2019). Combined with GIS techniques, the RUSLE has been extensively used to estimate soil erosion loss on a cell-by-cell basis and with reasonable costs and better accuracy (Millward and Mersey, 1999, Wang, et al., 2002). The RUSLE model can quantify sheet erosion and rill erosion on a cell-by-cell basis; this is why this study used it to estimate soil loss erosion in the study area.

The RUSLE model estimates yearly soil loss in the Geographic Information System (GIS) platform (Yitayew et al., 1999; Fig. 2) from a unit of property because of its convenience and compatibility with GIS (Milward and Mersey, 1999; Tang et al., 2015; Jha and Paudel, 2010; Šúri et al., 2002). Each of the elements of the soil loss equation was derived separately in raster data format and the erosion was calculated using the map algebra functions. The RUSLE model is expressed by the following equation:

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$$A = R * K * LS * C * P \tag{1}$$

where A = soil loss (t ha^{-1} $year^{-1}$), R = rainfall erosivity factor (MJ mm ha^{-1} $hour^{-1}$ $year^{-1}$), K = soil erodibility factor (t. h MJ^{-1} mm^{-1}), LS = slope-length and slope steepness factor (dimensionless), C = land management factor (dimensionless), and P = conservation practice factor (dimensionless).

The soil loss (A) represents the potential long-term average annual soil loss in tons per hectare per year. This amount is compared to the "tolerable soil loss" limits. The rainfall erosivity (R-factor) is a multi-year averaged index that measures rainfall kinetic energy and intensity to describe the effect of rainfall on sheet and rill erosion. The R-factor accumulates the rainfall erosivity of individual rainstorm events and averages this value over multiple years. The R-factor represents the input that drives the sheet and rill erosion process, and differences in R values represent differences in erosivity of the climate.

The soil erodibility factor (K-factor) is a quantitative description of the inherent erodibility of a given soil; it is a measure of the susceptibility of soil particles to detachment and transport by rainfall and runoff under standard conditions. American Soil conservation society (SCS) has identified K values for all major soil mapping units. The K-factor is influenced by soil texture, organic matter, soil structure, and permeability of the soil profile (Erencin et al., 2000).

The slope-length and slope steepness (LS factor) is the topographic factor created from two sub-factors: a slope gradient factor (S) and a slope-length factor (L), both determined from a 10 m Digital Elevation Model (DEM). L is the slope length factor and represents the effect of slope on erosion.

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The C-factor is used to reflect the effect of cropping and management practices on erosion rates. It is the factor used most often to compare the relative impacts of management options on conservation plans. C represents the effects of plants, soil cover, soil biomass, and soil disturbing activities on erosion. The C factor represents the conditions that can be managed most easily to reduce erosion. Values for C can vary from near zero for very well-protected soil to 1 for a finely tilled, ridged surface that produces much runoff and leaves the soil highly susceptible to rill erosion.

The P-factor accounts for control practices that reduce the erosion potential of runoff by their influence on drainage patterns, runoff concentration, runoff velocity, and hydraulic forces exerted by the runoff on the soil surface. The P-factor mainly represents surface conditions at flow paths and flow hydraulics.

2.3. Module Input Data

The model input data comprised rainfall, soil, digital elevation model data with 10 m of spatial resolution, and Normalized Difference Vegetation Index (NDVI) (Figure 3).

2.3.1. Rainfall Data

The mean annual rainfall data (mm) were calculated using rainfall data collected using tipping bucket rain gauges at three sites (Figure 3). From these means, a continuous surface was developed from the point data of the three rain gauge stations using the inverse distance weighting (IDW) method, a deterministic method based on the assumption that the attribute value of an unsampled point is the weighted average of known values within the neighborhood (Lu and Wong, 2008). The method assigns values to unknown points using values from a set of known points that are adjacent to the unknown site (Li and Heap, 2008). The value at the unknown point is a weighted sum of the values of known points based on the concept of distance weighting (Chen and Liu, 2012, Li and Heap, 2014). The IDW formulas are the following:

$$\widehat{R_p} = \sum_{i=1}^{N} w_i R_i \tag{2}$$

$$w_i = \frac{{d_i}^{-\alpha}}{\sum_{i=1}^{N} {d_i}^{-\alpha}} \tag{3}$$

where is the unknown rainfall data (mm); is the rainfall data of known rainfall stations (mm); N means the amount of rainfall stations; is the weighting of each rainfall station; means the distance from each rainfall station to the unknown site; α is the power or the control parameter. The parameter is assumed as two (Lin and Yu, 2008).

The continuous surface rainfall developed data were utilized to estimate R factor values using the R model recommended by Roose in Morgan and Davidson (1991) as follows:

$$R = P * 0.5 \tag{4}$$

where P is the mean annual rainfall (mm) and R = rainfall erosivity factor (MJ/ha.mm/h). The equation is among other equations used in estimating erosivity in over tropical wet and dry climatic zones (Ghosal and Das Bhattacharya, 2020).

2.3.2. Soil Data

Content of clay, silt, sand, and total organic carbon (TOC) were analysed in the soil laboratory of the College of Agriculture and Veterinary Medicine (CAVM) from soil samples collected in topsoil (0–20 cm). In total, 23 samples were collected using 53 x 50mm rings, labeled by plot code and geographical coordinates. The soils were collected in the natural forest (6 samples), plantation forests (6 samples), tea plantations (4 samples), and croplands (7 samples) (Figure 2). Soil texture elements were analyzed using the improved Bouyoucos method (Bouyoucos, 1962), and the TOC (%) by the Loss On Ignition (LOI) method (Davies, 1974).

The soil data were utilized to estimate the K-factor using the equation developed by Sharpley and Williams (1990) as follows:

$$K = \{0.2 + 0.3\, exp[0.0256\, SIL/100)]\} * \left(\frac{SIL}{CLA+SIL}\right)^{0.3} * \left[1.0 - \frac{0.25C}{C+exp(3.72-2.95C)}\right] * \left[1.0 - \frac{0.7SN_1}{SN_1+exp(-5.51+2.95SN_1)}\right] \quad (5)$$

where K is the soil erodibility, SAN, SIL and CLA are respectively the subsoil sand, silt and clay fractions (in %). C is the topsoil carbon content (in %) and SN1 equals (1-SAN/100).

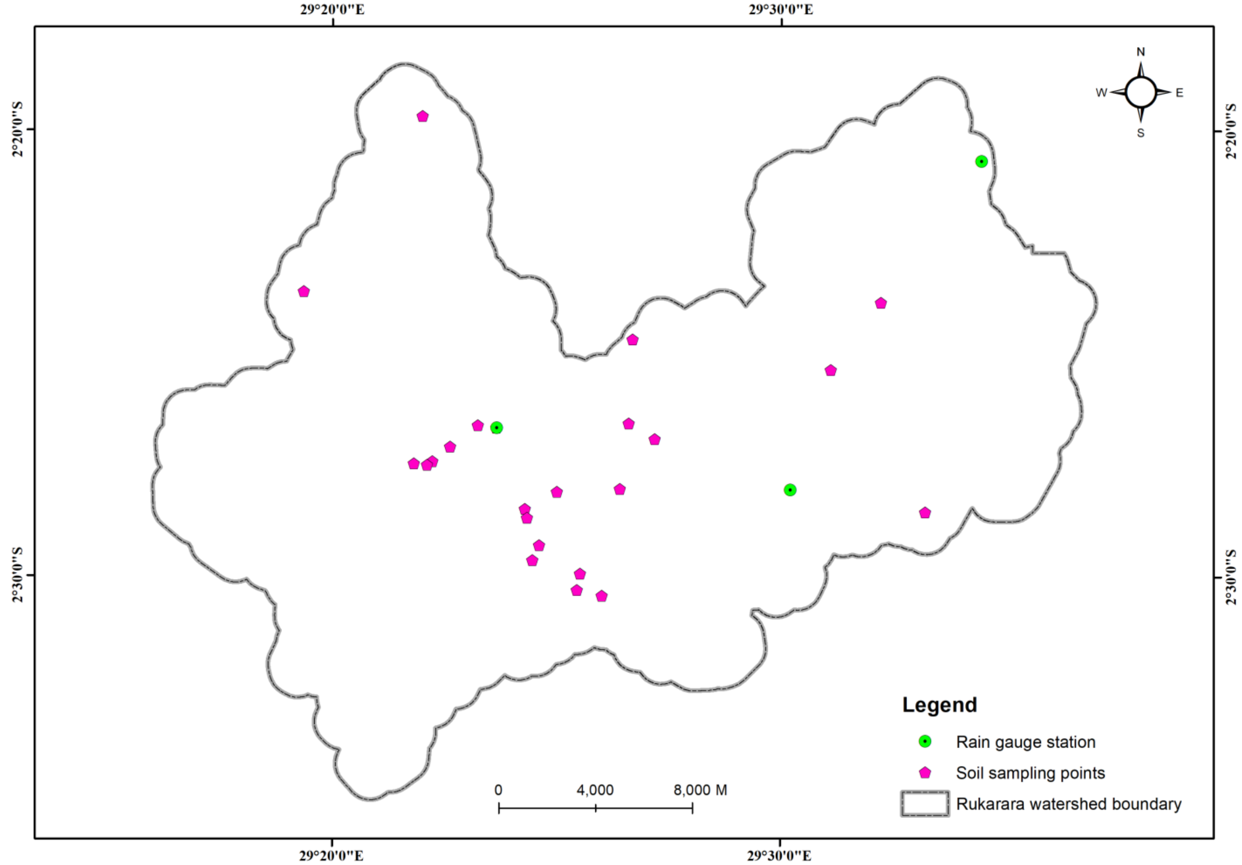

Figure 2: Soil sampling and rain gauges sites distribution in the study area

2.3.3. DEM and NDVI Data

The used DEM was provided by the Centre for Geographical Information System and Remote Sensing of the University of Rwanda (CGIS/UR) whereas the NDVI data were derived from the Moderate Resolution Imaging Spectroradiometer (MODIS) website (https://modis.ornl.gov/). The DEM data were used to calculate slopes and slope gradients used in return to empirically estimate the conservation practice factor (P-factor) and the slope-length and slope steepness factor (LS-factor). The conservation practice factor (P) was estimated using the Wenner (1981) method based on the linear interconnection between the slope (S) of an area and the amount of conservation practice (P) as follows:

$$\mathrm{P} = 0.2 + 0.03 * \mathrm{S} \qquad (6)$$

where P is the amount of conservation practice and S is the percentage of slope.
The LS factor was calculated using the following Arnoldus method (1977):

For a slope less than 20%:

$$LS = L^{0.5} * (0.0138 + 0.00965S + 0{,}00138S^{2}) \qquad (7)$$

For a slope greater than 20%:

$$LS = \frac{L^{0.6}}{22.2} * \frac{S^{1.4}}{9} \qquad (8)$$

where: L = slope length (m) and S = slope gradient (%). S, L, and LS factor values were calculated in ArcMap 10.6.

The NDVI data were 16 days composites (MOD13Q1) at a spatial resolution of 250 m and used .to estimate the land management factor (C) based on the relationship developed by Gutman and Ignatov (1998) between NDVI and the C-factor, as follows:

$$C = 1 - \frac{NDVI - NDVI_{min}}{NDVI_{max} + NDVI_{min}} \qquad (9)$$

2.4. Soil Erosion Prediction

Quantitative soil-erosion prediction was estimated using the Revised Universal Soil Loss Equation (RUSLE) and GIS. The RUSLE uses the combination of rainfall erosivity index, soil characteristics, topography factor, crop management, and conservation factor (Wischmeier and Smith, 1978; Morgan, 2005) to model soil erosion. The RUSLE is widely used to estimate soil loss due to erosion and provides a guideline for soil and water conservation plans under different conditions of land cover land use (Milward and Mersey, 1999). Combined with Geographical Information System (GIS), RUSLE is a good quantitative equation for soil loss estimation and spatial distribution on a cell-by-cell basis (Milward and Mersey, 1999). GIS enables a more accurate estimation of the factors used for calculation (TolIIrism 1995; Park et al., 2005; Ganasri and Ramesh, 2016; Atoma, 2018). However, the RUSLE and GIS predict only sheet and rill

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erosion; they cannot estimate the rate of gully erosion (Wang et al., 2002). The RUSLE and GIS in a particular area of interest at different spatial scales.

The study used RUSLE with GIS to estimate soil losses in the study area and therefore to provide a framework for decision-makers for planning soil and water conservation practices. All input data including rainfall erosivity index, soil erodibility, topography factor, land management factor, and conservation factor, were processed in ArcGIS 10.6 to generate composite maps of the estimated erosion loss on the Rukarara River watershed (Figure 3). Soil erosion within the study area was grouped into 6 classes: very low (0-5 t ha^{-1} $year^{-1}$), low (5–10 t ha^{-1} $year^{-1}$), moderate (10–25 t ha-^{1} $year^{-1}$), high (25–50 t ha^{-1} $year^{-1}$), very high (50–100 t ha^{-1} $year^{-1}$) and extremely high (> 100 t ha^{-1} $year^{-1}$) (Majoro et al., 2018). Spatial Analyst tools were used for computing areas of different classes of potential soil erosion, areas of soil conservation priority, or areas of high potential erosion risk within the study area. The areas of soil conservation priority were identified using the annual value of the classical tolerable soil loss set equal to 11.5 t ha^{-1} year.

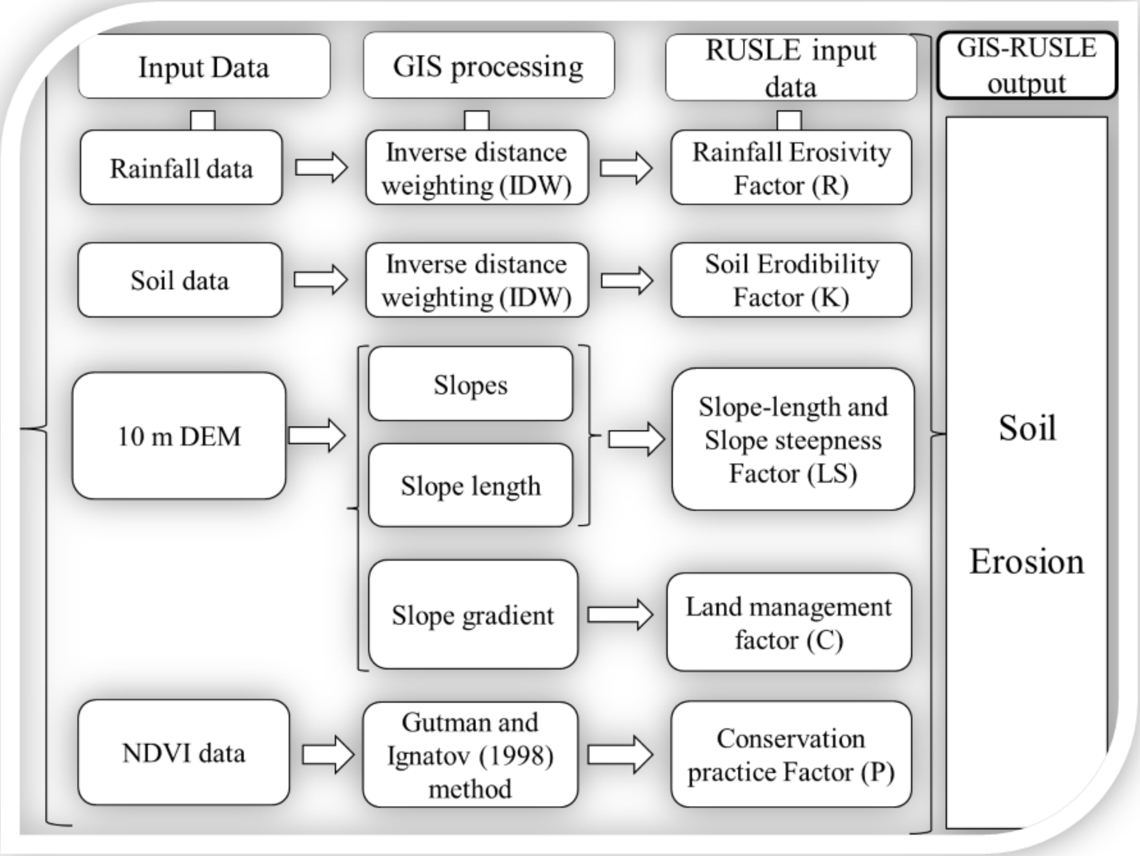

Figure 3: Methodological framework for estimating the potential soil erosion in the study area

3. Results

3.1. Spatial Pattern of Soil Erosivity in the Rukarara River Watershed

During the study period, the maximum annual rainfall (1502 mm) was observed at the western rainfall gauge located close to the Nyungwe National Park. The minimum annual rainfall (1239mm) was observed in the center rain gauging. The mean annual rainfall and, and the standard deviation were respectively 1394mm and 138 mm.

The R-factor is estimated. The latter values range from 112 to 120 120 MJ mm ha^{-1} hour^{-1} year^{-1} (Figure 4). The R-factor mean in the study area was 116±2.58 mm ha^{-1} year^{-1}. The results indicated that high R-factor values were found in the area of higher rainfall. The study indicated also that rainfall erosivity is in a particular part around the sectors Kibirizi and Uwinkingi. The lowest soil erosivity was found to be located in the Kibirizi sector (Figure 3).

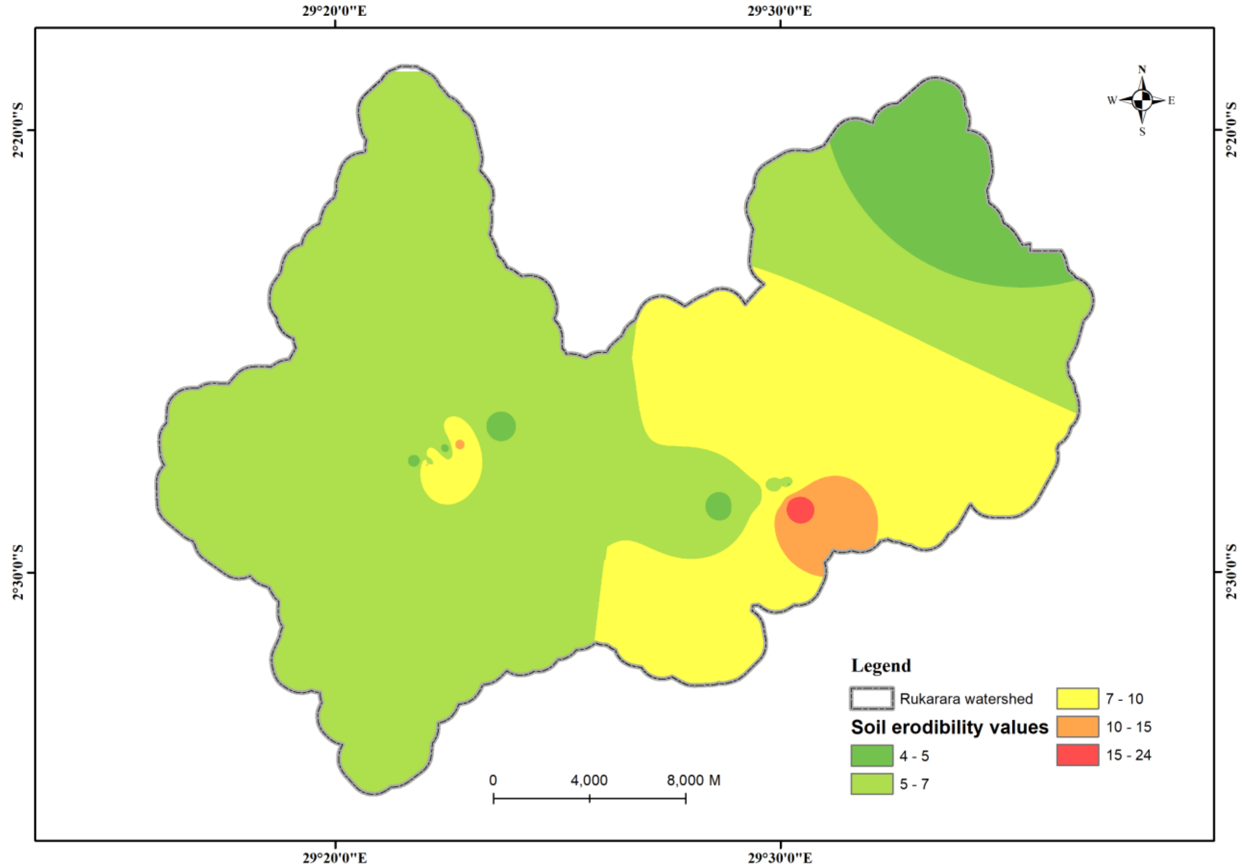

Figure 4: Spatial distribution of interpolated rainfall erosivity (MJ/ha.mm/h) within the Rukarara River watershed

3.2. Spatial Pattern of K-factor in the Rukarara River Watershed

The soil in the Rukarara River watershed is composed of 40.73±.29, 35.19±5.76, and 20.07±5.94 % of sand, clay, and silt, respectively. The maximum values of soil textural elements in the watershed were respectively 53, 46, and 38% of sand, clay, and silt. The observed minima were respectively 32, 20, and 12% of sand, clay, and silt (Table 1).

Table 1: Soil textural elements in the Rukarra River watershed

Statistics	Sand (%)	Silt (%)	Clay (%)
Min	32	12	20
Max	53	38	46
Mean	40.73	20.07	35.19
Standard deviation	4.29	5.94	5.76

The estimated K values range from 4 to 24 with 14±6.06 as the mean. The lowest K values were observed in the western and eastern parts of the watershed. The highest K values were found in the central part of the watershed in the area where low rainfall was observed (Figure 5). The study indicated that the soil erodibility is higher than the average in the transboundary between Tare, Kibirizi, and Gasaka sectors.

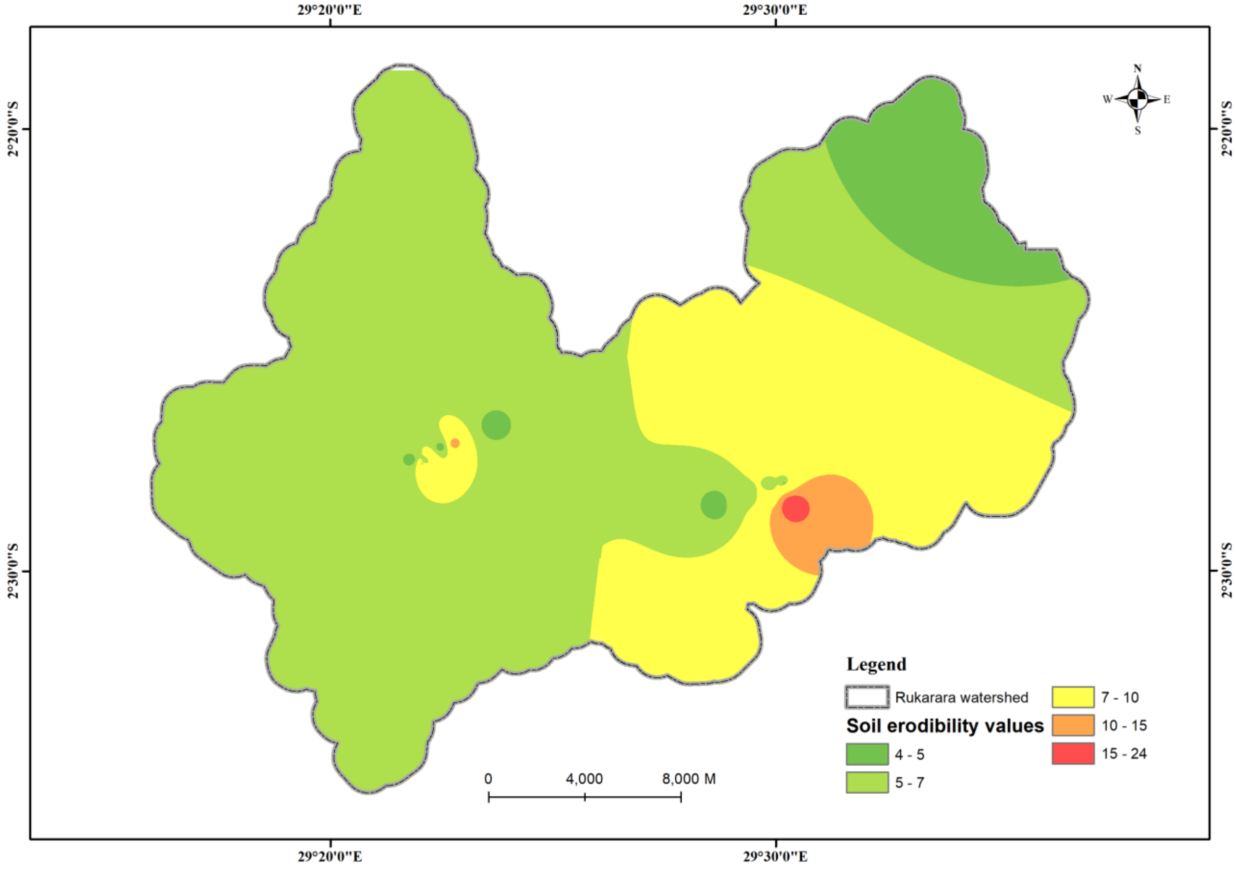

Figure 5: Spatial distribution of soil erodibility (t h MJ^{-1} mm^{-1}) in the Rukarara River watershed

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3.3. LS-factor for Rukarara River Watershed

The slopes of the study area range from 0 to 277%, with 43% and 24% as the corresponding mean and standard deviation. Most of the area of the watershed belongs to higher slopes than the mean. It is observed that the values of LS range from 0 to 7108 and the highest values tend to be centralized in the watershed (Figure 6).

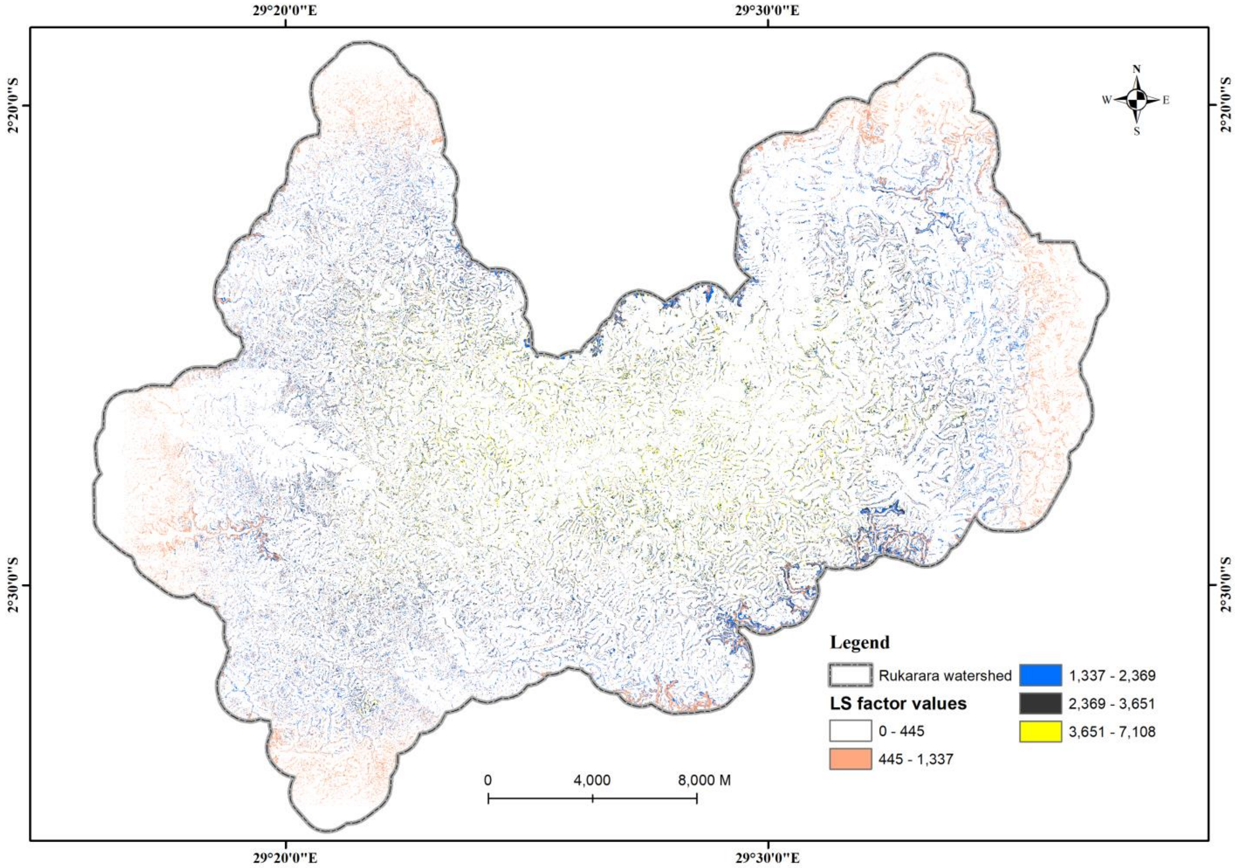

Figure 6: Slope length and steepness distribution in the study area

3.4. C-factor for Rukarara River Watershed

The vegetation cover of the RRW was computed by using NDVI. The observed values of the latter were from −0.3 to 0.9994. Regarding the values of the C-factor, they ranged from 0 to 1. Both the lower and the highest values of the C-factor are dispersed through the watershed (Figure 7). The lower value of the C-factor indicates the areas of solid vegetation, and the higher value of the C-factor implies the areas without vegetation. The study indicated that both the lower value and the higher value of the C factor disperse across the study area (Figure 7).

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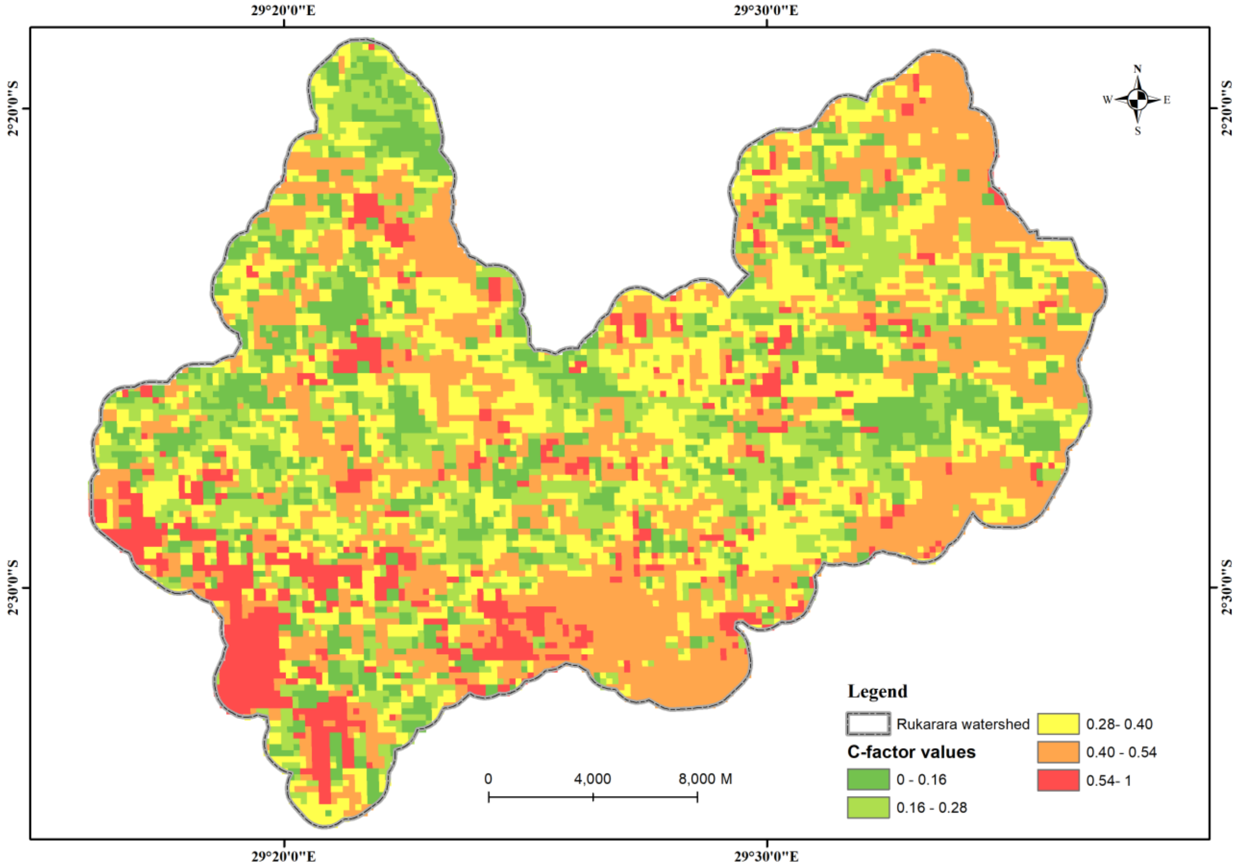

Figure 7: Effect of management practices on soil erosion in the Rukarara River watershed

3.5. P-factor for Rukarara Catchment

The P factor value varies from 0.20 to 0.51 and the mean value and the standard deviation were respectively 0.45 and 0.17. The P-factor highest values indicate the areas where there are no sufficient conservation practices and lower values indicate the areas that show high conservation practices. The conservation practices are more important in the western forested part compared to the central and eastern parts of the study area (Figure 8).

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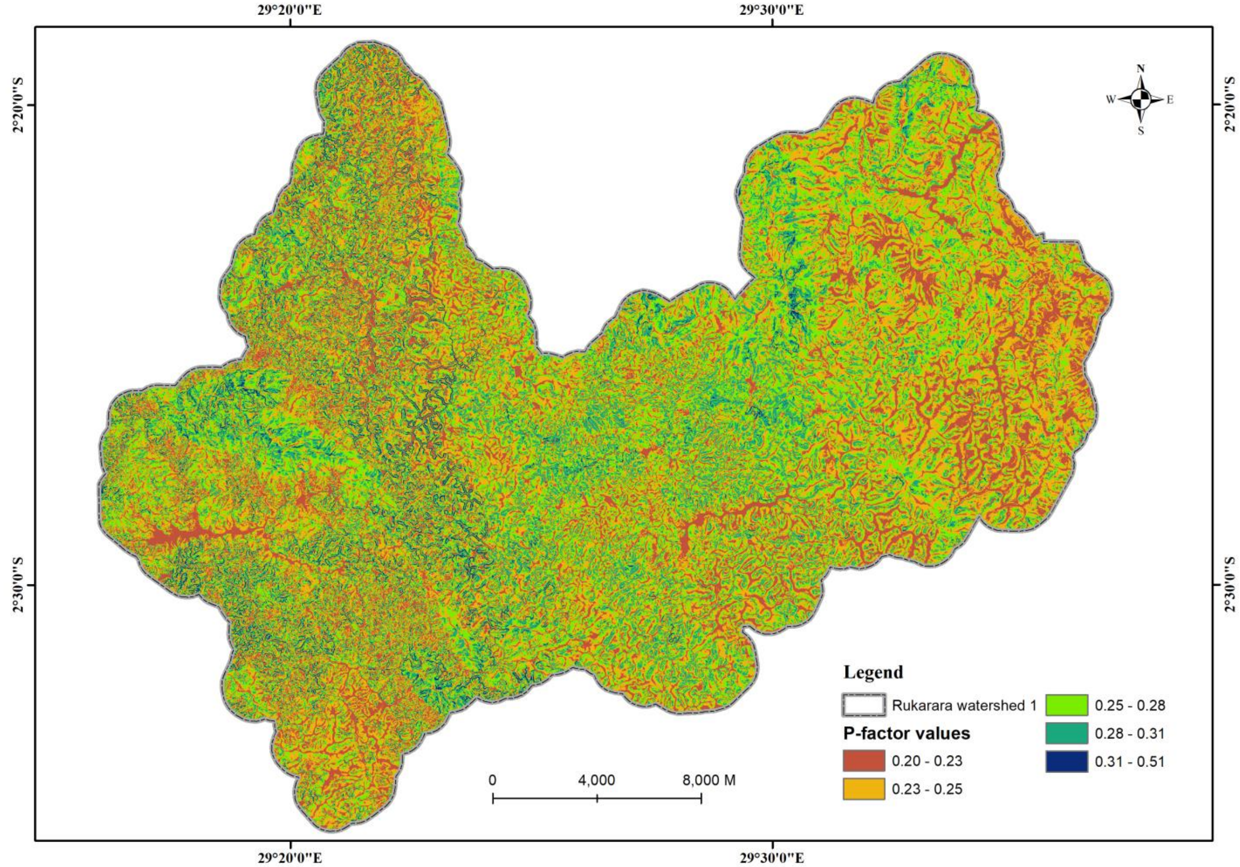

Figure 8: Spatial distribution of P-factor in the Rukarara River watershed

3.6. Annual Soil Erosion Estimates

The analysis indicated that the annual water-based soil erosion ranges from 0 to 1012 t ha^{-1} year^{-1} with the mean and standard deviation of 39.96 t ha^{-1} year^{-1} and 93.834t ha^{-1} year^{-1} respectively. All six soil erosion classes were found within the RRW but the very low class (≤5 t ha^{-1} year^{-1}) is the most dominant (81.82%), followed by the extremely high erosion class (6.35%), the low erosion class (5.15%), and the very high erosion class (2.97%), the high erosion class (1.97%) and the moderate erosion class (1.74%) (Table 2).

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Table 2: Area covered by erosion classes within the RRW

Erosion class (t ha^{-1} year^{-1})	Covered area (ha)	Area (%)
Very low (0 – 5 t ha^{-1} year^{-1})	50,562.07	81.82
Low (6 – 10 t ha^{-1} year^{-1})	3,182.43	5.15
Moderate (11- 25 t ha^{-1} year^{-1})	1,073.77	1.74
High (26 - 50 t ha^{-1} year^{-1})	1,217.61	1.97
Very high (51 – 100 t ha^{-1} year^{-1})	1,833.44	2.97
Extremely high (> 100 t ha^{-1} year^{-1})	3,924.44	6.35

All erosion classes except the low class were found to be dispersed across the watershed. The low erosion class dominates in the central part of the RRW as indicated on the following Figure 9.

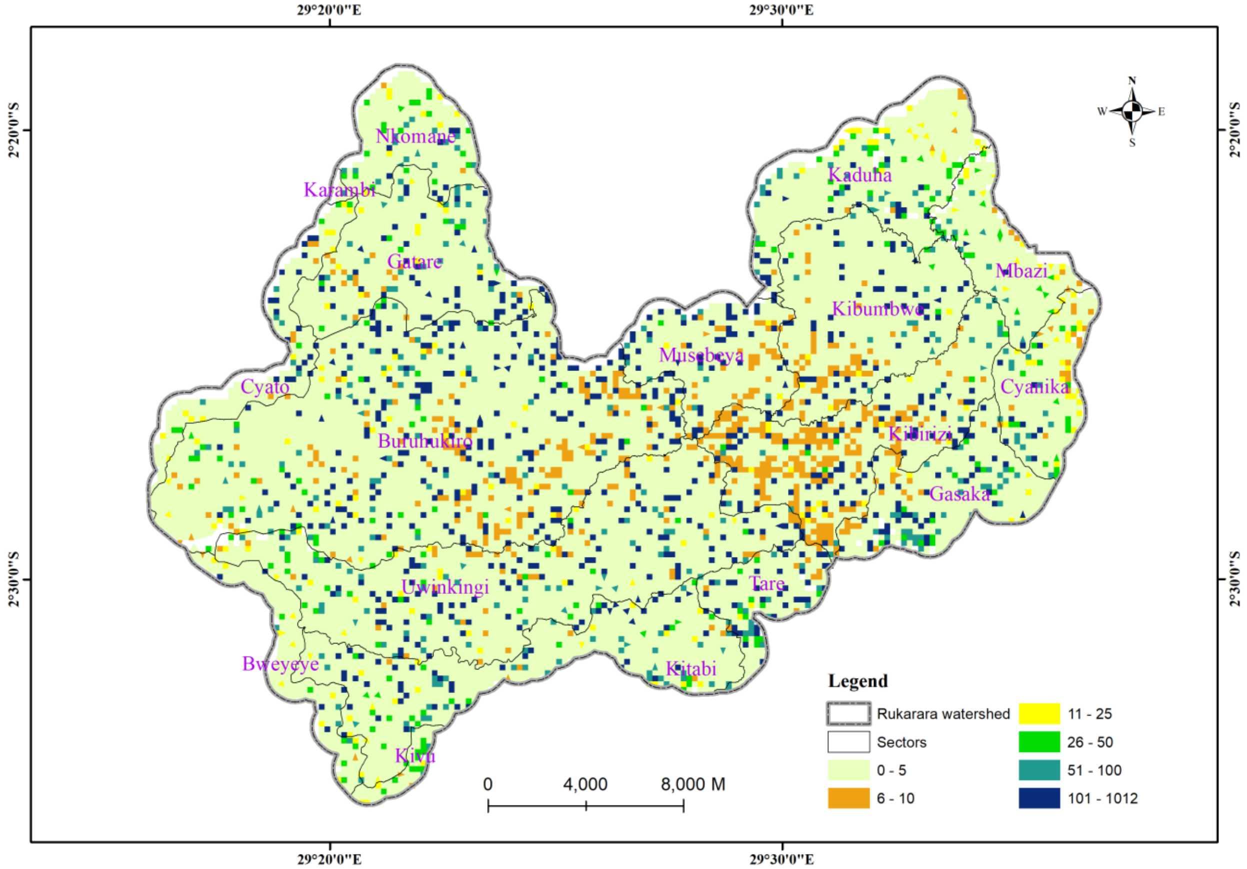

Figure 9: Spatial distribution of potential soil loss (t ha^{-1} year^{-1}) within the Rukarara River watershed

Regarding the spatial distribution of erosion in different land use land cover types as classified by Rizinjirabake et al. (2018), agricultural lands produce 20.43 t ha−1 year−1 (34%). The agricultural lands are followed by plantation forests that produce 18.45 t ha−1 year^{-1} (30%), built-up areas cause 14.03 t ha^{-1} year^{-1} (23%) and the natural forest causes the lowest amount of erosion of 7.67 (13%). The mean annual erosion is the highest in agricultural lands, followed by the plantation forest areas, the built-up areas, and the natural forest (Table 3).

Table 3: Distribution of soil erosion as a function of land use land cover in the RRW

Land use land cover	Total area covered (ha)	Area (%)	Erosion range (t ha^{-1} year^{-1})	Mean erosion (t ha^{-1} year^{-1})	Total erosion (t ha^{-1} year^{-1})	Total erosion (%)
Agriculture	27,278.73	44	0−898	61.29	20.43	34
Plantation forest	11,999.32	19	0−1012	32.92	18.45	30
Built up area	2,454.86	4	0−832	30.19	14.03	23
Natural forest	21,438.58	34	0−656	28.72	7.67	13

4. Results Discussion

4.1. Validation of the RUSLE in the study area

The mean water-based soil erosion in the study area (39.96 t ha^{-1} year^{-1}) was different from the result of the Food and Agriculture Organization of the United Nations' annual report in 2015 (FAO, 2015). The letter stated that the mean soil water-based erosion in tropical areas is often < 10 t ha^{-1} year^{-1} (Dissanayake et al., 2018). This soil erosion falls into the very low and the low erosion class as per Majoro et al. (2018) erosion classification. The results of the study showed that these two erosion classes represent 86.97% of the total erosion produced in the study area.

The annual estimated soil erosion was 60.58 t ha^{-1} year^{-1} in the study area whereas the annual erosion was 130.72 t ha^{-1} year^{-1} in the Sebeya watershed (Majoro et al., 2018). The annual erosion in these two watersheds is different, maybe because of the differences in erosion parameters and other factors such as land use land cover, and watershed total area. But the soil erosion observed in the RRW, compared to soil erosion observed on bare erosion plots, falls into the range of soil erosion found by other researchers in Rwanda. The studies conducted by these researchers found soil erosion ranging from 10 up to 700 t ha^{-1} year^{-1} at different slope gradients (König, 1992; Roose and Ndayizigiye, 1997; Rutebuka, 2019). This proves again that the RUSLE model integrated with GIS is an efficient tool to estimate soil erosion in tropical watersheds.

4.2. Soil Erosion Susceptibility

The soil erosion of all erosion severity classes was found to disperse across the whole RRW. This result reflects the homogeneity and propensity of the watershed to soil water-based erosion.

In the watershed, the annual average rainfall erosivity can be as high as 120 MJ mm ha^{-1} hour^{-1} year^{-1} and the slopes can exceed 100%. Also, the topographical factor (LS) of the RRW is higher (up to 7108) than that in the Satinskyi catchment (from 0.03 to 1164.81) (Byizigiro et al., 2020). The mean C-factor value of the RRW is 0.36 and its mean soil erodibility factor K is about 7.25 t hour^{-1} MJ^{-1} mm^{-1}. These results of hydrous erosion factors make the RRW the most susceptible watershed to erosion compared to the Satinskyi watershed.

4.3. Spatial Distribution of Soil Erosion

The highest mean potential soil erosion was found in agricultural lands and the lowest erosion was found in the natural forest. The higher mean soil erosion in agricultural lands conforms with other studies that confirmed agricultural lands to have the biggest contribution to soil erosion more than other land uses. For example, Horowitz (2014) and Stenfert Kroese et al., (2019) found that dry agricultural land is the biggest contributor to potential erosion in watersheds. Other studies such as Kidane et al. (2019), Esa et al. (2018), Aneseyee et al. (2020), Mariye et al. (2022), Gashaw et al. (2019), Tadesse et al. (2017) indicated that the conversion of forest into agricultural land in the watersheds has increased the soil water based erosion and therefore the sediment yield. The result would be due to plugging activities and less important vegetation cover which would cause poor resistance to erosion and therefore increased erosion rates in such agricultural areas. The RRW is greatly vulnerable to potential soil water-based erosion with a rate of 60.58 t ha^{-1}·year^{-1} due to two main natural factors, including a high mean tropical precipitation of 1450 mm year^{-1} and a mean steep slope of 49.73%. The RRW is still exposed to soil erosion; only 33% of the area is associated with tolerable soil loss based on the maximum threshold of soil loss tolerance of 10 t·ha^{-1}·year^{-1} for highlands of tropical areas (Morgan, 2009; Bamutaze, 2015). Within the agricultural lands, 13.6% of their area has soil loss values greater than tolerable soil loss. This can affect crop production and therefore impact on food security of the inhabitants within the RRW. Twagiramungu (2006) indicated that soil water-based erosion affects a big portion of cultivated lands in Rwanda and reduces the capacity to feed 40 000 persons per year.

The lowest mean soil erosion was found in the natural forest. The study is congruent with previous studies indicating that forestlands have usually very low erosion (Bamutaze et al., 2015). The low erosion rates observed in the forestlands are evidence of limited habitat disturbance, indicating the role of the forest overstorey canopy and the intactness of vegetation in that part of the RRW. For example, scattered vegetation showed very high soil loss rates (Panagos et al., 2015; Evans and Boardman, 2016). The low soil erosion loss in the part of the natural forest in the RRW shows that the Nyungwe natural forest is moderately effective in reducing soil erosion.

4.4. Implications of Predicted Soil Erosion for Soil Conservation

Soil loss values can help in the identification of hotspot erosion-prone areas where efforts and resources should be unified to control further erosion. Erosion control measures in hotspot erosion areas are a priority to significantly reduce soil losses in watersheds. The rate of soil loss less than 11.5 t ha^{-1} year^{-1} is 87.15% of the study area; this rate of soil loss is considered to be sustainable, given it is less than the classical soil loss tolerances. The remaining portion of the

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watershed (12.85%) needs to be managed sustainably. These areas are mainly located in Buruhukiro, Musebeya, and Kibilizi sectors (See Figure 9). In these areas, soil hydrous erosion represents a major environmental problem in these areas of the watershed and there is, therefore, an urgent need for soil conservation measures such as terraces, tree planting on terraces, and riverbank protection in these areas whose soil hydrous erosion is greater than the classical soil erosion tolerance (11.5 t ha^{-1} year^{-1}) (Bagarello et al. (2015).

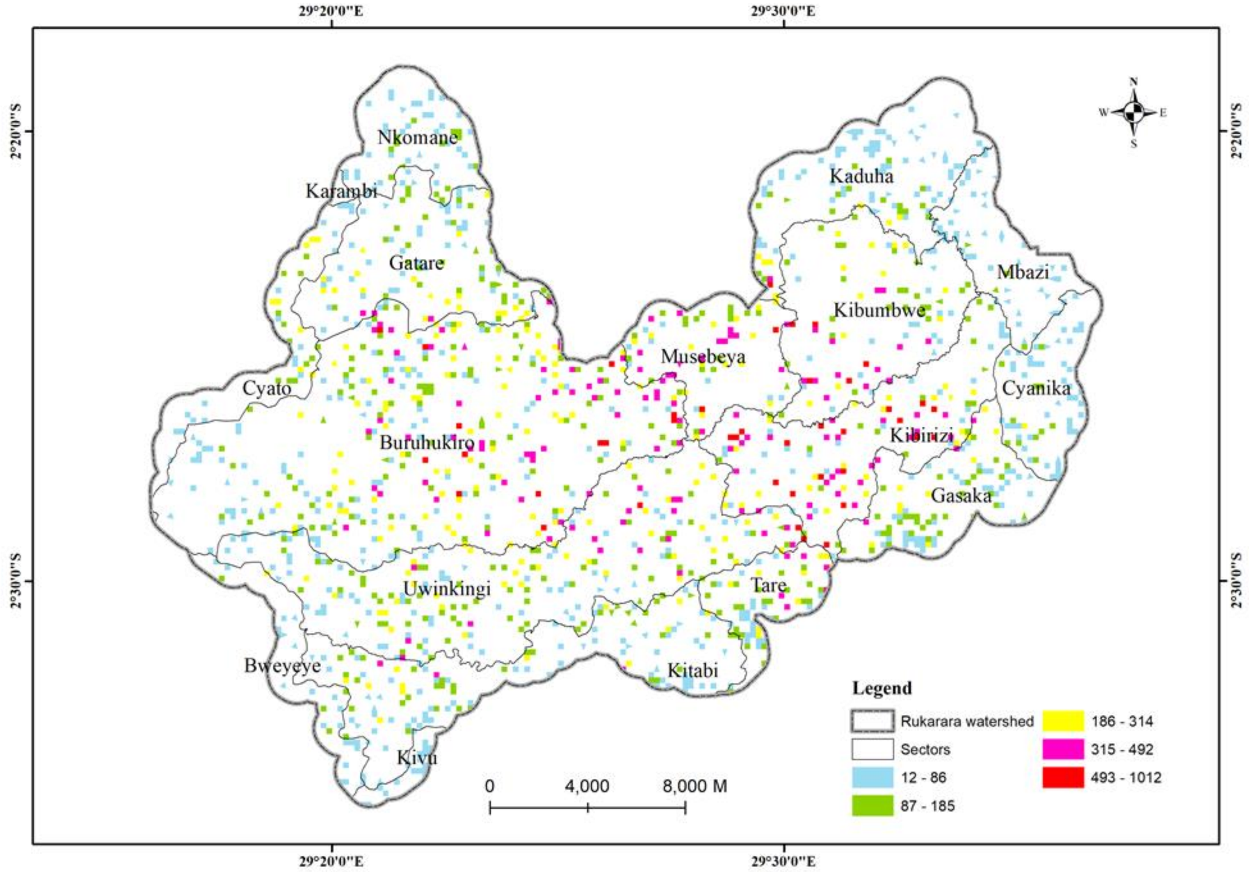

Figure 10: Distribution of areas of high erosion (t ha^{-1} year^{-1}) within the study area

5. Conclusions

Soil erosion in the Rukarara River watershed is both an economic and environmental concern. The watershed is geologically located in an area of successive rugged mountains and V-shaped valleys and characterized by steep slopes (greater than >15°). Also, the watershed is characterized by high population density (341 inhabitants / km^2) and, as in other remaining parts of the country; the majority of the population relies on agriculture. Sloppy landscapes, agricultural activities, high population density, and important rainfall in the watershed combine to cause soil erosion. Knowledge of the importance of soil erosion in the watershed is essential for better soil conservation. The mean soil loss was 39.96 t ha^{-1} year^{-1} and 11.29 % of the watershed area show high to extremely high erosion (> 26 t ha^{-1} year^{-1}). The watershed is generally characterized by low to very low erosion (<10 t ha^{-1} year^{-1}) and the potential severe erosion was found in the agricultural areas, followed by the plantation forests, built-up areas, and the natural forest. A part of the Rukarara River watershed of about 7944 ha has erosion risks greater than the classical soil tolerance and therefore urgently needs soil conservation measures such as terraces, mulching, agroforestry, etc. to protect the watershed against erosion. The study indicates that soil conservation practices particularly in agricultural areas should be enhanced and established where they do not exist to better protect the watershed against hydric erosion. The RUSLE, an empirical model, integrated with GIS, showed its capability to quantitatively and spatially predict rill and inter-rill soil erosion in the study area; but it did not estimate the rate of gully erosion. In further research, it would be better to estimate soil loss in the study area and similar watersheds using process-based models that can quantify all soil erosion processes.

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