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Asssesment of the Impact of Soil Erosion on Soil Fertility in Sebeya Catchement using Rusle Model

Mujanama Erick[1],
Ntwali Didier[1],
Byicaza Prince[1],
Hategeka Emmanuel[1],
Faculty of Environmental Studies, University of Lay Adventists of Kigali (UNILAK), Kigali, Rwanda

Abstract:- In Rwanda more than 745 thousand hectares of potential agricultural land are eroded annually in Rwanda. Using the reference year 2021A, more than 3 million tons (six million tons annually) of crop produce are expected to be lost each season, with severe erosion affecting 22,000 tons of maize and 15,000 tons of beans. Each season, severe erosion results in a total economic loss of 37.9 billion Rwandan francs (RWf) in agricultural productivity. The research's overall objective was to assess the impact of soil erosion on soil fertility on sebeya catchement. the specific objectives was to analyze to determine amount of soil loss in Sebeya catchment, determine the impact soil erosion on soil nutrients loss and estimate the value of replacement cost of soil nutrients lost in RWf for period of 2022, To achieve these objectives RUSLE model & Geographic Information System (GIS) techniques were combined to determine soil erosion .Soil mapdatabase was used to determine the quantinty of soil nutrients, whereas ministerial price guideline from MINAGRI was used to determine the value (RWf) of fertlizers (NPK) to replace the nutrients lost due to soil erosion. This study showed that amount of soil loss by combining all the five factors influencing soil erosion. After observation and analysis, it revealed that the big losses of soil in the sebeya watershed are only found on the surface covered by cropland and settlements with an estimated amount >300 t/ha/year, while other part of the catchment covered by forest and grasses loose a low quantity of soil with an estimation of 0 to 50 t/ha/year, which reconfirms that human activities are well managed and structured by rules and guidelines given by responsible institutions in charge such as MINAGRI, REMA, RWB, etc the sebeya catchment that is facing large amount of soil loss each year can be protected efficiently. The study has revealed that erosion is seriously taking place in Sebeya watershed, the results shows that, In general, the average soil composition of Nitrogen in the sebeya watershed is 0.378%, 9.051 mg/l of Phosphorous and 1,205 Cmol/kg of Potassium. Generally, Nitrogen is the soil nutrient that is highly lost with an estimated amount of 90 kg/ha/y. the highest amount of N lost is found in cropland about 173.4kg.ha/y while forestland loses the lowest amount of N estimated about 14.45kg/ha/y. the highest loss of nutrients amount of P and K are also observed in cropland with respective amount of 56.82kg/ha/y and 147.89kg/ha/y. These soil nutrients losses have a huge impact on soil fertility reduction, because the soil fertility is made at 80% of these three elements (N, P and K). This average value of soil loss in the catchment, which is estimated to be about 135t/ha/y, naturally indicates 90 kg/ha/y of N, 15kg/ha/y of P, and 74kg/ha/y of K. If three or five consecutive years of the same soil loss amount occur, soil fertility will be gone, and we will be left with a marginal soil unsuitable for cultivation. This study recommends the consideration of soil erosion control measures for all government plans to increase agricultural productivity through intensification and commercialization and suggest to conduct more research for other watershed to know exactly the amount for of soil and nutrient loss.

Keywords: *Soil loss, Soil Fertility , GIS and Remote Sensing, RUSLE, Sebeya Catchement.*

I. INTRODUCTION

The impact of water or wind on soil particles leads to gradual soil deterioration, according to FAO (2019). The global issue of soil erosion caused by cultivated fields has an impact on reservoir capacity, soil fertility, and water quality (Bhandari et al., 2021).

According to Moland Keesstra et al. (2012), erosion is regarded as one of the most widespread human-caused causes of land degradation. It has an effect on crop yields, threatens the soil system, and threatens the sustainability of human societies. As a result, the significance of soils in achieving the United Nations' Sustainable Development Goals (Keesstra et al., 2016). According to Garcia-Daz et al., erosion decreases soil fertility and biodiversity, reduces the thickness of the soil layer most beneficial to plant growth, and results in the loss of nutrients. 2017; Li and other, 2016).

More than 745 thousand hectares of potential agricultural land are eroded annually in Rwanda. Using the reference year 2021A, more than 3 million tons (six million tons annually) of crop produce are expected to be lost each season, with severe erosion affecting 22,000 tons of maize and 15,000 tons of beans. Each season, severe erosion results in a total economic loss of 37.9 billion Rwandan francs (RWf) in agricultural productivity (RWB, 2022).

The crop productivity loss results in a loss of approximately 37.9 billion RWf (5.5 percent) of the agricultural sector's contribution to Rwanda's GDP in the first quarter of 2021 (RWB, 2021). In terms of GDP, GDP was estimated to be 2,579 billion RWf at current market prices in the first quarter of 2021 (NISR, 2021).

This study aims to estimate and mapping the potential soil erosion risk using RUSLE model for the sebeya watersheds located in Western Part of Rwanda and replacement costs to determine the value of lost soil nutrients.

II. MATERIALS AND METHODS

- *Study Site*

Sebeya is in Lake Kivu's Level 1 catchment, which is a Level 2 catchment. Sebeya is one of the parts of the Congo River basin that is most upstream. It is on the western (Congo River) side of the Congo-Nile divide.

The total area of Sebeya is 336.4 km2, or 1.4% of Rwanda's total surface area (26,338 km2). The catchment is traversed by the 48-kilometer Sebeya River, which originates in the mountains at 2,660 meters above sea level and empties into Lake Kivu at the town of Rubavu (1,470 meters above sea level). The catchment's elevation ranges from 1,460-2,000 masl in the western part to 2,000-2,220 masl in the center, and from there quickly rises to 2,950 masl on the steep eastern side. (MoE, 2018)

- *Soil Erosion Modelling*

To evaluate soil erosion, a number of empirical and physical models are available. Because they were made for specific uses, some models that are useful in one area may not be useful in other areas. Assessing soil loss from agricultural fields under specific conditions is made possible by the Universal Soil Loss Equation (USLE) (Wischmeier and Smith, 1965). Through modified versions such as RUSLE, it has been adapted to other conditions (Merrittet al. 2003) to estimate sediment yield.

The most widely used erosion method is the RUSLE, which uses the parameters of soil erosion to predict the average annual loss of soil. Based on five parameters, the RUSLE determines the average annual soil loss in tons per hectare:

A = R, K, LS, C, and P), where:

In practice, the units chosen for K and the period chosen for Rare chosen so that A is defined in tons/acre/year or tons/ha/year. A is the calculated spatial and temporal average soil loss per unit area.

R is the rainfall erosion index multiplied by a factor accounting for any significant snowmelt runoff.

K = soil erodibility factor

S is the ratio of soil loss from a 9% slope to soil loss from the field slope gradient under otherwise identical conditions. C is the cover-management factor. P is the support practice factor

- *R Factor*

R factor was calculated using the following formula: R =47.5+0.38*P Where, R=rain erosivity (joules m-2); P=annual rainfall (mm year-1).

- *The Topographic Factor*

The L and S factors represent the effects of slope length (L) and slope steepness (S) on the erosion of a slope. The combination of the two factors is commonly called the “topographic factor.” The L factor is the ratio of the actual horizontal slope length to the experimentally measured slope length of 22.1m. The S factor is the ratio of the actual slope to an experimental slope of 9%. The L and S factors are designed such that they are one when the actual slope length is 22.1 and the actual slope is 9%. Accurately calculating the LS factor turns out to be something of an art. It requires that the user pay close attention to gathering good empirical data about the landscape and choosing an appropriate method of calculating LS (of which there are many). Readers might be interested in reading which provides a very high-level overview of the common problem of miscalculating the topographic factor from DEMs in GIS software. The topographic factor was calculated using the following formula LS = (Flow accumulation X Cell size/22.13)0.4 X (sin slope/0.0896)$^{1.3}$

- *K Factor*

To construct the soil erodibility map of the Sebeya basin, a lookup table is made using ArcGIS's joining attribute table methods to connect the K values of the acquired Table to the attribute table of the soil map shape file. The DSMW database is used to create the soil map shape file for the Sebeya basin. The shape file is transformed into a raster with a 30 m cell size using the "Feature to Raster" conversion function in the Arc Toolbox. According to Fayas et al. 2019; Thakuri and others' 2019 3-7 Equations, this factor is determined as follows:

K = ƒcsand x ƒcl-si x ƒorgc x ƒhisand
ƒcsand = (0.2+0.3 x exp-0.256 x ms (1- msilt/100))
ƒcl-si = (msilt/(mc + msilt) 0.3
ƒorgc = (1 – 0.25 x orgc + exp3.72-2.95 x orgc)
ƒhisand = 1-(0.7 x (1-ms/100) / (1-ms/100)) + exp-5.51 + 22.9 x (1-ms/100))

K is the erodibility factor, while Ms, Msilt, Mc, and Orgc represent the percentages of sand, silt, clay, and organic matter, respectively (FAO, Harmonize soil database, 2019).

- *C Factor*

C is the crop/vegetation and management factor. It is used to determine the relative effectiveness of soil and crop management systems in terms of preventing soil loss. The C factor is a ratio comparing the soil loss from land under a specific crop and management system to the corresponding loss from continuously fallow and tilled land. The main land use types and respective C values considered in this study are: Cropland (0.5), forestland (0.01), grassland (0.1) and settlement (0.001).

- *P Factor*

P is the support practice factor. It reflects the effects of practices that will reduce the amount and rate of the water runoff and thus reduce the amount of erosion. The P factor represents the ratio of soil loss by a support practice to that of straight-row farming up and down the slope. The most commonly used supporting cropland practices are cross-slope cultivation, contour farming and strip cropping. P values was estimated at 0.6 considering that in the area at least farmer practice contour cropping system. Slope classes considered were I) Low (0-2t/ha/year), ii) Moderate (2-9t/ha/year) and High (>9t/ha/year).

➢ *Soil Erosion Valuation*

Clark describes the replacement cost technique for valuing the effect of erosion (1996). This is based on the cost of replenishing lost soil nutrients with synthetic fertilizers; it may also include the expense of physically reintroducing eroded silt back into the soil. Soil loss value will be based on the cost of replenishing soil nutrients washed away depending on the soil's N, P, and K content. The Rwanda soil map database will be used to identify soil profiles and their nutrient content that were identified in the watershed. The average N, P, and K content was used to predict the amount of soil loss in the watershed that will be carried away.

III. RESULTS AND DISCUSSION

➢ *Soil Loss Quantification*

All the five parameters that determine soil loss caused by water erosion (cover management, Precipitation factor, topographic factor, and soil erodibility factor and support practices against erosion) are described in this part of the work with their analysis and interpretation.

➢ *R_Factor*

The Fig.1 here presented defines the soil erosivity factor and its contribution when determining the amount of soil loss in the studied watershed area.

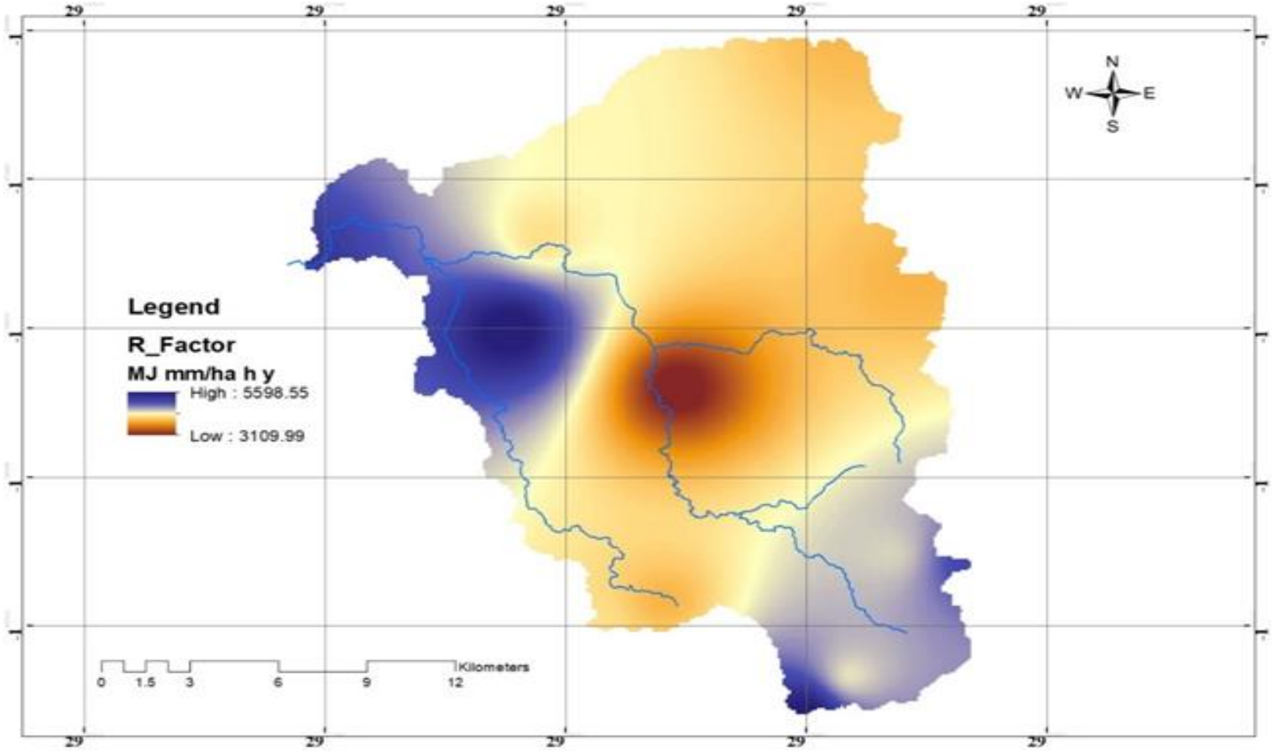

Fig 1 R Factor

The Figure 1 above shows the precipitation amount in Sebeya watershed. As presented in the figure, high rain is observed in North – Western and South – eastern parts of Sebeya watershed with an estimated erosivity factor closer to 5,598.55 MJ mm/ha h y; while low quantity of rain is met in the central point of the watershed with an estimated rainfall factor closer to 3,109.99 MJ mm/ha h y. this explains the variability of rainfall in sebeya watershed area which is one of the big factors of soil erosion in one hand and climate change in the other hand.

➢ *K Factor*

The illustrated map (Fig 2) represents the soil erodibility factor as the main factor that influence soil erosion in the sebeya watershed.

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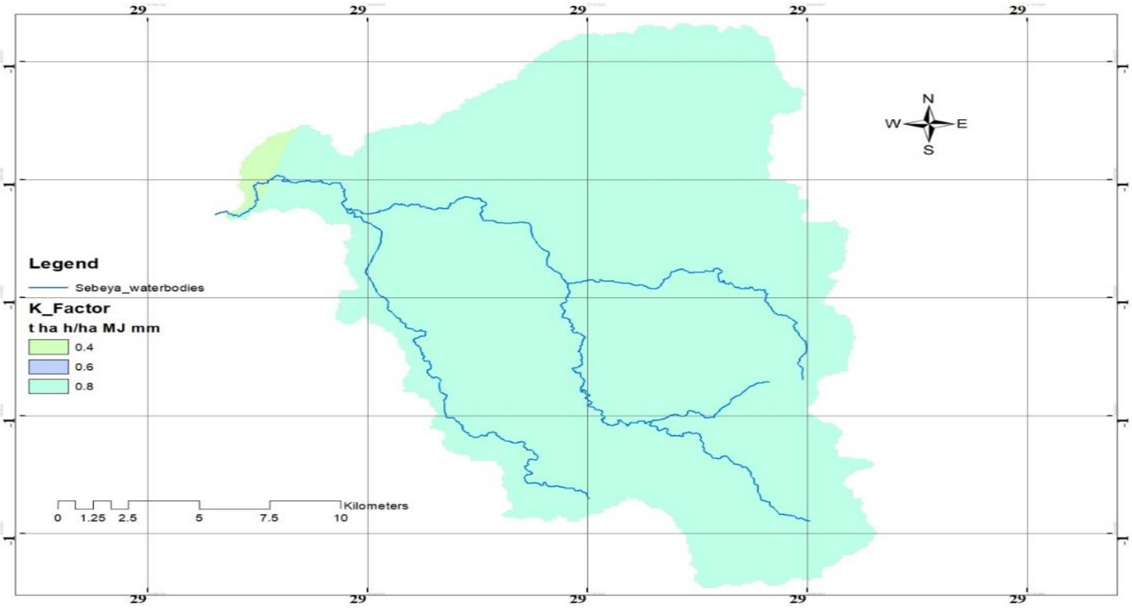

Fig 2 Soil Erodibility Factor (K)

Table 1 Sebeya Watershed Soil Composition in Percentage

Soil Type	Distribution Area (%)
Nh: Humic Nitosols	**95.45%**
Tm: Mollic Andosols	**0.11%**
L: Luvisols	**4.44%**

The illustrated image here above (fig.4) defines the Soil erodibility factor (K) as the major factor causing soil erosion. It measures the contribution of various type of soil and expresses the susceptibility of soil to erosion. As shown in the table above, three types of soil exist with a high dominancy of Humic Nitosols that cover a surface of 95.45% of the total catchment area while mollic andosol is the type of soil that cover the smallest surface of the catchment estimated of 0.11%.

According to the soil susceptibility level towards erosion, Humic Nitosol has the high susceptibility level with a K-factor estimated around 0.8 t ha h/ha MJ mm while Luvisol constitutes the sebeya catchment soil type with low level of erosion susceptibility (table 1). Based on the given result we can mention that the sebeya watershed soil type is highly susceptible to soil erosion.

- *C_Factor*

The Land use/cover factor of the sebeya watershed area is described in the given fig.3 and gives much details about its implication in soil erosion effects.

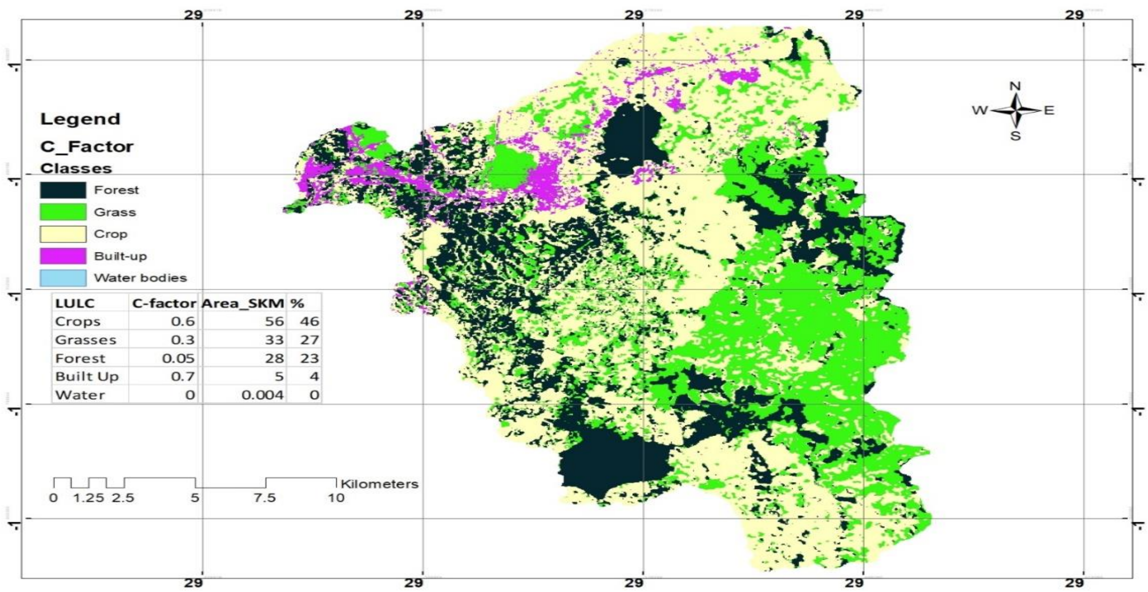

Fig 3 Land Use/Cover Factor

The land cover/use Factor (Fig.3) is a factor that contributes a lot in the definition of land vulnerability to soil erosion. It determines the importance of vegetation that covers, absorbs, limits and dissipates the splash and kinetic energy of rains and the runoff effects. The catchment LULC is made by five classes dominated by cropland and grassland with respective surface area of 56 SKM and 27 SKM while water bodies cover the smallest surface area estimated around of 0.004 SKM. According to the impact of Land cover (trees, grasses, water, forest etc) and land use (cropland, settlements, breed land) on soil loss, it is clear and obvious that the catchment is more susceptible to soil erosion because of its large area covered by cropland that has a high C-Factor estimated of 0.6 supported by the area covered by Built up on a surface of 5 SKM with the highest C-Factor of 0.7. The C-factor shown verifies that the land covered by forest (28 SKM) and Grasses (33 SKM) are two elements that prevent the most soil erosion in this catchment with their low respective C-Factor of 0.05 and 0.3. The estimated coefficient lowest values are found at areas that are highly vegetated, testifying the high land cover/use conservative effect against soil erosion by water, while cropland and settlements (Human activities) constitute the lowest covered surface.

➢ *Support Practices Factor (P)*

The Fig.4 shows the support practices against erosion used in the sebeya watershed and their efficiency in terms of soil protection.

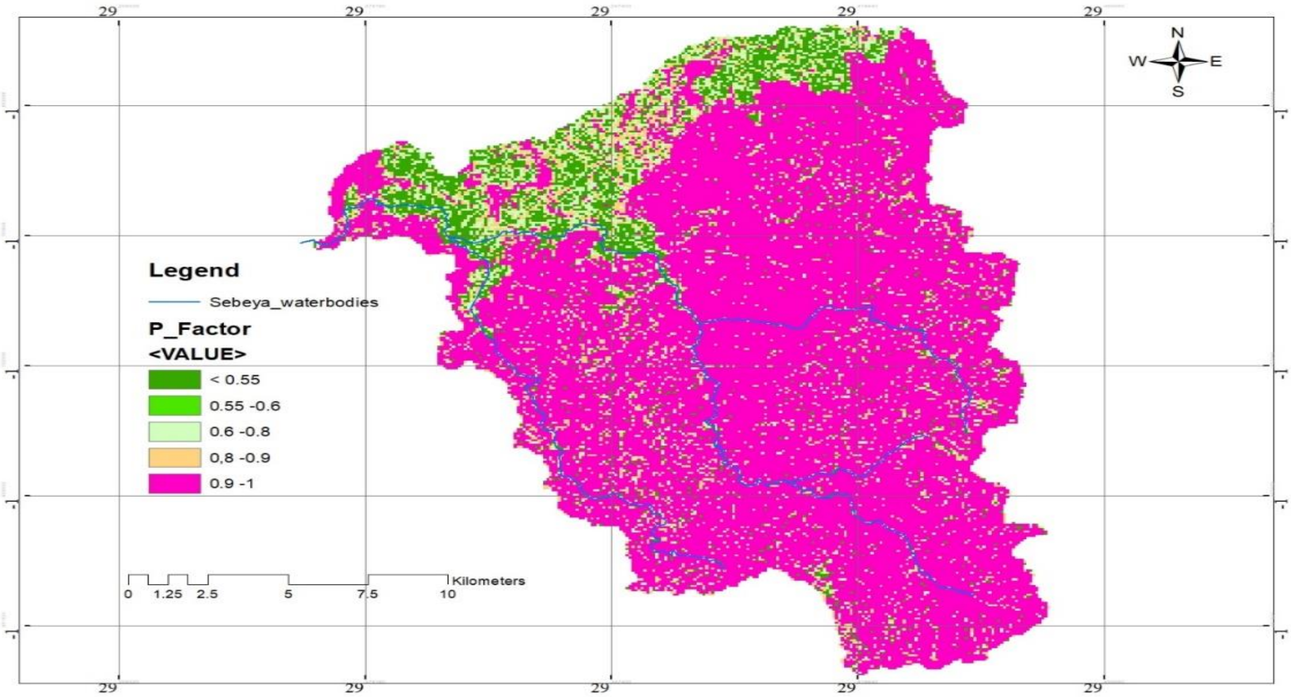

Fig 4 Human Support Practices Against Erosion

The P-factor illustrated here above (**Fig.4**) describes well the impact of manmade preventive measures against soil erosion. As seen in the figure, the large area of sebeya catchment is dominated by a P-factor varying from 0.9 to 1, which demonstrates with high precision that the erosion preventive measures are less conservative; and this justifies how much the sebeya watershed is susceptible to erosion. All the surface covered by a P-factor 0.9 to 1 has a topography > 17.26%. Only a small Northern part with a low P-factor < 0.55 is observable where the slope steepness varies between 0 to 7%; this testifies that the erosion preventive measures used in this part of the country is convenient for regions of low slope steepness.

➢ *Topographic Factor (LS)*

The fig 5 given here below determines the topographic factor as an important factor that affects highly the soil erosion in sebeya watershed.

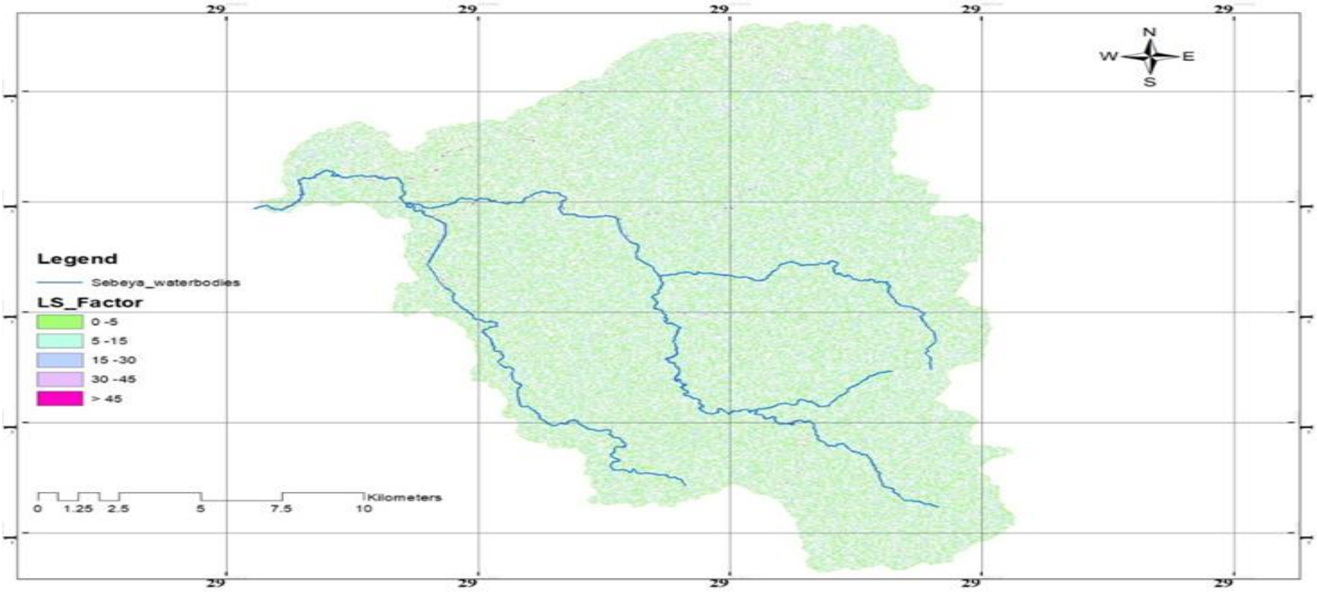

Fig 5 Topographic Factor

The illustrated LS-factor describes the steepness and elevation that define the watershed topography. As seen in the illustration, the LS-factor is grouped into five classes where the dominant LS-factor varies between 5 - 15 and 15 - 30 while the land covered by a LS-factor > 46 is less dominant. This defines a high slope steepness which implies also the catchment susceptibility to soil erosion. Based on these data, sebeya catchment should be well managed and protected by using efficient methods to limit soil loss, soil loss of nutrients such as N, P, K, etc. the fact is that the slope steepness and the slope length, so all the catchment surface must be covered by trees and grasses to prevent the splash that causes soil detachment.

- *Soil Loss* = **(A)**

The soil loss amount is estimated in the sebeya watershed is presented in the f below that figure combines the five factors.

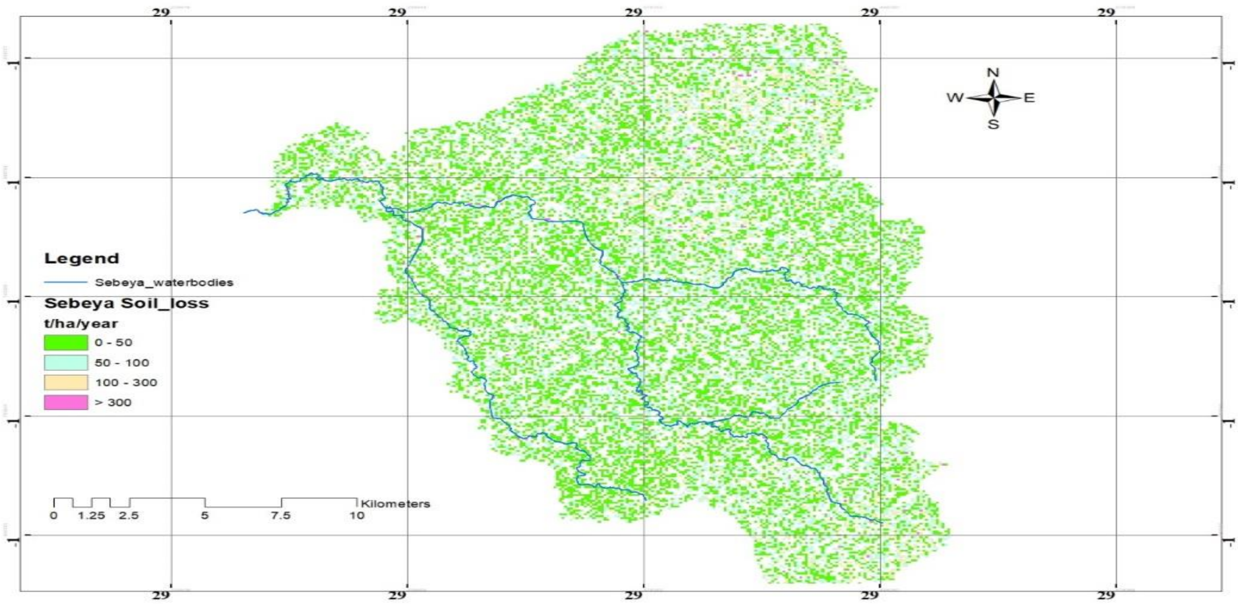

Fig 6 Soil Loss Estimation Amount

The presented figure 6 here above explains the amount of soil loss by combining all the five factors influencing soil erosion. After observation and analysis, we found that the big losses of soil in the sebeya watershed are only found on the surface covered by cropland and settlements with an estimated amount >300 t/ha/year while other part of the catchment covered by forest and grasses lose a low quantity of soil with an estimation of 0 to 50 t/ha/year. From these results we can confirm that the major cause of soil loss in sebeya catchment are human activities (Agriculture and Settlements). In average an amount of soil loss is estimated around 135t/ha/y (Table2) and has a high impact on soil loss of nutrients that in turn affects soil fertility and soil productivity.

This reconfirms that if human activities are well managed and structured respecting rules and guidelines given by responsible institutions in charge such as MINAGRI, REMA, RWB, etc the sebeya catchment that is facing large amount of soil loss each year can be protected efficiently

- *Impact of Soil Loss on Soil Fertility (Loss of Nutrients)*

The table 2 here discusses the composition of soil nutrients especially macro-elements.

Table 2 Average Nutrients Content in Sebeya Watershed

Watershed	**N (%)**	**P (Ppm)**	**K(Cmol/kg)**
Sebeya	0.378	9.051	1.205

Source: MINAGRI, Rwanda Soil Map Database 1981 and 1994

In general, the average soil composition of Nitrogen in the sebeya watershed is 0.378%, 9.051 mg/l of Phosphorous and 1,205 Cmol/kg of Potassium.

- *Estimation of the Quantity of N, P & K Nutrients Loss in the Sebeya Catchment*

The estimated soil nutrients loss in the sebeya catchment are presented in the table 3 given here below.

Table 3 Estimation of the Quantity of N, P & K Nutrients Loss in the Sebeya Catchment

	Land use / cover	**Soil loss(t/ha/year)**	**Nitrogen loss (N) (kg / ha /y)**	**Potatium loss (kg / ha / y)**	**K loss (kg / ha /y)**
Watershed Sebeya	Cropland	300	173.4	56.82	147.89
	Grassland	50	28.9	1.68	96.56
	Forestland	25	14.45	3.16	51.72
	Built up	250	144.5	0.04	0.25
	Water	0	0	0	0
	Average	**125**	**90**	**15**	**74**

Source: Our Analysis

The present table describes the quantity of soil nutrients loss in the studied watershed area. In Average Nitrogen is the nutrient of soil that is highly lost with an estimated amount of 90 kg/ha/y. the highest amount of N lost is found in cropland about 173. 4kg.ha/y while forestland loses the lowest amount of N estimated about 14.45kg/ha/y. the highest loss of nutrients amount of P and K are also observed in cropland with respective amount of 56.82kg/ha/y and 147.89kg/ha/y.

These soil nutrients losses have a huge impact on soil fertility reduction, because the soil fertility is made at 80% of these three elements (N, P and K). The mean amount of soil loss in the sebeya area (watershed) is radically estimated around 135t/ha/y and implies automatically 90 kg /ha /y of Nitrogen, 15 kg /ha /y of Phosphorus and 74 kg /ha / y of Potassium. if three or five successive years happen with the same soil loss amount the soil fertility will be lost and we'll remain with a marginal soil improper for agriculture.

- *Estimated of Nutrients Loss Amount in Terms of Rwandan Francs*

The estimated of nutrients loss from sebeya's soil in Rwandan francs are given in the table 4.

Table 4 Estimated of Nutrients Loss Amount in Terms of Rwandan Francs

	Land use/cover	**N loss (Rwf / ha / y)**	**P loss (Rwf /ha / y)**	**K loss (Rwf /ha / y)**
Watershed Sebeya	Cropland	225,760	73,970	192,500
	Grassland	37,600	2,180	125,700
	Forestland	18,800	4,100	61,300
	Built up	188,100	52	325
	Water	0	0	0
	Average	**470,260**	**80,300**	**379,800**

Given that NPK 17-17-17 costs 1302Rwf/kg, the mean amount of Nitrogen lost per year per ha (table 4) is 470,260Rwf, whereas P and K losses are 80,300Rwf and 379,800Rwf, respectively. This demonstrates how big a threat the Sebeya watershed faces in terms of destroying the soil's agricultural potential in terms of yield producing capability (loss of soil fertility).

IV. DISCUSSION

Bibliographic research indicates that, beginning in 1937, extraordinary efforts were made to control erosion in Rwanda, despite the fact that some infrastructures were abandoned and destroyed in 1962. Since 1966, the government of Rwanda has implemented a number of national programs to prevent soil erosion. However, erosion risks are still present in farmers' fields, which may be a sign of low adoption or of farmers' inability to upkeep soil erosion control infrastructures.

Ngororero District has the highest risk of soil erosion, with a total of 58,003 hectares, or 85 percent of its land, at high erosion risk. This is despite the government of Rwanda's progress in increasing soil erosion control measures. The second-highest erosion risk district is Muhanga, with 53,352 hectares at risk (82 percent of the district's land), followed by Rutsiro, with 48,143 hectares at risk (estimated at 73 percent of the district's land). Because the risk affects more than 60% of the district's land, additional districts like Karongi, Gakenke, Huye, Nyaruguru, Rulindo, and Nyamagabe require significant attention.

Today, people think that an attention to soil erosion can be given only when a visible portion of land is detached or landslides. However even when a smallest particle of soil is washed away it carries the value in it. As it has been discussed by Kabirigi et al. (2017) the impacts of soil erosion are big in crop production reduction cost, or the soil change in its physical, chemical and biological characteristics which will further results in gradual drop in its potential productivity.

A productive soil depends on the fertility of the soil. The topsoil (A-horizon) contains the majority of organic matter and approximately 50% of the potassium (K) and phosphorus (P) are available to plants. According to Gerald Miller, erosion of topsoil contributes to a decrease in potential crop yield as well as a decrease in soil fertility levels of nitrogen, phosphorus, and potassium. 2022).

The high increase of Rwanda population density associated with high dependency on agriculture of 83.4% (Gabriel et al., 2012) exerts enormous pressure on natural forests and ecosystems (Habiyaremye et al., 2011).

Unplanned occupation of land and Watersheds upstream result in severe loss, leading to a serious soil degradation (FAO, 2014). Noting that agricultural land use of 46% is dominant within the Sebeya watershed in 2022, the watershed is exposed to an average soil erosion amount of 135 t/ha/y.

The findings of this study show that, the highest quantity of soil loss and nutrients loss is observed in cropland areas with an estimation of 300t/ha/y. a high erosion amount can occur on steep slopes and heavy precipitation in cropland areas as previously defined by Karamage et al. while the risk of soil erosion in Rwanda is estimated with a mean erosion amount (421 t/ha/y) for the cropland area (Karamage et al., 2016).

The high and moderate actual erosion amounts were predefined over approximately 50% of the watershed area excluding water bodies, grasslands and forestlands (C-factor). The results of this study are different to the early data that estimated the erosion rate of 490t/ha/y for Nyabarongo River Catchment (Felix et al. 2016) where grassland and forestland had low impact on soil erosion.

Important plant nutrients like calcium, potassium, nitrogen, and phosphorus are removed from eroded soil. According to Gerald Miller, the eroded soil typically contains probably three or four times as many nutrients defined per unit weight as the remaining soil. 2022).

In general, the average soil composition of Nitrogen in the sebeya watershed is 0.578%, 15.987 mg/l of Phosphorous and 1,305 Cmol/kg of Potassium. Nitrogen is the soil nutrient that is highly lost with an estimated amount of 90 kg/ha/y. the highest amount of N lost is found in cropland about 173. 4kg.ha/y while forestland loses the lowest amount of N estimated about 14.45kg/ha/y. the highest loss of nutrients amount of P and K are also observed in cropland with respective amount of 56.82kg/ha/y and 147.89kg/ha/y.

These high losses of soil nutrients have a huge impact on soil fertility that in turn affects the agricultural productivity. To offset the loss of nutrients caused by crop production, large amounts of fertilizers are usually applied. (Troeh et al, 2004) estimated that the soil nutrients lost cost the United States agriculture billion dollars annually.

If the soil foundation is quite high, this implies that around 300 mm, and only 10 to 20 tons of soil are lost per acre each year, the lost nutrients can be restored by using livestock manure and/or commercial fertilizers. Nevertheless, the replacement technique is costly for both the farmer and the country, and most impoverished farmers cannot purchase fertilizer. Not only are fertilizer inputs dependent on fossil fuels, but these chemicals may affect human health and contaminate the land, water, and air (Pinentel al , 2013).

Through Organic Law No. 04/2005, the government of Rwanda has established measures to safeguard riverbanks and wetlands as a whole; This has necessitated the removal of agricultural crops in the 10 riparian meters and the planting of specific crops in those meters. If this law is followed, water quality would improve without water hyacinths, which would be advantageous for transportation activities, conservation of biodiversity, and tourism. The natural vegetation along the riverbanks will provide a favorable environment for fish reproduction and boost productivity

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