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Sustainability Analysis of Soil Erosion Control in Rwanda: Case Study of the Sebeya Watershed

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Abstract: Soil erosion is a complex process that results in soil and fertility losses from agricultural land and, ultimately, leads to river sedimentation. This study aimed to assess various influential factors and processes affecting soil erosion and to recommend suitable site-based Soil Erosion Control Measures (SECM) for sustainable agriculture while minimizing the downstream rivers and reservoir sedimentation in the Sebeya watershed of Rwanda. The present research used a literature review, site visits, and focus groups to assess various SECM within the Sebeya watershed. As a result, various site-based SECM were evaluated, recommended, and simulated to alleviate high soil loss rates in the Sebeya watershed using the Universal Soil Erosion Equation (USLE) model. Simulating existing and proposed SECM, soil loss was reduced significantly from 73 t/ha/y to 29 t/ha/y. To highlight the implication of the site-based recommended SECM in improving agricultural productivity, this study suggests field investigations in soil erosion plots and prediction of crop yields from an established linear correlation model between soil loss and crop yields in the Sebeya watershed. For effective action in reducing high soil erosion rates to tolerable rates in the Sebeya watershed, the present research recommends implementing the site-based recommended SECM with mulching and drainage channels on the same farmland. However, lack of money and knowledge are the main limitations in implementing SECM in the Sebeya watershed. Therefore, governmental and non-governmental organizations should technically and financially help farmers in the Sebeya watershed.

Keywords: Sebeya watershed; soil erosion causes; soil erosion effects; soil erosion control measures; crop yields; Rwanda

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1. Introduction

Globally, soil erosion threatens agricultural and environmental sustainability [1]. Approximately 99.7% of the world's food is produced by agriculture, while only 0.3% comes from aquatic ecosystems, with direct implications for adopting various soil conservation measures to protect limited land resources [2].

Water erosion is a natural geomorphologic process characterized by compaction, disintegration, detachment, transport, and deposition [3,4]. Based on its severity, water erosion can be classified into five types: splash, sheet or interrill, rill, gully, and streambank erosion [5]. Vegetation, amount and intensity of rainfall, physical and chemical properties of soil, and land topography are the main natural causes of soil erosion. In addition, human activities have been blamed for highly influencing soil erosion [6].

The degradation of soil quality (soil and nutrient losses and lower infiltration rates), and the downstream river and lake sedimentation, are the main on-site and off-site damages of water erosion. In addition, there are numerous consequences, such as food security and agricultural sustainability, water supply, reservoir storage capacity, and the ecology of freshwater bodies, that are adversely affected [7–9]. Therefore, soil erosion control is the best option for enhancing agricultural productivity while preventing river and lake sedimentation [10].

Using the USLE model to evaluate soil erosion in Rwandan level-1 watersheds between 1990 and 2015 [11], soil loss trends (t/ha/y) for the Mukungwa watershed were reported between 60 and 130; Upper Nyabarongo, between 60 and 90; Lower Nyabarongo, between 60 and 90; Kivu, between 30 and 70; Rusizi, between 50 and 60; Muvumba, between 45 and 60; Akanyaru, between 43 and 50; Upper Akagera, between 15 and 30; and Lower Akagera, between 15 and 20. In general, soil erosion rates increased between 1990 and 2015 due to deforestation for firewood, agriculture, and settlement, urbanization which has increased imperviousness, heavy rains in mountainous areas caused by climate change, and ineffective SECM.

As a level-2 watershed within Kivu level-1, the Sebeya watershed is experiencing severe soil erosion resulting from steep slopes and excessive rainfall [12]. Consequently, soil fertility has declined, and sedimentation in the Sebeya River has increased due to soil erosion. The large population accelerates this erosion. As mentioned earlier, anthropogenic erosion refers to different forms of soil erosion induced by human activity, such as deforestation to create new settlements, mining, road construction, steep slope reclamation, and firewood cutting. The Keya hydropower plant faces the challenge of difficult operation and maintenance because of an extremely large amount of sediment entering the plant with hard and abrasive minerals, especially during rainy seasons [13]. In addition, the excessive turbidity of the Sebeya River increases the coagulant consumption at the Gihira water treatment plant. It also harms the recreational and aquatic life of Lake Kivu.

There are several USLE-type models to assess and evaluate soil erosion rates [14]. Due to its simplicity, the USLE model will be used in this investigation to simulate the actual and predicted soil erosion rates within the Sebeya watershed for making suggestions and recommendations on long-term development and sustainability [15]. However, it does not include gully erosion, as it only considers sheet and rill erosion [14]. Modeling is a useful tool for assessing different scenarios associated with soil erosion, allowing the selection of the most effective SECM [16].

This study aimed to assess soil erosion's status and recommend appropriate site-based SECM for sustainable agriculture while minimizing the downstream rivers and reservoir sedimentation in the Sebeya watershed.

2. Methodology

2.1. Study Area

Located in Africa, Lake Kivu is among the East African Rift valleys. Its total surface area is 2700 km^2, at an altitude of 1460 m above sea level, and a maximum depth of about 480 m. It is shared by Rwanda and the Democratic Republic of Congo (DRC). The total number of 127 rivers flowing from the Congo Nile Crest into Lake Kivu includes the Sebeya River [17].

Situated in the Congo River Basin that flows into the Atlantic Ocean, the Sebeya watershed is one of the small watersheds draining the western slopes of the Nile Congo watershed of Rwanda between 1°50′57.15″ and 1°42′21.99″ degrees South (22.984 km) latitude and 29°23′52.04″ and 29°25′ 06.14″ degrees East (27.455 km) longitude [18].

This study is focused on the Sebeya watershed, which drains its water into Lake Kivu [19] in the Western Province of Rwanda, as presented in Figure 1. The main river flowing in this watershed is Sebeya, which originates in the mountains of the Rutsiro District. The Sebeya River runs in a north–westerly direction along 48 km from its source in the mountains of the Congo-Nile divide at an altitude of 2660 m (above mean sea level) of Gishwati forest to its outfall at Lake Kivu at an altitude of 1470 m. As shown in Figure 1, the Sebeya watershed is shared by four administrative units: Rubavu, Nyabihu, Rutsiro, and Ngororero.

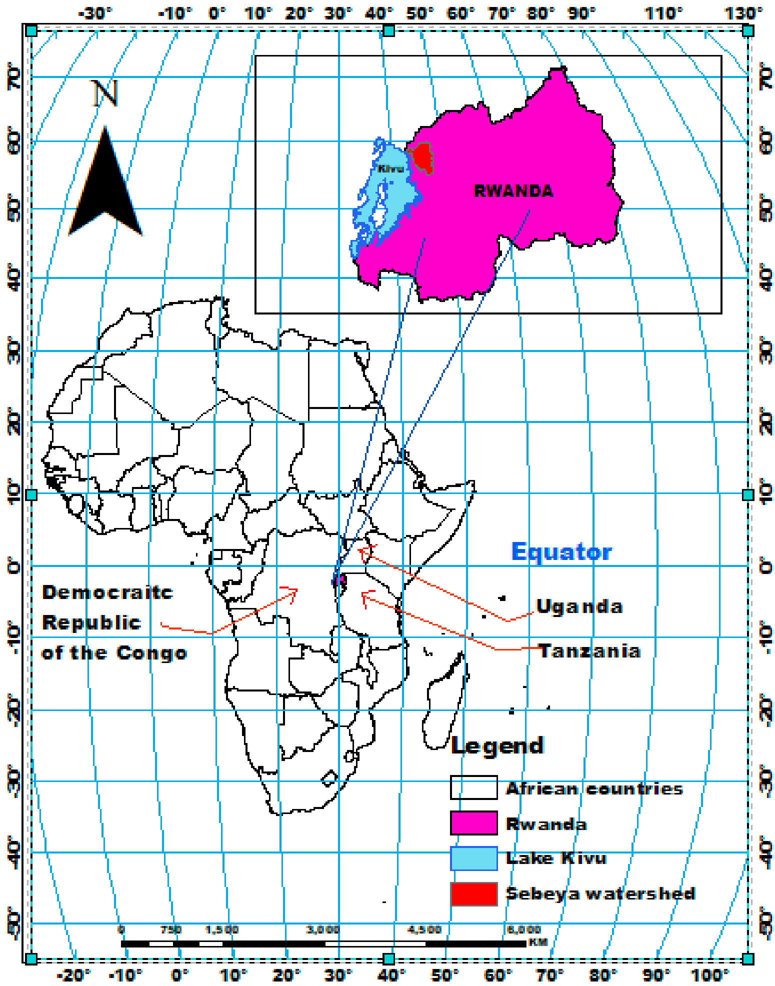

Figure 1. Sebeya watershed localization.

The Sebeya watershed covers 363.1 km^2, compared to the Rwandan territory area of 26,338 km^2 [20]. Compared to Rwanda's average population density of 415 inhabitants/km^2, the Sebeya watershed has 644 inhabitants/km^2 [12].

Butare complex and the volcanic rocks of the Virunga Mountains are two main geological formations in the Sebeya watershed, and nitosol, acricol, alisol, and lixisol are the main soil classes [12]. The clumping of the soil textural components of sand, silt, and clay forms aggregates, and the further association of those aggregates into larger units forms soil structures. The soil in this watershed favors agriculture due to its high infiltration rates and mineral content, except for the case of clay soils on flat topography.

As shown in Figure 2, the topography of the Sebeya watershed is among the mountainous chain of the Congo-Nile river divide extending north-south from the Nyungwe forest in the south to the Gishwati forest in the north. This mountainous chain divides the country into two watersheds. The watershed is characterized by steep slopes and complex topography (abrupt altitude changes at small distances).

The rainfall pattern of Rwanda is bi-modal, i.e., it has two distinct rainy seasons. A heavy rainy season (March, April, and May), and a light rainy season (September, October, November, and December). The Sebeya watershed is characterized by high rainfall (1200 mm/year and above) and a relatively short dry season in June–August. Erratic showers continue in January–February, the second dry season in the country [21]. Using rainfall data from the University of Rwanda's Center of Geographic Information Systems (UR-CGIS), the average precipitations in the Sebeya watershed in 2018 were 1187 mm, 1336 mm, 1538 mm, and 1233 mm at Tamira, Pfunda, Kanama, and Nyundo, respectively. By mapping, the rainfall distribution varies between 1187 mm and 1536 mm, while the digital display of this rainfall map indicates an average precipitation of $\overline{P}$ = 1318 mm for the Sebeya watershed (Figure 3).

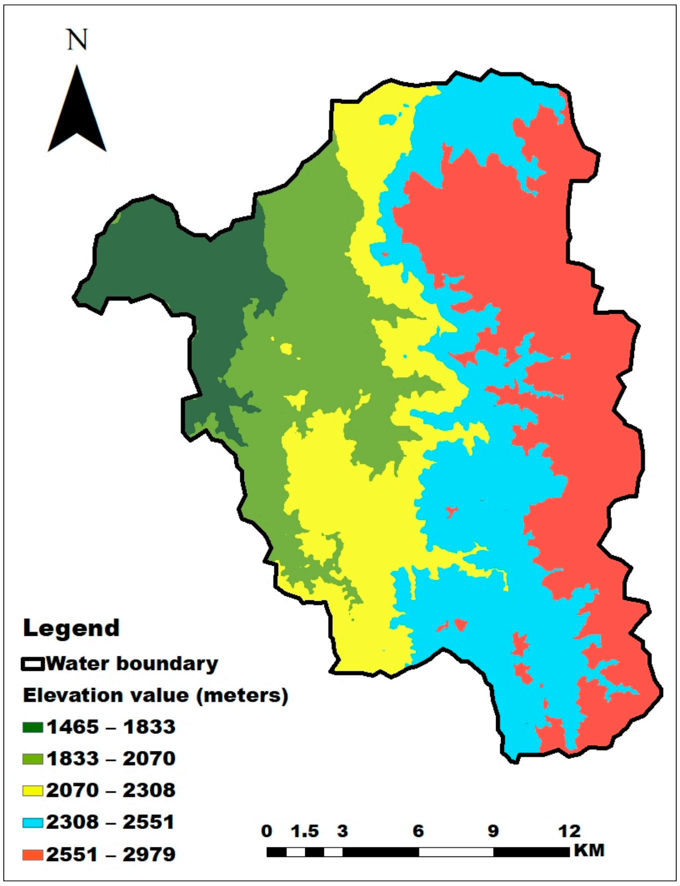

Figure 2. Sebeya watershed topographic map.

Rwanda has a climate with an average temperature of around 20 °C and low monthly variation, as the Sebeya watershed has various regions with a high elevation greater than 2000 m. In contrast, the annual average temperature is slightly lower at around 17 °C. Rwanda has a dry climate in the east (lower elevation) and a wet climate in the west (high altitude of mountains), resulting in a large and varied pattern of agro-ecological zones. This variation leads to a complicated and uncertain picture of potential changes in Rwanda's overall climate [18].

Land Use and Land Cover (LULC) are often referred to interchangeably, but they mean different things [22]. The Sebeya watershed has four major classes (settlement and buildings, cattle grazing, agriculture, and forest plantation) and several land cover types, including natural and planted forests, herbaceous crops and plants, vegetation and shrubs, waterways and reservoirs, and built-up areas. The Sebeya watershed's soil erosion is retarded by excessive trees and vegetation.

To this end, several factors accelerate water erosion in the Sebeya watershed, including its high elevation (1462–2979 m above sea level), steep topography, and excessive precipitation (1200–1700 mm) [12,23].

2.2. Data Collection

This study used government reports and journal articles to synthesize various researchers' views on the water erosion process, its causes, effects, and control in the Sebeya watershed.

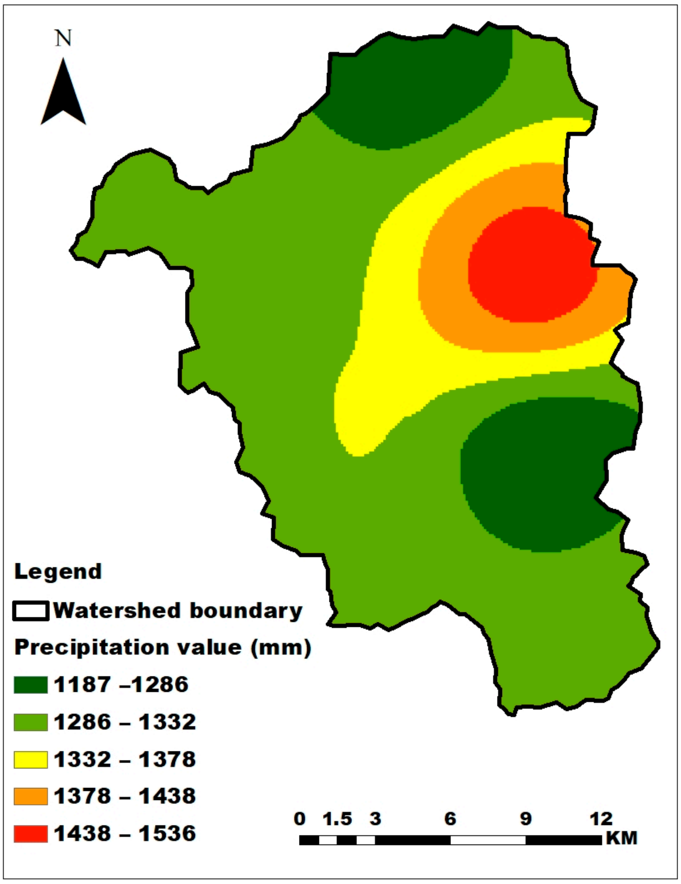

Figure 3. Rainfall map of the Sebeya watershed.

In this investigation, site visits were carried out to collect detailed information on the study area, observations of LULC, soil characteristics, the topography of the site, hydrographic network, agricultural practices, and main crops. Furthermore, monitoring of the sedimentation, water quality, and flooding issues of the Sebeya River, together with the SECM in the Sebeya watershed, was also conducted. In addition, focus group discussion was frequently organized to guess the farmers' knowledge on water erosion and its control.

The University of Rwanda's Center of Geographic Information Systems provided rainfall, soil, and topographic data for generating rainfall erosivity, soil texture, and topographic maps.

In this investigation, researchers used Landsat images [24] acquired in September 2008, September 2015, August 2018, and September 2022 to assess the LULC's influence on water erosion in the Sebeya watershed.

In order to determine high-risk erosion areas already affected by erosion features (gullies, landslides, rill erosion), the National Institute of Statistics of Rwanda (NISR) used World View images of 30 to 50 cm resolution. As a result, existing SECM were identified, unprotected areas visualized, and future site-based SECM to eradicate high soil erosion rates recommended based on this knowledge and judgment [25]. In July 2018, NISR [25] developed a Rwandan soil erosion risks map and proposed erosion prevention measures. The Ministry of Environment (MoE) is using the "Catchment Restoration Opportunity Mapping" (CROM) model created by the Environmental Systems Research Institute (ESRI) Rwanda Ltd. to classify soil erosion risks in Rwanda (Table 1). Advantageously, the study took this opportunity to collect different shapefiles for the existing and site-based recommended SECM from the Rwanda Water Resources Board (RWB).

Table 1. Classification of erosion risks in Rwanda [25].

Soil loss (t/ha/y)	<5	5–10	10–25	25–50	50–100	>100
Risk severity	very low	low	moderate	high	very high	extremely high

The following five steps explain the adopted procedures for determining the five USLE parameters to estimate soil erosion rates A (t/ha/y), using the USLE model defined with its five parameters as [26]:

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

Step 1: Determining R factor for the Sebeya watershed

If $\overline{P}$(mm) denotes the average precipitation, the value of R factor [27] can be estimated by the following formula recommended by Khare et al. [28]:

$$R = 81.50 + 0.38\overline{P} \quad (2)$$

From the spatial distribution of rainfall (Figure 3), the average precipitation in the Sebeya watershed may be estimated as $\overline{P}$ = 1318 mm. Using Equation (2), the induced R factor for the Sebeya watershed can be averaged as 582.34 MJ × mm/h/y.

Step 2: Determining K factor for the Sebeya watershed

Varying from 0 to 1 [29], Table 2 illustrates the erodibility of the soil texture throughout the literature.

Table 2. Typical values of the soil erodiblity (K) for different soil types.

Soil Type	K	References
Silty loam soil	0.05	[30]
Loamy soil	0.30	[31]
Clay	0.22	[31]
Sand clay loam	0.20	[31]
Clay loam	0.31	[31]
Sandy loam soil	0.23	[32]
Sand	0.05	[33]
Silt	0.35	[34]

Step 3: Determining LS factor for the Sebeya watershed

The slope length factor LS can be determined using field erosion plots [34]. More practically, if A_s (m/m width) denotes the upstream area, β the inclination angle (radian), and "m" and "n" the coefficients, many researchers [35] suggested using the following equation to estimate the slope length factor:

$$LS = \left(\frac{A_s}{22.13}\right)^m \times \left(\frac{\sin\beta}{0.0896}\right)^n \quad (3)$$

Using Equation (3), Figure 4 shows that the results vary from 0 to 470.882, with an average value of LS of 5.737 (dimensionless).

Step 4: Determining C factor and P factor associated to various LULC types in the Sebeya watershed

Table 3 displays typical values of C and P recommended by various researchers for different LULC types.

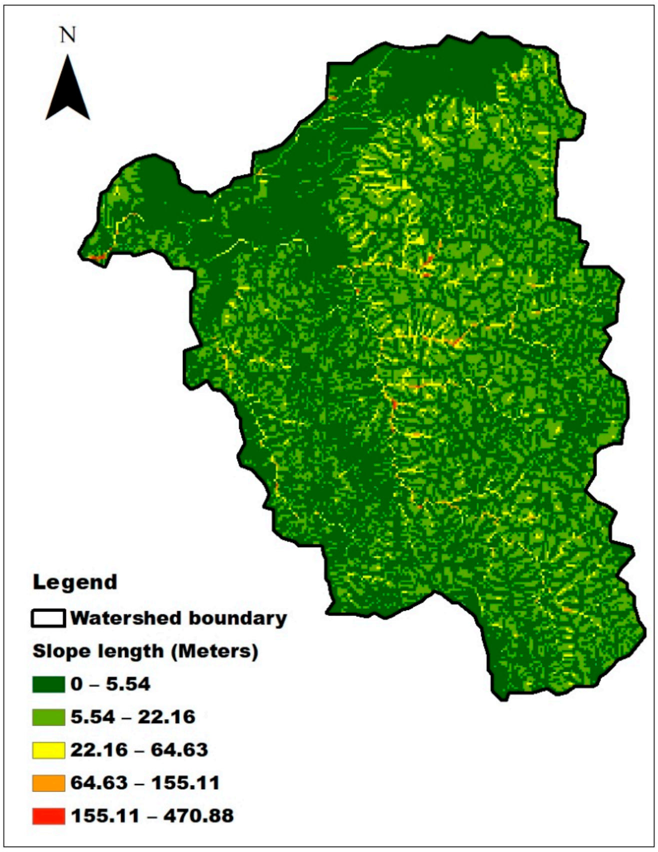

Figure 4. Slope length factor map.

Table 3. Crop management factor (C) and erosion control factor (P) for different land use/land cover types.

S.N.	LULC	C	References	P	References
1	Built-up	0.200	[15]	0.500	[36]
2	Closed agriculture	0.340	[15]	0.001	[37]
3	Forest plantation	0.020	[36]	0.300	[36]
4	Irrigation	0.340	[15]	0.500	[36]
5	Natural forest	0.008	[36]	0.001	[37]
6	Open agriculture	0.340	[15]	0.020	[38]
7	Open land	0.340	[15]	0.500	[36]

Step 5: Determining C factor and P factor for various SECM in the Sebeya watershed

C factor measures the implication of crop cover and BMPs in controlling soil erosion [39]. In this simulation, Table 4 exhibits different values of C proposed by various researchers throughout the literature.

The erosion control factor (P) measures the implication of SECM, BMPs, and cropping patterns in decreasing soil erosion [16,31]. It varies from 0 to 1 in the cases of water bodies and efficient soil conservation practices on farmlands [40]. Throughout the literature, Table 4 reveals typical values of P factors for different SECM to alleviate the excessive erosion rates in the Sebeya watershed.

Finally, this study intended to predict the efficiency of the site-based recommended SECM in increasing crop yields. Similar to the existing literature [52], the largest soil loss can be fixed at x_2 = 137 t/ha/y, while the maximum soil loss tolerance, x_1 = 11.5 t/ha/y, can be considered as the lowest observable soil loss rate. Based on the minimum crop yield from all Rwandan districts and the maximum crop yield from the four districts overlapping the

Sebeya watershed [53], Table 5 displays the ranges of crop yields assumed at the minimum and maximum soil losses (x_1 = 11.5 and x_2 = 130 t/ha/y) in the Sebeya watershed.

Table 4. Crop management factor (C) and erosion control factor (P) for different soil erosion control measures.

SN	Recommended SECM	C	References	P	References
1	Afforestation	0.02	[36]	0.001	[41]
2	Agroforestry	0.08	[42]	0.500	[43]
3	Bamboo to close gullies	0.01	[44]	0.500	[45]
4	Bench terraces	0.15	[44]	0.128	[46]
5	Contour bank terraces	0.15	[44]	0.150	[46]
6	Contour banks	0.50	[47]	0.600	[46]
7	Grassed waterways	0.20	[44]	0.100	[48]
8	Hedgerows	0.20	[44]	0.000	(*)
9	No-till	0.25	[42]	0.100	[48]
10	Perennial crops	0.23	[42]	0.800	[49]
11	Reforestation	0.02	[36]	0.001	[41]
12	River side bamboo	0.01	[44]	0.500	[45]
13	Silvopastoralism	0.09	[42]	0.000	(*)
14	Rainwater harvesting tanks	0.00	(*)	0.800	[50]
15	Drainage channels	0.58	[51]	0.800	[50]
16	Dense forest and water bodies	0.00	(*)	0.000	(*)

* Similar to dense forest or water body.

Table 5. Possible ranges of crop yields in the Sebeya watershed [53].

Crops	y_2 = Lowest Yield (t/ha)	y_1 = Highest Yield (t/ha)
Maize	0.776	2.154
Irish potatoes	4.000	15.000
Beans	0.700	1.000
Soybeans	0.575	0.875
Wheat	0.437	2.154
Peas	0.367	1.438
Groundnut	0.260	1.495
Sweet Potatoes	3.856	13.246
Banana	3.500	11.038

2.3. Data Analysis

Various soil erosion indicators, causes, and effects were identified and assessed based on the existing literature, site observations, and focus groups.

This research used Landsat images acquired in 2008, 2015, 2018, and 2022 to compare and find out how two or more different scenarios of LULC affect water erosion in the Sebeya watershed. Studies of soil erosion dynamics using sequential aerial photographs and remote sensing techniques, in combination with LULC analyses, have revealed a positive change of 54% from 1990 to 2015, indicating a significant increase in soil erosion on the Rwandan landscape [11].

The actual water erosion rates were estimated using different shapefiles obtained from the Rwanda Water Resources Board on the nature and efficiency of existing SECM in the Sebeya watershed.

Predicting water erosion rates using the USLE model has allowed assessment of the impact of LULC on soil erosion and deducing the efficiency of the site-based recommended SECM in the Sebeya watershed. Correlatively, crop yields were predicted using a linear relationship between soil losses and crop yields. USLE parameters were adopted referring to the previously-published studies and USLE parameters mapping. Analyzing data in figures and tables was done using ArcGIS map and Microsoft Excel.

3. Results

3.1. Hydrological Processes in the Sebeya Watershed

The main hydrologic parameters affecting water erosion within a watershed are precipitation, interception, infiltration, runoff, soil moisture changes, groundwater storage changes, and river flows. When rain falls, it causes soil detachment and transport by raindrop splashes or runoff. The complexity of erosive processes depends on many factors, such as soil type, slope, terrain size, LULC, and solar radiation within the watershed [54]. Figure 3 exhibits the spatial distribution of rainfall, while Figure 5 illustrates the rainfall patterns within the Sebeya watershed at Gisenyi airport station. The yearly precipitations in the Sebeya watershed are known to induce high water erosion rates [55].

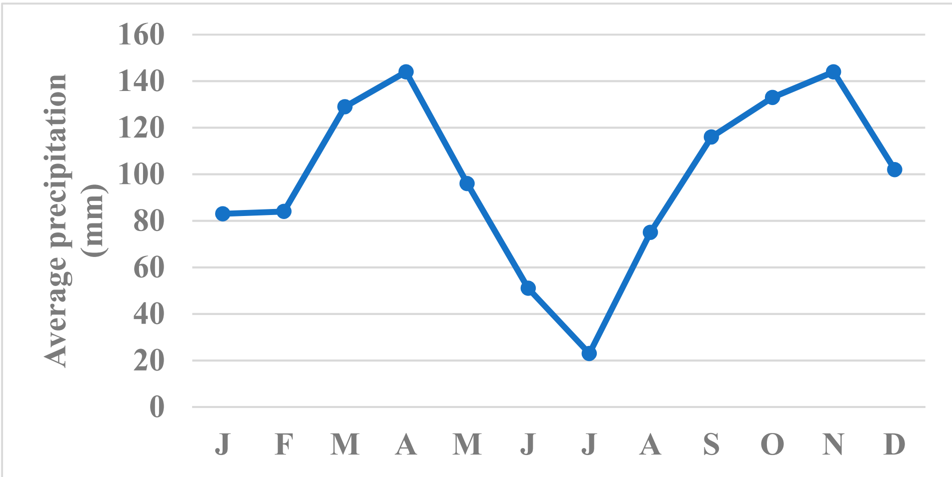

Figure 5. Typical monthly precipitations at Gisenyi airport station [55].

3.2. Impact of LULC on Water Erosion in the Sebeya Watershed

Due to its multiple effects on soil, land cover contributes to soil erosion control by decreasing the direct impact of raindrops, increasing organic matter, raising infiltration rates, and decreasing the runoff velocity, while controlling the sediment transport and yield.

In most developing countries like Rwanda, demographic pressure and associated demand for human activities have been the major cause of LULC changes [56–58]. Therefore, it is particularly important to pinpoint the aspects causing LULC changes in the Sebeya watershed. Figure 6 shows LULC detection in the Sebeya watershed for four years (2008, 2015, 2018, and 2022), while Tables 6 and 7 reveal the percentage of area covered by each LULC type.

Table 6. Area covered by each land use/land cover type in the Sebeya watershed (2008 and 2015).

SN	LULC Type	Covered Area in 2008		Covered Area in 2015	
		(km^2)	(%)	(km^2)	(%)
1	Built-up	6.96	1.92	10.97	3.02
2	Closed agriculture	4.97	1.37	107.31	29.51
3	Forest plantation	34.91	9.61	33.75	9.28
4	Irrigation	5.52	1.52	16.30	4.48
5	Natural forest	4.16	1.14	6.01	1.65
6	Open agriculture	224.40	61.75	37.71	10.37
7	Open land	82.45	22.69	151.63	41.69
Total		363.38	100.00	363.38	100.00

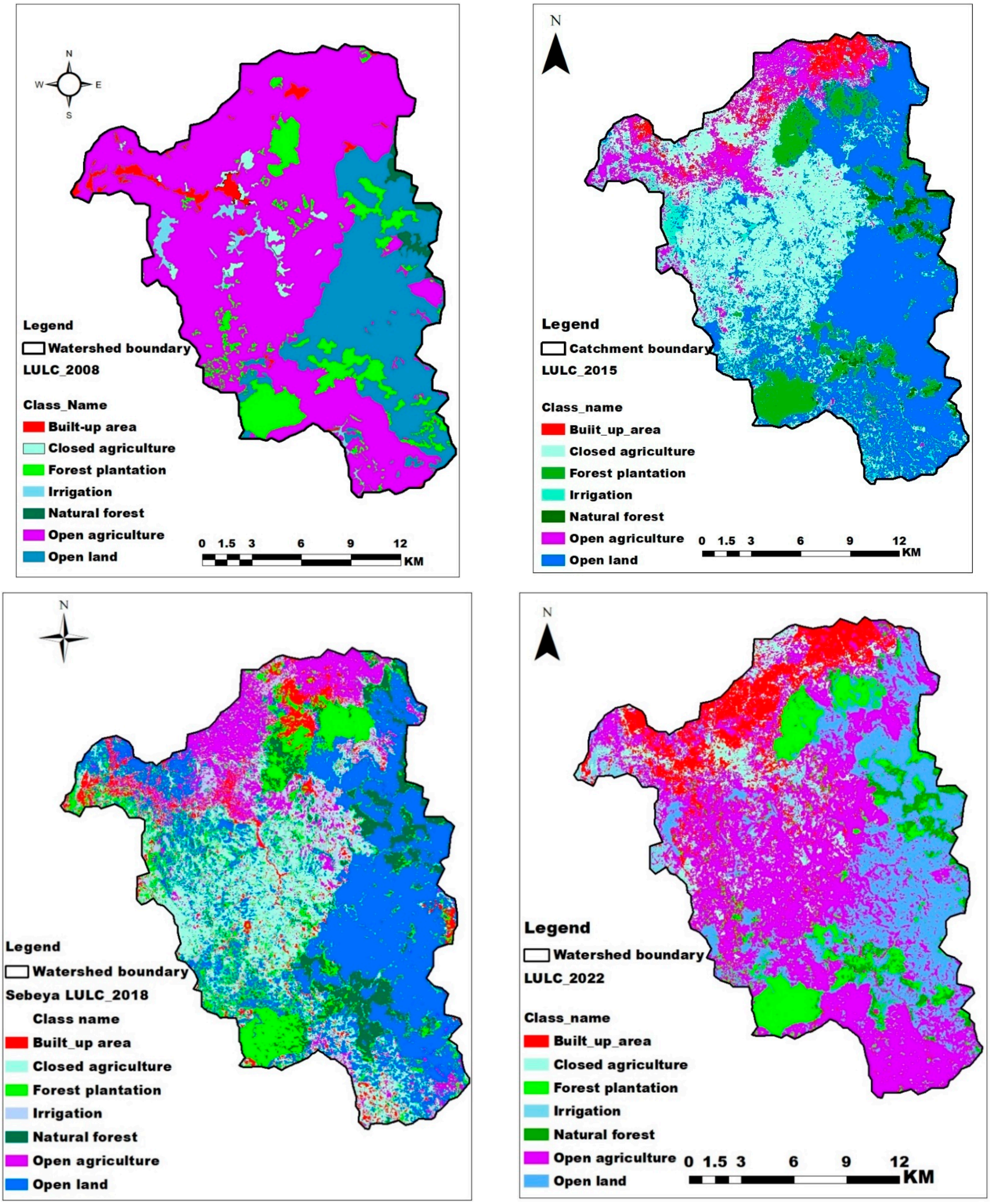

Figure 6. Land use/land cover detection for 2008, 2015, 2018 and 2022 in the Sebeya watershed.

Table 7. Area covered by each land use/land cover type in the Sebeya watershed (2018 and 2022).

SN	LULC Type	Covered Area in 2018		Covered Area in 2022	
		(km^2)	(%)	(km^2)	(%)
1	Built-up	11.38	3.13	39.64	10.90
2	Closed agriculture	0.05	0.01	22.51	6.19
3	Forest plantation	55.57	15.28	35.54	9.77
4	Irrigation	7.96	2.19	16.62	4.57
5	Natural forest	13.58	3.74	11.67	3.21
6	Open agriculture	185.63	51.04	147.38	40.52
7	Open land	89.50	24.61	90.32	24.84
Total		363.38	100.00	363.38	100.00

These results on LULC detection in the Sebeya watershed revealed that LULC change in the study area primarily comprised a decrease in open agriculture area, accompanied by an increase in closed agriculture, built-up area, and open land (Table 6). Tables 6 and 7 show that the land in the Sebeya watershed is mostly used for agriculture with seasonal crops in an area of about 53.4% (2008: 64.6%; 2015: 44.4%; 2018: 53.2%; 2022: 51.3%). This status of LULC exposes the land to splash erosion, and further detachment as the land is not permanently covered. Forests with high canopy density occupy an area of only about 2.4% (2008: 1.1%; 2015: 1.7%; 2018: 3.7%; 2022: 3.2%), and comparatively, built-up areas occupy about 4.7% (2008: 1.9%; 2015: 3.0%; 2018: 3.1%; 2022: 10.9%) of the total area of the Sebeya watershed (363.4 km^2). Therefore, the Sebeya watershed's land will continue to be eroded if no serious measures are taken in agricultural lands. In addition, built-up areas accelerate water velocity, runoff, and flow accumulation, creating severe gullies downstream. In such areas, stormwater management facilities, such as rainwater harvesting infrastructures and drainage channels, should be established to collect stormwater from houses in agglomerated zones.

Table 8 illustrates the adopted procedures for assessing soil erosion rates A (t/ha/y) induced by LULC, using the USLE model defined with its five parameters by Equation (1).

The results on LULC detection in the Sebeya watershed (Table 8 and Figure 7) revealed that soil erosion increased from 65 t/ha/y (2008) to 112 t/ha/y (2015) due to deforestation for firewood and shelter, urbanization, intense rainfall (climate change) in mountainous areas, over-cultivation, and the lack of SECM. Comparatively, the decreased soil erosion rates from 112 t/ha/y (2015) to 100 t/ha/y (2018) and from 100 t/ha/y (2018) to 87 t/ha/y (2022) are attributed to the particular attention paid to implementing SECM in different Rwandan watersheds and particularly in the Sebeya watershed, including afforestation, land consolidation, anti-erosive ditches and terraces programs [11].

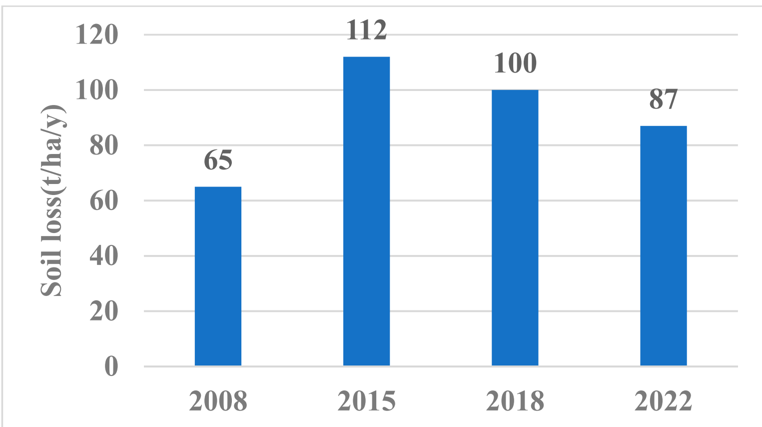

Figure 7. Historical variation of soil erosion rates induced by the land use/land cover in the Sebeya watershed.

Table 8. Effect of land use/land cover on water erosion within the Sebeya watershed in 2008, 2015, 2018 and 2022.

S.N.	LULC type	K	R	LS	C	P	Soil loss Ai (t/ha/y)	Covered area ai (ha)	Weighted (Ai × ai)
(a) Erosion rates induced by the land use/land cover in 2008									
1	Built-up	0.405	582.34	5.73	0.200	0.500	135.141	696	94,057.95
2	Closed agriculture	0.405	582.34	5.73	0.340	0.001	0.459	497	228.36
3	Forest plantation	0.405	582.34	5.73	0.020	0.300	8.108	3491	28,306.58
4	Irrigation	0.405	582.34	5.73	0.340	0.500	229.739	552	126,816.10
5	Natural forest	0.405	582.34	5.73	0.008	0.001	0.011	416	4.50
6	Open agriculture	0.405	582.34	5.73	0.340	0.020	9.190	22,440	206,213.90
7	Open land	0.405	582.34	5.73	0.340	0.500	229.739	8245	1,894,200.00
Total								36,337	2,349,827
Average soil loss is 2,349,827/36,337 = 65 t/ha/y									
(b) Erosion rates induced by the land use/land cover in 2015									
S.N.	**LULC type**	**K**	**R**	**LS**	**C**	**P**	**Soil loss Ai(t/ha/y)**	**Covered area ai (ha)**	**Weighted (Ai × ai)**
1	Built-up	0.405	582.34	5.73	0.2	0.5	135.1407	1097	148,203.90
2	Closed agriculture	0.405	582.34	5.73	0.34	0.001	0.459478	10,731	4930.81
3	Forest plantation	0.405	582.34	5.73	0.02	0.3	8.108444	3375	27,365.38
4	Irrigation	0.405	582.34	5.73	0.34	0.5	229.7392	1630	374,369.20
5	Natural forest	0.405	582.34	5.73	0.008	0.001	0.010811	601	6.49
6	Open agriculture	0.405	582.34	5.73	0.34	0.02	9.18957	3771	34,658.22
7	Open land	0.405	582.34	5.73	0.34	0.5	229.7392	15,163	3,483,612.00
Total								36,368	4,073,146
Average soil loss is 4,073,146/36,368 = 112 t/ha/y									
(c) Erosion rates induced by the land use/land cover in 2018									
S.N.	**LULC type**	**K**	**R**	**LS**	**C**	**P**	**Soil loss Ai (t/ha/y)**	**Covered area ai (ha)**	**Weighted (Ai × ai)**
1	Built-up	0.405	582.34	5.73	0.200	0.500	135.141	1991	269,084.10
2	Closed agriculture	0.405	582.34	5.73	0.340	0.001	0.459	8003	3673.51
3	Forest plantation	0.405	582.34	5.73	0.020	0.300	8.108	5203	42,187.51
4	Irrigation	0.405	582.34	5.73	0.340	0.500	229.739	1474	338,545.40
5	Natural forest	0.405	582.34	5.73	0.008	0.001	0.011	2710	29.81
6	Open agriculture	0.405	582.34	5.73	0.340	0.020	9.190	4167	38,294.22
7	Open land	0.405	582.34	5.73	0.340	0.500	229.739	12,818	2,944,847.00
Total								36,366	3,636,661
Average soil loss is 3,636,661/36,366 = 100 t/ha/y									
(d) Erosion rates induced by the land use/land cover in 2022									
S.N.	**LULC type**	**K**	**R**	**LS**	**C**	**P**	**Soil loss Ai (t/ha/y)**	**Covered area ai (ha)**	**Weighted (Ai × ai)**
1	Built-up	0.405	582.34	5.73	0.2	0.5	135.1407	3964	535,700.30
2	Closed agriculture	0.405	582.34	5.73	0.34	0.001	0.459478	2251	1034.41
3	Forest plantation	0.405	582.34	5.73	0.02	0.3	8.108444	3554	28,817.55
4	Irrigation	0.405	582.34	5.73	0.34	0.5	229.7392	1662	381,821.00
5	Natural forest	0.405	582.34	5.73	0.008	0.001	0.010811	1167	12.61
6	Open agriculture	0.405	582.34	5.73	0.34	0.02	9.18957	14,738	135,435.50
7	Open land	0.405	582.34	5.73	0.34	0.5	229.7392	9032	2,075,074.00
Total								36,368	3,157,895
Average soil loss is 3,157,895/36,368 = 87 t/ha/y									

3.3. Estimating the Actual Soil Erosion Rates in the Sebeya Watershed

Using different shapefiles obtained from the Rwanda Water Resources Board, Figure 8 shows various existing SECM and the spreading of erosion rates in the Sebeya watershed. Finally, Table 9 indicates that about 73 t/ha/y of soil is lost from the Sebeya watershed annually.

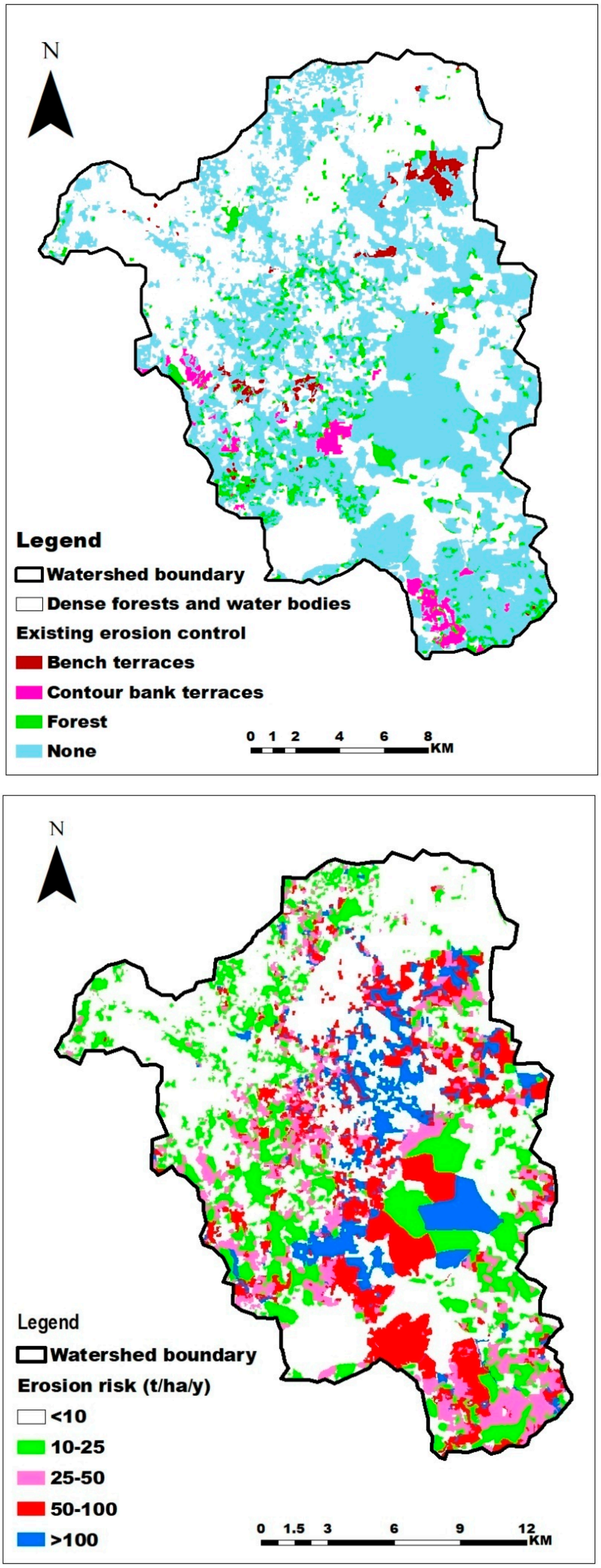

Figure 8. Existing soil erosion control measures and soil loss ranges in the Sebeya watershed [59].

Table 9. Existing soil erosion control measures and their induced soil loss rates in the Sebeya watershed [59].

(a) Existing SECM			(b) Calculation of the Actual Soil Loss				
Existing SECM	**Area Covered (ha)**	**%**	**Erosion Risk (t/ha/y)**	**Peak Value Ai (t/ha/y)**	**Coverage ai (ha)**	**% of Area Covered**	**Weighted Value (Ai × ai)**
None	15,319	42	<10	10	18,009	50	180,087
Forest	1959	5	25-Oct	25	6936	18	173,408
Contour bank terraces	606	2	25–50	50	3484	10	174,195
Bench terraces	442	1	50–100	100	4917	14	491,707
Dense forest and water bodies	18,009	50	>100	600	2989	8	1,791,702
Total	36,335	100	Total		36,335	100	2,654,323
			The actual soil loss from the Sebeya watershed is 2,654,323/36,335 = 73 t/ha/y				

In this study, the purpose of estimating soil loss based on LULC was to quantify the implications of LULC on water erosion within the Sebeya watershed (Table 8). However, in practice, soil loss estimation includes the action of the existing SECM within the watershed (Table 9). In 2018, for example, the soil loss induced by LULC (100 t/ha/y) was excessively greater than 73 t/ha/y, which is the estimated soil loss by taking account of the existing SECM in the Sebeya watershed. Therefore, SECM are essential to alleviate high soil erosion rates.

3.4. Soil Nutrients Depletion Due to Water Erosion in the Sebeya Watershed

The availability of nutrients in soils for the growth of plants defines their fertility. In many cases, farmers must increase soil nutrient levels by applying chemical fertilizers, animal manures, and compost to ensure crop growth [60]. Practically, nutrient testing provides results with an interpretive guide defined as high, medium, or low (Table 10).

Table 10. Quantifying various nutrients available in a soil [61,62].

Nutrients Level	Nitrogen (N) (ppm)	Phosphorus (P) (ppm)	Potassium (K) (ppm)	Organic Carbon (C) (%)	Calcium (Ca) (%)
Low	<430	<7	<80	<0.40	<0.50
Medium	430–600	7–15	80–180	0.40–0.60	0.50–0.75
High	>600	>15	>180	>0.60	>0.75

Although soil erosion threatens agriculture sustainability [63], few researchers have studied the spatial-temporal availability of soil nutrients within the Sebeya watershed (Table 11).

Table 11. Availability of soil nutrients within the Sebeya watershed (ppm).

S.N.	Soil Nutrient	Sampled Value at Nyamyumba Sector in 2017 [64]	Tested Samples from Mulinga Sector in 2021 [65]
1	P	7.000	<7 ppm
2	K	0.003	<180 ppm
3	C	75,560	<0.60 ppm
4	Ca	-	<0.75%
5	pH *	-	<7 (acidic)

* The soil pH was also assessed.

3.5. Sediments and Nutrients Dynamics in the Sebeya Watershed

Most Rwandan watersheds are affected by erosion, river runoff, and land slope, and river sediment transport varies proportionally to these factors [66]. Throughout the literature, soil erosion is washing away 945,200 tons of organic materials, nitrogen, phosphorus, and potash each year [67]. Challengingly, the amount of nutrients per unit weight of eroded soil is about three times higher than the nutrients in the remaining soil [68], agriculture being the main contributor to nutrients found in the Sebeya River [69]. In addition, the eroded sediments in the Sebeya River cause scouring on bridges, add pollutants to the river, and cause abrasion on hydropower turbines [13]. Therefore, it is essential to prevent excessive sedimentation and nutrient loading in the Sebeya River.

3.6. Site-Based Recommended Soil Erosion Control Measures and Associated Soil Loss Rates in the Sebeya Watershed

Without proper Best Management Practices (BMPs), soil erosion will continue to increase over the years [11]. Consequently, soil erosion control will always need improvement, and achieving the T-value (the maximum soil loss tolerance rate) will appear as a perfectionism concept within the watershed. For example, a farmer's interview in Nigeria revealed that farmers required improvement of all SECM in the Kogi region [70].

Using different shapefiles obtained from the Rwanda Water Resources Board, Figure 9 relates the simulated site-based recommended SECM intended to alleviate the excessive erosion rates in the Sebeya watershed. The following subsections explain the adopted procedures for predicting soil erosion rates A (t/ha/y) using the USLE model defined with its five parameters in Equation (1).

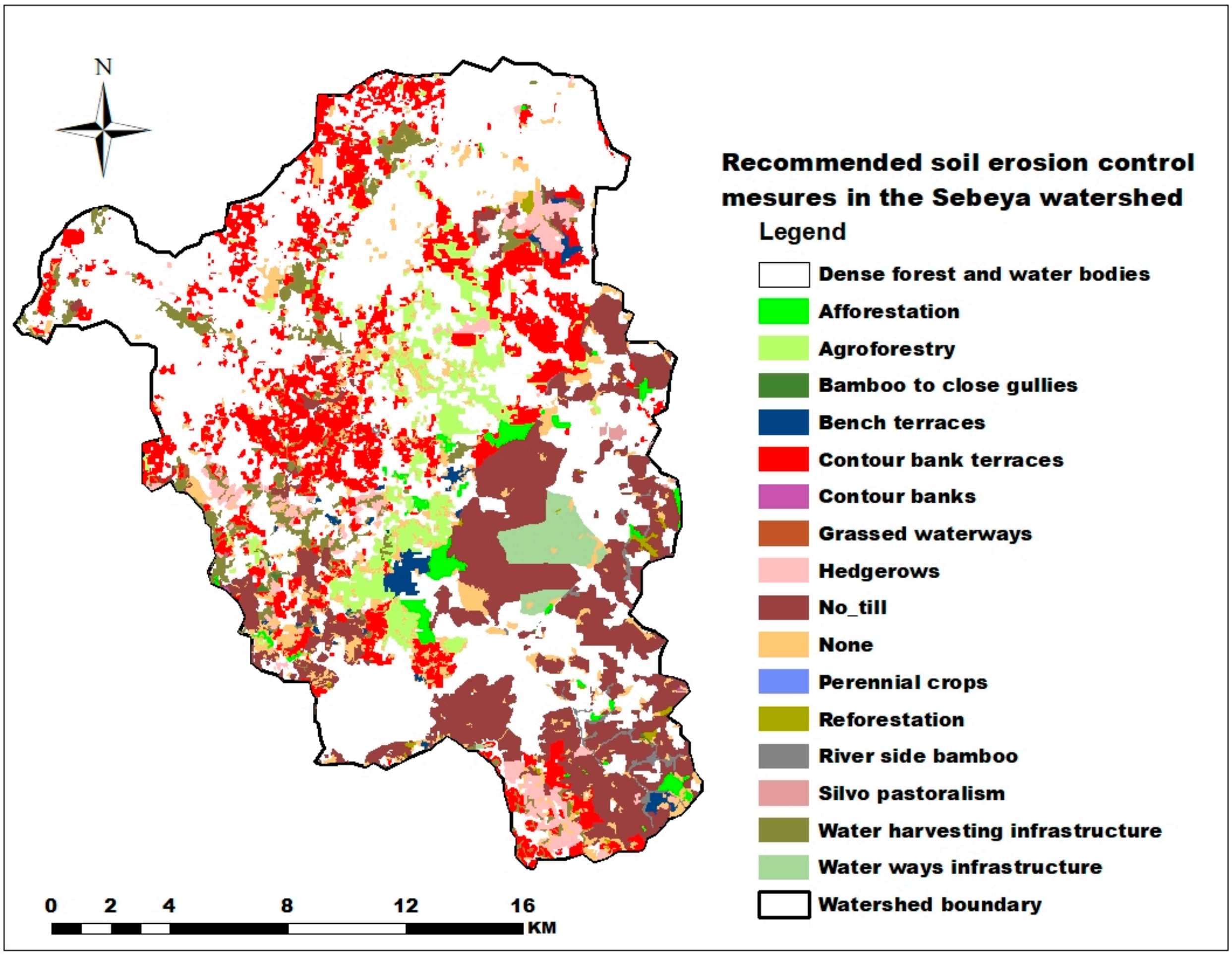

Figure 9. Recommended soil erosion control measures in the Sebeya watershed [59].

Figure 9 shows various site-based SECM recommended to alleviate the excessive erosion rates of 73 t/ha/y revealed by Table 9, while Table 12 reveals the extent of the areas for each site-based soil erosion control measure.

Table 12. Erosion rates induced by the site-based recommended soil erosion control measures in the Sebeya watershed.

S.N.	Recommended SECM	K	R	LS	C	P	Soil Loss Ai (t/ha/y)	Area ai (km^2)	Weighted (Ai × ai)
1	Afforestation	0.405	582.34	5.73	0.02	0.001	0.027	4.792	0.130
2	Agroforestry	0.405	582.34	5.73	0.08	0.500	54.056	17.500	945.966
3	Bamboo at gullies	0.405	582.34	5.73	0.01	0.500	6.757	0.284	1.919
4	Bench terraces	0.405	582.34	5.73	0.15	0.128	25.947	3.208	83.241
5	Progressive terraces	0.405	582.34	5.73	0.15	0.150	30.407	49.428	1502.934
6	Contour bunds	0.405	582.34	5.73	0.50	0.600	402.179	0.065	26.030
7	Grassed waterways	0.405	582.34	5.73	0.20	0.100	27.028	0.072	1.938
8	Hedgerows	0.405	582.34	5.73	0.20	0.000	0.000	8.714	0.000
9	No-till	0.405	582.34	5.73	0.25	0.100	33.785	58.323	1970.455
10	Existing SECM *	0.405	582.34	5.73	0.22	0.341	99.539	20.419	2032.489
11	Perennial crops	0.405	582.34	5.73	0.23	0.800	251.146	0.002	0.475
12	Reforestation	0.405	582.34	5.73	0.02	0.001	0.027	1.024	0.028
13	River side bamboo	0.405	582.34	5.73	0.01	0.500	6.757	1.767	11.943
14	Silvopastoralism	0.405	582.34	5.73	0.09	0.000	0.000	0.357	0.000
15	Rainwater tanks	0.405	582.34	5.73	0.00	0.800	0.000	12.653	0.000
16	Drainage channels	0.405	582.34	5.73	0.58	0.800	627.053	6.052	3794.661
17	Dense forest and water bodies	0.405	582.34	5.73	0.00	0.000	0.000	178.694	0.000
	Total							363.352	10,372.209
Predicted soil loss from the Sebeya watershed = 10,372.209/363.352 = 29 t/ha/y									

* (C = 0.216 and P = 0.341) are averages based on the existing SECM in Table 9.

Tables 4 and 8 have estimated the values of all five USLE parameters, as displayed in Table 12. In addition, Table 12 illustrates the estimation of erosion rates associated with the suggested SECM in the Sebeya watershed.

Comparatively, the proposed SECM reduced soil loss significantly from 73 t/ha/y (Table 9) to 29 t/ha/y (Table 12), raising the efficiency of SECM to 61%. For effective action to eradicate the excessive erosion rates within the Sebeya watershed, the present study emphasizes the implementation of the site-based recommended SECM with mulching and drainage channels on the same farmland.

3.7. Implications of Soil Erosion Control Measures on Crop Productivity in the Sebeya Watershed

About 80% of the Rwandan population depends on agriculture [71]. Due to Rwanda's high population density, soil erosion threatens the nation's food security and agricultural sustainability [72]. Therefore, adopting SECM is required to mitigate these effects and improve soil productivity.

The simulated efficiency of the site-based recommended SECM in reducing the high soil loss rates from 73 t/ha/y to 29 t/ha/y should be accompanied by an increase in crop yields ranging between the smallest (y_2) and the largest (y_1) values of the observed yields displayed in Table 5. In practice, the implication of the site-based recommended SECM in improving agricultural productivity should be highlighted by field investigations in soil erosion plots and the prediction of crop yields from an established linear correlation model between soil loss and crop yields in the Sebeya watershed [72].

4. Discussion

4.1. Erosion Process and Its Damages in the Sebeya Watershed

Raindrops striking the soil surface dislodge fine soil particles. The resulting overland flows erode soil particles of varying sizes, which slide along the land's surface and get transported to streams, channels, rivers, water reservoirs, and lakes. There are three distinct processes of water erosion: loosening and dislodging (displacement), transportation, and deposition of soil particles. Organic matter, silt, and finer sand particles will be washed away by runoff, but heavier rainfalls will also displace larger material components. Lands with high slopes will facilitate the process of water erosion [73]. With considerable damage, water erosion reduces soil fertility and water storage capacity. In addition, it increases sediment concentration in the runoff with possible depositions to increase the risk of flood disasters [74].

Many visible signs reflect the persistence of erosion in the Sebeya watershed, including accumulated transported sediment in depressions and above obstacles, rills or gullies on roadsides or upper slopes, exposure of roots, changes in soil color and texture, and excessive sediment loading rates in rivers and reservoirs. In addition, if the soil is tested regularly, a reduction in organic soil matter levels may indicate soil loss by erosion [75].

For proper land use management, researchers recommend launching various studies to identify mechanisms and driving forces of soil erosion, including precipitation, vegetation, land use type, and physical soil properties [76,77]. For instance, many factors accelerating soil erosion in the Sebeya watershed include excessive rainfall, soil cultivation without fallow, bare ground, insufficient SECM, artisanal mining, overgrazing, and deforestation [18]. Furthermore, in areas with expanding populations, diversified human activities for construction, agricultural production, and urbanization are the major contributors to soil erosion [78].

Various visual signs and information from social media (television, different websites, and newspapers) on causes, influential factors, and on-site and off-site effects of erosion within the Sebeya watershed inspired these investigations.

Due to declining soil fertility, erosion threatens agriculture sustainability [12,15,79]. For deep analysis, farmers may lose income due to lower yields or purchase more fertilizers to compensate for fertility loss. As a result, the eroded sediments will be highly concentrated in fertilizers and pesticides, polluting downstream rivers and reservoirs. Therefore, erosion control is essential for boosting crop production and protecting rivers and lakes from sediment loading [10].

In addition to depleting soil nutrients, water erosion causes land degradation, floods, silt buildup, and excessive pollution. The prevention and control of erosion are global issues targeted at ensuring food security and environmental sustainability [80–82].

4.2. Implications of LULC Changes on Water Erosion within the Sebeya Watershed

Land cover describes how the land surface is physically, chemically, or biologically classified. For example, grasslands, forests, roads, buildings, and water bodies belong to it. Typically, land use can refer to the use of that land – for instance, cattle ranches, recreation, housing (commercial, residential, industrial), and other human activities.

This study revealed seven different LULC types in the Sebeya watershed (Table 7): built-up area, closed agriculture, forest plantation, irrigation, natural forest, open agriculture, and open land. Despite the possibility of developing green agriculture and mining, there are some cases where unsustainable agricultural and mining activities are causing terrible sedimentation in the Sebeya River during rainy seasons [12]. To properly manage these landscapes, we must monitor their dynamic changes while minimizing the impacts caused by anthropogenic activities and natural phenomena [30,83–86].

4.3. Future Work

In addition to reducing soil fertility, erosion compacts the soil and decreases aeration and permeability. Briefly, water erosion alters the soil physically, chemically, and biologically [87].

In the Sebeya watershed, water erosion results in agricultural soil and nutrient losses, landslides removing crops, exposed roots, eroded materials covering crops or getting deposited in roads, and silting up of waterways. Ultimately, there is an increase in sediment concentration at Keya, Gihira, and Gisenyi hydropower plants and excessive turbidity at Gihira water treatment plant. It is also common for floods and landslides to occur during the rainy season, causing damage to buildings and sometimes killing livestock and people [88].

Water erosion is a stressful environmental issue for which the proverb "Prevention is better than cure" may help to sensitize farmers and stakeholders in the Sebeya watershed to adopt and implement SECM in their farmlands. This study assessed the efficiency of the site-based recommended SECM to alleviate the excessive soil loss rates (Table 12). Money and knowledge are the main limitations in implementing SECM in the Sebeya watershed [82].

For the ultimate objective of eradicating the high erosion rates in the Sebeya watershed, Majoro and Wali [89] assessed various factors affecting farmers' willingness to adopt SECM in the Sebeya watershed. However, there is a need to promote further studies intended to increase farmers' willingness to participate in the planning process, implementation, and maintenance of SECM in the Sebeya watershed. Practically, lowering the high soil loss rates below the maximum soil loss tolerance rate of 11.5 t/ha/y throughout the entire watershed should be the main target in implementing SECM [81].

To this end, farmers are the most perceptive and can identify rill erosion at its early stage; therefore, researchers should focus on BMPs easily applied by indigenous knowledge to prevent soil erosion. Government grants, donor agencies, and non-governmental organizations (NGOs) should empower the affected people (landowners and farmers) to adopt and implement SECM. All farmers should be trained and sensitized through awareness and education programs to ensure their farmlands are protected from soil erosion for sustainable agricultural operations.

5. Conclusions and Recommendations

This study aimed to assess various factors and processes affecting soil erosion to recommend suitable site-based SECM for sustainable agriculture while minimizing the downstream rivers and reservoir sedimentation in the Sebeya watershed.

In this research, the actual soil loss was estimated to be very high at 73 t/ha/y, due to various influential factors such as abrupt slopes and the natural soil's susceptibility to erosion, coupled with continuous cultivation and climatic conditions.

Using simulations and predictions with the USLE model, the proposed SECM reduced soil loss significantly from 73 to 29 tons per hectare annually, raising their efficiency to 61%. To highlight the implications of the site-based recommended SECM in improving agricultural productivity, this study suggests field investigations in soil erosion plots to predict crop yields from an established linear correlation model between soil loss and crop yields in the Sebeya watershed.

For effective action in reducing high soil erosion rates to tolerable rates in the Sebeya watershed, the present research suggests implementing the site-based recommended SECM with mulching and drainage channels on the same farmland. However, money and knowledge are the main limitations to implementing SECM in most of the Sebeya watershed farmlands. Therefore, the government should help famers in the Sebeya watershed by providing technical and financial assistance for implementing SECM in their farmlands.

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