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Estimation of Soil Erosion Using RUSLE Model and GIS: The Case of Satinskyi Catchment, Western Rwanda

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Abstract

The problem of soil erosion in Rwanda has been highlighted in previous studies. They have shown that half of the country's farmland suffers moderate to severe erosion, with the highest soil loss rates found in the steeper and highly rainy northern and western highlands of the country. The purpose of this study was to estimate soil loss in Satinskyi, one of the catchments located in Ngororero District of Western Rwanda. This has been achieved using the Revised Universal Soil Loss Equation (RUSLE) model, which has been implemented in a Geographic Information Systems (GIS) environment. The methods consisted of preparing a set of input factor layers including Slope Length and Steepness (LS) factor, Rainfall Erosivity (R) factor, Soil Erodibility (K) factor, Support Practice (P) factor, and Land Surface Cover Management Factor (C) factor, for the model. The input factors have been integrated for soil loss estimates computation using RUSLE model, and this has enabled to quantitatively assess variations in the mean of the total estimated soil loss per annum in relation to topography and land-use patterns of the studied catchment. The findings showed that the average soil loss in Satinskyi catchment is estimated at 38.4 t/ha/year. It was however found that about 91 % of the study area consists of areas with slope angle exceeding 15°, a situation which exposes the land to severe soil loss rates ranging between 31 t/ha/year and 41 t/ha/year. Apart from the steep slope, changes in land use also contribute to high rates of soil loss in the catchment.

Keywords: Soil Erosion Estimation, GIS, RUSLE, Satinskyi Catchment, Rwanda

1. Introduction

Previous studies have highlighted adverse impacts of widespread soil erosion which include soil degradation, water siltation, reduced agriculture production among others (Montgomery, 2007; Karamage *et al.*, 2016; Ashras & Issaka, 2017), all known to compromise human sustainability. Anthropogenic activities such as ploughing, man's search for mineral resources, and other human activities such as constructions, impact on land use and land cover are considered to be among the aggravating factors interplaying with natural factors to determine the rates of soil erosion in a given area (Zhao and Hou, 2019). The main natural factors of soil erosion include topography, rainfall, soil properties, and general land management. Estimation of soil loss is however often difficult due to the complex nature of interconnectivity and interdependency between the status of the human and the biophysical parameters (Gurebiyaw *et al.*, 2018). In this regard, researchers have put forward a range of models for estimating soil erosion rates.

Many computer-based models have been developed to explore soil erosion at the catchment scale. Merritt *et al.* (2003) have reviewed some of them and showed observed great differences of these models in terms of the scale of application, complexity, required inputs for model calibration, represented processes, and the types of final outputs (Renard *et al.*, 1997; Merritt et al. 2003).

Some of the widely used models in soil loss estimation include Water Erosion Prediction Project Model (WEPP), European Soil Erosion Model (EUROSEM), Griffith University Erosion System Template (GUEST), Soil and Water Assessment Tool (SWAT), Universal Soil Loss Equation (USLE), and Revised Universal Soil Loss Equation (RUSLE), among others.

Water Erosion Prediction Project (WEPP) is a physically-based model, incorporating the fundamentals of hydrology, soil physics, plant science, hydraulics, and erosion mechanics (Flanagan et al. 2001). It reflects the effects of soil surface conditions due to agricultural, range and forestry practices on storm runoff and erosion, but does not consider erosion, transport and deposition processes in permanent channels, such as classical gullies and perennial streams (Merritt et al. 2003).

The European Soil Erosion Model (EUROSEM) is a dynamic distributed model for simulating erosion, transport, and deposition of sediment over the land surface by interrill and rill processes (Morgan et al. 1998). It is designed as an event-based model for both individual fields and small catchments. Model outputs include total runoff, total soil loss, the storm hydrograph, and the storm sediment graph. However, the model doesn't apply for larger catchments and is unable to generate rills and gullies from an unrilled overland flow plane and doesn't account for storm soil surface dynamics (Favis-Mortlock et al., 2001).

GUEST (Griffith University Erosion System Template) was designed to interpret temporal fluctuation in sediment concentration for varying slopes, and from bare soil in single erosion events (Rose et al. 1998). It incorporates the simultaneous effects of rainfall and runoff and of deposition on sediment concentration. Although it great usefulness, GUEST is a complex process-based model and consequently has a reasonably large data requirement. Required data include among many other detailed surveys of the pilot site, such as the frequency and geometry of rills before modelling (Rose et al. 1998).

The Soil and Water Assessment Tool (SWAT) is a physically GIS-based distributed hydrological model that uses multi-criteria evaluation (MCE) (Setegn *et al.* 2009). It allows for the discretisation of a watershed by dividing it into multiple sub-watersheds, which can then be further sub-divided into hydrologic response units (HRUs) that consist of homogeneous land use, management, and soil characteristics (Setegn et al. 2009). The model, through the two phases (land and stream routing), simulates the routines for evapotranspiration, surface runoff, infiltration, percolation, return flow, groundwater flow, channel transmission losses, channel routing, and plant water use processes among others. However, researchers have noted some limitations of the model including but not limited to formulas, which are empirical, limitation in the representation of erosion and sediment transport, and the no-applicability for 2D or 3D hydraulics applications (Grey et al. 2014).

The Revised Universal Soil Loss Equation (RUSLE) model used in this study is an improved version of USLE model (Wischmeier & Smith, 1978), which has broadened its application to different situations, including forest, rangeland, and disturbed lands such as mining areas (Zhang et al., 2016; Renard *et al.* 1997). When using the RUSLE, the effects of topography on soil erosion are estimated by the slope length (L) and slope steepness (S) constituents of the dimensionless ***LS*** factor, where LS is one of five component factors including Support Practice Factor ***(P)***, Rainfall Erosivity Factor ***(R)***, Soil Erodibility Factor ***(K)***, and Land Surface Cover Management Factor ***(C)***.

Previous studies that applied the RUSLE model to study soil erosion in Rwanda have found that half of the country's agricultural land is affected by soil erosion (MoE, 2018; Karamage *et al.*, 2016, Nyesheja *et al.* 2019). The combination of steep hillsides, rain-fed small-scale agriculture, as well as high precipitations, leads to very high soil erosion rates in different parts of the country (REMA, 2015). The highly elevated and mountainous areas in the northern and western parts of the country, in which Satinskyi catchment is located, are highly exposed to the soil erosion and its effects, given the dominance of high inclination of slopes and heavy rainfall patterns (Rwanyiziri et al., 2019; RoR, 2018; Karamage *et al.* 2016).

A limited number of previous studies have used the RUSLE model to assess soil erosion in Rwanda. Some of them have assessed soil erosion countrywide and few studies have limited to local scales. Byizigiro (2016), Shao et al. (2016), and Zhang et al. (2016) evaluated soil erosion at local scale; He al. (2020) evaluated soil erosion countrywide. The topographic and Land Use factors were found to have an important role in the amount of soils eroded in Rwanda. Depending on the scale of research, rates of soil erosion vary and stay in reasonably same ranges, but far exceed the recommended tolerable soil loss accepted for maintaining crop productivity.

Nevertheless, RUSLE model has a number of weaknesses such as not being event responsive, ignoring the processes of rainfall-runoff, and how these processes affect erosion, as well as the heterogeneities in inputs such as vegetation cover and soil types. Given the fact that the model is not event-based, gully erosion and mass movement are ignored and the deposition of sediment is not considered to occur in the modelled area. This study will serve as a tool for territorial planning and decision-making as it points out the merits and limitations of some territorial management actions.

Satinskyi catchment, located in Ngororero District of Western Province, is one of the areas highly affected by soil erosion in Rwanda, where agriculture and mining constitute the economic activities for the majority of the population. In this region, natural conditions such as steep topography (> 26°), high annual precipitation (1090 – 1597 mm), and human impacts have made the area prone to intensive soil loss (Byizigiro et al., 2015).

2. Materials and Methods

2.1. Study Area Description

Satinskyi Catchment is located in Ngororero district, one of the seven districts making up the Western Province of Rwanda. The spatial location of the study area is bounded by 1°44'00" and 1°60'00" South Latitude and 29°27'0" and 29°40'0" of East Longitude. The area is deeply dissected by Satinskyi River and its tributaries, namely Muhembe, Gaseke, Rutemba, Mugogwe, Nyamahura, and Kazaba (Figure 1). It falls within a temperate climate with an annual average temperature of 18° C as a consequence of its high altitude ranging between 1401 and 2843 m, in spite of its equatorial latitude (Ngororero District, 2013). High annual precipitation (ranging between 1091 mm and 1597 mm) and a generally steep topography (> 26°) constitute the major natural factors influencing the geomorphological processes in the area, which are aggravated by agriculture and mining operations that contribute to increased soil erosion rates observed in the area. Mining has caused environmental damages in different mining sites and has exacerbated the problem of soil erosion in the Satinskyi catchment (Ngororero District, 2013).

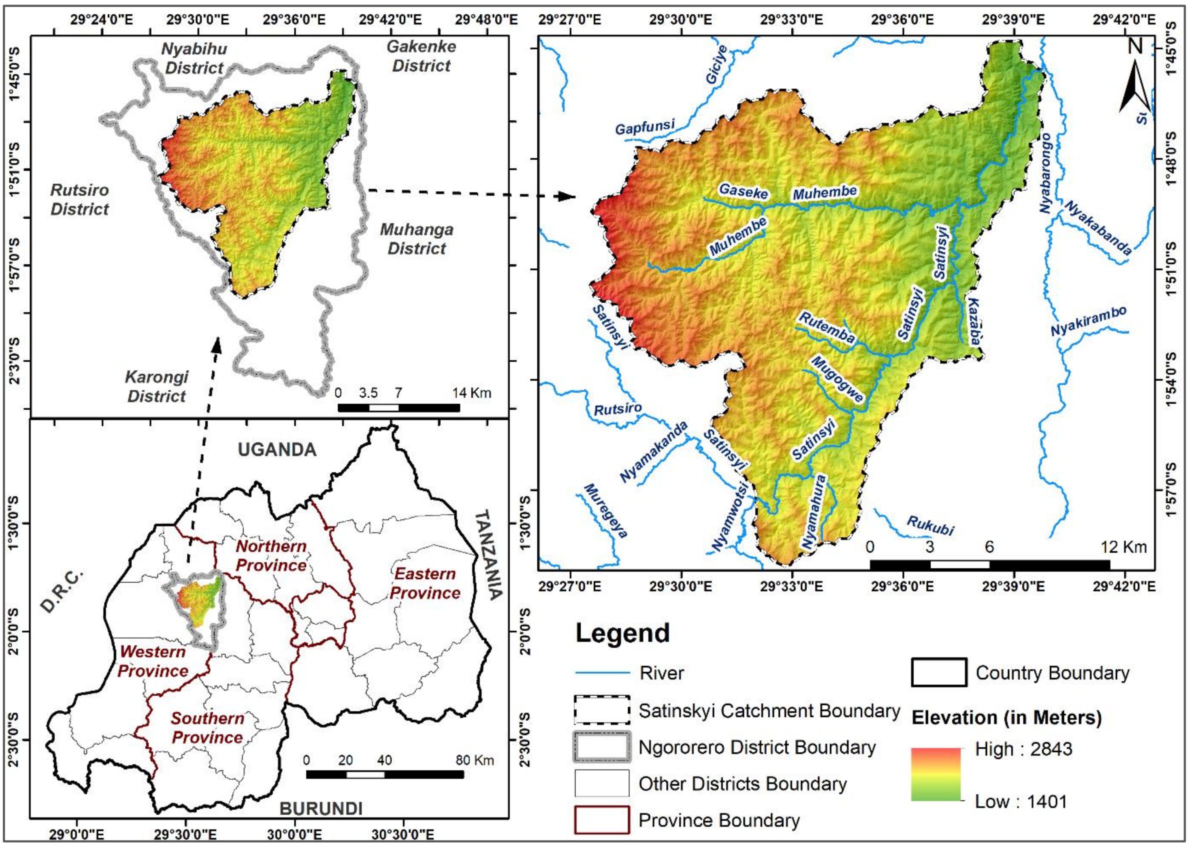

Figure 1: Location Map of Satinskyi Catchment

2.2 Research Data

The processed input factors in a GIS environment enabled the obtaining of the five factors: LS, R, P, K, and C, required for the RUSLE model. Land Use and Land Cover (LULC) data produced from Landsat 8 OLI time series, enabled us to produce the land cover Management Factor (C); while daily recorded rainfall data at various stations countrywide from 1950 up to 2018 (provided by Rwanda Meteorological Agency – RMA) enabled to determine the Rainfall Erosivity Factor (R). At the same time, the existing 10 m DEM was processed to generate the topographic Factor (LS). The slopes were reclassified to allocate them corresponding indices to produce the Support Practice or (Conservation) Factor (P) after Shin (1999). Finally, the Soil Erodibility Factor (F) was generated based on the soil data accessed through the Vital Signs Project (http://www.vitalsigns.org) which is a soil database project implemented in different African countries including Rwanda, by Conservation International (CI) through Wildlife Conservation Society (WCS) (WCS, 2019). The project has followed the methodology used in Tropical Ecology Assessment and Monitoring (TEAM), Africa Soil Information System (AfSIS) which draws on Land degradation Surveillance Framework (LDSF) and Living Standards Measurement Study (LSMS) during its soil sample collection and analysis (2015 – 2019) (Vågen et al. 2013). The following flowchart (Figure 2) captures the input data used, the GIS-RUSLE processing workflow, and derived outputs.

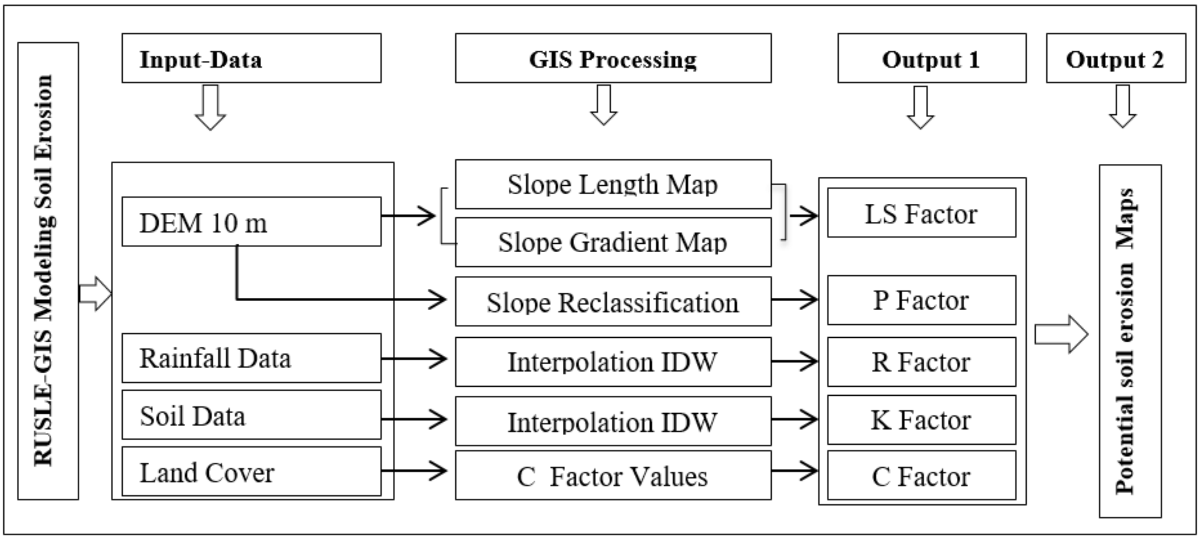

Figure 2: Flowchart showing RUSLE-GIS Workflow

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

A (ton/ ha/year): Spatial Average of Annual Total Soil Loss,

LS (dimensionless): Topographic Factor (Slope Length and Steepness)

P (dimensionless): Support Practice Factor (Soil Conservation Methods)

R (MJ mm /ha/hr/year)): Rainfall and Runoff Erosivity Factor

K (t. h/ MJ/mm/)): Soil Erodibility Factor

C (dimensionless): Land Surface Cover Management Factor

2.3. Research Methods

Data and their related attributes required for the model were input into the GIS by manual digitization and keyboard entry. The polygons and their attributes were connected with a uniform code. The obtained vector maps were later converted into raster, which had the same reference system and resolution as the 10 m resolution DEM. The data sources were integrated into ArcGIS with a grid-cell format. Each defined cell (pixel) had an exact location in space, determined by the grid orientation, cell size, and a list of assigned attributes. The area-weighted mean of the potential erosion rates for the study area was computed using a zonal statistics tool. Details on data and processing methods are provided under respective RUSLE Factors in the next section.

a) Topographic Factor (LS)

Topographic Factor, also referred to as Slope Length and Steepness Factor (LS), reflects the effect of topography on soil erosion. An increasing slope gradient and slope length cause higher overland flow velocities and therefore higher soil erosion resulting in an increased LS Factor. DEM sinks were filled to give the area an average value, estimated using the natural neighboring resampling technique. Both slope gradient and slope length factors were calculated and allowed the production of LS Factor grid using the following relations (Fayas et al., 2019; Thakuri et al., 2019):

$$L=\left(\frac{\lambda}{22.13}\right)^{m} \quad 2$$

Where, L = slope length factor, λ = slope length (m), m = slope-length exponent

$$m=\left(\frac{F}{1+F'}\right) \quad 3$$

$$F=\frac{Sin\beta/0.0896}{3\,(Sin\beta)^{0.8}+0.56'} \quad 4$$

Where, F = Ratio of rill erosion to inter-rill erosion, β = slope angle (°)

In ArcMap, L was computed as follows:

$$L=\frac{(Flow_{Acc}+625)^{(m+1)}-(Flow_{Acc})^{(m+1)}}{25^{(m+2)}*22.13^{m}} \quad 5$$

The Slope Gradient Factor, S, was estimated as follows:

S= Con((Tan(Slope*0.01745)<0.09),(10.8*Sin(Slope*0.01745)+0.03), 6
(16.8*(Sin(Slope*0.01745)-0.5))

Where *m*: is a slope angle contingent variable ranging from 0.01 to 0.56 (McCool et al. 1997), and is given a value of 0.5 for the slope greater than 4.5%; 0.4 on slopes of 30 % to 4.5%; 0.3 on slopes of 1% to 3%; and 0.2 on slopes less than 1%. Therefore, in this study a constant (*m*) of 0.5 was used in Equation (5) due to the mean slope greater than 30 % (15°) observed for the study area.

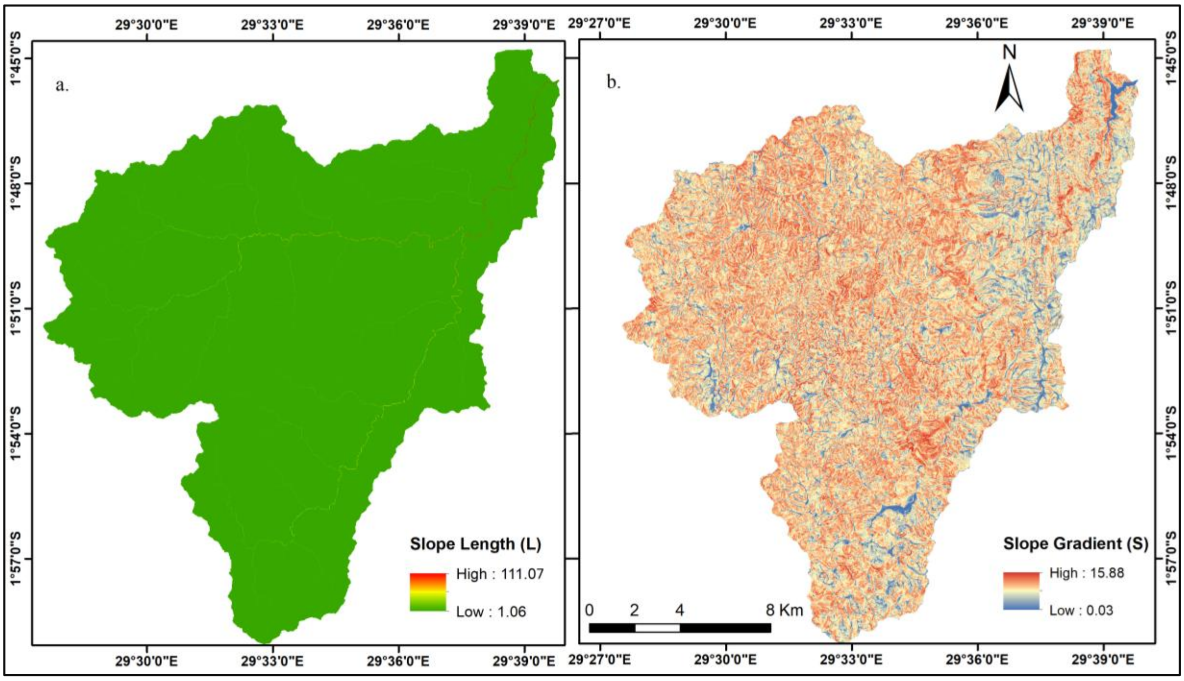

Figure 3**:** Slope Length Factor and Slope Gradient Factor

b) Support Practice Factor (P)

The Support Practice Factor "**P**" refers to the soil Conservation Practices implemented to alleviate soil erosion. Contour farming, terracing, and strip cropping are the commonly indexed and documented control measures (Shin, 1999). They are presented in Table 1. The P values range from 0 to 1, where the value 0 represents a very good anthropic erosion resistance facility, and the value 1 indicates a non-anthropic resistance erosion facility.

Table 1: Support Practice Factor Values as per Soil Conservation Practice (Shin, 1999)

Slope %	Strip Cropping	Contour Cropping	Terrace Cropping	
			Bench	*Broad-based*
0-7.0	0.27	0.55	0.10	0.12
7.0-11.3	0.30	0.60	0.10	0.12
11.3-17.6	0.40	0.80	0.10	0.16
17.6-26.8	0.45	0.90	0.12	0.18
> 26.8	0.50	1.00	0.14	0.20

P Factor was produced by allocating conservation indices to corresponding reclassified slopes. Given that the study area exhibits steep slopes, where farming practices have developed following topographical changes, conservation indices used in this study are that of contour cropping.

c) Rainfall Erosivity Factor (R)

Rainfall Erosivity Factor "**R**" takes into account the amount of rainfall to present the peak intensity sustained over an extended period, indicating the potential ability for rainfall to cause soil loss (Pandit & Isaac, 2015). Marco da Silva (2004) describes the concept of rainfall erosivity as an interaction between the kinetic energy of raindrops and the soil surface. This can result in a greater or lower degree of detachment and downslope transport of soil particles according to the amount of energy and intensity of rain by considering the same soil type, the same topographic conditions, soil cover, and management (Marco da Silva, 2004). Soil losses are therefore directly proportional to the total storm energy (E) times the maximum 30-min intensity (Pandit & Isaac, 2015). R factor has a very significant impact on soil loss (Zhang et al., 2016). R raster map for Satinskyi catchment was produced using the daily recorded mean rainfall data from 1950 up to 2018 provided by Rwanda Meteorological Agency, which led to the final computation of R factor map using to the following formula (Morgan, 1985):

$$R = 38.5 + 0.35P \qquad 7$$

Where, *R* represents the Rainfall Erosivity Factor, and *P* is the Mean Annual Rainfall in mm.

d) Soil Erodibility Factor (K)

K Factor is referred to as the susceptibility of a soil particle type to erosion by rainfall and runoff (Williams, 2000). All fractions of the topsoil layer including sand, clay, silt, and organic carbon (Figure 4) required to estimate K Factor were used according to the following mathematical relations described by Williams (2000). Many researchers consider the topsoil layer to calculate K Factor because it is affected directly by the raindrop energy.

$$K\_Factor = f_{Sand} . f_{Clay} . f_{OrgC} . f_{Silt} * 0.1317 \qquad 8$$

$$f_{Sand} = \left(0.2 + 0.3.exp\left[-0.256.m_{Sand}.\left(1 - \frac{m_{Silt}}{100}\right)\right]\right) \qquad 9$$

$$f_{Clay} = \left(\frac{m_{Silt}}{m_{Clay} + m_{Silt}}\right)^{0.3} \qquad 10$$

$$f_{orgC} = \left(1 - \frac{0.0256.OrgC}{OrgC + exp[3.72 - 2.95.OrgC]}\right) \qquad 11$$

$$f_{Silt} = \left(1 - \frac{0.7(1 - \frac{m_{Sand}}{100})}{\left(1 - \frac{m_{sand}}{100}\right) + exp\left[-5.51 + 22.9.\left(1 - \frac{m_{Sand}}{100}\right)\right]}\right) \qquad 12$$

Where

m_{Sand} is the proportion (%) of sand content (0.05-2.0 mm diameter particles), m_{Silt} is the proportion (%) of silt content (0.002-0.05 mm diameter particles), m_{Clay} is the proportion (%) of clay content (<0.002 mm diameter particles), and $orgc$ is the amount (%) of the organic carbon content of the layer (%).

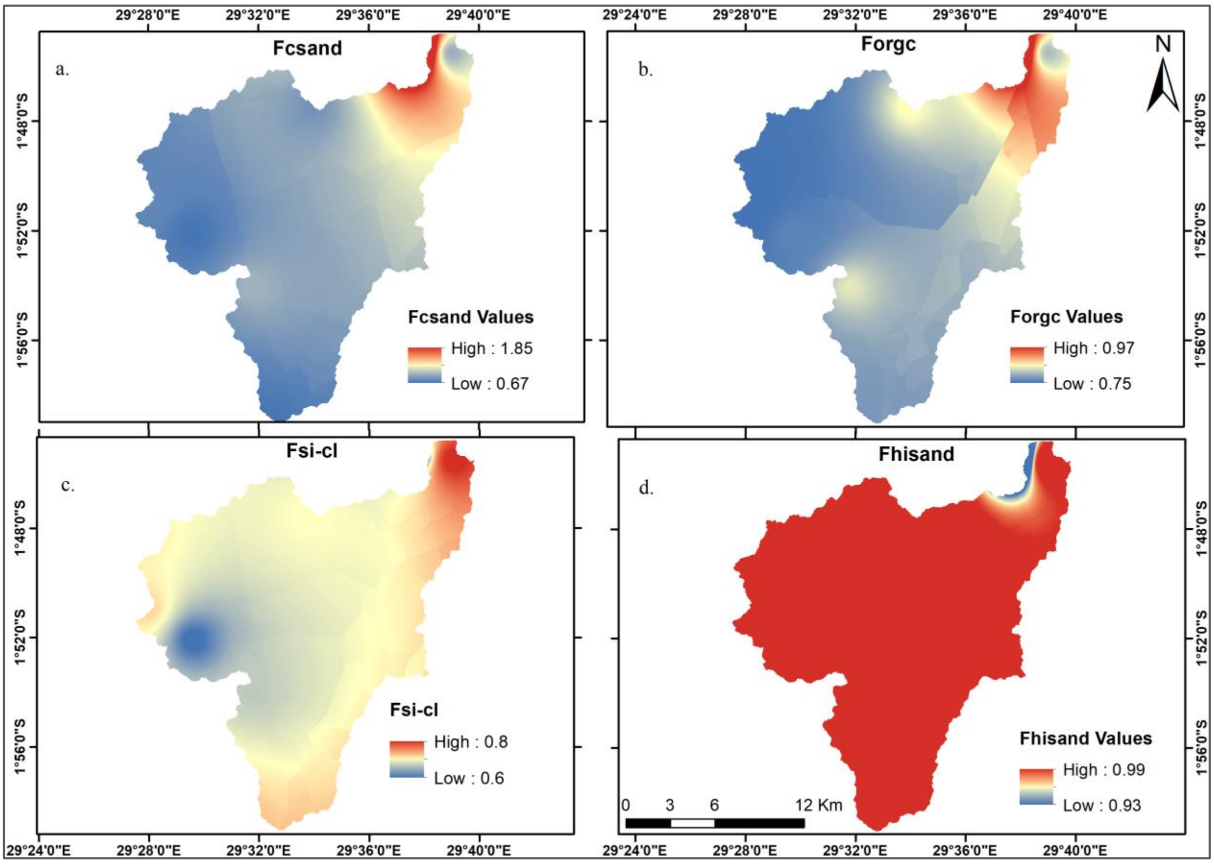

Figure 4: Soil Properties Used to Produce K Factor Map

e) Land Surface Cover Management Factor (C)

The Land Surface Cover Management Factor (C) represents the ratio of soil erosion from land cropped under specific conditions. It determines how natural vegetation or crop cover reduces rainfall energy and overflows or intercepts rainfall energy and increases infiltration. It is the second most important factor next to topography and rainfall erosivity that controls soil erosion risk (Henebry, G. M., & Kirsten, 2004). C equals 1 under standard fallow conditions where the vegetation cover has been totally stripped off. As vegetative cover approaches 100%, the C factor value approaches 0. The LULC for Satinskyi Catchment was extracted from the prepared LULC of Rwanda.

The used LULC data was clipped from the current 20 m resolution Rwanda land cover map which dates in 2018, produced through the fusion of Landsat 8 OLI (30 m resolution) and Synthetic Aperture Radar (SAR) data (Sentinel 1) (20 m resolution) taken at regular time intervals over all seasons (time series), to gain the representativeness over the year (RWFA, 2018). Given that factors in the RUSLE model are spatially evaluated through the GIS environment, resulting in layers corresponding to individual factors reflected in the equation were overlaid and multiplied on a grid basis. Table 2 below represents C factor values used for land cover and land use (Thakuri et al., 2019).

Table 2: Cover Management Factor

Land Use	C Factor
Forest	0.03
Shrubland	0.03
Grassland	0.01
Agricultural Land	0.21
Barren Land	0.45
Built-Up	0.00
Snow Glacier	0.00
Water Body	0.00

3. Results

The prepared input factors for RUSLE were integrated into the ArcGIS 10.6 raster calculator for generating the soil erosion map for the study area (Figure 5f). High mean annual precipitation (> 1,300 mm) and a generally steepened topography (> 26°) constitute the major natural factors influencing high soil loss rates observed in the study area. The results showed that R factor value comprised between 420.2 and 579.6 MJ mm/ Ha/h/year, with the highest values in the western part of the catchment and the lowest values being in the North-eastern. The Topographic Factor (LS) for the entire catchment value ranged from 0.03 to 1164.81. The steep cultivated hillsides are separated by groove-shaped valleys and contribute significantly to sediment yields in Satinskyi catchment.

3.1. Annual Soil Loss Rates per Slope

The average annual soil loss in the study area was estimated at 38.4 t/ha/year (Table 3). An extensive part of the land (91%) presents slopes exceeding 15°, which makes the area prone to severe soil loss estimates averaged between 31 and 41 t/ha/year (Figure 5f). Slopes with value comprised between 15 and 30° cover about 33 % of the total land and are attributed to soil loss estimated at an average of 31 t/ha/year.

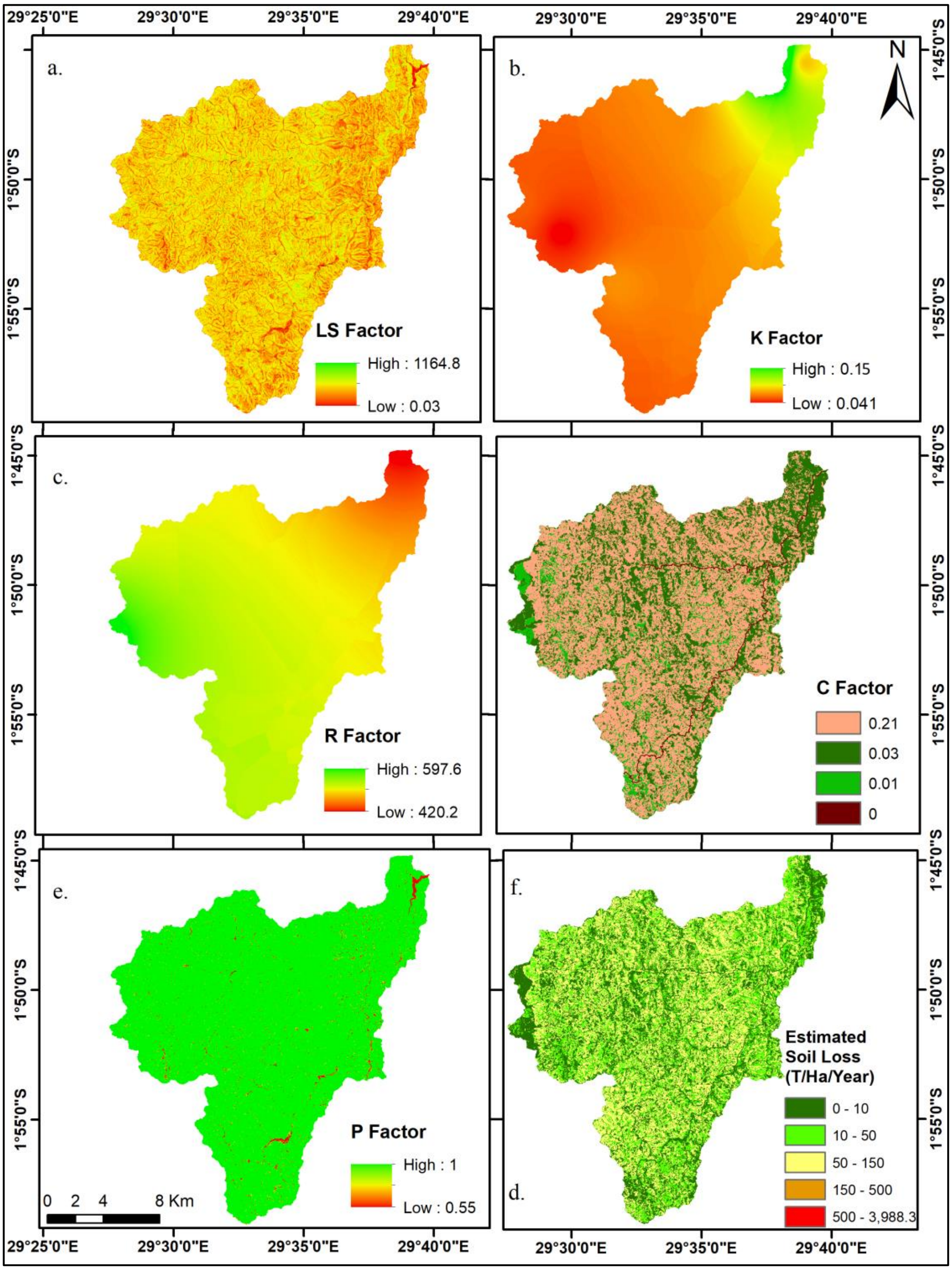

Figure 5: RUSLE Factors Maps (a, b, c, d, e) and Final Estimated Mean Annual Soil Loss (f)

Terrains with gentle slopes are limited, with only 6.6 % of land having slope comprised between 7° and 15° with a mean annual soil loss estimated at 17.9 t/ha/year. The very gentle sloping lands (0 – 7%) constitute about 2% of the area and present a mean soil loss estimated at 6.5 t/ha/year.

Table 3: Annual Soil Loss Rate per Slope

Slope Range (°)	Area (ha)	Percent of Total Area	Min	Max	Range	Mean	Std
0 - 7	619	2.05	0	841.5	841.5	6.5	17.2
7 - 15	1,988	6.58	0	2,349.1	2,349.1	17.9	33.2
15 - 30	10,109	33.44	0	3,988.3	3,988.3	30.9	32.2
30 - 77.3	17,513	57.93	0	3,408.6	3,408.6	40.8	30.8
Total	30,229	100.00	0	10,587.5	10,587.5	96.1	113.4

3.2. Annual Soil Loss Rates per LULC

The LULC has a significant impact on soil loss in the study area. The average soil loss estimates per annum in the study area (Table 4) was estimated at 13.5 t/ha/year, where seasonal agriculture alone which covers 60 % of total land accounting for 52.7 t/ha/year.

Table 4: Mean Annual Soil Loss per Land Cover Type

LULC Class	Area	Percent of Total Area	Min	Max	Range	Mean	Std.
Dense Forest	3,946	13.05	0	936.4	936.4	8.9	5.5
Sparse Forest	5,493	18.17	0	1,926.9	1,926.9	11.4	13.4
Water	314	1.04	0	0	0	0	0
Settlements and Buildings	10	0.03	0	165.1	165.1	2.4	10.4
Agriculture (Seasonal)	18,086	59.83	0	3,988.3	3,988.3	52.7	29.6
Agriculture (Perennial)	151	0.50	0	331.3	331.3	2.5	6.5
Open Areas or grass	2,229	7.37	0	870.5	870.5	3.1	7.3
Total	**30,229**	**100.00**	**0**	**10,040.7**	**10,040.7**	**82.2**	**86.9**

Soil loss rates decrease with an increased vegetative cover. Under sparse forest (18% of total land) soil loss is estimated at 11.4 t/ha/year, whereas on vegetated hill slopes (13% of the total land) soil loss rate accounts for 8.9 t/ha/year.

4. Discussion

Soil loss estimation as presented in table 3 and 4, and illustrated by Figure 6, indicates some values which far exceed the soil loss tolerance (T-value). The T-value represents a maximum rate of soil erosion that can occur and still permits crop productivity to be sustained economically (Renard et al., 1997). Chinese standard for classification and gradation of soil erosion (Yang, et al. 2013) has set an annual T-value comprised between 5 and 10 t/ha/year. In the USDA-NRCS manual, T was set at 10. Though the T threshold value is not defined yet for individual regions in Rwanda, the soil loss potential in the study area (38 t/ha/year) far exceeds the T 10 value recommended by the USDA-NRCS manual (Liu et al, 2012).

The findings were correlated with similar studies carried out in Rwanda and different parts of the world and rates of soil erosion are alike. Lewis et al. (1988) found that in Rwanda, seasonal soil losses ranged from 1 t/ha/year to 143 t/ha/year. The highest values of estimated mean annual soil loss per LULC has been attributed to seasonal agricultural land, which is in agreement with the statement by the previous studies, such as Mugabowindekwe and Rwanyiziri (2020), indicating that the agricultural land is the most frequently disturbed land use in Rwanda. Nevertheless, the range of average seasonal soil loss in Rwanda showed a pattern of local differences that closely followed variations in rainfall and topography.

The study of He et al. (2020) on Rwanda showed average annual soil losses comprised between 48.6 t/ ha/year and 39.2 t/ha/year in 2000 and 2015 respectively. Findings of Shao et al. (2016) indicated that the Lake Kivu basin is exposed to soil erosion risk with a mean annual rate of 30 t/ha/year and only 33% of the total non-water area is associated with a tolerable soil loss (≤10 t/ha/year). Byizigiro (2016) has found a slightly small soil erosion rate in the Gatumba sector (27 t/ha/year). In Nepal, Thakuri et al. (2019) found different rates of mean soil erosion under different topographies and land uses. Soil erosion based on the physiographic region of the country shows that the highlands of Nepal have mean erosion rates comprised between 38, and 28 t/ha/year. The same conclusion was made for the mean annual soil losses varying following the changing topographies, rainfall, and land use types.

Though the estimated soil loss in Satinskyi catchment is in the same order of magnitude of the findings mentioned above, it is, however, important to highlight other values, which show elevated soil loss ranges. The research of Zhang et al. (2016) on erosion over entire Rwanda showed that the mean soil erosion rate was 250 t/ha/year, whereas the mean soil erosion rate over cropland, which occupied 56% of the national land area, was estimated at 421 t/ha/year, and the current suitable cultivated land presents a mean soil erosion of 27 t/ha/year, contributing to the total annual soil loss by 4.87% countrywide.

Previous studies attempted to classify the soil loss rates in a numerical severity ranges with the purpose of planning and allocating appropriate remedial strategies, but ranges suggested are not uniform due to priority intervention (Thakuri, 2019; Rahaman et al., 2015; Kevers et al., 1955). Slopes of the study area have been reclassified after Kevers et al (1955) to identify how much land within a given slope class deserves allocation of particular management practices (Table 5).

Table 5: Manageability of the Satinskyi Catchment basing on Slope Classes

Slope Range (°)	Slope Range (%)	Slope Class	Area (ha)	Percent of Total Area	Mean Annual Soil Loss (tone)	Total Soil Loss (%)
0 - 2	0 - 5	**Class I**	121.2	0.4	1.5	0.02
2 - 7	5 - 12	**Class II**	498.0	1.6	7.8	0.36
7 - 15	12 - 25	**Class III**	1,988.7	6.6	17.9	3.34
15 - 35	25 -45	**Class IV**	15,999.0	52.9	33.7	50.52
> 35	> 45	**Class V**	11,623.8	38.5	42.0	45.76
Total			**30,230.7**	**100**		**100**

According to Kevers' classification, slopes between 0-2° (0-5%) correspond to ***Class I***. Soils of this class are not degraded and don't require soil erosion control practices. The soil productivity of land is taken as normal. ***Class II*** 2-7° (5-12%) terrain has normal productivity but needs minor correction to control soil erosion. Within ***Class III*** 7-15° (12-25%) lands present normal productivity but require major correction to control soil erosion (terrain relatively highly degraded). As can be seen, slope classes ***I***, ***II***, and ***III*** cover only 3.72% of total land. The remainder of the terrain (96.28% of total land) is classified within slope classes IV (15-35°) and V (>35°). ***Class IV*** 15-35 (25-45%) represents lands with poor productivity either because of the thin arable soil layer or soil is highly degraded. Beyond the slope of the ***V***, the terrain has to be abandoned from all farming purposes.

Based on their results, previous studies including Rahaman et al. (2015), Thakuri (2019), Kevers et al (1955) among others, attempted to classify soil erosion into soil erosion severity map, to which we referred to classify results for our study area with seven classes summarized in table 6 and illustrated by Figure 6.

Table 6: Estimated Soil Loss per Severity Class

Soil Loss (ton/ha/**year)**	Severity Class	Priority Class	Area (ha)	Percent of Total Area (%)	Mean Annual Soil Loss (ton)	Percent of Total Soil Loss
0 - 10	Low	VII	9,844.9	32.6	5.9	5.4
10 - 20	Moderate	**VI**	3,241.9	10.7	12.5	3.8
20 - 30	High	**V**	987.3	3.3	25.4	2.4
30 - 45	Very High	**IV**	3,197.1	10.6	38.5	11.5
45 - 60	Severe	**III**	6,294.2	20.8	53.1	31.3
60 - 80	Very Severe	**II**	5,768.9	19.1	67.3	36.4
> 80	Extremely Severe	**I**	896.4	3.0	108.5	9.1
Total			**30,230.7**			

The soil loss severity per slope class manageability was estimated at low (< 10 t/ha/year), moderate (10-20 t/ha/year), high (20-30 t/ha/year), very high (30-45 t/ha/year), severe (45-60 t/ha/year), very severe (60-80 t/ha/year) and extremely severe (> 80 t/ha/year). Referring to Kevers' classification of slopes described above, it appears that 96.28 % of the total land of the study area is difficult to manage. On that basis, it was possible to establish the relation between ranges soil loss rates per annum and severity which serves as guidelines to the allocation of remediation measures.

Considering the distribution of mean annual soil loss on the study area, 67.5% of the total land record annual soil loss exceeding 10 t/ha/year, with 58 % of land (from class I to class Iv) recording mean annual soil loss greater than 30 t/ha/year. 96.58 % of the total land has a slope exceeding 7° with soil loss estimates of more than 17.9 t/ha/year, which is a serious threat to the sustainability of the local population depending on agriculture in the study area. Considering the land-use practices, seasonal agriculture alone which covers 60 % of total land accounts for 52.7 t/ha/year of soil loss estimates. The identified highest soil loss rates (> 80 t/ha/year) could be associated with localized mining pits or barren land in the study area.

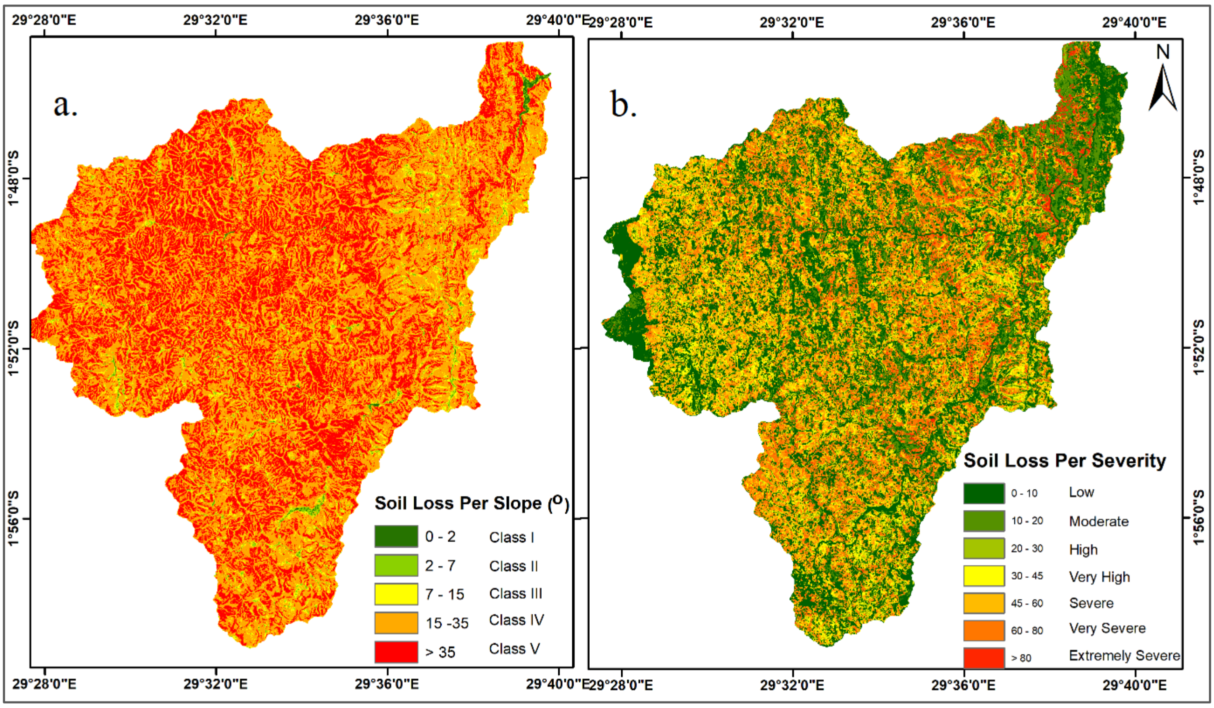

Figure 6: Annual Mean Soil Loss per Slope (a) and Soil Loss Severity classes (b)

The adverse effects of soil erosion in the study area might have many ramifications. As the maximum tolerable soil loss for cultivated slopes is well known (≤ 10 t/ha/year), it is obvious that crop production will keep on suffering strongly the greatest ecological damage through soil degradation processes threatening food security, given the high soil erosion rates (Hans, 1983). Many scientific discourses including Ashras and Issaka (2017) highlighted the on-site and off-site adverse effects of soil erosion on flora, fauna, soil productivity, open water bodies, wetlands, and dam operability. In such conditions, natural processes of soil erosion and earth material under the control of numbers of natural factors including substratum, slope, climate and vegetation already severe by nature are likely to be triggered by among others anthropogenic activities, ploughing, mining, and construction (Byizigiro et al. 2020).

In countries with an increasing population such as Rwanda, where there is a high demand for land for agricultural production and construction, soil erosion is a major problem. Poor land management may result in water runoff across landscape instead of adequate infiltration. Relocated topsoil which is rich in organic matter and nutrients may build up over time or is transported off-site where it accumulates in drainage channels and is usually severe on unprotected sloppy areas (Ashras and Issaka, 2017). Reduction of soil water holding capacity (WHC) and infiltration with an increasing overland flow reflect the level of soil degradation. The absence of reduced fallow periods, however, contributes to accelerated soil degradation. In almost all developing countries with similar land-use patterns, intensive soil erosion deprives plants and animals of their natural habitat with increasing pollution of air and siltation of open water bodies including dams (Berkun, 2010). Pollution of nearby water bodies and wetlands and the reduction in cropland productivity is linked to the erosion process. Though our study on Satinskyi catchment was bounded to estimating soil erosion, this research establishes a starting point for a further in-depth investigation of the negative impacts of soil erosion in the studied area.

5. Conclusion

Soil erosion is a national concern in Rwanda in general, particularly in the highly elevated and mountainous areas of the Northern and Western parts of Rwanda where Satinskyi catchment is located. In this area, steep slopes (greater than >15°) characterize more than 91% of the land. The catchment also accounts for high population density with 491 inhabitants/km^2, of whom the majority rely on agricultural activities. Steepened topography and intensive land-use/land-cover changes, in addition to high rainfall patterns, constitute, among others, major natural and anthropogenic factors triggering and aggravating soil loss rates characterizing the area. For average values of soil loss rate of 13.5 t/ha/year taking into consideration the effect of land cover and land use and 38,4 t/ha/year considering the mean slope (26°), Satinskyi catchment is classified as experiencing severe and very severe soil erosion rates. The highest soil erosion rates were identified in barren and highly disturbed lands, especially for land under seasonal agriculture.

Given that extensive part of Satinskyi catchment presents steeps slopes and thus, prone to soil high soil loss rates, knowledge of processes involved in soil erosion and their importance are essential for recommending appropriate mitigation measures. Outcomes of the studies will serve as a guide on whether terraces are the most recommendable or if supplementary measures have to be suggested to protect soil against erosion. The later should be agronomic measures of soil conservation such as mulching, agroforestry, etc., which would significantly contribute to alleviating devastating soil erosion processes.

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